RESEARCH REPORT

22

Growth and Development Following Partial Cutting of a Complex Stand in the Interior Cedar-Hemlock Zone of British Columbia: 40-Year Results

W.D. Johnstone

2002

British Columbia
Ministry of Forests
Forest Science Program

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ABSTRACT

The effects of partial cutting in an immature, complex stand in the Interior Cedar–Hemlock zone are analyzed 40 years after treatment. Three partial cutting treatments — improvement cut, diameter-limit cut, and salvage cut — were carried out in southern British Columbia. The results are presented for individual trees and the entire stand. Partial cutting had little effect on gross increment but a large effect on net increment over the 40-year period. The study demonstrates that partial cutting can be used to recover anticipated mortality. Partial cutting did not appear to increase the incidence of root rot, nor did it alter the pattern of ecological succession in the stand.

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INTRODUCTION

Forestry is the primary economic activity in the Interior Cedar–Hemlock (ICH) zone of British Columbia, and this is the most productive zone in the interior of the province for fibre production. Stands in the ICH typically display a high diversity of tree species, and often contain several high-value timber species. A description of past and present harvesting and silvicultural practices in the ICH is presented by Vyse and DeLong (1994). The ICH is also highly valued for the wildlife, recreational, and other non-timber resources found there. Recent changes to and restrictions on forest practices have led to a growing interest in partial cutting as a possible method for satisfying the needs of timber and non-timber users alike.

Despite its obvious importance, very little information is presently available on the effects of partial cutting on the growth, yield, and development of the complex stands of the ICH (Cameron 1998). Experimental Project (E.P.) 370b was established in 1957 with the following objectives:

1. to measure the response, in terms of growth and species composition, of a complex stand to a number of different methods of selecting trees for a partial cut, and
2. to study the economics of these methods, and to study the degree of damage to residual trees resulting from the different methods of tree selection.

This report focuses on the first objective by presenting results observed over the first 40 years of the experiment, and updates the 15-year results reported by Thompson (1977). Comparisons of the potential economic benefits of applying partial cutting treatments, similar to those used in this study, are provided by Stewart (1956) and Holmsen (1967).

METHODS

SITE AND STAND DESCRIPTION

This study is located at an elevation of 700 m, on a north-facing slope, on Fosthall Creek, approximately 20 km northwest of Nakusp in the Arrow Forest District (Figure 1). This site (50° 21'30" N, 118° 0'20" W) is ecologically classified as being primarily in the Redcedar–Western hemlock–Falsebox (04) site series of the Shuswap variant of the Moist Warm Interior Cedar–Hemlock biogeoclimatic subzone (ICHmw2) (Braumandl and Curran 1992). The soil is a well-drained, sandy loam with a moderate (40–50%) coarse-fragment content, and is classified as an Orthic Humo-Ferric Podzol, with a rooting depth of 30 cm. The moisture regime is classified as submesic, and the nutrient regime is classed as poor. The stand contained 12 tree species (Appendix 1), and is a fairly typical, mid-seral, fire-origin ICHmw2 stand, characterized by immature cedar and hemlock with an overstory of white pine, Douglas-fir, and larch. The average site index (based on top height at 50 years breast-height age) of the study area is 24.1 m for Douglas-fir, 23.3 m for western larch, and 20.6 for white pine, but varies among plots.[1] At the time of study establishment, the stand was estimated to be 60–70 years old (Thompson 1977). Stand conditions at the time of study establishment are shown in Appendices 2 and 3.

1 J.W. Goudie, Biometrician, Growth and Yield, B.C. Min. For., Res. Br., Victoria, B.C. pers. comm., Oct. 2000.

STUDY DESIGN AND ESTABLISHMENT

In 1956, prior to cutting, the study area was divided into 20 treatment plots. A 0.101-ha (0.25-acre), square sub-plot was then established within each treatment plot. A complete diameter at breast height outside bark (dbhob) tally of all trees 9.1 cm (3.6 in.) dbhob and larger, by species, was taken of each sub-plot. The treatment plots were ranked according to the basal areas of the sub-plots. Based on the similarity of their basal areas, the plots were then divided into five groups of four plots, to which the four treatments were randomly assigned. In the winter of 1956/57 and spring of 1957, the following treatments were applied:

1. **Improvement cut:** thinning of clumps, release of high-value trees, and removal of low-value trees, where this could be done without damage to the residual trees or prejudice to full stocking. Treatment 1 removed approximately 23% of the basal area.
2. **Diameter-limit cut:** removal of trees above a certain diameter class, such that the basal area removed was approximately equal to the basal area removed in the improvement

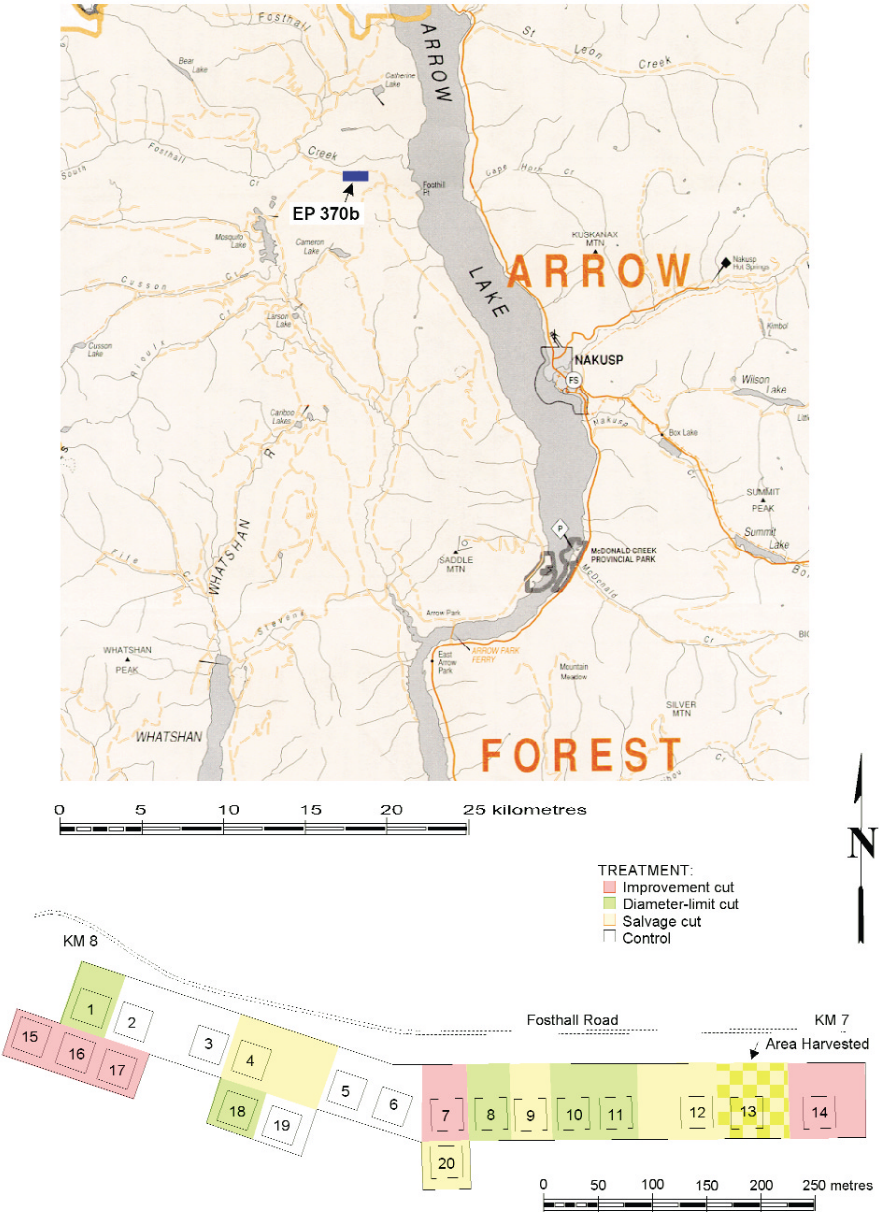

FIGURE 1 *Location map and plot layout of E.P. 370b.*

cut (Treatment 1). Treatment 2 removed approximately 22% of the basal area.

3. **Salvage cut:** removal of all hardwoods, plus all larch and white pine, except approximately five pine and five larch trees per ha for a seed source when the final cut is made. Treatment 3 removed approximately 39% of the basal area.
4. **Control:** no cutting.

Cutting in Treatments 1 and 3 was restricted to trees 20.3 cm (8.0 in.) dbhob and larger. Cutting in Treatment 2 corresponded to minimum diameter limits of 35.6–40.6 cm (14–16 in.) dbhob, depending upon the group, to ensure a similar level of removal to that of Treatment 1 within the same group. Treatment 3 (salvage cut) was predicated on the assumption that the white pine and larch would not survive disease or deterioration for a full rotation in the "wet-belt." In the summer of 1989, Plot 13 (one of the salvage plots) was accidentally destroyed by logging.

MEASUREMENT AND COMPILATION

Following the logging in 1957, the pre-cutting sub-plots were relocated, and all living trees 9.1 cm (3.6 in.) dbhob and larger were tagged and measured in November 1957. At that time, the dbhob and condition of all tagged trees were recorded, along with the total heights of approximately 18% of the tagged trees. All living tagged trees were remeasured, according to a 5-year measurement schedule, in the falls of 1962, 1967, 1972, 1977, and the spring of 1983. In the fall of 1990, 33 years after establishment, all living trees, including those previously omitted because they were below the threshold diameter limit, were assessed for diameter, height, and condition. All plots were stem-mapped at that time. All living trees were reassessed for diameter, height, and condition in the fall of 1997, and a survey of pest conditions was carried out.

Due to the logging in 1989, a complete measurement record is not available for Plot 13, and it was eliminated from this analysis. Individual-tree data are not available for the pre-cutting sub-plots. Instead, pre-treatment stand conditions are based on stand tables, which list the frequency of trees by 2.54-cm (1.0-in.) diameter classes for each species. Individual-tree data were compiled into post-treatment stand tables to allow the comparison of stand conditions at study establishment (Appendices 2 and 3), and to determine the intermediate yield recovered by partial cutting treatments. Between 1957 and 1990, the diameters of all trees tagged at study establishment were measured, but only a small percentage of these trees were measured for height. Therefore, it was necessary to derive height-diameter equations to estimate the heights of the trees in order to estimate individual-tree volumes.[2] Because the numbers of heights measured for several species, even across all treatments, were insufficient to produce reliable height equations, some grouping of species, across treatments, was necessary. For each assessment period, from 1957 to 1983, separate height-diameter equations were derived for the following species groups, irrespective of treatment: broadleaves (Act, At, Ep, Md), spruce-balsam (Sx, Bl), cedar (Cw), Douglas-fir (Fd), hemlock (Hw), larch (Lw), and pine (Pl, Pw). In 1990 and 1997, the diameter and height of all living trees, including those not previously tagged (i.e., "ingrowth" trees), were measured, and, therefore, height-diameter equations were not required.

2 Volumes are inside-bark volumes calculated from Kozak's taper functions. Merchantable volume is the bole volume between a 30-cm stump and a 10-cm dib (diameter inside bark) top for all trees 12.5 cm dbhob and larger.

ANALYSES

Because of the large number of tree species involved in this study, the data were combined into four species groups: "FLP" (Fd, Lw, Pw, Pl), "SB" (Sx, Bl), "CH" (Cw, Hw), and "Bdlf" (Act, At, Ep, Md). Mean-tree and per-hectare stand values of each plot were calculated for each measurement period based on the values of the trees tagged at study establishment. Unless otherwise noted, per-hectare values are net values (i.e., exclude ingrowth and mortality), and were determined for each plot by multiplying the mean value of the tagged trees by the current stand density of that plot. Data from all replications of each treatment were combined to produce the summary data provided in this report. Because of the exclusion of Plot 13, and because different compilation procedures and different height-diameter and volume equations were used, differences may be noticed between the present results and those previously reported (Thompson 1977) for this experiment.

Analyses of variance, based on a randomized complete-block design, were used to determine the effects of the treatments on mean-tree and per-hectare stand values. These analyses were limited to the observations made immediately following treatment (1957) and following 40 growing seasons (1997). Furthermore, the analyses were based on data for all species combined; comparisons were not made for individual species or species groups. The Tukey-Kramer method was used to make pairwise comparisons between treatments. All analyses were performed using SAS statistical procedures (SAS Institute Inc. 1990).

RESULTS

Due to the large variation among replicates within treatments, few statistically significant ($p \leq 0.05$) treatment effects on mean-tree and per-hectare stand characteristics were observed in this study (Appendix 4). However, these results do indicate that, immediatedly following treatment, the partial cutting did result in significant differences in the levels of the residual growing stock in terms of basal area ($p = 0.001$), total volume ($p = 0.000$), and merchantable volume ($p = 0.001$), but, as prescribed, the differences between Treatments 1 and 2 were not significant. These results also indicate that only the salvage cut (Treatment 3) significantly reduced the accumulated total volume ($p = 0.035$) and merchantable volume ($p = 0.034$) mortality losses over the 40-year response period.

STAND DIAMETER

The effect of partial cutting on stand diameter development is shown in Figure 2. During the 40 years since cutting, diameter growth in the treated plots has generally exceeded the growth in the untreated controls (Figure 3), but the differences are small. The increase in 40-year diameter increment, for the surviving trees (all species combined), varied from a low of 12% in the diameter-limit cut (Treatment 2) to a high of 16% in the salvage cut (Treatment 3) compared to the controls. For those surviving trees, the FLP species group had the largest average 40-year diameter increment in the improvement cut, while the SB species group had the largest 40-year increment in the diameter-limit, salvage, and control plots; however, it must be noted that the trees in the FLP species group in all treatments were substantially larger at the start of the growth period.

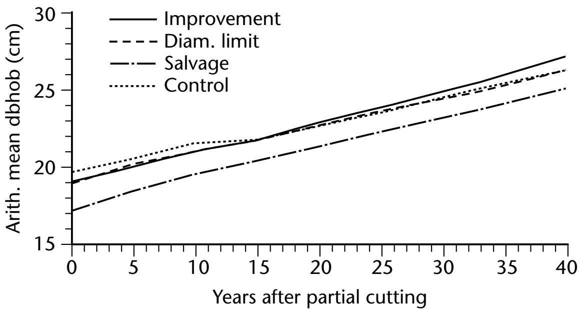

FIGURE 2 *Diameter development following partial cutting.*

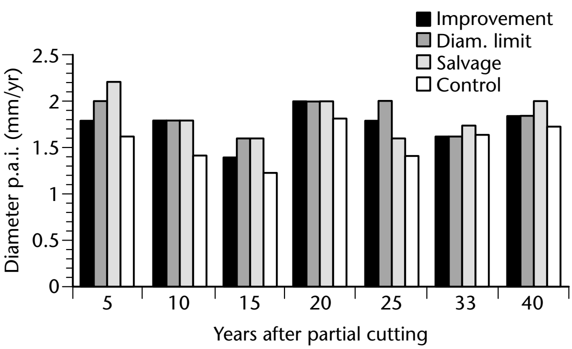

FIGURE 3 *Periodic annual diameter increment following partial cutting.*

STAND HEIGHT

Figure 4 shows the effect of partial cutting on height development. At study establishment, the mean height of the salvage plots was slightly shorter than that of the remaining plots, probably because this treatment harvested many of the taller larch and white pine trees. In terms of mean height, the FLP species group was the tallest, followed, in order, by the Bdlf, SB, and CH species groups. The tallest individual species was cottonwood, followed in order by Douglas-fir, larch, aspen, birch, and white pine. Forty years after treatment, the mean heights of all treatments were very similar, but the mean height in the salvage plots remained slightly shorter. The FLP remained the tallest species group, but the SB group assumed second position ahead of the Bdlf and CH group, respectively. At that time, the tallest individual species was aspen, followed, in order, by Douglas-fir, larch, cottonwood, lodgepole pine, and spruce. As with diameter, partial cutting did not have a major impact on height development or growth (Figure 5) over the 40 years following treatment. Over the 40-year observation period, the height growth of surviving trees (all species combined) was essentially the same for all of the treatments, and, within all treatments, the fastest height growth was observed in the SB species group, followed by the CH, FLP, and Bdlf groups, respectively. The reasons for the negative Bdlf periodic height increment during the second-to-last growth period (Figure 5) are unclear, but may be due, in part, to top dieback and breakage, and also to an overestimation of height by the height-diameter equations.

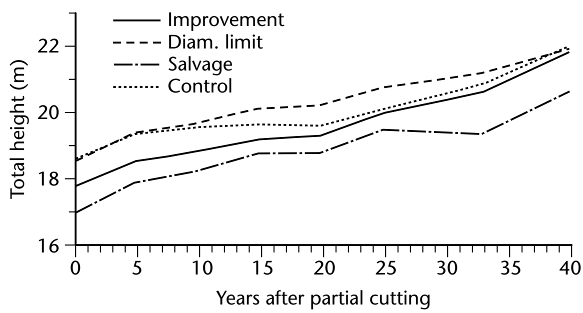

FIGURE 4 *Height development following partial cutting.*

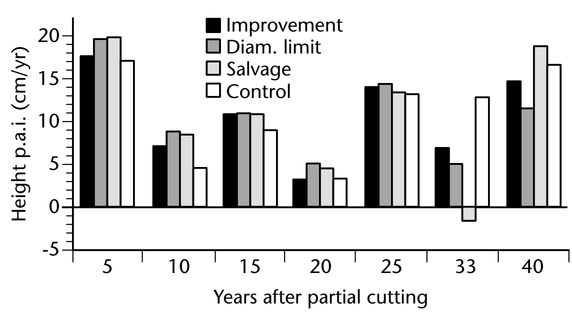

FIGURE 5 *Periodic annual height increment following partial cutting.*

INDIVIDUAL-TREE VOLUME

Given the lack of any dramatic effect on diameter and height, it is not surprising that partial cutting had little effect on mean-tree volume (Figure 6) or volume growth (Figure 7) during the 40-year period following treatment. Trees in the improvement cut grew slightly faster following treatment. For surviving trees (all species combined), the mean 40-year individual-tree total volume increment in the improvement cut was 13% higher than in the diameter-limit cut, 16% higher than in the salvage cut, and 19% higher than in the uncut control. Within treatments, the FLP species group had the highest mean 40-year total volume increment in the improvement cut, while the SB group had the highest increments in the remaining treatments. Figure 8 shows the effects of partial cutting on individual-tree merchantable volume over the 40-year response period. In terms of mean, individual-tree, 40-year merchantable volume increment (Figure 9), the improvement cut was 16, 18, and 20% higher than the diameter-limit, salvage, and control treatments, respectively, and the highest treatment-species group combinations were the same as those observed for total volume increment.

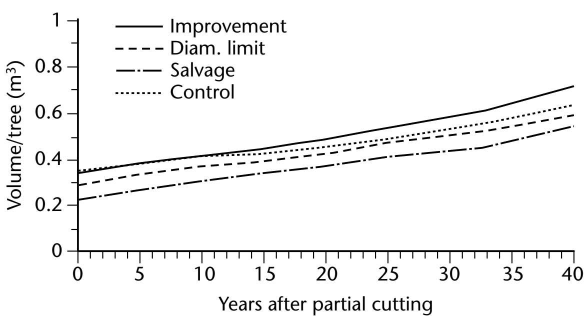

FIGURE 6 *Individual-tree total volume development following partial cutting.*

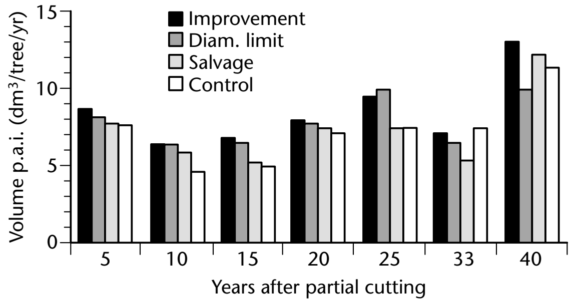

FIGURE 7 *Periodic annual total volume increment per tree following partial cutting.*

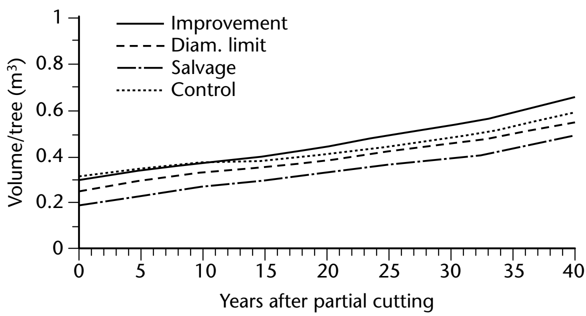

FIGURE 8 *Individual-tree merchantable volume development following partial cutting.*

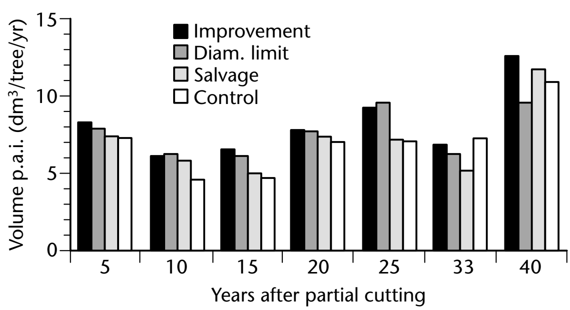

FIGURE 9 *Periodic annual merchantable volume increment per tree following partial cutting.*

STAND BASAL AREA

Figure 10 shows the effects of partial cutting on stand basal area. All of the treated plots increased substantially in basal area over the 40 years compared to the control plots, where only a slight increase was observed. Both net and gross periodic increments were determined for the stand basal areas of the various treatments (Table 1). Partial cutting had little effect on gross periodic annual increment. However, because partial cutting resulted in lower mortality, the net periodic annual growth rates in the treated stands were 235–282% higher than in untreated stands. If the basal area of the trees removed by the cutting is taken into consideration, the gross periodic annual production of the treated plots was 59–87% higher than that of the control plots. Appendix 5a shows the accumulated gross basal area accretion (gross increment including mortality, but excluding ingrowth), by species groups, of the four treatments. In all treatments, including the controls, the largest proportion of basal area accretion was accrued by the CH species group.

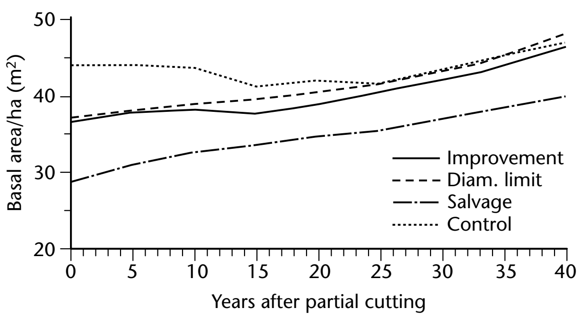

FIGURE 10 *Stand basal area per hectare (m^2/ha) following partial cutting.*

STAND VOLUME

As with basal area, the stand total volume of the partially cut plots increased dramatically compared to that of the control plots (Figure 11). Table 2 shows a comparison of the net and gross increments in total volume of the various treatments.

TABLE 1 *Net and gross increments in stand basal area for all species combined*

Measurements	Basal area (m^2/ha)				% of control			
	Improvement	Diam. limit	Salvage	Control	Improvement	Diam. limit	Salvage	Control
1957 basal area before cut	47.44	47.16	47.00	43.87	108.1	107.5	107.1	100.0
Basal area removed in 1957	11.03	10.26	18.43	0.00	-	-	-	-
1957 basal area after cut	36.41	36.90	28.57	43.87	83.0	84.1	65.1	100.0
1997 basal area[a]	46.33	47.97	39.89	46.83	98.9	102.4	85.2	100.0
Net increment 1957–1997[a]	9.92	11.07	11.32	2.96	335.1	374.0	382.4	100.0
Net periodic annual increment	0.248	0.277	0.283	0.074	335.1	374.0	382.4	100.0
Mortality 1957–1997	12.68	13.91	11.48	18.31	69.3	76.0	62.7	100.0
Ingrowth 1957–1997	4.35	3.64	3.51	2.62	166.0	138.9	134.0	100.0
Gross increment 1957–1997[b]	26.95	28.62	26.31	23.89	112.8	119.8	110.1	100.0
Gross periodic annual increment	0.674	0.716	0.658	0.597	112.8	119.8	110.1	100.0

a Excludes ingrowth.
b Includes ingrowth and mortality.

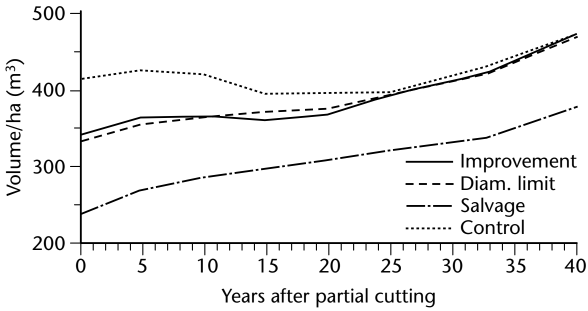

FIGURE 11 *Stand total volume per hectare (m^3/ha) following partial cutting.*

Again, as with basal area, there was little difference among the gross periodic annual increments of the treated and untreated plots. However, the net increments in total volume were 125–139% higher in the treated plots than in the controls and, if the volume removed by partial cutting is considered, the gross production was 49–69% higher in the treated plots compared to the controls. Cumulative gross total volume accretion (gross increment including mortality, but excluding ingrowth) for the last 40 years is shown in Appendix 5b. In the improvement cut, the largest total volume accretion has been accrued by the FLP species group. In all other treatments, including the control, the greatest total volume accretion occurred in the CH species group. In all treatments, the proportion of accretion is increasing for the CH species group and declining for the remaining species groups.

Partial cutting has also had a dramatic effect on stand merchantable volume over the 40-year response period (Figure 12). Although the gross increments in merchantable volume are quite similar for all treatments, partial cutting increased the net increments 94–106% and the gross production 46–64% compared to the controls (Table 3). Cumulative gross merchantable volume accretion (gross increment including mortality, but excluding ingrowth) is shown in Appendix 5c. Accretion patterns for merchantable volume were the same as those for total volume.

TABLE 2 *Net and gross increments in stand total volume for all species combined*

Measurements	Total volume (m³/ha)				% of control			
	Improvement	Diam. limit	Salvage	Control	Improvement	Diam. limit	Salvage	Control
1957 volume before cut	450.85	449.26	429.96	412.12	109.4	109.0	104.3	100.0
Volume removed in 1957	110.55	117.48	194.27	0.00	-	-	-	-
1957 volume after cut	340.30	331.78	235.69	412.12	82.6	80.5	57.2	100.0
1997 volume[a]	474.28	467.59	378.06	471.75	100.5	99.1	80.1	100.0
Net increment 1957–1997[a]	133.98	135.81	142.37	59.63	224.7	227.8	238.8	100.0
Net periodic annual increment	3.350	3.395	3.559	1.491	224.7	227.8	238.8	100.0
Mortality 1957–1997	131.21	143.72	102.25	195.17	67.2	73.6	52.4	100.0
Ingrowth 1957–1997	27.83	22.70	17.42	15.87	175.4	143.0	109.8	100.0
Gross increment 1957–1997[b]	293.02	302.23	262.04	270.67	108.3	111.7	96.8	100.0
Gross periodic annual increment	7.326	7.556	6.551	6.767	108.3	111.7	96.8	100.0

a Excludes ingrowth.
b Includes ingrowth and mortality.

TABLE 3 *Net and gross increments in stand merchantable volume for all species combined*

Measurements	Merchantable volume (m³/ha)				% of control			
	Improvement	Diam. limit	Salvage	Control	Improvement	Diam. limit	Salvage	Control
1957 volume before cut	398.84	396.20	369.78	363.17	109.8	109.1	101.8	100.0
Volume removed in 1957	101.69	110.71	176.52	0.00	-	-	-	-
1957 volume after cut	297.15	285.49	193.26	363.17	81.8	78.6	53.2	100.0
1997 volume[a]	439.17	428.25	343.99	436.32	100.7	98.2	78.8	100.0
Net increment 1957–1997[a]	142.02	142.76	150.73	73.15	194.1	195.2	206.1	100.0
Net periodic annual increment	3.551	3.569	3.768	1.829	194.1	195.2	206.1	100.0
Mortality 1957–1997	115.17	127.66	86.67	174.66	65.9	73.1	49.6	100.0
Ingrowth 1957–1997	18.45	14.76	8.66	10.24	180.2	144.1	84.6	100.0
Gross increment 1957–1997[b]	275.64	285.18	246.06	258.05	106.8	110.5	95.4	100.0
Gross periodic annual increment	6.891	7.130	6.152	6.451	106.8	110.5	95.4	100.0

a Excludes ingrowth.
b Includes ingrowth and mortality.

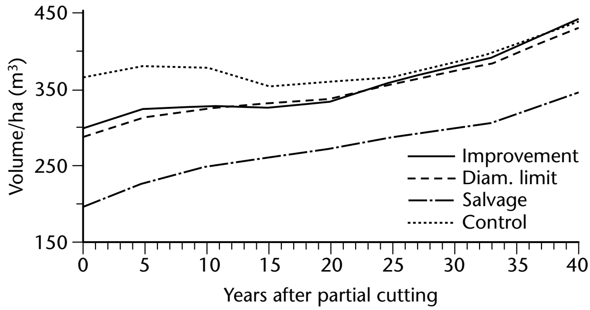

FIGURE 12 *Stand merchantable volume per hectare (m³/ha) following partial cutting.*

INGROWTH

Ingrowth is the trees that, subsequent to the establishment of the experiment, have grown past the 9.1-cm measurement threshold. These may be advanced growth or trees that have regenerated since the study was established. Because no attempt was made to account for these trees during the first 33 years of the trial, their origin is unknown. As can be seen in Tables 1–3, ingrowth has had a substantial effect on the gross periodic increments of all of the treatments, particularly for the improvement and diameter-limit cuts. In all of the treatments, the vast majority of ingrowth total volume accrued to the CH species group (varying from 68% in the diameter-limit treatment to 99% in the improvement treatment). SB ingrowth, in a very small amount, occurred only in the diameter-limit and improvement cuts, and there was no FLP ingrowth in the salvage cut. All of the plots presently contain a large number of trees (ranging from 1000 trees/ha in the controls to 2100 trees/ha in the salvage plots) below the threshold diameter limit. As with the ingrowth trees, virtually all of these trees are in the CH species group.

Mortality is the original measurement trees that have died since the establishment of the study. As shown in Figure 13, there has been a large reduction in the number of trees per hectare in all of the treatment plots. The effect of this loss of growing stock on the gross and net increments of all treatments is shown in Tables 1–3. Because they do not include losses to ingrowth, the mortality estimates presented here are expected to be conservative. Appendix 6 shows the cumulative mortality during the last 40 years, by species group, for each treatment. On a volume basis, by far the largest proportion of the mortality occurred in the FLP species group, irrespective of treatment. The broadleaf species suffered the second-highest level of mortality in all treatments except for the salvage cut, where CH suffered the second-highest level of mortality. Especially early in the study, mortality in the CH species group occurred in smaller trees compared to the other species groups (Appendix 7).

Many of the tree species involved in this trial are at risk from a number of biological agents. For example, Douglas-fir, interior spruce, subalpine fir, hemlock, pine, and cedar are either susceptible or moderately susceptible to *Armillaria ostoyae* root disease (Morrison et al. 1991), which occurs throughout the study area. This is of particular concern in partial cutting because the root systems of infected, harvested trees become colonized by the fungal pathogen. The inoculum potential is at its maximum because the food base is newly

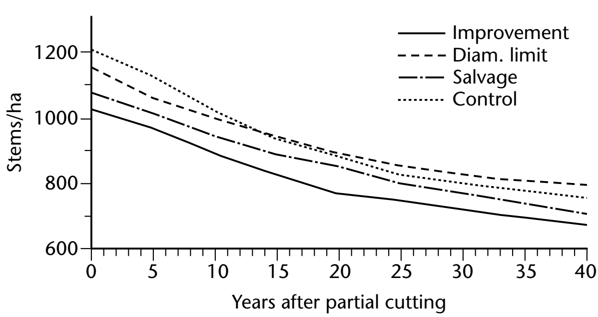

FIGURE 13 *Stems per hectare following partial cutting.*

colonized. If the roots of adjacent, healthy trees come in contact with the colonized root systems, they are exposed to the inoculum. Given the high level of mortality observed in the uncut controls, it does not appear that partial cutting has exacerbated the root disease problems in this stand. This observation is supported by the results of the recent root disease survey,[3] which found no significant differences in infection levels among treatments, and no significant differences between the partial cutting treatments and the uncut control. However, it should be noted that these survey results are based on non-destructive sampling, and that the detection of root disease infection is difficult in living trees using this technique. In addition, white pine is at very high risk from blister rust (*Cronartium ribicola*), and this fungus is believed to have caused the major decline in this highly valued timber species during the last 40 years (Appendix 3). Although these two diseases were the leading causes of mortality in the present study, it appears that the mortality of intolerant species, such as larch, lodgepole pine, Douglas-fir, and birch, particularly in subordinate crown classes, was attributable to shading by the overstory.

3 Schulting, J. and M. Schulting. 1998. Root disease assessment of Experimental Project (EP) 370-B 40-years post-treatment. Unpublished report for the Nelson Forest Region prepared by Pathocon Consulting.

STAND DEVELOPMENT

Over the course of this experiment, the stand has continued its ecological succession from late-seral to early-climax stages of stand development. As shown in Figures 14 and 15, the pioneer species, which are found mainly in the FLP and Bdlf species groups, are dying out and are being replaced, both in terms of stand density and stand total volume, by the climax species of the CH species group. If ingrowth is taken into consideration, this transition is even more dramatic. The relative frequencies of individual species, at study establishment and after 40 years, are shown in Appendix 3. Appendices 8a–8d show the vertical stratification of the species groups, for the four treatments, at study establishment and after 40 years. Irrespective of treatment, these results illustrate the decline in the pioneer species, and show that they are being replaced by the CH group in the upper crown stratum. If ingrowth is taken into consideration, these results also illustrate the virtual absence of species other than cedar and hemlock in the lower crown layers. The results clearly show that the partial cutting had little or no overall impact on successional development.

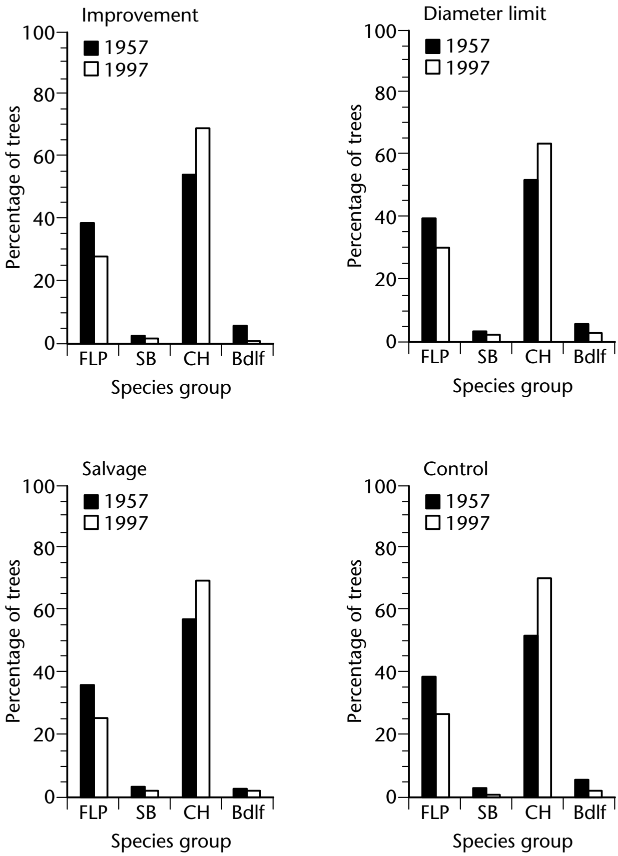

FIGURE 14 *Stand composition, by species group, as a percentage of total number of trees, following treatment (1957) and after 40 growing seasons (1997).*

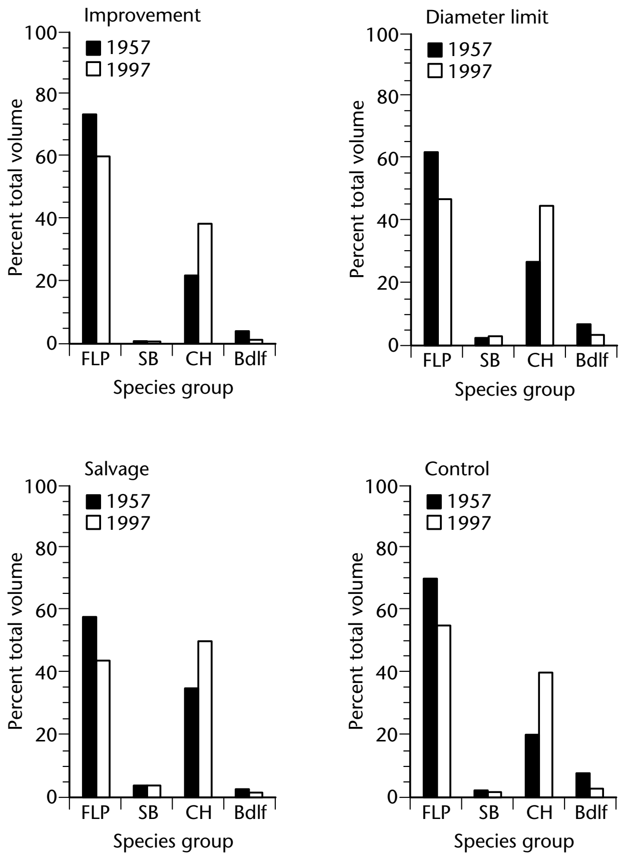

FIGURE 15 *Stand composition, by species group, as a percentage of stand total volume, following treatment (1957) and after 40 growing seasons (1997).*

DISCUSSION AND CONCLUSIONS

Intermediate cuttings are usually undertaken to stimulate and control the growth of the residual stand, regulate species composition, enhance stand health, and provide an early financial return (yield). The degree to which partial cutting achieved these objectives in the present study is mixed. Partial cutting had little detectable effect on stimulating the growth of the residual trees. On the other hand, partial cutting was successful, primarily through the recovery of potential mortality and the stimulation of ingrowth, in increasing the gross and net increments at the stand level. The results tend to support Thompson's (1977) conclusions that the levels of cut were too conservative, and that the removal of the high-value species, particularly white pine and larch, should have been greater.

The results clearly demonstrate that this stand is progressing from a late-seral to an early-climax stage of stand development. Many of the pioneer species, including larch, white and lodgepole pine, Douglas-fir, and the broadleaf species, are dying out and being replaced by cedar and hemlock. Partial cutting has not reversed or slowed this trend. Given the heavy stocking of CH advanced growth in the understory, this trend is likely to continue in the absence of heavy cutting and extensive site disturbance. The results also support the patterns of stand development and vertical stratification observed in the ICH by Cameron (1996).

This study clearly demonstrates the need to recognize which trees are at risk when developing treatment prescriptions. Over the last 40 years virtually all of the highly valued white pine have been lost due to blister rust. In addition, most of the remaining species are at least moderately susceptible to Armillaria root disease, which is present throughout the site. Given the high level of mortality observed in the uncut controls, it does not appear that partial cutting has exacerbated the root disease problems in this stand. Although these two diseases were the leading causes of mortality in the present study, it appears that some of the mortality in intolerant species may be due to shading by the overstory.

The results suggest that high-risk stands, such as the one in this study, should be clear-cut, and the site regenerated to non-host tree species. Where this strategy is not acceptable, the results show that partial cutting can be effectively used to salvage a substantial yield that would otherwise be lost to mortality. Of the treatments tested, the salvage cut, which removed the largest volume and many of the high-risk trees, provided the largest reduction in mortality and the highest net increment. The diameter-limit and improvement cuts were roughly equal in their effect on both mortality and increment. This supports similar earlier conclusions by Holmsen (1967) and Thompson (1977).

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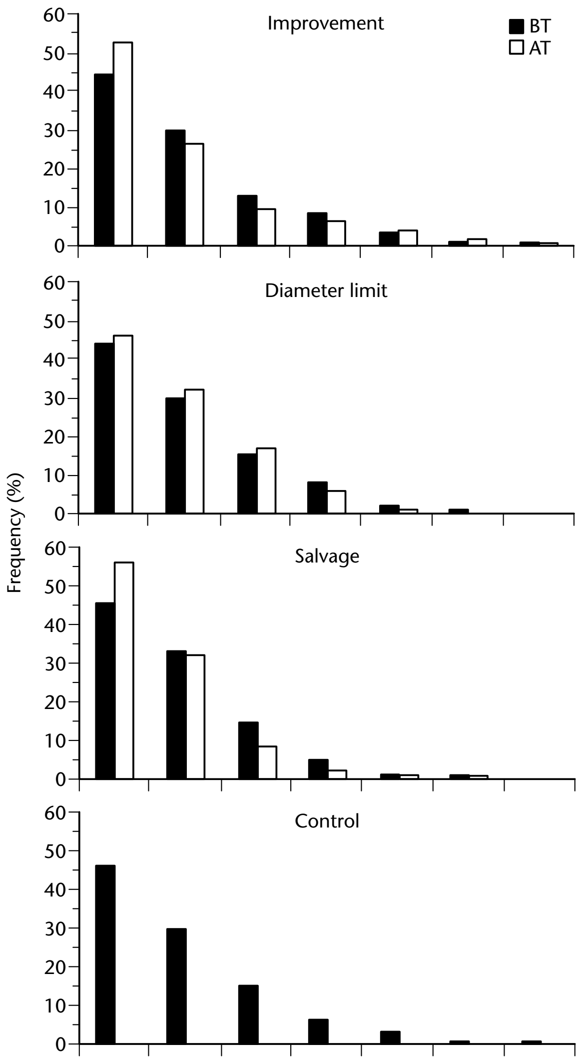
APPENDIX 1

Tree species present in E.P. 370b, and their species symbols.

Common name	Scientific name	Species symbol
Black cottonwood	*Populus balsamifera* ssp. *trichocarpa*	Act
Trembling aspen	*Populus tremuloides*	At
Subalpine fir	*Abies lasiocarpa*	Bl
Western redcedar	*Thuja plicata*	Cw
Paper birch	*Betula papyrifera*	Ep
Douglas-fir	*Pseudotsuga menziesii*	Fd
Western hemlock	*Tsuga heterophylla*	Hw
Western larch	*Larix occidentalis*	Lw
Douglas maple	*Acer glabrum*	Md
Lodgepole pine	*Pinus contorta*	Pl
Western white pine	*Pinus monticola*	Pw
Hybrid white spruce	*Picea engelmannii* x *glauca*	Sx
Western yew	*Taxus brevifolia*	Tw
Mountain alder	*Alnus tenuifolia*	Dm

APPENDIX 2A

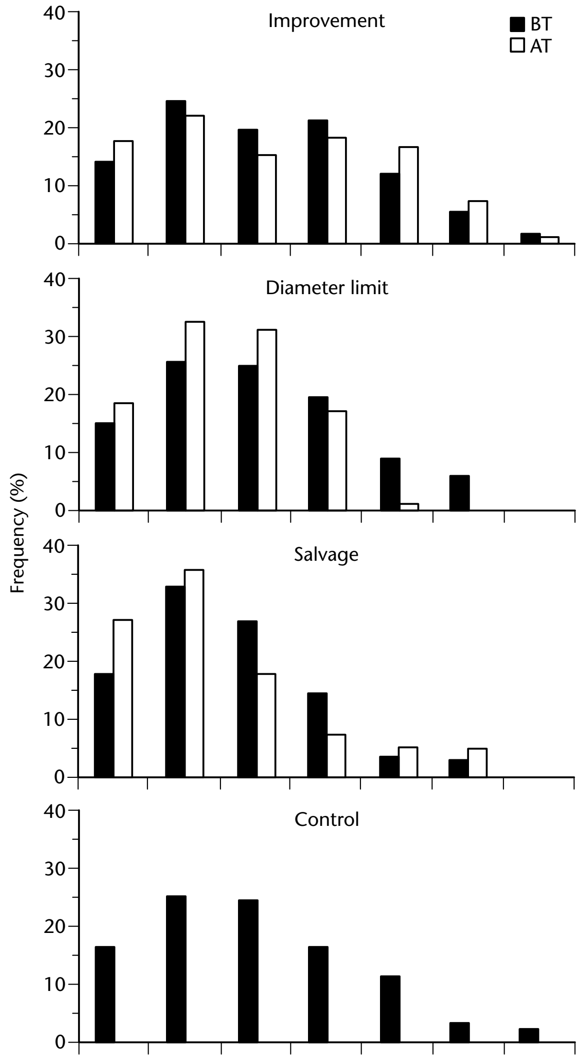
Distribution of stems per hectare (% frequency), by diameter class, before (BT) and after (AT) partial cutting in 1957.



Diameter class	12.7	20.3	27.9	35.6	43.2	50.8	58.4
Inches	4–6	7–9	10–12	13–15	16–18	19–21	22–24
Centimetres	9.1–16.5	16.6–24.1	24.2–31.7	31.8–39.4	39.5–47.0	47.1–54.6	54.7–64.8

APPENDIX 2B

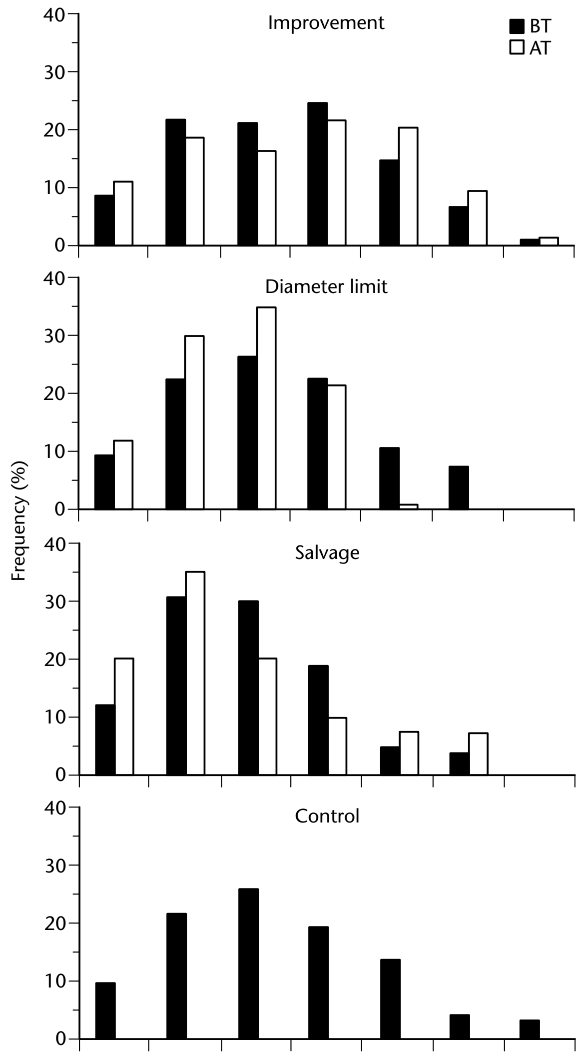
Distribution of basal area per hectare (% frequency), by diameter class, before (BT) and after (AT) partial cutting in 1957.



Diameter class	12.7	20.3	27.9	35.6	43.2	50.8	58.4
Inches	4–6	7–9	10–12	13–15	16–18	19–21	22–24
Centimetres	9.1–16.5	16.6–24.1	24.2–31.7	31.8–39.4	39.5–47.0	47.1–54.6	54.7–64.8

APPENDIX 2C

Distribution of total volume per hectare (% frequency), by diameter class, before (BT) and after (AT) partial cutting in 1957.



Diameter class	12.7	20.3	27.9	35.6	43.2	50.8	58.4
Inches	4–6	7–9	10–12	13–15	16–18	19–21	22–24
Centimetres	9.1–16.5	16.6–24.1	24.2–31.7	31.8–39.4	39.5–47.0	47.1–54.6	54.7–64.8

APPENDIX 3A

Species composition, as a percent of number of trees, before and after partial cutting in 1957, and after 40 growing seasons in 1997.

	FLP				SB		CH		Bdlf			
Treatment	FD	Lw	Pw	Pl	Sx	Bl	Cw	Hw	Act	At	Ep	Md
Improvement:												
1957 - Before cut	14.5	10.3	16.7	1.8	2.3	0.3	24.6	22.4	0.0	5.2	0.0	1.9
1957 - After cut	14.6	6.7	15.8	1.2	1.5	0.4	29.1	25.2	0.2	2.9	0.0	2.3
1997 - Original trees	16.5	5.6	5.3	0.6	1.8	0.0	39.8	29.5	0.0	0.6	0.0	0.3
1997 - Original trees + Ingrowth	12.1	3.9	4.1	0.4	1.2	0.2	42.9	33.9	0.0	0.4	0.0	0.8
Diameter limit:												
1957 - Before cut	12.1	15.8	14.4	0.5	3.0	0.0	24.9	24.0	0.0	3.8	0.9	0.6
1957 - After cut	10.3	15.6	13.2	0.5	2.9	0.3	26.4	25.4	0.0	3.4	1.2	0.7
1997 - Original trees	10.7	15.2	4.5	0.2	2.5	0.0	37.3	26.6	0.0	1.0	1.5	0.5
1997 - Original trees + Ingrowth	8.5	11.5	3.8	0.2	2.3	0.0	39.1	32.3	0.0	0.8	1.1	0.4
Salvage:												
1957 - Before cut	9.3	21.0	16.2	0.7	2.5	0.0	22.7	22.2	0.0	4.4	0.2	0.8
1957 - After cut	12.2	15.2	8.3	0.5	3.7	0.0	29.7	27.6	0.0	1.8	0.2	0.9
1997 - Original trees	13.7	8.4	3.9	0.0	2.5	0.0	41.4	28.1	0.0	0.7	0.4	1.1
1997 - Original trees + Ingrowth	9.7	6.0	2.7	0.0	1.7	0.0	43.6	34.4	0.0	0.5	0.2	1.0
Control:												
1957 - Before cut	15.2	7.4	15.7	1.0	2.8	0.2	19.7	32.5	0.5	3.6	1.0	0.5
1957 - After cut	-	-	-	-	-	-	-	-	-	-	-	-
1997 - Original trees	18.2	7.4	1.1	0.3	0.8	0.0	30.8	39.5	0.3	0.8	1.1	0.0
1997 - Original trees + Ingrowth	14.6	6.2	0.8	0.2	0.6	0.0	34.0	41.4	0.2	0.6	1.1	0.2

APPENDIX 3B

Species composition, as a percent of stand basal area, before and after partial cutting in 1957, and after 40 growing seasons in 1997.

	FLP				SB		CH		Bdlf			
Treatment	FD	Lw	Pw	Pl	Sx	Bl	Cw	Hw	Act	At	Ep	Md
Improvement:												
1957 - Before cut	28.0	15.6	21.9	1.1	1.7	0.2	13.5	12.6	0.0	4.9	0.0	0.5
1957 - After cut	32.2	11.4	21.3	0.6	0.9	0.3	15.9	13.9	0.1	2.7	0.0	0.7
1997 - Original trees	37.5	9.9	5.7	0.4	1.0	0.0	26.1	18.4	0.0	1.0	0.0	0.1
1997 - Original trees + Ingrowth	35.1	9.0	5.3	0.3	0.9	0.0	27.3	20.9	0.0	0.9	0.0	0.2
Diameter limit:												
1957 - Before cut	21.8	20.3	20.7	0.6	2.3	0.0	13.6	14.0	0.0	5.6	0.9	0.2
1957 - After cut	15.5	19.7	20.0	0.8	2.6	0.1	17.1	17.8	0.0	5.0	1.2	0.2
1997 - Original trees	16.9	18.4	6.4	0.3	3.0	0.0	30.2	21.3	0.0	1.3	2.0	0.1
1997 - Original trees + Ingrowth	16.8	17.1	6.1	0.2	2.8	0.0	30.6	23.0	0.0	1.2	1.9	0.1
Salvage:												
1957 - Before cut	17.0	23.6	22.6	1.3	2.2	0.0	13.9	13.3	0.0	5.7	0.3	0.2
1957 - After cut	28.3	13.9	7.7	0.5	3.7	0.0	22.4	21.1	0.0	2.1	0.1	0.3
1997 - Original trees	29.8	6.5	2.2	0.0	3.4	0.0	34.9	21.6	0.0	1.0	0.2	0.3
1997 - Original trees + Ingrowth	27.4	6.0	2.1	0.0	3.1	0.0	35.6	24.4	0.0	0.9	0.2	0.3
Control:												
1957 - Before cut	29.1	11.6	21.4	1.3	2.0	0.2	10.6	17.4	1.6	4.0	0.8	0.1
1957 - After cut	-	-	-	-	-	-	-	-	-	-	-	-
1997 - Original trees	36.0	11.8	0.8	0.2	1.4	0.0	21.5	25.8	0.2	1.2	1.1	0.0
1997 - Original trees + Ingrowth	34.0	11.4	0.8	0.2	1.3	0.0	22.6	26.8	0.2	1.1	1.5	0.0

APPENDIX 3C

Species composition, as a percent of stand total volume, before and after partial cutting in 1957, and after 40 growing seasons in 1997.

	FLP				SB		CH		Bdlf			
Treatment	FD	Lw	Pw	Pl	Sx	Bl	Cw	Hw	Act	At	Ep	Md
Improvement:												
1957 - Before cut	29.6	16.3	26.3	1.1	1.6	0.2	10.0	9.1	0.0	5.4	0.0	0.4
1957 - After cut	35.0	12.2	25.8	0.6	0.8	0.2	11.7	10.0	0.1	3.0	0.0	0.5
1997 - Original trees	42.2	10.8	6.1	0.5	1.0	0.0	22.0	16.1	0.0	1.2	0.0	0.0
1997 - Original trees + Ingrowth	40.7	10.2	5.8	0.4	0.9	0.0	22.7	17.9	0.0	1.2	0.0	0.1
Diameter limit:												
1957 - Before cut	23.0	20.8	25.0	0.7	2.2	0.0	9.9	10.4	0.0	7.0	0.9	0.1
1957 - After cut	16.0	20.9	24.7	1.1	2.6	0.0	13.1	13.9	0.0	6.2	1.3	0.2
1997 - Original trees	18.4	21.2	7.5	0.3	3.4	0.0	25.5	20.0	0.0	1.6	2.0	0.1
1997 - Original trees + Ingrowth	18.9	20.2	7.3	0.3	3.3	0.0	25.8	20.7	0.0	1.5	1.9	0.1
Salvage:												
1957 - Before cut	18.0	24.0	26.9	1.7	2.1	0.0	10.1	9.8	0.0	6.9	0.3	0.2
1957 - After cut	33.6	14.6	9.1	0.7	3.8	0.0	18.3	17.0	0.0	2.6	0.1	0.3
1997 - Original trees	35.0	6.8	2.1	0.0	4.2	0.0	29.8	20.2	0.0	1.5	0.2	0.2
1997 - Original trees + Ingrowth	33.5	6.5	2.0	0.0	4.0	0.0	30.3	21.8	0.0	1.4	0.2	0.2
Control:												
1957 - Before cut	31.1	12.3	25.3	1.7	1.9	0.2	7.6	12.2	2.2	4.7	0.8	0.1
1957 - After cut	-	-	-	-	-	-	-	-	-	-	-	-
1997 - Original trees	40.1	13.6	1.0	0.3	1.7	0.0	17.5	22.7	0.2	1.8	1.1	0.0
1997 - Original trees + Ingrowth	38.8	13.4	0.9	0.3	1.7	0.0	18.2	23.3	0.2	1.7	1.5	0.0

APPENDIX 3D

Species composition, as a percent of stand merchantable volume, before and after partial cutting in 1957, and after 40 growing seasons in 1997.

	FLP				SB		CH		Bdlf			
Treatment	FD	Lw	Pw	Pl	Sx	Bl	Cw	Hw	Act	At	Ep	Md
Improvement:												
1957 - Before cut	31.3	17.0	27.1	1.0	1.5	0.1	8.1	8.2	0.0	5.5	0.0	0.2
1957 - After cut	37.4	12.8	26.7	0.6	0.7	0.2	9.4	8.7	0.1	3.1	0.0	0.2
1997 - Original trees	43.6	11.2	6.1	0.5	0.9	0.0	20.5	15.9	0.0	1.3	0.0	0.0
1997 - Original trees + Ingrowth	42.8	10.7	5.8	0.4	0.9	0.0	20.6	17.4	0.0	1.2	0.0	0.0
Diameter limit:												
1957 - Before cut	24.2	21.3	26.0	0.7	2.1	0.0	7.9	9.4	0.0	7.5	0.9	0.1
1957 - After cut	16.8	21.5	26.0	1.2	2.5	0.0	10.9	13.0	0.0	6.7	1.3	0.0
1997 - Original trees	19.1	21.8	7.6	0.3	3.5	0.0	23.9	20.1	0.0	1.7	2.0	0.1
1997 - Original trees + Ingrowth	19.8	21.0	7.5	0.3	3.4	0.0	23.9	20.5	0.0	1.6	1.9	0.1
Salvage:												
1957 - Before cut	19.3	24.2	28.2	1.9	2.0	0.0	8.2	8.6	0.0	7.3	0.3	0.0
1957 - After cut	37.8	13.9	9.1	0.7	3.8	0.0	15.9	15.9	0.0	2.8	0.0	0.0
1997 - Original trees	36.7	6.8	2.0	0.0	4.3	0.0	28.0	20.4	0.0	1.5	0.2	0.1
1997 - Original trees + Ingrowth	35.8	6.6	2.0	0.0	4.2	0.0	28.2	21.5	0.0	1.5	0.2	0.1
Control:												
1957 - Before cut	32.8	12.8	26.1	1.8	1.8	0.2	6.1	10.5	2.3	4.9	0.8	0.1
1957 - After cut	-	-	-	-	-	-	-	-	-	-	-	-
1997 - Original trees	41.3	14.0	0.9	0.3	1.8	0.0	16.2	22.4	0.2	1.8	1.1	0.0
1997 - Original trees + Ingrowth	40.4	13.9	0.9	0.3	1.7	0.0	16.5	22.8	0.2	1.8	1.5	0.0

APPENDIX 4

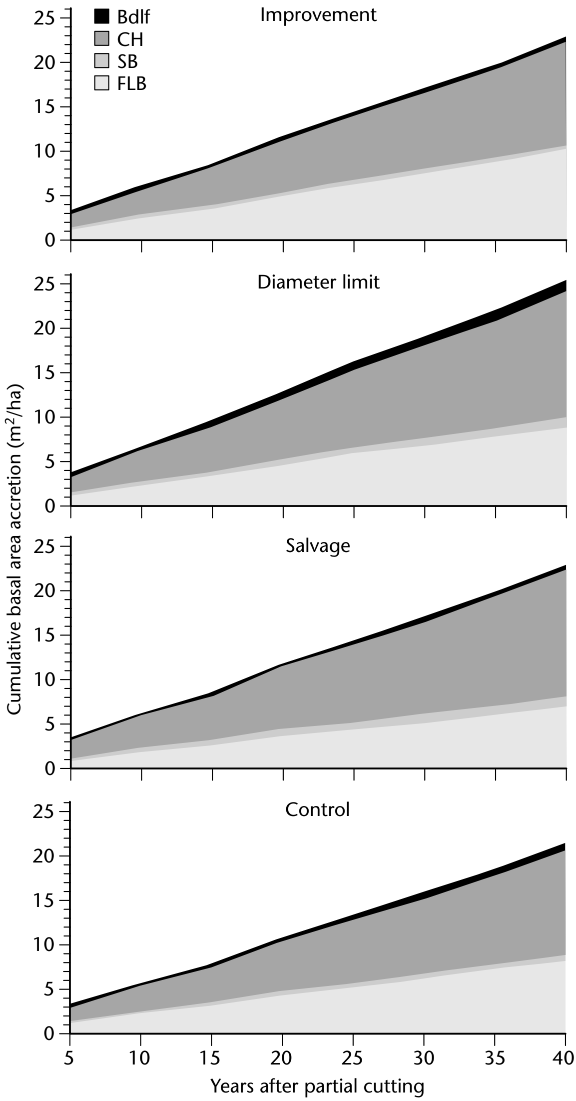
*Probability (p-values)[a] that the treatments **did not** affect the tree and stand characteristics (all species combined) following partial cutting.*

Characteristic	ANOVA results	Pairwise treatment comparisons 1-2	1-3	1-4	2-3	2-4	3-4
Arithmetic mean dbhob - 1957	0.230	0.705	0.409	0.207	0.932	0.735	0.980
- 1997	0.737	0.997	0.737	0.906	0.833	0.964	0.977
Mean height - 1957	0.752	0.842	0.778	0.815	0.998	1.000	0.999
- 1997	0.142	0.940	0.317	0.980	0.146	0.998	0.189
Mean total volume/tree - 1957	0.334	0.744	0.491	0.314	0.956	0.850	0.994
- 1997	0.410	0.709	0.348	0.753	0.882	1.000	0.850
Mean merch. volume/tree - 1957	0.320	0.733	0.489	0.296	0.960	0.838	0.991
- 1997	0.363	0.659	0.304	0.742	0.873	0.999	0.809
Basal area/ha - 1957	0.001	0.997	0.028	0.047	0.020	0.066	0.000
- 1997	0.608	0.992	0.742	1.000	0.593	0.997	0.697
Net basal area increment 1957–97	0.241	0.993	0.989	0.414	1.000	0.293	0.314
Gross basal area increment 1957–97	0.166	0.826	0.979	0.429	0.644	0.128	0.702
Basal area mortality 1957–97	0.139	0.970	0.963	0.235	0.810	0.423	0.138
Total volume/ha - 1957	0.000	0.986	0.009	0.067	0.014	0.038	0.000
- 1997	0.471	1.000	0.511	1.000	0.567	1.000	0.532
Net total volume increment 1957–97	0.383	1.000	0.999	0.500	0.999	0.481	0.461
Gr. total volume increment 1957–97	0.505	0.987	0.723	0.857	0.547	0.687	0.989
Total volume mortality 1957–97	0.046	0.970	0.695	0.167	0.461	0.315	0.035
Merch. volume/ha - 1957	0.001	0.965	0.011	0.092	0.022	0.043	0.000
- 1997	0.426	0.998	0.458	1.000	0.554	0.999	0.482
Net merch. volume increment 1957–97	0.403	1.000	0.998	0.520	0.999	0.512	0.472
Gr. merch. volume increment 1957–97	0.522	0.984	0.716	0.913	0.525	0.750	0.967
Merch. volume mortality 1957–97	0.046	0.964	0.678	0.172	0.431	0.336	0.034

a Analyses of variance (ANOVA) based on 3 and 11 degrees of freedom.
Pairwise treatment comparisons based on Tukey-Kramer criterion.

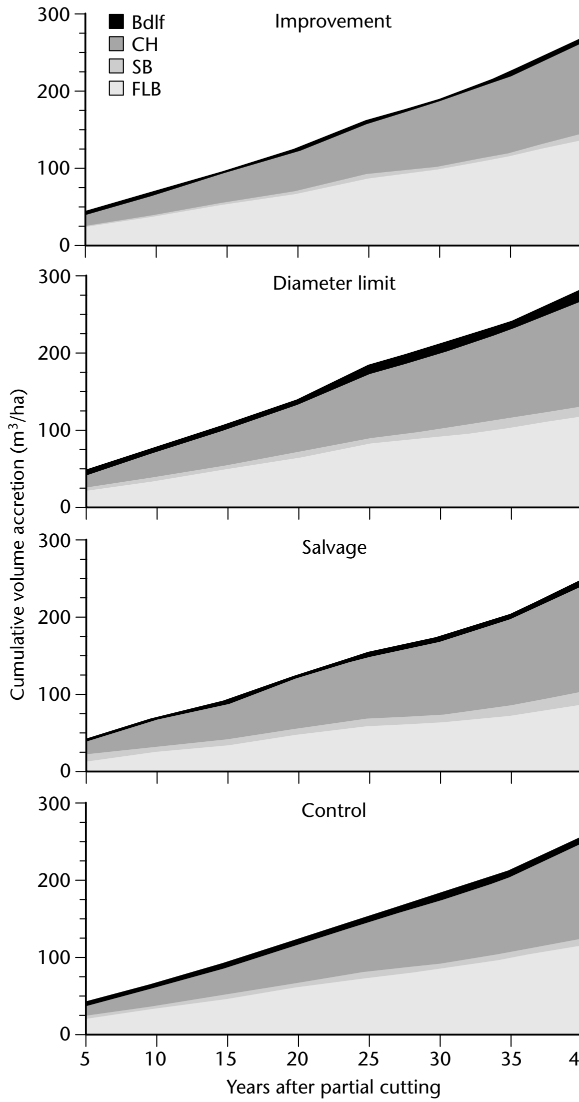
APPENDIX 5A

Cumulative basal area accretion (m^2/ha), by species group, following partial cutting.



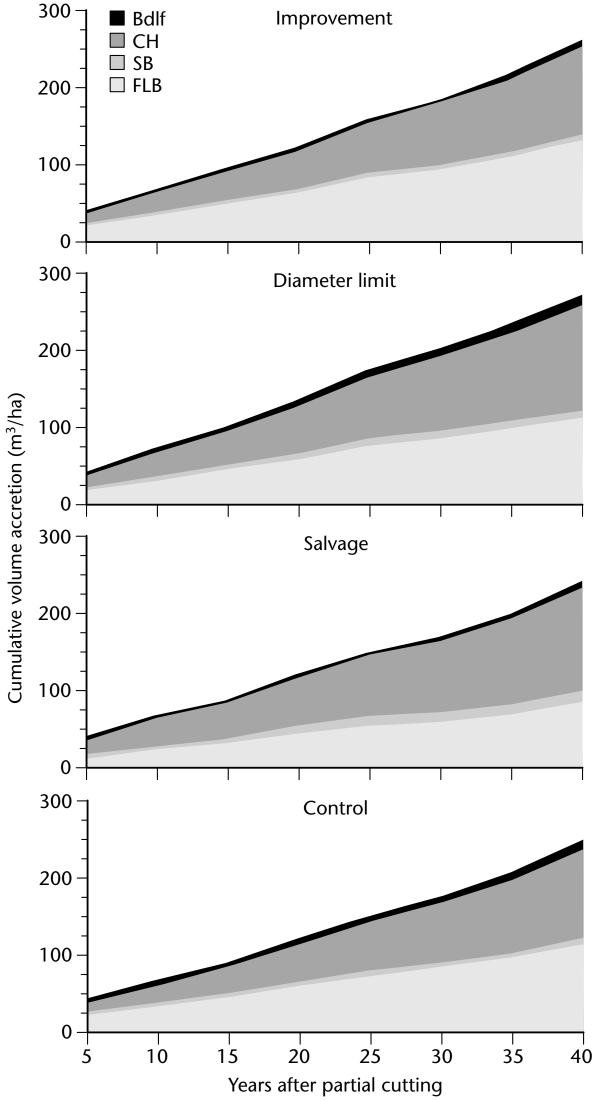
APPENDIX 5B

Cumulative total volume accretion (m^3/ha), by species group, following partial cutting.



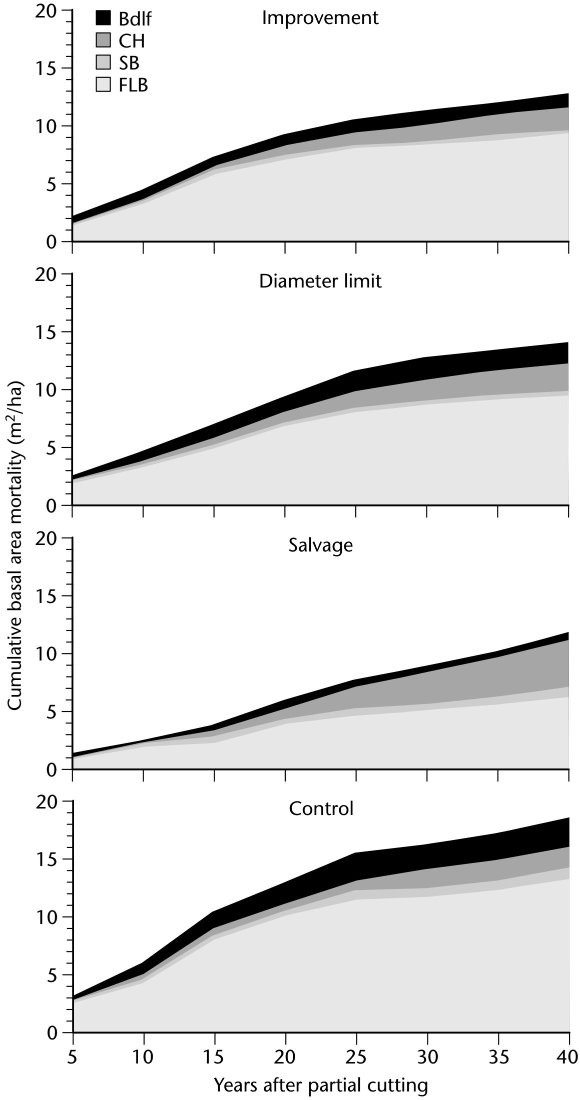
APPENDIX 5C

Cumulative merchantable volume accretion (m³/ha), by species group, following partial cutting.



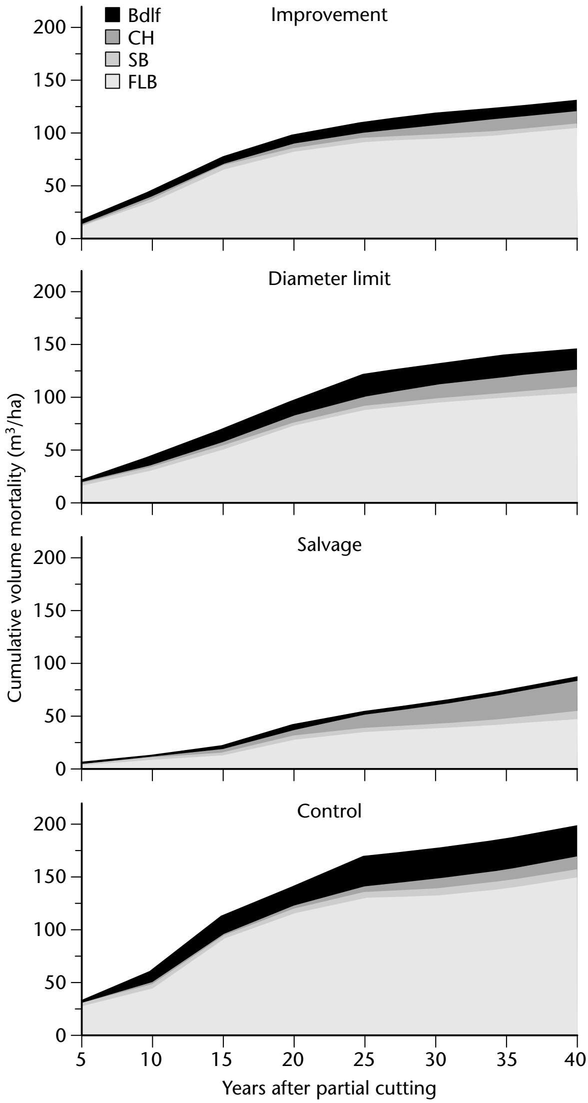
APPENDIX 6A

Cumulative basal area mortality (m^2/ha), by species group, following partial cutting.



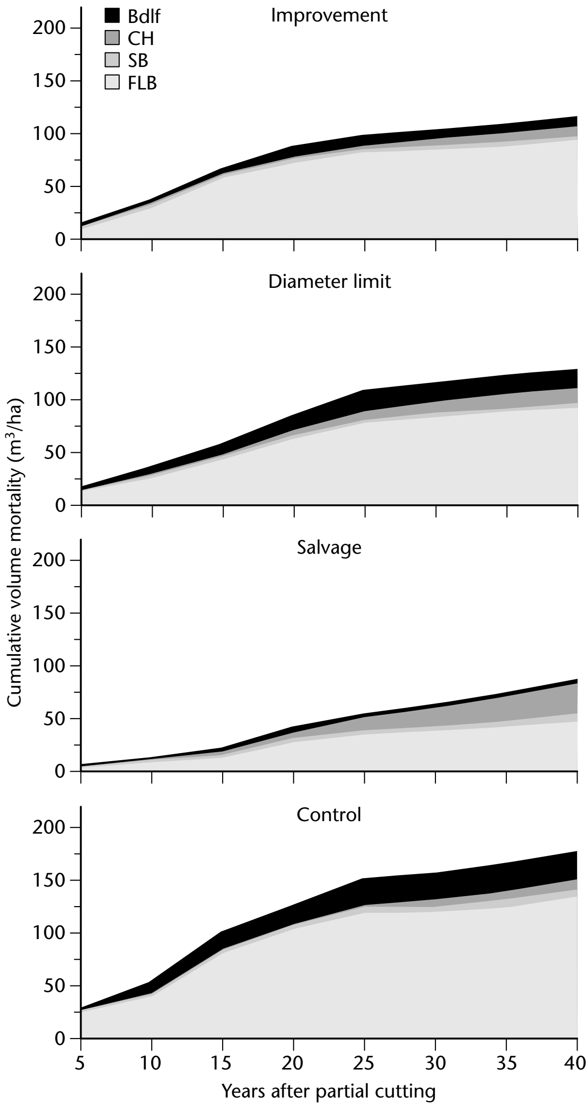
APPENDIX 6B

Cumulative total volume mortality (m^3/ha), by species group, following partial cutting.



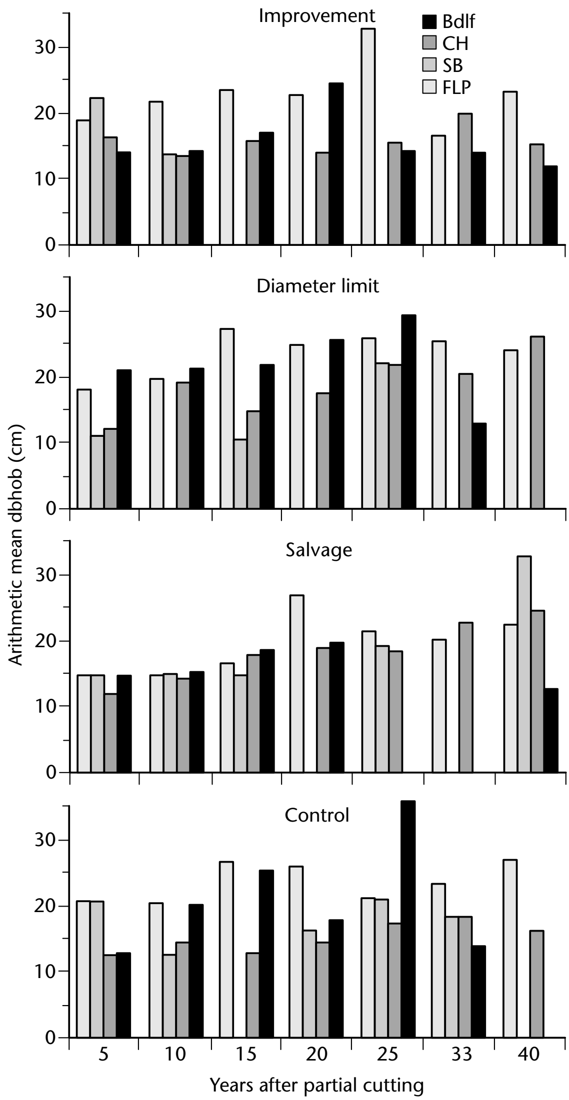
APPENDIX 6C

Cumulative merchantable volume mortality (m^3/ha), by species group, following partial cutting.



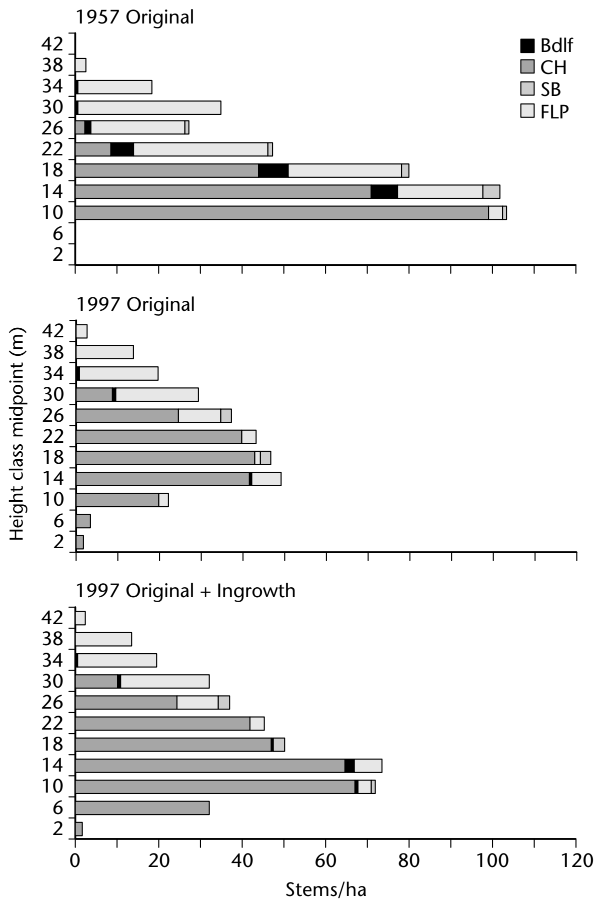
APPENDIX 7

Mean diameter of mortality, by species group and treatment.



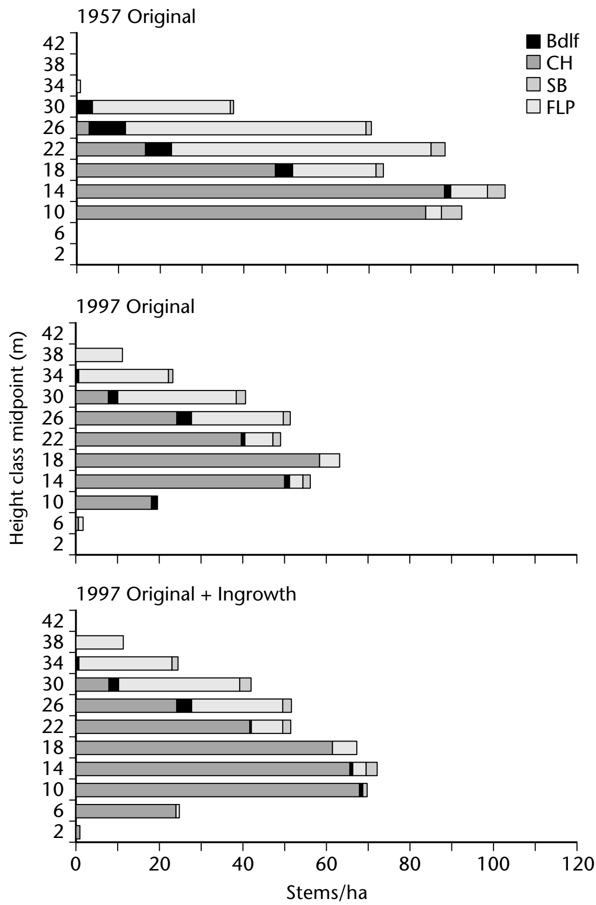
APPENDIX 8A

Vertical stratification of trees 9.1 cm dbhob and larger, by species group, in the improvement plots immediately following partial cutting (1957) and after 40 years (1997).



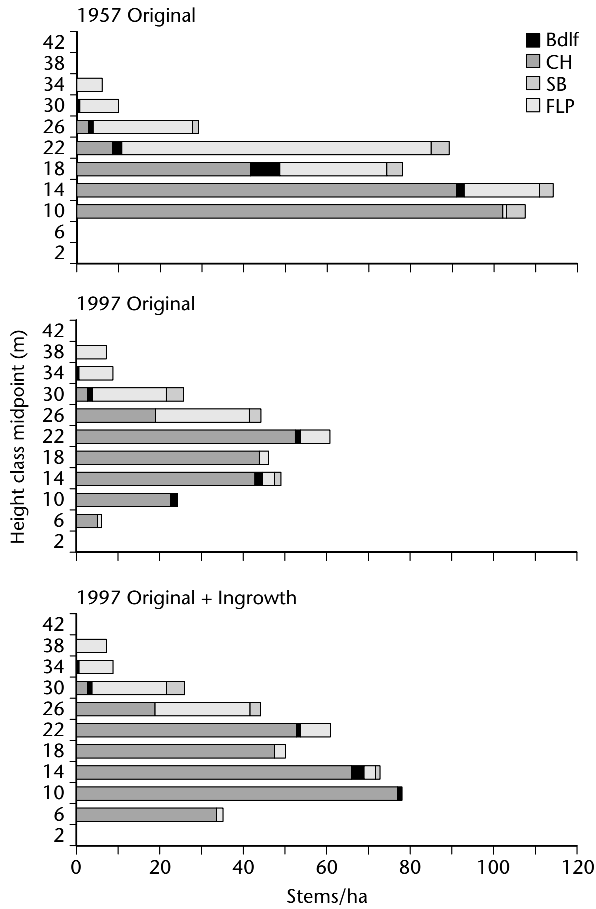
APPENDIX 8B

Vertical stratification of trees 9.1 cm dbhob and larger, by species group, in the diameter-limit plots immediately following partial cutting (1957) and after 40 years (1997).



APPENDIX 8C

Vertical stratification of trees 9.1 cm dbhob and larger, by species group, in the salvage plots immediately following partial cutting (1957) and after 40 years (1997).



APPENDIX 8D

Vertical stratification of trees 9.1 cm dbhob and larger, by species group, in the control plots immediately following partial cutting (1957) and after 40 years (1997).