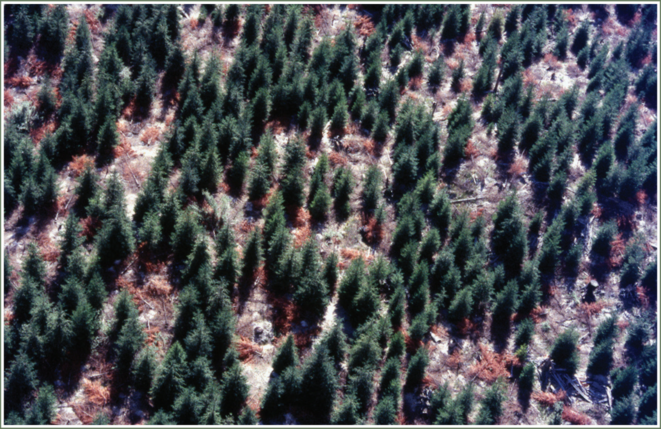
United States Department of Agriculture

# Stand Development 18 Years After Gap Creation in a Uniform Douglas-Fir Plantation

Robert O. Curtis, Constance A. Harrington, and Leslie C. Brodie



Forest Service | Pacific Northwest Research Station | Research Paper PNW-RP-610 | December 2017

## Authors

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Cover: (upper photo) landscape view of uniform plantation in Mount St. Helens blast zone; (lower left) aerial view of uniform thinning (treatment B); (lower right) aerial view of irregular thinning and gap creation (treatment D). Photos by Constance A. Harrington.

## Abstract

**Curtis, Robert O.; Harrington, Constance A.; Brodie, Leslie C. 2017.** Stand development 18 years after gap creation in a uniform Douglas-fir plantation. Res. Pap. PNW-RP-610. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 28 p.

This report gives early results, 18 years after treatment and 30 years after planting, from a trial of early thinning and gap creation intended to increase biodiversity in a very uniform extensive Douglas-fir plantation. Gap creation has introduced canopy irregularity and a substantial hemlock component into what was originally a very uniform pure Douglas-fir plantation, produced some natural regeneration of Douglas-fir, and considerably changed diameter distributions. Long-term effects will depend on whether additional stand density manipulation is carried out in coming years.



Keywords: *Pseudotsuga menziesii*, variable density thinning, biodiversity, stand structure.

## Summary

This report gives early results, 18 years after treatment and 30 years after planting, from a trial of early thinning and gap creation intended to increase biodiversity in a very uniform, extensive Douglas-fir plantation. Gap creation has introduced canopy irregularity and a substantial hemlock component into what was originally a very uniform pure Douglas-fir plantation, produced some natural regeneration of Douglas-fir, and considerably changed diameter distributions. Long-term effects will depend on whether additional stand density manipulation is carried out in coming years. The stands are now at or near a stage at which commercial thinning would be feasible and desirable for both timber production and wildlife habitat objectives. The area would be very well suited to a large-scale trial of uneven-aged management.

## Contents

## Introduction

The most common management system in the Douglas-fir region has been to clearcut and then plant Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). This may or may not be followed by more or less uniform thinning, with subsequent harvest at a relatively young age in the range of 40 to 80 years.

In recent decades, there have been increasing concerns about the implications of creating extensive young stands of a single species and uniform even-aged structure on associated nontimber values, particularly wildlife habitat and visual acceptability to the public. These concerns have produced an interest in alternative management systems and practices that may produce more diverse stand conditions while maintaining an acceptable level of timber production (Curtis et al. 2007, O'Hara 2001). A number of trials of unconventional management in the Pacific Northwest were begun in the 1990s. Many of these are referred to in Harrington and Nicholas, eds. (2007); Anderson and Ronnenberg, eds. (2013); and Poage and Anderson (2007).

This report gives early results from a trial of early gap creation and thinning in an extensive and very uniform Douglas-fir plantation.

## The Study

The study is located in the Upper Clearwater Valley planning unit of the Mount St. Helens National Volcanic Monument (within the Gifford Pinchot National Forest), in T9N R6E, sections 2, 3, 11, 12, 14, 22, 23, and 25. The original forest in the area used for the study had been destroyed by the 1980 eruption of Mount St. Helens, and the area was subsequently salvage logged.

The area is fairly level and is at about 700 m elevation. The original soil has been overlaid by 20 to 25 cm of ash and pumice. The area is considered fairly productive, and, based on early tree height development, would be classified as site 2 (King 1966).

The area was planted to Douglas-fir at a nominal 2.8 m spacing, over the period 1982 to 1984. Once established, early growth of the planted trees was rapid, probably in part because of the mulching effect of the ash layer and lack of competing vegetation.

### Objectives

The objectives of the study (Crisafulli and Harrington 1994) were to modify an initially very uniform Douglas-fir plantation to (1) produce forest stands with increased variability in species composition and structure and (2) compare tree growth, development of stand structures, and production of forest products in different stand conditions.

## Experimental Design

The originally proposed design was randomized blocks, with blocks defined by location-related characteristics that it was thought might influence the response of birds, small mammals, and amphibians. However, there was some confusion in implementation of treatments by blocks, and the initially planned wildlife inventories were never carried out. With hindsight, we think that the block definitions had little relevance to stand growth. We have therefore treated this as a fully randomized experiment.

The study has five treatments, each replicated five times, for a total of 25 plots. Each treatment plot is of area 6.5 ha, located as shown in figure 1. Within each plot, two subplots were established in treatments A and B and three in treatments C, D, and E (defined below). Each subplot is a rectangle of dimensions 40 by 60 m (area = 0.24 ha). Subplot corners are points on a 20-m grid.

## Treatment Definitions

The five treatments (table 1) are:

- Treatment A: The Douglas-fir plantation as established, with no subsequent stand treatment.
- Treatment B: The Douglas-fir plantation was thinned uniformly in 1995 to one-half the number of trees then present, giving an approximate average spacing of 4.0 m.
- Treatment C: After thinning as in treatment B above, additional clumps of Douglas-fir were removed. Openings created were more or less circular and centered on grid points (fig. 2). Based on comparative basal areas before and after gap creation, the percentage of the area in gaps in 1995 was estimated as 31 percent. Estimated average initial area per gap was 124 $m^2$, corresponding to an average gap diameter of about 13 m. An alternative estimate of 41 percent in gaps that was derived from delineation of openings on 1995 air photos gave an estimated average area per gap of 164 $m^2$ and approximate average gap diameter of about 14.5 m.

  Openings were planted to a mixture of red alder (*Alnus rubra* Bong), western redcedar (*Thuja plicata* Donn ex D. Don), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), in an effort to promote development of a future stand that would be multilayered, uneven-aged, and composed of mixed species. Numbers of trees planted within gaps were in the approximate proportions, by species, of 100 alder to 40 hemlock to 40 redcedar. Spacing was approximately 2.1 m.

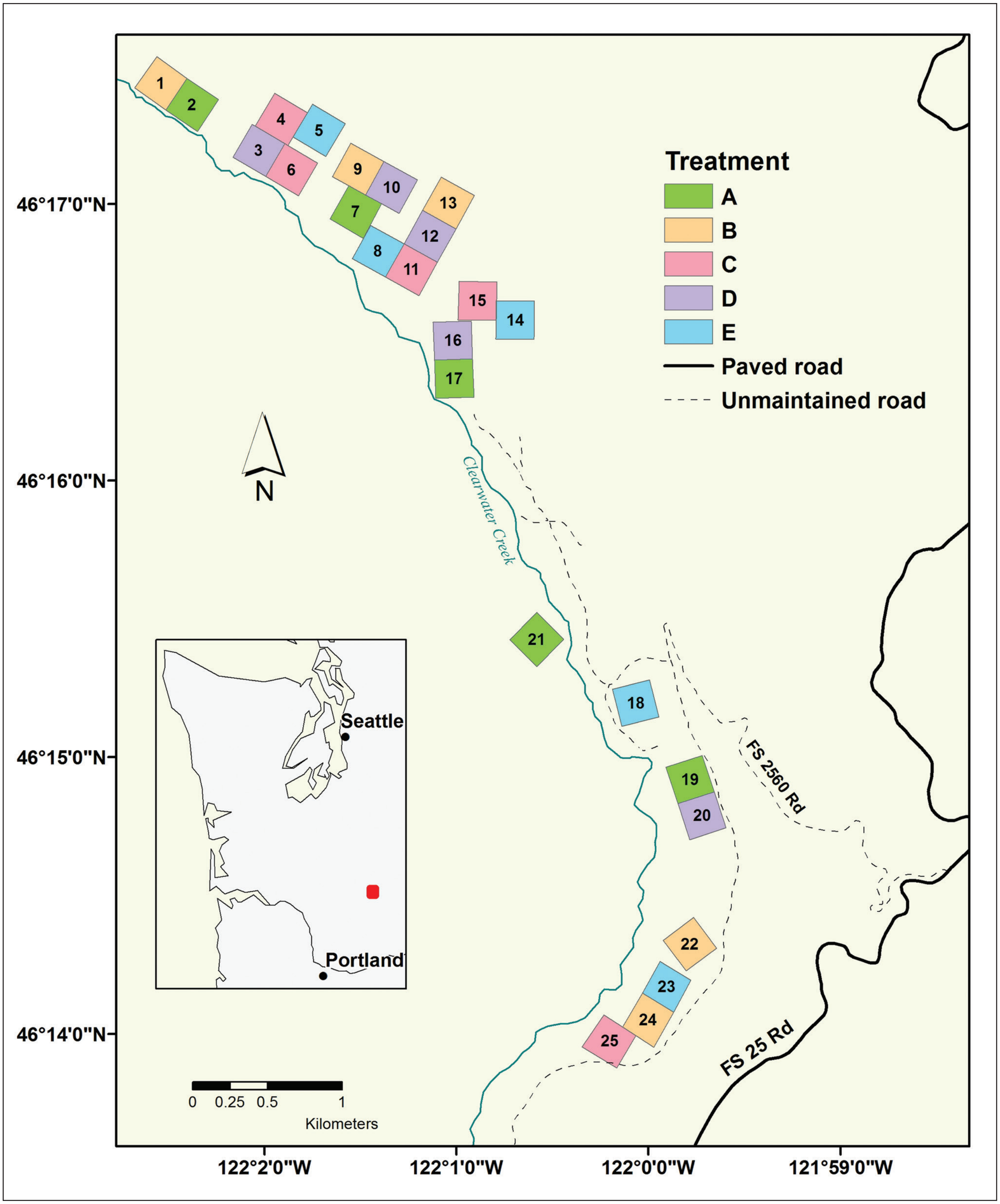


Figure 1—Map showing locations of the 6.5-ha main (treatment) plots in the Clearwater study.

- Treatment D: After treatment as in B above, gaps of varying size were created, and some irregular thinning was done in the matrix. Total area in openings was more or less comparable to that in C. Gaps were centered on grid points. No planting was done.
- Treatment E: This was similar to D, except that openings were planted to a mixture of red alder, western hemlock, and western redcedar as in C. The smaller gaps were planted to western hemlock and western redcedar and all three species were planted in the larger gaps.

**Table 1—Treatment definitions**

| Treatment | Uniform thin | Gaps | Gap size | Planting |
|---|---|---|---|---|
| A | None | None | None | None |
| B | Yes | None | None | None |
| C | Yes | Yes | Uniform | Yes |
| D | Yes | Yes | Variable | None |
| E | Yes | Yes | Variable | Yes |

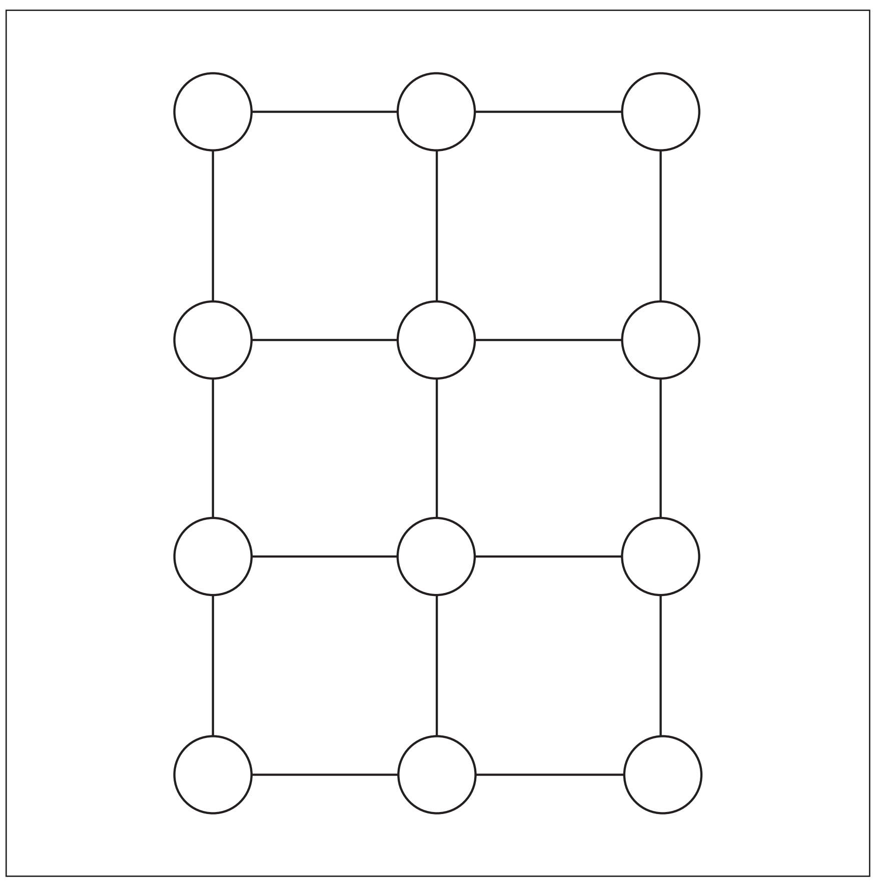

Figure 2—Arrangement of gaps within subplots in relation to grid points in treatment C.

## Measurements

Three types of measurements were taken. These were:

1. Conventional tree measurements on the 0.24 ha subplots: diameter at 1.3 m of all trees of diameter ≥ 4 cm; and height, crown width, and height to live crown on a subsample of these trees.
2. Estimates of percentage cover by species categories, derived from a series of small quadrats distributed along transects within each subplot.
3. Estimates of percentage cover by species categories on one circular plot of radius 5.64 m (area = 100 $m^2$) located at a grid point, and one intermediate between grid points, within each subplot.

Results of these measurements will be discussed separately.

## Stand Statistics (0.24-ha subplots)

Tree measurements on subplots were made in 1995, 1998, 2003, 2006, 2010, and 2013. Not all subplots were measured at each date. Only one subplot within each plot was measured at the most recent (2013) measurement. Because the 2013 remeasurement spans the longest time period since stand establishment, we chose to confine present comparisons to the 2013 data.

### Top Heights (H100) and Site Quality

Top heights, defined as mean heights of those Douglas-fir included in the largest 100 per hectare (all species), were calculated separately for each subplot. Because not all such trees had measured heights, regressions of height on diameter were fit to the available height/diameter measurements, and H100 was taken as the estimated height from this equation corresponding to the mean diameter of the Douglas-fir included in the largest 100 trees per hectare. An average planting date of 1983 and an assumed 4 years from planting to reach breast height indicates a mid-site class 2 (King 1966). H100 can be regarded as a surrogate for site index.

Treatment means of H100 and corresponding standard errors are given in table 2.

The apparent absence of any trend (table 2), plus a nonsignificant F in an ANOVA, indicates no difference in H100 among treatments.

**Table 2—Means and associated standard errors of H100 and D100 of Douglas-fir in 2013, by treatment**

| Treatment | H100 | D100 |
|---|---|---|
| | *Meters* | *Centimeters* |
| A | 21.52 ± 0.79 | 36.38 ± 0.50 |
| B | 22.66 ± 0.87 | 39.30 ± 0.87 |
| C | 22.56 ± 0.58 | 39.44 ±1.26 |
| D | 23.10 ± 0.81 | 41.10 ±0.76 |
| E | 21.56 ± 1.09 | 40.49 ±1.59 |

## D100

D100, defined as the mean diameter at breast height (dbh) of those Douglas-fir included in the largest 100 trees per hectare, is one measure of comparative stand development. Values are shown in table 2.

As with H100, an ANOVA gave a nonsignificant F. A graphical comparison suggests that D100 for treatment A may be slightly less that for the other treatments; a result that would be anticipated although differences were not large enough to affect the overall ANOVA. A t-test of the difference in mean of treatment A vs. mean of combined treatments (B + C + D + E) did reach significance ($p < 0.05$).

## Quadratic Mean Diameter (QMD)

QMDs of trees ≥4 cm in 2013 for (1) Douglas-fir, and (2) all species combined are shown in figure 3.

QMD of treatment A (no thinning or gaps) is considerably below that in other treatments, as would be expected. There are no obvious differences among treatments B, C, D, and E.

## Basal Area (BA)

Basal areas per hectare in trees of dbh ≥4.0 cm in 2013 for (1) Douglas-fir, and (2) all species combined are shown in figure 4.

These show clearly that values for treatment A are greater than those for treatment B, which in turn are greater than those for treatment C. There is no indication of differences among treatments C, D, and E.

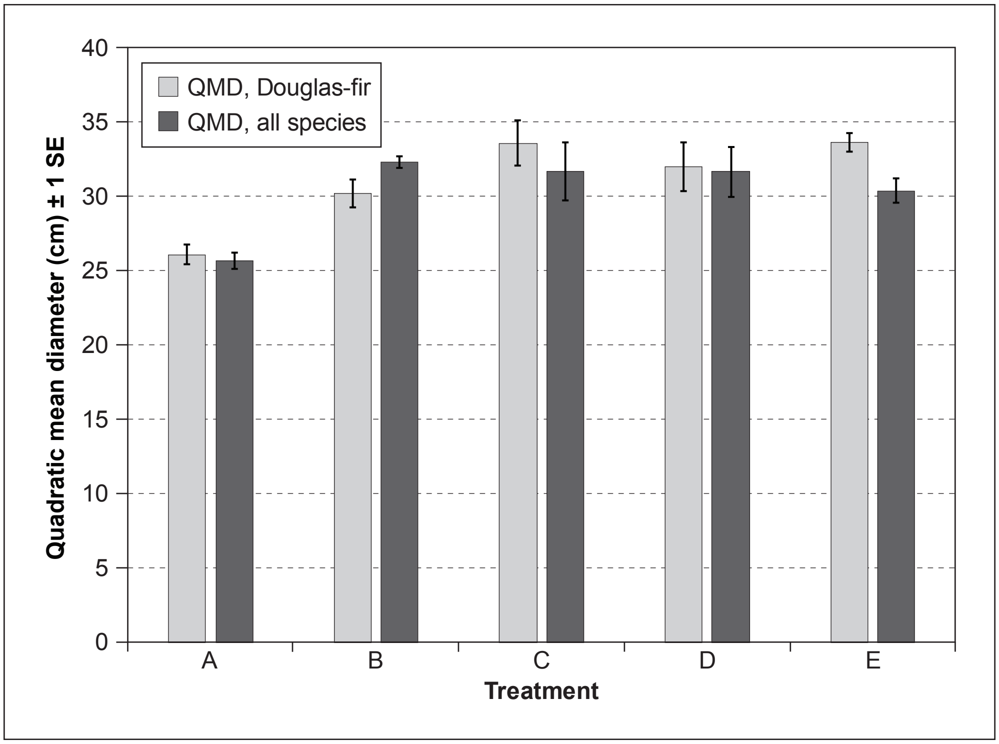


Figure 3—Treatment means of 2013 quadratic mean diameters (QMD) of trees of diameter at breast height ≥ 4.0 cm for (1) Douglas-fir and (2) all species combined, ± 1 standard error (SE).

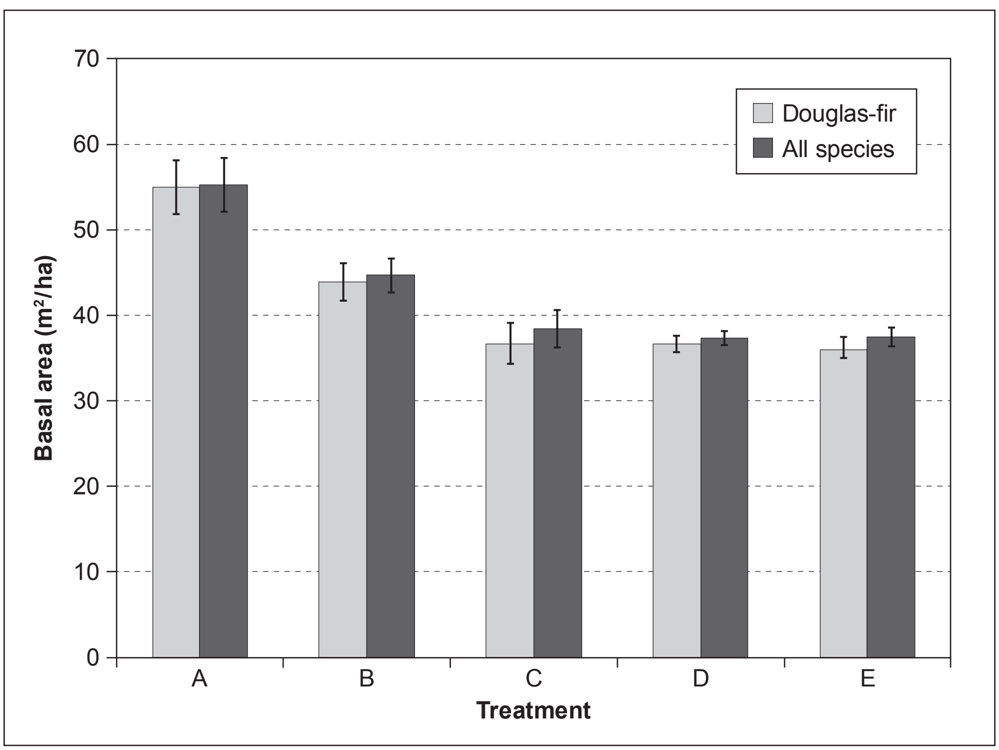


Figure 4—Treatment means of 2013 basal areas of trees of diameter at breast height ≥ 4.0 cm for (1) Douglas-fir and (2) all species combined, ± 1 standard error (SE).

## Number (N)

Mean numbers of trees per hectare of dbh ≥4.0 cm in 2013 by treatment for (1) Douglas-fir and (2) all species combined, are shown in figure 5. As expected, treatment A has the greatest number of trees followed by treatment B, and then the gap treatments C, D, and E. Again, there is little indication of differences among treatments C, D, and E.

## Volume (CVTS)

Cubic volume of total stem (CVTS) in trees of dbh ≥4.0 cm in 2013 was calculated, by treatment, for all species combined (fig. 6), using the Bruce and DeMars (1974) volume equation. Treatment A had the greatest CVTS in 2013 and the greatest variability; B had a lesser CVTS, while C, D, and E had the lowest volumes with little indication of differences among these.

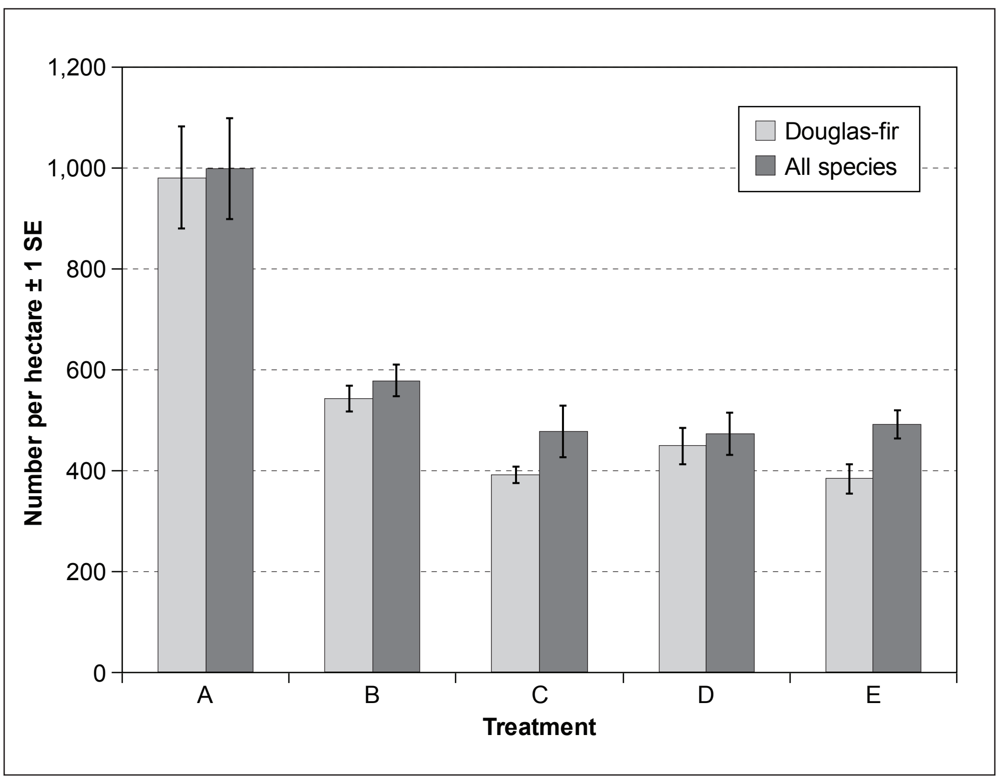


Figure 5—Treatment means of 2013 numbers per hectare of trees of diameter at breast height ≥ 4.0 cm, for (1) Douglas-fir and (2) all species combined, ± 1 standard error (SE).

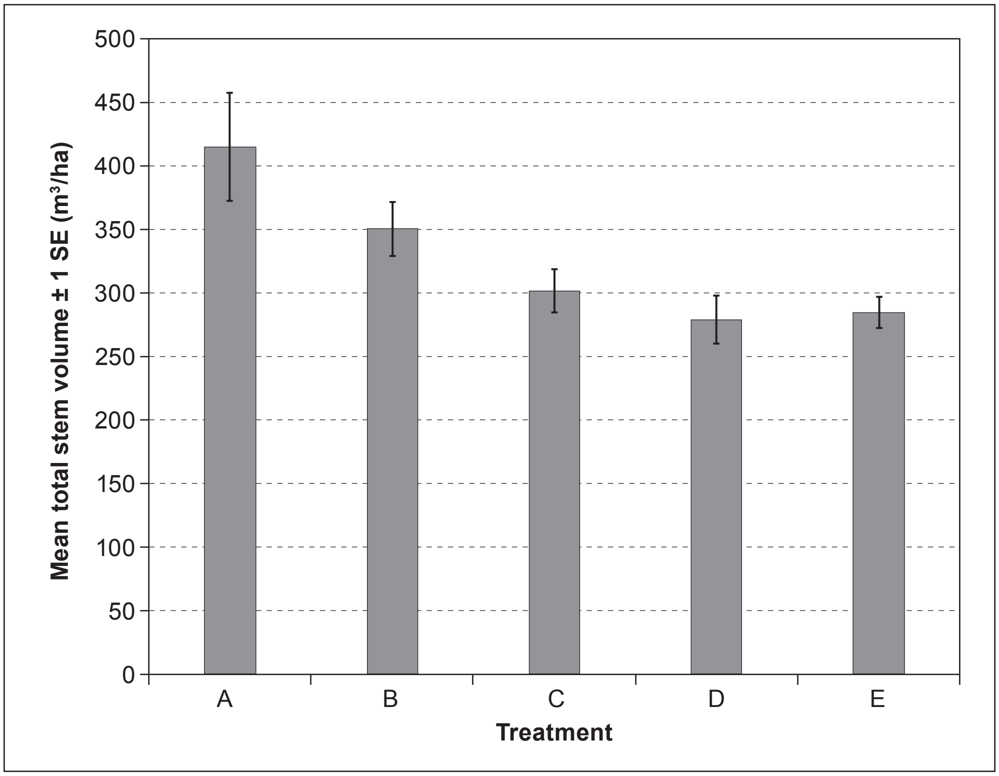


Figure 6—Treatment means of 2013 total stem volume (CVTS) of trees of diameter at breast height ≥ 4.0 cm for all species combined, ±1 standard error (SE).

## Relative Density (RD) and Stand Density Index (SDI)

Means of relative density in 2013 expressed as the summation forms of RD and SDI (Curtis 2010, Long and Daniel 1990) for treatment A were: $RD_{sum}$ = 10.5 and $SDI_{sum}$ = 1,049. Approximate maximum limiting values in metric units are $RD_{sum}$ =14 and $SDI_{sum}$ =1,450.

$RD_{sum}$ was calculated as 0.00007854*∑d^1.5/area, consistent with $RD_{qmd}$ values calculated as $BA/(QMD)^{0.5}$ (Curtis 1982).

Corresponding means for treatment B in 2013 were $RD_{sum}$ = 7.8 and $SDI_{sum}$ = 801.

Trends of $RD_{sum}$ over time by treatment are shown in figure 7. Those for $SDI_{sum}$ follow the same pattern. Trends for treatments C, D, and E were almost identical.

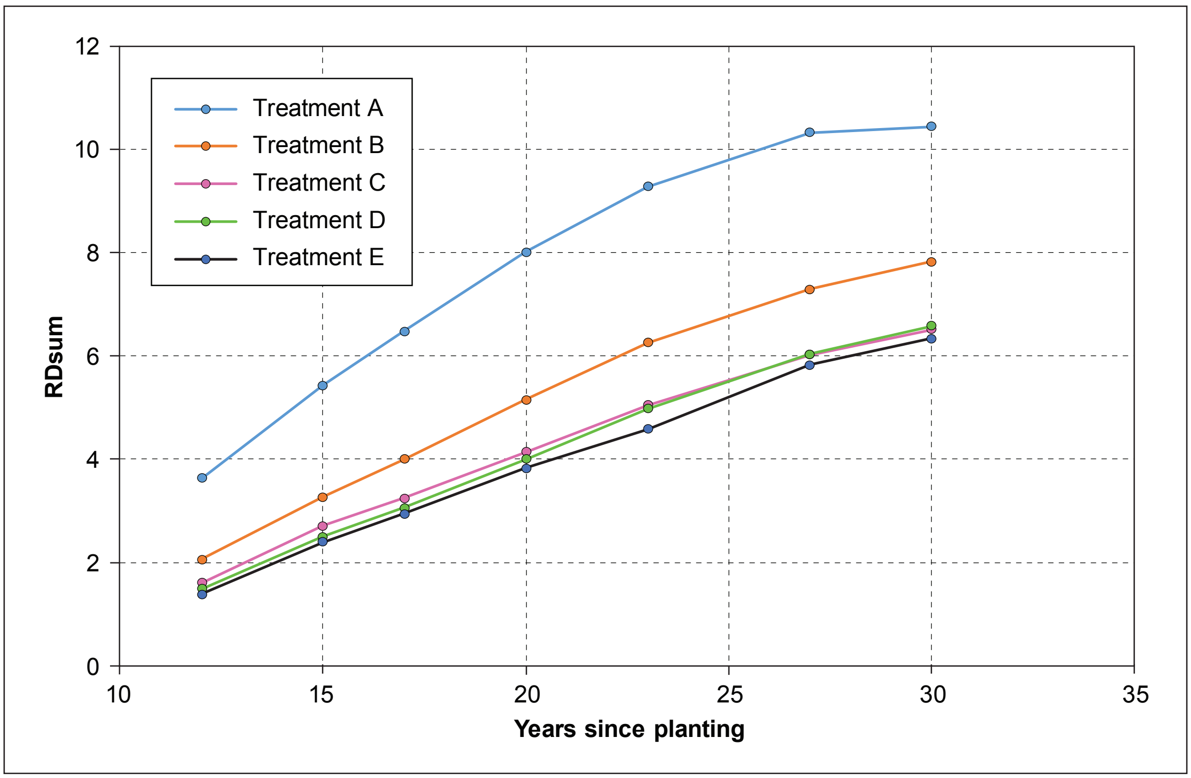


Figure 7—Time trends of observed development of relative density (RDsum), by treatment.

## Diameter Distributions

2013 stand tables were prepared showing number of trees by 5-cm classes, subdivided into Douglas-fir, other conifers, and hardwoods. This was done for each individual plot, and values were averaged over the five plots within each treatment.

The averages for treatments A, B, and C are shown as figures 8, 9, and 10. Diameter distributions for treatments D and E are very similar to that shown for C. Figure 11 compares diameter distributions for all species combined, by treatment.

The principal effect of the treatments to date has been on the shape and species composition of the diameter distributions.

Treatment A (fig. 8) is a symmetrical frequency distribution that is almost entirely Douglas-fir.

Treatment B (fig. 9) is a nearly symmetrical distribution of smaller numbers of Douglas-fir, with a few other conifers and hardwoods as a "tail" in the smallest diameters.

In contrast, treatment C (fig. 10) has, in addition to a more or less symmetrical distribution of the larger diameters of Douglas-fir, very considerable numbers of smaller other conifers (mostly hemlock) and smaller Douglas-fir, plus a few hardwoods. Diameter distributions for D and E were very similar to that for C.

Treatment B, when compared to A (fig. 11) has not only reduced numbers but has produced a pronounced shift of the maximum toward the larger diameters. This shift continues, less markedly, in the comparison of B vs. (C, D, and E).

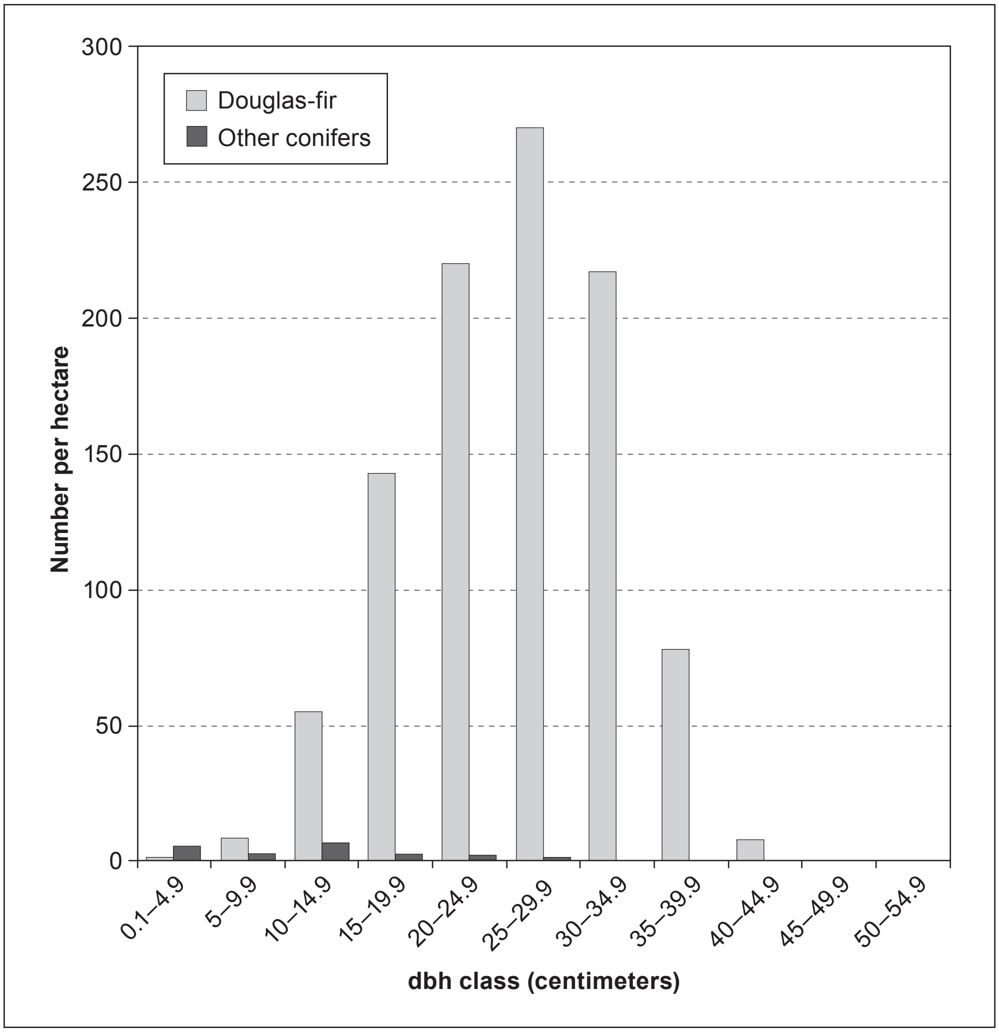


Figure 8 —Mean numbers per hectare in treatment A, by diameter at breast height (dbh) class and species, 2013.

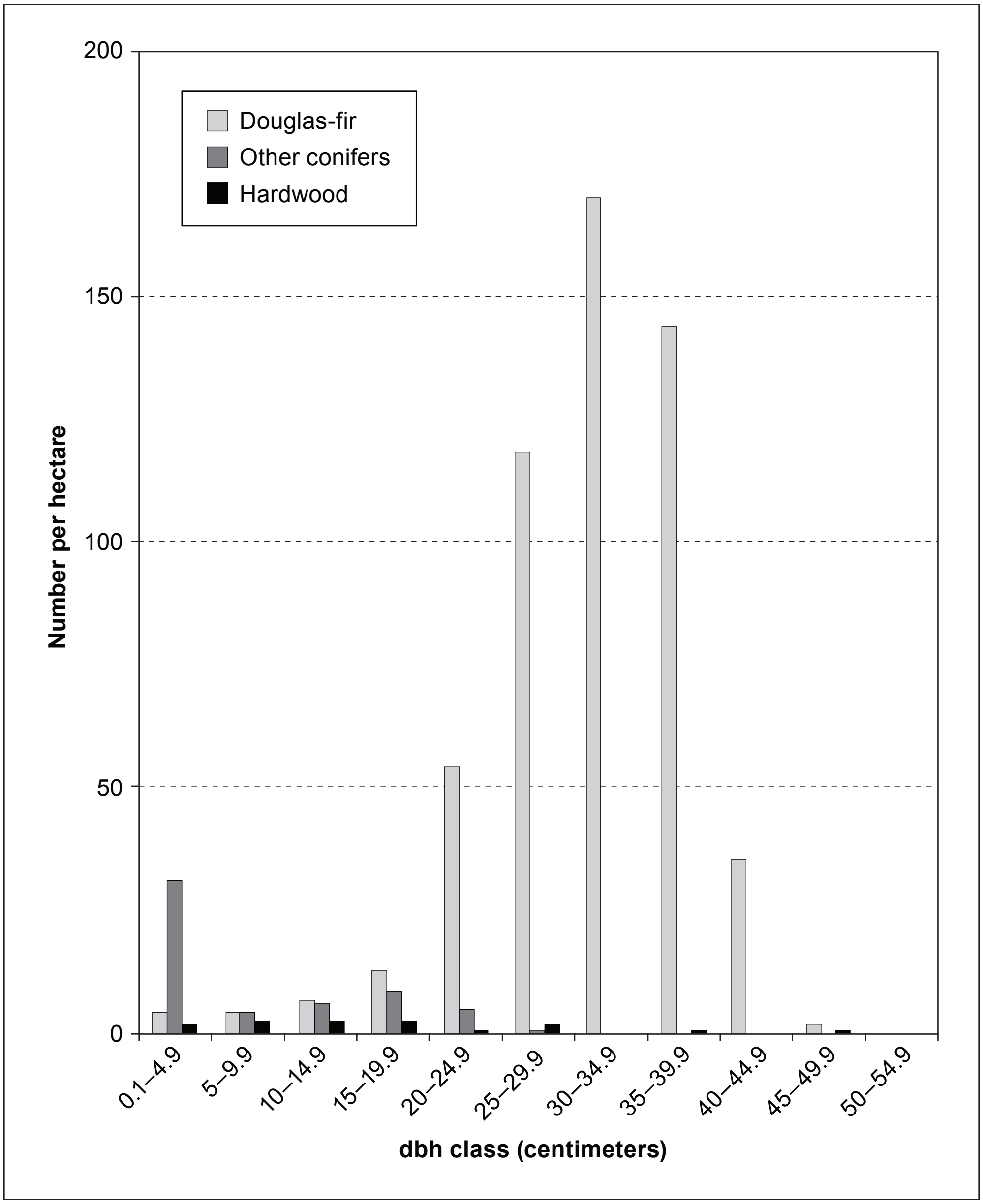


Figure 9—Mean numbers per hectare in treatment B, by diameter at breast height (dbh) class and species, 2013.

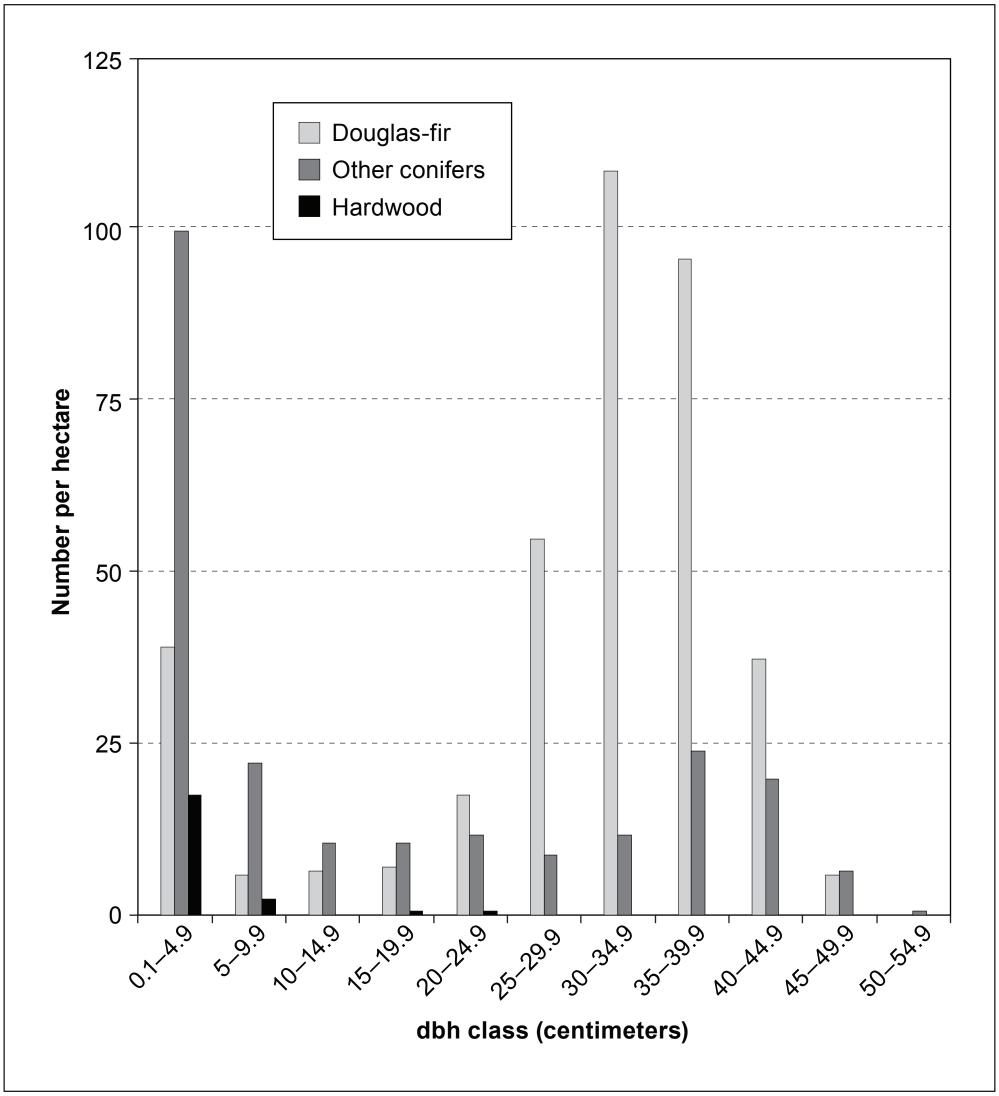


Figure 10—Mean number per hectare in treatment C, by diameter at breast height (dbh) class and species, 2013.

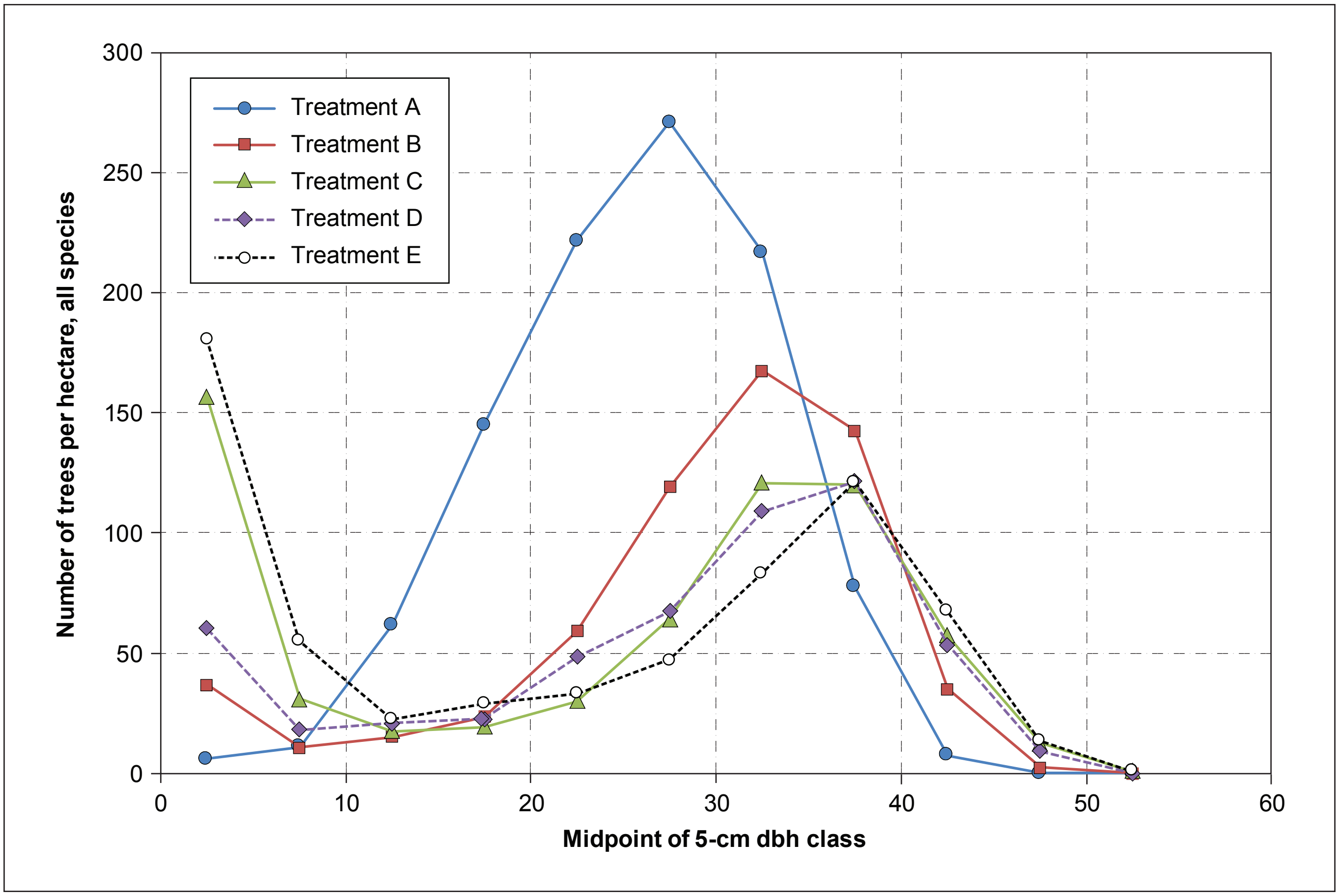


Figure 11—Comparison of diameter distributions by treatment, using mean values for each treatment, 2013; dbh = diameter at breast height.

## Live Crown Ratio (LCR)

Regressions LCR = f(D) were fit to the Douglas-fir data for each subplot, and used to estimate LCR corresponding to D100 and QMD of Douglas-fir on that subplot. Means and standard errors of these values were then calculated for each treatment.

An ANOVA for differences among treatments was significant ($p<0.01$). The principal difference (fig. 12) is clearly that between treatment A and the other treatments. The graph also suggests that LCR for B may be slightly less than for C, D, and E.

Mean heights to lowest live branch for Douglas-fir in 2013 were 8.6 m in treatment A, 6.4 m in B, 5.6 m in C, 5.3 m in D, and 5.2 m in E.

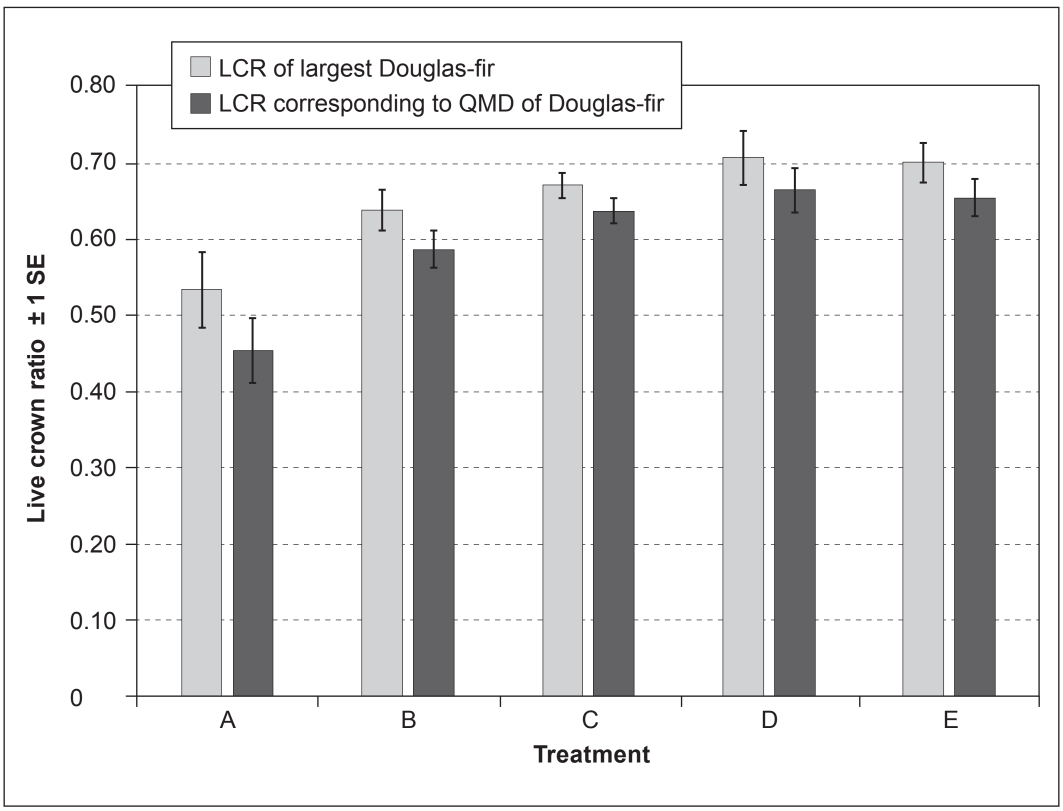


Figure 12—Treatment means of live crown ratios (LCR) corresponding to 2013 values of D100 and quadratic mean diameter (QMD) of Douglas-fir, ± 1 standard error (SE). D100 = mean diameter at breast height of trees included in the largest 100 trees per hectare.

## Crown Width (CW)

Because of the limited number and poor distribution of crown width measurements within individual plots, measurements were combined by species within each treatment. Regressions of CW on dbh were fit for each treatment, and these were then used to estimate values of CW corresponding to D100 and QMD of Douglas-fir ≥4.0 cm dbh in 2013. These are compared in figure 13. The graphical comparison of means suggests that:

- There is little difference in CW for mean D100 between treatments A and B.
- CW corresponding to QMD is greater in B than in A, corresponding to the greater value of QMD in B.
- There is no evident difference in the CW corresponding to QMD among treatments C, D, and E. These are greater than in A and B.
- The graph also suggests that crown widths corresponding to D100 in treatments C, D, and E are greater than in A or B. This can perhaps be interpreted as an effect of the increased edge associated with gap creation.

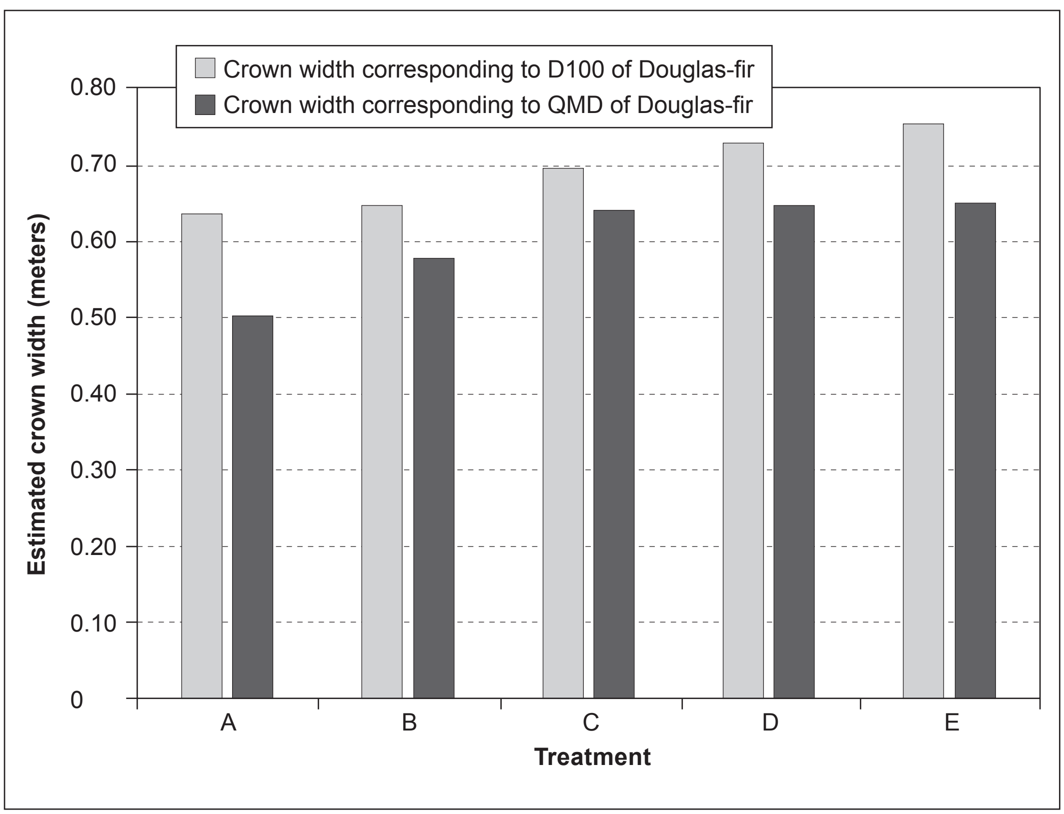


Figure 13—Crown widths corresponding to 2013 values of D100 and quadratic mean diameter (QMD) of Douglas-fir. D100 = mean diameter at breast height of trees included in the largest 100 trees per hectare.

## Regeneration

Seedlings of red alder, western hemlock, and western redcedar were planted in treatments C and E in 1995. None were planted in treatment D. As of 2013, there is no certain way of distinguishing in the data between planted and naturally established trees of these species.

As an approximation of the natural regeneration established subsequent to planting, we calculated numbers per hectare by species of trees present in 2013 with dbh > 0, for which the initial year of record was 2000 or later. The larger trees in the regeneration in C, D, and E were about 5 to 6 m in height in 2013.

Regeneration subsequent to the initial planting and present in 2013 is summarized in table 3.

- There is negligible natural regeneration in A and very little in B.
- Species present in regeneration in C, D, and E are highly variable among subplots, probably reflecting location with respect to surviving seed sources. Most regeneration is in the gaps, which initially comprise only about one-third of the subplot area. Thus, numbers in gaps are therefore much higher than the overall subplot values shown in table 3.
- The few alder and redcedar are mostly in C and E and are probably survivors of the 1995 planting. Most planted alder and redcedar did not survive. The redcedar was heavily browsed by elk. We note that elk populations expanded greatly within the Mount St. Helens blast zone; also, that the measured subplots are located within a much larger area of similar conditions.
- Most natural reproduction is Douglas-fir and hemlock. The greater numbers of hemlock in C and E, compared to D, probably includes survivors from the 1995 planting, but there has also been considerable natural seeding. The Douglas-fir is all from natural seeding. There are also considerable numbers of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in a few subplots, as well as occasional other species.

**Table 3—Subplot means of numbers of tree regeneration present in 2013, by species groups; trees with diameter at breast height >0 in 2013 and with initial year recorded as 2000 or later, by treatment**

| | Number per hectare | | | | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Douglas-fir** | **Hemlock** | **Redcedar** | **Other conifer** | **Alder** | **Other hardwood** |
| A | 4 | 5 | 0 | 0 | 0 | 0 |
| B[a] | 5 | 11 | 1 | 0 | 5 | 0 |
| C[b] | 48 | 78 | 6 | 2 | 19 | 1 |
| D | 22 | 22 | 0 | 21 | 0 | 0 |
| E[b] | 42 | 115 | 8 | 2 | 12 | 2 |

[a] Plot 9 subplot B omitted because of damage and replacement of part of plot in 2000.
[b] Includes alder, redcedar, and hemlock planted in gaps.

### Comparison with FVS Simulations

For comparison, we ran the Pacific Northwest Coast Variant of the Forest Vegetation Simulator (FVS) (Keyser 2011). This was chosen in preference to the West Cascades Variant on the basis of the relatively low elevation and the plant associations present.

A simulation, begun with the 2013 observed values, predicted basal area values through age 90 since planting, assuming no further stand treatment. Relative ranking of basal areas by treatments was A > B > (C, D, E). Relative differences decreased over time, becoming inconsequential by age 90. Total and merchantable cubic volumes had similar rankings, while predicted QMDs for treatment A were substantially less than for other treatments.

## Cover Estimates From Transects (0.4-$m^2$ quadrats)

Estimates were made in 2006 of percentage cover by species groups.

The procedure used was a variation of that discussed by Daubenmire (1959). Quadrat size was 40 by 100 cm (0.4 $m^2$). Quadrats were systematically located along transects, such that each transect included one quadrat at a grid point (which is the center of a gap location in treatments C, D, and E).

For each quadrat, an estimate was made of cover percentage by the following species groups:

- Herbs+ (including ferns, grasses, and sedges)
- Shrubs
- Mosses and liverworts

Within each subplot, there were 4 quadrats located at a grid point (gap in C, D, E) and 6 not at a grid point (matrix). The ratio of these is **not** an estimate of the fraction of the area in gaps, and the values cannot simply be averaged to get subplot means.

Comparison of the 1995 basal area of trees in treatments C, D, and E with the corresponding value in treatment B led to an estimate of 0.31 as the average fraction of the subplot area in gaps created in treatments C, D, and E. Therefore, an estimate of subplot cover percentage for a given vegetation category is:

adjusted cover % =[0.31(mean grid point cover %) + 0.69(mean non-grid point cover %)].

Figures 14 through 16 compare cover percentages for gaps vs. matrix, by treatment; and also show the weighted means calculated by the above equation. An alternative estimate of 0.41 in gaps that was derived from delineation of openings on 1995 air photos gives slightly lower values for the weighted means.

The estimates of herbs+ cover (fig. 14) show no obvious differences among quadrats located in the matrix, but—although highly variable—those located in gaps (grid points) have much greater herbs+ cover. Weighted mean subplot values are clearly greater in treatments C, D, and E than in A or B.

Matrix shrub cover (fig. 15) was least in treatment A, slightly greater in B, and consistently greater in C, D, and E. Though highly variable, shrub cover percentage in gaps (grid points) was consistently greater than in the matrix. Subplot shrub cover was greater in B than in A, and much greater in C, D, and E.

Moss and liverwort cover was greater in gaps (grid points) than in corresponding matrix (fig. 16). Weighted mean subplot cover was greatest in D and E, and least in A. Although mosses in general are often associated with shaded or moist habitats, the predominant species recorded in this study area was *Polytrichum juniperinum*, which is common on mineral soil on disturbed sites.

In sum, gap creation has markedly increased cover percentages of herbs+, shrubs, and mosses and liverworts.

Cover of coarse woody debris was also recorded, but did not show any trends.

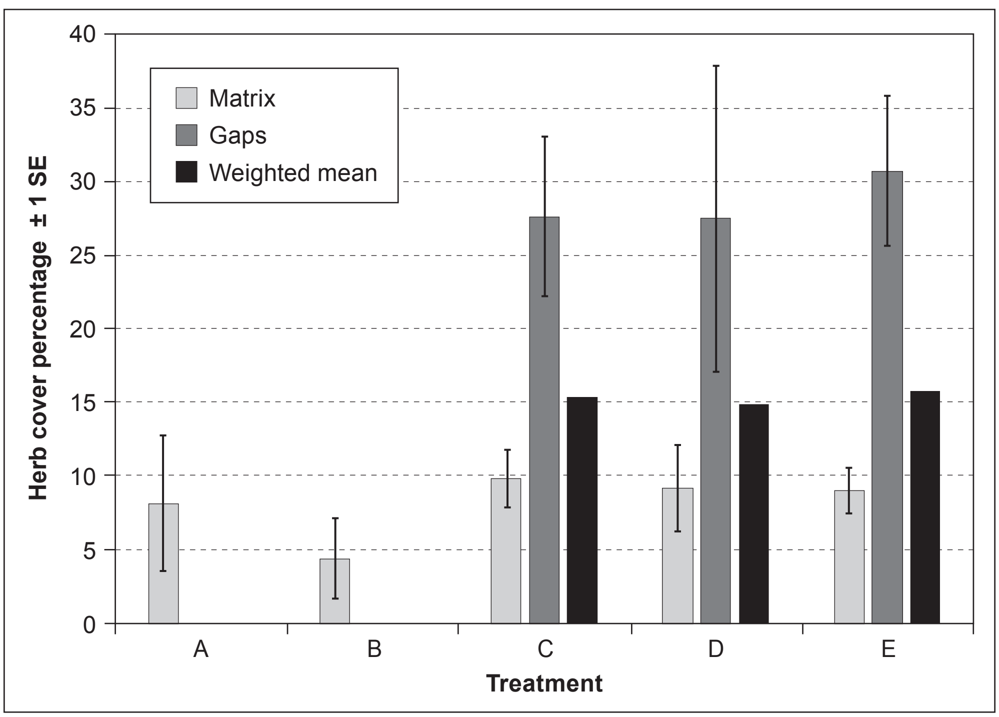


Figure 14—Herb+ cover percentages for matrix vs. gaps (grid points) in 2006 by treatment. SE = standard error.

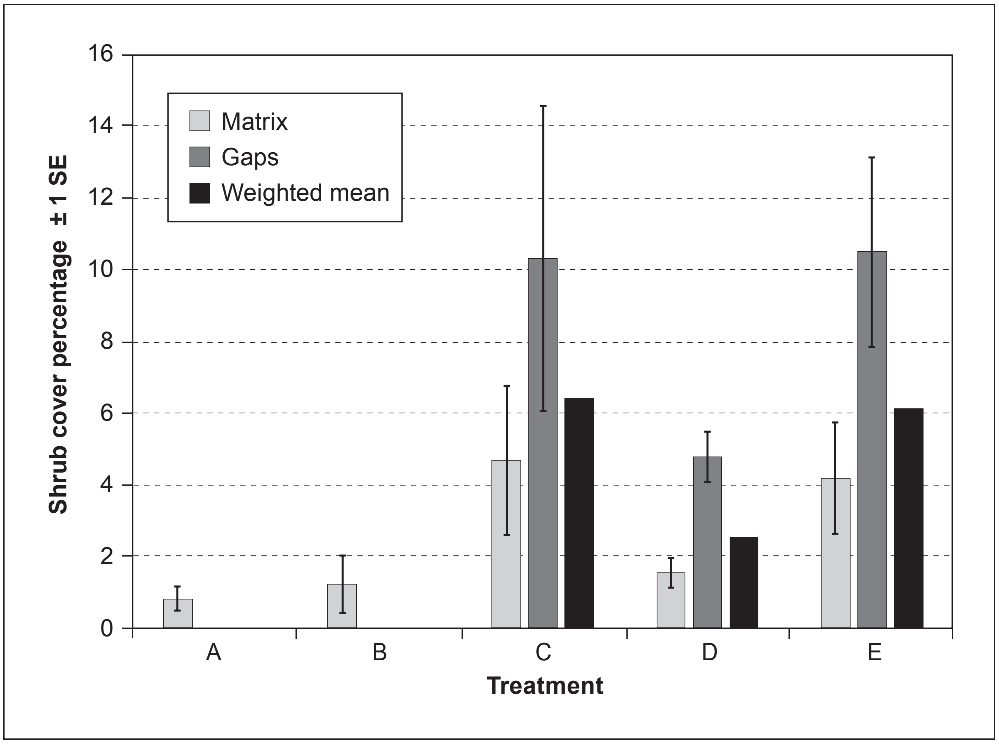


Figure 15—Shrub cover percentages for matrix vs. gaps (grid points) in 2006 by treatment. SE = standard error.

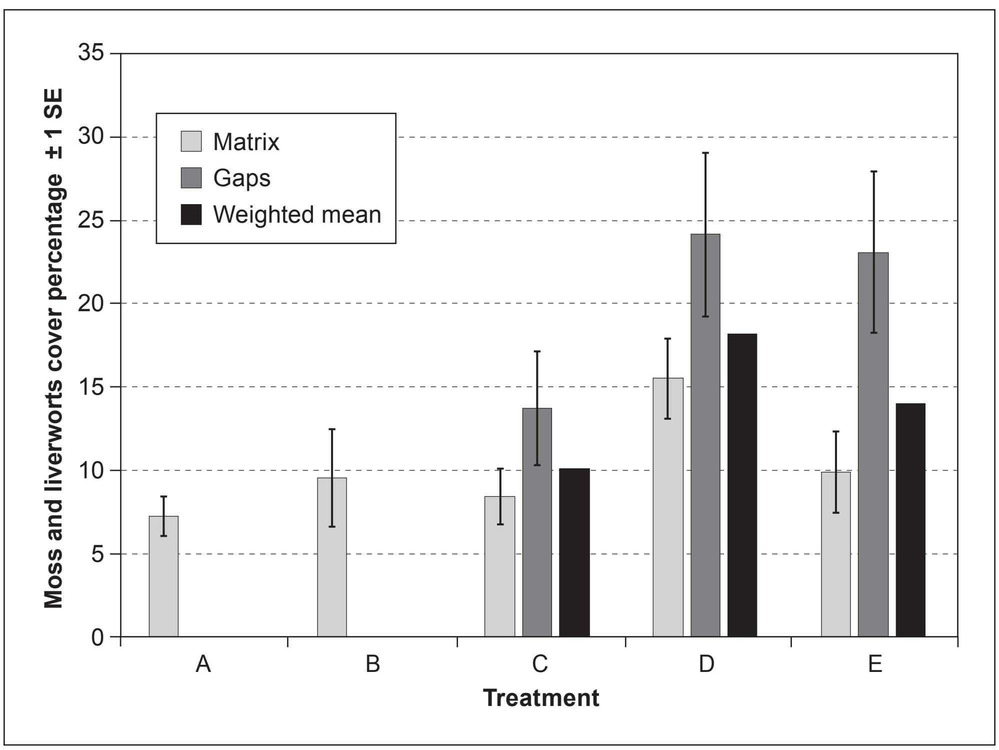


Figure 16—Moss and liverwort cover percentages for matrix vs. gaps (grid points) in 2006 by treatment. SE = standard error.

## Fixed-Area Plots (100 $m^2$)

An alternative 2006 sampling for cover percentage and species composition used circular 5.64-m radius (100-$m^2$) fixed-area plots. Within each 0.24-ha subplot, one such fixed-area plot was measured in 2006 in each subplot at a location intermediate between grid points; and one centered on a grid point (a gap in treatments C, D, and E).

Estimates of percentage of cover were made on all fixed-area subplots measured in 2006, comparable to those in the quadrats along transects and also including tree species. Species present were recorded.

Patterns of estimated cover percentage for herbs+ and for moss and liverworts, by treatment and matrix vs. gap, from the fixed-area plots did not differ much from those from the quadrats along transects. An exception is that estimates of shrub cover percentage in the gaps in treatments D and E from the fixed-area plots were much lower than those from the transects. This difference may arise in part from simple sampling error, as gap means are based on only one plot per subplot, and shrub distribution is frequently patchy. However, another factor is likely involved; namely, that—although the 100-$m^2$ fixed-area plot is roughly comparable in size to the average gap size in treatment C—it is not consistent with gap size in treatments D and E. Treatments D and E have a range of gap sizes, including some considerably smaller than those in C. Therefore, some portion of any 100-$m^2$ fixed-area plot superimposed on small gaps in treatments D and E necessarily includes a portion of the surrounding matrix.

Estimated 2006 tree cover was about 90 to 95 percent for treatments A and B and in the matrix of C, D, and E; and half that or less at grid points (gaps) in C, D, and E.

Figure 17 shows the mean number of species recorded per 100-$m^2$ plot in 2006, by treatment and type of vegetation, based on all subplots measured in each treatment. Treatment A has lower species richness than other treatments, and gaps in C, D, and E have more herb+ species than in the matrix. Otherwise, there are no obvious trends.

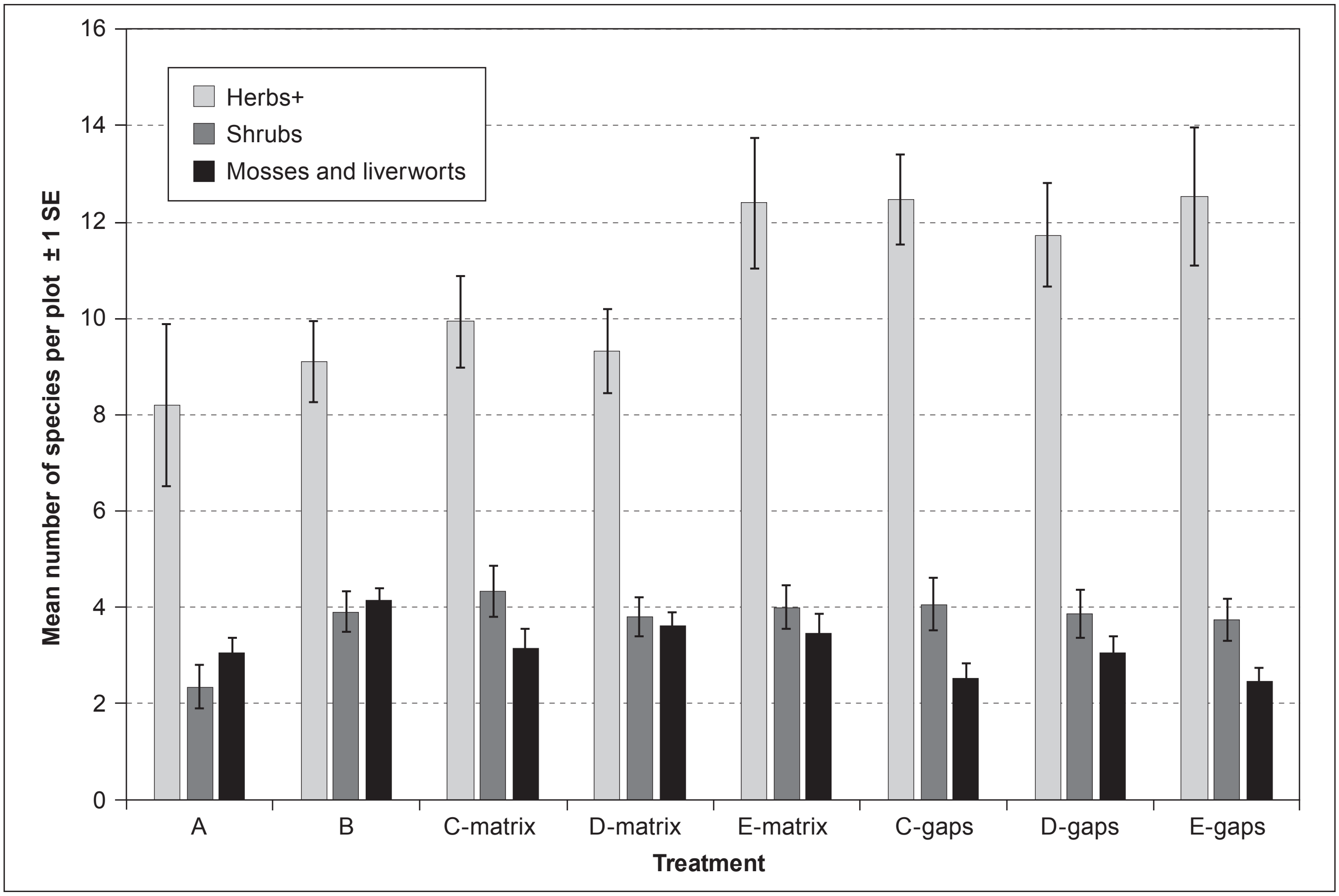


Figure 17—Mean number of species recorded per fixed-area plot in 2006 by species group, treatment, and location in matrix vs. gap. SE = standard error.

## Discussion

To summarize stand development on the 0.24-ha subplots as of 2013 (30 years after planting):

- There was no detectable differences among treatments in H100, the mean height of the largest Douglas-fir included in the largest 100 stems/ha.
- D100 (the diameter corresponding to H100) appeared to be slightly less in unthinned treatment A, compared to the several thinned treatments.
- There was a considerable difference in QMD between the unthinned treatment vs. the several thinned treatments (fig. 2), with treatment A having substantially lower QMD.
- Basal areas (fig. 4) were in the order A > B > (C or D or E).
- As expected, the mean number of trees (fig. 5) in A was greater than in B, which was greater than in treatments with gaps. There was no evident difference between C, D, and E.
- Total cubic volumes (fig. 6) were in the order A > B > (C or D or E). Volumes in A were also considerably more variable than in the other treatments.
- Treatments have produced considerable differences in diameter distributions, as shown in figures 8, 9, 10, and 11.

There is nothing surprising in the above.

The trees surrounding the gaps were only about 8 to 9 m in height at the time of gap creation (1995) and did not shade the openings to any great extent. Mean initial gap diameter in treatment C was estimated at about 13 m. Thus, the ratio of gap diameter to H100 was about 1.5, close to the minimum value for satisfactory growth of Douglas-fir regeneration specified by Malcolm et al. (2001).

This ratio must necessarily decrease with time as the surrounding trees grow in height and border trees expand their crowns into the gaps. The shade-tolerant hemlock and the few redcedar will no doubt survive. Conditions will become increasingly unfavorable for the existing Douglas-fir regeneration unless there is further management action to reduce the density of the surrounding stand.

There are also substantial differences in average crown development of A vs. B vs. C, D, and E, as expressed by live crown ratio corresponding to the 100 largest per hectare and that corresponding to the quadratic mean diameter of Douglas-fir (fig. 12). There are similar differences in estimated average crown widths (fig. 13).

## Vegetation Cover Estimates (2006)

As would be expected, gap creation considerably increased cover percentages of vegetation other than trees.

With hindsight, we think that although the 0.4-$m^2$ quadrat size used was smaller than desirable, with the frequently patchy distribution of vegetation, distribution of quadrats along transects provides a better overall sample of vegetation than do single fixed-area plots. Therefore, we used the transect estimates of cover percentages for herbs+, shrubs, and mosses and liverworts. Any future sampling of patchy vegetation would probably give the most repeatable results if larger and more numerous quadrats were used.

## Probable Future Stand Development

Long-term effects on timber production and on biodiversity will depend on future treatment of the stands. The difference in age between matrix and regeneration in gaps is not large, and the area in gaps in treatments C, D, and E is only about a third of the whole. Crown expansion of residual trees can be expected to limit development of the regeneration recently established in the gaps. If no further treatment is done prior to a final harvest, it seems likely that long-term effects of this early gap creation on total timber volume production will be fairly minor, although differences in average tree dimensions would be expected and the proportion of hemlock will increase. The FVS simulation is consistent with this subjective opinion. (However, FVS does not explicitly account for gaps.)

If harvest and regeneration occurred at about age 80 without further intermediate stand treatment, the stands in treatments A and B would still be nearly pure Douglas-fir, while C, D, and E would be predominantly Douglas-fir but with a considerable proportion of younger hemlock and rather small differences in total volume production compared to B.

If harvest were delayed indefinitely, the eventual result would be gradual conversion to stands that were predominantly hemlock. Early small gap creation hastens this change.

## Future of the Study

Further field measurements in the area are currently severely hampered, and further stand treatments prevented by loss of road access. If and when the Gifford Pinchot National Forest undertakes active stand management in the area, the future of the study should be reconsidered.

These stands are now at or near a stage where commercial thinning would be feasible and desirable from the joint standpoints of timber production and enhancement of wildlife habitat. This could take the form of irregular thinning in C, D, and E to enlarge some existing gaps and thus provide for survival and growth of the Douglas-fir regeneration established after the 1995 gap creation. This could logically lead to a transition to a group selection system for long-term management, producing an uneven-aged mixed-species structure with possible wildlife benefits and landscapes visually more acceptable to the public than those produced by conventional even-aged management. Conventional uniform thinning in B would provide a basis for comparison.

## Conclusions

Results to this point have shown that early gap creation (treatments C, D, E) in a very uniform Douglas-fir plantation has modified diameter distributions and introduced some irregularity in the crown canopy. It has also introduced some diversity in tree species composition, mostly through introduction of a hemlock component, and has substantially altered the composition of the understory vegetation. There has been considerable Douglas-fir regeneration in the gaps that will probably not survive without further stand treatment. Long-term effects will depend on whether additional stand density manipulation is carried out in coming years.

Volume production has been in the order A > B > ( C or D or E). Gap creation has initially somewhat reduced volume production, but it appears that relative differences will decrease over time and will probably become unimportant by an age of 80 or more years.

Differences in results among treatments C, D, and E were negligible. Most trees planted in gaps in C and E did not survive (primarily because of animal browsing), and the differences in gap size distribution in C vs. D. and E were insufficient to materially influence results.

## Acknowledgments

We thank Dean S. DeBell and Charlie Crisafulli for their efforts in designing and installing this study and our field crews for their efforts in tree and vegetation measurements. Also, we thank David Marshall, Bernard Bormann, Kevin Senderak, and Scott McLeod for helpful reviews.

## U.S. Equivalents

1 centimeter = 0.3937 inch
1 meter = 3.2808 feet
1 square meter = 10.76 square feet
1 hectare = 2.47 acres
1 square meter per hectare = 4.36 square feet per acre
1 cubic meter per hectare = 14.3 cubic feet per acre

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