

Effects of Operational Brushing on Conifers and Plant Communities in the Southern Interior of British Columbia

Results from PROBE 1991–2000
PRotocol for Operational Brushing
Evaluations

Suzanne W. Simard, Jean L. Heineman,
W. Jean Mather, Donald L. Sachs, and
Alan Vyse

Section Three



Ministry of Forests
Research Program

CONTENTS

SECTION 1	1
Introduction	1
SECTION 2	9
Objectives.....	9
SECTION 3	11
Methods	11
Experimental Design	11
Criteria for replicate site selection.....	11
Location and installation of brushing treatment and control plots.....	12
Measurements	12
Measurement schedule	12
Conifers	13
<i>Growth</i>	13
<i>Stocking and density</i>	13
Vegetation.....	13
<i>Abundance</i>	13
<i>Treatment efficacy</i>	14
Richness and diversity of individual vascular plant species.....	14
Richness and diversity of vegetation groups	15
Statistical Analysis	15
Analysis of variance.....	15
Regression analysis	16
Competition thresholds	17
SECTION 4 <i>Fireweed</i> Complex	19
Abstract.....	19
Introduction	20
Description of the <i>Fireweed</i> Complex	20
Development of the <i>Fireweed</i> Complex	20
Interactions with Conifer Seedlings.....	20
Importance to Wildlife and Range	21
Common Brushing Treatments in the <i>Fireweed</i> Complex	21
Results	23
Manual Cutting.....	23
Engelmann spruce in the ESSF zone and higher-elevation ICH zone.....	23
Lodgepole pine in the ICH zone	34
Ground Foliar Glyphosate Application	48
Engelmann spruce in the ESSF zone.....	48
Sheep and Cattle Grazing	57
Engelmann spruce in the ESSF zone.....	57
Discussion.....	66
Manual Cutting.....	66
Conifer response.....	66
Plant community response.....	66
Glyphosate	67

SECTION 13	341
References	341

SECTION 14	359
APPENDIX 1 Trends in Conifer and Vegetation Response in the <i>Willow</i> and <i>Pinegrass</i> Complexes.....	359
APPENDIX 2 Summary Statistics for Conifer and Vegetation Responses to Brushing Treatments on Single Replicate Sites	379

TABLES

1 Average brushing costs per hectare in 1997–1998	2
2 Treatment matrix used to guide selection of PROBE sites.....	4
3 Comparison of programs used to monitor brushing efficacy.....	7
4 Analysis of variance table for individual PROBE treatment cells.....	16
5 Common brushing treatments applied to the <i>Fireweed</i> Complex in the southern interior of B.C.	22
6 Characteristics and history of the four replicate study sites where the ESSF/ICH <i>Fireweed</i> Complex was manually cut in Engelmann spruce plantations prior to treatment.....	24
7 A description of manual cutting treatments applied to the four replicate study sites to release Engelmann spruce seedlings growing in the ESSF/ICH <i>Fireweed</i> Complex	25
8 Survival and growth responses of Engelmann spruce seedlings to manual cutting in the ESSF/ICH <i>Fireweed</i> Complex	25
9 Cover and height of vegetation in the ESSF/ICH <i>Fireweed</i> Complex before and after manual cutting in Engelmann spruce plantations.....	29
10 Richness and diversity of vascular plant species in the ESSF/ICH <i>Fireweed</i> Complex before and after manual cutting in Engelmann spruce plantations.....	30
11 Richness and diversity of structural vegetation groups in the ESSF/ICH <i>Fireweed</i> Complex before and after manual cutting in Engelmann spruce plantations	30
12 Vascular plant species that exhibited trends of increasing cover, decreasing cover, or no change in cover following manual cutting of the ESSF/ICH <i>Fireweed</i> Complex in Engelmann spruce plantations.....	31
13 Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting Engelmann spruce stem diameter from the competition indices, fireweed cover, and CRH, in the <i>Fireweed</i> Complex in the ICH zone.....	33
14 Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting Engelmann spruce stem diameter from the competition indices, fireweed cover, and CRH, in the <i>Fireweed</i> Complex in the ESSF zone.....	36
15 Characteristics and history of the three replicate study sites where the ICH/ESSF <i>Fireweed</i> Complex was manually cut in lodgepole pine plantations	38
16 A description of manual cutting treatments applied to the three replicate study sites to release lodgepole pine seedlings growing in the ICH/ESSF <i>Fireweed</i> Complex.....	39
17 Survival and growth responses of lodgepole pine seedlings to manual cutting in the ICH/ESSF <i>Fireweed</i> Complex	39
18 Cover and height of vegetation in the ICH/ESSF <i>Fireweed</i> Complex before and after manual cutting in lodgepole pine plantations	40
19 Richness and diversity of vascular plant species in the ICH/ESSF <i>Fireweed</i> Complex before and after manual cutting in lodgepole pine plantations	43
20 Richness and diversity of structural vegetation groups in the ICH/ESSF <i>Fireweed</i> Complex before and after manual cutting in lodgepole pine plantations.....	44
21 Vascular plant species that exhibited trends of increasing cover, decreasing cover, or no change in cover following manual cutting of the ICH/ESSF <i>Fireweed</i> Complex in lodgepole pine plantations.....	44

140	Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting Douglas-fir stem diameter from the competition indices, broadleaf density, broadleaf cover, and CRH, in the <i>Mixed Broadleaf-Shrub</i> Complex in the ICH zone	294
141	Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting lodgepole pine stem diameter from the competition indices, broadleaf density, broadleaf cover, and CRH, in the <i>Mixed Broadleaf-Shrub</i> Complex in the ICH zone	296
142	Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting hybrid spruce stem diameter from the competition indices, broadleaf density, broadleaf cover, and CRH, in the <i>Mixed Broadleaf-Shrub</i> Complex in the ICH zone	296
143	Summary of conifer responses.....	314
144	Summary of competition analyses	325
145	Summary of vegetation responses	329
A1.1	Common brushing treatments applied to the <i>Willow</i> Complex in the southern interior of British Columbia	362
A1.2	Average survival and growth responses of Douglas-fir seedlings to glyphosate on an unreplicated site in the IDF <i>Willow</i> Complex.....	363
A1.3	Average cover and height of vegetation in the IDF <i>Willow</i> Complex before and after foliar glyphosate application to an unreplicated Douglas-fir plantation.....	363
A1.4	Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting Douglas-fir stem diameter from the competition indices, willow cover, and CRH, in the <i>Willow</i> Complex in the IDF zone	365
A1.5	Common brushing treatments applied to the <i>Pinegrass</i> Complex in the southern interior of British Columbia	370
A1.6	Average survival and growth responses of lodgepole pine seedlings to spot application of glyphosate on an unreplicated site in the MS <i>Pinegrass</i> Complex.....	371
A1.7	Average cover and height of vegetation in the MS <i>Pinegrass</i> Complex before and after spot application of glyphosate in an unreplicated lodgepole pine plantation	372
A1.8	Competition thresholds, regression equation parameter estimates, p-values, and adjusted r^2 values for predicting lodgepole pine stem diameter from the competition indices, pinegrass cover, and CRH, in the <i>Pinegrass</i> Complex in the MS zone	373
A2.1	Site descriptions for single replicate sites	380
A2.2	Mean conifer survival for non-replicated PROBE treatments.....	382
A2.3	Mean conifer growth measurements for non-replicated PROBE treatments.....	384
A2.4	Mean vegetation cover measurements for non-replicated PROBE treatments.....	386
A2.5	Mean vegetation height measurements for non-replicated PROBE treatments.....	388
A2.6	Summary of responses for non-replicated PROBE treatments	390

FIGURES

1	Brushing trends in the Kamloops Forest Region from 1981 to 1998.....	1
2	Brushing trends in the Nelson Forest Region from 1981 to 1998.....	2
3	Schematic diagram of a single treatment or control plot	12
4	Hypothetical relationship between crop tree stem diameter and interspecific competition.....	18
5	The <i>Fireweed</i> Complex prior to manual cutting treatment at Bugle Creek (Site 108) in the ESSFwc1 variant in the Arrow Forest District	20
6	Comparison of Engelmann spruce vigour between the manual cutting treatment and control before, and 1 and 3 years after, treatment of the ESSF/ICH <i>Fireweed</i> Complex	25
7	Engelmann spruce seedlings in the (a) treatment and (b) control 5 years following manual cutting at Bugle Creek.....	26
8	Frequency of control and treated trees in standardized diameter classes for Engelmann spruce in the ESSF/ICH <i>Fireweed</i> Complex before and after manual cutting	27

METHODS

The methods described here are more fully detailed in Simard (1993). The PROBE program strives to meet the basic criteria for measuring treatment response using statistical inference, which includes randomization and replication of treatments and controls. Several populations were studied, specifically defined based on their ecosystem (biogeoclimatic unit and site series), vegetation complex, conifer tree species, and operational brushing treatment received. All populations occurred in the Kamloops and Nelson forest regions. Installation sites were randomly selected from the list of sites available each year. It must be recognized, however, that the populations from which sites were randomly selected were small because of restrictions imposed by site uniformity criteria, number of suitable operational brushing projects, and availability of funding in a given year. Paired plots were subjectively located in each opening to ensure comparability in site and vegetation characteristics. Treatment and control designations were then randomly assigned to each of the paired plots.

Experimental Design

The PROBE program is composed of a series of separate brushing experiments that are individually defined by their particular combination of ecosystem–vegetation complex–target conifer species–brushing method (hereafter called treatment cell).

For each treatment cell, two treatments (brushing treatment, control) were replicated a minimum of three times in a randomized complete block design (RCBD). Each replicate block occurred on a

separate opening in the Kamloops and Nelson forest regions (hereafter called PROBE site).

A matrix of treatment cells, based on common brushing treatments and vegetation complexes in southern interior British Columbia, was developed to guide PROBE site selection (Table 2). This matrix was developed and modified based on input from forest districts and licensees regarding common operational treatment application. Brushing treatments were included if they were frequently applied by more than one forest district in the Kamloops and Nelson forest regions. For example, manual cutting is the most commonly applied treatment in the southern interior, and therefore was given the highest priority for sampling. The vegetation complexes examined were previously identified as competitive threats to conifer crop trees and are fully described in Kimmins and Comeau (1990). Table 2 lists high priorities for vegetation management research, and indicates where PROBE sites have been or will be installed in the future. Other treatment cells in Table 2 are currently rare in operational brushing programs, and therefore are not currently being examined in the PROBE program. PROBE strives to accommodate new operational treatments, however, within the confines of annual funding availability.

Criteria for replicate site selection

Between 1991 and 1999, up to 15 PROBE sites were installed each year in the Kamloops and Nelson forest regions, depending on availability of funds. The funding restriction resulted in staggered replication of treatment cells over the 9-year period

(i.e., full replication of a treatment cell occurred over several years rather than all within a single year). Fairly strict criteria for replicate site selection were also imposed so that between- and within-site variability did not overwhelm treatment responses. These factors resulted in a small population of appropriate sites for a particular treatment cell, from which PROBE sites were selected.

The population of potential PROBE sites for a particular treatment cell was identified through consultation with district or licensee representatives. All potential PROBE sites met the following criteria:

1. The site was considered in need of operational brushing.
2. The ecosystem, vegetation complex, conifer species, and brushing method for the site fell within PROBE high-priority research needs (Table 2).
3. The site had a medium moisture regime.
4. The site had been disturbed (i.e., harvested or site prepared) within the last 15 years.
5. The site had enough area with homogenous ecosystem characteristics and site history to allow establishment of two plots (brushing treatment and control) of approximately 0.8 ha each.

Location and installation of brushing treatment and control plots

Each PROBE installation consisted of two plots (brushing treatment and untreated control) that were installed prior to operational brushing. Plots were located to be representative of the area being brushed, and also to minimize site and stand variability between the brushing treatment and control plots (i.e., minimized within-site variability). A completely random approach to plot location was not taken because we expected that small treatment responses could be masked by between-plot variation. Brushing treatment and control plots were similar with regard to the following characteristics: slope ($\pm 10\%$), slope position, aspect ($\pm 45^\circ$), elevation (± 50 m), soil texture, soil coarse fragment content, soil moisture regime, biogeoclimatic (BEC) site series, dominant vegetation species, and site preparation/planting history. Once plots were located, treatments (brushing and control) were randomly assigned.

Plots were either square (90×90 m) or rectangular (most often 70×120 m), including a

15–20 m buffer zone inside the perimeter of the plot (Figure 3). Inside the buffer zone of each of the brushing treatment and control plots, 36 tree-centred subplots were located in a square 6×6 grid (or a rectangular grid such as 9×4 , depending on the plot configuration). This was done by locating the first gridpoint at a measured distance of 15–20 m inside one of the measurement plot corners, and then systematically locating six gridpoints at 10-m intervals along each of six gridlines. From each gridpoint, the closest, undamaged tree of the target conifer species was chosen as a subplot centre and tagged. Trees that were undamaged but unhealthy due to vegetation competition still qualified as “targets.” Re-bar was placed 50 cm north of the crop tree to permanently mark the location of subplot centres. Subplot size varied with size of the target conifers: 10-m^2 subplots ($r = 1.78$ m) were used when average conifer height was ≤ 2 m and 20-m^2 subplots ($r = 2.52$ m) when average conifer height was > 2 m. The same subplot size was used for all subplots within a given assessment period, but on some sites it changed from one assessment period to the next as conifers grew.

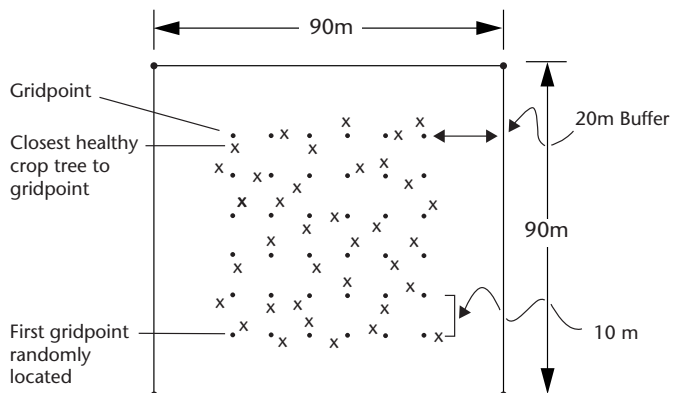


FIGURE 3 Schematic diagram of a single treatment or control plot.

Measurements

Measurement schedule

The PROBE measurement schedule specifies that information should be collected immediately before brushing, and 1, 3, 5, and 10 years afterward. However, none of the treatment cells reported here have

yet exceeded 5 years; some have been measured for only 1 or 3 years. Conifer stocking surveys are scheduled to be carried out before brushing and 5 and 10 years afterward. The following information was collected at each assessment date:

1. Growth, survival, and condition of target conifer crop trees
2. Abundance and condition of target vegetation
3. Treatment effects on target woody vegetation
4. Abundance of all vascular plant species
5. Photographs from established photo-points

We recognize the potential for an “observer effect” in this project because several individuals were involved in carrying out the assessments. However, subjectivity was minimized, wherever possible, by having the same individuals carry out both pre- and post-treatment assessments on individual sites. Assessors were also required to participate in periodical reviews of the PROBE methodology to ensure that data were being collected in a consistent manner across all sites.

Conifers

Growth

Growth of the target conifer seedlings was assessed in the 36 subplots in each of the brushing treatment and control plots. Measured variables were: total height (ground level to apical bud), leader length (to apical bud), stem diameter (measured at root collar), crown length, and crown width (average of N–S, E–W measurements). Calculated variables were height:diameter ratio and stem diameter increment (change in stem diameter between measurement years). Damage to the foliage, leader, and stem that could potentially affect performance of the target conifer was also recorded according to Herring and Pollack (1985), and, if possible, the damage cause was noted using Silviculture Survey damage codes (B.C. Ministry of Forests 1989). Seedling vigour was visually assessed according to Herring and Pollack (1985) and Simard (1993) as follows:

- Good-vigour seedlings had vigorous shoot growth, large leaf area, long needles, deep green colour, and thick caliper.
- Moderate-vigour seedlings had moderate shoot growth, leaf area, needle length, and caliper.
- Poor-vigour seedlings had little or etiolated shoot growth, few and/or short needles, and small caliper.

- Moribund seedlings were near death with little or no shoot growth.
- Dead seedlings.

Competitive status was visually assessed according to Herring and Pollack (1985) and Simard (1993) as follows:

- “Free-of-vegetation” seedlings had leaders that were well above surrounding vegetation and were unlikely to become overtopped within two growing seasons.
- “Threatened” seedlings had leaders at approximately the same height as surrounding vegetation.
- “Overtopped” seedlings had leaders that were overtopped by vegetation.

Seedling survival rates were assessed using the frequency of dead trees. Mortality causes were determined by visual integration of damage causes and competitive status.

Stocking and density

Density of all species of conifers and stocking of well-spaced and free-growing trees were determined in the 36 subplots in each of the brushing treatment and control plots before and 5 years after brushing. This assessment will be repeated 10 years post-treatment. Established subplot centres were used, but instead of 10-m² or 20-m² subplots, stocking was assessed in 50-m² subplots ($r = 3.99$ m). A modification of the standard Silviculture Surveys procedure was used to assess stocking (B.C. Ministry of Forests 1989), and free-growing (with the exception of the minimum age criteria for some sites) was assessed using current standards (B.C. Ministry of Forests 1995a, 2000). Only free-growing results collected according to the old guidelines (B.C. Ministry of Forests 1995a) are reported in this document.

Vegetation

Abundance

The frequency of each potentially competitive species was assessed during the initial layout of treatment and control plots to facilitate selection of “target” species for repeated evaluation. Species were selected as targets if they represented, or could potentially represent, a competitive threat to crop trees, and if they occurred in at least 80% of subplots in both the brushing treatment and control in the pre-treatment assessment. An example of a “potential competitive threat” is fireweed in

the understorey of paper birch in the *Mixed Broadleaf-Shrub* Complex. Fireweed may occur in minor, non-threatening amounts prior to treatment, but removal of the birch overstorey could create favourable conditions for its expansion to levels that are competitive with conifers. Selection of competitive or potentially competitive species or species groups (see below) was based on results of earlier studies in the southern interior (e.g., Simard 1990a, 1990b; Simard and Heineman 1996a, 1996b, 1996c; Simard, Heineman, and Youwe 1998). A minimum of one and a maximum of five target species were chosen on each site.

At each measurement, modal height and percent cover were estimated in each subplot for the selected target species as well as for the vegetation groups: "all vegetation," broadleaf trees, shrubs, and herbs. All broadleaf stems (regardless of origin) were counted in each subplot, and density per hectare was calculated.

Treatment efficacy

In vegetation complexes where broadleaf trees or shrubs with woody, persistent stems were chosen as target species, one stem of each of these species was chosen in, or near, each subplot and tagged for on-going assessment of treatment effects. Usually, the closest stem to the subplot centre was chosen, as long as it met criteria for brushing (e.g., if a girdling prescription called for treatment of all stems >5 cm diameter, then the tagged target specimen had to be >5 cm). Measured variables for target stems were total height and leader height. If leader growth was less than 80% complete, based on a subjective estimate, then the previous year's height growth was measured. Where sprouting had occurred in response to the brushing treatment, the number of sprouts was counted, and the average sprout length was estimated. Vigour was assessed according to Herring and Pollack (1985). Damage to the foliage, leader, and stem was also recorded according to Herring and Pollack (1985), and, if possible, the damage cause was noted using Silviculture Survey damage codes (B.C. Ministry of Forests 1989). The phenology of the vegetation complex (not the target specimen) at the time the brushing treatment was applied was recorded to help interpret treatment efficacy (Dierschke 1972; B.C. Ministry of Forests 1989). The efficacy of the chemical treatments for damaging the target specimen was rated using the Expert Committee on

Weeds (ECW) rating system. ECW rating is based on subjective estimation of the level of vegetation control for a plant species, as evidenced by degree of top kill, defoliation, abnormal growth form, or mortality. A 0–100% rating scale was used, where 0 indicated no control and 100 indicated complete control (Walstad and Wagner 1982; Expert Committee on Weeds Abstracts 1983).

Richness and diversity of individual vascular plant species

Abundance of individual vascular plant species was measured in four 50-m² subplots, in each of the brushing treatment and untreated control, at each scheduled measurement. Subplots were crop-tree centred, and were randomly selected from the 36 subplots in the treatment and control plots during the pre-treatment measurement. The same subplots were monitored in subsequent measurement years. For each vascular plant species, stratum, percent cover, distribution, and vigour were recorded (Habitat Monitoring Committee 1990), although here we report only percent cover. This information was used to identify trends in the effects of brushing on richness, diversity, and abundance of individual species within each PROBE treatment cell. It also contributed to the provincial Habitat Monitoring database.

Vascular plant species data were used to determine species richness (the number of species) in the treatment and control plots, and to calculate diversity indices according to Simpson (1949)

$$[1] \quad SDI = 1 - \sum_{i=1} ((n_i/N)^2)$$

and Shannon and Weaver (1949)

$$[2] \quad H = -(\sum_{i=1} (n_i/N) \log(n_i/N))$$

where n = cover of each species and N = sum of cover of all species.

Trends in brushing effects on individual plant species were identified by examining consistent increases and decreases in the abundance of individual species across a minimum of two replicate sites. The procedure for identifying these trends was necessarily subjective because it involved examining the data on a site-by-site basis, and attempting to exclude changes that were due to differences in assessment date, increased or decreased visibility of the species in question

(particularly for herbs of very small stature), and assessor subjectivity.

Richness and diversity of vegetation groups

The percent cover data for individual vascular species were also used to study the richness and diversity of vegetation groups, which were defined based on plant growth forms. We defined eight vegetation groups:

1. Shade-tolerant conifers (e.g., western redcedar [*Thuja plicata*], western hemlock [*Tsuga heterophylla*], subalpine fir [*Abies lasiocarpa*])
2. Moderately shade tolerant conifers (e.g., Douglas-fir [*Pseudotsuga menziesii*], Engelmann spruce [*Picea engelmannii*], lodgepole pine [*Pinus contorta* var. *latifolia*])
3. Shade-intolerant conifers (e.g., western larch [*Larix occidentalis*], ponderosa pine [*Pinus ponderosa*])
4. Tall broadleaves (e.g., trembling aspen [*Populus tremuloides*], paper birch [*Betula papyrifera*], black cottonwood [*Populus trichocarpa*])
5. Tall shrubs, short broadleaves, short conifers (e.g., willow [*Salix* spp.], alder [*Alnus* spp.], cherry [*Prunus* spp.], yew [*Taxus brevifolia*])
6. Short shrubs (e.g., blueberry and huckleberry [*Vaccinium* spp.], white-flowered rhododendron [*Rhododendron albiflorum*], thimbleberry [*Rubus parviflorus*])
7. Tall herbs (e.g., fireweed [*Epilobium angustifolium*], Sitka valerian [*Valeriana sitchensis*], Indian hellebore [*Veratrum viride*])
8. Short herbs (e.g., oak fern [*Gymnocarpium dryopteris*], foamflower [*Tiarella* spp.], sedges [*Carex* spp.])

Each of the vascular plant species was assigned to one of the eight vegetation groups, and then group richness and diversity were calculated for each site. Richness was the number of vegetation groups that occurred. Diversity was calculated using Simpson [1] and Shannon-Weaver Diversity Indices [2], but where n = cover of each vegetation group and N = sum of cover of all vegetation groups.

Statistical Analysis

Between 1991 and 1998, 96 PROBE sites were installed and maintained, resulting in full replication of 15 treatment cells and partial replication of another 30 cells. The focus of this report is the fully replicated treatment cells, for which Analysis

of Variance (ANOVA) was conducted separately for each measurement year. For individual sites in the partially replicated treatment cells, summary statistics were generated to provide qualitative treatment comparisons with the ANOVA results. Where these results are referred to, they are called “non-replicated treatments.” Frequency tables were used to summarize the categorical variables (crop tree vigour and competitive status). Regression analysis was used to examine individual tree responses to neighbourhood vegetation abundance, and scattergrams were used to identify competition thresholds for conifer stem diameter. All statistical analyses were performed using SAS for Windows, version 6.10 (SAS Institute, Inc. 1996).

Analysis of variance

The distribution of residuals and the tests for normality showed that transformations were generally not necessary for the variables tested. Data were analyzed separately by measurement year and treatment cell using one-way ANOVA with a randomized complete block design ($n = 3$ or 4 for each treatment cell and each replicate in the treatment cell is the mean of ≤ 36 subplot measurements). Sites were considered replicates in a treatment cell if they were comparable in terms of vegetation complex, brushing treatment, ecosystem, and conifer crop species. Differences in history among replicate sites were of secondary importance to comparability in vegetation complex at the time of treatment. In some cases, sites from adjacent biogeoclimatic zones were combined in a single treatment cell for ANOVA, but the sites were carefully examined to ensure that they were similar in vegetation composition and physiographic features. In a few cases, sites were dropped from treatment cells because the vegetation complex did not closely resemble that of other sites in the cell.

Differences between brushing treatment and control means were considered statistically significant at $\alpha = 0.10$. An α level of 0.10 was chosen because it allowed identification of early responses to treatments, which otherwise may not have been detected because of the high variability characteristic of such ecological data. Other vegetation management studies have frequently shown that the significance of differences following treatment increases with time. However, this choice of α level comes at the expense of increased probability of committing a Type I error (finding a treatment

effect that does not exist), which must be recognized by the reader. The degrees of freedom, expected mean squares, and F statistics of the ANOVA are shown in Table 4. The standard error of the treatment mean $\bar{y}$ was calculated as $sg = \sqrt{MSE/n}$ where $s_{\bar{y}}$ MSE = Mean Square Error and n = number of replicates (Peterson 1985). The confidence interval estimate of the mean difference between the treatment (T) and control (C) can be calculated as $((y_t - y_c) \pm \sqrt{2MSE/n})$, where t_{∞} has (n-1)(p-1) degrees of freedom and n = number of replicates and p = number of treatments.

Conifer variables tested using one-way ANOVA were total height, leader length, stem diameter, stem diameter increment, and height:diameter ratio. Vegetation variables tested were modal height and percent cover of all vegetation, broadleaf trees, shrubs, herbs, and each target species. Density of broadleaves (stems/ha) was also compared between the brushing treatment and control. Treatment efficacy variables that were tested for target woody stems were total height, current year's growth, number of sprouts, and Expert Committee on Weeds rating.

Interpretation of ANOVA results was enhanced with the use of frequency diagrams that compared stem diameter and height distributions between the brushing treatment and control. In construction of the frequency diagrams, data for each site within a particular ANOVA were standardized to a mean of zero and a standard deviation (s.d.) of 1 regardless of whether the data came from the treatment or the control. This removes site effects from the frequency distribution, while allowing treatment effects to be displayed. For each brushing treatment and control, the frequency of trees over all replicate sites was presented for 0.5 unit standardized diameter or height classes, up to four classes from the mean. Frequency diagrams comparing the brushing

treatment and control were constructed for the pre-treatment measurement, as well as each post-treatment measurement year. Qualitative interpretations were made of changes in the diameter and height distributions as a result of brushing treatments.

Regression analysis

Linear and nonlinear regression analyses were used to examine site-specific relationships between crop tree performance and the abundance of surrounding vegetation, which were measured in each tree-centred subplot in the treatment and control (n = 72 for each site). The most recent measurements were used in the analyses. The crop tree response variable used was stem diameter. Competition studies have frequently shown that stem diameter is the most sensitive measure of crop tree response to interspecific competition (e.g., Simard 1990a; Wagner and Radosevich 1991; Simard [2001, in review]). The vegetation abundance measures used were percent cover, modal height, and density of broadleaf trees in stems per hectare (*Mixed Broadleaf-Shrub* and *Aspen* complexes only). Several studies have found good correlations between crop tree stem diameter and interspecific competition indices based on percent cover (Wagner and Radosevich 1991; Wagner and Radosevich 1998), density (Simard 1990a; Newton and Jolliffe 1998), and the competition index, CRH (Brand 1986; Comeau et al. 1993). Therefore, this study used three groups of competition indices based on percent cover, broadleaf density, and CRH. CRH was defined as:

$$CRH = (C * R)/H$$

where C was percent cover of the dominant vegetation species or species group, R was the modal

TABLE 4 Analysis of variance (ANOVA) table for individual PROBE treatment cells

Source of variation	Factor type	Level	Degrees of freedom	MS	Expected F-test (df)
Treatment	fixed	k = 2	k - 1 = 1	MST	MST/MSE (1,2)
Replicate (block)	random	n = 3 ^a	n - 1 = 2	MSB	MSB/MSE (2,2)
Error			(n - 1)(k - 1) = 2	MSE	
Total			nk - 1 = 5		

^a In some treatment cells n = 4

height of the dominant vegetation species or species group, and H was total height of the crop tree. The CRH indices calculated for each complex were based on certain dominant species and species groups that had been shown in earlier studies to have the most important competitive effects on target crop trees, and also were the main targets of operational brushing treatments. This approach contrasts with some other studies where all species or species groups were summed into a single CRH index (e.g., Comeau et al. 1993). The dominant species and species groups used in calculating CRH for each complex were:

- fireweed in the *Fireweed* Complex
- herbs in the *Fern* Complex
- shrubs in the *Mixed Shrub* Complex
- shrubs in the *Ericaceous Shrub* Complex
- herbs in the *Subalpine Herb* Complex
- alder in the *Dry Alder* Complex
- alder in the *Wet Alder* Complex
- broadleaves in the *Aspen* Complex
- broadleaves in the *Mixed Broadleaf-Shrub* Complex
- willow in the *Willow* Complex
- pinegrass in the *Pinegrass* Complex

One linear and one non-linear model were tested. The linear equation takes the form:

$$Y = a + bX$$

where Y is crop tree stem diameter, X is percent cover, broadleaf density, or CRH of the dominant species or species group, *a* is stem diameter (intercept) at zero cover, density, or CRH, and *b* is the slope of the relationship. The non-linear model tested was the exponential decay function. It was tested on only one example site for each treatment cell to determine whether the non-linear model improved the data fit over the linear model of stem diameter versus CRH. The non-linear equation takes the form:

[3]
$$Y = ae^{-bX}$$

where Y is crop tree stem diameter, X is CRH of the dominant species or species group, *a* is the y-intercept, and *b* is the shape parameter. The regression models were evaluated based on their significance (p-value) and coefficient of determination (adjusted *r*² value).

Competition thresholds

Competition thresholds were determined for each site from scattergrams of stem diameter versus one of the three measures of competition (percent cover, broadleaf density, and CRH). Competition thresholds were identified on the assumption that competition is a constraint of target crop tree performance (Burton 1993). The constraint perspective is supported by many studies that show high variability in crop tree performance across low to intermediate neighbourhood abundance, and where regression relationships generally have low coefficients of determination. Those trees experiencing high competition have competition as a limiting factor, whereas trees experiencing low and medium levels of competition appear to be limited primarily by other factors.

For each scattergram, a ceiling function that described the upper boundary of the scattergram, and enveloped at least 95% of the observations, was used to identify competition thresholds (after Wagner et al. 1989; Burton 1993). Ceiling functions were defined using neighbourhood data (percent cover, broadleaf stem density, and CRH) collected from the most recent measurement year, taking into account treatment responses. Using these graphs, threshold competition levels were identified, below which target conifer stem diameter was independent of decreasing neighbourhood abundance, and above which diameter declined sharply in response to increasing neighbourhood abundance (i.e., the level at which competition became the primary constraint on stem diameter) (Figure 4).

Competition thresholds and regression coefficients were tabulated for each site in each complex in order to illustrate their between-site variability (e.g., Table 13). Competition thresholds were also averaged among the replicate sites for each vegetation complex-ecosystem-conifer-tree species combination, regardless of brushing treatment. In some cases, sites not used in ANOVA were included in mean and standard error calculations. As a result, threshold means included between one and 10 replicate sites. Discussion of threshold results focused on mean threshold values and their variability, rather than on individual sites. It is recognized that competition thresholds vary on a site-specific basis according to ecosystem, site quality, species composition, stand age, disease or

insect problems, and other factors (Burton 1993; Simard [2001, in review]). However, there was insufficient replication in this study to examine the effects of these individual factors on threshold variation.

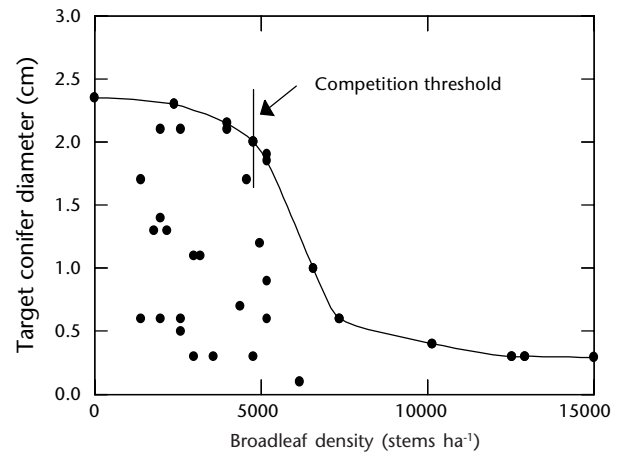


FIGURE 4 *Hypothetical relationship between crop tree stem diameter and interspecific competition. The maximum-response (or competition) threshold is the competition level at which tree diameter becomes constrained by interspecific competition.*