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 Twelve

BRITISH COLUMBIA
Ministry of Forests
Research Program

FIGURES

SECTION 12

OVERALL SUMMARY

This section ideally should be read as a summary to the preceding sections for individual vegetation complexes, but given the length and scope of the document, we recognize that it may be read independently. It is important, however, that the summary be read in the context of our study, keeping in mind its objectives and limitations, as they are described below.

The PROBE program investigated the effects of operational brushing treatments on conifer performance and plant community condition in the southern interior of British Columbia with the overall goal of advancing our ability to assess, predict and treat vegetation competition problems in young conifer stands. The general objectives of our study were:

1. to quantify the effects of operational brushing treatments on conifer seedling survival, growth, health, and free-growing status;
2. to quantify the effects of operational brushing treatments on the abundance, structure, diversity, and condition of the plant communities;
3. to identify competition thresholds for conifer growth;
4. to discuss possible effects of operational brushing treatments on various ecosystem attributes; and
5. to assess whether brushing treatments were meeting biological and management objectives.

STUDY SCOPE

The PROBE program was designed to test the effects of operational brushing on conifer crop tree performance and plant community condition across a broad array of vegetation complexes and brushing treatments in the southern interior of British Columbia. The experimental design, which used replicated, randomized, and paired control and brushing treatment plots, allowed standard parametric statistical analyses to test the effects of "brushing" versus "doing nothing." The experimental design provided an effective tool to realistically evaluate impacts of operational brushing on conifer performance and plant communities. PROBE differs in design and approach with many vegetation management research experiments, which helps explain why we sometimes found less dramatic effects of brushing. These include: (1) we evaluated variable and moderate vegetation problems characteristic of operational brushing projects rather than the highly brushy conditions often evaluated in many research studies; (2) we measured average responses rather than potential responses; and (3) we replicated our studies across variable sites rather than a single or few similar sites. The replication of operational treatments in PROBE across variable site conditions provides broader scope of inference of the results than most research studies, but also results in limitations in its power to detect small treatment effects.

Application of the results of this study is limited to the operational conditions that were examined. These conditions must be carefully considered when relating the results to silviculture practices.

1. The brushing treatments and plant communities we studied were common components of operational brushing programs in the Kamloops and Nelson forest regions. They were studied because of the high frequency with which the plant communities were targeted, and brushing treatments were applied by southern interior licensees and forest districts. We were not able to study all treatments that are commonly applied in the southern interior because there were limitations in the availability of candidate sites as well as the availability of funding. Most treatments that were chosen for study in the early to mid-1990s were still commonly applied in 1998, as shown in provincial summaries of brushing activities (Figures 1 and 2). However, practices apparently have changed in some areas of the southern interior since PROBE was initiated, including faster application of brushing following planting as well as more frequent application of multiple rather than single manual treatments. Because of the time required for treatment responses to occur and be evaluated, and the shortage of funding available to track treatment changes, there necessarily is a lag between some of these recent operational treatments and those evaluated and reported here.
2. Our study was limited to circum-mesic sites. There were two interrelated reasons for this limitation. Limitations in funding necessitated that we narrow the scope of our study, and we focused on circum-mesic conditions because they were most widely applicable to operations. In addition, circum-mesic sites were the most frequently brushed sites in the southern interior, and were therefore the most frequently available for study. Terrestrial ecosystem mapping projects show that circum-mesic sites comprise approximately 75% of the forested landbase, and an even larger proportion of the logged and brushed landbase (D. Lloyd, pers. comm. 2000). Because of this limitation, this study may not have detected potential vegetation problems on highly specific sites (e.g., subhygric sites). Similarly, we may not have detected problems at certain ages (e.g., 1–2 years old) because most brushing treatments are operationally applied several years post-treatment, when competitive conditions are apparent.
3. Brushing treatments were not always applied in exactly the same way to each replicate site in a particular treatment cell. Therefore, our interpretations are made of general treatment methodology (e.g., manual versus chemical, broadcast versus tree-centred) rather than specific treatment attributes (e.g., specific times or rates of application). Care must be taken not to extrapolate our results to treatments or complexes that were not measured in our study, just as our results should not be extrapolated to other regions of the province.
4. We have measured brushing responses for five years in most cases (9 out of 15 treatments), and only three years for four treatments and one year for two treatments (Table 143). Care must be taken in extrapolating the results of this study beyond the measurement years. It is possible that brushing responses may appear, disappear, magnify, or diminish as time since treatment increases. Additionally, competitive interactions are expected to change with time, and the results presented here apply only to the plantation age range operationally treated and measured (see Table 143).
5. The objective of our study was to evaluate brushing treatments rather than to evaluate the more complex silviculture treatment regime (harvest, site preparation, planting) that led to the treatable vegetation condition. The competitive status of seedlings and the need for brushing was determined by the silviculturist prescribing treatment for the site, and our study set out to test the assumptions made about competition and to measure the average responses to the operational prescriptions. Evaluating the silviculture regime that led to the competitive condition being treated was beyond the stated scope of this study, and was not feasible given the level of funding committed to the program. Nevertheless, we recognize that different harvesting, site preparation, and planting regimes can affect the competitive status of plantations. We have tried to address this variance by restricting our replicate

TABLE 143 *Summary of conifer responses*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Pre-treatment vegetation characteristics: Vegetation component	Cover (%)	Height (cm)	Seedling survival response[b]	Seedling growth response[b]	Remarks about vegetation responses	Will treatment help meet free-growing?	Remarks about free-growing
Herb and low-elevation complexes												
Fireweed	ESSF/ ICH	Se 2–4 years	Manual	3	Fireweed All vegetation Herbs Shrubs	45 76 66 16	110 95 96 62	NO	NO	• Vegetation competition was not severe enough to cause mortality or growth losses to seedlings (average survival across the treatment and control was 96% after 3 years) or cause large reductions in growth. • Vegetation recovered rapidly from a single manual cutting treatment.	NO	• Vegetation competition did not reduce stocking. • Seedlings outgrew this complex without brushing. • Brushing is not predicted to decrease the time required to meet free-growing.
Fireweed	ICH/ ESSF	Pl 1-3 years	Manual	5	Fireweed All vegetation Herbs Shrubs	45 76 64 17	90 85 79 52	NO	NO	• As above (average survival across the treatment and control was 88% after 5 years)	NO	• As above
Fireweed	ESSF/ ICH	Se 1-5 years	Glyphosate	5	Fireweed All vegetation Herbs Shrubs	53 82 76 13	105 88 88 65	NO	YES(+)	• Vegetation competition was not severe enough to cause seedling mortality (average survival across the treatment and control was 91% after 5 years). • Reduced vegetation abundance resulted in minor or temporary growth improvements (e.g., a short-lived increase in stem diameter that disappeared by year 5 and reduced H:D ratio)	NO	• As above
Fireweed	ESSF	Se 0–5 years	Grazing	1	Fireweed All vegetation Herbs Shrubs	29 82 68 19	93 79 74 94	NO	NO	• Vegetation competition was not severe enough to cause seedling mortality or growth losses (average survival across the treatment and control was 94% in year 1). • Vegetation recovered rapidly from a single grazing treatment.	NO	• As above

TABLE 143 *Continued*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Pre-treatment vegetation characteristics: Vegetation component	Cover (%)	Height (cm)	Seedling survival response[b]	Seedling growth response[b]	Remarks about vegetation responses	Will treatment help meet free-growing?	Remarks about free-growing
Fern	ICH	Sx 2–4 years	Glyphosate	5	Lady fern Thimbleberry All vegetation Herbs Shrubs	28 13 86 64 30	79 57 99 90 94	**NO**	**YES(+)**	• Vegetation competition was not severe enough to cause seedling mortality or or growth losses (average survival across the treatment and control was 93% after 5 years). On one site, brushing was applied after extensive mortality had already occurred. • Reduced vegetation abundance caused significant improvements in stem diameter, stem diameter increment, height, leader length, and H:D ratio.	**NO**	• We predict minimum height and conifer:vegetation height ratio requirements will be met without brushing. • Treated seedlings grew above vegetation 2 years ahead of control seedlings • Stocking could have been improved by earlier brushing on at least one of the sites.
Mixed Shrub	ICH/ ESSF	Sx 1 year	Manual	3	All vegetation Shrubs Herbs	81 44 51	85 78 81	**NO**	**YES(+)**	• Vegetation-related mortality was high in both the treatment and control (average survival across the treatment and control was 75% in year 3) because vegetation recovered rapidly following manual cutting. • Stem diameter and H:D ratio improved among surviving seedlings as a result of manual cutting.	**NO**	• Stocking requirements are likely to be met if there is little future mortality. • Surviving seedlings are likely to meet minimum height and conifer:vegetation height ratio requirements without brushing. • Treated seedlings are predicted to be as tall as surrounding vegetation only 1 year ahead of control seedlings.

TABLE 143 *Continued*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Pre-treatment vegetation characteristics: Vegetation component	Cover (%)	Height (cm)	Seedling survival response[b]	Seedling growth response[b]	Remarks about vegetation responses	Will treatment help meet free-growing?	Remarks about free-growing
Mixed Shrub	ICH/ ESSF	Sx 1–2 years	Sheep grazing	1	Fireweed All vegetation Shrubs Herbs	26 89 51 46	82 86 91 71	NO	NO	• Grazing reduced fireweed height and cover for one year, but this had no effect on first-year seedling survival (average 94% across the treatment and control) or growth.	NO	• Minimum height and conifer:vegetation height ratio requirements are likely to be met without brushing. • There is potential for future mortality among these young seedlings, which are declining in vigour. This could affect stocking requirements.
High-elevation shrub complexes												
Ericaceous Shrub	ESSF	Se 0–2 years	Manual	5	All vegetation Shrubs Herbs	88 58 45	113 117 48	YES(+)	YES(+)	• Seedling survival was significantly higher in the manual cutting treatment (89%) than in the control (71%) in year 5. • Minor growth improvements (longer leaders, lower H:D ratio) also resulted from manual brushing.	YES	• Brushing will help meet the stocking requirement. • Brushed seedlings are likely to meet the conifer conifer:vegetation height ratio requirement 4 years ahead of control seedlings.
Tall shrub complexes												
Dry Alder	MS	Pl 5 years	Manual	5	Alder Shrubs Herbs	22 48 34	192 170 71	NO	NO	• Vegetation competition had no effect on survival (average survival across the treatment and control was 93% in year 5) or growth of pine seedlings.	NO	• Seedlings in both the control and treatment were taller than the *Dry Alder* Complex by year three (age 8). • Brushing is not necessary to meet any of the free-growing requirements.

TABLE 143 *Continued*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Pre-treatment vegetation characteristics: Vegetation component	Cover (%)	Height (cm)	Seedling survival response[b]	Seedling growth response[b]	Remarks about vegetation responses	Will treatment help meet free-growing?	Remarks about free-growing
Wet Alder	ESSF	Se 4–6 years	Manual	3	Alder Shrubs Herbs	32 55 44	258 234 87	NO	YES(+)	• Most seedling mortality had occurred prior to the cutting treatment. • Manual cutting had no effect on survival of the established seedlings (average survival across the treatment and control was 93% in year 3). • H:D ratio is **slightly** lower in the brushing treatment after 3 years.	YES & NO	• Brushing will help meet the minimum height and conifer:vegetation height ratio requirements. • Stocking could be reduced below minimum standards because of mortality that occurred prior to brushing and because of accidental cutting. • A second cutting will likely be necessary to meet conifer:vegetation height ratio requirements.
Broadleaf complexes												
Aspen	IDF/ MS	Pl 7–10 years	Manual	3	Aspen Shrubs Herbs	26 25 59	326 116 29	NO	YES(+)	• Brushing was not needed to ensure excellent survival (100% in both the treatment and control after 3 years). • H:D ratio and stem diameter improved **slightly** following manual cutting.	YES	• Reductions in broadleaf height and cover were not statistically significant; however, they were likely sufficient to allow pine to outgrow surrounding vegetation.
Mixed Broadleaf-Shrub	ICH	Fd 5–6 years	Manual	5	Broadleaves Shrubs Herbs	16 35 23	291 87 67	YES(-)	YES(+)	• Brushing **reduced** third-year survival because of increased *Armillaria*-related mortality. • Brushing had no effect on survival by year 5 (average across the treatment and control was 88%). • Brushing improved vigour of surviving seedlings and resulted in larger stem diameters and longer leaders after 5 years.	YES	• Brushing was necessary to meet the conifer:vegetation height ratio requirement.

TABLE 143 *Concluded*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Pre-treatment vegetation characteristics			Seedling survival response[b]	Seedling growth response[b]	Remarks about vegetation responses	Will treatment help meet free-growing?	Remarks about free-growing
					Vegetation component	Cover (%)	Height (cm)					
Mixed Broadleaf-Shrub	ICH	Pl 3–10 years	Manual	5	Broadleaves Shrubs Herbs	16 40 26	293 95 64	**YES(-)**	**YES(+)**	• Manual cutting caused an increase in *Armillaria*-related mortality of pine in year 3. • Cutting improved vigour of surviving seedlings and resulted in larger stem diameter and stem diameter increment and lower H:D ratio after 5 years.	**YES & NO**	• Brushing was necessary to meet the conifer:vegetation height ratio requirement. • Our data suggest manual cutting may increase the spread of *Armillaria*, which could affect stocking.
Mixed Broadleaf-Shrub	ICH	Fd 8–9 years	Cut stump–glyphosate	5	Broadleaves Shrubs Herbs	54 46 30	438 85 65	**NO**	**YES(+)**	• Cut stump–glyphosate had no effect on Douglas-fir survival (average across the treatment and control was 95% in year 5). • Cut stump–glyphosate resulted in relatively large improvements in seedling stem diamter, stem diameter increment, height, and H:D ratio.	**YES**	• Brushing was necessary to meet the conifer:vegetation height ratio requirement. • Other studies suggest chemical treatments may be less likely to stimulate the spread of *Armillaria* than manual treatments.
Mixed Broadleaf-Shrub	ICH	Fd 5–17 years	Girdle	5	Broadleaves Shrubs Herbs	25 29 34	604 110 94	**YES(-)**	**YES(+)**	• Girdling **reduced** survival in year 5 (90% in the treatment vs. 97% in the control), mainly as a result of of increased *Armillaria*-related mortality. • Girdling resulted in a **minor** increase in leader length after 5 years. Seedlings may be responding slowly to girdling because treated broadleaves died gradually.	**YES & NO**	• Brushing was necessary to meet the conifer:vegetation height ratio requirement. • Our data suggest manual cutting may increase the spread of *Armillaria*, which could affect stocking.

[a] Age (years since planting) at the time of brushing.
[b] NO indicates no significant treatment response, YES(+) indicates a significant positive treatment effect, and YES(-) indicates a significant negative treatment effect.

sites to those that were clearcut, site prepared (in most cases), and planted with specific tree species. We have also considered, in our management recommendations, site preparation and planting treatments that may result in lowered competitive conditions and reduced need for brushing. There is, however, a need to expand silviculture treatment evaluations to include a regime of treatments rather than brushing alone.

6. Our evaluation of brushing effects on plant communities was limited by the methodology used. For example, particular tree and plant species were chosen for measurement when PROBE sites were established, and changes in other species as a result of brushing (e.g., species shifts) would therefore not have been detected. In addition, we used conventional measures of plant species diversity in our analysis (i.e., Shannon-Weaver and Simpson Diversity Indices), and these measures are limited in their ability to detect changes to particular properties of diversity as well as in their relationship to ecological function (Hurlbert 1971).

Conifer survival was improved in only one of the fifteen operational brushing treatment cells examined in this study (Table 143). We offer several possible explanations for this survival response:

1. Vegetation competition was, on average, not intense enough to threaten overall conifer survival in many of the vegetation complexes studied. We found examples of this phenomenon on circum-mesic sites in the *Fireweed, Dry Alder, Mixed Broadleaf-Shrub,* and *Aspen* complexes. In these complexes, survival in the untreated controls was consistently >85%. Plant communities were well developed on these sites, but we found that agents other than vegetation competition appeared to have contributed to most of the mortality (e.g., disease, rodents, microclimate), except in localized, dense vegetation patches. Many other studies have shown that vegetation competition in operational plantations is commonly not intense enough to cause mortality of established conifers, even though it can cause growth losses (Wagner et al. 1989; Wagner and Radosevich 1998; Simard, Heineman, and Youwe 1998). Competition-related mortality has been observed to occur during the lag between planting and brushing, in the wetter subzones of the ICH, and over long time periods, but this was not evaluated in our study because of limitations in treatment method and timing that were operationally applied, the candidate sites that were available for study, the period of time that had lapsed since treatment application, and the funding that was available to establish new trials.
2. In our studies of the *Dry Alder*, *Mixed Broadleaf-Shrub* and *Aspen* complexes, plantations were generally adequately stocked with well-established conifers at the time of brushing. We found that brushing had no effect on conifer survival in these complexes, which agrees with most other brushing studies in British Columbia (Comeau et al. 2000b).
3. In some cases, brushing may have been applied too late to have an effect on seedling survival. This applies to some of the moister sites in the *Fern, Fireweed,* and *Mixed Shrub* complexes, where silviculture survey information and history records suggest that vegetation-dependent mortality occurred soon after plantation establishment. To improve survival and stocking on moist to wet sites, or on mesic sites in wetter subzones, observations suggest that brushing should be applied within 1–2 years of planting, before competition intensifies.
4. The single manual cutting and grazing treatments that were commonly applied to dense herb and shrub patches in the *Fireweed* and *Mixed Shrub* Complexes were ineffective at improving conditions for early survival. Vegetation usually rebounded to pre-treatment levels within one growing season, which was too soon to reduce seedling mortality. Other studies suggest that brushing treatments that result in sustained vegetation suppression, such as glyphosate or multiple manual and grazing applications, are necessary if survival is to be improved. Foliar glyphosate application is the most cost-efficient treatment, but multiple manual or grazing treatments can be equally effective where there are site or social constraints to the use of herbicides.
5. Subhygric sites, where the *Fireweed, Fern* and *Mixed Shrub* complexes tend to be most vigorous, were not generally evaluated. Instead, the PROBE program focused on evaluating circum-mesic sites because that is where most operational brushing occurred. Subhygric areas where vegetation is dense are often small patches embedded within a mesic matrix, and are difficult to assess using the large PROBE plots.
6. There was one complex in which conifer survival was improved by brushing. Survival of Engelmann spruce seedlings was substantially improved following selective, tree-centred manual cutting in the well-developed *Ericaceous Shrub* Complex. Seedlings were very young (≤2 years old) at the time of brushing and had not yet suffered substantial vigour losses. Consequently, small reductions in the slowly growing ericaceous shrubs, mainly rhododendron and false azalea, were sufficient to reduce early seedling mortality.

Some brushing treatments applied in the *Mixed Broadleaf-Shrub* Complex reduced survival because of significantly increased mortality due to *Armillaria* root disease. Five-year mortality among lodgepole pine was 4.5 times greater where neighbouring broadleaves were manually cut (9%) compared to where they were left untreated (2%).

Similarly, 5-year mortality of Douglas-fir increased from 3% to 8% following broadleaf girdling. Greater incidence of *Armillaria* following brushing has been observed in other studies as well (Woods 1994; Simard and Heineman 1996a), and has been attributed to increased disease inoculum loads and increased rates of conifer root growth and inoculum contact. In contrast to girdling, manual cutting and cut stump–glyphosate treatments had no effect on Douglas-fir survival. In the manual cutting treatment, Douglas-fir and the broadleaves were younger and smaller than in the other girdling and cutting treatments, and therefore the rate of contact with *Armillaria* inoculum may have been slower and inoculum potential may have been lower. In the cut stump–glyphosate treatment, the chemical may have slowed the spread of *Armillaria* root disease by killing roots faster and increasing their attractiveness to more competitive saprophytes.

Longer-term measurements are required to quantify changes in *Armillaria* mortality rates as inoculum potential decreases with stand age, and therefore to determine the importance of treatment-related mortality to stand performance. At present, we suggest that caution be exercised in prescribing brushing for young conifers growing among the *Mixed Broadleaf-Shrub* Complex on infected sites to ensure that resultant mortality does not outweigh growth benefits. Where conifer performance is substantially compromised by vegetation competition, our results suggest that *Armillaria*-caused mortality may be reduced by applying chemical rather than manual treatments. To minimize inoculum loads on these sites, we suggest that treatments be applied selectively to release stressed individuals only, rather than using a broadcast approach. Our suggestions support the *Root Disease Management Guidebook* of the Forest Practices Code (B.C. Ministry of Forests 1995c), which indicates that brushing be restricted where *Armillaria* root disease incidence reaches the levels measured in our study.

Conifer diameter increased on average following ground-foliar glyphosate treatment in the *Fern* Complex, manual cutting in the *Mixed Shrub* Complex, and manual cutting and cut stump–glyphosate treatments in the *Mixed Broadleaf-Shrub* Complex (Table 143). Average diameter of 2- to 4-year-old hybrid spruce increased by 58% (1.5 cm) 5 years after foliar glyphosate treatment of the *Fern* Complex. By contrast, glyphosate application had no significant effect on 5-year diameter of spruce growing in the less competitive *Fireweed* Complex, but it did reduce height:diameter ratio. Manual cutting resulted in a smaller response among newly planted to 3-year-old spruce growing in the *Mixed Shrub* Complex, where average diameter increased by 23% (0.3 cm) 3 years after treatment. Five to 9-year-old Douglas-fir growing in the *Mixed Broadleaf-Shrub* Complex exhibited 5-year diameter increases ranging between 14% (0.6 cm) and 51% (2.6 cm) following manual cutting and cut stump–glyphosate treatments, respectively. In general, the greatest average diameter increases occurred following treatments that caused sustained reductions in vegetation, and in complexes where dense vegetation had overtopped conifers and suppressed their growth.

Conifer diameter was not affected by the single, manual cutting treatments studied in the *Fireweed, Ericaceous Shrub, Dry Alder, Wet Alder,* and *Aspen* complexes, by the single grazing treatments studied in the *Mixed Shrub* and *Fireweed* complexes, or by the foliar glyphosate treatment studied in the *Fireweed* Complex, even though diameter increment sometimes improved slightly or temporarily. We suggest that the lack of diameter responses in these complexes occurred for one or more of the following reasons:

1. Vegetation competition with well-established, thrifty lodgepole pine in the *Dry Alder* Complex was of low intensity, and control pine outgrew the alder canopy soon after those in the manual cutting treatment. We found that competition was of low to moderate intensity in the *Aspen* complex but long-term measurements are needed to determine when pine will outgrow the aspen canopy.
2. Brushing did not alleviate environmental factors (e.g., cold, wet soils) that appeared to override competitive effects in the *Wet Alder* Complex.
3. Vegetation reductions were too small and short-lived, and vegetation competition was neither important nor intense enough, for seedlings to respond, on average, in the *Fireweed* and *Mixed Shrub* complexes.
4. Conifer responses to brushing may have been delayed in the *Ericaceous Shrub* and *Wet Alder* complexes. Even though diameter was unaffected by brushing after 3–5 years, small decreases in height:diameter ratio and slow recovery of the vegetation may foreshadow future diameter increases. In these complexes, it is possible that seedlings were suppressed at the time of brushing and may eventually respond to release in the future. Responses may also have been delayed following girdling in the *Mixed Broadleaf-Shrub* Complex because girdled stems died slowly. Delayed responses are unlikely in the other complexes because either treated vegetation had already rebounded to control levels, both treated and control trees had outgrown neighbouring vegetation, or competition was of low intensity.

Conifer height was generally unaffected by brushing in our studies. The one exception was a 25% increase in Douglas-fir height 5 years following cut stump–glyphosate treatment in the *Mixed Broadleaf-Shrub* Complex. Many other studies demonstrate that height is less responsive than stem diameter to interspecific competition (Lanner 1985), and if height responds to release at all, it is usually delayed for several years (Simard and Heineman 1996a).

Whether short-term increases in growth following brushing result in greater yield at rotation, or shorter rotations, can only be determined with long-term measurement and maintenance of the studies. Several alternative outcomes have been discussed among foresters:

1. Yield may be unaffected because brushing has no effect on stocking, conifer species composition, or site productivity, and any short-term increases are masked by subsequent events in the life of the stand.
2. Yield may increase, but to a small degree, because growth of treated trees may parallel that of untreated trees once they have surpassed neighbouring vegetation. Theories (1) and (2) have been suggested for the herb- and shrub-dominated

complexes in particular. Convergence of treatment effects on 10-year conifer growth has similarly been observed following site preparation in interior British Columbia (Bedford and Sutton 2000).

3. Yield may increase substantially because growth curves of treated and untreated trees continue to diverge over time. This is commonly assumed to be the case for the *Mixed Broadleaf-Shrub* and *Aspen* complexes, but there is no published evidence for interior British Columbia conditions.
4. Yield in the *Mixed Broadleaf-Shrub* Complex may decrease as a result of brushing if mortality due to *Armillaria* root disease reduces stocking below site occupancy for conifers. Such unexpected effects have been reported for a variety of species, site conditions, and silvicultural treatments in British Columbia (e.g., Simard 1990b and unpublished data; Taylor et al. 1994; Simard and Heineman 1996a; Bedford and Sutton 2000).

Our neighbourhood analyses suggest that vegetation competition, considered over whole plantations, was of low or moderate importance and intensity to conifer diameter growth in the vegetation complexes studied (Table 144). This was evaluated on the basis of the adjusted r^2 (importance) and slope (intensity) of regression models (Weldon and Slauson 1986) relating conifer diameter to competition indices (cover, CRH, and broadleaf density) (see footnotes to Table 144 for definitions of low, moderate, and high importance or intensity). In general, tree size was highly variable under low to moderate levels of competition and constrained only by high levels of competition in localized, dense vegetation patches. More specifically, we found that vegetation competition was of low importance and low intensity in the *Fireweed* and *Dry Alder* complexes on mesic sites, which helps explain why conifers naturally outgrew these communities and did not respond to brushing treatments. In the *Fern* and *Mixed Broadleaf-Shrub* complexes, competition was of moderate importance and moderate intensity, which helps account for the larger conifer growth responses following brushing. In the *Mixed Shrub, Ericaceous Shrub,* and *Aspen* Complexes, competition was of moderate importance but low intensity, indicating that competition was an important determinant to overall conifer performance, but was too weak to illicit a substantial growth response to brushing. Conversely, competition was of low importance, but moderate intensity in the *Wet Alder* Complex, indicating that competition was locally intense, but not very important to overall conifer performance relative to other determinant factors (e.g., cold, wet soils). Other studies have also shown that neighbour competition is often of low to moderate importance to conifer performance in plantations, and that other factors can be of greater importance, including initial seedling size, damage incidence (e.g., by animals, insects, disease, frost), microsite, and genetic variability (Brand 1986; Coates 1987; Simard 1989a; Wagner et al. 1989; Wagner and Radosevich 1991; Burton 1993).

Competition thresholds for conifer growth were evident in all of the vegetation complexes studied, but were often diffuse in nature and varied considerably among replicate sites. This indicates that vegetation competition, and its effect on conifer growth, is variable both within and across sites. Average cover thresholds ranged between 18–28% for broadleaves in the *Mixed Broadleaf-Shrub* Complex, 13–31% for broadleaves in the *Aspen* Complex, 33–37% for alder in the *Dry Alder and Wet Alder* complexes, 35–46% for fireweed in the *Fireweed* Complex, and 68–78% for shrubs in the *Mixed Shrub* Complex. CRH thresholds and regression analysis generally followed similar patterns, indicating that the *Mixed Broadleaf-Shrub* was the most competitive complex to conifers, and the *Fireweed* and *Dry Alder* complexes were the least competitive.

We found that broadleaf thresholds for maximum conifer diameter growth in the *Aspen* Complex averaged 3180 and 2600 stems/ha for lodgepole pine and Douglas-fir, respectively. In the *Mixed Broadleaf-Shrub* Complex, the broadleaf thresholds averaged 2500, 3367, and 3664 stems/ha for hybrid spruce, lodgepole pine, and Douglas-fir, respectively. At the time the thresholds were derived, conifers were <13 years old (except for one site in the *Mixed Broadleaf-Shrub* Complex where they were 19 years old) and broadleaves were within 4 years of the age of the conifers (Table 144). These thresholds included broadleaf trees of all sizes, whether shorter or taller than the target conifers. In a separate study, Simard [2001, in review] derived two sets of thresholds for diameter growth of 9–13-year-old conifers in the ICHmw subzone of southern interior British Columbia: one using all-sized paper birch trees and another using only those paper birch trees that were taller than the target conifers. In that study, the density thresholds for western redcedar, Douglas-fir, and western larch were 4500, 4050, and 4000 birch stems/ha where all-sized paper birch were included, and 3325, 2575 and 733 birch stems/ha where only taller paper birch were included. Simard [2001, in review] found that broadleaf density thresholds declined with stand age, reflecting the dynamic nature of seral ICHmw forests. The thresholds were 1967, 485, and 370 taller broadleaf stems/ha in 25-year-old stands and 400, 173, and 40 stems/ha in 50 year-old stands for western redcedar, Douglas-fir, and western larch, respectively. The decline in thresholds corresponded with changes in the identity of

TABLE 144 *Summary of competition analyses*

Vegetation complex	BEC zone	# of sites used to determine thresholds	Conifer species	Conifer age[a] (yr)	Vegetation component used as a measure of competition[b]	Cover threshold[c] (%)	CRH threshold[d]	Density threshold[e] (stems/ha)	Competition importance[f]	Competition intensity[g]
Herb and low-elevation shrub complexes										
Fireweed	ICH	6	Se	0–4	Fireweed	46	60	-	Low	Low
	ESSF	13	Se	0–5	Fireweed	35	46	-	Low	Low
	ICH	5	Pl	0–5	Fireweed	40	49	-	Low	Low
Fern	ICH	4	Sx	1–4	Herbs	None	58	-	Moderate	Moderate
Mixed Shrub	ICH/ESSF	5	Sx	0–2	Shrubs	76	84	-	Moderate	Low
	ICH/ESSF	2	Cw	0–1	Shrubs	68	187	-	Moderate	Low
	ICH/ESSF	2	Fd	2–3	Shrubs	78	48	-	Moderate	Low
High-elevation shrub and herb complexes										
Ericaceous Shrub	ESSF	8	Se	0–9	Shrubs	52	73	-	Moderate	Low
Subalpine Herb	ESSF	1	Se	0	Herbs	None	184	-	Low	Low
Tall shrub complexes										
Dry Alder	MS	4	Pl	5–11	Alder	33	38	-	Low	Low
Wet Alder	ICH/ESSF	3	Se	5–10	Alder	37	107	-	Low	Moderate
Broadleaf complexes										
Aspen	IDF/MS	6	Pl	2–10	Aspen	31	31	3180	Moderate	Low
	ICH	4	Fd	2–10	Aspen	21	19	2400	Moderate	Low
Mixed Broadleaf–Shrub	ICH/IDF	14	Fd	2–19	Broadleaves	28	39	3664	Moderate	Moderate
	ICH	3	Pl	3–11	Broadleaves	18	15	3367	Moderate	Moderate
	ICH	3	Sx	1–13	Broadleaves	20	27	2500	Moderate	Moderate

[a] Age of conifers used in the threshold determinations.
[b] Vegetation component used in determinations of cover, CRH, and density thresholds (notes c, d, e).
[c] A threshold for conifer diameter was determined using cover of the chosen vegetation component.
[d] A threshold for conifer diameter growth was determined using CRH, which was calculated as: CRH = ("vegetation component" cover * "vegetation component" modal height)/conifer height.
[e] A threshold for conifer diameter growth was determined using the density of broadleaf stems.
[f] Competition importance was evaluated based on the adjusted r^2 values of simple linear regressions relating conifer diameter to competition index (cover, density, or CRH).
[g] Competition intensity was evaluated based on the slope of simple linear regressions relating conifer diameter to competition index (cover, density, or CRH).

the most important and intense competitors with stand age, from broadleaves to conifers, and changes in stand structure as stands self-thinned and stratified according to species height growth patterns.

Thresholds derived in this study varied among biogeoclimatic zones according to environmental limitations, such that conifers had higher thresholds (i.e., tolerated more competition) in milder than harsher climates within a particular vegetation complex. Thresholds also usually varied among conifer species along traditional patterns of shade tolerance, such that shade tolerant conifers generally had higher thresholds than intolerant conifers within a particular vegetation complex and biogeoclimatic zone. One exception was the *Mixed-Broadleaf Shrub* Complex, where there was little pattern in broadleaf density thresholds among moderately shade tolerant conifers (hybrid spruce, lodgepole pine, and Douglas-fir). In the study by Simard [2001, in review], threshold densities were also similar among conifers when all paper birch were included in the calculation, but closely followed traditional patterns of shade tolerance when only taller paper birch were included (western redcedar>Douglas-fir>western larch). Density thresholds for lodgepole pine were similar in the two broadleaf complexes, but those for Douglas-fir were greater in the *Mixed Broadleaf-Shrub* Complex than the *Aspen* Complex. We think this is because Douglas-fir growth is slower relative to neighbouring broadleaf trees and is more severely affected by soil water limitations in the dry belt *Aspen* Complex than the wet belt *Mixed Broadleaf-Shrub* Complex, whereas lodgepole pine performs well across a broad range of environmental conditions.

Our analyses of competition importance, intensity, and thresholds showed that vegetation competition was an important constraint to only a portion of conifers in the young plantations we studied. Averaged across all sites, only 30% of untreated conifers occurred in competitive environments above the thresholds. Brushing was applied to all trees to relieve competition constraints, as is usually done in operations, but only a portion of treated trees responded. We found, on average, that only 5% of treated trees achieved maximum growth (defined by 80% of the size of the largest tree) measured on the sites. The remaining 95% were growing at slower rates, probably because other growth-limiting constraints were not relieved by brushing. This, together with the patchiness of vegetation, implies that the broadcast approach to brushing, such as has been common in the past, may not be necessary. Instead, selective treatments could focus on competition-stressed trees only, possibly reducing brushing costs and preserving, as much as possible, the plant communities and their roles in succession.

The effect of broadleaf trees on conifer productivity in southern interior *Mixed Broadleaf-Shrub* and *Aspen* complexes is a contentious issue. Several short-term experiments, retrospective studies, process studies, and modelling studies (e.g., Simard 1990a, Sachs 1996, Simard and Heineman 1996a, Wang 1997, Simard and Hannam 2000, Comeau et al. 1999, Simard [2001, in review]) indicate that conifer productivity can be maintained in the presence of broadleaf trees, but there is little agreement on management of the composition (density and proportion of species) and dynamics of the mixtures. Some of the disagreement originates from the variability that exists among ecosystems, differences in methods of data collection and analysis, and differences in viewpoints on stand dynamics. Long-term experiments should provide answers to some of the questions. Different theories regarding broadleaf effects on yield of concurrently established conifers may be summarised as follows:

1. Yield may be substantially diminished at the relatively high density thresholds for taller broadleaves found in this study and Simard (2001, in review). At these densities, broadleaves will eventually suppress conifers and dominate the stands for a long period of time.
2. Yield may not be diminished at the relatively high density thresholds for taller broadleaves found in this study and Simard (2001, in review). This follows threshold theory that has been applied to forest stands, where relationships of growth to competition are described using ceiling functions (constraints) because individual tree size is highly variable under low competition (due to other limiting factors) and suppressed under high competition (Wagner et al. 1989, Burton 1996). Management to these thresholds would involve selective brushing of suppressed conifers. Conifers would naturally outgrow broadleaf neighbours according to height growth curve predictions in mixed stands. The appropriate density thresholds vary with site conditions.

3. Yield may be diminished at relatively low broadleaf density thresholds if brushing to meet these thresholds results in increased *Armillaria* mortality, or has other unexpected effects, and reduces conifer stocking below site occupancy.
4. Yield may not be diminished at relatively low broadleaf density thresholds. This theory, as well as (1), follows yield/density theory derived from agricultural studies, and commonly applied to forest stands, where least-square regression is used to describe relationships where individual plant size declines log-linearly with increasing weed density in fully occupied plots (Shinozaki and Kira 1956). Management to these low thresholds may involve broadcast brushing, with no or low retention of non-threatening broadleaf trees. Conifers will dominate the stands through rotation. Density thresholds are portable across a broad range of site conditions.

The effects of brushing on the height and cover of individual species or groups of species (i.e., herbs, shrubs, broadleaf trees) varied depending on the vegetation complex and type of treatment applied (Table 145). Here we discuss treatment effects and rates of recovery within various vegetation complex groupings.

Fireweed, Fern, and *Mixed Shrub* Complexes

Manual cutting, sheep grazing, and foliar glyphosate were used to reduce vegetation competition in the highly productive *Fireweed, Fern,* and *Mixed Shrub* complexes that occur in the interior wet-belt. Single-pass manual cutting and grazing treatments had minor, short-lived effects on herbs and shrubs in both the *Fireweed* and *Mixed Shrub* complexes. Most plant species recovered from these treatments within the season of application, which was usually too soon to release suppressed seedlings. In contrast, foliar glyphosate (1.4–2.1 kg ai/ha) reduced abundance of herbs, ferns, and shrubs for at least 5 years after application to the *Fireweed* and *Fern* complexes. In both complexes, the intensity and duration of vegetation control was sufficient to release seedlings, but only those in the *Fern* Complex significantly increased in diameter. The *Fireweed* Complex is sparser and less competitive than the *Fern* Complex on mesic sites, and the lower intensity and importance of competitive effects may explain why seedlings did not respond to the large and sustained vegetation reductions.

Ericaceous Shrub Complex

Ericaceous shrubs, mainly rhododendron, false azalea and *Vaccinium* spp., recovered slowly following single-pass manual cutting in the *Ericaceous Shrub* Complex, supporting the results of other studies (Coates et al. 1991). Manual cutting effects were sufficient to improve conditions for Engelmann spruce seedling survival, and to allow minor growth increases. Shifts from *Ericaceous Shrubs* towards a *Subalpine Herb* plant community have been observed following foliar glyphosate or mechanical site preparation (Boateng and Comeau 1997a), but this did not occur following the minor shrub canopy reductions made by manual cutting in our study.

Dry Alder and *Wet Alder* Complexes

Alder height and cover were dramatically reduced by single-pass manual cutting treatments applied from late June to mid-September in the *Dry Alder* and *Wet Alder* complexes. In both communities, alder recovered to approximately half of control levels within 3 years. Other shrub and herb species were not affected by the cutting treatments, and did not increase in abundance following removal of the alder canopy. This agrees with other *Dry Alder* manual cutting studies (Simard and Heineman 1996c). Glyphosate application to the *Dry Alder* Complex, on the other hand, has been shown to severely suppress alder for a much longer period, and has stimulated increases in understorey shrub and herb layers (Simard 1990b). In the *Wet Alder* Complex, shifts towards more competitive fireweed- or herb-dominated communities have also been documented following glyphosate application or mechanical site preparation (Stathers et al. 1994). Conifer seedling survival and growth did not improve following manual cutting in either the *Dry Alder* or *Wet Alder* complexes, but for different reasons in the two communities.

In the *Dry Alder* Complex, this and other studies have shown that lodgepole pine responds little or not at all to alder reductions by either manual or chemical means, mainly because interspecific competition is not severe. Pine naturally outgrows alder canopies within 10–15 years of establishment in the dry belt. In the *Wet Alder* Complex, spruce seedlings did not respond to vegetation reductions, possibly because other growth limitations (most likely cold, wet soils) were not relieved, and because alder sprouts were growing at faster rates than the conifers. That spruce was 4–6 years old at the time of brushing may also have been an important factor.

Mixed Broadleaf-Shrub and *Aspen* Complexes

Manual cutting, girdling, and cut stump–glyphosate were studied in the *Mixed Broadleaf-Shrub* Complex. Height of paper birch trees was immediately reduced by manual cutting, but sprouts grew in height at rates that were at least as fast as neighbouring Douglas-fir and lodgepole pine, and were approximately half the conifer height after 5 years.

TABLE 145 *Summary of vegetation responses*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Vegetation component	Years to return to control cover	Years to return to control height	Remarks about vegetation responses	Were vascular plant richness and diversity affected?	Remarks about the effects of brushing on vascular plant richness and diversity
Herb and low-elevation shrub complexes										
Fireweed	ESSF/ ICH	Se 2–4 years	Manual	3	Fireweed All vegetation Herbs Shrubs	<1 <1 <1 <1	<1 <1 <1 <1	• Vegetation height and cover had returned to control levels before the first-year assessment was carried out.	NO	• Manual cutting had no significant effects on vascular plant species richness or diversity.
Fireweed	ICH/ ESSF	Pl 1–3 years	Manual	5	Fireweed All vegetation Herbs Shrubs	<1 <1 <1 <1	<1 <1 <1 <1	• Vegetation height and cover had returnedto control levels before the first-year assessment was carried out.	NO	• Manual cutting had no plant significant effects on vascular plant species richness or diversity.
Fireweed	ESSF/ ICH	Se 1–5 years	Glyphosate	5	Fireweed All vegetation Herbs Shrubs	>5 >1 but <3 >1 but <3 >1	>5 >1 but <3 >1 but <3 >5	• After 5 years, fireweed had recovered to an average 15% cover and 100 cm tall in treated plots, compared to an average 46% cover and 115 cm tall in the control.	NO	• Foliar glyphosate application had no significant effects on vascular plant species richness or diversity.
Fireweed	ESSF	Se 0–5 years	Grazing	1	Fireweed All vegetation Herbs Shrubs	<1 <1 <1 <1	<1 <1 <1 >1	• Herb height continued to be reduced by grazing after 1 year, but otherwise, vegetation had returned to control levels before the first-year assessment was carried out.	NO	• Grazing had no significant effects on vascular plant species richness or diversity.
Fern	ICH	Sx 2–4 years	Glyphosate	5	Lady fern Thimbleberry All vegetation Herbs Shrubs	>5 >3 but <5 >5 >5 >1 but <3	>5 >5 >5 >3 but <5 >5	• Reductions in vegetation abundance were most pronounced in the first year following glyphosate application.	NO	• Foliar glyphosate application had no significant effects on vascular plant species richness or diversity. • Two berry-producing shrubs and several herbs tended to decrease in abundance.

TABLE 145 *Continued*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Vegetation component	Years to return to control cover	Years to return to control height	Remarks about vegetation responses	Were vascular plant richness and diversity affected?	Remarks about the effects of brushing on vascular plant richness and diversity
Mixed Shrub	ICH/ ESSF	Sx 1 year	Manual	3	All vegetation Shrubs Herbs	<1 >1 but <3 <1	>1 but <3 <1 <1	• Reductions in vegetation abundance were significant in the first year after manual cutting, but the actual reductions were small (i.e., 4-cm difference in vegetation height and 9% (41 vs. 50%) difference in shrub cover). • Herb cover increased briefly following cutting, but the effect was gone by year 3.	YES	• Manual cutting reduced vascular plant species diversity slightly in year three. • There were no significant effects on species richness.
Mixed Shrub	ICH/ ESSF	Sx 1–2 years	Sheep grazing	1	All vegetation Shrubs Herbs Fireweed	<1 <1 <1 >1	<1 <1 <1 >1	• Fireweed abundance was reduced for at least 1 year because it is a preferred forage for sheep.	NO	• Grazing had no significant effects on vascular plant species richness or diversity.
High-elevation shrub complexes										
Ericaceous Shrub	ESSF	Se 0–2 years	Manual	5	Shrubs Herbs All vegetation	>1 but <3 <1 >1 but <3	>1 but <3 <1 >1 but <3	• Vegetation cover and height were significantly reduced for 1 year, but reductions were relatively small (i.e., manual cutting reduced all vegetation height from 90 to 76 cm). • The small magnitude of the treatment effects is due partly to measurement methodology (see Section 7).	YES	• Manual cutting increased vascular plant species diversity for 3 years, but the difference was gone by year 5. The difference reflects a minor, short-lived reduction in the dominant shrub species. • Species richness was not significantly affected by manual cutting.
Tall shrub complexes										
Dry Alder	MS	Pl 5 years	Manual	5	Alder Shrubs Herbs	<1 >3 but <5 <1	>1 but <3 <1 <1	• Differences in alder cover were not significant because of large variability between sites. • After 5 years, 54% of alder had sprouts and they averaged 104 cm tall. • The reduction in shrub cover mainly reflects a reduction in alder abundance. • Herb abundance did not increase in response to removal of the alder canopy.	NO	• Manual cutting had no significant effects on vascular plant species richness or diversity.

TABLE 145 *Continued*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Vegetation component	Years to return to control cover	Years to return to control height	Remarks about vegetation responses	Were vascular plant richness and diversity affected?	Remarks about the effects of brushing on vascular plant richness and diversity
Wet Alder	ESSF	Se 4–6 years	Manual	3	Alder Shrubs Herbs	>3 >3 <1	>3 >3 <1	• Alder height and cover were significantly reduced for at least 3 years. • After 3 years, 58% of alder had sprouts, and they averaged 73 cm tall.	**YES**	• Manual cutting significantly reduced species richness in year 1 but the difference was gone by year 3. • There were no significant effects on species diversity.
Tall shrub complexes										
Aspen	IDF/ MS	Pl 7–10 years	Manual	3	Aspen Shrubs Herbs	<1 <1 >1 but <3	(see remarks) <1 <1	• Reductions in aspen height were not significant because there was large variability across the study sites (cutting was spread across 2 years on one site). After 3 years, aspen height was reduced to 194 cm in the treatment vs. 510 cm in the control ($p = 0.11$). • 94% of stumps suckered, and suckers grew to an average height of 138 cm during the 3 years following cutting. • Herb cover decreased slightly in the first year after cutting, possibly because it was pressed by aspen slash.	**NO**	• Manual cutting had no significant effects on vascular plant species richness or diversity.
Mixed Broadleaf-Shrub	ICH/ IDF	Fd 5–6 years	Manual	5	Broadleaves Shrubs Herbs	<1 <1 <1	>5 >3 but <5 <1	• Broadleaves were 386 cm tall in the cutting treatment compared to 688 cm tall in the control after 5 years. • 86% of birch stumps had sprouts and they averaged 253 cm tall after 5 years.	**NO**	• Manual cutting had no significant effects on vascular plant species richness or diversity.
Mixed Broadleaf-Shrub	ICH	Pl 3–10 years	Manual	5	Broadleaves Shrubs Herbs	<1 <1 <1	>5 >3 but <5 <1	• Broadleaves were 329 cm tall in the cutting treatment compared to 504 cm tall in the control after 5 years. • 67% of birch stumps had sprouts, and they averaged 200 cm tall after 5 years.	**NO**	• Manual cutting had no significant effects on vascular plant species richness or diversity.

TABLE 145 *Concluded*

Vegetation complex	BEC zone	Crop tree species and age[a]	Brushing method	Years measured	Vegetation component	Years to return to control cover	Years to return to control height	Remarks about vegetation responses	Were vascular plant richness and diversity affected?	Remarks about the effects of brushing on vascular plant richness and diversity
Mixed Broadleaf-Shrub	ICH	Fd 8–9 years	Cut stump–glyphosate	5	Broadleaves Shrubs Herbs	>5 >1 but <3 <1	>5 >3 but <5 <1	• Broadleaves in the treatment had 15% cover and were 385 cm tall after 5 years. Those in the control had 70% cover and were 952 cm tall. • 24% of birch stumps had sprouts and they averaged 273 cm tall after 5 years.	**NO**	• Cut stump–glyphosate had no significant effects on vascular plant species richness or diversity.
Mixed Broadleaf-Shrub	ICH	Fd 5–17 years	Girdle	5	Broadleaves Shrubs Herbs	>1 but <3 (see remarks) <1 <1	<1 (see remarks) <1 <1	• Girdling effects on broadleaf cover were significant for only 1 year because of large variability between sites in the rate at which girdled stems died. In year 5, broadleaf cover was 10%. • Girdling effects on broadleaf height were not significant because girdled stems died slowly. • 11% of birch stumps had sprouts and they averaged 205 cm tall after 5 years.	**YES** `	• Vascular plant species diversity was significantly greater in the girdling treatment than the control in the first year. • The difference was gone by year 3. • Girdling had no effect on species richness.

[a] Age (years since planting) at the time of brushing.

Cutting date did not appear to affect sprout growth rates, but Peterson et al. (1997) suggest that cutting in May-June may reduce sprouting because of seasonal carbon allocation patterns. Shrubs were also temporarily reduced in height because they were cut at the same time as broadleaves, but otherwise shrubs and herbs neither decreased nor increased in abundance following broadleaf canopy removal. Girdling in August-October slowly killed birch trees so that the treatment was not fully expressed until 3 years post-treatment. Five years after treatment, broadleaves in the girdling treatment had only one-quarter the cover of those in the control, and little sprouting had occurred. Herb abundance increased temporarily, but the plant community appeared unaffected 5 years after the girdling treatment was applied. The cut stump-glyphosate treatment (full concentration applications at 0.74–3.20 kg ai/ha) had the most dramatic and prolonged effect on the *Mixed Broadleaf–Shrub* Complex. Five years after application, fewer than one-quarter of broadleaf stumps had sprouts, and crown cover was approximately one-quarter that of the control. Shrub height was also reduced for 3 years by cutting; otherwise, shrub and herb layers were unaffected by the treatment. Douglas-fir growth rate increased following all of these treatments, but the increase was greatest following cut stump–glyphosate application. All treatments resulted in a change in height dominance within the stands from mixed broadleaf/conifer to conifer-dominated. The conversion was most dramatic following cut stump–glyphosate treatment, where sprouting of birch was minimal.

Manual cutting in the *Aspen* Complex immediately reduced aspen height, which was still less than half that of neighbouring lodgepole pine after 3 years. Similar height growth rates of lodgepole pine and aspen should ensure that pine continues to dominate these stands, resulting in a shift in height dominance from a mixed to a conifer-dominated stand. Cutting aspen had no effect on understorey shrubs or herbs.

Species Richness and Diversity

None of the brushing treatments had a sustained effect on either vascular plant species richness (number of species) or diversity in any of the vegetation complexes studied (Table 145). (The diversity indices used in this study, Shannon-Weaver's and Simpson's, incorporate species richness and evenness, which is the proportional abundance of species). These results agree with findings in other brushing studies in early seral stands in British Columbia (Haeussler et al. 1999; Boateng et al. 2000). However, we did find a few short-lived differences in species richness and diversity. These are discussed below in the context of trends in increasing or decreasing abundance of individual species within groupings of vegetation complexes.

Trends of Increasing or Decreasing Abundance for Individual Plant Species

***Fireweed, Fern,* and *Mixed Shrub* complexes**
Manual cutting treatments had little effect on the abundance of individual species in the *Fireweed* and *Fern* complexes because vegetation recovered very rapidly. In the *Mixed Shrub* Complex, species diversity decreased 3 years after manual cutting, which was associated with treatment reductions in the abundance of three common shrubs (thimbleberry, elderberry, and black huckleberry), four herbs (spiny wood fern, oak fern, small twisted stalk, and dandelion), and grasses. However, we expect this will be a temporary change because the *Mixed Shrub* community was quickly recovering to control conditions.

Vegetation rapidly returned to control levels in the *Fireweed* and *Mixed Shrub* complexes following single-pass grazing treatments, and we did not detect any trends of increasing or decreasing abundance among individual plant species. However, sheep grazing has the potential to cause species shifts because of sheep preferences for certain forage species, and because of the potential for introduction of exotic species. Species shifts should be carefully considered in grazing prescriptions because they do not always favour seedling performance (Newsome et al. 1995). Greater potential for changes in the plant community exist with 2–3 seasons of grazing, which appears necessary for seedling release in dense, competitive communities.

Foliar glyphosate treatments consistently reduced the abundance of several herb species (e.g., lady fern, bracken, fireweed) in the *Fern* and *Fireweed* complexes during the study period. This was expected because those species were targeted by the brushing treatments. Of some concern, however, are the reductions in abundance of berry-producing shrubs associated with these communities, including: black huckleberry, oval-leaf blueberry, black gooseberry, thimbleberry, and Sitka mountain ash. Chemical brushing treatments could have negative consequences for wildlife species that browse these berries, and may be opposed by the public or special-interest groups. However, compared with manual treatments, chemical brushing is currently applied on a relatively small scale in the southern interior. As with other complexes, some low-stature herbs increased in response to decreasing abundance of taller herbs and shrubs. In this case, grasses and purple-leaved willowherb increased following glyphosate application in the *Fireweed* Complex.

***Ericaceous Shrub* complex**
In the *Ericaceous Shrub* Complex, the diversity of vascular plant species increased 3 years following manual cutting. Decreased abundance of prominent shrubs, such as white-flowered rhododendron, Sitka mountain ash, and thimbleberry allowed several minor herb species to invade or increase in cover. The increase in diversity reflects a more even distribution of cover over a greater number of species, compared with the control where the community was dominated by a few, high-cover shrub species. The difference was short-lived, however, and disappeared by the fifth-year assessment.

***Dry Alder* and *Wet Alder* complexes**
Few trends of increasing or decreasing abundance of individual species were observed following manual cutting in these communities. Greater light availability to the low herb layer following removal of the alder canopy allowed bunchberry to increase in abundance in the *Wet Alder* Complex.

***Mixed Broadleaf-Shrub* and *Aspen* complexes**
All treatments applied to these communities

resulted in decreases in the abundance of broadleaf species because they were the targets of treatment. At the same time, cover of cut shrubs, such as willow, usually increased because of sprouting. Several herb species increased in abundance following most brushing treatments, including fireweed, Hooker's fairy bell, strawberry, tiger lily, and rattlesnake plantain. Dandelion and thistle, both common weeds, also increased following brushing. The implications of these changes for wildlife are unknown, but most are probably minor (Sullivan et al. 1998; Boateng et al. 2000). One possible exception is the reduction in tall broadleaves, which could affect the availability of perching and nesting sites for birds (Machmer and Steeger 1995). Sprouts that occur following manual cutting are known to increase summer browse for moose and deer, but winter browse may decrease because fewer shoots remain above the snowpack (Simard and Heineman 1996a; Peterson et al. 1997). Brushing treatments can also negatively affect the quality of paper birch by favouring smaller-diameter stems, and may therefore reduce the utility of birch for wood or other products.

Structural Vegetation Groups

Brushing had few effects on the structure of plant communities (according to the Shannon-Weaver and Simpson Diversity Indices), with some exceptions in the *Mixed Broadleaf-Shrub, Ericaceous Shrub,* and *Aspen* complexes. In the *Mixed Broadleaf-Shrub* Complex, manual cutting and cut stump–glyphosate treatments resulted in an increase in the diversity of structural vegetation groups because of the decreased dominance of broadleaves and increased evenness among all plant species. These changes persisted throughout the 5-year measurement period. A similar increase in diversity was observed following manual cutting in the *Ericaceous Shrub* Complex because of reduced shrub dominance. In contrast, structural diversity decreased following girdling in the *Mixed Broadleaf-Shrub* Complex and manual cutting in the *Aspen* Complex. Prior to brushing, these stands were characterized by the presence of tall dominants, and their removal served to decrease structural diversity.

Some common trends in conifer and plant community responses to brushing occurred among the different vegetation complexes. These trends have improved our ability to predict where competition will be a problem and where brushing will be beneficial to conifer performance. In addition, they can help improve management recommendations regarding method, intensity, and timing of brushing treatments. Here we summarize important trends and management implications for the main groups of vegetation complexes studied, based on our own and other studies.

***Fireweed, Fern,* and *Mixed Shrub* Complexes**

On circum-mesic sites, where vegetation in these complexes was moderately dense (<50% cover), seedlings performed well and have naturally outgrown, or are projected to outgrow, vegetation within the free-growing window. The results from our study sites indicate that brushing was not necessary to ensure good plantation performance. However, seedling survival can be at risk in the dense herb or mixed shrub complexes that sometimes develop in moist to wet ecosystems, in wetter ICH subzones, and at high elevations where the growing season is short. Most mortality occurs soon after plantation establishment on those sites, well before the majority of brushing operations are carried out. These wetter sites should be site prepared soon after harvest (within 1–2 years of harvest), planted promptly with large-caliper, high-quality stock, and, if necessary, brushed within 1–2 years of planting. Where these complexes are well developed, single-manual or grazing treatments appear to be ineffective at improving the seedling-growing environment. Three consecutive manual cutting passes (best applied in summer), three consecutive grazing seasons, or a single glyphosate application, which result in sustained vegetation reductions, should be used instead. Three manual treatments average $1,614/ha and three grazing passes average $744/ha, compared to $700/ha for a single ground chemical treatment (Table 1).

***Ericaceous Shrub* Complex**

At high elevation, vegetation has indirect effects on frost, light availability, and to some extent, soil temperature. Prompt site preparation can discourage the *Ericaceous Shrub* and more competitive *Subalpine Herb* complexes, and relieve severe environmental constraints to some extent (Boateng and Comeau 1997a). In combination with the planting of high-quality stock, site preparation can facilitate the establishment of free-growing stands and reduce or eliminate the need for brushing. In our study, site preparation and planting occurred 3–4 years after harvest, and ericaceous shrubs were well established (46–82% cover, 103–135 cm height) at the time of brushing. Shrubs were manually cut once in variable, tree-centered radii, which was sufficient to ensure good survival and adequate growth rates of the 2-year-old spruce seedlings.

***Dry Alder, Wet Alder,* and *Willow* Complexes**

In our study, conifers that established immediately after disturbance performed well and naturally outgrew the *Dry Alder* Complex in the MS zone. Similar results were found for the *Dry Alder* Complex, as well as the *Willow* Complex, in other brushing studies in the southern interior (Simard and Heineman 1996b, 1996c; Simard, Heineman, and Youwe 1998). Interspecific competition between conifers and shrubs in these communities was of low intensity, except in small, localized patches. Alder and willow play key roles in succession, site productivity, and wildlife habitat, and should not be brushed unnecessarily. Chemical brushing of the Dry Alder Complex has also been shown to reduce range value on some sites (Simard, Heineman, and Youwe 1998). Where brushing is used to release conifers growing inside dense alder or willow patches, a single manual cutting has been as effective at improving seedling performance as glyphosate treatments (Simard and Heineman 1996b, 1996c).

Conifers are not expected to outgrow the taller, denser *Wet Alder* Complex that develops on moist, rich sites in the ICH and ESSF zones. Plantation establishment is particularly problematic in alder swales that occur in a patchy mosaic with conifers prior to harvest. For conifer production, the *Wet Alder* Complex should be managed pre-emptively with prompt site preparation and planting. If brushing is necessary, chemical treatments are preferred over repeated manual treatments because of poor visibility in the dense brush, the potential for substantial accidental cutting of seedlings, and the high cost of repeated treatments.

Mixed Broadleaf-Shrub Complex

The *Mixed Broadleaf-Shrub* Complex is naturally clumpy. Dense patches of paper birch can suppress growth of conifers, whereas moderate densities on the same site appear to have small effects (<4050 total birch stems/ha or <2575 over-topping stems/ha for 5–13-year-old Douglas-fir, where birch established within 1–4 years of Douglas-fir) (this study and Simard [2001, in review]). Conifers can be expected to tolerate lower densities of birch if they are planted well after disturbance and into an established birch stand, as was found in studies by Simard and Hannam (2000) and Comeau et al. (1999). In our study, rarely were broadleaf densities so uniformly high that established conifers actually died, or appeared likely to die, from resource limitations. Comeau et al. (2000b) also documented that survival of established conifers has been unaffected by brushing treatments in British Columbia. Broadcast brushing of paper birch does consistently increase average conifer growth. However, many conifers perform well without brushing because not all are experiencing suppressive competition in the clumpy stands. Moderate densities of broadleaves have been shown to have a protective effect on conifers from *Armillaria* root disease, frost, and browsing (e.g., Perala and Alm 1990; Simard and Heineman 1996a). Broadleaf trees also provide important habitat for many creatures, from micro- to macroscopic, and play important roles in succession (Peterson et al. 1997). In developing brushing prescriptions, both potential conifer growth gains and potential losses associated with root disease or other factors should be considered. We recommend selectively brushing only those conifers that are suppressed by competition rather than using broadcast treatments. On sites with high levels of *Armillaria* inoculum, disease spread may be reduced by using chemical instead of manual treatments.

There are concerns that this management approach will result in broadleaf domination, conifer mortality, and the loss of plantations in the future. However, studies on competition dynamics in the *Mixed Broadleaf-Shrub* complex indicate that paper birch at moderate densities (below the thresholds identified in this study) becomes less competitive with conifers as stands age, it is outgrown by Douglas-fir by 50 years of age, and on productive sites where concern is greatest, it comprises a small portion of stand volume at 80–100 years of age (Cameron 1996; Wang 1997; Simard [2001, in review]; Simard and Sachs [2001, in review]). There may be some sites where paper birch is of sufficient density and productivity to reduce survival of neighbouring conifers, but the extent of their occurrence is unknown. Simard and Vyse (1992) found that average broadleaf density on 10-year-old clearcut ICH sites was usually <5000 stems/ha, regardless of site preparation method, which according to the study of Simard [2001, in review] is suggestive of moderate competitive conditions for conifers, except in localized patches. Broadleaf-dominated stands are rare following natural disturbance in the southern interior wet belt (Sachs et al. 1998), and the potential for them to increase following conventional harvesting and different methods of site preparation is poorly understood. The potential threat of low to moderate densities of paper birch on productive sites should be carefully evaluated in future studies.

Aspen Complex

In our study, lodgepole pine that had established immediately after disturbance performed well in association with the *Aspen* Complex in the drier, southern subzones of the IDF and MS zones. Interspecific competition between aspen and pine in these southern ecosystems appears to be much less intense than that between aspen and pine or spruce in northern ecosystems, probably because pine and aspen tend to grow at similar rates in the south. Aspen provides many ecological benefits, similar to those described above for paper birch, which should be considered in development of brushing prescriptions. Our early results suggest that brushing of aspen may be avoided on southern IDF and MS sites without loss of conifer productivity. Where interspecific competition is intense in small, localized patches, selective manual cutting should sufficiently release individual conifers. Alternatively, girdling could be applied when the aspen is older, larger, and possibly more competitive. Girdling is advantageous in that (a) treatment can be postponed until competition problems, if they occur at all, are fully expressed, and (b) conifers can better acclimate to the changed environment because the girdled trees die slowly. Girdling could be applied in a similar manner in the *Mixed Broadleaf-Shrub* Complex.

The PROBE program expands our understanding of interspecific competition between conifers and early seral plant communities in young plantations in the southern interior. The main contributions of the work, including our improved ability to assess, predict, and treat vegetation problems, need to be further expanded to include a wider array of vegetation complexes, treatments, and ecosystem effects. We see several interrelated directions as priorities for further research.

1. The effects of the brushing treatments on growth, yield, and stand dynamics need to be evaluated over the long term. This represents an important information gap both locally and worldwide. The PROBE plots were designed to meet the minimum size criteria for Permanent Sample Plots as established by the Forest Productivity Council of British Columbia (1990), and therefore can continue to be maintained and measured through to rotation age. This will require that full-stem DBH tallies are completed and permanently marked in large plots overlain on the existing treatment and control plots of each PROBE installation, as outlined by Biring et al. (1998). This should be completed after the 10-year re-measurement of each installation.
2. Brushing effects on yield at rotation should be modelled to fill short-term information gaps in Timber Supply Reviews. Existing vegetation management and yield models need to be reviewed for their applicability to southern interior conifer species and vegetation complexes. Different models may be appropriate for herb/shrub complexes than broadleaf complexes. A meta-model approach should be explored, where vegetation management models provide input data for stand structure or growth and yield models. Vegetation management models that should be considered include BRITE (Comeau, pers. comm., 2000), SYSTUM-1 (Ritchie and Powers 1993), RVMM (Shula and Marshall 1998), and a New Zealand growth model by Mason et al. (1997). Mixed species stand models that should be reviewed include MGM (Titus 1999), SORTIE (Pacala et al. 1993, 1996), TASS (Mitchell 1975), and PROGNOSIS (Greenough et al. 1999).
3. Additional replicate sites are needed for approximately 30 treatments, where we currently have only 1–2 replicates, before we can statistically evaluate responses to brushing. For treatments that currently have 3–4 replicate sites (i.e., those reported here), replication should be increased to 5 in order to improve the power of the parametrical statistical tests. Three replicates represent the minimum requirement for ANOVA and results in low power to detect treatment differences, especially if the differences are small. At present, the variability among replicate sites is indicated in the reported ANOVA results and standard errors, and further information can be derived by the reader by calculating confidence intervals as described in Section 3 (Methods). To address statistical power and variability for future analysis of these treatments, of greatest importance is to increase replication in those treatment cells where (a) replicates are from more than one biogeoclimatic zone (e.g., ICH and ESSF zones in *Mixed Shrub* and *Fireweed* complexes), (b) the vegetation complex is quite variable from site to site (e.g., *Mixed Shrub* and *Fern* complexes), and (c) brushing treatments are variable (e.g., different sized radii in tree-centred manual brushings).
4. Vegetation complexes examined in this study were classified based on published descriptions by Kimmins and Comeau (1990). Most complexes were well defined with one or two dominant herb, shrub, or broadleaf species. However, the *Mixed Shrub, Fern,* and *Fireweed* complexes are comprised of several common species that vary in their relative abundance. For some PROBE sites, the plant community did not correspond well with complex definitions, or was similar to more than one complex, and a qualitative judgement was therefore made in assignment to a particular treatment cell. Further research and analysis is needed in classification of vegetation complexes and description of seral vegetation by ecosystem unit. In addition, better identification of problematic sites is needed.
5. Identification of competition thresholds for conifer growth lacks rigorous quantitative techniques. Alternative methods need to be investigated or developed for objectively identifying

competition thresholds and examining their variability. In addition, facilitation thresholds were evident in most complexes, but remain to be quantified. Facilitation thresholds mark a minimum vegetation level necessary for optimal conifer growth, below which performance is depressed. Our neighbourhood data repeatedly showed that sparsely covered ground was a suboptimal environment for tree growth. The regression analyses used to evaluate competition importance and intensity could also be strengthened and expanded. A variety of competition indices could be explored and different models tested to determine if the relationships can be improved. Different models could be instructive in assessing competition processes (e.g., Newton and Jollife 1998; Wagner and Radosevich 1998; Simard and Sachs [2001, in review]).

6. The conifer response and vegetation data could be analysed using alternative approaches, including repeated measures MANOVA, Bayesian analysis, and multivariate analysis. Repeated measures MANOVA will be particularly useful after 10-year response data has been collected and can be used to examine treatment by time interactions. Additional ANOVAs, where replicate sites are pooled over more than one biogeoclimatic zone or vegetation complex for a particular treatment, could also be conducted in order to increase the power of the tests and to test for interactions among zones or complexes. Bayesian analysis could be used to examine probabilities of reaching biological or management goals under various treatment regimes. Multivariate analysis could be used to examine changes in plant community composition over gradients of treatment intensity. For survival, precision in estimates could be increased by using stocking survey data instead of target tree data because the sample size is much greater (>200 versus 36 trees). These analytical tools could be used to present data in alternative ways that would highlight particular features of the data sets for different end-users.
7. Broadcast manual and chemical treatments remain the core focus of brushing programs in the southern interior of British Columbia, but variations to these treatments are being applied operationally in many areas. For example, paper birch and trembling aspen are being retained in low densities in the *Aspen* and *Mixed Broadleaf-Shrub* complexes during manual and chemical brushing treatments. Shrubs and herbs are being manually brushed multiple times and during different times of the growing season in the *Mixed Shrub, Fireweed,* and *Fern* complexes. Conifers are also being treated using tree-centred, selective approaches rather than broadcast treatments. These operationally applied treatments need to be evaluated to determine their efficacy at releasing conifers from interspecific competition and creating free-growing stands.
8. Effects of brushing on ecosystem attributes other than conifer performance and plant community condition should be studied. The network of PROBE plots provide an excellent opportunity for other researchers to study more detailed ecosystem patterns and processes within an existing replicated and randomized framework. One example would be to expand studies of brushing effects on specific changes in plant community diversity and structure. We used published species diversity indices as well as our own structural diversity indices, but their power to detect subtle plant community changes was limited. In addition, brushing effects on wildlife species, particularly small mammals and birds, could be studied in relation to changes in habitat, building on the work of Sullivan (1985) and Sullivan et al. (1998). Another area in need of further study is the longer-term brushing effects on insect and disease patterns among conifers, deciduous trees and other plants in the community. Finally, our studies focused on the effects of competition, not competition processes. Detailed process studies would improve our ability to predict vegetation problems in other ecosystems and vegetation complexes.
9. Cumulative effects of silviculture practices, including brushing treatments, should be evaluated over large scales, particularly where tree species composition is affected. For example, reductions or increases in broadleaves may alter broadleaf patterns at large scales. Brushing treatments may be accompanied by spacing of less desirable conifers to encourage dominance by one or a few, favoured conifer species, which may affect composition and diversity of stand dominants. Because different species and combinations of species differ in their resistance and resilience to disturbance, broad changes in vegetation patterns as a result of brushing and other

silviculture practices may affect patterns of natural disturbances caused by wildfire, root disease, and insects (Turner et al. 1989). The cumulative effects of brushing treatments over large scales could be examined using landscape-level models that exist, such as TELSA (Kurz et al. 2000), or that can be developed using SELES (Fall and Fall 1999). As in (2) above, a meta-model approach could be explored, where vegetation management and yield models provide input data for a landscape model.

10. Further extension is needed to increase access of PROBE and other vegetation management information to silviculturists. An extension plan currently under development involves inclusion of PROBE results in field workshops, field handbooks, extension notes, newsletters, and web sites. For example, a series of district-based workshops could be conducted where results are reviewed in relation to local field conditions. In addition, an interactive, computer-based, expert system could be developed that provides end-users with (a) the most recent vegetation management research results, (b) projections of treatment effects on growth, yield and stand dynamics as well as attainment of management goals, and (c) guidance on development of vegetation management prescriptions.
11. Evaluation of operational silviculture treatment effects in relation to management and ecological objectives is needed for all major silviculture activities. This has long been recognised, a variety of programs have been attempted in the past, and committees continue to explore options. To our knowledge, there are currently no other broad programs in progress in the southern interior that measure silviculture treatment effects on conifer yield and plant communities other than those that inventory areas that are treated and administrative goals that are met. Common silviculture treatments that could be evaluated, in addition to brushing, include site preparation, planting, natural regeneration, spacing, thinning, pruning, and fertilisation. There is also a need to measure vegetation management treatments and other silviculture treatments in a range of silviculture systems, particularly partial canopy retention and partial cutting systems. Addressing treatments will require a series of integrated protocols that provide evaluations from pre-harvest to the next harvest.

In conclusion, PROBE has been an effective program for evaluating conifer and plant community responses to operational brushing. Combined with experimental results of other studies, this study has advanced our ability to assess, predict, and treat vegetation competition problems in young conifer stands. There is a critical need to continue remeasurement of the study sites, establish new installations to fill data gaps, and examine new techniques and practices. In addition, there is a need to further extend the information and develop new tools to support vegetation management decisions. The PROBE program may serve as a successful example for other programs aimed at evaluating silviculture treatment effectiveness.