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The Effects of Site Preparation and Harvesting Practices on Planted Seedling Productivity and Microenvironment in Southern Interior Dry, Grassy IDF Forests

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BRITISH COLUMBIA

Ministry of Forests Forest Science Program

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ABSTRACT

Dry, pinegrass-dominated sites in the Interior Douglas-fir (IDF) zone of southern interior British Columbia are challenging to regenerate, despite ongoing improvements in nursery and silviculture practices. Using results from three separate studies (Fehr Mountain, Murray Creek, and Opax Mountain), we discuss conifer seedling survival and growth responses to silvicultural system and site preparation treatments that were applied to relieve harsh site conditions. At the flat, frost-prone site at Fehr Mountain, Douglas-fir survival was low, even where site preparation treatments resulted in exposed mineral soil. Lodgepole pine had much higher survival on the same site, and is therefore recommended for planting where there is a high risk of growing-season frost. On the steep slopes at Murray Creek, frost was of minor importance to survival and growth of lodgepole pine. Stem diameter of lodgepole pine increased as a result of chemical and mechanical site preparation treatments at both Fehr Mountain and Murray Creek, although differences at Fehr Mountain were no longer statistically significant after 11 years. Douglas-fir growth also improved as a result of site preparation at Fehr Mountain, but the species could not be assessed past year 3 because of high mortality following frost damage. At Opax Mountain, Douglas-fir and lodgepole pine survived well across a range of light regimes and canopy opening sizes, as long as site preparation and planting took place promptly following harvest.

To help interpret conifer seedling survival and growth responses, the effects of silvicultural system and site preparation treatments on seedling microenvironment are also discussed. For example, chemical and mechanical treatments increased soil water availability equally well by reducing the presence of pinegrass, and nighttime air temperature at seedling height also increased as a result of both types of treatment. Removal of forest floor materials in mechanical treatments resulted in short-term reductions in soil and foliar nutrient concentrations at both Fehr Mountain and Murray Creek, but there was no evidence of long-term deficiencies. At Murray Creek, however, ectomycorrhizal diversity was significantly lower in the mechanical treatment than the untreated control 28 months after planting.

ACKNOWLEDGEMENTS

This Technical Report uses results from three separate studies over the last decade. We thank Andy Black, Ralph Adams, Rob Fleming, and their co-workers for their work at Fehr Mountain. We thank the many people who assisted with establishing and measuring the Murray Creek experiment: Karen Baleshta, Trevor Blenner-Hassett, Aleisha Cline, Rhonda DeLong, Ed Elmes, Cora Gordon, Kirsten Hannam, Kim Johnson, Kim Mackenzie, Scott McLean, Todd Redding, Sara Short, and Barbara Zimonick for installation and seedling measurements; Bob Stathers for microclimate studies; and Jian Wang and Karen Baleshta for physiology measurements. Many thanks to Melanie Jones and Dan Durall at Okanagan University College for studying the ectomycorrhizae, and to their assistants, Kerry McLean, Debbie Classen, Matt Green, and Michelle Harniman. We appreciate the soil and foliar analysis of Clive Dawson at the B.C. Ministry of Forests Research Lab, and data analysis of NaDene Sorenson and Trevor Blenner-Hassett. We thank Vera Sit for her advice on statistical analysis. Many people also made valuable contributions to the Opax project. With regard to information presented in this study, we particularly thank André Arsenault, Dan Bissonnette, Mike Bissonnette, Dan Burgess, Melanie Butcher, Nicole Brand, Mona Doney, Vanessa Larson, Kim Johnston, Shane Ford, Bruce Hanna, Kim Johnston, Jessica Macdonald, Hana Masata, Joel McColl, Fraser Russell, Mike Ryan, John Stigger, Kathleen Wallach, Tanya Zender, and Cindy Prescott. We also thank Mark Faliszewski, Reg Newman, and Teresa Newsome of the B.C. Ministry of Forests for reviewing the manuscript.

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INTRODUCTION

Forests of the Interior Douglas-fir (IDF) zone are important for timber, range, wildlife, and recreation. In southern interior British Columbia, IDF forests have been extensively managed for almost a century, especially on lower slopes of valleys where access is relatively easy (Vyse et al. 1991). The driest IDF variants in the Kamloops area of the Southern Interior Forest Region are the IDFxh2, IDFxh1, and IDFdk1 (Lloyd et al. 1990). Stands that occur on well-drained submesic-mesic sites in these biogeoclimatic variants are typically open mosaics of even- and uneven-aged patches with abundant pinegrass in the understory (Figure 1). During the past half-century, lodgepole pine stands in the IDF have been clearcut and Douglas-fir stands have mainly been selectively cut. However, selection standards for cutting Douglas-fir have fluctuated over the years, which has led to concern over sustainability of forest management practices in these ecosystems. Silvicultural systems that are currently recommended for the IDF zone include individual-tree and group selection, clearcutting with or without retention, and seedtree.

Dry, grassy sites are difficult to regenerate following harvesting because of harsh climatic conditions that include summer drought, winter temperature extremes, and summer frosts (Table 1). Less than half the annual precipitation occurs during the growing season, and the droughty conditions are exacerbated by the presence of pinegrass, which competes efficiently for soil water (Nicholson 1989). Natural regeneration is unlikely to be successful on these sites because of factors such as climate, frequent low levels of seed production, seed predation, and the destruction of advance regeneration during harvest (Vyse et al. 1991). Survival of planted seedlings, particularly Douglas-fir, is typically low on dry IDF sites (e.g., sites in the IDFxh2), although the situation has improved due to the use of larger stock types (Simard et al. 1997; Newsome 1998) and probably also due to improvements in stock and

FIGURE 1 *A typical IDF forest with patchy distribution of Douglas-fir and a pinegrass-dominated understory.*

TABLE 1 *Environmental characteristics of the IDFxh2, IDFdk1, and IDFdk2 variants*[a]

Characteristic	**IDFxh2**	**IDFdk1**	**IDFdk2**
Area in the Kamloops Forest Region[b] (ha)	339 166	613 912	442 087
Proportion of Kamloops Forest Region (%)	4.2	7.6	5.5
Elevation range (m)	850–1130	1130–1460	600–1300
Mean annual precipitation (mm)	379	438	568
Mean growing season precipitation (mm)	185	193	221
Mean annual snowfall (cm)	128	155	222
Mean annual temperature (°C)	4.8	3.4	4.1
Mean growing-season temperature (°C)	13.1	11.1	11.1
Mean minimum January temperature (°C)	-13.4	-13.1	-11.9
Mean growing degree-days (> 5°C)	1429	1139	1133
Frost-free period (days)	92	86	95

[a] Lloyd et al. (1990).

[b] These values are based on information available for the previous Kamloops Forest Region. As of April 1, 2003, the Kamloops Forest Region was incorporated into the Southern Interior Forest Region.

stock handling. Site preparation practices that ameliorate climatic and vegetation factors have partly overcome limitations to plantation success (e.g., Vyse et al. 1991; Newsome 1998). Due to the high grazing potential of the IDF, both artificial and natural regeneration are also subject to damage from cattle trampling (Newman et al. 1998; Newsome 1998).

This Technical Report summarizes the latest findings from two site preparation studies and one silvicultural systems study that examined the effects of these practices on planted seedlings in the southern interior IDF zone (Table 2). All three studies were done on pinegrass-dominated sites. Although other grass communities are common in dry IDF ecosystems (e.g., those dominated by bluebunch wheatgrass or fescue), harvesting and site preparation activities occur far more often on sites where pinegrass is the dominant understory species. On a clearcut site at Fehr Mountain, near Savona, B.C. (IDFdk1), the effectiveness of mechanical and chemical site preparation for improving survival and early growth of Douglas-fir and lodgepole pine was investigated, with particular interest in frost damage and water availability. The effects of these treatments on soil nutrient availability and foliar nutrient status were also investigated to determine whether removal of the forest floor was likely to reduce conifer growth or site quality over the longer term. At the Murray Creek site, near Spences Bridge, B.C. (IDFdk1), which had been clearcut with tree patches reserved, mechanical and chemical patch site preparation treatments were studied to determine their effects on lodgepole pine seedling survival, growth, and physiology on steep slopes. Seedling responses were also considered in relation to microclimate, nutrient and soil water availability, and the richness and diversity of ectomycorrhizae on their root systems. The effects of various silvicultural systems on microclimate, vegetation, and Douglas-fir survival are currently being studied at Opax Mountain, near Kamloops, B.C. (IDFxh2 and IDFdk2), with special interest in canopy gap size and edge effects. Site locations are shown in Figure 2.

This Technical Report synthesizes results from the three studies concerning silvicultural systems and site preparation, but does not attempt to address all factors relevant to successful regeneration on pinegrass-dominated IDF sites. Physical damage from cattle trampling, wildlife browsing, choice of planting species other than Douglas-fir or lodgepole pine, choice of

TABLE 2 *A description of the Fehr Mountain, Murray Creek and Opax Mountain projects, where the effects of site preparation and silvicultural system[a] practices in dry Douglas-fir forests in the Kamloops area of the Southern Interior Forest Region were studied*

Project	Subzone/ variant	Aspect/ slope	Elevation (m)	Objectives	Variables measured	Primary references[b]
Fehr Mountain	IDFdk1	Level	1220	To examine the effects of the following site preparation techniques on planted Douglas-fir performance, water relations, microclimate, and nutrition: • scalping[c] • scalping + ripping[c] • chemical (glyphosate @ 1.44 kg ai ha^{-1}) • untreated control	***Microenvironment*** • Soil water content • Soil temperature at 5 and 15 cm depth • Net solar radiation • Precipitation • Air temperature • Soil nutrient status ***Seedlings*** • Frost damage • Survival • Stem diameter and height • Stomatal conductance • Foliar nutrient status	Fleming et al. (1994) Fleming et al. (1996) Fleming et al. (1998) Hope (1991)
Murray Creek	IDFdk1	40–55% west and east (two sites)	1200–1300	To examine the effects of mechanical (excavator) and chemical (glyphosate @ 2.14 kg ai ha^{-1}) site preparation techniques on planted lodgepole pine performance, levels of environmental resources and conditions, and richness and diversity of ectomycorrhizal fungi: • mechanical scalp in small patches (90 × 90 cm) • mechanical scalp in large patches (90 × 180 cm) • chemical removal of pinegrass in small patches (90 × 90 cm) • chemical removal of pinegrass in large patches (90 × 180 cm) • untreated control	***Microenvironment*** • Precipitation • Air temperature • Relative humidity • Soil temperature at 20 cm depth • Soil water potential • Soil nutrient status • Soil bulk density and porosity • Soil aggregate stability ***Seedlings*** • Survival and vigour • Stem diameter and height • Net photosynthetic rate • Stomatal conductance • Foliar nutrient status • Ectomycorrhizal richness and diversity	Simard et al. (1997) Simard et al. (2003)

Continued

TABLE 2 *Continued*

Project	Subzone/ variant	Aspect/ slope	Elevation (m)	Objectives	Variables measured	Primary references[b]
Opax Mountain[d]	IDFxh2	variable	950–1100	To test the effects of the following silvicultural systems on microenviroment, growth and yield, wildlife (small mammals, salamanders, insects, cavity nesters, song birds), vascular and non-vascular plants, soil chemistry, forest health, tree seed production and dissemination, and seed germination and predation: • 20% volume removal by individual-tree selection • 50% volume removal by individual-tree selection • 50% volume removal by partial cutting with uncut reserves on 25% of area (for a total of 35% volume removal over the treatment unit area) • 20% volume removal by patch cuts of 0.1, 0.4, 1.6 ha • 50% volume removal by patch cuts of 0.1, 0.4, 1.6 ha • uncut forest Within the silvicultural systems treatments, a series of complementary studies were developed to study vegetation and regeneration responses to varying canopy gap size, residual stand density, and opening orientation.	***Microenvironment*** • Growing-season soil temperature at 1 and 15 cm depth (at monthly intervals) • Light (Global Light Index and PAR) • Soil water content • Precipitation and air temperature • Soil nutrient status ***Seedlings*** • Survival and vigour • Stem diameter • Leader length • Total height	Vyse et al. (editors, 1998) Lloyd et al. (2001) Hope and Prescott (2001)
	IDFdk2	variable	1200–1370			

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a In this paper, "silvicultural system" refers only to the characteristics of timber harvest (e.g., opening size, shape, density of leave trees).

b "Primary references" are the individual reports on which this Technical Report is based. Results from these reports are usually not referenced individually.

c At Fehr Mountain, scalping involved removal of the organic horizons and the top 2–5 cm of mineral soil with the straight blade of a Caterpillar D6 crawler tractor. Ripping was conducted by making several passes over scalped areas with flanged ripper teeth that penetrated the soil to a depth of about 50 cm. Ripper tooth paths were spaced 0.3–0.5 m apart and soil was levelled with shovels and rakes (Fleming et al. 1994).

d The Opax Mountain study consists of an upper-elevation site in the IDFdk2 and a lower-elevation site in the IDFxh2 (also known as Mud Lake). Cattle were excluded from these sites.

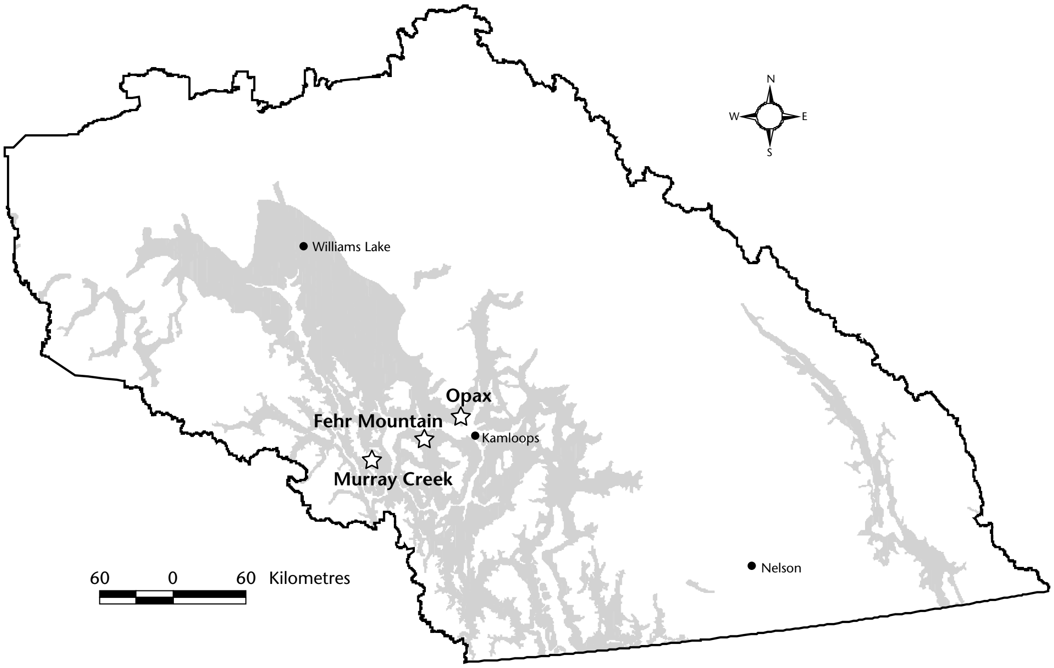

FIGURE 2 *Location of the Fehr Mountain, Murray Creek, and Opax study sites in the Southern Interior Forest Region. Shading shows distribution of the IDF biogeoclimatic zone.*

stock type, and natural regeneration potential are important considerations, but were not part of the three studies upon which this report is based.

The three research sites are located in the IDFxh2, IDFdk1, and IDFdk2[1] variants, which are among the driest of the southern interior IDF ecosystems. We expect that these results are transferable to pinegrass ecosystems in the IDFdm, IDFmw, IDFxm, and IDFxw subzones of the Kamloops, Cariboo, and Nelson areas of the Southern Interior Forest Region.

CONIFER SEEDLING RESPONSES

On mesic and submesic sites in the IDFxh2, the choice of planting species is limited to Douglas-fir or ponderosa pine. In the IDFdk, both Douglas-fir and lodgepole pine are acceptable, as well as ponderosa pine on drier sites (Lloyd et al. 1990). Lodgepole pine tends to be preferred over Douglas-fir because it has greater frost tolerance and higher early survival and growth rates.

Survival

Summary Planted Douglas-fir seedlings had lower survival than planted lodgepole pine on dry, pinegrass-dominated IDF sites, especially at Fehr Mountain, where frost damage was prevalent. Even mechanical site preparation treatments that expose mineral soil may not adequately improve survival on flat, frost-prone sites in the IDFdk. Frost contributed somewhat to early seedling mortality of lodgepole pine on the steep slopes of Murray Creek; however, soil water availability was more important to survival, and

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[1] The Opax Mountain site has recently been reclassified as IDFdk2 rather than IDFdk1. It is at the dry end of the range of growing-season precipitation that occurs in the IDFdk2.

was increased by large patch chemical or mechanical site preparation. At Opax Mountain, which is not a particularly frost-prone site, opening size did not appear to affect survival of Douglas-fir or pine unless planting was delayed.

Specific Responses

Fehr Mountain In the year of planting, 93% of Douglas-fir in the control and herbicide plots suffered from frost damage, compared with 47% and 22% in the ripping and scalping treatments, respectively. In contrast, lodgepole pine showed no symptoms of frost injury. Three growing seasons after planting, Douglas-fir survival was below 50% in control and herbicide treatments, approximately 60% in the scalping treatment, and approximately 80% in the ripping treatment (Figure 3). After 11 years, so few Douglas-fir seedlings had survived in all treatments that they were dropped from the study. Newsome (1998) also noted that the overall poor performance of planted Douglas-fir on flat, frost-prone sites in the IDFdk made it difficult to make site preparation recommendations. In contrast to Douglas-fir, third-year lodgepole pine survival at Fehr Mountain exceeded 85% in all treatments, including the control.

Murray Creek Two years after lodgepole pine seedlings were planted at Murray Creek, survival was 78% and 81% in the control and small patch herbicide treatments, respectively, but was greater than 97% in all other treatments (Figure 4). These treatment patterns were still expressed 10 years after the treatments were applied. Mortality was predominantly associated with drought, and to a lesser extent summer frost, on these steep slopes.

Opax Mountain Douglas-fir and lodgepole pine were operationally planted 1 year after harvest into excavator-screefed patches that were approximately 80 × 100 cm, in the treatments where 20% and 50% volume had been removed by patch cuts. After four growing seasons, Douglas-fir survival in the 0.1-, 0.4-, and 1.6-ha openings averaged 70% and 78% in the IDFxh2 and IDFdk2, respectively, while lodgepole pine survival averaged 94% and 91%, respectively (Figure 3 and Figure 4). In a second study, Douglas-fir and pine seedlings were planted in screefed patches under different canopy closure classes in the treatment where 50% volume had been removed by individual tree selection. After 3 years, survival averaged 84% for both species, with a noticeable increase in mortality where crown closure was greatest.

In a third study at Opax, Douglas-fir planting was delayed until 4 years after harvest, at which time seedlings were planted into unprepared ground and manually screefed patches. Three years later, survival varied between 19% and 96% in different light classes and screef treatments. Where canopy gaps exceeded 0.2 ha, survival was significantly higher in screefed than in unprepared spots. Although the trend was similar in the two variants, it was much more pronounced in the IDFdk2 than in the IDFxh2 (Figure 5). The greater effect of screefing on seedling survival in the IDFdk2 than in the IDFxh2 was likely due to the somewhat steeper slope, and therefore drier soil conditions, in the IDFdk. In the 4 years since harvest, vegetation, including pinegrass, had increased more in large than in small gaps, but pinegrass abundance was similar in the IDFdk2 and IDFxh2. Screefing likely improved survival in the openings by increasing soil water availability to newly planted

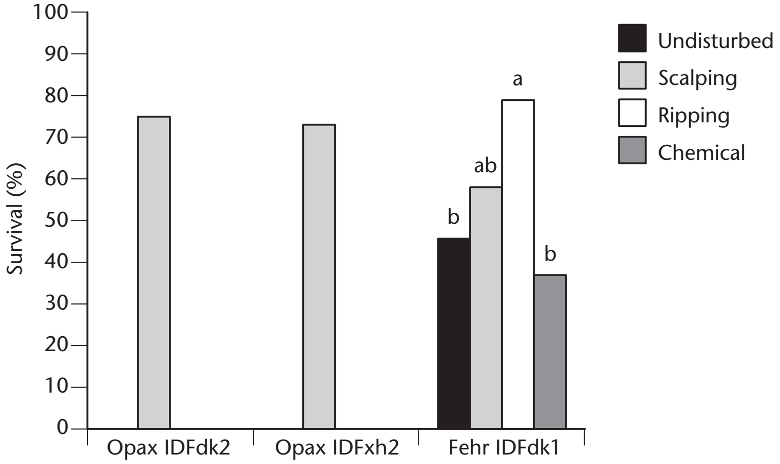

FIGURE 3 *Average 4-year survival of operationally planted Douglas-fir in 1.6-ha openings in the IDFdk2 and IDFxh2 at Opax Mountain, compared with 3-year survival of Douglas-fir on a large clearcut at Fehr Mountain. Within the "Fehr Mountain" group of bars, treatments having different letters are significantly different ($p \leq 0.05$). Note that survival at Fehr Mountain decreased beyond year 3 to the point where Douglas-fir was dropped from the study. Similar trends of decreasing survival have not been observed at the less frost-prone Opax site.*

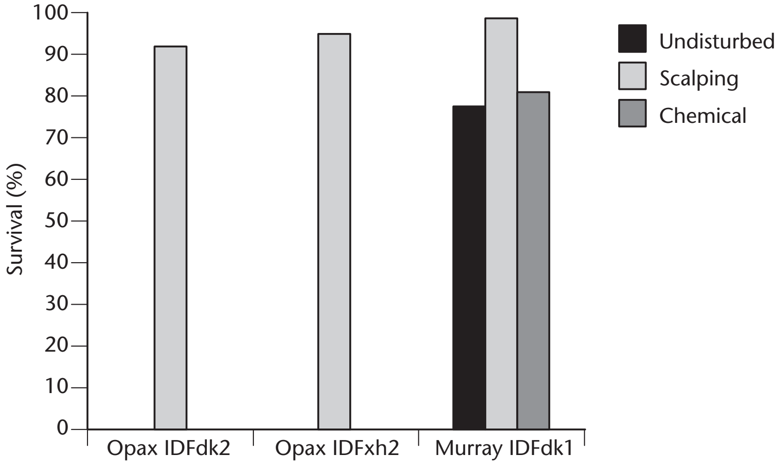

FIGURE 4 *Average 4-year survival of operationally planted lodgepole pine in 1.6-ha openings in the IDFdk2 and IDFxh2 at Opax Mountain, compared with 3-year survival on a clearcut at Murray Creek. Treatments shown for Murray Creek are the undisturbed control, small patch mechanical scalp (90 × 90 cm), and small patch chemical spot treatment (90 × 90 cm).*

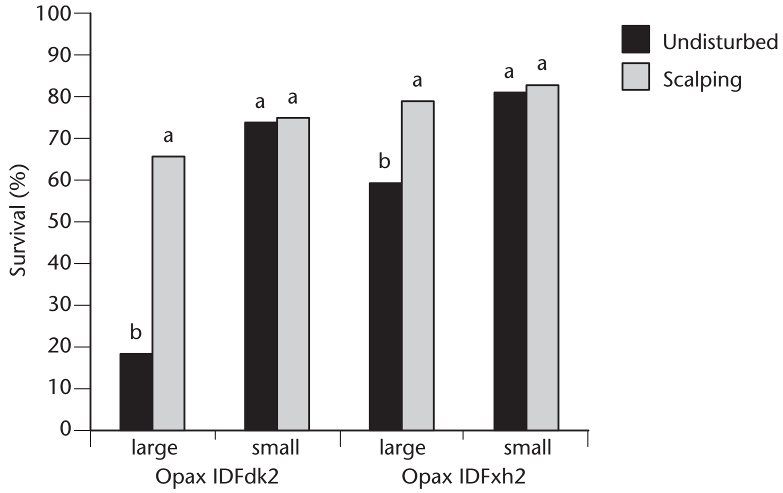

FIGURE 5 *Third-year survival of Douglas-fir planted 4 years after harvest in large (> 0.2 ha) and small (0.01–0.02 ha) canopy gaps in the IDFdk2 and IDFxh2 at Opax Mountain, in manually screefed and undisturbed ground. Within each group of bars, treatments having different letters are significantly different ($p \leq 0.05$).*

seedlings. Survival rates for operationally planted seedlings suggest that opening size is not an important factor on pinegrass-dominated sites as long as site preparation and planting are done promptly following harvest. This does not apply to very small gaps, such as those created by removal of a single tree, where the combined effects of low light availability and water use by surrounding trees may have a negative effect on conifer establishment.

Growth

Summary Lodgepole pine diameter growth improved following mechanical and chemical site preparation. Differences were statistically significant after 8 years at Murray Creek, but not after 11 years at Fehr Mountain. Height and stem diameter of Douglas-fir at Fehr Mountain increased as a result of site preparation by year 3, but could not be assessed in later years because of low survival.

Specific Responses

Fehr Mountain Three years after planting, surviving Douglas-fir in the site preparation treatments were approximately twice as large in diameter and 1.5 times as tall as those in the control. Growth was not assessed in year 11 because so few survived. Lodgepole pine in site preparation treatments also had at least twice the diameter of control seedlings after 3 years, and were tallest in the ripping and herbicide treatments (57–61 cm tall, compared with 48 cm tall in the scalping treatment and 32 cm tall in the control). After 11 years, pine continued to be significantly taller in all site preparation treatments than in the control, and those in the herbicide and ripping treatments were taller than those in the scalping treatment (data not shown). Diameter still tended to be largest in the ripping and herbicide treatments, but none of the differences remained statistically significant (Figure 6).

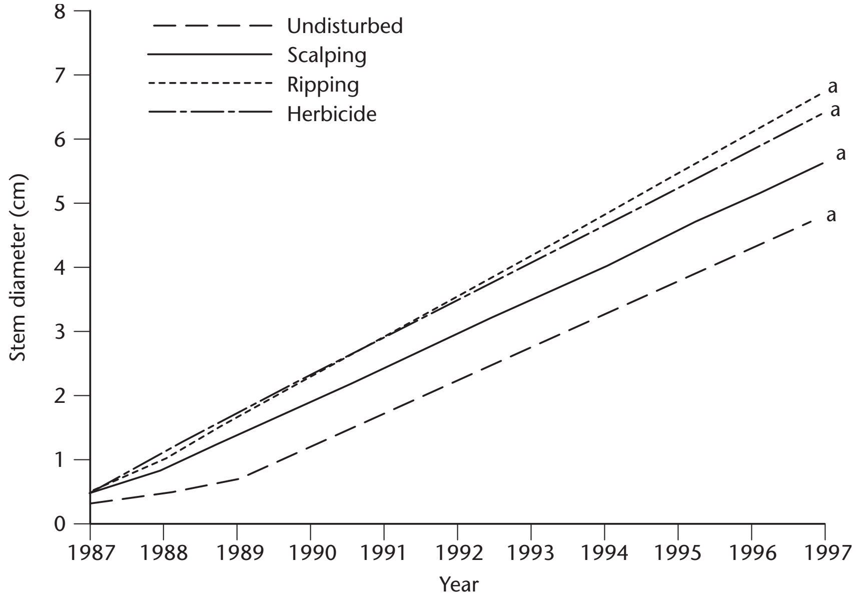

FIGURE 6 *Mean lodgepole pine diameter from 1987 to 1997 at Fehr Mountain. Similar letters indicate no significant differences in 1997 (p > 0.05). Growth appears to be linear from 1989 to 1997 because data were interpolated between those dates.*

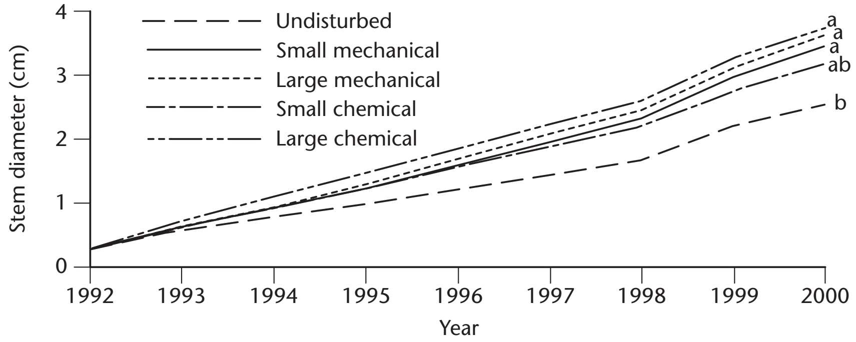

FIGURE 7 *Mean lodgepole pine diameter from 1992 to 2000 at Murray Creek. Different letters indicate significant differences in 2000 (p ≤ 0.05). Data were interpolated between 1995 and 1997.*

Murray Creek At Murray Creek, many factors were affecting lodgepole pine growth, but soil water availability was probably the most important. Within 3 years of planting, lodgepole pine diameter was significantly greater in all site preparation treatments than in the control, and was greater in large (90 × 180 cm) than in small (90 × 90 cm) patches. By year 5, seedlings were also significantly taller in both the large mechanical and large chemical patches than in the control. Both diameter and height of pine in the site preparation treatments continued to diverge from the control during the 8 years following planting, and seedlings in the large chemical and mechanical patches tended to have the best growth (Figure 7). This result is consistent with improved soil water availability following removal of pinegrass.

EFFECTS OF SITE PREPARATION AND SILVICULTURAL SYSTEMS PRACTICES ON SEEDLINGS

To successfully regenerate sites with climatic limitations that are severe enough to negatively affect conifer seedling survival and growth, it is important to understand the potential effects of treatments on seedling microenvironment. This section reviews factors that affect seedling survival and growth in the dry, grassy IDF, and discusses how site preparation and silvicultural system treatments influenced these factors at the three study sites.

Soil water

Summary Both mechanical and chemical site preparation treatments improved water availability to seedlings at Fehr Mountain and Murray Creek because they reduced competition from grasses and other plants. Large patch treatments (90 × 180 cm) resulted in greater water availability than small patch treatments (90 × 90 cm).

Discussion The most critical factor for survival and early growth of planted seedlings is water uptake (Örlander et al. 1990); this is especially true for dry IDF sites where pinegrass is common. Pinegrass is an efficient competitor for soil water, partly because its growth peaks early in the growing season, well before conifer growth (Nicholson 1989). Pinegrass continues to photosynthesize at reduced levels where it is under moisture stress, which also provides it with a growth advantage over conifer seedlings and allows it to use an even greater share of soil water (Vogel 1985, cited by Haeussler et al. 1990). Pinegrass increases in abundance in response to greater light availability following harvest (Haeussler et al. 1990), which suggests that the choice of silvicultural system and opening size may indirectly affect water availability to seedlings. Site preparation techniques that reduce pinegrass cover and/or remove the forest floor can also influence soil water availability in the dry IDF. As well, site preparation can ameliorate dry soil conditions that are related to aspect and steepness of slope in dry IDF ecosystems; the driest conditions occur on steep, south-facing slopes (Lloyd et al. 1990).

The effects of site preparation on water availability in the seedling root zone were studied in detail at Fehr Mountain. Pinegrass was abundant on that site, and water potentials at 15 cm depth fell as low as -0.9 MPa in late summer. Spittlehouse and Goldstein (1989) suggest that newly planted seedlings require about 4 weeks during which soil water potential does not drop below -0.1 MPa. Mechanical and chemical treatments improved water availability equally well at Fehr Mountain, maintaining potentials above -0.1 MPa throughout the growing season. For both Douglas-fir and lodgepole pine, increases in the availability of root-zone water improved stomatal conductance, which is known to be positively correlated with photosynthetic rates and growth rates.

At Murray Creek, soils were measurably drier on east than on west aspects, a result that was attributed to the east aspect having 100 m lower elevation, steeper slope, and coarser soils than the west aspect. Soil water potential was commonly higher in large mechanical and chemical patches than in the control, suggesting that those treatments had greater potential for increasing water availability to seedlings. However, none of the site preparation treatments consistently reduced the number of days where water potentials fell below -0.1 MPa, and the chemical treatments appeared to increase the number of days with moisture stress. Reduced infiltration of rain through a hydrophobic mulch that formed on the sprayed forest floor, or greater transpiration of larger seedlings, may have caused this result.

At Opax Mountain, edge orientation of 1.4-ha openings appeared to affect mid-summer soil water availability. Soils were slightly drier at the north than at the south edges, which is consistent with greater exposure to solar radiation and more abundant vegetation at the north edge. However, there was little overall difference in soil water content at 10-cm depth between the opening and the adjacent forest, possibly because pinegrass transpiration in the opening approached that of trees in the forest (Paterson 1997). Further measurements are needed to assess growing-season water availability and to evaluate year-to-year and seasonal variation.

Air temperature

Summary Air temperature at seedling height can be an important limitation to conifer seedling survival and growth on frost-prone IDF sites. The risk of frost damage is higher on flat sites than on steep slopes, and is higher for Douglas-fir than for lodgepole pine. The occurrence of damaging frosts can vary within as little as a few hundred metres, depending on site factors. Excessively high air temperatures (> 50° C) also have the potential to damage seedlings, but are not generally associated with the IDF zone.

Discussion Growing-season frosts occur during any month of the year in the dry IDF, particularly on flat sites where dense grass or herb cover can trap a layer of cold, moist air at seedling height. Frost damage can be particularly problematic on flat valley-bottom sites that collect cold air from upslope positions. Frost damage was linked to low Douglas-fir survival at the flat Fehr Mountain site in the IDFdk1, but Douglas-fir was not affected by frost on the somewhat steeper IDFdk2 site at Opax, nor on the slightly warmer IDFxh2 site. At Murray Creek, a small amount of pine mortality in the first year after planting was attributed to frost damage, but the problem was relatively minor because of the steep slopes and low susceptibility of lodgepole pine.

Scalping and ripping site preparation treatments can reduce frost damage more effectively than herbicide or control treatments because exposed mineral soil allows the nighttime release of stored heat energy (Stathers 1989) that is blocked by intact forest floor material. At Fehr Mountain, Douglas-fir in treatments with exposed mineral soil sustained less than half the frost damage of seedlings in the herbicide and control treatments. At Murray Creek, both mechanical and chemical large patch treatments reduced by half the number of nights with mild (< 0° C) or damaging (< -4° C) frosts.

The type of silvicultural system may also affect the incidence of frost damage. A tall tree or shrub canopy reduces nighttime radiative heat loss (Stathers 1989), which suggests that seedlings underplanted following individual tree selection cutting may be subject to less frost damage than those growing in patch cuts or clearcuts. Underplanting has had some success at reducing frost damage to Douglas-fir in the Cariboo Forest Region (Newsome et al. 1991), although gains in frost protection may be offset by growth losses due to light and water deficits created by the overstory trees.

Air temperature also affects seedling physiological processes such as photosynthesis and respiration, which are optimal in the 15–25° C range (Spittlehouse and Stathers 1990). At Murray Creek, air temperatures at seedling height were highest in the large mechanical patch treatment, which corresponded with a 16–23% increase in the number of growing degree-days compared with the untreated control. The number of growing degree-days also increased in the chemical patch treatments, but to a lesser degree.

Soil temperature

Summary Soil temperature is part of the complex of factors governing seedling root growth and the ability to take up soil water, but it is not the single most important limiting factor in the IDF zone. In both our site preparation studies, mechanical treatments increased soil temperature because they exposed mineral soil. Chemical site preparation resulted in increases in soil temperature at Murray Creek but not at Fehr Mountain.

Discussion Soil temperature affects the rate at which roots grow and their physiological ability to take up water and respire (Spittlehouse and Stathers 1990), which in turn affects rates of photosynthesis and shoot growth. On dry sites, it is important that seedlings develop extensive root systems to optimize water uptake. Even though IDF ecosystems are not particularly cold (Table 1), increases in soil temperature during the seedling establishment phase may improve root growth and the subsequent ability to survive summer drought.

At Fehr Mountain, soil temperature increased as a result of scalping and ripping treatments that exposed mineral soil, but not as a result of the chemical treatment that removed vegetation and left the forest floor intact. All site preparation treatments increased the number of soil growing degree-days (≥ 5° C) in comparison with the undisturbed control. The greatest increase occurred in the ripping treatment. Surface temperatures as high as 52° C were measured for forest floor materials in the herbicide treatment at Fehr Mountain, but there was no associated seedling damage. In comparison, forest floor materials reached a maximum temperature of 34° C in the untreated control, and mineral soil in the scalping treatment reached a maximum surface temperature of 47° C.

Soil temperature was monitored for 4 years following site preparation at Murray Creek. In that study, all site preparation treatments, including the chemical ones, increased soil temperature in comparison with the untreated control. Soil temperatures were higher in large patches (both mechanical and chemical) than in small patches. Snowmelt occurred 1–5 days sooner in the site-prepared patches than in the undisturbed control, which increased the number of soil growing degree-days in those treatments. The east aspect had warmer soils, and hence a greater number of soil growing degree-days, than the west aspect. At Opax Mountain, screefed plots were warmer than undisturbed plots, both at the surface and at 15-cm depth, and the magnitude of the difference varied with distance from the forest edge (Figure 8).

Soil temperature can be affected by the choice of silvicultural system because of differences in the amount of solar radiation reaching the soil surface. At Opax Mountain, density of forest cover, opening size, and edge orientation all had an effect. In that study, soils were monitored monthly during the summer. Mid-day temperatures on clear days were always higher in openings than in the adjacent forest. Soils in the centre of large openings were on average 2–3° C warmer at 15-cm depth than those in the forest interior in mid-summer (Figure 8). The greatest changes in soil temperature occurred within 24 m of the forest edge, and the changes were larger at north than at south edges because of greater insolation. As a result, soils were consistently slightly warmer within 12 m of the north than of the south edges. By late fall, there were no soil temperature gradients across opening edges, and differences between the forest and large opening had disappeared.

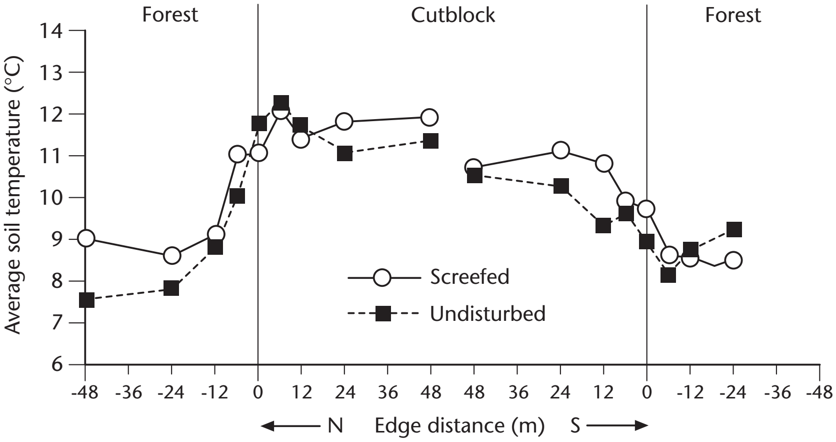

FIGURE 8 *General soil temperature patterns at 15-cm depth in screefed and undisturbed site preparation treatments, across 1.6-ha openings at Opax (reproduced from Bissonnette 2000).*

Light

The quality and quantity of light available to conifer seedlings affect the rate at which they photosynthesize, with some variation according to the shade tolerance of individual species. Light availability also affects the composition and abundance of post-harvest vegetation, and hence, influences the competitive environment experienced by conifer seedlings. Season, weather, latitude, and to some extent forest type, influence the quality and quantity of light available in the seedling microenvironment, but silvicultural system characteristics (i.e., opening size, edge orientation, canopy retention) also have a strong effect. Because pinegrass abundance increases with light availability, soil water availability to seedlings may also be influenced by the choice of silvicultural system.

Silvicultural system treatments at Opax Mountain (Table 2) produced canopy gaps of different shapes and sizes and different canopy densities, even where similar amounts of wood were removed. Patch cuts resulted in square-shaped canopy gaps, whereas partial cuts produced a variety of canopy gap sizes (25–2500 m^2) with a range of configurations. Shapes varied from long and narrow to circular or irregular. Gaps of the same size, but with different geometry and cardinal orientation, had different light regimes. Light levels varied from 10–26% full sunlight in the small gaps (77 m^2) to 82–98% full sunlight in the large gaps (4000 m^2). Studies have shown that Douglas-fir and lodgepole pine are able to achieve 70% of maximum radial growth at 87% and 84% full sunlight, respectively (Chen 1997; Wright et al. 1998).

Nutrient availability

Summary Mechanical site preparation treatments that removed the forest floor resulted in short-term reductions in soil and/or foliar nutrient concentrations at Fehr Mountain and Murray Creek. However, 11 years after treatments were applied at Fehr Mountain, lodgepole pine showed no evidence of deficiencies. Likewise, pine at Murray Creek showed no evidence of deficiencies 5 years after treatment.

Discussion Removal of the forest floor during harvesting and site preparation treatments can negatively affect both the quantity of nutrients and their availability. Forest floor materials contain large amounts of nutrients, and also provide habitat for organisms that convert those nutrients to forms available for uptake by conifers. IDF soils generally have medium to rich nutrient status due to the predominance of base-rich bedrock and low rates of leaching (Lloyd et al. 1990). The potential for scalping treatments to have long-term effects on overall nutrient content, on both gentle and steep slopes, is likely related to the size and depth of the scalps. Small scalps that remove only forest floor down to the mineral soil are likely to have little long-term effect because surface mineral horizons are relatively nutrient-rich in the IDF. Treatments that produce large, deep scalps (i.e., that remove surface mineral horizons) have greater potential to affect long-term productivity, but are not commonly applied in the southern interior IDF, except where they occur as landings and skid trails. On steep slopes, deep screefs have the potential to increase erosion hazard because of reduced soil structural stability. With medium- to fine-textured soils, any type of screefing on steep slopes can result in surface erosion following high-intensity rainstorms.

One year after the scalping treatment was applied at Fehr Mountain, total soil nitrogen (N) content was reduced to 60% of the untreated control, extractable phosphorous (P) to about 80% of the control, and extractable potassium (K) and sulphur (S) to 85–90% of the control. The effect on exchangeable cations was small and presumably biologically insignificant. When comparisons were made among biogeoclimatic zones within the Kamloops Forest Region, the effect of forest floor removal on soil nutrient status was less in the IDF zone, where the forest floor is relatively thin, than in either the Montane Spruce (MS) or Engelmann Spruce–Subalpine Fir (ESSF) zones (Hope 1991).

For Douglas-fir and lodgepole pine at Fehr Mountain, concentrations of most foliar nutrients had decreased somewhat in the scalping treatment compared with the untreated control after 3 years, and boron (B) was reduced to possible deficiency levels. However, the presence of B is highly variable year-to-year, and depends on variations in weather conditions (R. Brockley, pers. comm., 2000). Nitrogen was somewhat deficient in both the control and treatments. By the time lodgepole pine seedlings were 11 years old, significant differences in foliar nutrient levels between treatments remained. Foliar aluminum (Al) and manganese (Mn) concentrations were significantly lower in the scalping treatment than in the control, but were still well above deficiency levels. Foliar sulphur (S) levels were low enough in both the control and scalping treatment to suggest a possible deficiency (G. Hope, unpublished data). Douglas-fir at Fehr Mountain was not sampled at age 11 because of low survival rates.

At Murray Creek, the effects of scalping and chemical site preparation treatments on soil and lodgepole pine foliar nutrient concentrations were assessed 5 years after site preparation. The removal of forest floor materials in both large and small patches significantly reduced total soil carbon (C) and N capital in comparison with the untreated control (Figure 9), whereas chemical treatments did not reduce quantities significantly. Nutrient levels were affected only within the screefed patches and not across the entire treatment plot, however, because forest floor materials were displaced but not removed from the site. Removal of the forest floor in large and small patches resulted in significant decreases in foliar Al, B, and Mn compared with the control, possibly due to a dilution effect in the larger seedlings, increased microbial assimilation of nutrients following from dead grass C inputs, or

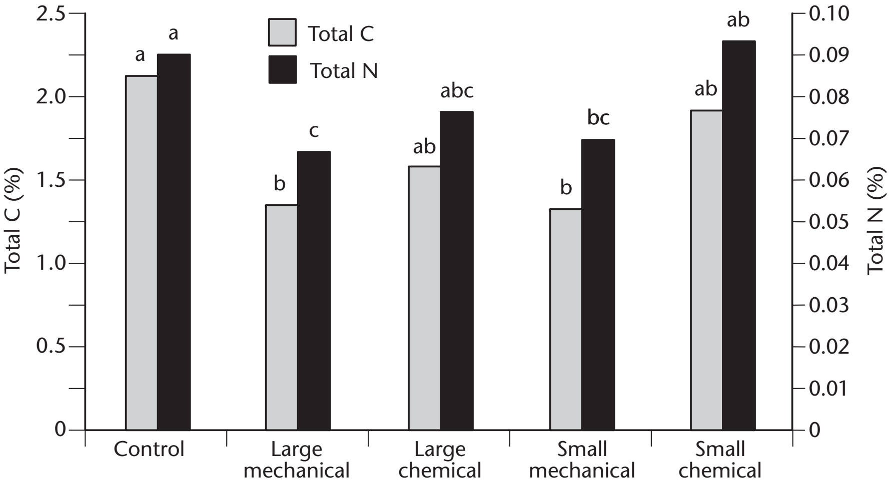

FIGURE 9 *Total carbon and nitrogen content at Murray Creek, 5 years after large (90 × 180 cm) and small (90 × 90 cm) patch mechanical and chemical site preparation treatments were applied. Within each set of bars (i.e., nitrogen and carbon), treatments having different letters are significantly different ($p \leq 0.05$).*

increased leaching following grass mortality. In contrast, foliar N and S were slightly lower in the chemical patches than in the mechanical patches or the control. Despite the reductions, foliar nutrient concentrations were above deficiency levels.

Currently, little information is available regarding the effects of silvicultural system characteristics on nutrient availability, except where whole-tree harvesting is a factor (Kimmins 1977; Hope and Prescott 2001). However, the choice of silvicultural system can potentially affect nutrient availability and soil nutrient content by influencing rates of decomposition and nitrogen mineralization. Nitrate-N (NO_3-N) is relatively mobile, and can be lost through leaching, but there is rarely enough soil water for this to occur on dry IDF sites. Reductions in forest floor thickness are commonly observed in clearcuts, and have been attributed to increases in forest floor temperature and faster rates of decomposition. However, Prescott et al. (2000) found no evidence of increased rates of forest floor or litter decomposition on clearcut sites throughout British Columbia (Opax Mountain was one of the study sites), nor were there differences among opening sizes. Nitrogen mineralization rates were measured in a separate study at Opax Mountain, and although there were no overall differences between openings and the forest, ammonium-N (NH_4-N) levels tended to decrease and NO_3-N levels tended to increase in the openings. This trend was measurable beyond approximately 10 m from the forest edge, depending on aspect.

Ectomycorrhizae

Summary Both mechanical and chemical site preparation treatments caused short-lived increases in richness (number of species) and diversity (a measure of the relative abundance of individual species) of ectomycorrhizal species at Murray Creek. However, 28 months after planting, ectomycorrhizal diversity was significantly reduced from untreated control levels in the mechanical treatment but not in the chemical treatment.

Discussion The forest floor and mineral soil are home to a variety of microorganisms that play critical roles in maintaining the health of the plant–soil system. These organisms include ectomycorrhizae, rhizobacteria, protozoa, amoebae, nematodes, and microarthropods (Perry et al. 1989). Ectomycorrhizae are associated with increased seedling uptake of water and phosphorous, as well as with the conversion and absorption of organic forms of nutrients that are otherwise unavailable for conifer root uptake. Seedlings planted onto harvested sites quickly become colonized by fungi that are present in the soil or that are associated with the roots of other plants. Because ectomycorrhizal fungi differ in their ability to break down and absorb organic forms of nutrients, and to absorb and transport ions (e.g., phosphate) and soil water, it is important to retain their richness and diversity as much as possible following harvesting and site preparation (Jones et al. 1997).

Ectomycorrhizal fungi, as well as most other soil organisms, occur predominantly in the forest floor, and site preparation treatments that remove forest floor materials may have a negative effect on the health of the soil community. Sixteen months after site preparation at Murray Creek, ectomycorrhizal species diversity was lower in the control than in the chemical or mechanical patch treatments (Figure 10), which appeared to be related to slower pine growth rates in the presence of pinegrass competition. There was also a significant increase in ectomycorrhizal richness in the herbicide treatment relative to the control (data not shown). After 28 months, ectomycorrhizal species diversity was similar in the control and herbicide treatment, but was significantly lower in the mechanical treatment, possibly because of removal of forest floor materials. Species richness decreased relative to the control during the same period. None of the common ectomycorrhizal fungi were totally eliminated by either of the site preparation treatments, but the mechanical treatment significantly reduced E-strain and increased MRA mycorrhizae relative abundance, which may have contributed to reduced seedling performance in that treatment. Interestingly, M. Jones et al. (unpublished data) recently found that E-strain mycorrhizae stimulated N

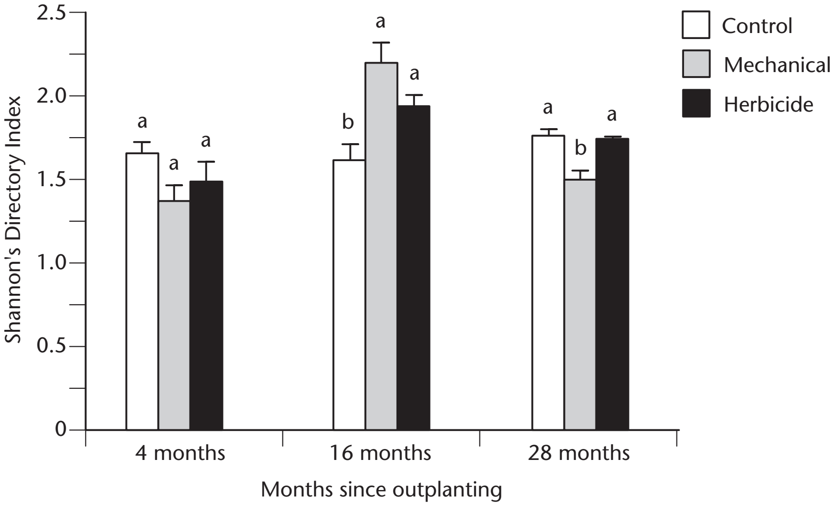

FIGURE 10 *Comparison of mean ectomycorrhizal diversity per plot among site preparation treatments during the first 28 months following planting at Murray Creek. Within groups of bars, treatments having different letters are significantly different (p ≤ 0.05).*

uptake by spruce seedlings growing in high-elevation clearcuts compared with seedlings forming MRA mycorrhizae.

Clearcut harvesting is known to reduce the quantity and diversity of ectomycorrhizal innoculum in the soil (e.g., Durall et al. 1999). However, some plant species that are commonly retained following harvest can act as "refuge plants" by associating with the same fungal species as conifers. At Opax Mountain, kinnikinnick (*Arctostaphylos uva-ursi*) and advance regeneration of Douglas-fir were associated with many of the same fungal species, even though kinnikinnick formed endomycorrhizae while Douglas-fir formed ectomycorrhizae. The richness of fungal species associated with kinnikinnick was similar in the forest and the clearcut, suggesting that this shrub may help maintain mycorrhizal populations on harvested IDF sites (Hagerman et al. 2001). In other ecosystems, seedlings planted near refuge trees have been shown to have increased richness of ectomycorrhizae (Kranabetter 1999). It is likely that green-tree retention has similar effects on dry Douglas-fir sites.

Soil physical properties

Mechanical treatments have the potential to increase bulk density, reduce porosity, and reduce soil aggregate stability, which can affect soil water availability, root activity, and activity of soil organisms. At Murray Creek, the mechanical treatment reduced soil porosity and aggregate stability. The effects of such changes on seedling performance are not well understood, but none appeared sufficiently large to limit seedling growth. On steep slopes, increased erosion hazard as a result of the lowered soil stability may be of greater concern.

INTERPRETATIONS

The following interpretations are intended to assist in the selection of harvesting and site preparation options that will enhance seedling microenvironment and increase artificial regeneration success. Other factors not addressed in this Technical Report, such as cattle damage, browsing by wildlife, and climatic extremes, may also affect regeneration success, and should be considered. Based on results from the Fehr Mountain, Murray Creek, and Opax studies, we present strategies for overcoming various limitations to conifer seedling establishment on dry, grassy IDF sites. In some cases, these strategies conflict with one another, and the best option will depend on individual site characteristics and the specifics of management objectives.

Site preparation is applied to improve the microenvironment for seedling establishment and early growth. In dry, pinegrass-dominated IDF ecosystems, the main objectives of site preparation are to increase soil moisture availability for newly planted seedlings, and on many sites, to reduce the potential for frost damage.

Both chemical and mechanical site preparation treatments have many advantages and disadvantages. Chemical treatments are cheaper and easier to apply than mechanical treatments that involve excavators, and they do not affect soil physical properties or reduce nutrient availability. Other mechanical site preparation options not presented here (e.g., disc trenching) may be less costly than chemical site preparation. Chemical treatments can also be applied regardless of topography, whereas most mechanical treatments are

TABLE 3 *Strategies for overcoming growth limitations on dry, pinegrass-dominated IDF sites, based on results from the Fehr Mountain, Murray Creek, and Opax studies*

Strategy	**Possible management options based on available information**
Reduce early frost damage to seedlings on flat, frost-prone sites	1. Plant promptly after harvest with lodgepole pine rather than Douglas-fir. 2. Mechanically prepare the site to expose patches of mineral soil and plant lodgepole pine. Improvements in air temperature at seedling height will increase with the scalp size, but must be balanced against the possible negative effects of removing forest floor materials. 3. Harvest by selection cutting and underplant Douglas-fir.
Increase soil water availability to seedlings	1. Plant promptly after harvest with Douglas-fir or lodgepole pine. 2. Chemically (e.g., glyphosate @ 1.0–1.4 kg ai ha^{-1}) prepare the site to reduce pinegrass abundance in planting spots. Recommended size of treatment patches is 90 × 180 cm. 3. Mechanically prepare the site to reduce pinegrass abundance in planting spots. The recommended screef size will vary according to pinegrass abundance and size of the excavator bucket to be used. Large screefs (e.g., 90 × 180 cm) are recommended where pinegrass is abundant. Although linear trenching is not discussed in this report, a study near Williams Lake suggests that it may be more effective than scalping on sites where moisture is very limiting (T. Newsome, pers. comm., 2003).
Increase light availability to seedlings	1. Create large gaps during harvesting, followed by prompt site preparation and planting to offset soil water competition from pinegrass.
Improve soil temperature regime for seedlings on cool sites	1. Low soil temperature is not a strong limitation to seedling establishment on dry, grassy IDF sites, so improving the soil temperature regime is unlikely to be a primary consideration in the selection of a silvicultural system or site preparation method. However, soil temperature may increase as a side effect of mechanical or chemical patch treatments applied to ameliorate other limiting factors.
Avoid erosion on steep slopes	1. Use chemical rather than mechanical site preparation. 2. Plant promptly after harvest.
Minimize costs	1. When selecting the harvesting system, consider whether site preparation will also be needed. It may be possible to create adequate soil disturbance during harvest without additional treatment. 2. Plant within 1 year of harvest so that seedlings can become established before pinegrass becomes abundant. 3. Use chemical patch treatments rather than mechanical site preparation treatments involving excavators. 4. Use small rather than large screef sizes on sites with moderate pinegrass cover and/or where the risk of frost damage is not extreme. This will reduce the number of excavator passes required.
Avoid short-term local nutrient deficiencies	1. Avoid mechanical treatments that remove large (> 90 × 180 cm) patches of nutrient-rich forest floor materials. 2. Avoid whole-tree harvesting on nutrient-poor sites.
Avoid local losses of soil flora and fauna diversity	1. Avoid mechanical treatments that remove forest floor materials. 2. Minimize disturbance to pre-harvest understory vegetation so that possible refuge species can be retained.

limited by slope steepness. Broadcast herbicide treatments have the potential to reduce range and wildlife forage (Simard et al. 1998), but patch chemical treatments, which appear adequate for enhancing pine seedling establishment, are less likely to have a lasting negative effect. On particularly harsh sites where it is difficult to establish seedlings, high-impact mechanical treatments have greater potential to improve microclimate than do chemical treatments, but at the possible expense of nutrient availability in the short and medium term. Provided that soil disturbance, including erosion on the rare steep slopes, is minimized, mechanical treatments are also currently more socially acceptable than chemical treatments.

Results from Fehr Mountain and Murray Creek suggest that mechanical and chemical treatments improved soil water availability equally well. Both treatments also improved the soil thermal regime to some extent. At the flat Fehr Mountain site, frost damage was strongly associated with Douglas-fir mortality. Even ripping, which removed the forest floor and loosened soil, did not increase nighttime air temperature at seedling height enough to improve long-term survival. At Opax, frost damage did not occur in the IDFdk2 because of slope and aspect, whereas it was an important factor on a nearby flat site at Dairy Creek (G. Hope, unpublished data). On sites with a low risk of frost damage, such as the steep Murray Creek site, or the Opax sites because of the slightly warmer climate and/or moderate slope, chemical site preparation is a favourable option because it costs less and has fewer short-term environmental impacts than excavator screefing.

Results from Opax show that patch cut and partial cut (individual-tree selection) silvicultural systems produced canopy gaps of varying size and distribution, which resulted in differing post-harvest environments for seedling growth. Canopy gap characteristics affected light environments and soil thermal regimes, but if site preparation and planting took place soon after harvest, there were no differences in survival rates associated with opening size.

CONCLUSIONS

Conifer regeneration in dry, grassy IDF ecosystems is challenging, largely because of climatic limitations. The three studies presented in this Technical Report took place in the IDFdk and IDFxh subzones. Results suggest that both mechanical and chemical site preparation can improve early conifer seedling performance, but each has advantages and disadvantages, depending on site characteristics. Douglas-fir is more difficult to regenerate than lodgepole pine on dry, grassy IDF sites, mainly because of its greater susceptibility to frost damage. However, lodgepole pine does not occur naturally in the IDFxh, and should not be widely promoted in that subzone. More study is required to define the characteristics of sites where artificial regeneration of Douglas-fir is likely to be successful.

Bissonnette, D. 2000. Soil temperature response to cutblock edges at the Opax silvicultural systems research site. Kamloops Forest Region, Kamloops, B.C. Unpublished rep.

Chen, H.Y.H. 1997. Interspecific responses of planted seedlings to light availability in interior British Columbia: Survival, growth, allometric patterns, and specific leaf area. Can. J. For. Res. 27:1383–1393.

Durall, D.M., M.D. Jones, P. Kroeger, E. Wright, and K.D. Coates. 1999. Ectomycorrhizae and ectomycorrhizal sporocarps in cutblocks of different sizes in the Interior Cedar-Hemlock forests of northwestern British Columbia. Can. J. For. Res. 29:1322–1332.

Fleming, R.L., T.A. Black, and R.S. Adams. 1996. Site preparation effects on Douglas-fir and lodgepole pine water relations following planting in a pinegrass-dominated clearcut. For. Ecol. Manage. 83:47–60.

Fleming, R.L., T.A. Black, R.S. Adams, and R.J. Stathers. 1998. Silvicultural treatments, microclimatic conditions and seedling response in Southern Interior clearcuts. Can. J. Soil Sci. 78:115–126.

Fleming, R.L., T.A. Black, and N.R. Eldridge. 1994. Effects of site preparation on root zone soil water regimes in high-elevation forest clearcuts. For. Ecol. Manage. 68:173–188.

Haeussler, S., D. Coates, and J. Mather. 1990. Autecology of common plants in British Columbia: A literature review. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Rep. 158.

Hagerman, S.M., S.M. Sakakibara, and D.M. Durall. 2001. The potential for woody understory plants to provide refuge for ectomycorrhizal inoculum at an Interior Douglas-fir forest after clear-cut logging. Can. J. For. Res. 31:711–721.

Hope, G. 1991. Effects of mechanical site preparation on soil and foliar nutrients in the drier subzones of the IDF, MS, and ESSF zones—Project 3.50. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Memo. 193.

Hope, G. and C.E. Prescott. 2001. Opax Mountain Silvicultural Systems Project. Effect of silvicultural systems on soil productivity in the IDF zone: Impacts on soil organic matter and soil nitrogen. SCBC/FRBC final rep. Unpublished.

Jones, M.D., D.M. Durall, S.M.K. Harniman, D.C. Classen, and S.W. Simard. 1997. Ectomycorrhizal diversity on *Betula papyrifera* and *Pseudotsuga menziesii* seedlings grown in the greenhouse or outplanted in single-species and mixed plots in southern British Columbia. Can. J. For. Res. 27:1872–1889.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Manage. 1:169–183.

Kranabetter, J.M. 1999. The effect of refuge trees on a paper birch ectomycorrhiza community. Can. J. Bot. 77:1523–1528.

Lloyd, D., K. Angove, G. Hope, and C. Thompson. 1990. A guide to site identification and interpretation for the Kamloops Forest Region. B.C. Min. For., Victoria, B.C. Land Manage. Handb. 23.

Lloyd, D., D.J. Miège, N. Brand, M. Doney, and D. Bissonette. 2001. Summary of vegetation, soil temperature, and regeneration results from the Opax Mountain silvicultural research area. Unpublished draft rep.

Newman, R., G. Powell, K. Cameron, and C. Demaere. 1998. Effects of cattle trampling and browsing on lodgepole pine plantations. *In* Managing the Dry Douglas-fir Forests of the Southern Interior: Workshop Proc. A. Vyse, C. Hollstedt, and D. Huggard (editors). Apr. 29–30, 1997, Kamloops, B.C., pp. 77–80.

Newsome, T. 1998. Site preparation on dry grassy sites in the Cariboo Forest Region. *In* Managing the Dry Douglas-fir Forests of the Southern Interior: Workshop Proc. A. Vyse, C. Hollstedt, and D. Huggard (editors). Apr. 29–30, 1997, Kamloops, B.C., pp. 53–61.

Newsome, T.A., D.C. Sutherland, and A. Vyse. 1991. Establishing Douglas-fir plantations in the dry belt of interior British Columbia. *In* Proc. Symp. Interior Douglas-fir: The Species and Its Management. D.M. Baumgartner and J.E. Lotan (editors). Washington State Univ., Cooperative Extension Service, Pullman, Wash.

Nicholson, A. 1989. Water relations, survival and growth of Douglas-fir seedlings at a pinegrass dominated site in south-central British Columbia. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Memo 121.

Örlander, G., P. Gemmel, and J. Hunt. 1990. Site preparation: A Swedish overview. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Handb. 105.

Paterson, L. 1997. An evaluation of Gabel Corporation's Model MP-917 Time Domain Reflectometry equipment for measuring the moisture content of a forest soil. B.Sc. thesis. Univ. B.C., Faculty of Agriculture, Vancouver, B.C.

Perry, D.A., M.P. Amaranthus, J.G. Borchers, S.L. Borchers, and R.R. Brainerd. 1989. Bootstrapping in ecosystems. Bioscience 39:230–237.

Prescott, C.E., L.L. Blevins, and C.L. Staley. 2000. Effects of clearcutting on decomposition rates of litter and humus in forests of British Columbia. Can. J. For. Res. 30:1751–1757.

Simard, S.W., J. Heineman, and P. Youwe. 1998. Brushing and grazing effects on lodgepole pine, vascular plants, and range forage in three plant communities in the southern interior of British Columbia: Nine-year results. B.C. Min. For., Victoria, B.C. Land Manage. Handb. 45.

Simard, S.W., M.D. Jones, D.M. Durall, G.D. Hope, R.J. Stathers, N.S. Sorensen, and B.J. Zimonick. 2003. Chemical and mechanical site preparation: Effects on *Pinus contorta* growth, physiology, and microsite quality on steep forest sites in British Columbia. Can. J. For. Res. In press.

Simard, S.W., D.A. Perry, J.E. Smith, and R. Molina. 1997. Effects of soil trenching on occurrence of ectomycorrhizae on *Pseudotsuga menziesii* seedlings grown in mature forests of *Betula papyrifera* and *Pseudotsuga menziesii.* New Phytol. 136:327–340.

Spittlehouse, D.L. and M.J. Goldstein. 1989. Modeling soil water availability for seedling establishment. *In* Climate Applications in Forest Renewal and Forest Production. D.C. MacIver, R.B. Street, and A.N. Auclair (editors). Proc. Forest Climate '86, Nov. 17–20, 1986, Orillia, Ont.

Spittlehouse, D.L. and R.J. Stathers. 1990. Seedling microclimate. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 65.

Stathers, R.J. 1989. Summer frost in young forest plantations. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Rep. 73.

Vogel, S.A. 1985. Influence of canopy cover and simulated grazing on water relations, stomatal conductance and photosynthesis of pinegrass and elk sedge. M.Sc. thesis. Univ. Montana, Missoula, Mont.

Vyse, A., C. Hollstedt, and D. Huggard (editors). 1998. Managing the dry Douglas-fir forests of the Southern Interior: Workshop Proc. Apr. 29–30, 1997, Kamloops, B.C.

Vyse, A., R.A. Smith, and B.G. Bondar. 1991. Management of Interior Douglas-fir stands in British Columbia: Past, present and future. *In* Proc. Symp. Interior Douglas-fir: The Species and Its Management. D.M. Baumgartner and J.E. Lotan (editors). Washington State Univ., Cooperative Extension Service, Pullman, Wash.

Wright, E.F., K.D. Coates, C.D. Canham, and P. Bartemucci. 1998. Species variability in growth response to light across climatic regions in northwestern British Columbia. Can. J. For. Res. 28:871–886.