Research Report

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Natural regeneration of lodgepole pine following partial harvesting on northern caribou winter range in west-central British Columbia

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Abstract

This study compares pine natural regeneration density and height growth in small harvested openings (0.01–0.07 ha) within two biogeoclimatic subzones (Sub-Boreal Pine–Spruce [SBPS] xc and Montane Spruce [MS] xv) and three partial harvesting treatments on northern caribou (*Rangifer tarandus caribou* Gmelin) winter range in the western Chilcotin region of British Columbia, Canada. Regeneration density was assessed annually for 7 years (1996–2002). In year 7, post-logging ingress stems ≥ 1 year old had a significantly greater density on SBPSxc blocks (5898 stems per hectare) than on the higher-elevation MSxv blocks (1829 stems per hectare). The percentage of 2-m^2 plots with a natural post-logging seedling ≥ 1 year old averaged 52% in the SBPSxc and 31% in the MSxv. Advance regeneration added substantially to density and stocking in the SBPSxc but not in the MSxv. These results indicate that small (0.01–0.07 ha) harvested openings in the SBPSxc can be naturally restocked by lodgepole pine without post-logging site preparation, but higher-elevation blocks in the MSxv will need to be planted to ensure full stocking by lodgepole pine within 7 years. However, the long period between harvest entries on caribou winter range may still allow sufficient time to naturally regenerate openings in the MSxv.

KEYWORDS: *British Columbia, caribou winter range, forest management, group selection, lodgepole pine, natural regeneration, partial harvesting.*

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Introduction

Public recognition of the diverse values of forest lands in western North America has resulted in calls for changes to traditional forest practices. In recent years, foresters have increasingly considered needs to manage natural ecosystem processes, wildlife habitat, riparian functions, visual aesthetics, and recreational values in addition to timber production (Guldin 1996; Coates and Burton 1997; Monserud and Stage 1999; Malcolm *et al.* 2001; Kimmins 2002; York *et al.* 2004). As a result, clearcutting is no longer considered acceptable for all sites and partial harvesting practices are increasing (Oliver and Larson 1996; Coates and Burton 1997; Emmingham [compiler] 1999; Bliss 2000). The increase of partial harvesting has, in turn, led to renewed interest in natural regeneration.

Partial harvesting systems that maintain substantial residual tree cover throughout the harvest cycle (uneven-aged systems) have most commonly been applied to old-growth forest types where natural disturbance regimes are predominantly gap-based and have resulted in multi-cohort or all-aged stands (see, for example, Phillips and Shure 1990; McCaughey *et al.* 1991; McDonald and Abbott 1994; Gray and Spies 1997; Vyse *et al.* [editors] 1998; Eastham and Jull 1999; LePage *et al.* 2000; Coates 2000b; Stevenson and Coxson 2003; Parish and Antos 2005). In contrast, partial harvesting practices have rarely been applied to forest types such as lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm. ex S. Wats.), where natural disturbance regimes have been frequent and stand-replacing, resulting in predominantly even-aged stands. Because seedlings of canopy trees in these forests are generally shade-intolerant, single-tree, uneven-aged systems have traditionally been considered inappropriate and rarely used (Alexander 1972, 1986; Klinka *et al.* 1990; Coates 2000b). As a result, public pressure to increase the use of uneven-aged systems in these and other even-aged forests has outpaced knowledge of the silviculture implications of these systems (Coates and Burton 1997; Kimmins 2002; York *et al.* 2004).

The lodgepole pine forests of the Chilcotin region in west-central British Columbia are important winter habitat for northern caribou (*Rangifer tarandus caribou* Gmelin, northern ecotype), which is nationally designated as threatened (Youds *et al.* 2002). Caribou depend on the terrestrial and arboreal lichens in these forests for critical forage during winter (Stevenson and Hatler 1985; Cichowski 1993). Clearcutting is the traditional method of harvesting lodgepole pine forests in British Columbia (Vyse and Navratil 1985). It results in substantial mortality of these lichens, which leads to loss of the site as winter forage-producing habitat for caribou, potentially for decades (Coxson and Marsh 2001; Miège *et al.* 2001a, 2001b). Extensive clearcutting concentrates winter forage-producing habitat into increasingly smaller areas where the caribou become very susceptible to predation (Youds *et al.* 2002). To allow caribou to disperse over wide areas, partial harvesting practices that retain 50% or greater tree cover throughout the harvest cycle have been recommended to maintain sites as suitable caribou winter habitat (Youds *et al.* 2002).

> *Clearcutting results in substantial mortality of terrestrial and arboreal lichens, which leads to loss of winter forage-producing habitat for caribou, potentially for decades.*

The group selection system, which removes all trees within patches smaller than 1 ha, is the only uneven-aged system in which natural or planted lodgepole pine regeneration is likely to meet generally accepted regeneration standards (Alexander 1972; Lotan 1975; Lotan and Perry 1983; Schmidt and Alexander 1985). Harvested openings less than two tree lengths in diameter have been shown to significantly limit regeneration in Alberta (Bernier 1987), but abundant natural regeneration has been observed in small openings in Oregon (Cochran 1969), in northwest British Columbia (Coates 2000b), and in the west-central region of British Columbia (pers. observation). Coates (2000a) found that fifth-year height and diameter of planted lodgepole pine were similar in a range of opening sizes from 0.1 to 0.5 ha, but decreased sharply in opening sizes smaller than 0.1 ha. No studies of natural regeneration have previously been conducted in small (< 1 ha) openings in west-central British Columbia. Due to the cold, very dry climate and low-growing vegetation of this region (Pojar 1993; Steen and Demarchi 1996), natural regeneration studies in other areas cannot be confidently extrapolated to this region.

A study was initiated in 1996 to investigate alternatives to clearcutting that would retain a substantial amount of terrestrial and arboreal lichens for caribou and would still be conducive to establishment and growth of pine regeneration (Armleder *et al.* 1996; Waterhouse *et al.* 2001). Preliminary evidence from a pilot trial within the study area indicated that survival and vigour of terrestrial lichens were poor when 70% or more of the stand area was harvested (Miège *et al.* 2001a). As a result, the treatments developed for this trial targeted a 33% and 50% area removal in small (0.01–0.07 ha) openings spaced throughout the blocks. Openings were harvested on a snowpack and no further site preparation was done to minimize impacts to terrestrial lichens. The opening sizes were chosen to be near the maximum size that would result in limited mortality of terrestrial lichens, based on field observations.

The objective of this study is to determine whether these small openings will be naturally restocked by lodgepole pine within 7–10 years. The study examines the effects of two biogeoclimatic subzones—Sub-Boreal Pine–Spruce very dry cold (SBPSxc) and Montane Spruce very dry very cold (MSxv) (Meidinger and Pojar [editors] 1991; Steen and Coupé 1997)—and three partial harvest treatments on natural regeneration of lodgepole pine. It was expected that biogeoclimatic subzone differences in stand structure, climate, and forest floor thickness may have significant effects on natural regeneration of pine following partial harvesting.

Study Area

The study area is a gently rising, high-elevation plateau near Satah Mountain, approximately 50 km northwest of Puntzi Lake in the western Chilcotin region of central British Columbia (52°28'N, 124°38'W). The terrain is level to gently rolling and elevations are predominantly 1250–1700 m. Within the study area, the SBPSxc subzone occurs at elevations below, and the MSxv at elevations above, 1400 m.

Climate of the SBPSxc and MSxv is very dry and cold. Mean annual precipitation within the wider geographic distribution of the SBPSxc is 413 mm and increases to 563 mm in the MSxv (Reynolds 1997). Mean annual temperature is 1.1°C in the SBPSxc, but such data are not available for the MSxv. The MSxv is colder than the SBPSxc due to higher elevations, and as indicated by microclimatic data collected on-site. Microclimate was monitored within the study area on two clearcuts within the SBPSxc and one clearcut within the MSxv from 1997 to 2003 (Sagar *et al.* 2005). Between June 1 and August 15 (76 days) during these years, frost occurred on an average of 40, 31, and 49 nights on two sites in the SBPSxc and one site in the MSxv, respectively. Accumulated degree-days above 5°C in the soil (15 cm below the surface) on the clearcuts were higher in the SBPSxc (815 and 748 degree-days) than in the MSxv (581 degree-days). Number of days per year that maximum air temperatures at 15 cm above surface reached 45°C or warmer averaged only 0.7 (SD = 2.0) on one of the clearcuts in the SBPSxc and 0.0 on each of the remaining two clearcuts (unpublished data).

Lodgepole pine forests blanket most of the study area with codominant trees that are 17–23 m tall. In the SBPSxc, lodgepole pine stands are relatively open because of dry site conditions and past mountain-pine-beetle-initiated mortality. Pine regeneration is common in the understorey, although no other tree species are usually present (Steen and Coupé 1997). In contrast, stands within the MSxv have been less affected by mountain pine beetle, are typically closed, and have little or no pine or other tree species regeneration in the understorey. In the SBPSxc, the forest floor is mostly less than 3 cm thick, but is about 3.5–6.5 cm thick in the MSxv. Undergrowth vegetation in the SBPSxc is low growing and dominated by kinnikinnick (*Arctostaphylos uva-ursi* [L.] Spreng.); pinegrass (*Calamagrostis rubescens* Buckl.); and a rich diversity of terrestrial lichens, especially species of *Cladonia* P. Browne and *Cladina* Nyl. Moss cover averaged 1–4% and lichen cover averaged 13–15% in the SBPSxc plots in this study. In the MSxv, the undergrowth is composed of a greater (30–35%) moss cover (predominantly *Pleurozium schreberi* [Brid] Mitt.), fewer lichens (5–7% cover), and little or no kinnikinnick, which is largely replaced by crowberry (*Empetrum nigrum* L.) and grouseberry (*Vaccinium scoparium* Leib.). Pine stands before logging in this study were even-aged in the MSxv and even-aged or two-aged in the SBPSxc. Tree ages in four blocks of this study ranged from 220 to 250 years. In a fifth block, trees were nearly all approximately 150 years old with the exception of a few small patches (< 2 ha) of trees older than 300 years. Many of the trees in these patches were fire scarred.

Lodgepole pine cones in the study area are considered to be predominantly serotinous; however, some are not—as indicated by young seedlings in uncut stands and by the small, but consistent, seed rain recorded in partially harvested stands in this study (see Results).

Soils throughout the study area are predominantly Orthic Dystric Brunisols developed in loamy glacial till. Dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) was common on pine trees in the SBPSxc portion of the study area but was essentially absent in the MSxv.

Methods

Study Design

The study was set up in a completely randomized split-plot design. The main-plot treatment is biogeoclimatic subzone and the split-plot treatment is harvest treatment. The study includes three replicates (harvest blocks 1, 2, and 3) of the SBPSxc and two (harvest blocks 4 and 5) of the MSxv. Each block is a minimum of 60 ha. All blocks were examined before final selection to ensure consistency of soil texture, soil moisture regime, and slope features between and within blocks. The five blocks occur on an elevational gradient from 1280 to 1300 m at block 1 to 1570–1670 m at block 5 (Daintith *et al.* 2005). One of the three SBPSxc blocks (block 3 at 1400–1440 m) lies on the boundary between the SBPSxc and the MSxv. Although key plant indicator species (Steen and Coupé 1997) place the block marginally within the MSxv, abundance of terrestrial lichens, stand structure, and forest floor thickness are more characteristic of the SBPSxc.

Silvicultural Systems and Harvesting Treatments

Irregular Group Shelterwood–Stem-only Harvesting (IGS–SO)

This treatment is an application of an irregular group shelterwood silvicultural system with a target area removal of 50% of the stand in small, roughly circular openings (i.e., 20–30 m or 1–1.5 tree lengths in diameter). The system is considered irregular because the regeneration period is extended to maintain a greater degree of stand structure that protects (i.e., shades) terrestrial lichens and facilitates re-establishment of arboreal lichens. Opening size diameters averaged 26.2 m (SD = 7.5 m), or approximately 1.3 tree heights. This treatment included stem-only harvesting, in which trees were delimbed, topped, and cut-to-length at the stump with a processor and the logs transported to the roadside by a forwarder. Slash was piled rather than spread to minimize the amount of terrestrial lichen covered by slash. In this treatment, harvesting 50% of each block's area is proposed every 70 years, so about 140 years will elapse between harvesting of the same area in each block.

Irregular Group Shelterwood–Whole-tree Harvesting (IGS–WT)

This treatment is also an irregular group shelterwood system with a targeted area removal of 50% of the stand in small, roughly circular openings. Opening size diameters averaged 22.9 m (SD = 5.6 m), or approximately 1.2 tree heights. This treatment differs from the IGS–SO treatment in that it included whole-tree rather than stem-only harvesting. Trees were harvested using a feller-buncher, grapple skidder, and roadside processor. Tops and branches were piled at the roadside and burned. Less slash was left on site, but the roadside processing affected 3–7% of the treatment unit area. Planned harvest re-entry is the same as for blocks in the IGS–SO treatment.

Group Selection–Stem-only Harvesting (GS–SO)

The third treatment is a group selection silvicultural system with a target area removal of 33% of the stand in small, roughly circular openings. Opening size diameters averaged 14.5 m (SD = 3.3 m), or about 0.7 of a tree height. This treatment included stem-only harvesting similar to the IGS–SO treatment. In this treatment, harvesting 33% of each block's area is proposed every 80 years, so about 240 years will elapse between harvesting of the same area in each block.

No-harvest Treatment

No-harvest treatment units were established on each of the five blocks, but were not included in this study dealing with restocking of harvested openings.

Harvesting began in December 1995 and was completed in April 1996. A treatment unit layout diagram is included in Daintith *et al.* (2005).

Field Methods

Seed fall from residual trees on partially harvested treatment units was measured on block 3 once each year from 1997 to 2001. Ten seed traps (0.5 × 0.5 m) were systematically located in each of the IGS–SO, GS–SO, and no-harvest treatments. Seed was removed in May of each year, then counted and cut to determine number of filled and unfilled seed.

Natural regeneration ingress density was monitored in 2-m^2 circular fixed plots established on a 50 × 50 m grid in each of the treatment units. Plot locations at each grid point were fixed by two steel pins. Approximately 50 plots were located in each of the harvested treatment units before logging, but only those plots that fell in openings were monitored for regeneration ingress. A total of 190 plots were monitored with the number of plots per block ranging from 30 to 50, and number of plots per harvest treatment ranging from 57 in the GS–SO treatment to 69 in IGS–SO treatment.

Numbers of mature lodgepole pine cones on slash, in debris, or on the ground were counted before logging and following logging in each of the plots. Tallies included total cones and number of seed cones, which consisted of all mature new (tan or brown) cones plus all old (gray) cones that were fully closed. Old open and old reclosed cones were included only in the total number.

The potential seedling substrate of each plot was described in June 1997 by estimating the percentage of the plot covered by exposed mineral soil, intact forest floor (soil humus form layers), and mixed mineral/organic materials. Mixed materials originated primarily from logging disturbance. Mean depth of the forest floor (humus form) on each plot was estimated from three systematic samples. The percentage cover of logging slash on each plot was visually estimated.

Other microsite characteristics recorded at each plot included slope gradient, slope aspect, mesoslope position and shape, microslope position and shape, ecological moisture regime, soil drainage class, soil surface texture, and percentage of the plot area covered by woody debris larger than 1 cm in diameter. Descriptions followed Luttmerding *et al.* (1990).

The total number of lodgepole pine and spruce seedlings less than 130 cm tall on the partial harvest treatments was monitored during late August to October from 1997 to 2002. Seedling densities in the fall of 1996 were estimated by recording seedling densities in the following spring (June 1997).

Numbers of pine and spruce seedlings on all blocks were recorded as less than 1 year old (current growing-season germinant) or 1 or more years old. Seedlings 1 or more years old in spring 1997 were treated as advance regeneration and subtracted from the total count in each year to conservatively estimate density of post-logging regeneration ingress.

In the fall of 2002, total height and annual height increments (leader growth) during the previous 2 years were measured on the tallest and second tallest pine ingress (i.e., post-logging) seedlings on each plot in the partial harvest treatments. Stems that were obviously advance regeneration (based on their size) were not included in the selection of the tallest stems.

Data Analyses

Analysis of variance, using the SAS Mixed Procedure (SAS Institute 1996), tested effects of subzone and harvest treatment, and their interaction on post-harvest cone density, post-logging regeneration ingress density (stems < 1 year old and stems ≥ 1 year old separately), total regeneration density (post-logging plus advance regeneration), and leader growth of lodgepole pine. Block was included as a random factor. Because data from the plots were not normally distributed due to many zero values, treatment unit means were analyzed. Tests of effects on leader growth used the mean annual leader increment during 2001 to 2002 as the dependent variable. Effects were considered significant at $\alpha = 0.05$ in all tests.

Planned contrasts for all dependent variables tested the following hypotheses:

- mean of treatment IGS–SO – mean of treatment GS–SO = 0, and
- mean of treatment IGS–SO – mean of treatment IGS–WT = 0.

The first planned contrast tests whether responses to the 50% area removal treatment, with its larger openings, differed from those of the 33% area removal treatment, when only stems are harvested. The second contrast tests whether responses to the stem-only harvesting treatment differed from those of the whole-tree harvesting treatment under the irregular group shelterwood system.

Before analyzing for biogeoclimatic and harvest treatment effects on ingress density, similarity of substrate characteristics and advance regeneration density among biogeoclimatic subzones and harvest treatments were tested by ANOVA. Multiple comparisons of Least Squares Means, using the Scheffé method (Sokal and Rohlf 1995), were used to test for significant effects.

Results

Substrate and Microsite Uniformity

Soil surface disturbance due to logging was minimal. Only one of the 190 plots had more than 5% exposed mineral soil and only two had more than 5% organic materials mixed with mineral soil. There were no significant ($\alpha = 0.05$) differences between subzones or harvest treatment units in percentage of plot area with exposed mineral soil or mixed mineral/organic materials. Soil humus layers were generally thicker on the MSxv blocks than on the SBPSxc blocks (Table 1).

Ecological microsite characteristics differed little among the 15 treatment units. Median slope gradient was less than 15% on all treatments. Mesoslope position was mid, and slope shape was straight on nearly all plots. Ecological moisture regime of nearly all plots was mesic. Soil texture was predominantly sandy loam or loam at all sites.

TABLE 1. Mean (SE) depth of undisturbed forest floor on the five partial harvest blocks

Block	Depth (cm)
SBPSxc	
1	1.9 (0.1)
2	2.3 (0.2)
3	3.1 (0.2)
MSxv	
4	6.1 (0.5)
5	4.0 (0.4)

TABLE 2. Mean (SE) post-logging density of new and old closed lodgepole pine cones (cones per square metre)

	Treatment		
Block no.	IGS–SO	IGS–WT	GS–SO
SBPSxc			
1	1.47 (0.62)	0.16 (0.09)	1.31 (0.62)
2	1.55 (0.71)	2.00 (0.87)	0.65 (0.33)
3	0.77 (0.26)	0.88 (0.54)	1.42 (0.58)
MSxv			
4	1.57 (0.93)	0.69 (0.28)	0.40 (0.21)
5	1.04 (0.35)	1.41 (0.39)	0.96 (0.49)

Most (82–86%) plots had 5% or less cover of woody debris. Of the remaining plots, most had 15% or less cover. As would be expected, the IGS–WT treatment had a lower percentage of plots with 75% or greater cover of logging slash (mean, 4.4%; SD, 9.9) than did the stem-only treatments (mean, 12.1%; SD, 15.3). However, differences are not statistically significant (t-test p-value = 0.265) because of the high variability among treatment units.

Cones and Seed Fall

The mean density of potential seed cones by subzone and harvest treatment following logging is presented in Table 2. There were no significant subzone ($F = 0.16$; df = 1, 9; $p = 0.70$), harvest treatment ($F = 0.54$; df = 2, 9; $p = 0.60$), or subzone × harvest treatment interaction ($F = 0.28$; df = 2, 9; $p = 0.76$) effects on the mean density of seed cones.

Mean numbers of filled seeds and total seeds in the seed fall traps on an unlogged area and the IGS–SO and GS–SO treatments on site 3 are presented in Table 3. Differences in seedfall between the unlogged area and the two partial harvest treatments were small. Data show a light but consistent seedfall from year to year.

Post-logging Advance Regeneration

Advance regeneration includes all pine stems of 1 year old or older, but less than 130 cm tall that were present in the first year after logging. Although mean density was much greater in the SBPSxc (l.s. mean = 6510 stems per hectare; SE = 1196) than in the MSxv (l.s. mean = 818 stems per hectare; SE = 1464), differences were not statistically significant ($F = 9.07$; df = 1, 3; $p = 0.057$) because of the high variability among treatment units. There were also no significant differences between harvest treatments ($F = 2.52$; df = 2, 6; $p = 0.161$).

Regeneration Ingress

Mean densities of established (≥ 1 year old) lodgepole pine post-logging regeneration tended to increase slowly throughout the study period in the MSxv, but to stabilize or decrease slightly after 5 years in the SBPSxc (Table 4). Density differences between the SBPSxc and the MSxv were apparent by the second growing season following logging (1997) (Table 4). By the seventh year after logging (2002), mean densities on the SBPSxc blocks were more than three times those on MSxv blocks. Subzone had a significant ($\alpha = 0.05$) effect on ingress density in years 6 and 7 (Table 4).

TABLE 3. Mean density of total (T) and filled (F) lodgepole pine seeds (seeds per square metre) from seed rain in May on block 3 over 5 years

	1996–1997		1997–1998		1998–1999		1999–2000		2000–2001	
Treatment	T	F	T	F	T	F	T	F	T	F
Unlogged	5.6	2.0	20.4	15.1	3.6	2.2	10.4	6.2	15.0	8.4
IGS–SO	4.9	3.6	11.6	7.2	7.6	5.2	8.0	4.8	10.0	8.0
GS–SO	3.2	0.4	9.2	6.4	6.8	3.4	12.4	7.4	4.0	4.0

TABLE 4. Mean (SE) density of post-logging pine seedlings of 1 year old or older (seedlings per hectare) on partial harvest blocks by biogeoclimatic subzone and harvest treatment for each year of assessment. Values are means of raw plot data.

		Year					
	n	2 (1997)	3 (1998)	4 (1999)	5 (2000)	6 (2001)	7 (2002)
SUBZONE							
MSxv	75	800 (233)	813 (273)	1098 (301)	1173 (282)	1456 (314)	1829 (363)
SBPSxc	115	3217 (1009)	3770 (982)	4922 (1000)	5920 (1315)	5547 (1105)	5898 (1057)
Subzone effect ANOVA statistics:							
F		5.90	9.47	8.51	9.45	11.17	17.71
df		1, 3	1, 3	1, 3	1, 3	1, 3	1, 3
p		0.09	0.05	0.06	0.05	0.04	0.02
HARVEST TREATMENTS							
IGS–SO	69	1884 (594)	1875 (550)	3313 (1006)	4051 (1458)	3734 (960)	3688 (705)
IGS–WT	64	3359 (1678)	4194 (1822)	4766 (1512)	5794 (1849)	5726 (1875)	5859 (1865)
GS–SO	57	1491 (500)	2031 (586)	2273 (640)	2344 (630)	2652 (685)	3561 (762)
Harvest treatment effect ANOVA statistics:							
F		0.73	0.56	1.72	0.86	1.14	0.44
df		2, 6	2, 6	2, 6	2, 6	2, 6	2, 6
p		0.52	0.61	0.26	0.47	0.38	0.67

In contrast, harvest treatments had no significant effect on density of established ($\geq$ 1 year old) regeneration ingress seedlings in any year of assessment (Table 4). Density of seedlings tended to be greater in treatment IGS–WT than either of the other treatments in all years, but contrast analyses (mean of IGS–SO – mean of IGS–WT) showed no significant difference between the stem-only and whole-tree logging treatments in any year (*p*-values of contrast analysis = 0.29, 0.27, 0.21, 0.42, 0.25, 0.27 for 1997–2002, respectively). Subzone × harvest treatment interaction effects on ingress density were not significant ($\alpha = 0.05$) in any year (e.g., $F = 0.46$, df = 2, 6; $p = 0.65$ for 2002 densities).

Pine germinants (seedlings < 1 year old) were present on all partially harvested blocks except in the first (1996) and last (2002) assessment years. Although germinants tended to be more abundant on the SBPSxc blocks than on those in the MSxv, subzone had no statistically significant effect in any year (Table 5). There were also no significant treatment effects in any year (Table 5). Germinant densities tended to be greatest in 1998 and 1999.

The percentage of 2-m^2 sample plots (all treatments combined) that contained at least one post-logging seedling of 1 year old or older in 2002 was 30.7% and 52.2% in the MSxv and SBPSxc, respectively. Percentages by harvest treatment ranged from 42.1% on openings in the GS–SO treatment to 43.8% in the IGS–SO treatment and 44.9% in the IGS–WT treatment.

Advance regeneration contributed substantially to total regeneration density in the SBPSxc and increased the regeneration density difference between the SBPSxc and MSxv (Table 6). Biogeoclimatic subzone had a significant effect on total regeneration density in year 7 (2002) ($F = 24.99$; df = 1, 3; $p = 0.015$). However, harvest treatment had no significant effect on total density ($F = 1.31$; df = 2, 6; $p = 0.337$). The percentage of 2-m^2 plots containing at least one seedling 1 year old or older that was either advance or post-logging was 33.3% and 67.0% in the MSxv and SBPSxc, respectively. Percentages by harvest treatment ranged from 50.9% in the GS–SO to 53.6% in the IGS–SO and 56.3% in the IGS–WT.

Mean annual height growth of the tallest post-logging lodgepole pine stem in each plot during 2001–2002 is presented in Table 7 by subzone and harvest treatment. There were no significant subzone, harvest treatment, or subzone × harvest treatment interaction effects on 2001–2002 height growth of pine (Table 7).

TABLE 5. Mean (SE) density of post-logging pine germinants less than 1 year old (seedlings per hectare) on partial harvest blocks by biogeoclimatic subzone and harvest treatment for each year of assessment. Values are means of raw plot data.

		Year					
	n	**1 (1996)**	**2 (1997)**	**3 (1998)**	**4 (1999)**	**5 (2000)**	**6 (2001)**
SUBZONE							
MSxv	75	67 (67)	400 (247)	500 (229)	671 (242)	617 (283)	127 (89)
SBPSxc	115	0 (0)	261 (136)	1825 (483)	1992 (539)	1560 (366)	1641 (351)
Subzone effect ANOVA statistics:							
F		1.80	0.16	2.33	3.16	7.32	6.24
df		1, 3	1, 3	1, 3	1, 3	1, 3	1, 3
p		0.27	0.72	0.22	0.17	0.07	0.09
HARVEST TREATMENTS							
IGS–SO	69	73 (73)	507 (295)	2000 (715)	1625 (732)	1203 (405)	1139 (371)
IGS–WT	64	0 (0)	156 (110)	1532 (424)	1641 (473)	1429 (511)	806 (329)
GS–SO	57	0 (0)	263 (195)	234 (133)	1136 (455)	938 (384)	1212 (459)
Harvest treatment effect ANOVA statistics:							
F		1.80	1.48	2.48	0.20	0.06	0.33
df		2, 6	2, 6	2, 6	2, 6	2, 6	2, 6
p		0.24	0.30	0.16	0.82	0.94	0.73

TABLE 6. Mean (SE) density of total pine seedlings (advance plus post-logging) 1 year or older (seedlings per hectare) by biogeoclimatic subzone and harvest treatment in 2002. Values are means of raw plot data.

	Stems per hectare
SUBZONE	
MSxv	2 563 (526)
SBPSxc	10 433 (1476)
Subzone effect ANOVA statistics:	
F	29.5
df	1, 3
p	0.01
HARVEST TREATMENTS	
IGS–SO	5 897 (1157)
IGS–WT	10 313 (2263)
GS–SO	6 308 (1563)
Harvest treatment effect ANOVA statistics:	
F	1.7
df	2, 6
p	0.25

TABLE 7. Mean (SE) annual height growth (cm), during 2000–2001, of tallest post-logging pine stem in each plot by biogeoclimatic subzone and harvest treatment. Values are means of raw data.

	Height growth (cm)
SUBZONE	
MSxv	3.19 (0.53)
SBPSxc	3.62 (0.49)
Subzone effect ANOVA statistics:	
F	0.03
df	1, 9
p	0.86
HARVEST TREATMENTS	
IGS–SO	4.08 (0.72)
IGS–WT	3.34 (0.55)
GS–SO	2.98 (0.73)
Harvest treatment effect ANOVA statistics:	
F	0.67
df	2, 9
p	0.53

Discussion and Management Implications

By year 7, the small openings on the three SBPSxc blocks contained, on average, 5898 stems per hectare of naturally established post-logging pine that was 1 year old or older. Advance regeneration raised density to 10 433 stems per hectare. In the SBPSxc blocks, 52% of the 2-m^2 plots contained a post-logging pine seedling of 1 year old or older and 67% contained either a post-logging or advance regeneration stem. For comparison, a normal 2 × 2 m grid planting would be expected to result in 2500 stems per hectare and 50% of 2-m^2 plots with a planted seedling. Natural regeneration can apparently restock openings as small as 0.7 tree lengths in diameter in the SBPSxc. At higher elevations in the MSxv, however, the mean density of post-logging regeneration was only 1829 stems per hectare and the percentage of 2-m^2 plots with a post-logging seedling of 1 year old or older was only 31%, or about half of that in the SBPSxc.

The low density and stocking of pine seedlings on the two MSxv blocks compared with the SBPSxc blocks are probably due, in part, to seedbed differences. Seedling establishment is known to be generally poor on duff layers more than 2–3 cm thick, if those duff layers become dry during the growing season (Lotan and Perry 1983). The root system of first-year lodgepole pine seedlings develops slowly and is relatively weak (Lotan and Perry 1983). If the root system does not reach mineral soil before the forest floor becomes dry, the seedlings will likely die. On both MSxv blocks, thickness of the forest floor (humus form) layer averaged 4.0 cm or more; on the SBPSxc blocks, average thicknesses were all 3.1 cm or less.

Scarification of seedbeds to expose mineral soil and to mix mineral and organic material can significantly increase regeneration establishment (Lotan 1975; Thompson 1978; Reid, Collins Nurseries 1983; British Columbia Ministry of Forests 1996). Thompson (1978) concluded that approximately 60% mineral soil seedbed was required in southeastern British Columbia to obtain 50% stocking in milacre (0.001 acre, 4.048 m^2) plots within 4 years, given adequate cone supply and fresh logging slash. Scarification is generally considered most important on winter-logged sites (Clark 1974; Glen 1979). Although scarification may increase density and stocking of pine seedlings, especially in the MSxv, scarification would also negatively affect the terrestrial lichens on which caribou depend for winter food.

Other factors that may have reduced regeneration success on the two high-elevation MSxv blocks include growing season frost and low growing season temperatures. Growing season frosts are very frequent in both the MSxv and the SBPSxc (Steen *et al.* 1990; Sagar *et al.* 2005). However, frequencies of measured growing season frosts on the partially harvested sites of this study were similar in the MSxv and the SBPSxc (Sagar *et al.* 2005). Frost damage of planted pine was low (3–5%) across all treatments and sites (Daintith *et al.* 2005). Growing season frost was unlikely a major factor contributing to regeneration density differences.

Low growing season temperatures have been noted to reduce germination and establishment of pine seedlings (Lotan and Perry 1983). Air and soil growing season temperatures are generally lower in the MSxv than in the SBPSxc (Steen and Coupé 1997; Waterhouse *et al.* 2001) and soils in the small openings are cooler than the soils on the adjacent clearcuts (Sagar *et al.* 2005). Post-logging density and stocking of pine seedlings are consistent with these temperature patterns, suggesting that low temperatures may have contributed to the reduced regeneration success in small openings on the MSxv sites. However, this study cannot separate the relative roles of seedbed and growing season temperatures on seedling establishment. The absence of significant differences in measured height growth of natural regeneration among the five blocks suggests that the range of temperature regimes in this study does not strongly affect seedling height growth at this early age.

The three harvesting treatments, with their differences in opening size and slash treatment, had no statistically significant ($\alpha = 0.05$) effect on density of pine natural regeneration. However, the IGS–WT treatment tended to have the greatest density of seedlings in all years. In an assessment of the amount of pine seed contained in cones on study blocks 1, 3, and 5, the total amount of seed was highest on the stem-only logging treatment (Daintith n.d.). However, most of the seed in stem-only logging treatments was in piled slash. The amount of seed in cones on the ground was greater in the whole-tree logging treatment (2.8 million seeds per hectare vs. 0.9 million seeds per hectare in stem-only logging treatment). Consistent with previous studies, cones on the ground released a higher percentage of their seed than did cones elevated in slash. The whole-tree logging treatment also tended to have the smallest percentage of plots with very high cover of logging slash, which can reduce seedling establishment.

Although natural regeneration density on the partially harvested blocks cannot be statistically tested for similarity to regeneration on a clearcut, data for anecdotal comparisons are available from separate studies that examined natural regeneration densities on three clearcut blocks adjacent to the partially harvested blocks of this study (unpublished data) and one block in the MSxv and two in the SBPSxc elsewhere in the region (Steen and Coupé 2002). The six clearcut blocks are all on sites similar to the partially harvested sites and, with one exception, were winter-logged. For the one MSxv clearcut block logged in summer, comparisons can be made by using only regeneration data from plots with less than 15% logging disturbance. Only regeneration data from clearcut areas that were not scarified subsequent to logging were compared. We caution that the clearcut blocks were logged in different years than the partially harvested blocks of this study and that annual precipitation and temperature differences may partially affect differences in regeneration densities between blocks.

On the four clearcuts in the SBPSxc, density of pine natural regeneration (advance plus post-logging) 5–7 years after logging ranged from 6000 to 34 000 stems per hectare with an overall mean density of nearly 20 000 stems per hectare. Percentage of 2-m^2 plots on the clearcuts with one or more seedlings at least 1 year old ranged from 33 to 80%, with an overall mean of 62%. These density values are slightly higher than the densities recorded on the partially harvested blocks in the SBPSxc, but the percentage of plots with at least one seedling more than 1 year old spans the range of percentages on the partially harvested blocks. This suggests that pine natural regeneration density by year 7 in the small openings of the partially harvested blocks in the SBPSxc is generally similar to density that might be expected on a clearcut. However, most natural regeneration on the clearcuts was established in the first 3–4 years following logging and is thus older and more likely to survive than some of the regeneration on the partially harvested blocks that was established 5–7 years after logging. Conversely, new seedlings will likely continue to become established in the partially harvested blocks due to continued seed rain from adjacent standing trees.

In contrast to the SBPSxc, natural regeneration on the partially harvested blocks in the MSxv was much lower than previously recorded on clearcut blocks in the MSxv. On two MSxv clearcut blocks, densities of pine natural regeneration 5–7 years after logging were about 6000 and 23 500 stems per hectare and percentages of 2-m^2 plots with at least one seedling of 1 year old or older were 42% and 67%. On the partially harvested blocks, year 7 average densities and percentage of plots with a seedling 1 year old or older were both lower than the lowest values recorded on the clearcut blocks. On the partially harvested blocks, however, continued seed rain may reduce the regeneration density differences.

The lack of treatment effects on height growth of naturally established pine is consistent with the lack of treatment effects on height growth of planted pine in the same treatment units (Daintith *et al*. 2005). After 5 years, mean annual height growth of planted pine (5.0–5.6 cm/yr) was greater than the mean annual height growth of natural regeneration stems (generally 3–4 cm/yr) measured in this study, although these differences cannot be statistically compared. Basal diameter of natural regeneration was not recorded in this study.

The results of this study have implications for the Northern Caribou Strategy (Youds *et al*. 2002), which was developed to guide implementation of portions of the Cariboo-Chilcotin Land Use Plan (Province of British Columbia 1995). The strategy identified nearly 182 000 ha of caribou habitat that is to be managed primarily by silvicultural systems employing partial harvesting. Recommended systems are irregular group shelterwood to conserve terrestrial lichens, and group selection where heavy loads of arboreal lichens are present. Natural regeneration appears to be an appropriate option for restocking small group selection and group shelterwood openings in the SBPSxc. However, most of the identified area is within the MSxv biogeoclimatic subzone where relatively thick forest floor layers and a more closed forest canopy adjacent to the small openings appear to limit natural regeneration. Disturbance of forest floor layers to enhance natural regeneration is not an option since it would destroy terrestrial lichens that are critical for northern caribou. To meet current stocking and free-growing standards that were developed for "normal" silvicultural systems (even-aged using clearcutting), planting would probably be necessary to restock small openings in the MSxv.

The extended harvest rotation periods recommended for pine stands within the caribou management area may provide sufficient time for natural regeneration to adequately restock small openings even in the MSxv subzone. The normal harvest rotation of 80 years for lodgepole pine stands is extended by 60 and 160 years for the irregular group shelterwood system (140-year rotation) and the group selection system (240-year rotation), respectively (Youds *et al.* 2002). Therefore, even if natural regeneration requires much longer than 7 years to fully restock the small openings, the openings may still support mature (> 80 years) trees by the next harvest entry. No data are currently available to confidently estimate the length of time required for natural regeneration to fully restock small openings in the MSxv subzone.

Because of the extended periods between harvest, post-logging lodgepole pine stems in the SBPSxc may experience significant growth reductions due to dwarf mistletoe infection. In the group shelterwood system, post-logging stems would not be harvested for 140 or more years; in the group selection system, post-logging stems would not be harvested for 240 or more years. Although no infection of post-logging stems was noted in this study, its presence on residual trees in the SBPSxc suggests that infection will increase as the post-logging stands develop. Height and diameter reductions due to dwarf mistletoe can be severe—about 0.7%/yr in young stands if infection is heavy (Hawksworth and Hinds 1964; Hawksworth and Dooling 1984). In the MSxv subzone, dwarf mistletoe is much less common than in the SBPSxc subzone and growth losses due to infection of post-logging stems are expected to be very small.

The extended periods between harvest also increase the likelihood of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) initiated mortality of residual mature trees, due to the increased susceptibility of large diameter, old trees to attack (Safranyik and Carroll 2006), especially in the SBPSxc. However, most of the forests recommended for partial harvest are within the MSxv (Youds *et al.* 2002), where trees killed as a result of mountain pine beetle attack are much less common than at lower elevations, due apparently to the colder climate. Lodgepole pine trees more than 350 years old have frequently been noted in the MSxv.

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The three harvesting treatments, with their differences in opening size and slash treatment, had no statistically significant effect on density of pine natural regeneration.

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Test Your Knowledge . . .

Natural regeneration of lodgepole pine following partial harvesting on northern caribou winter range in west-central British Columbia

How well can you recall some of the main messages in the preceding Research Report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. By the seventh year after partial harvesting, what was the average percent of 2-m^2 plots on the SBPSxc and MSxv blocks, respectively, that contained a post-logging pine seedling of 1 year old or older?
   A) 71 and 62
   B) 31 and 62
   C) 52 and 31

2. Differences in post-logging regeneration between the SBPSxc and MSxv blocks were probably due primarily to what factor?
   A) Growing season frost
   B) Forest floor (duff) thickness
   C) Seed supply

3. Which harvesting treatment had the greatest number of seed cones on the ground?
   A) Irregular group shelterwood–whole tree harvesting
   B) Irregular group shelterwood–stem only harvesting
   C) Group selection–stem only harvesting

ANSWERS

1. C 2. B 3. A