An alternative to clear-cutting in the boreal forest of Alaska: a 27-year study of regeneration after shelterwood harvesting

T.L. Wurtz and J.C. Zasada

Abstract: We present 27-year results from a comparison of clear-cutting and shelterwood harvesting in the boreal forest of Alaska. Three patch clear-cut and three shelterwood units were harvested in 1972; about 100 dispersed white spruce (*Picea glauca* (Moench) Voss) leave trees per hectare were retained in the shelterwoods. Units were mechanically scarified and an exceptionally large seed-crop was dispersed that year. Shelterwood trees were removed after 15 years. After 27 years, overstory treatment had no effect on the density or growth of the species we studied, while scarification had highly significant effects. In 1999, scarified areas were densely populated with white spruce seedlings and saplings (118 000 – 129 000 stems/ha, with spruce in 100% of plots). Unscarified areas had far fewer spruce stems but were nevertheless well stocked (11 000 –15 000 stems/ha, with 87% frequency). Initially, spruce grew best on scarified surfaces, but by 27 years, growth of the tallest spruce saplings was significantly greater on unscarified than scarified surfaces. By 27 years, cover of the grass *Calamagrostis canadensis* (Michx.) Nutt. had returned to preharvest levels in all treatment types. Because criteria for evaluating forest management practices have changed since this study was begun, partial overstory retention systems for the management of Alaska's boreal forest deserve further study.

Résumé : Cet article présente les résultats d'une comparaison entre la coupe à blanc et la coupe progressive basée sur 27 années d'étude dans la forêt boréale de l'Alaska. Trois aires de coupe à blanc et trois unités de coupe progressive ont été récoltées en 1972; environ 100 épinettes blanches (*Picea glauca* (Moench) Voss) résiduelles à l'hectare et dispersées dans les zones de coupe progressive ont été conservées. Les parterres de coupe ont été scarifiés mécaniquement et une quantité exceptionnelle de graines ont été produites et dispersées cette année-là. Les arbres résiduels ont été enlevés après 15 ans dans les zones de coupe progressive. Après 27 ans, le traitement de l'étage dominant n'avait eu aucun effet sur la densité ou la croissance des espèces étudiées, tandis que la scarification a eu des effets très significatifs. En 1999, les zones scarifiées étaient densément peuplées avec des semis et des gaules d'épinette blanche (118 000 – 129 000 tiges/ha, avec de l'épinette blanche dans 100% des parcelles. Les zones non scarifiées avaient beaucoup moins de tiges d'épinette, mais elles avaient néanmoins une bonne densité relative (11 000 – 15 000 tiges/ha, avec une fréquence de 87%). Au début, l'épinette a eu une meilleure croissance sur les surfaces scarifiées mais, à 27 ans, la croissance des gaules d'épinette les plus hautes était significativement plus forte sur les surfaces non scarifiées que scarifiées. Après 27 ans, la couverture herbacée par le *Calamagrostis canadensis* (Michx.) Nutt. était revenue aux niveaux d'avant la récolte dans tous les types de traitements. Étant donné que les critères pour évaluer les pratiques d'aménagement forestier ont changé depuis le début de cette étude, les systèmes qui consistent à conserver une partie de l'étage dominant pour l'aménagement de la forêt boréale de l'Alaska méritent d'être étudiés davantage.

[Traduit par la Rédaction]

Introduction

White spruce (*Picea glauca* (Moench) Voss) is a principal species in the boreal forests of North America. Though white spruce is the main commercial species in interior Alaska, little attention had been given to its regeneration after harvesting before this study was begun in 1971. It was assumed that harvesting resulted in conditions similar to those produced by natural disturbance and that a new stand would develop naturally. Yet achieving natural regeneration of white spruce in Alaska and boreal Canada after clear-cutting proved to be difficult (Lees 1964; Steill 1976; Greene et al. 1999). Regeneration was rarely adequate to produce well-stocked stands.

Several characteristics of white spruce make it difficult to regenerate naturally. Two that are critical on upland sites in interior Alaska are seed availability and seedbed condition. Seed production is episodic; significant seed crops can be separated by as much as 12 years (Waldron 1965; Zasada and Viereck 1970; Rupp 1998). White spruce seeds do not survive in the soil and there is no persistent, on-site seed supply as is present in the semi-serotinous cones of black

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Table 1. Stand characteristics for white spruce and birch at Bonanza Creek Experimental Forest study site.

	White spruce		Birch
	Original	Residual	Original
Density (trees/ha)			
Shelterwood	400	98	37
Patch clearcut	402	—	42
Basal area ($m^2 \cdot ha^{-1}$)			
Shelterwood	31	9	1.9
Patch clearcut	35	—	2.4
DBH (cm)[a]			
Shelterwood	31±1	34±2	21±2
Patch clearcut	30±1	—	18±3
Volume[b]			
Shelterwood	15 700	4430	134
Patch clearcut	17 350	—	263

[a] Data are expressed as mean ± SE.

[b] Scribner decimal C log rule. In board feet per acre for white spruce and in cubic feet per acre for birch (1 board foot = 1 × 12 × 12 = 144 in^3, 1 cubic foot = 28 327 cm^3, and 1 acre = 0.404 685 6 ha).

spruce (*Picea mariana* (Mill.) BSP). Seed dispersal is usually limited to within 50 m of the seed source (Dobbs 1972; Youngblood and Max 1991).

Though white spruce can germinate on a variety of substrates, it does best on mineral soil seedbeds (Zasada and Gregory 1969; Ganns 1977; Greene et al. 1999). The main natural disturbance of upland sites, wildfire, creates a mosaic of seedbed conditions depending on its severity, the substrate type, and shading by living and dead plant materials (Zasada et al. 1983; Cater and Chapin 2000). These substrates interact with local climatic conditions to present a range of probabilities for germination and seedling establishment. In managed forests, various harvesting and site preparation methods can be used to create a similar mosaic of seedbed conditions, with a goal of increasing the probability of germination and establishment.

The typically poor natural regeneration of white spruce following clear-cut harvesting was the original driving force behind this study. One of us (Zasada) predicted that leaving dominant trees regularly dispersed throughout the cutting unit would help overcome the problem of seed availability. Mechanical scarification could be used to distribute mineral soil seedbeds regularly and at the optimal time. Both our study design and data collection thus focused primarily on following the germination, survival, and growth of a cohort of white spruce germinants in the years after harvest, along with the development of common trees, shrubs, and herbs associated with white spruce.

Methods

Study site

This research was conducted on the Yukon-Tanana Uplands, about 30 km southwest of Fairbanks, Alaska (latitude 64°51′N, longitude 148°44′W) in the Bonanza Creek Experimental Forest. Terrain is a gentle southwest-facing slope (5–25% gradients) ranging from 215 to 260 m in elevation. Bedrock is strongly weathered Precambrian quartz-mica and quartzite schist, overlain with deposits of micaceous loess 2–3 m or more in depth. The depth of forest floor (excluding the live moss layer) averaged 18 cm. Within the range of forest sites in interior Alaska, this type of site is considered productive (Van Cleve and Viereck 1981). The soil is well drained; permafrost does not occur in the study area.

The climate of the study area is strongly continental, with extreme winter temperatures to –50°C. Maximum temperatures during the growing season (85–100 days) range between 18 and 35°C. Annual growing degree-days range from 970 to 1230. Annual precipitation averages 280 mm, about 30% of which falls as snow (Van Cleve et al. 1986). August is generally the wettest month, with rainfall averaging about 60 mm.

The dominant plant community type was *Picea glauca – Viburnum edule* (Michx.) Raf. – *Equisetum arvense* L. – *Hylocomium splendens* (Hedw.) B.S.G. as described by Foote (1983). Before harvesting, the stand had a density of 400 trees/ha and basal area for white spruce varied from 31 to 35 $m^2 \cdot ha^{-1}$ (Table 1). White spruce made up about 90% of the overstory and averaged about 31-cm dbh; the maximum diameter was 60 cm. The tallest white spruce tree was 36.6 m. Site index (base, 100 years at breast height) was 26 m (Farr 1967). A modest number of paper birch (*Betula papyrifera* Marsh) (Table 1), and a few aspen (*Populus tremuloides* (Michx.) and balsam poplar (*Populus balsamifera* L.) were also present. Overstory white spruce ranged in age from 150 to 180 years (at breast height) and we presume that it established following a fire. Evidence of more recent stand disturbance was noted, including selective cutting from the 1920's, and stem breakage from snow loading that occurred primarily in 1968 (Van Cleve and Zasada 1970). Before the units were harvested, a grid of 50 temporary sampling points was established in each designated cutting unit. At each point, woody stems were counted and the percent cover of herbaceous species estimated. A relatively sparse understory stratum consisted of 160–270 stems/ha of white spruce, and lesser amounts of paper birch, aspen, and balsam poplar. Common understory species in a low shrub layer included *Viburnum edule*, *Rosa acicularis* Lindl., and *Linnaea borealis* L. Green alder (*Alnus crispa* (Ait.) Pursh.) and lowbush cranberry (*Vaccinium vitis-idaea* L.) were also present. The herbaceous layer consisted of *Equisetum arvense*, *Pyrola* spp., *Geocaulon lividum* (Richards) Fern, fireweed (*Epilobium angustifolium* L.), and *Calamagrostis canadensis* (Michx.) Beauv. The forest floor was covered by a thick layer of mosses comprised of *Hylocomium splendens*, *Pleurozium schreberii* (Brid.) Mitt., and *Dicranum* spp. Common lichen genera included *Parmelia*, *Cladonia*, and *Peltigera*.

Silvicultural treatments

Six small study units were logged during the summer of 1972: three 2.3-ha shelterwood units and three 1.3-ha patch clear-cut units. Thirty-meter-wide leave strips separated the patch clear-cut units from one another and from the shelterwoods. Shelterwood leave trees were selected from dominant and codominant strata, resulting in about 100 regularly distributed trees/ha at 9- to 12-m spacing and a residual basal area of 9.2 $m^2 \cdot ha^{-1}$. Whole-tree harvesting was used to minimize fuel loading and site preparation costs; all trees ≥5 cm in diameter were felled in all units except the shelterwood leave trees. Immediately following harvesting in late September 1972, the site was scarified. A small crawler tractor scarified patches measuring about 1.8 m wide (the width of the blade) and 1.8–3 m long. Damage to shelterwood leave trees was assessed after site preparation was complete. We defined significant damage as (1) severed roots >5 cm in diameter, (2) scars on the bole totaling >900 cm^2, or (3) top broken, extensive loss of branches from 75% or more of one face. Leave trees were felled and removed in 1987 (15 years after the initial harvest). To minimize logging damage to the young trees, the shelterwood removal operation was conducted so that it coincided with maximum annual snowpack. The growth of the shelterwood leave trees and the effects of shelterwood removal on seedling survival were described by Youngblood (1990, 1991).

Measurements of seed production and solar radiation

Following site preparation, seed traps were placed in two of the patch clear-cut and two of the shelterwood units (Sarvås 1957). Our measurements probably underestimated the total seed rain for 1972, however. Site preparation was not completed until about 2–4 weeks after the mature trees at our site had begun to release seed, and thus removed a portion of the seed rain from scarified surfaces. All traps were emptied 2 or 3 times annually through 1976. Broad band irradiation was measured with Belfort pyranometers in each harvested unit and in three locations in an adjacent uncut stand from 1973 to 1975.

White spruce germinant appearance and early survival

Because we expected few seedlings to become established on unscarified surfaces (Zasada and Gregory 1969; Dobbs 1972), we examined the dynamics of white spruce germination and very early establishment on scarified surfaces only. First-year germination, and first- and second-year seedling survival were followed in six scarified patches in each cutting unit. During the first year, observations were made daily from snowmelt until the first seedlings appeared, then weekly until August 1. Additional seedling counts were made on August 15 and September 9. Colored plastic toothpicks were used to label seedlings by germination cohort. Many of the toothpicks frost-heaved over the winter, so first-winter and second-growing-season survival could not be linked to germination cohort. During the second growing season, seedlings were counted once after snowmelt and again at the end of the growing season. In 1999, we aged 25 spruce stems growing on unscarified surfaces, to determine their year of origin.

Seedling density and growth and long-term development of other vegetation

After harvesting and site preparation, 20 permanent 1-m^2 plots were established on scarified surfaces in all six units. Another permanent 1-m^2 plot was established on an unscarified surface nearby; locations were chosen so as to avoid any young spruce that might have survived the harvesting operation. These 240 permanent sampling locations were visited 1, 2, 3, 4, 5, 13, and 27 years after logging, with 27-year measurements made in 1999. After the first few years, these plots were no longer large enough to adequately sample the trees and tall shrubs. Plots were thus increased to 4 m^2 in size at 13 years and to 16 m^2 in size for the 27-year measurements. Data were collected on soil surface condition, cover of mosses and vascular plant species, and density, height, and diameter of trees and tall shrubs.

In each sampling year, the height and diameter of the tallest individuals of each tree species were measured in each plot. The number measured varied by sampling year, as did the location at which we measured diameter. Early on, diameters were measured at the groundline. But after trees had reached at least 1.4 m in height, diameters were measured at that level.

Data analysis

Means were computed for stem density, percent cover, and growth measurements for all years, along with frequencies of occurrence for each species. Because the distribution of some species was extremely patchy, we wanted mean density and percent cover values to reflect conditions when that species was present. Thus, zero values were excluded from the calculation of mean density and cover; these values should be evaluated in concert with frequency data. Because we increased the size of our sampling plots at 13 and 27 years, differences in frequency between treatments after 1977 should be considered within-years only. To have a standard unit of measure, all density data are presented per hectare. The 27-year density data only were subjected to a split-plot ANOVA with overstory treatment (clearcut and shelterwood cut) at the whole-plot level and site preparation at the subplot level. Though some types of data were collected in nearby uncut forest (e.g., seedfall, solar radiation), these variables were not analyzed statistically.

Results

Residual overstory

About half of the shelterwood leave trees were damaged during logging and site preparation. Most of this damage was minor, however, with only 1% of the leave trees sustaining significant damage. During the first growing season after harvest, 7.5% of the residual trees died but remained standing. We attribute this to various factors associated with the sudden increase in exposure to sunlight, to logging damage, and to insect attack. Additional mortality occurred in 1975 during a severe summer windstorm, when about 20% of the original residual trees were uprooted. Trees that survived both the initial exposure and the windstorm exhibited increased radial growth. Youngblood (1991) determined that by the time they were removed in 1987, the standing basal area in the shelterwood units was similar to what it had been immediately after harvest, and net mean increase in radial growth 8 years after harvesting was 164%. By 1999, no signs of disturbance from the removal of the overstory in 1987 were apparent in our sampling plots.

Public reaction to the appearance of the shelterwood units was generally favorable, with some people commenting that they looked “like a park.” Aerial photos taken shortly after the initial harvest indicated that the shelterwood units were far less visible from low altitudes than the patch clearcuts. Removal of the leave trees in 1987 substantially increased the visibility of those units from the air.

Effects of treatments on seedbed conditions

Before harvesting, there was no exposed mineral soil on the forest floor. The forest floor consisted of living moss and undecomposed organic matter averaging 18 cm in depth (range, 10–30 cm). Downed logs in various stages of decomposition were common, contributing about 30% of cover. Following harvesting but before scarification, 75% of the forest floor of both patch clearcuts and shelterwoods was undisturbed or only slightly disturbed, with no apparent mixing of the mineral and organic layers. Twenty percent of the area was disturbed with some mixing of the mineral soil and organic layers, but no exposed mineral soil. The remaining 5% of the forest floor had exposed mineral soil; this occurred primarily along skid trails. The site preparation used in this study was effective in exposing mineral soil. Within scarified plots, from 70 to 85% of the soil surface was mineral soil. The area of exposed mineral soil declined rapidly in the first 3 years after scarification.

In the first three growing seasons after harvesting, the shelterwoods received an average (± standard error, SE) of 66 ± 2.4% as much direct beam solar radiation as the patch clearcuts, while an adjacent uncut stand received an average of 22.6 ± 0.8% as much.

Table 2. Percent of the first-year white spruce seedling population contributed by seedlings germinating at different times during the growing season.

	Before May 10	May 17–30	May 31 to June 13	June 14–26	June 27 to July 10	After July 10	Total germinants/survivors
Patch clearcut	5.5	42.0	36.7	11.7	3.2	0.9	3264/2415
Shelterwood	0	26.8	48.4	18.8	3.0	3.0	4542/3525

Note: There were no germinants between May 10 and 17. Data are for scarified surfaces only.

Seed production

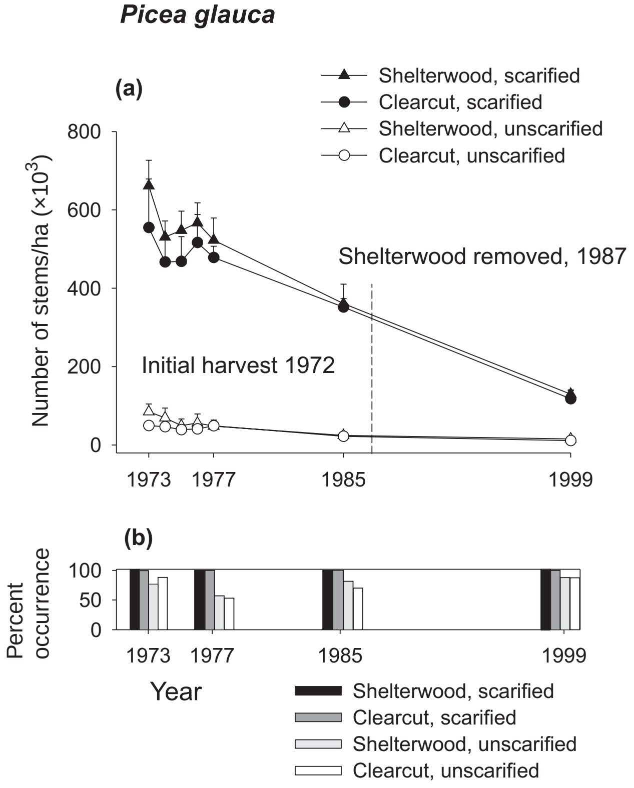
The 1972 white spruce seed crop was very large. We measured an average seed rain of 579 seeds/m^2 in clearcuts and 436 seeds/m^2 in the shelterwoods. About 68% of the seeds were filled, corresponding to 394 and 296 seeds/m^2 in the clearcuts and shelterwoods, respectively. The lowest filled seed rain measured in an individual seed trap was 200 seeds/m^2. Total seed production estimates from two undisturbed upland white spruce stands about 5 km from the study site ranged from 2 to 3 times the number estimated here (Zasada 1980; Zasada et al. 1991). Over the next 4 years, seed production at the present study site consisted of one large crop in 1975 (measured nearby in untreated stands at 261 filled seeds/m^2; Rupp 1998), two poor crops, and 1 year in which no seeds were found in the traps at all.

White spruce germinant appearance and early survival

In 1973, white spruce germinants were first observed on scarified seedbeds in patch clear-cut units on May 10 (Table 2). Germination was about 50% completed in the patch clearcuts by May 30 and a week later in the shelterwoods. By June 26, about 95% of all germinants had appeared. The survival of these weekly cohorts averaged 76%; the date of germination did not affect the likelihood of survival. Seedling survival during the first growing season on the mineral soil seedbeds was 74% in the patch clearcuts and 78% in the shelterwoods. Grazing was the likely cause of mortality for 35% of the seedlings that died the first growing season. The remaining seedlings that died during the first growing season simply disappeared, and thus may also have been grazed. No obvious drought-killed seedlings were recorded. By the end of the second growing season, overall survival of white spruce germinants on scarified surfaces was 61% in both the patch clearcuts and shelterwoods. No new seedlings were observed on scarified surfaces as a result of the poor seed crops of 1973, 1974, and 1976. The 1975 seed crop produced a number of first-year survivors, but they comprised less than 1% of the total spruce seedling population on scarified surfaces. Thus, effectively all of the spruce seedlings on scarified surfaces originated from the 1972 seed crop.

Because we did not follow patterns of germination or very early establishment on unscarified plots, we do not know the exact year of origin for the seedlings that gradually became apparent on those surfaces. However, the stems collected from unscarified surfaces in 1999 all ranged from 22 to 26 years old, suggesting that they originated from the 1972 and 1975 cone crops. We thus interpret the apparent increase in spruce frequency on unscarified surfaces from 1977 to 1999 (Fig. 1) as an artifact of the increase in plot size during that time.

Fig. 1. Mean number of white spruce stems per hectare for plots having at least one spruce (*a*) and frequency of occurrence of white spruce in sampling plots (*b*) from 1973 through 1999. Shelterwood leave trees were not included in these counts. Error bars represent 1SE.



Seedling density and growth

Scarified surfaces had far more woody stems of all species than unscarified surfaces throughout the 27 years of this study. For example, in 1973, shelterwoods averaged 66 white spruce seedlings/m^2 on scarified surfaces compared with 8 on unscarified surfaces. The number of seedlings on scarified surfaces declined rapidly in the years following harvesting (Fig. 1*a*). Nevertheless, by 1999, scarified surfaces were still densely populated with young trees, supporting 129 000 and 118 000 white spruce stems/ha in the shelterwoods and patch clearcuts, respectively (Table 3). One hundred percent of scarified plots were stocked with white spruce in 1999 (Fig. 1*b*). On unscarified surfaces, in 1999, there were 15 000 and 11 000 spruce stems/ha in the shelterwoods and patch clearcuts respectively, and 87% of plots contained at least one spruce. On unscarified surfaces, by 1999, there

Table 3. 1999 stem numbers of trees and tall shrubs at Bonanza Creek Experimental Forest study site.

	No. of stems/ha						
	White spruce						
	Total	Height ≥ 4.5 feet	Paper birch	Balsam poplar	Aspen	Willow spp.	Green alder
Shelterwood scarified	129 916 ± 10 896	10 245 ± 1 998	25 703 ± 4 039	3750 ± 1250	5000 ± 0	3194 ± 694	21 914 ± 1 363
Patch clearcut scarified	118 250 ± 20 686	13 551 ± 1 781	23 681 ± 3 654	2500 ± 0	7175 ± 875	5750 ± 1448	17 361 ± 2 083
Shelterwood unscarified	15 479 ± 2 077	3 479 ± 438	4 223 ± 1 137	1744 ± 338	1692 ± 286	625 ± 0	4 513 ± 1 118
Patch clearcut unscarified	11 229 ± 1 762	4 016 ± 606	3 805 ± 884	3437 ± 0	3575 ± 4	729 ± 104	1 239 ± 194
			P* >*F				
Patch clearcut vs shelterwood	0.5646	0.2873	0.7344	0.8411	0.0493*	0.2091	0.0587
Scarified vs unscarified	0.0005***	0.0024**	0.0007***	0.6214	0.0174*	0.0334*	0.0002***
Interaction	0.7479	0.3080	0.7280	0.3135	0.8164	0.3285	0.6308

Note: Data are expressed as mean ± SE. For all columns, plots in which the species was entirely absent were excluded from the calculation of the mean and standard error. *, $p \le 0.05$; **, $p \le 0.01$; ***, $p \le 0.001$.

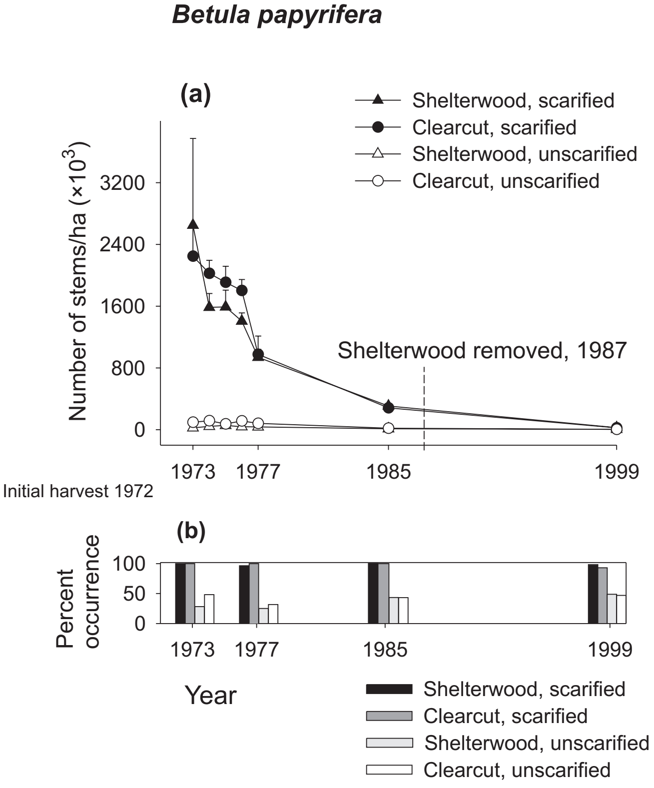


Fig. 2. Mean number of paper birch stems per hectare for plots having at least one birch (*a*) and frequency of occurrence of paper birch in sampling plots (*b*) from 1973 through 1999. Error bars represent 1SE.

were more than 3400 stems/ha ≥1.4 m tall in shelterwoods and more than 4000 of these in clear-cut units (Table 3). On scarified surfaces that year, there were more than 10 000 stems/ha ≥1.4 m tall in shelterwoods and more than 13 000 of these in patch clear-cut units (Table 3).

The dynamics of paper birch were similar to those of spruce, but the percent mortality of birch was far greater (Fig. 2*a*, Table 3). Birch density on scarified surfaces declined by two orders of magnitude between 1973 and 1999. Nevertheless, by 1999, 23 000 and 25 000 stems/ha remained in patch clearcuts and shelterwoods, respectively, and more than 93% of scarified plots had birch stems (Fig. 2*b*). The density of willow stems on scarified surfaces increased for the first 4 years after harvesting and dropped in 1977 (Fig. 3*a*). By 1999, there were only 3100 and 5700 willow stems/ha on scarified surfaces in shelterwood and patch clear-cut units, respectively; the frequency of willow on scarified plots ranged from 23 to 28% (Fig. 3, Table 3). Unscarified surfaces had lower density and much lower frequency of willow throughout the study period. Only 7 out of 120 unscarified plots had willow stems by 1999 (Fig. 3*b*).

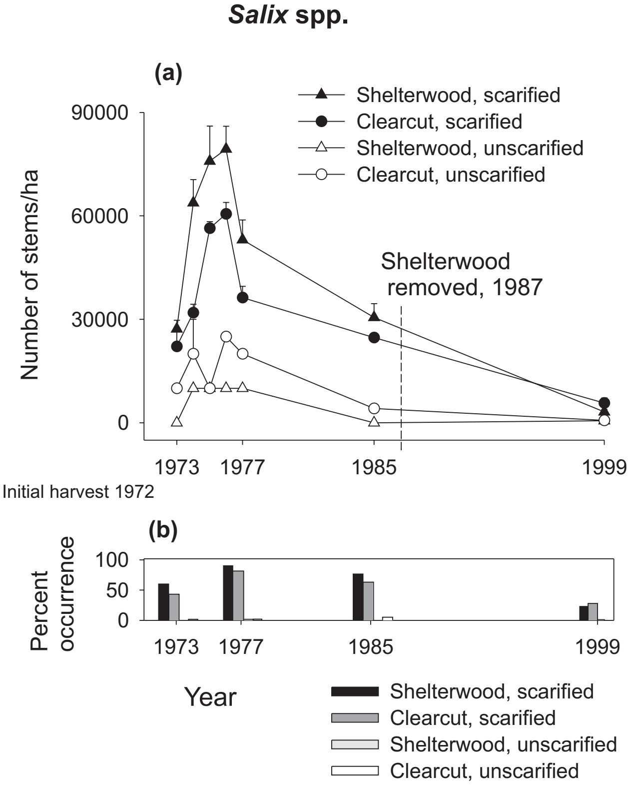
In 1999, the mean height of the overall population of birch and spruce seedlings or saplings in our treatment plots did not differ between patch clear-cut and shelterwood units. Birch saplings on unscarified surfaces were somewhat taller than those on scarified surfaces (Fig. 4). For spruce <1.4 m tall, there was no difference between scarified and unscarified surfaces. For spruce ≥1.4 m tall, 43% of saplings on

Table 4. 1999 heights and diameters for the tallest trees in each sampling plot.

	White spruce		Paper birch		Aspen		Balsam poplar	
	Height (m)	Diameter (mm)	Height (m)	Diameter (mm)	Height (m)	Diameter (mm)	Height (m)	Diameter (mm)
Shelterwood scarified	2.6 ± 0.1	18.7 ± 1.3	7.7 ± 0.1	52.8 ± 1.5	9.2 ± 0.9	73.9 ± 16.0	10.0 ± 1.0	94.2 ± 14.5
Patch clearcut scarified	2.6 ± 0.3	19.1 ± 3.8	7.6 ± 0.3	53.1 ± 4.2	12.4 ± 0.4	100.6 ± 3.6	8.7 ± 1.9	67.9 ± 16.3
Shelterwood unscarified	3.7 ± 0.3	39.9 ± 6.9	6.3 ± 0.1	43.0 ± 0.3	6.8 ± 0.7	61.6 ± 5.8	4.2 ± 0.8	36.5 ± 22.0
Patch clearcut unscarified	3.5 ± 0.3	34.6 ± 3.7	6.9 ± 0.3	45.9 ± 4.3	11.8 ± 0.1	91.0 ± 6.3	4.4 (na)	37.0 (na)
				P >F				
Shelterwood vs patch clearcut	0.5633	0.5370	0.5186	0.7274	0.0125*	0.0913	0.5776	0.6697
Scarified vs unscarified	0.0450*	0.0238*	0.0002***	0.0023**	0.1689	0.2530	0.0712	0.1790
Interaction	0.5633	0.6132	0.2460	0.3240	0.2880	0.5382	0.4778	0.9209

Note: Data are expressed as mean ± SE. na, not available. *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$.

Fig. 3. Mean number of willow stems per hectare for plots having at least one willow (*a*) and frequency of occurrence of willow in sampling plots (*b*) from 1973 through 1999. Error bars represent 1SE.



unscarified surfaces were ≥2.4 m in height, compared with only 16% on scarified surfaces.

Both the height and diameter of the tallest white spruce individuals were greater on scarified surfaces than unscarified in the first few years (Fig. 5). By 1985, 13 years after logging, this trend had reversed, and by 1999, this difference had become significant (Fig. 5, Table 4). The tallest paper birch experienced a similar reversal in the first few years of the study (Fig. 6). However, following the removal of the shelterwoods, trends in birch growth shifted, so that by 1999 the height and diameter of the largest birch was significantly greater on scarified, rather than unscarified, surfaces (Fig. 6, Table 4). In 1999, neither species exhibited a significant overstory effect in the height or diameter of the tallest individuals. Growth trends of the tallest aspen and balsam poplar were similar to that of birch (Table 4).

Understory vegetation

No understory species exhibited a significant overstory treatment effect, while scarification affected a number of species. Scarification removed the mat of feathermosses completely. On unscarified surfaces, live mosses accounted for 30–50% of cover immediately after harvest, but these died out within 5 years. By 1999, feathermosses had begun to recolonize this site, with 2–3% cover on scarified surfaces, and 10–13% cover on unscarified surfaces. Spread of the grass *Calamagrostis canadensis* was limited by scarification. By 1985, *Calamagrostis* accounted for 13 and 27% of cover on unscarified surfaces in shelterwood and patch clear-cut units, respectively, compared with only 2 and 3% of cover on scarified surfaces (Fig. 7*a*). Frequency of occurrence of *Calamagrostis* was less than 60% on all types of plots and in all years (Fig. 7*b*). By 1999, *Calamagrostis* cover on both types of surfaces had returned to preharvest levels. Cover of *Rosa* and *Epilobium* were also limited by scarification, but scarification promoted *Equisetum* in the first few years after harvest (Fig. 8).

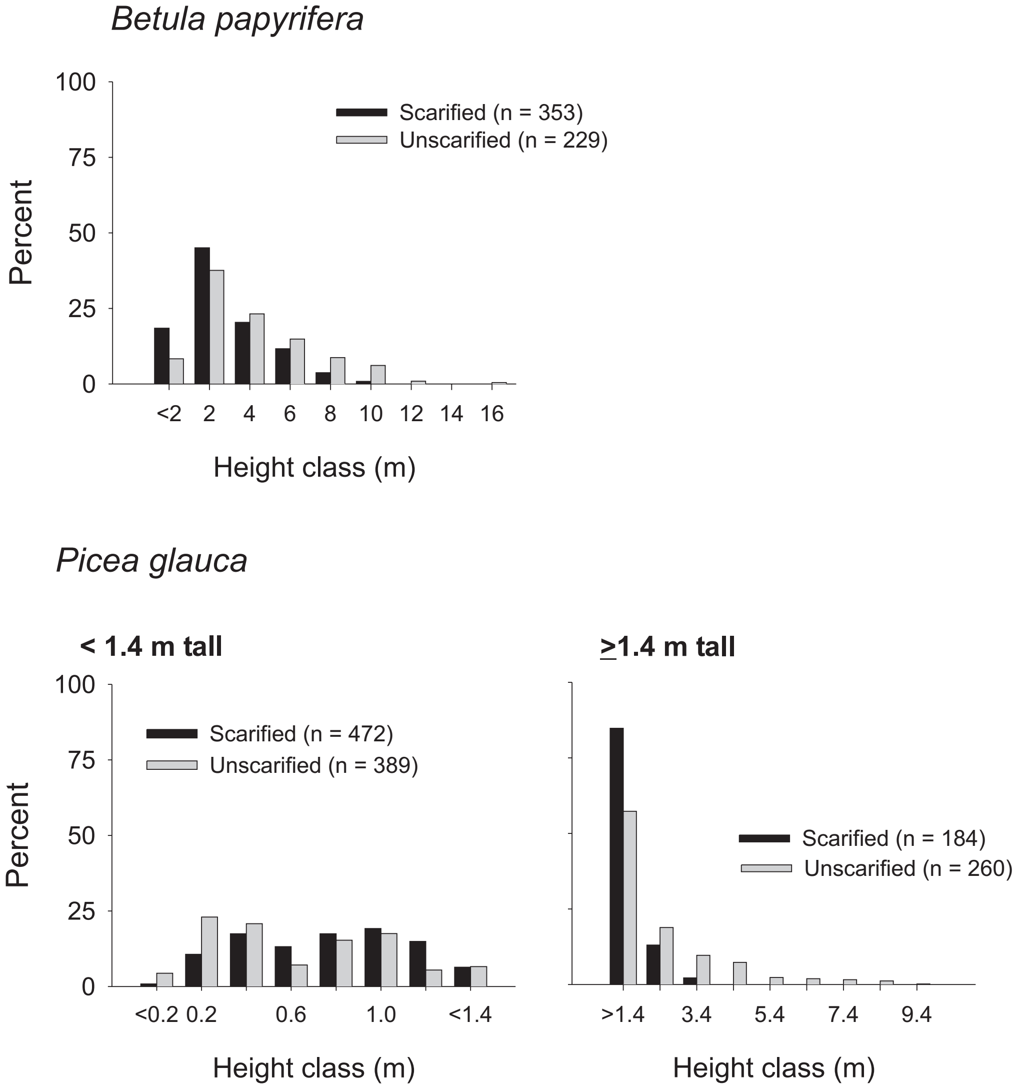
Two species, *Rubus idaeus* L. var. *strigosus* (Michx.) Maxim., and *Geranium bicknellii* Britt., are generally uncommon or absent in undisturbed white spruce stands and were not found in the stand prior to harvesting. Immediately following harvest, both were common on scarified surfaces. *Rubus* cover on scarified surfaces increased for 2 years, then it began to decline. On unscarified surfaces, *Rubus* cover increased for at least 5 years after harvesting. Immediately after harvesting, *Geranium* occurred on as many as half the sampling plots in shelterwood units. It took only 3 years for *Geranium* to disappear.

Discussion

Residual overstory

The time that retained overstory trees remain standing (whether live or standing dead) is a function of their dispersion or aggregation, wind patterns, and topography (Franklin et al. 1997), as well as their level of infestation or infection

Fig. 4. Frequency distributions of 1999 heights of the overall population of white spruce and paper birch seedlings or saplings in each treatment plot. Data from both overstory treatments are combined in this figure.



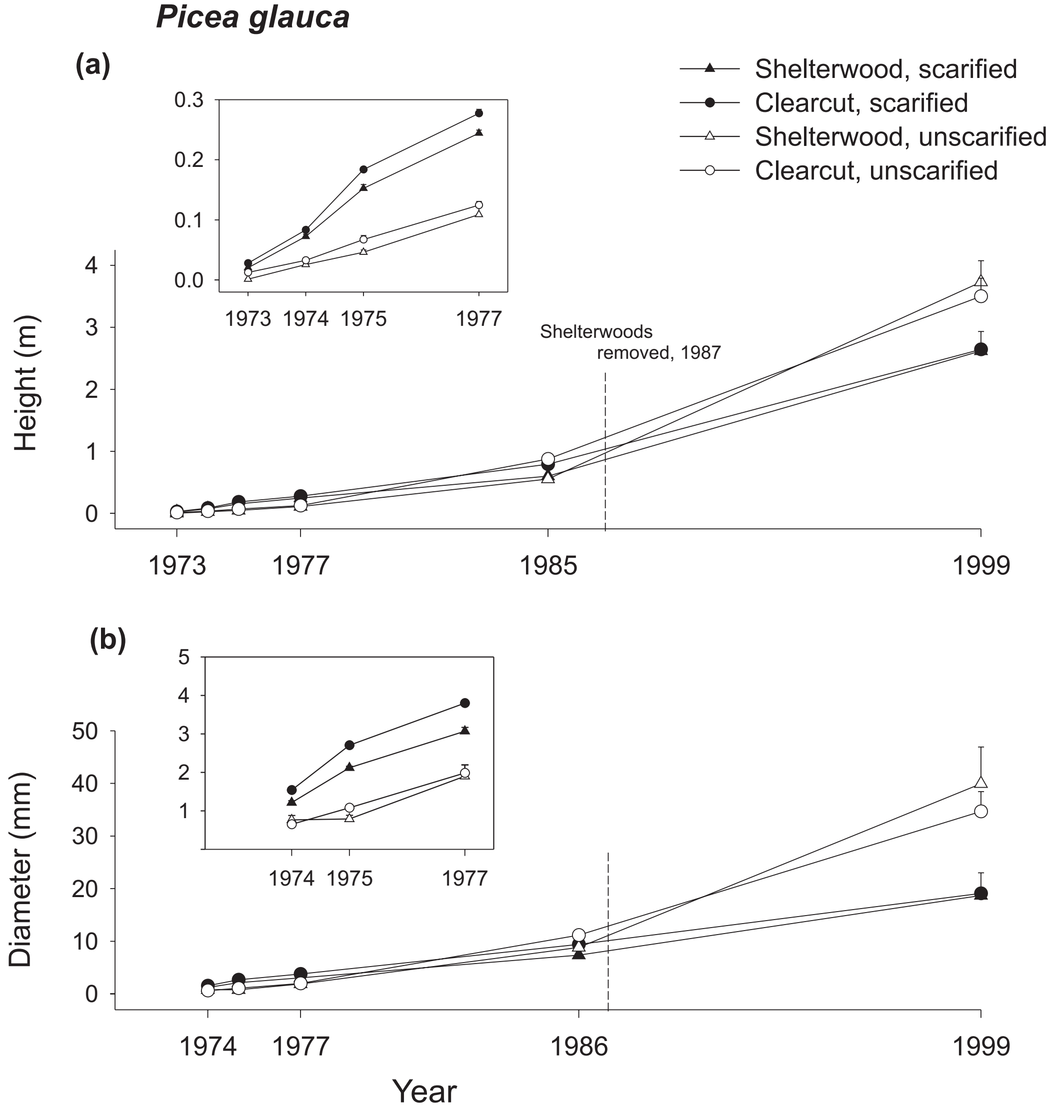
(Bull et al. 1997). No snags were left standing during the initial harvest operation in the present study, but about seven of the retained overstory trees per hectare died shortly after harvesting. Virtually all of these standing dead trees, along with 10–12 live trees/ha, were blown down in the 1975 windstorm. We estimate that roughly 15 $m^3 \cdot ha^{-1}$ of volume of coarse woody debris fell to the forest floor from the shelterwood overstory over its 15-year life. At a research site on the Tanana River in which shelterwoods were also used (Zasada et al. 1987; Dyrness et al. 1988), 41% of all retained, live white spruce trees were blown down by 16 years after the initial harvest (Wurtz and Zasada, unpublished data). In both the present study and at the Tanana River floodplain site, the boles of the blown-down trees were supported by branches and remained partly off the forest floor, likely slowing their decomposition. Such coarse woody debris can provide habitat for plants, animals, and fungi, and is important in nutrient cycles and carbon budgets (Harmon et al. 1986). Features such as snags, upturned root masses, and downed logs have been associated with habitat use by American marten (*Martes americana*) (National Council of the Paper Industry for Air and Stream Improvement, Inc. 1999) and lynx (*Lynx canadensis*) (Koehler and Aubry 1994).

Aesthetics is a recurring issue in forest management, and much opposition to forest management actions has centered on visual perceptions of clear-cut logging (Ribe 1999). Forest managers now routinely analyze the natural lines and shapes of a landscape to make cutting units less visible (British Columbia Ministry of Forests 1981; Diaz and Apostol 1992). In the present study, shelterwood units were harder to see from the air and were perceived more favorably from the ground than clear-cut units. Such preliminary findings suggest that shelterwood harvesting may have potential to mitigate some aesthetic concerns associated with clear-cut harvesting.

Tree density and growth

The original focus of this study was to examine alternative methods to promote the natural regeneration of white spruce. Toward this end, we retained a seed source well within the dispersal range of white spruce (Dobbs 1972; Youngblood and Max 1991) and used scarification to expose mineral soil

Fig. 5. Mean height (*a*) and diameter (*b*) of the tallest white spruce seedlings or saplings in each plot. Inset figures show growth trends during the early years, expanded in size for visibility. The number of trees sampled in each plot varied by year. Diameter data were first collected in 1974 and were collected in 1986 rather than 1985. Error bars represent 1SE.

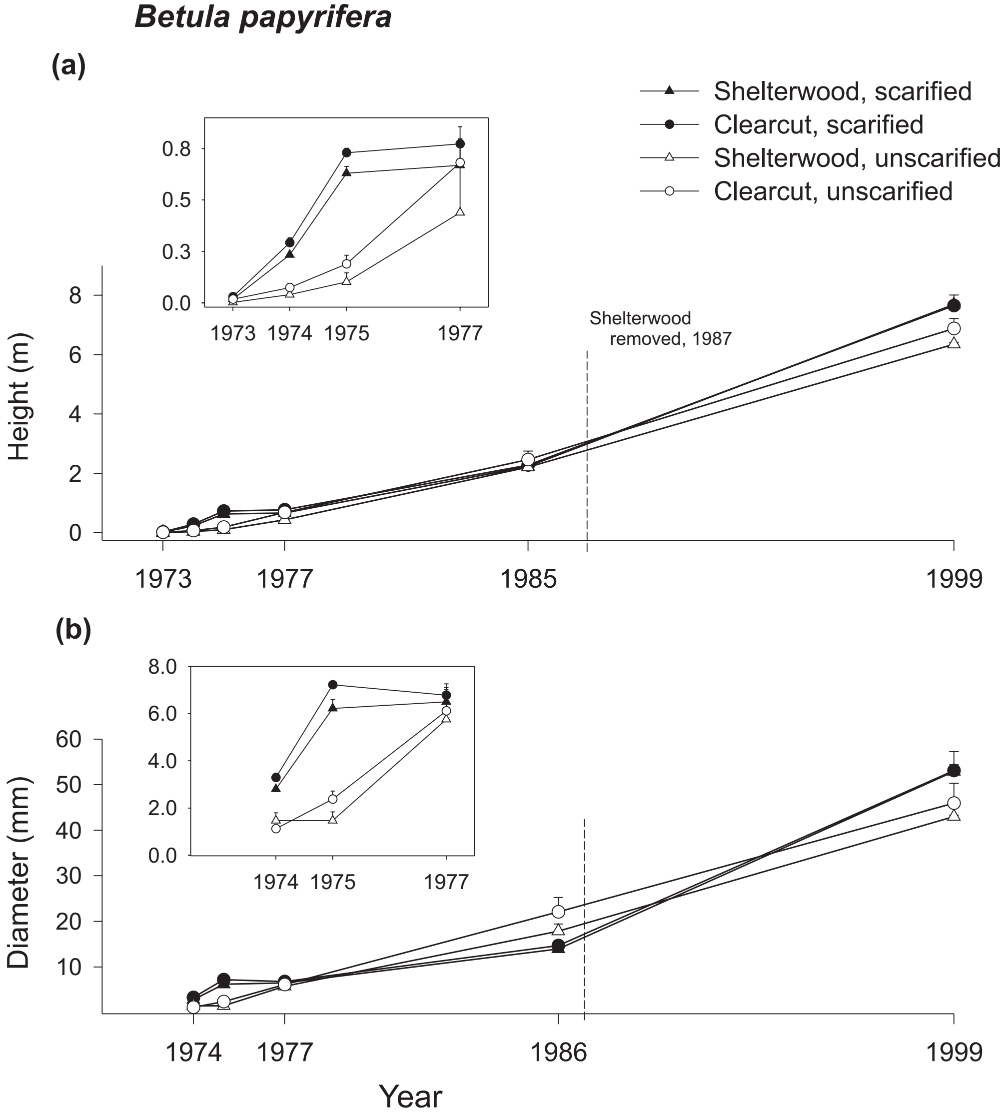


(Sutton 1969; Zasada and Gregory 1969). Scarified areas were made small enough so that nutrient displacement would be minimized, yet large enough to minimize competition between spruce seedlings and vegetation at the edge of the scarified patches. We tried to time scarification to precede the period of maximum seedfall. What we did not plan on was an exceptionally large seed crop in 1972. In addition, weather during the first growing season after harvest was atypical for interior Alaska (data not shown). Early summer drought commonly limits spruce germination and establishment (Clautice 1974; Zasada et al. 1978; Zasada 1985), but the summer of 1973 was unusually wet.

The large number of spruce seedlings that became established on unscarified surfaces that year was thus unexpected. When this study was begun, most boreal silviculturists considered scarification a virtual requirement for the natural regeneration of white spruce (Lees 1964; Dobbs 1972; Steill 1976). The present study shows that, when certain conditions occur together, undisturbed forest floor can be an excellent seedbed for white spruce regeneration. In such instances, site preparation is not only unnecessary but is actually counterproductive. Even after 27 years and significant density-dependent thinning, scarified surfaces remained densely populated with stems, many of which were clearly stunted. Our work in these plots was accompanied by a continual shower of needles from dead and nearly dead spruce stems.

These results do not affect the well-established recommendation for scarification in more typical seed years, however. The timing of this scarification, relative to seed dispersal, is critical. The lack of seedlings from the 1975 cone crop on the scarified surfaces of our study site (Zasada and Grigal 1978) illustrates the narrowness of the window for seedling establishment on this type of surface. Less than 1 year after site preparation was completed, scarified surfaces had been colonized by more than 220 birch

Fig. 6. Mean height (*a*) and diameter (*b*) of the tallest paper birch seedlings or saplings in each plot. Inset figures show growth trends during the early years, expanded in size for visibility. The number of trees sampled in each plot varied by year. Diameter data were first collected in 1974 and were collected in 1986 rather than 1985. Error bars represent 1SE.



seedlings/m^2. By the summer of 1975, cover of *Equisetum* on scarified surfaces ranged from 43 to 50%.

Seed/seedling ratios can be useful in assessing the quality of a regeneration patch (Table 5). Essentially all the spruce we found growing on scarified surfaces in 1999 originated from the 1972 seed crop, which consisted of at least 400 filled seeds/m^2 in these units. Spruce stems on unscarified surfaces in 1999, on the other hand, are the result of the combination of the 1972 and 1975 seed crops. Because the exact seedfall on these plots is not known, the “effective,” or combined, seed crop on those surfaces could thus have been as much as 800 or even 1200 seeds/m^2. In 1976, scarified surfaces had from 51 to 56 spruce seedlings/m^2; by 1999, this had dropped to 12–13 seedlings (or saplings) per square metre. The 1999 seed/sapling ratio was thus approximately 4.3 times greater than the seed/seedling ratio in 1976. On unscarified surfaces, we found a similar (3.3) increase in ratio over time. In effect, the density of spruce stems declined nearly proportionately over time on the two types of surfaces.

The growth patterns documented for spruce and birch over the last 27 years are among the most interesting results of this study. Because Zasada and Grigal (1978) found no difference in the nutrient content of 3-year-old white spruce seedling tissue between the scarified and unscarified surfaces of this site, the difference in early growth (Figs. 5 and 6 inset) may have been due to enhanced moisture availability on mineral soil surfaces (Waldron and Cayford 1967). By 1985, the shading effect of the shelterwood overstory may have become a factor, with seedlings in patch clearcuts beginning to outgrow those in shelterwoods. When the shelterwood overstory was removed 2 years later, light became equally available in all units. By 1999, young spruce trees on scarified surfaces were growing significantly less than those on unscarified surfaces. This slow growth, relative to trees of the same age on unscarified surfaces, is likely primarily the

Fig. 7. Mean estimated percent cover of *Calamagrostis canadensis* for plots in which that species occurred (*a*) and frequency of occurrence in sampling plots (*b*) from 1973 through 1999.

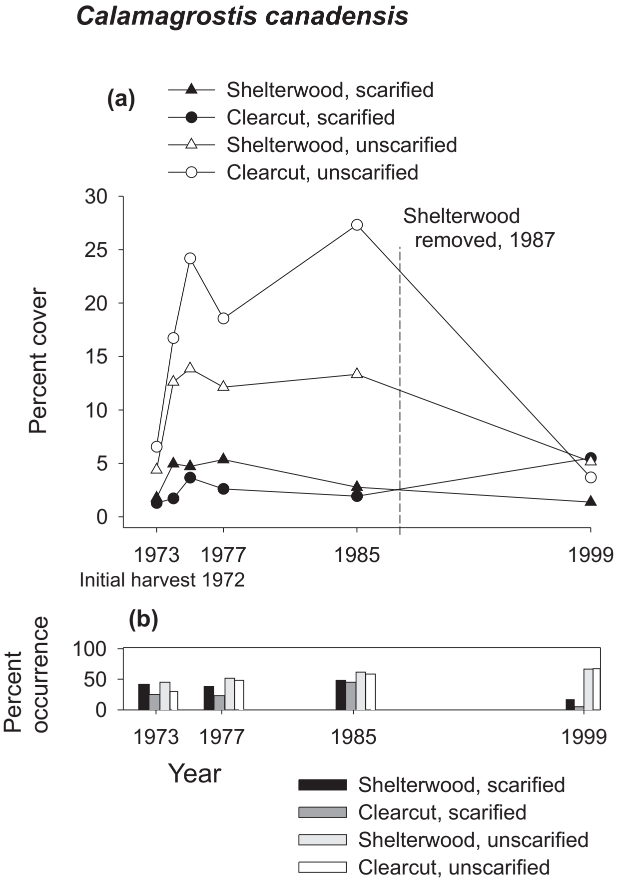
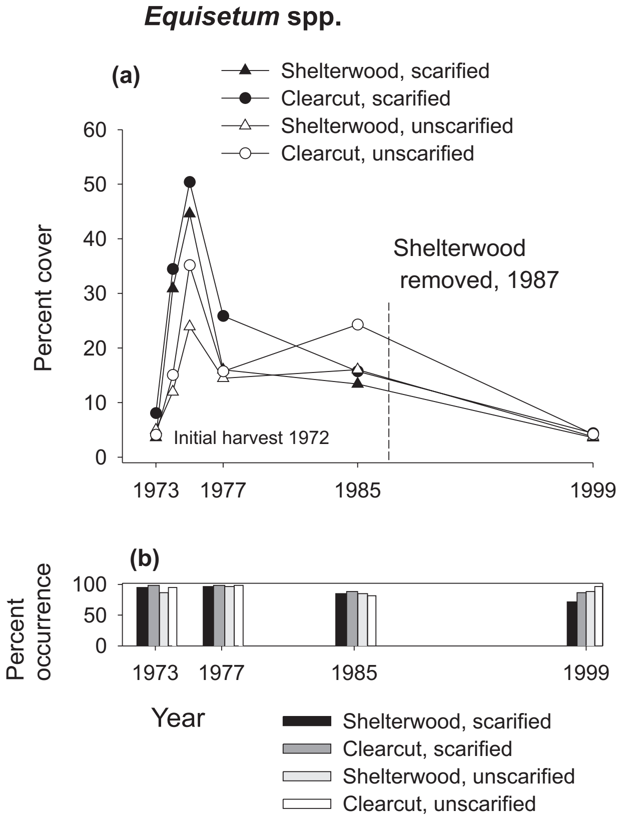


Fig. 8. Mean estimated percent cover of *Equisetum* spp. for plots in which that species occurred (*a*) and frequency of occurrence in sampling plots (*b*) from 1973 through 1999.



result of intense competition on scarified surfaces. It may also be due to differences in the nutrient status of mineral and organic soils. Work on similar, nearby sites has documented the low nutrient status of mineral soil relative to organic soil layers (Pare and Van Cleve 1993; Wurtz 1995).

Though 1999 aspen height showed a significant overstory effect (Table 4), this is an artifact of its irregular initial distribution. Before harvesting, the only aspen at the study site occurred in areas designated for clear-cutting. When these units were harvested, the resulting root suckers had a significant and long-lasting size advantage over the aspen in shelterwood units, which originated solely from seed.

Understory vegetation

Long-term domination of a disturbed site by *Calamagrostis* is considered undesirable for a variety of reasons. It depresses soil temperatures (Hogg and Liefers 1991; Cater and Chapin 2000), prevents the establishment of white spruce (Lieffers et al. 1993; Cater and Chapin 2000), and competes with plant species that are palatable to wildlife (Collins and Schwartz 1998). This study gives the first data on the long-term persistence of *Calamagrostis* following timber harvest in Alaska: by 27 years, cover of this grass had returned to preharvest levels in all treatment types. *Equisetum* exhibited a similar trend, peaking a few years after harvest, and returning, by 1999, to preharvest levels. Unlike what we observed for *Calamagrostis*, however, scarification promoted the spread of *Equisetum*; the rhizomes of this species spread rapidly through mineral soil. Cater and Chapin (2000) found that spruce seeds germinated and established preferentially in patches of *Equisetum* (when compared with patches of aspen or *Calamagrostis*). Patches of *Equisetum* were also warmer and had less light attenuation than patches of the other two species (Cater and Chapin 2000).

Treatment costs and benefits

In this study, scarification had both positive and negative effects. It limited the spread of *Calamagrostis*, *Rosa*, and *Epilobium*, all species that can compete vigorously with white spruce (Eis 1981). It provided regularly spaced patches of dense moose browse and horizontal cover. Yet it had a net detrimental effect on the regeneration of white spruce, resulting in grossly overstocked patches of stunted trees. Though unscarified surfaces proved to be excellent seedbeds for regenerating white spruce under the seedfall and weather conditions that occurred at the start of this study, the combination of these conditions occurs infrequently. We suggest that managers seeking to regenerate white spruce from seed should assess the developing cone crop, and forego scarification only when a very large crop is imminent.

Table 5. Seed/seedling and seed/sapling ratios resulting from three hypothetical effective seed crops.

	1976				1999			
	Scarified surfaces		Unscarified surfaces		Scarified surfaces		Unscarified surfaces	
Effective seed crop (filled seeds/m^2)	Seedlings/m^2	Seed/seedling ratio	Seedlings/m^2	Seed/seedling ratio	Saplings/m^2	Seed/sapling ratio	Saplings/m^2	Seed/sapling ratio
400	56	7.1	5	80	12.9	31	1.5	267
800	56	14.2	5	160	12.9	62	1.5	534
1200	56	21.4	5	240	12.9	93	1.5	800

Note: Because stems per square metre values for clear-cut and shelterwood units were similar, only shelterwood values are shown here. Values of seedlings per square metre and saplings per square metre are actual data collected in this study. For scarified surfaces, effective seed crop refers to actual number of seeds dispersed per square metre in 1972; for unscarified surfaces, effective seed crop is the combination of seeds dispersed in 1972 and 1975.

Though shelterwood and clear-cut harvesting also have benefits and costs, they were not made clear by the present study. Overstory treatment had no effect on density or growth of any plant species, our primary foci. With respect to white spruce, we believe this result is related to both the dimensions of our clear-cut units and to the large size of the 1972 cone crop. The patch clear-cut areas used in the present study were small compared to typical operational clearcuts. If the seed crop immediately following harvest had been more typical, or if the clear-cut units had been larger, the shelterwood overstory would possibly have enhanced spruce stocking above the rate observed in clearcuts. The shelterwood overstory did provide some measure of structural diversity to the regenerating stand, and through mortality and windthrow, served as a source of coarse woody debris to the forest floor. There is some indication that the shelterwood overstory mitigated the visual impact of harvesting. Though we did not compare the economic costs of shelterwood harvesting with clear-cutting (either in terms of revenue deferred or costs at the time of harvest), overstory retention systems are typically more costly than clear-cutting to implement (Keegan et al. 1993). An evaluation of the costs of these treatments is clearly needed before they can be recommended for operational use.

Interest in alternatives to clear-cutting has increased in recent years (Lieffers et al. 1996; Franklin et al. 1997), and these alternatives are typically based on a partial removal of the overstory, like the shelterwood treatment used here. Unlike a shelterwood, however, many of the systems being discussed today intend for a portion of the overstory to be left on site permanently, as the trees age, die, fall, and decompose. In any case, the present study provides the first data available on one example of such a system in Alaska. Because many questions about the costs and benefits of these cutting systems have yet to be addressed, we think they should be examined further.

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