Effects of mechanized careful logging on natural regeneration and vegetation competition in the southeastern Canadian boreal forest

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Abstract: Careful logging regulations in Quebec restrict circulation of harvesting and forwarding or skidding machinery to evenly spaced, parallel trails, which creates a particular pattern of disturbed and relatively undisturbed zones in cutovers. A 7-year monitoring study was established to evaluate the effects of careful logging on vegetation development in the southern boreal forest of Quebec. A total of 255 sample plots (2 m^2) were located in seven cutovers in predominantly black spruce (*Picea mariana* (Mill.) BSP) forests that were whole-tree "careful logged": 120 on fresh to moist silty clays or silty clay loams and 135 on dry to fresh loamy sands. Three microsites were sampled: skid trails and the edge and the centre of protection strips. A gradient of disturbance from the skid trail to centre of the protection strip was evident for finer textured sites. Careful logging resulted in high densities of black spruce and balsam fir (*Abies balsamea* (L.) Mill.) (> 20 000 stems/ha each) in the protection strip. Survival of other understory species was also favoured in protection strips. Higher disturbance levels in skid trails favoured establishment of larch (*Larix laricina* (Du Roi) K. Koch), raspberry (*Rubus idaeus* L.), and graminoids. Reduction of ericaceous cover occurred in skid trails on coarse-textured sites but was only temporary. Softwood stocking 7 years after harvest (based on 2-m^2 plots), ranged from 69 to 74% on fine- to medium-textured sites and from 31 to 51% on coarse-textured sites. The pattern of vegetation development created by careful logging has important implications for silvicultural decisions and stand modelling.

Résumé : La coupe avec protection de la régénération et des sols (CPRS) restreint la circulation de la machinerie forestière à des sentiers également espacés créant un patron particulier de zones perturbées et de zones moins perturbées. Un suivi du développement végétal a été réalisé dans des CPRS en forêt boréale méridionale au nord-ouest du Québec. Au cours des 7 années suivant la coupe, 255 placettes de 2 m^2 situées dans sept aires de coupe, principalement des pessières, ont été échantillonnées annuellement : 120 sur sols frais à humides de texture fine à moyenne et 135 sur sols secs à frais de texture grossière. Trois microsites ont été échantillonnés : les sentiers de débardage, la bordure et le centre des bandes protégées. Sur les sites à texture fine, la coupe a engendré un gradient de perturbation physique, du sentier jusqu'au centre de la bande protégée. Dans la bande, les densités d'épinette noire (*Picea mariana* (Mill.) BSP) et de sapin baumier (*Abies balsamea* (L.) Mill.) étaient élevées (> 20 000 tiges/ha chaque) et les espèces du sous-bois demeuraient abondantes. La perturbation plus sévère dans les sentiers a favorisé l'établissement du mélèze (*Larix laricina* (Du Roi) K. Koch., du framboisier (*Rubus idaeus* L.), et de graminoïdes. Suite à la coupe, une réduction temporaire du recouvrement des éricacées a été observée dans les sentiers de débardage sur les sites à texture grossière. Le coefficient de distribution de résineux, 7 ans après la coupe (basé sur les placettes de 2 m^2), variait de 69 à 74% sur les sites à texture fine à moyenne et de 31 à 51% sur les sites à texture grossière. Le patron de développement végétal créé par la CPRS comporte des implications importantes pour les décisions sylvicoles et soulève des questions relativement à la croissance et au rendement des peuplements.

Introduction

As in other regions of the boreal forest, regeneration management in Quebec shifted from what was essentially a nonissue prior to 1980 to an increasing emphasis on plantations in the latter part of that decade. In the early 1990s, concerns were increasingly expressed about the possible effects of wide-scale conversion of natural forest ecosystems into conifer monocultures (Mosquin et al. 1995). The Quebec Forest Protection Strategy (ministère des Ressources Naturelles du Québec 1994) identified harvesting with protection of advanced regeneration and soil ("coupe avec protection de la régénération et du sol"), or careful logging, as the primary means to maintain genetic diversity in logged

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Fig. 1. Aerial view of a careful logging cutover in the boreal forest, Quebec.

sites, protect site integrity, and reduce forest renewal costs by increasing reliance on survival of advance regeneration. Over the course of a few years in the early 1990s, all existing harvesting methods were modified to comply with careful-logging regulations. Moreover, since its adoption, careful logging has been applied to all boreal forest types and on all site types (Fig. 1). However, it should be noted that where advance regeneration is lacking, cutovers are generally planted with or without prior site preparation.

Essentially, careful-logging regulations stipulate that trails used by harvesting and forwarding or skidding equipment must not cover, without penalty, more than 33% of the area of a cutover (25% since March 2001). To conform to the regulations, all machinery circulates on parallel trails separated by harvested "protection strips," which are generally about twice the operable reach of a harvester or feller–buncher's boom or a skidder's cables. The anticipated effect is that disturbance of site and vegetation should be considerably reduced in the protection strips although at the expense of relatively greater disturbance within and in proximity of trails. Effects of different disturbance intensities depend on a number of factors related to (*i*) the harvesting itself (type of machinery and methods used (Ruel 1992), exerted ground pressure, and direct physical injury to advance regeneration and other plants); (*ii*) training and experience of equipment operators; (*iii*) site and environmental conditions prior to, during, and following harvesting (Harvey and Bergeron 1989); and (*iv*) biotic factors, including stand and understory density and structure, species composition and life traits, and seed bank composition. Disturbance caused by clear-cut logging on rich, lacustrine soils in the eastern boreal forest has been shown to favour an invasion of ruderal species and a shift of softwood-dominated stands into mixed and intolerant hardwood compositions (Jeglum 1983; Harvey et al. 1995). However, despite the generalized adoption of careful logging in the Quebec boreal forest, there have been very few studies aimed at evaluating its effects on either vegetation dynamics (Laflèche et al. 2000) or site conditions (Brais and Camiré 1998).

To evaluate, spatially and temporally, the effects of careful logging on early stand development, specifically on survival, recruitment, and growth of conifer regeneration and other plant species, a medium-term monitoring program was established in 1993 in the Abitibi region of northwestern Quebec. We hypothesized that given the differential effect of careful logging disturbance within a cut block, two distinct vegetation communities would develop following this type of harvest: one associated with protection strips characterized by advance regeneration and forest understory species and another characterized by ruderals and species favoured by high site disturbance. The project was designed to characterize vegetation development in three distinct disturbance zones within cut blocks: (*i*) skid trails between wheel tracks, (*ii*) shoulder zones of protection strips beside skid trails (outer strip), and (*iii*) the centre section of protection strips themselves (centre strip). We also anticipated differences between the contrasting two site types studied. This paper reports the results from the first 7 years of the project.

Materials and methods

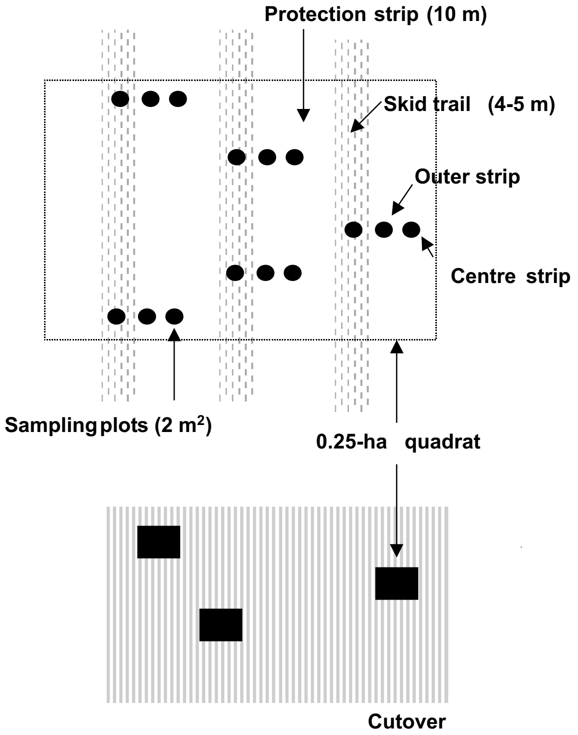
Study area

The study area is in the Abitibi region of Quebec between 48°00′ and 48°15′N and 78°40′ and 78°50′W, in the southern part of the Clay Belt, a large physiographic zone that straddles the Quebec–Ontario border. The climate is continental with mean annual temperature of 1.7°C and precipitation of 937 mm, falling mainly as rain (Environment Canada 1982). The region is part of the Precambrian Shield, and the topography is generally gently rolling with short slopes. Most of the bedrock is covered with Quaternary surface deposits. Because of their size, eskers are important features of the landscape, while the clay plain (fine- to medium-textured glaciolacustrine deposits) formed by sedimentation in glacial Lake Barlow–Ojibway lies between the eskers (Allard 1974). The transition zone between the eskers and the clay plain is often covered with reworked glaciofluvial material overlying the bottom of the ancient lake (coarse-textured glaciolacustrine deposits). The soils in the study area have evolved from fine-textured and coarse-textured glaciolacustrine deposits under fresh to moist moisture regimes (Brais and Camiré 1992). Gray Luvisol soils develop on finer material and Humo-Ferric Podzols are found on coarse-textured deposits (Canada Soil Survey Committee 1987). The region is situated in the southeastern boreal forest and is characterized by forests of balsam fir (*Abies balsamea* (L.) Mill.), white birch (*Betula papyrifera* Marsh.), and white spruce (*Picea glauca* ((Moench) Voss) stands on mesic sites with a transition towards black spruce (*Picea mariana* (Mill.) BSP) stands in more humid moisture regime classes. Poor, well-drained sites are usually occupied by jack pine (*Pinus banksiana* Lamb.) and (or) black spruce.

Sampling design

Seven cutovers that were carefully whole-tree logged in the summer of 1992 were located for study in 1993. Harvesters and cable skidders were restricted to equally spaced trails. Careful logging created an alternating pattern of 10 m wide protection strips and 4–5 m wide skid trails. Four of the cutovers were located on fresh to moist silty clays or silty clay loams, and three were on dry to fresh loamy sands. We refer to these as fine- to medium-textured sites and coarse-textured sites, respectively, throughout this paper. According to forest cover maps, all harvested stands were composed primarily of mature black spruce except one (block 2 on the fine- to medium-textured sites), which was a balsam fir dominated stand that had incurred previous spruce budworm defoliation. Two 0.25-ha quadrats on fine- to medium-textured sites and three quadrats on coarse-textured sites were located within each cutover, to ensure adequate coverage of cutover area and uniform soil moisture conditions. Within each quadrat, at five equally spaced locations, vegetation surveys were conducted on 2-m^2 circular plots: (*i*) within the trails, between the wheel tracks (skid trail); (*ii*) in the outer portion of the protection strip next to the wheel track (outer strip); and (*iii*) in the central portion of the protection strip (centre strip) (Fig. 2). Because preharvest vegetation surveys were not conducted, first-year vegetation values for centre strip positions provided the best indication of conditions prior to harvesting. The approximate coverage of the various microsites created by careful logging was as follows: skid trails occupied ~33% of cutovers (13% wheel tracks + 20% between tracks) and protection strips occupied ~66% (20% protection strip border + 46% protection centre). While this study reports on contrasting zones of disturbance, it does not include the roughly 13% of cutovers that was most disturbed, that is, the zone directly impacted by the weight of harvesters and skidders. A total of 30 sampling locations per cutover (10 per position relative to skid trails) were surveyed for fine- to medium-textured sites (total 120 plots) and a total of 45 locations (15 per position) for coarse-textured sites (total 135 plots). Field surveys were conducted during July for a period of 7 years following the year of harvest. Percent cover values were visually estimated, and mean heights were measured for low shrubs (species with maximum height <1 m), herbs, sedges (*Carex* spp.), and grasses (principally *Calamagrostis canadensis* Michx.). Cover was also estimated for feathermosses (*Pleurozium schreberi* (Brid.) Mitt., *Hylocomium splendens* (Hedw.) Schimp. in B.S.G., *Polytrichum* spp.) and *Sphagnum* mosses. Stems counts were done for red raspberry (*Rubus idaeus* L.) and all deciduous tree and high shrub species. This latter group was dominated by speckled alder (*Alnus rugosa* (Du Roi) Spreng.) but also included willows (*Salix* spp.), mountain maple (*Acer spicatum* Lam.), pin cherry (*Prunus pennsylvanica* L.f.), and choke cherry (*Prunus virginiana* L.). Natural regeneration was counted by species, and each stem was attributed to a vigour class (class 1, >50% foliage green and leader intact; class 2, >50% foliage green but leader broken or dead; class 3, <50% of foliage green and leader broken or dead). Stem heights were measured individually and mean stem height was calculated by vigour class for each plot. Lack of vigour (%) was calculated for each softwood species as (no. stems in classes 2 + 3)/(no. stems in classes 1 + 2 + 3) × 100. On all 255 plots, percent exposed mineral soil was estimated and forest floor thickness was measured in 1994, two years after harvest.

Fig. 2. Schematic plan showing location of quadrats and sample plots.



Statistical analyses

We assumed that harvesting equipment operators located their trails only to respect the 33% regulation and without regard to other aspects that could have influenced vegetation. Hence, although the treatments were not assigned randomly to the experimental plots, the sampling design was treated as a randomized complete block design, where each cutover constitutes a block, and positions relative to skid trails represent the treatments. Data from fine- to medium- and coarse-textured sites were analysed separately by means of an univariate repeated-measures analysis (Freund et al. 1986). The Huynh–Feldt estimator was used when the hypothesis of sphericity of orthogonal component was rejected. The among-subject effects were based on means over the 7-year sampling period of the main effects (position relative to skid trail). Comparisons were conducted by means of contrasts between skid trail and averaged values for protection strip (centre strip and outer strip) as well as between centre strip and outer strip positions. Within-subject mean effects tested the hypothesis that relationships between response variables and time followed either a linear or a quadratic relationship. Interactions between position contrasts and time contrasts tested the hypothesis that the nature of the relationships between response variables and time differed across positions. Homogeneity of variance was tested using Bartlett's procedure. Variables that did not meet the requirement were submitted to a square-root transformation.

Finally, to summarize changes in vegetation between the first and seventh years of the study on fine- to medium-textured sites, a principal component analysis (Legendre and Legendre 1983) was conducted on vegetation characteristics measured in 1993 and 1999. Twelve experimental plots (four blocks and three locations relative to skid trails) were used in the calculations, and data from 1993 and 1999 were treated as individual observations (total of 24). This analysis was not done for coarse-textured sites because of low species diversity.

Results

Forest floor disturbance induced by careful logging

On fine- to medium-textured sites, surface scarification by harvesting operations was observed in 79% of sample plots within skid trails ($n = 38$) compared with 56% in the outer portion of protection strips and 10% in the centre of protection strips. Mean values for exposed mineral soil cover were higher ($p < 0.011$) in skid trails (18%) than in protection strips (2%), but no difference was observed within the protection strip. Significant reductions in forest floor thickness were found between skid trails (mean 5 cm) and protection strips (–73%, $p = 0.001$) and between the outer strip and centre strip positions (–31%, $p = 0.038$), which had mean thicknesses of 12.5 and 18 cm, respectively.

On coarse-textured soils, there was little forest floor scarification within skid trails. Exposure of mineral soil was observed in 22% of sampling quadrats ($n = 45$) in skid trails compared with 11% in outer strip and 9% in the protection strip centre. Mean exposed mineral soil values were low everywhere (<1.5%) but, nevertheless, higher ($p = 0.062$) in skid trails than in protection strips. Forest floor thickness was significantly reduced ($p = 0.001$) by 20% within skid trails (mean thickness 19.5 cm) and by 6% ($p = 0.006$) in the outer strip (23 cm) compared with the strip centre position (24 cm).

Competition on fine- to medium-textured sites

Moss cover on fine- to medium-textured sites was dominated by feathermosses and *Sphagnum* species. Following harvesting, cover values for both groups of species were below 4% in all positions (Fig. 3). Feathermoss cover increased linearly with time for all positions, but increases were more pronounced in protection strips than in trails (Table 1). Seven years after harvesting, feathermoss cover reached 10% in the centre strips but remained below 4% in skid trails. Despite a pattern similar to that of feathermoss (Fig. 3), differences among positions for *Sphagnum* species were not significant (Table 1). Cover increased linearly with time in all positions, but a significantly sharper increase was noted in trails.

The herb group was composed of species that were present before harvesting, notably wild sarsaparilla (*Aralia nudicaulis* L.), large-leaved aster (*Aster macrophyllus* L.), horsetails (*Equisetum* spp.) as well as ruderal species such as fireweed (*Epilobium angustifolium* L.) and touch-me-not (*Impatiens capensis* Meerb.). Following harvesting, little difference in herb cover was observed among positions, and values remained below 10% in all positions for most years (Fig. 3). Outer strip values surpassed those of the centre strip during the second year following harvesting and remained higher thereafter. Height growth of herbs was greater in trails, where highest values were observed in the sixth and seventh years. The observed plateau in height growth reached for all positions at year 3 was significant (Table 1).

Throughout the study period, grasses and sedges were significantly more abundant (*i*) in skid trails than in protection strips and (*ii*) in the outer strip than in the centre strip (Fig. 3). There was no overall relationship with time (Table 1). However, despite high year-to-year variations, there was a significant linear increase in skid trail cover with time, while mean strip values remained constant. One year following harvesting, there was little difference in heights of grasses and sedges between positions, whereas at the end of the study period, heights were 45% greater in outer strips and trails than in the centre strips.

Red raspberry was the most abundant of low shrub species. Other species included skunk currant (*Ribes glandulosum* Graver), wild red currant (*Ribes triste* Pallas), fly honeysuckle (*Lonicera canadensis* Bartr.), and bush honeysuckle (*Diervilla lonicera* Mill.). Ericaceous shrubs were treated as a separate group, but mean cover values never exceeded 1%. One year after harvesting, raspberry densities were similar for all positions (44 000 – 57 000 stems/ha) (Fig. 3). While densities in the centre strip remained more or less constant throughout the study period, densities in skid trails and in outer strips increased until the third year after harvesting, when they reached 324 000 and 236 000 stems/ha, respectively. The increase was significantly greater in skid trails than in the strip position (Table 1), where the outer strip position never reached values as high as those of trails. After the third year, there was a slow decrease in density. After 7 years, differences between the skid trail and the outer strip had considerably narrowed. Harvesting operations reduced mean height of raspberry stems in skid trails and in outer strips by half, but by the fifth year, heights had attained similar values (46–50 cm) in all positions and remained constant thereafter.

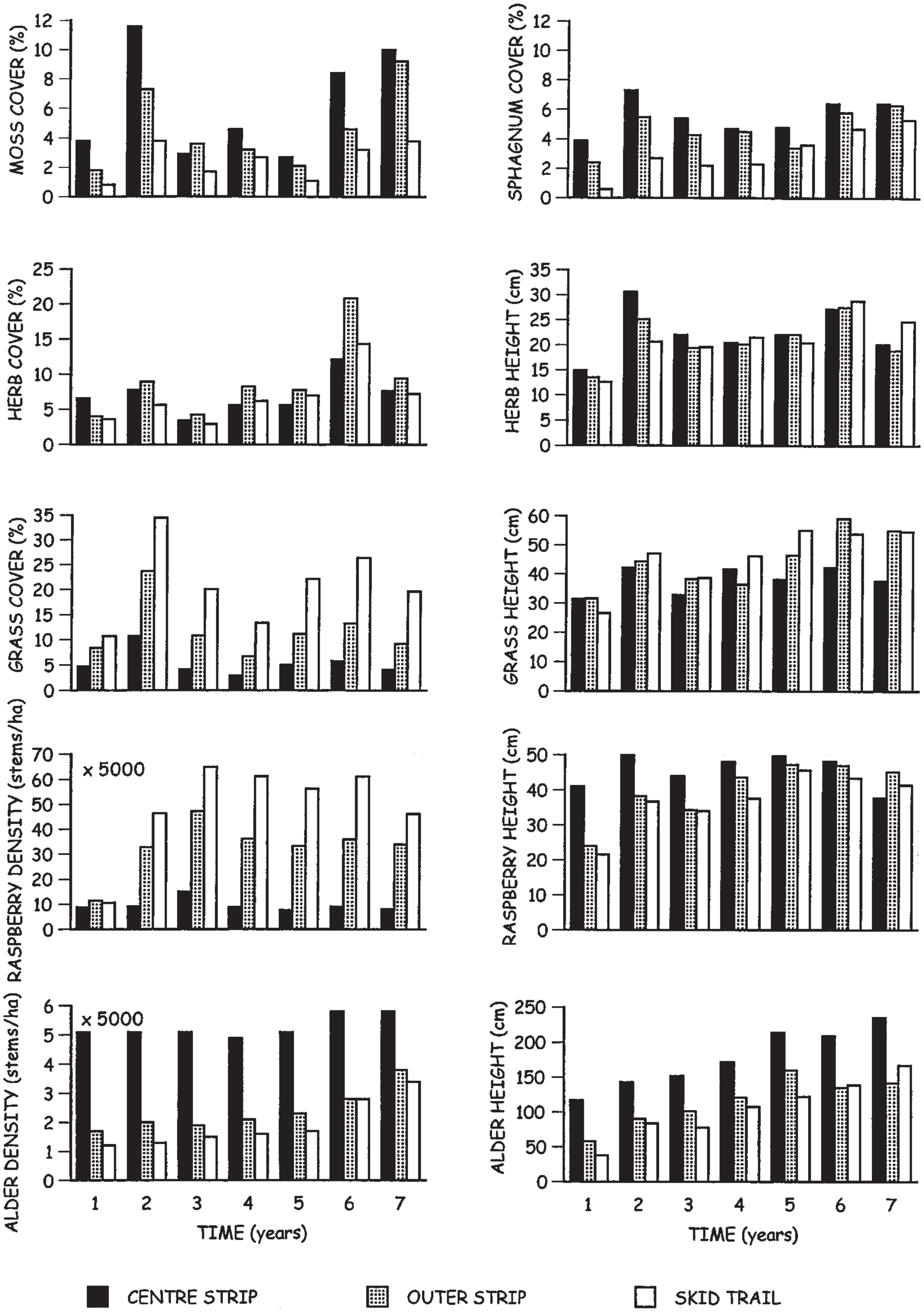
Speckled alder dominated the high shrub group, and only its values are reported here. Harvesting operations reduced alder densities by 67% in the outer strips and by 77% in skid

Table 1. Univariate repeated measures analysis of relationships among vegetation dynamics, position relative to skid trails, and time 1–7 years after harvesting on fine- to medium- and coarse-textured sites.

	Among-subject effects				Within-subject effects							
						Mean effect		Skid trail vs. strip		Centre strip vs. outer strip		
Variable	Contrast for position	MS	*p*	MSE	Contrast for time	MS	*p*	MS	*p*	MS	*p*	MSE
Fine- to medium-textured sites												
Feathermoss cover*	Trail vs. strip	9.1845	0.035	1.2508	Linear	3.9071	0.007	0.0313	0.733	0.1186	0.513	0.2457
	Centre vs. outer	2.3107	0.223		Quadratic	2.6521	0.001	1.0052	0.003	0.0494	0.324	0.0427
Sphagnum spp. cover*	Trail vs. strip	5.9131	0.337	5.4259	Linear	5.000	0.009	1.5256	0.082	0.2012	0.478	0.3512
	Centre vs. outer	0.5363	0.764		Quadratic	0.0103	0.624	0.0171	0.530	0.0113	0.609	0.0386
Herb cover*	Trail vs. strip	1.080	0.119	0.327	Linear	11.821	0.001	0.185	0.326	1.493	0.023	0.162
	Centre vs. outer	1.326	0.090		Quadratic	0.231	0.218	0.133	0.336	0.610	0.066	0.122
Herb height	Trail vs. strip	5.0	0.709	32.6	Linear	348.8	0.002	132.2	0.018	15.2	0.317	12.7
	Centre vs. outer	32.6	0.355		Quadratic	159.3	0.005	14.7	0.241	0.5	0.826	8.7
Grass cover*	Trail vs. strip	53.198	0.003	2.166	Linear	0.127	0.544	1.700	0.057	0.000	0.995	0.307
	Centre vs. outer	17.419	0.030		Quadratic	0.139	0.473	0.519	0.190	0.094	0.553	0.237
Grass height	Trail vs. strip	422.1	0.053	73.3	Linear	2894.5	0.001	222.5	0.113	495.2	0.032	64.5
	Centre vs. outer	580.1	0.031		Quadratic	59.9	0.168	108.4	0.080	107.0	0.081	24.4
Raspberry density*	Trail vs. strip	116.78	0.002	3.86	Linear	14.51	0.008	8.43	0.026	5.08	0.062	0.97
	Centre vs. outer	94.11	0.003		Quadratic	34.21	0.001	10.62	0.002	4.02	0.017	0.38
Raspberry height	Trail vs. strip	213.0	0.136	67.4	Linear	1161.5	0.001	159.6	0.055	614.7	0.004	25.7
	Centre vs. outer	25.7	0.564		Quadratic	708.1	0.001	0.2	0.894	1.3	0.735	9.8
Speckled alder density*	Trail vs. strip	5.5492	0.106	1.5377	Linear	2.2329	0.015	0.3044	0.261	0.2749	0.283	0.198
	Centre vs. outer	8.1811	0.060		Quadratic	0.3716	0.026	0.0154	0.570	0.0158	0.566	0.0427
Speckled alder height	Trail vs. strip	32675	0.080	6816	Linear	90621	0.001	343	0.268	1540	0.046	221
	Centre vs. outer	54357	0.037		Quadratic	728	0.284	1044	0.210	1358	0.162	506
Coarse-textured sites												
Feathermoss cover*	Trail vs. strip	61.824	0.018	4.195	Linear	0.002	0.897	0.873	0.030	0.364	0.102	0.081
	Centre vs. outer	0.697	0.704		Quadratic	2.980	0.003	0.050	0.441	0.058	0.410	0.069
Ericaceous cover*	Trail vs. strip	7.026	0.188	2.788	Linear	36.435	0.001	1.605	0.025	0.520	0.118	0.132
	Centre vs. outer	0.301	0.759		Quadratic	0.293	0.083	0.633	0.028	0.160	0.166	0.556
Ericaceous height	Trail vs. strip	422.68	0.013	23.37	Linear	745.29	0.001	5.05	0.317	0.04	0.923	3.87
	Centre vs. outer	3.63	0.714		Quadratic	5.04	0.233	12.47	0.092	3.52	0.306	2.56

*Values are square-root transformed.

Fig. 3. Vegetation competition on three microsites 1–7 years after careful logging on fine- to medium-textured sites. Mean square errors are given in Table 1.



trails (Fig. 3). Over the study period, densities followed the same pattern across positions (Table 1): they increased slowly until year 5 then more rapidly in the two following years. Alder heights increased linearly during the course of the study and never reached a significant plateau over 7 years. The increase was steeper in the centre strip position than in the outer strip.

Natural regeneration on fine- to medium-textured sites

Natural regeneration on fine- to medium-textured sites was composed of black spruce, balsam fir, and larch, although species representation was quite different from block to block (Table 2). Harvesting operations reduced black spruce density by at least 89% in skid trails (Fig. 4). The apparent difference in density between the centre and outer

Table 2. Univariate repeated measures analyses for stocking (frequency (%) of 2-m^2 quadrats with at least one stem) of different species as affected by position relative to skid trails on fine- to medium- and coarse-textured sites 1 and 7 years after harvesting.

	Stocking, year 1			Stocking, year 7			ANOVA			
Block	Centre strip	Outer strip	Skid trail	Centre strip	Outer strip	Skid trail	Effect	MS	*p*	MSE
Black spruce: fine- to medium-textured sites										
1	50	10	10	60	70	50	Mean time effect	3400	0.005	177.0
2	10	0	0	0	11	11	Skid trail vs. strip	715	0.091	
3	50	30	10	50	60	30	Centre strip vs. outer strip	2850	0.007	
4	80	40	20	50	60	60				
Mean	48	20	10	40	50	38				
Balsam fir: fine- to medium-textured sites										
1	90	60	0	90	50	10	Mean time effect	90	0.217	47.81
2	40	50	20	44	56	33	Skid trail vs. strip	384	0.030	
3	70	40	30	70	40	30	Centre strip vs. outer strip	40	0.393	
4	50	50	30	50	40	50				
Mean	62	50	20	64	46	31				
Larch: fine- to medium-textured sites										
1	0	0	0	70	90	90	Mean time effect	14 840	0.001	196
2	0	0	0	0	0	22	Skid trail vs. strip	1410	0.036	
3	0	0	0	0	10	20	Centre strip vs. outer strip	800	0.090	
4	20	10	10	20	60	80				
Mean	5	2	2	22	40	53				
Black spruce: coarse-textured sites										
1	60	20	13	53	13	53	Mean time effect	19	0.710	117.4
2	40	27	13	13	13	7	Skid trail vs. strip	2134	0.013	
3	93	80	13	87	67	40	Centre strip vs. outer strip	6	0.832	
Mean	64	42	13	51	31	33				

Note: The time effect and the interaction between time and position were examined.

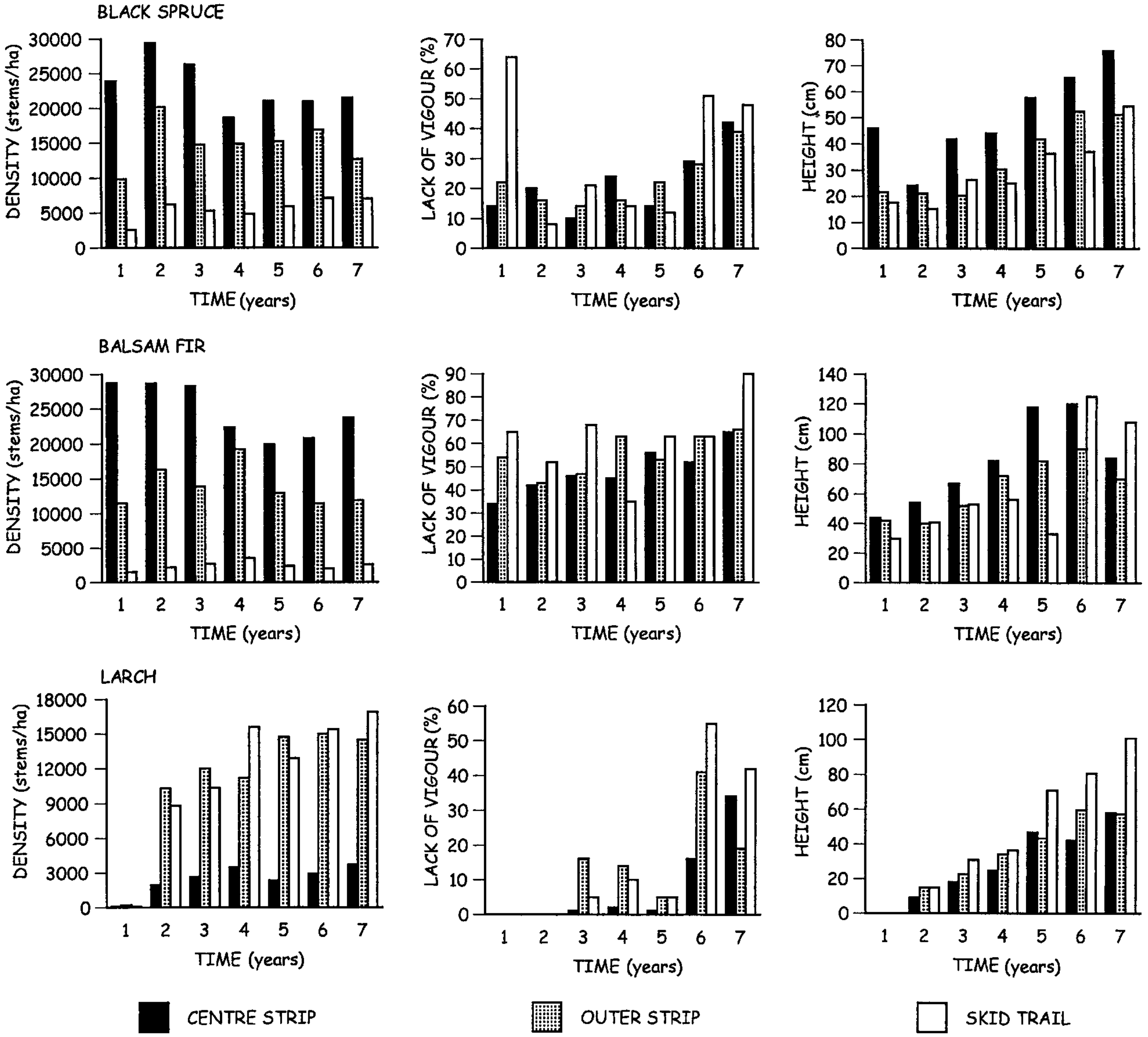
portions of protection strips was not significant over the 7-year period (Table 3). No significant overall change in black spruce regeneration density occurred during the surveyed period in any of the positions, but stocking increased in outer strips and trails (Table 2). There was a significant relationship between time and the proportion of trees showing a lack of vigour. In all positions, the percentage of trees showing lack of vigour increased from below 25% in the second year of the survey to over 40% in the seventh year, but the skid trail showed a steeper increase at the end of the study period. Black spruce mean tree height was highest in strip positions, and mean height differences between positions remained significant during the study. Mean annual height growth of black spruce (all positions) was 6.1 cm/year from year 2 to 7.

Harvesting operations appeared to reduce balsam fir natural regeneration density by at least 95% in skid trails (Fig. 4). Differences between trail and strip positions remained significant over the 7 years, as no changes in density were observed in any of the positions (Table 3). No significant difference in fir density was observed within the protection strip. Stocking remained unchanged through time in the protection strip but increased somewhat in the skid trail position from 20 to 30% over 7 years (Table 2). There was a linear increase through time in the proportion of balsam fir stems showing a lack of vigour, from 48 to 74%, on average, that affected all positions equally. The increase in lack of vigour of fir was lower in the protection strip in the last years of the survey but continued to increase in the trails (Table 2). No significant differences in height nor in growth rate of fir were found among positions. Mean height of balsam fir increased linearly over the 7-year period, from 39 to 81 cm (Fig. 4). Mean annual height growth (all positions) was 6.6 cm/year from year 2 to 7.

One year after harvesting, eastern larch regeneration was found in only one of the four surveyed cutovers (Table 2); its presence was linked to the proximity of residual trees that provided a source of seed. In subsequent years, seedling establishment occurred in three of the four blocks; as a result, one block (No. 2) was removed from the analysis for lack of regeneration. In the centre strips of the three remaining blocks, larch density remained more or less constant over the study period and was 3692 stems/ha at year 7; stocking was 22.5% (Fig. 4). Densities increased linearly in the outer strip and skid trail positions until year 5 when they reached a plateau at 14 715 and 12 888 stems/ha (40 and 53% stocking), respectively. Despite a large increase in the proportion of trees showing a lack of vigour during the last 2 years of the survey, the numbers were not consistent enough to demonstrate any significant trend (Table 3); skid trails were more affected than protection strips, although differences were not highly significant. Because of the lack of regeneration in some positions, the height data was somewhat unbalanced, but results showed a clear linear relationship with time that was similar for skid trail and protection strip positions. Mean (over all positions) yearly increase in height, from year 2 to 7, was 10.9 cm/year.

Total softwood stocking values (spruce, fir, and larch) based on the 2-m^2 plot size for skid trail, outer strip, and

Fig. 4. Natural regeneration on three microsites 1–7 years after careful logging on fine- to medium-textured sites. Mean square errors are given in Table 3.



centre strip positions were 25, 55, and 78%, respectively, in year 1 and 69, 74, and 71%, respectively, in year 7.

Vegetation trends between 1993 and 1999

Of the two principal components retained, the first explained 36% of the variance, and the second explained 22%. The first component was highly correlated with heights of grasses, herbs, and raspberry and, to a lesser extent, with raspberry and grass abundance (Fig. 5). The four blocks (cutovers) are particularly distinguished from one another along this axis. Block 2, the balsam fir cutover, is distinguished from black spruce cutovers by its situation in the lower-right quadrant, which indicates a distinctive vegetation character and possibly a more productive site. The second component was positively correlated with black spruce and balsam fir density, feathermoss and sphagnum cover, and alder height and negatively correlated with grass cover and, thus, reflects a gradient of disturbance. The first-year position of the skid trail, outer strip, and centre strip microsites for each block relative to this axis supports this inference regarding disturbance. Arrows drawn between the 1993 and 1999 positions for each individual plot indicate a shift in vegetation for all treatments from lower to higher heights for competing species (axis 1) and toward higher abundance of the residual community of species that occurred in the understory of harvested stands (axis 2). The shift is greater for the disturbed area of the skid trails and the outer part of the protection strip, although there is not a clear convergence of vegetation characteristics among the three microsites on any block.

Competition of coarse-textured sites

On coarse-textured sites, ground-cover vegetation was mostly composed of feathermoss species. Following logging, mean feathermoss cover was reduced to 2% in skid trails compared with 21% in strip centres (Fig. 6). Differences between trail and strip positions remained significant over the 7-year period (Table 1). From year 1 to year 5, centre strip

Table 3. Univariate repeated measures analyses of relationships between natural regeneration dynamics, position relative to skid trails, and time 1–7 years after harvesting on fine- to medium- and coarse-textured sites.

	Among-subject effects				Within-subject effects							
						Mean effect		Skid trail vs. strip		Centre strip vs. outer strip		
Variable	Contrast for position	MS	p	MSE	Contrast for time	MS	p	MS	p	MS	p	MSE
Black spruce: fine- to medium-textured sites												
Density*	Trail vs. strip	55 054	0.015	3292	Linear	47	0.768	1678	0.132	675	0.298	472
	Centre vs. outer	9521	0.164		Quadratic	378	0.234	1	0.946	721	0.126	193
Lack of vigour	Trail vs. strip	1126.2	0.091	228.9	Linear	1735	0.088	314.9	0.392	29.8	0.783	343.0
	Centre vs. outer	4.6	0.894		Quadratic	5094.8	0.023	1904.8	0.095	7.6	0.897	400.4
Height	Trail vs. strip	1622.3	0.078	230.5	Linear	9684.4	0.002	69.5	0.441	12.0	0.738	88.7
	Centre vs. outer	2908.0	0.038		Quadratic	600.4	0.089	18.9	0.689	108.4	0.368	97.0
Balsam fir: fine- to medium-textured sites												
Density*	Trail vs. strip	144 357	0.015	12855	Linear	849	0.178	1173	0.123	495	0.289	365
	Centre vs. outer	21 548	0.243		Quadratic	443	0.308	85	0.643	1608	0.078	356
Lack of vigour	Trail vs. strip	1823.6	0.355	1759.2	Linear	4084.1	0.001	10.0	0.649	123.7	0.150	42.8
	Centre vs. outer	682.5	0.561		Quadratic	969.3	0.081	866.9	0.094	33.0	0.704	204.2
Height	Trail vs. strip	405	0.679	1939	Linear	15 342	0.011	343	0.460	606	0.343	480
	Centre vs. outer	4120	0.241		Quadratic	1297	0.110	84	0.607	307	0.353	256
Larch: fine- to medium-textured sites												
Density*	Trail vs. strip	8725	0.211	3943	Linear	35 336	0.001	1884	0.025	1825	0.027	155
	Centre vs. outer	26 320	0.061		Quadratic	15 155	0.001	356	0.393	785	0.228	388
Lack of vigour	Trail vs. strip	0.286	0.097	0.007	Linear	81.865	0.111	0.844	0.666	0.362	0.770	2.523
	Centre vs. outer	0.115	0.151		Quadratic	0.006	0.819	0.023	0.681	0.002	0.886	0.075
Height	Trail vs. strip	43	0.682	145	Linear	17 837	0.037	1	0.938	281	0.276	61
	Centre vs. outer	57	0.644		Quadratic	81	0.101	2	0.522	93	0.094	2
Black spruce: coarse-textured sites												
Density†	Trail vs. strip	7.0817	0.082	1.325	Linear	0.131	0.139	0.583	0.017	0.04	0.373	0.038
	Centre vs. outer	1.5788	0.336		Quadratic	0.1165	0.129	0.0002	0.937	0.1303	0.114	0.0320
Lack of vigour	Trail vs. strip	1061.2	0.336	886.8	Linear	174.0	0.464	145.8	0.500	21.1	0.792	266.4
	Centre vs. outer	418.9	0.530		Quadratic	1807.7	0.023	331.8	0.198	109.1	0.426	139.3
Height	Trail vs. strip	7957.8	0.114	1950.2	Linear	7371.5	0.027	859.3	0.310	41.2	0.812	635.6
	Centre vs. outer	251.7	0.738		Quadratic	5.3	0.908	201.2	0.493	88.0	0.644	353.7

*Values were square-root transformed.

†$\times 10^8$ for MS and MSE values.

and outer strip cover decreased, while cover in skid trails remained stable. From year 5 to 7, feathermoss cover increased in all positions, and the rate of increase was similar over all positions (Table 1).

Harvesting operations reduced ericaceous shrub cover, primarily composed of sheep-laurel (*Kalmia angustifolia* L.), Labrador-tea (*Ledum groenlandicum* Oed.), and blueberries (*Vaccinium* spp.), from at least 11 to 3% in skid trails (Fig. 6). Cover values were 9% in the outer strip. After harvesting, cover increased linearly in all positions, but the increase was steeper in trails (from 3 to 26% over 7 years) than in protection strips (from 11 to 29% in the centre strip) (Table 1). Mean height of ericaceous shrubs increased linearly with time. The rate of increase was similar for all positions, and heights remained significantly lower in trails than in strips over the entire period.

Natural regeneration on coarse-textured soils

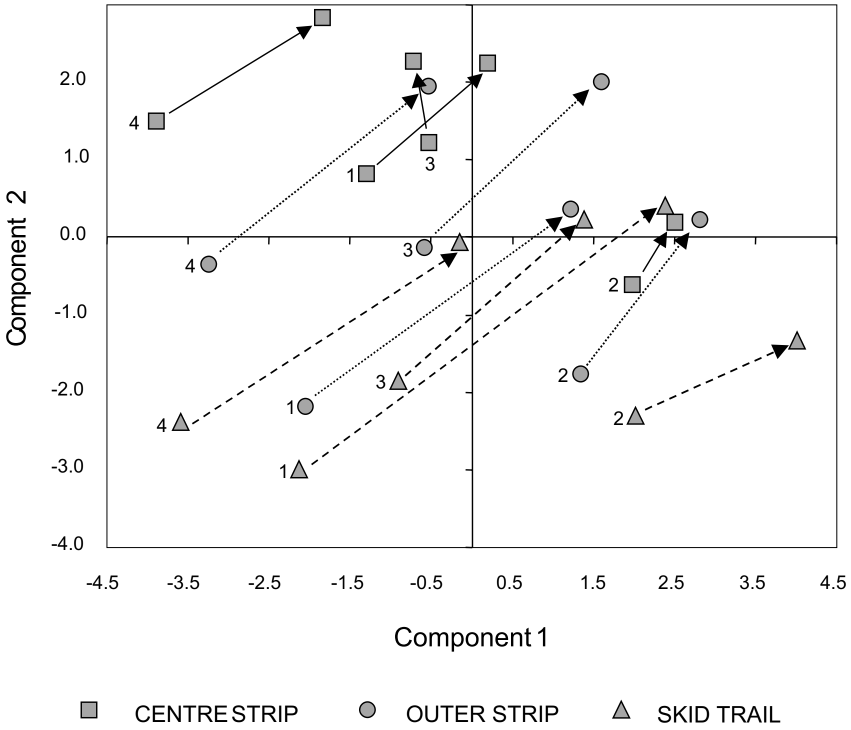
Careful logging operations caused at least a 89% decrease in black spruce density in skid trails (Fig. 7). During the following years, spruce densities in protection strips decreased linearly, while densities in skid trails increased slightly. Changes in density occurred primarily in the first 4 years of the survey (Table 3). At the end of the study, black spruce densities in trails were half those of centre strips with a stocking of 33% compared with 51% for centre strip (Table 2). Proportion of black spruce stems showing a lack of vigour followed a significant U-shaped curve that was similar for all positions. Values increased from year 4 and reached 40% by 7 years after harvesting (Fig. 7). Rate of height growth was also similar over all positions and averaged 4.5 cm/year for years 2–7. Differences in heights between positions were not significant (Table 3).

Discussion

Vegetation development

The protection afforded to soil and vegetation by the type of careful logging used in this study was by no means absolute, even in protection strips. Harvesting occurred in summer, so no additional protection was provided by thick snow cover or frozen soils. The different conditions created by

Fig. 5. Ordination (principal component analysis) of vegetation dynamics on fine- to medium-textured sites. Arrows show changes from year 1 to year 7 for each of three microsites in different blocks. Number beside year 1 symbols identifies the block. Significant correlations between the original variables and component 1 are as follows: grass height, 0.94; herb height, 0.90; raspberry height, 0.82; grass cover, 0.78; raspberry density, 0.77; herb cover, 0.50; speckled alder height, 0.49; and black spruce density, –0.55; and significant correlations with component 2 are as follows: black spruce density, 0.73; feathermoss cover, 0.65; balsam fir density, 0.65; speckled alder height, 0.62; *Sphagnum* cover, 0.55; herb cover, 0.45; and grass cover, –0.51.



careful logging clearly influence vegetation development patterns and the capacity of a site to re-establish a plant community similar to preharvest conditions. Community resilience is greatest where disturbance is lightest (Halpern 1988), and species that were present in the stand understory at the time of harvest were favoured by the greater protection afforded in the centre of protection strips. These tend to be moderate to very shade-tolerant species, Rowe's (1983) "avoiders" and "endurers". In our study, they included black spruce and balsam fir advance regeneration, speckled alder, forest herbs such as sarsaparilla and large-leaved aster, feathermosses and *Sphagnum* mosses on fine- to medium-textured sites, and black spruce, primarily of layer origin (Doucet 1988), ericaceous shrubs, and feathermosses on coarse-textured sites. In contrast, the more severe disturbance on skid trails on fine- to medium-textured sites, characterized by removal or severe injury of existing vegetation and perturbation of surface soil layers, favoured pioneer species, "invaders" and "evaders" according to Rowe (1983), that are able to rapidly exploit newly created niches. In this study, grasses, sedges, raspberry, and larch were clearly more successful in the first years following harvesting in invading skid trails, the most disturbed parts of cutovers. Grasses and sedges may initially establish primarily by seeding in disturbed areas, although rhizome growth is most likely responsible for their expansion in the years immediately following disturbance (MacDonald and Lieffers 1993). Greater mean height values of grasses and sedges for skid trail and outer strip positions compared with the centre strip position suggest that environmental conditions, and possibly less resource competition, favoured growth in the most disturbed sites.

Raspberry followed the same trend as grasses and sedges on fine- to medium-textured sites. Raspberry generally germinates from buried seed in the first year following disturbance, then expands vegetatively and vigorously for about 3 years (Whitney 1986; Harvey et al. 1995; Lautenschlager 1999). It would appear then that by reducing site disturbance in the centre strip position, careful logging was successful in maintaining raspberry at reasonably low levels in this portion of cutovers.

The dominance of grasses, sedges, and raspberry on most disturbed microsites concurs with results of a number of other studies that have evaluated vegetation establishment and development following natural and silvicultural disturbances (Dyrness 1973; Halpern 1988). For example, in a comparison of wildfire and logging disturbances in black spruce – feathermoss forests of western and central Quebec, Nguyen-Xuan et al. (2000) found that shade-intolerant invading species tended to colonize more readily on post-fire sites with thinner duff layers than on clear-cut sites and that these latter sites generally had a higher proportion of species that regenerated vegetatively or by seed under forest cover. Peltzer at al. (2000), comparing effects on vegetation of fire, harvesting, and site preparation in Saskatchewan, found highest cover values of grasses and annual forbs on sites with greatest soil disturbance, that is, those that were most intensively site prepared. Our herb group, which included both indigenous forest species and ruderals, was the one species group that generally had highest cover values in the outer

Fig. 6. Development of moss cover and ericaceous vegetation on three microsites 1–7 years after careful logging on coarse-textured sites. Mean square errors are given in Table 1.

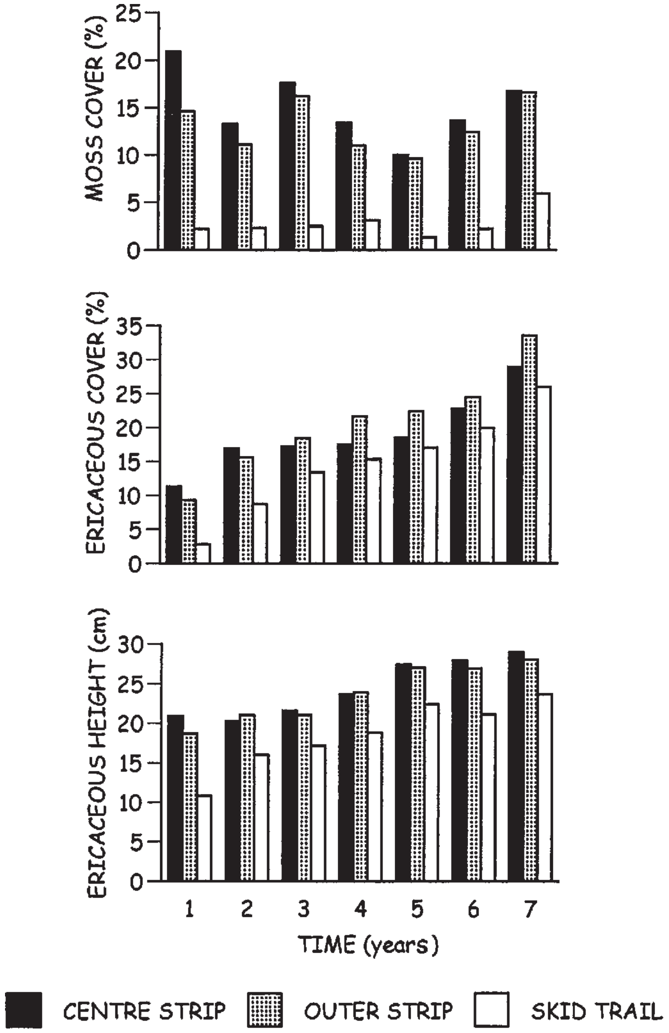
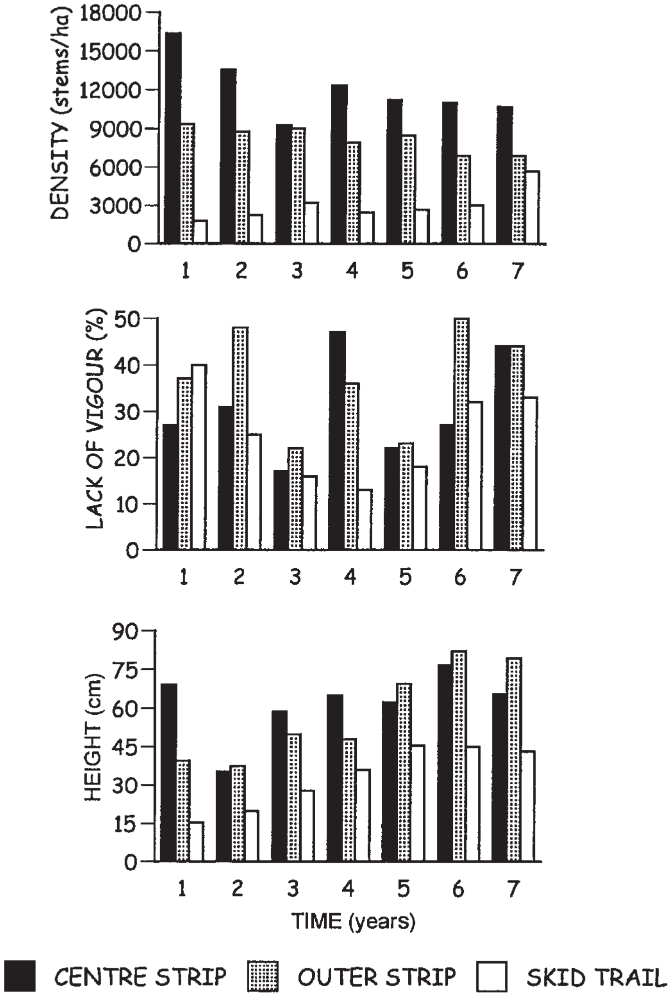


Fig. 7. Natural black spruce regeneration on three microsites 1–7 years after careful logging on coarse-textured sites. Mean square errors are given in Table 3.



strip position. This would suggest that the intensity of disturbance in the intermediate zone, between the skid trails and the protection strip centres, was such that both residual forest herbs and invasive pioneer species were accommodated.

Alder, a species present in the undisturbed forest understory, shows the opposite trend to raspberry, grasses, and sedges and may be a factor limiting the expansion of these latter species in the centre strip position. In its current practice, careful logging is species indiscriminate and has the effect of protecting understory shrubs and woody vegetation as well as advance softwood regeneration. Alder stems in trails consisted largely of damaged residual stems that survived skidding. Density levels in the centre strip position remained high and relatively constant, possibly because of the lack of ground disturbance and the competitive and buffering effects of high densities of spruce and fir in the protection strip.

Conifer regeneration

Because sites were not sampled prior to careful logging, our best minimum estimate of advance regeneration densities, and the best indication of direct mortality in proximity to skid trails caused by harvesting operations, are provided by first-year values for the centre strip positions. Obviously, however, because mortality did occur in this zone, this reference undervalues both real preharvest densities and mortality rates caused by harvesting operations in other positions. Advance regeneration levels of black spruce and balsam fir on the fine- to medium-textured sites were at least 25 000 stems/ha, a figure that corresponds well with Doucet's (1988) global study of advance regeneration in Quebec. These values also indicate that the cutovers, six of seven of which were mapped as having >80% black spruce overstory, are shifting to a spruce–fir codominance in the future stand. Frisque et al. (1978) documented mortality levels of 58–80% caused by conventional logging without regeneration protection and, like Brumelis and Carleton (1988), observed changes in cover dominance after harvesting from softwood to mixed or hardwood. Careful logging has been demonstrated elsewhere to reduce mortality of advance softwood regeneration compared with conventional practices (Pomminville 1993; Ruel 1992), although it is not necessarily effective in preventing invasion of competitive woody species that may establish from buried seed or from vegetative sprouts (Laflèche et al. 2000).

Some recruitment of black spruce was observed in year 2 in the skid trail and outer strip positions and, to a lesser extent, of fir although only in the latter position. Reports on the period of release of viable black spruce seed vary in the literature but tend to suggest that most seedlings establish within about 3 years after disturbance. Fleming and Moss (1996) suggested that 65–90% of viable seed may be released from cones contained in logging slash within 1 year of harvesting and St-Pierre et al. (1992) reported that 95.5% of seedlings present 5 years after fire established within the first 3 years. In our study, no residual mature spruce stems were left in cutovers. Thus, the only sources of black spruce seed were cones contained in slash, and as harvesting was done by whole-tree logging, most cones were exported to roadside. Cut-to-length harvesting and (or) seed-tree retention would likely have produced more recruitment of black spruce than occurred in this study. The rapid invasion of raspberry and grasses might also partially explain the lack of recruitment of black spruce on skid trails after year 2; however, this did not appear to negatively influence larch recruitment, especially in skid trail and outer strip positions, in years 2–4. In fact, the low stocking of fir and spruce in skid trails and outer strip positions was largely compensated for by seeding in of larch.

A high percentage of black spruce stems in the skid trail position showed poor vigour in year 1. Mean stem height in the centre strip position actually decreased from years 1 to 2 as a result of stem leader mortality, especially in taller stems. Balsam fir did not incur leader loss to the same extent as spruce but did maintain relatively high levels of lack of vigour throughout the study period and in all positions. Height decreases in balsam fir in year 7 were primarily due to an early summer frost. Lack of vigour may be attributed in part to a longer period of physiological acclimatization to post-harvest environmental conditions. However, given that softwood densities reached over 50 000 stems/ha in centre strips, this lack of vigour is likely also the result of inter- and intra-specific crowding, especially on smaller stems. Our indicators of vigour based on live crown ratio and leader characteristics were relatively simple, but support work by Ruel et al. (2000). Although preharvest growth rates were not measured, height growth following harvesting may also be a good indicator of vigour or stress due to harvesting. Mean growth rates through the study period for fir (6.6 cm/year) and spruce (6.1 cm/year) suggest considerable lack of vigour but are comparable with values for the same period and on similar mesic boreal sites reported by Boily and Doucet (1993) for dominant black spruce layers. These authors observed annual leader growth of 15 cm at 7–8 years after harvest and 36 cm at 20 years. In a related study undertaken on our sites, container-grown black spruce seedlings planted in skid trails in year 1 had a mean annual height growth of 10.7 cm over 6 years and attained heights similar to those of natural stems in the protection strip by year 7 (S. Brais and B. Harvey, unpublished data).

Silvicultural and management interpretations

In the short term, the heterogeneity of post-harvest stand structure and composition can confound silvicultural prescriptions in that in some instances, protection strips with softwood densities exceeding 50 000 stems/ha may require precommercial thinning or cleaning, while skid trails may benefit from spot planting. Careful logging has the local effect of creating an undulation of alternating linear communities: protection strips characterized by dense softwood regeneration with considerable height variability of residual stems and a high proportion of native understory species and skid trails characterized by fewer and shorter softwood stems and a plant community dominated by ruderal species. Our results suggest that vegetation characteristics in the three microsite positions do not converge in the short (7 years) term (Fig. 5), although on the temporal scale of a forest rotation, differences will tend to diminish. Nonetheless, the patterns created by careful logging raise a number of questions concerning stand structure, growth, and yield (Morin and Gagnon 1991; Lussier et al. 1992; Groot and Horton 1994).

On coarse-textured sites, careful logging had the immediate effect of significantly reducing ericaceous cover in the skid trail. No rapid invasion of pioneer species occurred on coarse-textured sites; rather, ericaceous species showed particular resilience to harvest disturbance by expanding into outer strip and skid trails positions from residual plants and surviving belowground structures. From a first-year mean ericaceous cover ratio of about 5:1 between centre strip and skid trail positions, this difference essentially disappeared over the 7-year period of the study. Comparing burns and carefully logged black spruce stands in Quebec, Smith et al. (2000) found no significant differences in fine-root length of ericaceous shrubs between disturbance types in recent (<11 years) burns and cutovers but found older cutovers (~55 years) to contain over three times the quantity of older fires (~75 years). Moreover, Yamasaki et al. (1998) found an inverse relationship between proximity of sheep-laurel and growth and vigour attributes of black spruce in clearcuts in central Newfoundland. Therefore, the aspect which may be of greatest concern for post-harvest development of the stands in our study is the sustained increase in ericaceous cover in all positions, including the protection strip.

Compared with fine- to medium-textured sites, post-harvest regeneration on the coarse-textured sites was considerably lower, showed little recruitment, and was primarily composed of black spruce. Although there was considerable variability in black spruce stocking values among blocks, the lower density and slow growth of the spruce regeneration, coupled with a linear increase in ericaceous cover through the 7-year study period, signal possible future problems on these sites.

Conclusion

On both site types, careful logging succeeded in maintaining a substantial portion of advance regeneration and understory vegetation. While the study was not intended to compare the effects of careful logging with natural disturbance, careful logging does not emulate crown fires that generally consume an important part of surface soil layers. Bergeron et al. (1999) suggest that careful logging is more similar to disturbance caused by spruce budworm infestations in which repeated defoliation of the softwood overstory kills canopy host trees without direct physical disturbance to surface soil layers. Interestingly, after a decade of extensive application of careful logging in Quebec, there is now a growing interest in developing other harvesting methods, including partial-cutting systems, which find their justification in a greater understanding of natural disturbance dynamics.

The differential impact of careful logging has the local short-term effect of creating alternating bands of plant communities that reflect relatively high and low levels of disturbance. While these differences may gradually attenuate with time, the heterogeneity created by careful logging has important implications both for short-term silvicultural treatments and stand-level growth and yield modelling. Forest renewal options can be affected by suboptimal site occupancy. High densities and vertical structure of stems and abundant downed logs can hinder precommercial thinning in protection strips, and spot planting limited to trails is expensive. Long-term concerns are related to the fact that mean values of stand growth do not necessarily provide a true portrait of the variability of field conditions.

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