Regeneration development under shelterwoods in a lowland red spruce – balsam fir stand

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Abstract: The shelterwood system can be used to establish regeneration and to improve the growing conditions of seedlings and, thereby, increase their probability of survival after final harvest. To determine the cutting intensity that best promotes the development of red spruce (*Picea rubens* Sarg.) regeneration, an experiment, including four repetitions of five treatments (control; low, moderate, and heavy partial cuttings; and clear-cutting), was established in a lowland stand in Quebec, Canada, dominated by red spruce and balsam fir (*Abies balsamea* (L.) Mill.). Regeneration development responses to treatments varied according to cutting intensity, species, and position relative to the skidding trails in the residual stands. Ten years after treatment, red spruce seedlings were well established but were smaller than those of balsam fir and deciduous species. Red spruce seedling height was generally greater in partial-cut skidding trails, as was light availability. However, in clearcuts, the size of red spruce seedlings established in skidding trails seemed to be negatively affected by the considerable quantity of woody debris strewn over them. Among the partial-cut treatments, tree regeneration leaf biomass was the highest where 60% of the initial basal area was removed. Thus, this treatment is an attractive alternative to clear-cutting in such lowland stands where watering-up is anticipated after final harvest.

Résumé : La coupe progressive d'ensemencement peut être utilisée pour établir la régénération et pour améliorer les conditions de croissance des semis, ce qui augmenterait leur probabilité de survie après la coupe finale. Dans le but de déterminer l'intensité de coupe maximisant le développement de la régénération d'épinette rouge (*Picea rubens* Sarg.), un dispositif expérimental, comprenant quatre répétitions de cinq traitements (témoin; coupe partielle d'intensités faible, modérée et forte; et coupe totale), a été établi dans un peuplement mal drainé et dominé par l'épinette rouge et le sapin baumier (*Abies balsamea* (L.) Mill.) de la province de Québec, Canada. La réaction du développement de la régénération aux traitements a varié en fonction de l'intensité de coupe, de l'espèce et de la position des semis par rapport aux sentiers de débardage dans les peuplements résiduels. Dix ans après l'application des traitements, les semis d'épinette rouge étaient bien établis, mais étaient plus petits que les semis de sapin baumier et des espèces caducifoliées. Les semis d'épinette rouge étaient généralement plus hauts dans les sentiers de débardage des coupes partielles tout comme l'était la disponibilité de la lumière. Cependant, dans les coupes totales, la taille des semis d'épinette rouge établis dans les sentiers de débardage semblait négativement affectée par la quantité considérable de débris ligneux répandus sur et autour d'eux. Parmi les traitements de coupe partielle, la plus forte biomasse foliaire de la régénération d'espèces arborescentes a été observée dans l'intensité de coupe qui a enlevé 60 % de la surface terrière initiale du peuplement. Ce traitement constitue donc un choix intéressant pour remplacer la coupe totale dans ces peuplements mal drainés où une remontée de la nappe phréatique est anticipée après la coupe finale.

Introduction

The shelterwood method is generally intended to establish natural regeneration by gradually removing the overstory through one or more partial cuttings followed by a final harvest. This silvicultural system is normally used where a dense canopy hinders seedling establishment and when stands composed of intermediate to shade-tolerant species are desired. In mixed conifer stands dominated by red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.), the shelterwood method often has the secondary objective of promoting regeneration of red spruce at the expense of less desired balsam fir, which is more vulnerable to spruce budworm (*Choristoneura fumiferana* (Clem.)) defoliation (MacLean and MacKinnon 1997; Solomon et al. 2003) and has lower commercial value than spruce (Sendak et al. 2003). Red spruce seedling establishment can be improved by partial cutting, especially if, through logging operations, the humus layer can be disturbed locally to expose receptive mineral soil, as is the case for other spruce species (Wurtz and Zasada 2001; Nilsson et al. 2002; Prévost and Pothier 2003).

Because red spruce and balsam fir are both very shade tolerant, they can be present in the regeneration stratum below a dense canopy, where seedlings survive but, generally, stay small. These small seedlings are commonly rooted in the upper part of the organic layer, which dries out after clear-cutting or the final harvest of the shelterwood method, a situation that often results in extensive seedling mortality (Jablanczy 1969; Örlander and Karlsson 2000; Nilsson et al. 2002). Red spruce is also particularly sensitive to full light

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Table 1. Mean merchantable basal area of sample plots immediately before and after treatment application.

	Cutting intensity				
	Control	Low	Moderate	Heavy	Total
Basal area before treatment (m^2/ha)					
Red spruce	20.2±11.1	25.3±13.8	24.1±3.1	22.3±4.5	19.0±14.5
Balsam fir	10.8±2.5	9.6±7.4	7.8±2.9	8.8±4.8	5.8±1.4
Other conifer species	6.0±8.8	4.6±4.5	2.1±2.3	1.7±2.8	12.7±13.0
Deciduous species	5.4±4.7	2.4±2.2	3.2±2.1	4.4±3.1	10.2±4.9
Total	42.4±3.3	41.9±3.7	37.2±2.1	37.2±2.1	47.7±7.1
Basal area after treatment (m^2/ha)					
Red spruce	20.2±11.1	17.4±8.6	16.7±3.6	11.9±2.5	0.0±0.0
Balsam fir	10.8±2.5	4.7±4.5	2.1±0.9	2.3±2.8	0.0±0.0
Other conifer species	6.0±8.8	2.9±3.2	0.7±1.4	0.8±1.5	0.0±0.0
Deciduous species	5.4±4.7	0.2±0.6	0.0±0.0	0.4±0.5	0.0±0.0
Total	42.4±3.3	25.2±2.0	19.5±2.6	15.4±1.4	0.0±0.0

Note: Basal area per hectare was calculated for trees that had a diameter at breast height >9 cm. Each mean and standard deviation was calculated for four 20 m × 20 m plots. Cutting intensity targets for removal of merchantable basal area are as follows: control, 0%; low, 15% ; moderate, 30%; heavy, 40%; total (clearcut), 100%.

and to temperature extremes at the juvenile stage (Dumais and Prévost 2007). Moreover, seedlings of both these species tend to die from the rise in the water table that can occur on clear-cut wetlands (Roy et al. 2000). Hence, the shelterwood method can also have the objective of developing tree seedlings until they have reached a minimum height under the moderate microclimate of the sheltering overstory to ensure that they can survive the sudden changes in environmental conditions caused by final harvest. This minimum height was calculated to be at 20 cm by Frank and Bjorkbom (1973) and Baldwin (1977) for red, white (*Picea glauca* (Moench) Voss), and black (*Picea mariana* (Mill.) BSP) spruces and balsam fir in northeastern North America, whereas Sikström and Glöde (2000) considered a seedling height between 1 and 2 m necessary to minimize Norway spruce (*Picea abies* (L.) Karst.) mortality in Sweden.

Thus, on many sites, the shelterwood method is used not only for establishing new seedlings of the desired species, but also for acclimating advance regeneration to increased light intensity and for stimulating their growth so as to minimize mortality after the final harvest. Moreover, the development of this regeneration should build up a substantial leaf biomass that would decrease water table rise after the final cut by increasing site evapotranspiration (Pothier et al. 2003). Accordingly, the objectives of this study are to determine the seed cut intensity that (*i*) promotes establishment of red spruce seedlings, (*ii*) reduces development of broadleaved species, (*iii*) stimulates diameter growth of residual standing trees, and (*iv*) mitigates water table rise after final harvest. These objectives will be achieved by analysing the results of an experiment that includes four repetitions of five partial cutting intensities. The results on water table rise during the first 5 years following partial cutting are already available (Pothier et al. 2003). This paper deals with the 10 year survey of regeneration establishment and development and of shelter tree growth response.

Materials and methods

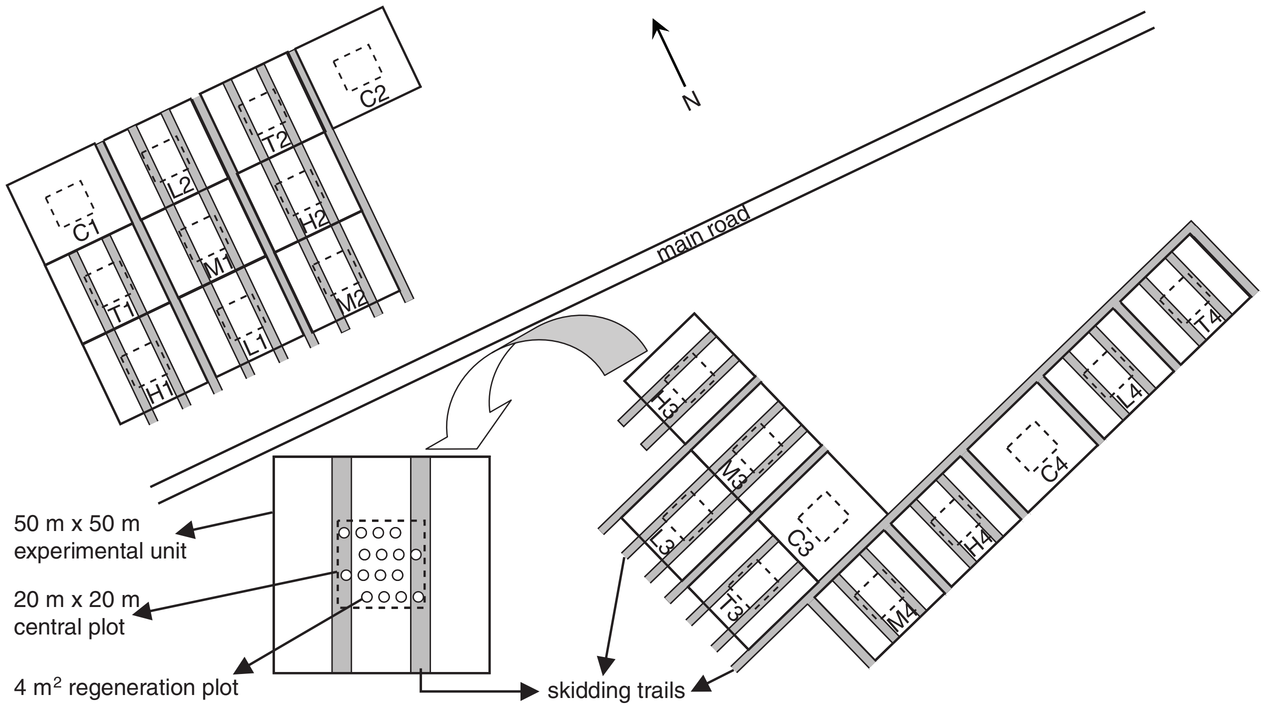
Study area

The 30 ha stand is located in the eastern part of the sugar maple (*Acer saccharum* Marsh.) – basswood (*Tilia americana* L.) bioclimatic domain known as St. Lawrence Lowland ecological region 2b (Saucier et al. 1998), near Villeroy (46°30′N, 71°45′W), Quebec, Canada. The study area is characterized by flat topography, a mean annual precipitation of 1083 mm (837 mm of which falls as rain), and a mean annual temperature of 4.5 °C. The growing season typically extends from the beginning of May to the end of September, during which rainfall averages 510 mm and mean air temperature reaches 15.7 °C. The soil is a gleyed, humo-ferric podzol characterized by the presence of a compacted layer at a depth of 80–100 cm, which is responsible for the poor drainage of the site. The organic layer is about 10 cm thick, and roots of dominant trees are found mainly to a depth of 25 cm.

The experiment was established in 1994 in a stand dominated by red spruce and balsam fir. The remainder of the stand was composed of eastern hemlock (*Tsuga canadensis* (L.) Carr.), eastern white cedar (*Thuja occidentalis* L.), red maple (*Acer rubrum* L.), and yellow birch (*Betula alleghaniensis* Britt.). The merchantable basal area (BA) of this 80 year old stand was approximately 40 m^2/ha (Table 1), and its dominant height was near 18 m. The understory was mainly composed of numerous, small (<30 cm in height) balsam fir seedlings that were established on an almost continuous carpet of *Sphagnum* spp. and feathermoss (mostly *Pleurozium schreberi* (Brid.) Mitt. and *Hylocomium splendens* (Hedw.) BSG). Other species were sparse in the understory and included red maple, *Coptis groenlandica* (Oeder) Fern., *Oxalis montana* Raf., and *Dennstaedtia punctilobula* (Michx.) Moore.

In 1994, a complete, randomized block design with four repetitions (blocks) was established in the stand (Fig. 1). In each block, five 50 m × 50 m experimental units (EUs) were delimited, and each received one of the following treatments: an uncut control; three partial-cutting levels that aimed to remove 15% (low), 30% (moderate), or 45% (heavy) of the merchantable BA; and a clearcut (removal of 100% of the merchantable BA). Because we tried to control the composition, the BA, and the mean tree size among EUs of each block, it was not possible to use EUs >0.25 ha, even

Fig. 1. Layout of experimental units (EUs) in the complete experimental block design. For each EU, the uppercase letter refers to the cutting intensity (C, control; L, low partial cutting; M, moderate partial cutting; H, heavy partial cutting; and T, total cutting), and the number is the repetition (block).



though operational harvested blocks near the study area covered approximately 10 ha. This can limit the scope of the results, especially for clear-cut EUs, which were expected to produce higher watering-up than was measured (Pothier et al. 2003). In the partial-cut treatments, trees to be removed were marked according to a low thinning prescription (i.e., the lower crown classes were marked first). These treatments were applied in March 1995 to take advantage of the presence of a 1 m thick snow cover that protected the soil and advance regeneration from machine traffic and other potential harvest-related damage. The harvesting system was composed of a harvester and a forwarder that were restricted to 4.6 m wide trails (Fig. 1), which corresponded to approximately 25% of the stand area (the strips between skidding trails were 13.6 m wide). Trees were delimbed on site, and logging debris was placed on the skidding trails for the most part. Because prescribed partial cuttings were defined without taking into account the narrow, clear-cut skidding trails, the 15%, 30%, and 45% partial cuts resulted in the actual removal of about 40%, 50%, and 60% of the BA, respectively (Table 1).

Tree inventory

A forest inventory was conducted immediately after harvesting during spring 1995, at which time each tree was numbered. This inventory was repeated during fall 1999 and again in fall 2004. This inventory consisted in measuring the diameter at breast height (DBH) (±1 mm) of all trees (>1.1 cm) of each species in 20 m × 20 m plots located in the central part of each of the 20 EUs (Fig. 1). Thus, these 20 m × 20 m central plots were surrounded by 15 m buffer strips that isolated these plots from the influence of other treatments applied in adjacent EUs. Moreover, five dominant trees per plot were selected to determine their total height. From the repeated measurements of each numbered tree, we were able to calculate their diameter increment for 5 and 10 year periods as well as to determine tree mortality.

Regeneration inventory

A regeneration inventory was performed at the end of every growing season from 1995 to 1999 and then in 2001 and 2004 (year 10). This inventory only took into account small regeneration, i.e., <1.3 m in 1995, composed of commercial species and was carried out by counting the seedlings per species and height classes in 16 permanent, circular, 4 m^2 plots systematically established in each central plot of the 20 EUs (5 treatments × 4 blocks, 320 plots total; Fig. 1). Twelve of these sixteen 4 m^2 plots were located below the shelter trees, and the four others were placed in skidding trails. This regeneration inventory excluded small trees that were>1.3 m in 1995, because they were already measured in the tree inventory. However, the regeneration inventory took into account seedlings that were <1.3 m in 1995 but that had reached this height in the following years. Seedling height classes were as follows: (*i*) 0–30 cm; (*ii*) 31–100 cm; and (*iii*) 101–400 cm. The median of these height classes was used to calculate the diameter of the seedlings, with the linear regressions published by Roussopoulos and Loomis (1979). Then, this calculated diameter was used to calculate regeneration leaf biomass according to the species-specific power equations developed by Roussopoulos and Loomis (1979). For balsam fir, red spruce, and red maple, these equations all had R^2 values >0.90. Moreover, within each plot, we calculated the mean height and the percentage of ground covered by woody debris left after logging as well as the regeneration stocking, which was de-

Table 2. Probability values for red spruce, balsam fir, and deciduous species of different height classes associated with factors and interactions submitted to a mixed model of covariance analysis that took into account irregular time intervals between repeated measurements of regeneration stocking.

	Red spruce			Balsam fir			Deciduous species		
Source of variation	>0 cm	>30 cm	>100 cm	>0 cm	>30 cm	>100 cm	>0 cm	>30 cm	>100 cm
Covariable	<0.0001	0.0019	0.1287	0.9119	0.0023	<0.0001	0.5911	0.0003	0.0056
Cutting intensity (CI)	0.3180	0.0018	0.0003	0.0053	0.0598	0.0002	0.0250	0.0130	0.0003
Position (P)	0.0001	0.4531	0.5458	0.0043	0.1225	0.4785	0.0695	0.3489	0.0787
Year (Y)	0.0010	<0.0001	<0.0001	0.0091	<0.0001	<0.0001	0.0410	<0.0001	<0.0001
CI × P	0.4035	0.0762	<0.0001	0.0001	0.6410	0.0712	0.0073	0.5269	0.0756
CI × Y	0.2694	<0.0001	<0.0001	<0.0001	0.0172	<.0001	0.0031	0.0006	<0.0001
P × Y	0.0001	0.4519	0.5454	0.0044	0.1239	0.4816	0.0700	0.3489	0.0778
CI × P × Y	0.4138	0.0762	<0.0001	0.0001	0.6430	0.0708	0.0075	0.5272	0.0747

Note: The tree height classes of >0, >30 and >100 correspond to stocking of seedlings 0–30, 31–100, and 101–400 cm, respectively. Position refers to location of regeneration plots (between or in skidding trails).

fined as the percentage of the 4 m^2 plots with at least one live seedlings of the considered species.

Light availability

In July 1997, the proportion of incident solar irradiance that reached the seedlings was calculated using hemispherical photography. A self-levelled Nikon camera mounted on a monopod and equipped with a Sigma 8 mm fish-eye lens was placed just above the seedlings in each of the 320 regeneration plots, and photographs were taken using color slide film. The processed slides were scanned with a Nikon LS-2000 35 slide scanner, and the digitized images were analyzed using the gap light analyser software developed by Frazer et al. (1999). This software calculated the amount of direct plus diffuse radiation below the canopy for a growing season that was specified to extend from mid-May to mid-September. This index, expressed as a percentage of the radiation found above the canopy, was individually calculated for the 320 digitized images. For each EU, percentage of radiation was averaged for regeneration plots located under the shelter trees (12 plots) and those located in the skidding trails (4 plots).

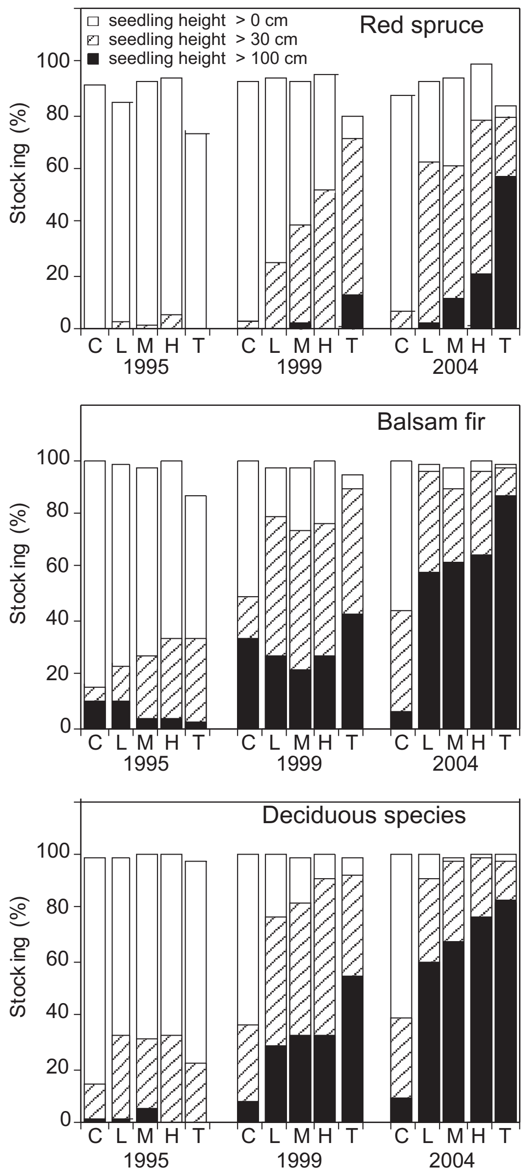
Statistical analyses

Regeneration data (stocking and number of seedlings per hectare) were submitted to a mixed model of covariance applied to a completely randomized block design with repeated measurements using the MIXED procedure of the SAS system (SAS Institute Inc., Cary, N.C.). The fixed effects used in these analyses were the years of inventory, the cutting treatments, the positions of the regeneration plots relative to the skidding trails, and the interactions among these factors. The blocks and the interaction between the blocks and the cutting treatments were used as random effects. Covariables submitted to these analyses corresponded to the stocking or the number of seedlings per hectare measured before the application of the cutting treatments when the independent variables were stocking and number of seedlings after treatment, respectively. Moreover, a power covariance structure, with time interval between two consecutive inventories as the power, was used in the model to take into account the irregular time intervals between repeated measurements of each regeneration plot (Moser 2004). For tree data, the 10 year diameter growth was submitted to an analysis of covariance for a completely randomized block design using the general linear models (GLM) procedure of the SAS system (SAS Institute Inc., Cary, N.C.). The covariable used in this analysis was tree diameter measured at year 0, and the classification variables were the blocks and the cutting treatments. This analysis allowed us to detect a significant effect of the interaction between cutting treatments and tree diameter at the beginning of the experiment. To help understand this significant interaction and to facilitate presentation of the results, we grouped tree diameter at the beginning of the experiment into four classes: (1) DBH < 10 cm, (2) 10 cm ≤ DBH < 20 cm and (3) 20 cm ≤ DBH < 30 cm, and (4) DBH ≥ 30 cm. These DBH classes, together with the cutting treatments, were then submitted to an analysis of variance for a completely randomized block design and a Tukey multiple comparison test was performed to detect differences among the levels of the significant interaction between DBH classes and cutting treatments. Solar radiation below the canopy and percentage of ground covered by woody debris were both submitted to an analysis of variance for a completely randomized block design that was followed by a Tukey multiple comparison test to determine statistical differences among the levels of the interaction between cutting treatments and position relative to the skidding trails.

Results

Damage to advance regeneration caused by winter harvesting was very limited in all cutting treatments, except in skidding trails of total clear-cutting. Immediately after cutting (1995), this damage decreased stocking of red spruce and balsam fir (the two main species that composed advance regeneration) by approximately 15% in total clear-cuttings (Fig. 2). Analyses of variance indicate that some factors significantly explained the variation in regeneration stocking of red spruce, balsam fir, and deciduous species (Table 2). However, these significant effects differed among species depending on the regeneration height class considered. Hence, when red spruce stocking of all height classes was considered, no differences were observed among cutting intensities (Table 2, height class >0), which were all associated with stocking values >70% for each measurement period (Fig. 2). The significant interaction between year and regeneration plot position calculated for red spruce stocking

Fig. 2. Changes in mean regeneration stocking over time (n = 4 blocks) for red spruce, balsam fir, and deciduous species after application of five cutting treatments: untreated control (C); low (L), moderate (M), and heavy (H) partial cuttings; and total clear-cutting (T). Regeneration stocking was calculated for the three seedling height classes defined in Table 1.



of all height classes can be explained by the gradual increase over time in the skidding trails, whereas stocking between the trails remained constant near 100% during the entire study period (data not shown).

For red spruce seedlings >30 cm, the pattern of change in stocking over time differed among treatments as indicated by the significant interaction between cutting intensity and year (Table 2). In 1999 (i.e., 5 years after treatment), red spruce regeneration stocking was proportional to cutting intensity, whereas the control was the only treatment that significantly differed from the others after 10 years (2004) (Fig. 2). In the case of red spruce regeneration >100 cm, treatment effects were only apparent after 10 years, at which time stocking was proportional to cutting intensity (Fig. 2). Ten years after treatment, the results on the number of red spruce seedlings per hectare (Table 3) followed the same proportional response to treatment as that found for stocking (Fig. 2). For balsam fir and deciduous species, cutting treatment effects were similar to those observed with red spruce, except that height development was much faster as indicated by stocking values of balsam fir and broadleaved seedlings >100 cm (Fig. 2).

The threefold interaction occurring among cutting intensity, position, and time was significant for the stocking of red spruce seedlings >100 cm (Table 2). This means that red spruce stocking values between and in skidding trails followed different trends for at least one treatment during 1 year. Such a result is well illustrated by red spruce regeneration established 10 years after cutting between and in skidding trails (Fig. 3). In this figure, stocking of red spruce seedlings >100 cm for the three partial cuttings was higher in skidding trails than between them, whereas the opposite was true in the case of clear-cutting.

Seedling environment differed according to the cutting treatments and to their position relative to the skidding trails. Hence, the availability of solar radiation, as calculated through analyses of hemispherical photographs taken over each regeneration plot, was greater in skidding trails than between them for the three partial cut treatments, whereas no differences were observed in total clear-cuttings (Table 4). However, the abundance of woody debris, as estimated by percentage of ground coverage, was greater in skidding trails of all cutting treatments (Table 5). The difference between the two positions relative to the skidding trails (between and in skidding trails) was particularly important in total clear-cuttings (Table 5), where the harvested volume was more important than in partial cuts.

An analysis of variance concerning the growth data of residual trees indicates that the interaction between cutting treatment and diameter of residual trees before treatment was significant 10 years after cutting. This result means that the effect of at least one cutting treatment on diameter growth differed among initial tree diameters. Multiple-comparison testing indicates that it is mostly small-diameter trees that benefit from partial cuttings, as can be seen from the effects of these treatments relative to the controls (Fig. 4). Moreover, the highest partial-cutting intensity tended to produce the best improvement in diameter growth for all diameter classes (Fig. 4).

The number and size of tree seedlings allowed us to calculate seedling leaf biomass established after treatment. For all treatments, regeneration leaf biomass was for the most part composed of balsam fir (~70%), red spruce (~20%), and red maple (~10%). In every treatment except the control, regeneration leaf biomass accumulated slowly during the first 5 years following cutting and then sharply increased until the end of the 10 year survey period (Fig. 5). At this time, regeneration leaf biomass was proportional to cutting intensity and ranged from about 550 kg/ha in the control treatment to 7000 kg/ha in the clearcuts (Fig. 5).

Discussion

Red spruce – balsam fir stand regeneration is largely dependent on advance growth. Compared with red spruce, bal-

Table 3. Mean number of seedlings per hectare 10 years after treatment applications for red spruce, balsam fir, and deciduous species of three height classes.

	Red spruce seedlings/ha			Balsam fir seedlings/ha			Deciduous species seedlings/ha		
Cutting intensity	>0 cm	>30 cm	>100 cm	>0 cm	>30 cm	>100 cm	>0 cm	>30 cm	>100 cm
Control	75 977	195	0	372 891	4 648	195	227 344	2 148	234
Low	88 008	10 781	117	184 609	59 688	7 266	92 461	23 945	5 703
Moderate	54 178	8 789	391	137 695	60 469	8 516	57 500	28 164	7 109
Heavy	61 367	17 305	742	157 422	66 484	10 586	84 102	36 484	11 797
Total	21 445	18 242	3438	80 273	66 641	24 375	48 398	32 344	14 453

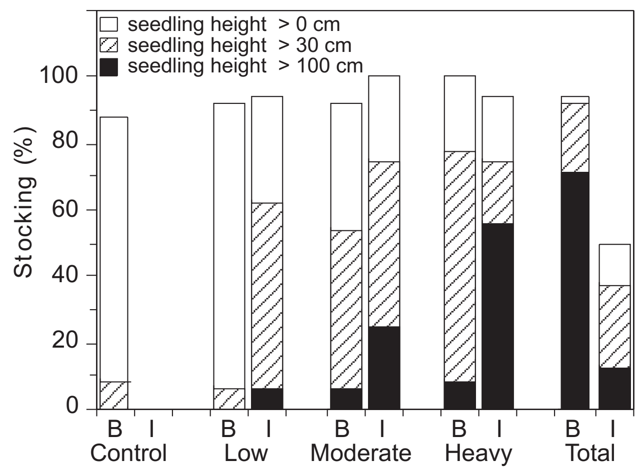
Note: Values are means of the four blocks for each treatment. See Table 1 for seedling height classes.

sam fir produces good seed crops more frequently (Seymour 1995), is better adapted to a variety of seedbeds (Simard et al. 1998), and has a more extensive root development (Place 1955); consequently, it often dominates the regeneration stratum (Frank and Bjorkbom 1973). This situation is generally not welcomed by forest managers, because balsam fir is shorter lived, is less resistant to spruce budworm and decay, and has a lower commercial value than red spruce (Sendak et al. 2003). Hence, silvicultural treatments, such as shelterwood cutting and scarification, have been proposed to improve seedbed conditions and growing environment of red spruce regeneration (Frank and Bjorkbom 1973, Baldwin 1977, Sendak et al. 2003). However, in this study, the establishment of red spruce seedlings was not a problem, because stocking of this species was present at levels >70% in all treatments—as well as the untreated control—at the beginning of the experiment (Fig. 2). Thus, the principal goal of the shelterwood method was to improve the growing conditions of these small red spruce seedlings to increase the probability of survival after final harvest.

Relevant information about red spruce seedling development can be drawn from the pattern of change in stocking over time for regeneration of different height classes (Fig. 2; Table 3). Five years after cutting, stocking of red spruce seedlings >30 cm was proportional to cutting intensity, with a 50% value for the heaviest partial cutting. Ten years after treatments, all partial-cutting intensities have reached the generally accepted 60% stocking value for red spruce seedlings >30 cm and, thus, could be considered as having well regenerated. However, both deciduous species and balsam fir were also well established, with seedlings being generally taller than those of red spruce (Fig. 2; Table 3). Vigorous red maple sprouts, in particular, contributed to the greater stocking values of deciduous species >100 cm, 10 years after cutting. Therefore, if forest managers want to maintain the spruce proportion as it was in the preceding mature stand, a precommercial thinning should be planned over the medium term to adjust future stand composition. However, to make precommercial thinning successful on these lowland sites the leaf biomass of the remaining trees must be sufficient to avoid watering-up, which could be detrimental to tree survival.

The present shelterwood experiment was performed following observations of high seedling mortality in adjacent 10 ha clear-cut blocks. This regeneration mortality was presumed to have resulted from watering-up, which forced forest managers to prescribe costly treatments such as drainage and planting. However, in our experiment's 0.25-ha clear-cut EUs, seedlings of all species had low mortality rates and were able to use available resources efficiently, such that their numbers and growth levels were higher than those of the other treatments (Fig. 2; Table 3). The low mortality rate observed in these 0.25 ha clear-cut EUs most likely stemmed from restricted watering-up caused by low rainfall during the first year after treatment, from the small size of the clear-cut EUs, and from the presence of uncut forest around the experimental area (Pothier et al. 2003). Because of their small size, clear-cut EUs could inaccurately represent operational clear-cut areas, which are much larger and, thus, more prone to watering-up and related damage to regeneration.

Fig. 3. Mean red spruce regeneration stocking (n = 4 blocks) 10 years after application of five cutting intensities for plots established between skidding trails (B) and in skidding trails (I). Regeneration stocking was calculated for the three seedling height classes defined in Table 1. There were no skidding trails in the controls; hence only one value is shown.



Height development of red spruce seedlings was different between the two positions relative to the skidding trails, as is demonstrated by the stocking values for different height classes 10 years after treatment (Fig. 3). In the three partial-cut treatments, red spruce seedlings established in the skidding trails tended to be taller than those under the shelter trees (Fig. 3). This result can be explained by the difference in the availability of solar radiation between these two environments. Indeed, the percentage of solar radiation, calculated using hemispherical photographs, was systematically 4% higher in the skidding trails of each partial-cut treatment (Table 4) than between the trails.

Table 4. Amount of direct and diffuse solar radiation below the canopy, expressed as a percentage of radiation received above the canopy, calculated using analyses of hemispherical photographs taken above 16 regeneration plots in each experimental unit (12 between skidding trails and 4 in skidding trails except in the control treatment, where all 16 plots were located between skidding trails).

	Cutting intensity				
Position	Control	Low	Moderate	Heavy	Total
Radiation between skidding trails (%)	27.0±6.3f	42.2±6.9e	47.2±9.4d	50.6±10.8c	88.0±6.8a
Radiation in skidding trails (%)	—	46.5±3.5d	51.1±5.0bc	54.3±9.1b	89.5±2.6a

Note: Values are means ± SDs calculated from the means of the four blocks. Values followed by different letters indicate significant differences (α = 0.05) according to a Tukey multiple comparison test.

Table 5. Percentage of ground covered by woody debris during the summer following cutting for each cutting treatment and each position relative to the skidding trails.

	Cutting intensity				
Position	Control	Low	Moderate	Heavy	Total
Woody debris between skidding trails (%)	0.0±0.0c	4.0±15.7c	8.5±20.0c	2.8±11.1c	6.8±20.7c
Woody debris in skidding trails (%)	—	51.9±34.2b	55.5±33.5b	56.6±33.4b	77.2±34.1a

Note: For each experimental unit, the percentage of ground covered by woody debris was calculated for sixteen 4 m^2 plots (12 located between skidding trails and 4 located in skidding trails). Values are means ± SDs calculated from the means of the four blocks. Values followed by different letters indicate significant differences (α = 0.05) according to a Tukey multiple comparison test.

According to Valkonen et al. (2002) and Strand et al. (2006), the greater growth of Scots pine (*Pinus sylvestris* L.), Norway spruce, and lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) seedlings located far from the shelter trees is better explained by decreasing nutrient competition than by increasing light level. However, if nutrient availability was more important than light availability, different tall seedling stocking values would have been observed for seedlings exposed to the same light level but that had been established at various distances from shelter trees. This can be verified by comparing, on the one hand, the stocking levels of tall seedlings established in the skidding trails associated with low partial cutting and, thus, that are relatively far from shelter trees and, on the other hand, the stocking levels of tall seedlings established below the shelter trees of the moderate partial cutting and, thus, that are relatively close to the shelter trees; both sorts of seedlings were exposed to about 47% of solar radiation (Table 4). However, red spruce seedling stocking levels were the same for both situations, i.e., approximately 60% for seedlings taller than 30 cm and 6% for seedlings >100 cm (Fig. 3). Slightly different results can be observed in a comparison of the stocking levels obtained, on the one hand, for tall seedlings in the skidding trails associated with moderate partial cutting and, on the other hand, for tall seedlings under the shelter trees associated with heavy partial cutting; in both instances, the seedlings were exposed to about 51% of solar radiation (Table 4). However, although the red spruce stocking level was similar for seedlings >30 cm (approximately 75%), it differs for seedlings >100 cm: 25% for seedlings in the skidding trails of the moderate partial cuttings and 8% for seedlings between the skidding trails of the heavy partial cuttings (Fig. 2). Consequently, it is thus possible that light and nutrients interact to explain differences in height growth of red spruce seedlings established in different locations relative to the skidding trails. A more detailed study, including accurate measurements of light and nutrient availability, is needed to quantify the impact of each factor in these lowland environments.

In the case of the clear-cut treatment, red spruce stocking results show a trend opposite to those observed in partial cuttings, because tall seedlings were more frequent between the skidding trails than in the skidding trails (Fig. 3). This can be related to the percentage of ground covered by logging slash, which was much greater in the skidding trails of clear-cut EUs than in those of partial cuttings (Table 5). Furthermore, we observed that logging slash tended to be thicker and more compacted in total cuttings than in partial cuttings. Hence, it seems that logging slash in skidding trails of clear-cut EUs was abundant enough to deteriorate seedbed conditions, to delay red spruce establishment, and (or) to shade small seedlings with the consequence of reducing their survival and their height growth.

The partial-cut treatments not only affect seedling growth but also the diameter growth of residual trees, particularly small-diameter trees (Fig. 4). This result supports the observation that small-diameter trees respond to various silvicultural treatments faster and with greater magnitudes than large-diameter trees, (e.g., Shen et al. 2000; Deal and Tappeiner 2002; Mäkinen and Isomäki 2004; Prévost et al. 2005). The partial cuts were applied very carefully by experienced harvester and forwarder operators, so that very few injuries were observed on residual trees. This certainly contributes to the slightly better diameter growth of partial cut treatments over controls for larger diameter classes, although most of these differences were not statistically significant. In this regard, the heavy partial cutting, which removed 60% of the initial basal area, was associated with the larger diameter increment among all initial diameter classes (Fig. 4), which suggests that this cutting intensity must be considered by forest managers on low windthrow hazard areas.

The residual trees left on areas subject to partial cutting were responsible for mitigating water table rise during the first 5 years after treatment (Pothier et al. 2003). During

Fig. 4. Ten year diameter growth increment of trees (all species) remaining after four cutting intensities: untreated control (C) and low (L), moderate (M), and heavy (H) partial cuttings. Trees were grouped in four diameter at breast height (DBH) classes. Within each DBH class, the different letters indicate significant differences (α = 0.05) among treatment means. Treatment means (bars) and SEs (error bars) were calculated on the basis of the mean values obtained from the four repetitions (blocks).

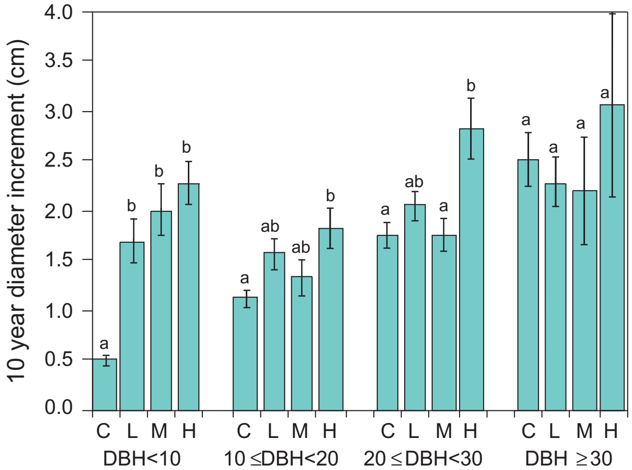
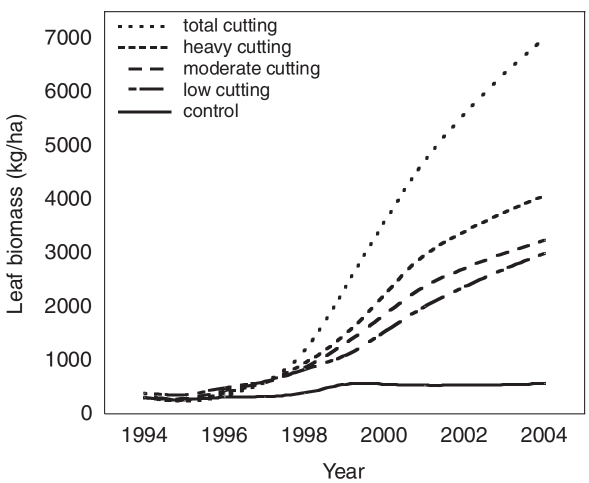


Fig. 5. Changes in mean leaf biomass over time for regeneration of all tree species after application of five cutting treatments. Leaf biomass was calculated according to the species-specific equations developed by Roussopoulos and Loomis (1979).



this period, the leaf area supported by these trees was the largest source of evapotranspiration in the partial-cut treatments and the control, whereas clear-cutting, in which very few small trees were left standing, resulted in the largest watering-up (Pothier et al. 2003). However, because the final step in shelterwood method is careful clear-cutting around advance growth, a vigorous and abundant regeneration stratum must be established to mitigate, in turn, the anticipated watering-up following logging. Therefore, in the absence of significant windthrow, final harvest was delayed until sufficient leaf biomass accumulated in the regeneration stratum. This leaf biomass accumulation was particularly substantial during the second 5 year period after treatment (Fig. 5), which justifies the decision to delay the final harvest commonly applied as soon as the desired regeneration is well established, i.e., 5 years after treatment (Fig. 2). Ongoing monitoring of the water table following final harvest will help quantify the impact of this 5 year delay on the anticipated water table rise.

Ten years after treatment, tree regeneration leaf biomass was proportional to cutting intensity, and logically enough, the heavy partial cutting that removed about 60% of the initial basal area produced the highest regeneration leaf biomass among partial-cut treatments (Fig. 5). Thus, as a result, heavy partial cutting presents the potential advantage of helping to mitigate watering-up following final harvest. Moreover, because the trees remaining after heavy partial cutting had sufficient leaf area to control the water table rise immediately after treatment (Pothier et al. 2003), the shelterwood method using this first-cut intensity is an attractive alternative to clear-cutting to achieve forest-management objectives in this type of lowland conifer stand.

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