Do harvest methods and soil type impact the regeneration and growth of black spruce stands in northwestern Quebec?

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Abstract: Machinery traffic restrictions during forest harvest have been adopted to minimize soil damage and protect tree regeneration. However, this practice is questioned for paludifying black spruce (*Picea mariana* (Mill.) BSP) stands in which severe soil disturbance by wildfire restores forest productivity. The objective of this study was to determine, 8 years after harvest, how soil disturbance created by clearcutting and careful logging affected black spruce natural regeneration and growth and how this effect varied by soil type. While regeneration density was higher following careful logging, stocking was not influenced by harvest method. Regenerating stands were taller following clearcutting despite potentially greater damages to preestablished regeneration. Compared with careful logging, clearcutting also resulted in reduced cover of *Sphagnum* spp. and ericaceous shrubs. Spruce stem density and stocking were both higher on organic and subhydric soils and lower on mesic soils. No significant interactions were observed between harvest method and soil type, indicating that the observation of taller black spruce stands and adequate stocking with clearcutting may be applicable to all soil types considered in this study. These results suggest that an adequate level of soil disturbance is an important part of forest regeneration, particularly in ecosystems where an autogenic reduction in productivity occurs.

Résumé : Afin de préserver les sols et la régénération durant la récolte, la circulation de la machinerie forestière est fréquemment restreinte à des sentiers définis. Toutefois, cette pratique est remise en question dans les peuplements d'épinette noire (*Picea mariana* (Mill.) BSP) susceptibles à la paludification où de sévères perturbations des sols causées par le feu sont aptes à améliorer la productivité des peuplements. L'objectif de cette étude était de déterminer comment la perturbation des sols causée lors de la coupe totale et la coupe de protection affectent la régénération de l'épinette noire 8 ans après la récolte, et comment cet effet est conditionné par le type de sol. Alors que la densité de régénération de l'épinette noire était supérieure après la coupe de protection, le coefficient de distribution n'était pas influencé par la méthode de récolte. Les peuplements d'épinette régénérés après coupe totale étaient plus hauts en dépit d'un potentiel de dommage plus grand à la régénération préétablie. Comparée à la coupe de protection, la coupe totale a aussi résulté en une réduction de la couverture au sol de la sphaigne et des éricacées. La densité et le coefficient de distribution de l'épinette noire étaient supérieurs sur les sols organiques et subhydriques et inférieurs sur les sols mésiques. Aucune interaction significative n'a été observée entre la méthode de récolte et le type de sol, indiquant qu'une plus grande hauteur des peuplements et un coefficient de distribution d'épinette adéquat après coupe totale pourrait être applicable à toute la gamme de types de sol considérée dans cette étude. Ces résultats suggèrent qu'un niveau de perturbation des sols suffisant lors des opérations forestières est nécessaire, particulièrement dans les écosystèmes où des processus autogéniques réduisant la productivité s'opèrent.

Introduction

Black spruce (*Picea mariana* (Mill.) BSP) is one of the most wide-ranging and abundant conifers in North America (Burns and Honkala 1990) and sustains an important forest industry in several regions. Historically, black spruce stands have been harvested by clearcutting (Keenan and Kimmins 1993). The rationale for using clearcutting in black spruce stands was that clearcutting was compatible with the ecological requirements of black spruce (Keenan and Kimmins 1993; McRae et al. 2001). However, in recent decades, concerns were raised about the protection of soils and tree regeneration during forest operations, as clearcutting was thought to damage both. These concerns sparked important changes in harvest methods, and many jurisdictions in North America replaced clearcutting by careful logging, whose objectives are to protect soils and natural tree regeneration.

In certain areas, however, careful logging may not be as efficient at maintaining forest productivity as previously thought. For instance, in areas prone to paludification, such

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as parts of Alaska, northern Minnesota, and the Clay Belt of eastern Canada, the productivity of black spruce stands naturally declines as a thick (>30 cm) organic layer accumulates, the water table rises, soil temperature decreases, and tree root access to the mineral soil is restricted (Viereck et al. 1993; Simard et al. 2007). The understory of paludified black spruce stands is dominated by *Sphagnum* spp. and ericaceous species (e.g., Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd) and sheep laurel (*Kalmia angustifolia* L.)), both of which contribute to the accumulation of the organic layer (Fenton et al. 2005) and, in the case of ericaceous species, may also directly limit tree growth (Mallik 1987; Inderjit and Mallik 1996). Studies conducted in northeastern Canada have recently suggested that careful logging, which by definition does not disturb the accumulated organic layer, could contribute to a long-term decline in black spruce stand productivity by favouring paludification (Fenton et al. 2005; Lavoie et al. 2005). In parallel, it has been suggested that harvest methods that severely disturb organic soils, and subsequently result in a reduction in organic layer thickness and (or) accelerate its mineralization, could help restore stand productivity (Simard et al. 2009). Therefore, while careful logging is likely to leave more residual trees than clearcutting, natural regeneration on clearcut sites may establish in more favourable microsites and have a higher growth rate than the residual stems of the carefully logged sites. In this context, the height advantage of advanced regeneration could disappear over time.

Furthermore, in a black spruce dominated landscape, stand growth and composition can respond differently following disturbance according to soil type. For instance, in the boreal mixedwoods of central Manitoba, Martin and Gower (2006) found that black spruce trees grew taller on clay soils than on sandy soils following fire, whereas in Ontario, Chen et al. (2002) observed that hardwood species such as trembling aspen (*Populus tremuloides* Michx.), a species associated with reduced organic layer thickness and enhanced tree growth in black spruce stands (Légaré et al. 2004, 2005), were more frequent on well-drained sites after harvest.

In this context, the objective of this study was to determine the landscape-scale effects of two harvest methods (i.e., careful logging and clearcutting) and five soil types (as characterized by their texture and drainage) on tree seedling density, stand height, and the cover of *Sphagnum* spp. and ericaceous shrubs 8 years after harvest. We hypothesize that (*i*) black spruce stem density will be higher after careful logging than after clearcutting, (*ii*) stand height will be greater after clearcutting than after careful logging, and (*iii*) the cover of the *Sphagnum* spp. carpet and of ericaceous shrubs will be lower after clearcutting than after careful logging. Regarding soil types, we hypothesize that (*iv*) black spruce stem density will be higher on poorly drained soils as compared with well-drained soils and, in contrast, (*v*) hardwood stem density will be higher on well-drained soils as compared with poorly drained soils. A better understanding of the possible interacting effects between harvest method and soil type could allow the readjustment of silvicultural practices according to forest management objectives at the landscape scale.

Methods

Study area

The study area (48°50′N–50°10′N, 78°08′W–79°34′W) is located in northwestern Quebec and covers approximately 1 000 000 ha (Fig. 1). The southern part of the study area, the Clay Belt, is covered by thick (>10 m) glaciolacustrine clay and silt deposited by the glacial Lake Ojibway, while the northern part is covered by the Cochrane till, a compact till made up of a mixture of clay and gravel, created by a southward ice flow approximately 8000 years BP (Veillette 1994). Thick (>30 cm) organic deposits are found in many locations in both the southern and northern parts of the study area. According to the nearest weather station (Joutel, Quebec), the average annual temperature was 0.1 °C and average annual precipitation was 892 mm, with 35% falling during the growing season, 1971–2000 (Environment Canada 2009). The average number of degree-days (>5 °C) is 1249, and the frost-free season lasts about 60 days; frost can occasionally occur during the growing season. Fire frequency in the study area has diminished from a 100-year cycle to an approximately 400-year cycle since the little Ice Age (ca. 1850; Bergeron et al. 2004).

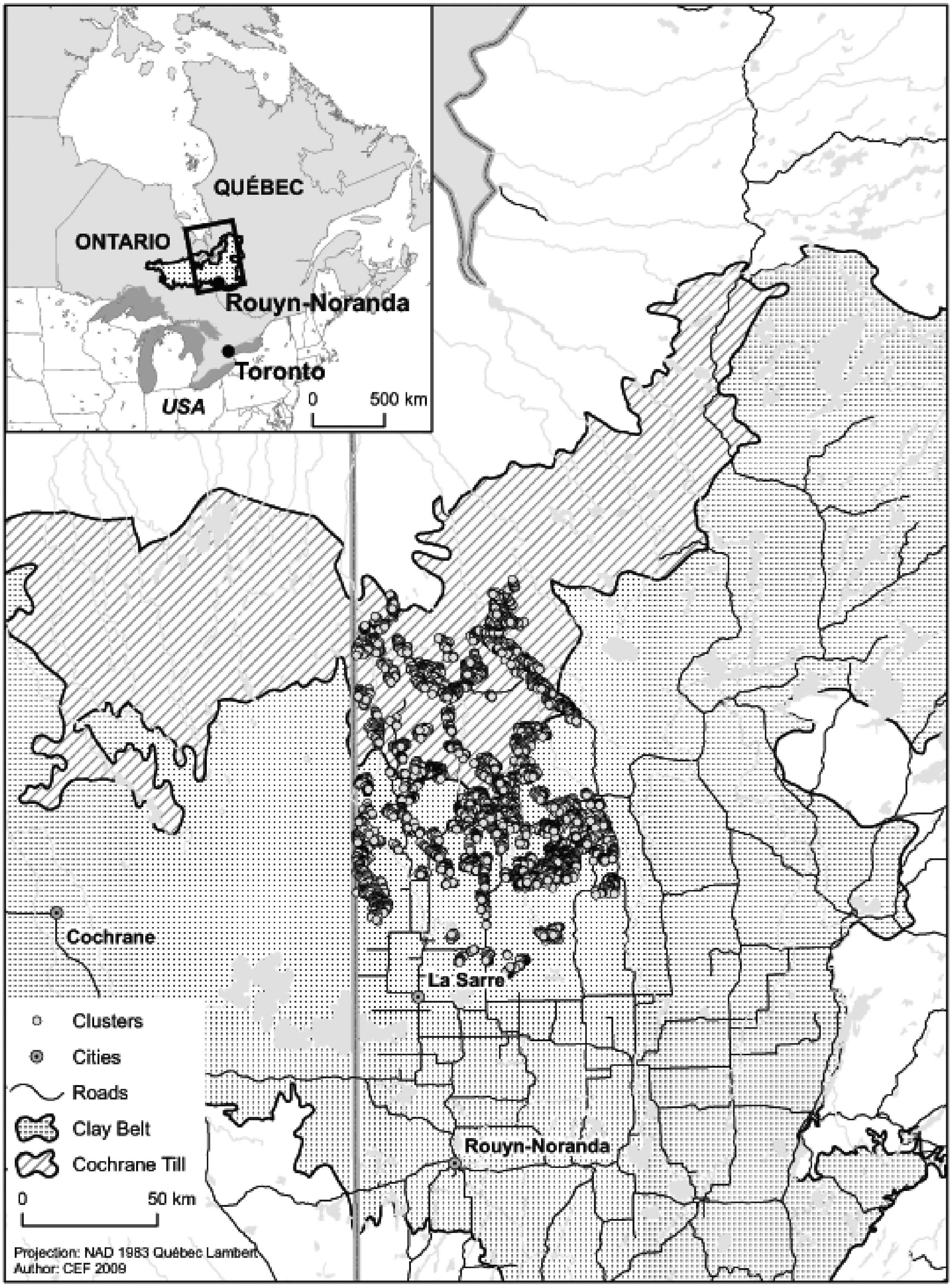
The study area is part of the western black spruce – feathermoss bioclimatic domain (Robitaille and Saucier 1998). In some stands, balsam fir (*Abies balsamea* (L.) Mill.), tamarack (*Larix laricina* (Du Roi) K. Koch), paper birch (*Betula papyrifera* Marsh.), and trembling aspen are also found. Ericaceous shrubs such as *R. groenlandicum*, *K. angustifolia*, and blueberry (*Vaccinium myrtilloides* Michx. and *Vaccinium angustifolium* Ait.) dominate the understory, while the forest floor is dominated by *Sphagnum* spp. (e.g., *Sphagnum recurvum* P. Beauv. sensu lato, *Sphagnum capillifolium* (Ehrh.) Hedw., *Sphagnum fuscum* (Schimp.) Klinggr., *Sphagnum girgensohnii* Russ., and *Sphagnum magellanicum* Brid.) and feathermosses (e.g., *Pleurozium schreberi* (Brid.) Mitt. and *Hylocomium splendens* (Hedw.) Schimp.).

Forest policy context

As in most coniferous forests in North America, black spruce stands in the study region have historically been harvested by clearcutting. During clearcutting operations, machinery traffic was originally allowed across the entire cutover area, all commercial tree stems were harvested, and damage to soils and natural regeneration was usually high. During the 1990s, the Ministère des Ressources naturelles et de la Faune du Québec (MRNFQ) modified the province's forest policy to protect natural regeneration and soil physical, chemical, and biological properties and introduced careful logging (in Quebec, cut with protection of regeneration and soils (CPRS)). CPRS consists of harvesting all commercial trees (diameter at breast height >9.1 cm) with machinery traffic restricted to parallel trails that cover approximately 25% (33% prior to March 2001) of the logged area (MRNFQ 2003). Trails are separated by "protection strips" in which commercial stems are harvested.

The database used in this study comprises data from postharvest monitoring compiled by two major forest companies in Quebec (Tembec Inc., Montreal, Quebec, and Norbord Inc., Toronto, Ontario) between 1997 and 2007, as required by law. In the original database, 7759 clusters were avail-

Fig. 1. Location of the Clay Belt, the Cochrane till, the study area, and the clusters in Quebec (inset).



able. Clusters were excluded where planting, seeding, cleaning, and (or) thinning were completed following harvest to focus exclusively on natural regeneration. Moreover, to minimize the possible influence of pre-harvest forest composition on our results, we selected only stands that were dominated by black spruce prior to harvest (Table 1). Finally, it should be noted that for each response variable, the number of clusters varies from 5 to 2258 because not all data were collected at each sampling location due to the 10-year time span covered by the database.

Experimental design and sampling

At each sampling location (Fig. 1), one cluster of ten 4 m^2 circular plots was sampled. At the cluster scale, this experimental design allowed us to determine (*i*) stocking and stem density (i.e., number of seedlings per hectare) for each tree species, (*ii*) average stand height, and (*iii*) percent cover of *Sphagnum* spp. and ericaceous shrubs. Stocking was determined by calculating the percentage of the ten 4 m^2 circular plots containing at least one stem taller than 0.30 m. Stem density was determined by tallying the number of stems taller than 0.30 m in three of the 10 circular plots and is reported as number of seedlings per hectare. Stocking and stem density were calculated separately for black spruce and hardwood species (i.e., paper birch and trembling aspen). In these three circular plots, stand height was also determined by averaging black spruce seedling height. Finally, in each circular plot, the percent cover of *Sphagnum* spp. and ericaceous shrubs (i.e., *R. groenlandicum* and *K. angustifolia*) was noted.

Determination of harvest method and soil type

At each sampling location (i.e., cluster), harvest method (i.e., CPRS and clearcutting) and soil type (as determined by a combination of texture and drainage) were determined using the forest maps of the MRNFQ. Although harvest season (e.g., summer or winter) might have an important effect on tree regeneration and growth (B. Lafleur et al., unpublished data), the ecological classification maps of the MRNFQ do not indicate seasons. Consequently, statistical analyses were conducted without discriminating harvest season.

Surficial deposit and drainage classes were grouped to create functional groupings (hereafter referred to as soil types). Five soil types were retained, and they covered the largest surface, together accounting for approximately 85% of the study area. They are organic (ORG), mesic lacustrine clays (MLC), subhydric lacustrine clays (SLC), mesic clay till (MCT), and subhydric clay till (SCT). Mesic soils refer to well- and moderately well-drained soils, whereas subhydric soils refer to imperfectly and poorly drained soils (Brais and Camiré 1992; Saucier 1994). MLC and SLC are predominantly found in the southern part of the study area, i.e., the Clay Belt, whereas MCT and SCT are mainly found in the northern part of the study area, i.e., the Cochrane till. Organic soils are equally distributed in the Clay Belt and on the Cochrane till.

Data analyses

All clusters were sampled 8 years after harvest, as required by law in Quebec; therefore, we did not take cluster (stand) age into account in our analyses. To determine the effects of harvest method and soil type and any interactions on stocking, stem density, and mean stand height, the data were analyzed using mixed effect ANOVAs. Harvest method and soil type were introduced in the model as fixed effects, while cluster was used as a random effect. The general form of the model for these analyses was

$$[1] \quad Y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \delta_k + \varepsilon_{ijkl}$$

where α (harvest method) and β (soil type) are fixed effects and δ (cluster) is a random effect. When needed, data were log or square root transformed to meet the assumptions of normal distribution and homogeneity of variances. Analyses were conducted on the responses of black spruce, the dominant species in the study area, and hardwood species (i.e., trembling aspen and paper birch, hereafter referred to as hardwood). Stand height was not analyzed for hardwood species because of insufficient data. As we were not able to meet the assumptions for parametric tests, even after transformation, for the data on the cover of ericaceous shrubs and *Sphagnum* spp., data were analyzed using nonparametric tests (Kruskal–Wallis and Wilcoxon). Mixed model analyses were done using the Mixed procedure in SAS (SAS Institute Inc. 2004). Post hoc comparisons were made to contrast the levels of the fixed variables, and differences were deemed significant when $\alpha \leq 0.05$. Pearson correlations were then used to determine the strength of the relationships between stand height and the cover of competing vegetation.

Results

Regeneration and growth parameters

Stocking differed more among soil types than between harvest methods, while the interaction (harvest method × soil type) was not significant for black spruce. Our results showed that overall, black spruce and hardwood stocking did not significantly differ between CC and CPRS (black spruce: CC = 61% and CPRS = 63%; hardwood: CC = 15% and CPRS = 10%) (Fig. 2). Stocking did, however, differ significantly among soil types. Black spruce stocking was highest on ORG (79%), intermediate on SLC (71%) and SCT (67%), and lowest on MLC (51%) and MCT (43%). Hardwood stocking was highest on MLC (33%), intermediate on SLC (11%) and MCT (10%), and lowest on SCT (6%) and ORG (4%). There were no interactions between harvest method and soil type for either black spruce or hardwood stocking.

In contrast with stocking, stem density differed both between harvest methods and among soil types. Black spruce stem density was significantly higher after CPRS (7743 $stems{\cdot}ha^{-1}$) than after CC (5410 $stems{\cdot}ha^{-1}$) (Fig. 2) and was highest on SCT, SLC, and ORG (9222, 7766, and 7162 $stems{\cdot}ha^{-1}$, respectively) and lowest on MCT (4837 $stems{\cdot}ha^{-1}$) and MLC (3894 $stems{\cdot}ha^{-1}$). In contrast with black spruce, hardwood stem density was significantly higher after CC than after CPRS (1020 versus 595 $stems{\cdot}ha^{-1}$) (Fig. 2), primarily due to the very high density of stems on MCT after CC. Significant differences were also found among soil types, with higher hardwood stem density on MCT (1594 $stems{\cdot}ha^{-1}$) and MLC (1560 $stems{\cdot}ha^{-1}$), intermediate levels on SLC (604 $stems{\cdot}ha^{-1}$),

Table 1. Number of clusters analyzed for each response variable by edaphic class.

Response variable	MLC–CPRS	MLC–CC	SLC– CPRS	SLC–CC	ORG– CPRS	ORG–CC	MCT– CPRS	MCT–CT	SCT– CPRS	SCT–CC	Total
Stocking (%)	90	23	716	178	498	26	226	32	879	22	2690
Density (stems·ha^{-1})	172	89	1016	249	488	29	234	16	816	5	3114
Stand height (m)	419	242	2258	647	232	69	29	23	444	59	4422
Shrubs and *Sphagnum* cover (%)	82	74	381	152	121	13	15	12	109	11	970

Note: MLC, mesic lacustrine clays; SLC, subhydric lacustrine clays; ORG, organic; MCT, mesic clay till; SCT, subhydric clay till; CPRS, cut with protection of regeneration and soils; CC, clearcutting.

and lower density on SCT and ORG (144 and 137 stems·ha^{-1}, respectively). There were no interactions between harvest method and soil type for either black spruce or hardwood stem density.

At the stand scale, black spruce stand height was significantly higher following CC (80 cm) than following CPRS (67 cm) (Fig. 3) 8 years after harvest. Although the absolute differences were small, black spruce stand height also differed significantly among soil types, as black spruce stands were tallest on ORG (79 cm) and MCT (77 cm), intermediate on MLC and SCT (73 and 70 cm, respectively), and shortest on SLC (68 cm). Again, no significant interactions were detected between harvest method and soil type.

Ericaceous shrubs and *Sphagnum* spp. cover

Percent cover of *K. angustifolia* and *R. groenlandicum* was significantly lower after CC than after CPRS (Fig. 4). Soil type also influenced their percent cover, with lower cover on MCT for *K. angustifolia* and on MLC for *R. groenlandicum* (Fig. 4). Percent cover of *Sphagnum* spp. also differed significantly between harvest methods and among soil types, with lower cover after CC than after CPRS and significantly lower and higher cover on MCT and SLC, respectively (Fig. 4).

Relationships between tree growth parameters and competing vegetation

Pearson correlations revealed that black spruce stand height was significantly negatively correlated with *R. groenlandicum* (r = –0.256, $p < 0.01$) and *Sphagnum* spp. (r = –0.253, $p < 0.01$) cover, whereas it was not significantly correlated with *K. angustifolia* (r = –0.103, $p > 0.05$).

Discussion

Our results are in agreement with previous studies (e.g., Deal et al. 2002; Kreutzweiser et al. 2008; Man et al. 2008) that indicated that careful logging (CPRS) provides better protection for tree regeneration, ground vegetation, and soil than clearcutting. Despite this, our results also show that 8 years after harvest, clearcut stands are taller than stands carefully logged, despite the potentially greater damage to preestablished regeneration. While soil type influenced tree regeneration, stand growth, and ground vegetation, there was no interaction between harvest method and soil type on spruce tree regeneration and stand height. This suggests that the impact of harvest treatment found here applies to the range of site types considered.

Impact of harvest method

Our results indicate that 8 years following harvest, sites harvested by CPRS and clearcutting showed similar levels of black spruce stocking. Previous studies in northern Ontario found similar results and suggested that while CPRS is specifically designed to protect regeneration, greater soil disturbance severity during clearcutting favoured seed germination and seedling establishment (Groot and Adams 2005). Furthermore, harvest method had a significant effect on black spruce stem density, as it was on average 45% higher following CPRS than following clearcutting. As the aim of CPRS is to protect regeneration, machinery traffic is

Fig. 2. Stand regeneration parameters according to harvest method and soil type. Stocking (±1 SD) and density (±1 SD) for black spruce (*Picea mariana*) and hardwoods. MLC, mesic lacustrine clays; SLC, subhydric lacustrine clays; ORG, organic; MCT, mesic clay till; SCT, subhydric clay till; CPRS, cut with protection of regeneration and soils (careful logging); CC, clearcutting. Soil types identified by different letters are significantly different.

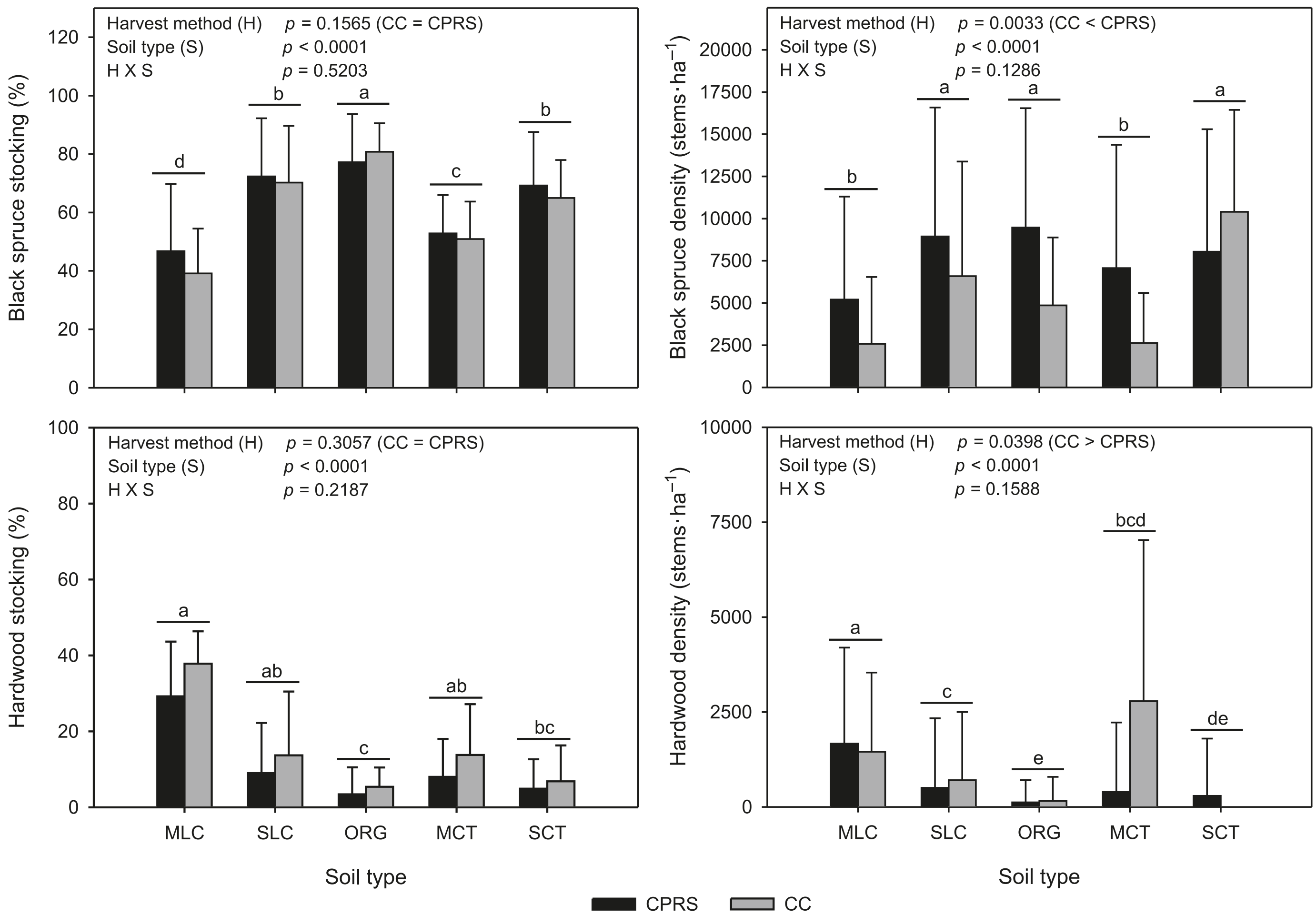
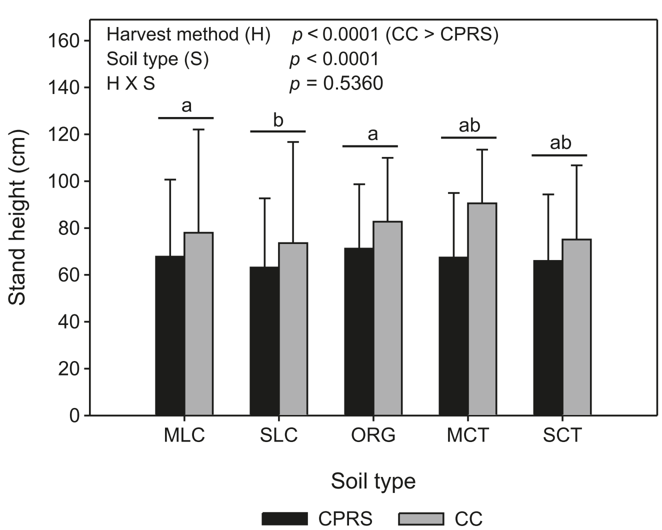


Fig. 3. Black spruce (*Picea mariana*) stand height (±1 SD) according to harvest method and soil type. See Fig. 2 for explanations of soil types and harvest methods. Soil types identified by different letters are significantly different.

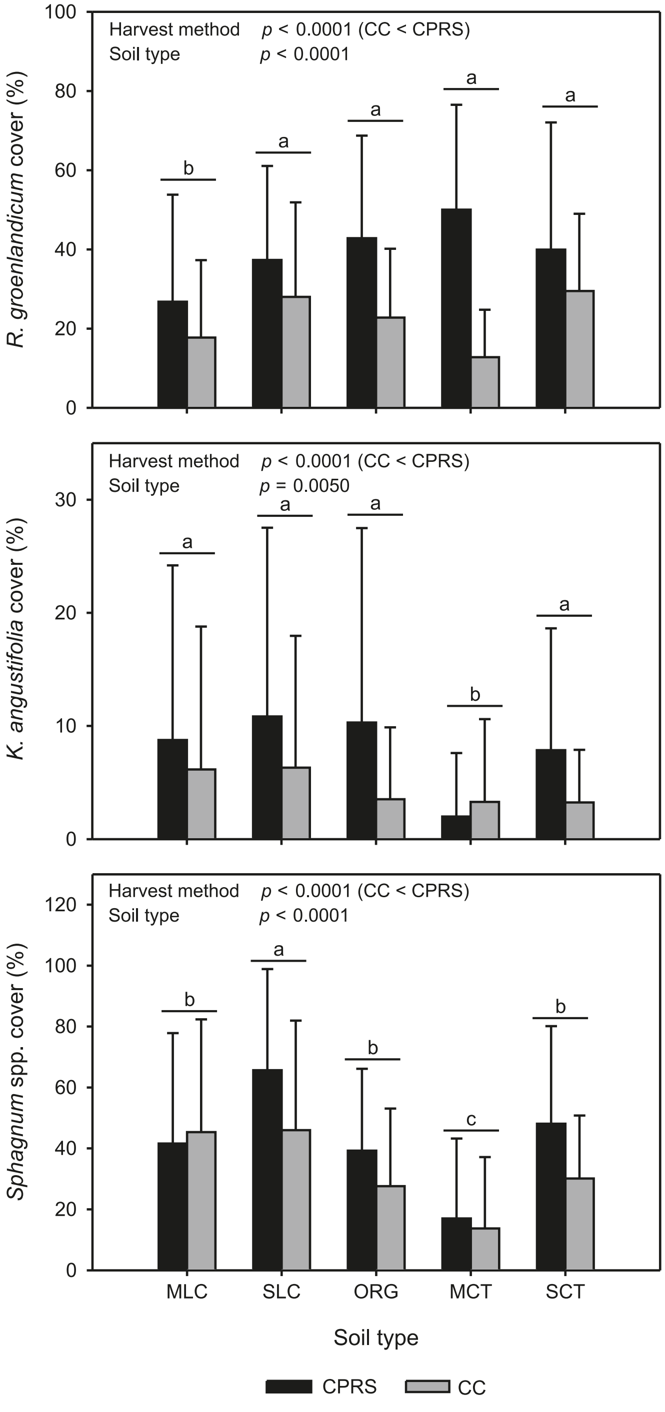


restricted to specific skid trails located 20–30 m apart. That spacing protects some black spruce regeneration. In contrast, during clearcutting, machinery traffic is not restricted and regeneration and soil are submitted to disturbance across the entire harvested area, which explains the lower black spruce stem density following clearcutting.

The nonsignificant but systematically higher stocking of hardwoods after clearcutting compared with CPRS (also found by Bujold 2005) could be explained by the ability of trembling aspen to produce root suckers following injury to its root system (Fraser et al. 2004). Injury may be caused by harvesting operations (Corns and Maynard 1998) and would presumably be higher after clearcutting than after CPRS. Harvest method also had a significant effect on hardwood stem density, which was on average 70% higher after clearcutting than after CPRS. The higher hardwood stem density following clearcutting could also be explained by the ability of trembling aspen to produce root suckers following root injury (Brumelis and Carleton 1988).

Eight years following harvest, clearcut sites supported slightly but significantly taller black spruce stands than those harvested using CPRS. These landscape-level results are in accordance with those of a parallel study (B. Lafleur

Fig. 4. Ericaceous shrub and *Sphagnum* spp. cover (±1 SD) according to harvest method and soil type. See Fig. 2 for explanations of soil types and harvest methods. Soil types identified by different letters are significantly different.



et al., unpublished data), which showed that at the stand scale, clearcutting tends to produce taller stands because it creates a greater abundance of microsites conducive to better tree growth.

Our results also indicate that clearcutting is more efficient than CPRS at controlling ericaceous competition, as cover of *R. groenlandicum* and *K. angustifolia* was significantly lower following clearcutting. Because soils are disturbed (both at the surface and in depth) over a larger area during clearcutting, the root systems of *R. groenlandicum* and *K. angustifolia* are more likely to be broken or disrupted, limiting or slowing down their short-term recovery. In addition, greater soil disturbance may expose mineral soil, which is known to constitute a barrier to ericaceous shrubs (Titus et al. 1995). The control of ericaceous shrubs early in stand recovery may have important consequences on stand growth, as both *R. groenlandicum* and *K. angustifolia* are known to have a negative impact on black spruce growth (Mallik 1987; Inderjit and Mallik 1996). Furthermore, clearcutting was also more efficient than CPRS at controlling *Sphagnum* spp. cover. Whereas a *Sphagnum* spp. carpet is generally considered an appropriate seedbed (Jeglum 1979), *Sphagnum* peat is also considered to be a poor substrate for black spruce growth (Lavoie et al. 2007). Because soils are disturbed over a larger proportion of the area during clearcutting than during CPRS, the *Sphagnum* spp. carpet is more likely to be fragmented, which slows its recovery. Therefore, in black spruce stands prone to paludification, any harvest method capable of reducing ericaceous shrubs and *Sphagnum* spp. cover should also favour black spruce growth.

Impact of soil type

Although harvest method did not have any significant effect on black spruce stocking, our results indicate that site soil type did influence black spruce stocking. While black spruce stocking was 79% on organic sites (i.e., ORG), it dropped to 70% on subhydric sites (i.e., SLC and SCT) and to 50% on mesic sites (i.e., MLC and MCT). Similarly, black spruce stem density was significantly lower on mesic sites as compared with organic and subhydric sites. These results indicate that wetter sites (organic or subhydric) provide better microsites for black spruce establishment, while the stocking of mesic sites may be more vulnerable if harvest causes great damage to established regeneration.

Furthermore, hardwood species had higher stocking and stem density on mesic sites (i.e., MLC and MCT) compared with the other soil types. These results are similar to those of Bujold (2005) and Laquerre et al. (2009) who both showed that mesic deposits are more liable to hardwood encroachment than subhydric or organic deposits, where excess moisture, low oxygen diffusion, and low temperatures restrict trembling aspen establishment and root suckering (Frey et al. 2003).

Although soil type had a significant effect on black spruce stand height, the absolute difference was very small. In addition, the time elapsed between stand initiation and post-harvest monitoring (i.e., 8 years) is quite short, which renders hazardous any discussion on the effects of soil type on stand height. However, one can note that the soil type with the shortest stands (i.e., SLC) also has the highest *Sphagnum* spp. cover, supporting the idea that extensive *Sphagnum* spp. carpets can restrict black spruce regeneration and growth.

Finally, the lower *Sphagnum* spp. cover on MCT could be explained by both the better drainage of mesic soil and the higher hardwood density. On the Clay Belt, Légaré et al. (2005) found that the presence of trembling aspen in black spruce stands reduced organic layer accumulation by producing litter rich in nutrients, therefore decomposing more rapidly than black spruce litter.

Management considerations

Although it is widely acknowledged that CPRS provides a "head start" to stand regeneration by protecting advance growth, our results show that in a paludified landscape, clearcutting yields, 8 years after harvest, taller stands than CPRS and that this conclusion applies to the full range of soil types that were studied. These results indicate that black spruce trees establishing after clearcutting have a higher growth rate than advance regeneration in CPRS. Although the results are a snapshot at age 8 following harvest, it is likely that this will continue because a critical phase for black spruce growth is the early stage where a lag can persist for up to 20 years (Groot and Hökkä 2000). As for the possible mechanisms involved, clearcutting likely disturbs the soil over a greater percentage of the area, which could stimulate soil processes, such as nutrient mineralization, and favour plant species that are functionally different in that they are prone to stimulate soil nutrient cycles (i.e., trembling aspen) either directly or by limiting the growth of the moss layer. Despite a greater destruction of the established regeneration, clearcutting would simultaneously create seedbeds that ensure site regeneration and favour microsite conditions that enhance tree growth.

Clearcutting resulted in a lower stem density than CPRS, although on all soil types, stocking of black spruce was not significantly different between harvest treatments. In Quebec, the provincial norms require that 8 years after harvest, stocking levels of free-to-grow stems >1 m tall be equal or higher than pre-harvest levels. In the study region, pre-harvest stocking level is approximately 30% and Quebec's provincial norms are met approximately 10 years after harvest (L. Dumas, personal communication). Therefore, on every soil type considered in this study, both harvesting methods can produce levels of stocking that meet Quebec's provincial norms. Of all soil types, mesic sites may require the most attention because of relatively low black spruce density and stocking. These results offer a paradox because it is on the wettest sites and not on the mesic ones that stocking has been thought to be most at risk because of soil rutting (Groot 1998). More research may be needed to determine the optimal treatment that would restore site regeneration and productivity as well as protect soil and water quality.

Finally, our results are in accordance with other studies and indicate that in ecosystems that are prone to an autogenic reduction in productivity (Wardle et al. 2004), a certain level of disturbance to the soil may be required to restore stand productivity. In paludified forests, a thick moss layer insulates the soil and disturbance to this layer may cause an effect similar to the assart effect (Rommell 1935; Kimmins 1997) in other ecosystems, i.e., a "kick start" for nutrient cycles and tree development in the early regeneration stage.

Conclusion

Although the restriction of machinery traffic to specific skid trails is acknowledged to help maintain forest productivity by protecting soils and regeneration (Harvey and Brais 2002), in the black spruce stands of the Canadian Clay Belt that are prone to paludification, our results have shown that clearcutting with unrestricted traffic circulation provides black spruce stands of adequate stocking and with a better growth than CPRS over the range of soil types where paludification occurs. Clearcutting, however, may have greater impact than careful harvesting on several ecosystem properties and functions that were not evaluated in this study, for instance on streamflow, water quality, and biodiversity and wildlife habitats (Keenan and Kimmins 1993). Hence, the wise use of clearcutting and careful logging, along with the creation of conservation areas, could favour, at the landscape level, the maintenance of wood production as well as that of ecosystem properties and functions. Therefore, knowing what level of disturbance is required in what types of ecological conditions to achieve optimal benefits (in terms of forest productivity as well as in terms of soil and habitat protection) may require additional work. Nonetheless, our results suggest that conventional machine traffic has historically generated conditions for adequate stocking and growth.

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