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Prescribed burning after clearcut limits paludification in black spruce boreal forest

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Paludification, the accumulation over the mineral soil of poorly decomposed organic matter mainly originating from *Sphagnum* spp., transforms black spruce (*Picea mariana*) boreal forests into forested peatlands in the prolonged absence of fire, which diminishes forest productivity. High-severity wildfires reset this process by burning the soil organic layer (SOL) and reinitiating forest succession. In contrast, low severity wildfires impact mainly the soil surface and tree layer and do not significantly reduce SOL depth. In the Clay Belt region of eastern Canada, an area prone to paludification, the current forest harvest practice (careful logging around advanced growth [CLAAG]) removes trees but has little impact on the SOL and the understorey vegetation. This is thought to further promote paludification, which consequently reduces forest productivity. Conversely, clearcut (CC) disturbs the SOL and the understorey vegetation, and is thought to favor tree growth. Furthermore, prescribed burning after clearcut (CCPB) is used as a site preparation technique, but may also be used to control paludification as it can burn part of the organic soil layer. Using a retrospective approach, our study examines three hypotheses: compared to CLAAG, CC and CCPB: (1) have positive effects on soil conditions (e.g. decomposition level and pH), (2) reduce *Sphagnum* spp. and ericaceous shrub cover and (3) result in enhanced black spruce growth. We sampled 22 sites in which we measured SOL characteristics (e.g. depth, decomposition state), understorey vegetation cover and black spruce growth. Compared to CLAAG, CCPB resulted in increased soil decomposition level and higher pH. CCPB also reduced *Sphagnum* spp. cover but not ericaceous shrub cover. Black spruce growth rate was higher following CCPB than CC, and mean dominant tree height was marginally higher following CCPB than CLAAG and CC. Our results demonstrate that CCPB is beneficial to black spruce growth, presumably through its effects on forest understorey and SOL chemistry. While not similar to a high severity fire, prescribed burning after clearcut in paludified stands on the Clay Belt emulates some wildfire effects such as increasing soil pH. We suggest that unlike CLAAG, prescribed burning after clearcut can restore black spruce stand productivity and should be considered in the context of forest ecosystem management.

1. Introduction

Paludification, the accumulation of poorly decomposed organic matter over the mineral soil, is a natural process in black spruce (*Picea mariana* [Mill.] BSP) boreal forests. In these forests, paludification is associated with shallower water table, increased soil moisture, decreased soil temperature, decreased organic matter decomposition rate and nutrient availability, *Sphagnum* spp. mat expansion, and ericaceous shrub dominance (Fenton et al., 2005; Foster, 1984). The changes in soil organic layer (SOL) conditions and understorey composition associated with paludification decrease forest productivity and eventually lead to a forested peatland in the prolonged absence of wildfire (Lavoie et al., 2005; Simard et al., 2007). Severe wildfires leaving a residual organic layer less than 5 cm thick (*sensu* Simard et al., 2007) are thought

Abbreviations: CI, confidence interval; CC, clearcut; CCPB, clearcut followed by prescribed burning; CLAAG, careful logging around advanced growth; CN, carbon nitrogen ratio; RG, relative growth; SD, standard deviation; SOL, soil organic layer; TSD, time since disturbance.

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to return paludified forests to a more productive state, while low severity fires may have little or no impact on SOL depth and forest productivity (Lecomte et al., 2005; Simard et al., 2009). Even if the whole stand is not severely burnt during a fire event, the spatial variability of fire effects creates good microsites for black spruce regeneration and growth (Zasada et al., 1983). Compared to fire, forest harvesting practices are hypothesized to favor the paludification of black spruce cutovers because of their low impact on SOL and understorey vegetation cover (McRae et al., 2001).

Until the 1980s, clearcut was the main harvesting practice in Canada's boreal forest, but concerns about soil protection and tree regeneration led to a change in harvesting methods towards careful logging techniques, such as careful logging around advanced growth (CLAAG), which is now the current harvest practice in the province of Ontario, Canada (Groot and Adams, 2005; OMNR, 1997). The machinery used for CLAAG is equipped with high flotation tires and machinery movement is restricted to parallel logging trails in order to protect the soil and pre-established regeneration (Chen and Wang, 2006; Jeglum et al., 2003). Consequently, impact on SOL depth and physico-chemical properties is restricted to logging trails, as is impact on understorey vegetation composition and cover. Typically, stands regenerate from the dense pre-established regeneration, especially if harvesting is conducted during winter (Harvey and Brais, 2002; Lafleur et al., 2010). However, the low impact of CLAAG on SOL and understorey vegetation in paludified stands may lead to a loss of forest productivity (Bergeron et al., 2007). Removing tree evapotranspiration results in the rise of the water table which in turn promotes SOL waterlogged conditions (Roy et al., 2000). Consequently the growth of regenerating black spruces is reduced, notably because waterlogged conditions reduce soil temperature, organic matter decomposition and nutrient availability (Simard et al., 2007). Careful logging also favors understorey species such as *Sphagnum* spp. and ericaceous shrubs, which are detrimental to black spruce regeneration and growth (Bisbee et al., 2001; Fenton et al., 2007). *Sphagnum* spp. tend to outcompete vascular plants by reducing nutrient availability (Malmer et al., 2003), and ericaceous shrubs limit black spruce regeneration and growth through allelochemical leachates and competition for light and nutrients (Hébert et al., 2010; Mallik, 2003). Without management practices targeting soil conditions and understorey composition, cutovers in paludified black spruce stands could lead to regeneration failure and loss of stand productivity.

Unlike CLAAG, clearcut harvesting (CC) allows machinery movement across the entire site. Because of low bearing soil, especially when applied during summer, CC mixes the layers of the organic soil and the underlying mineral soil as well as disturbs the understorey vegetation (Marshall, 2000; Lafleur et al., 2010). Clearcut, by mixing the upper organic layers, can increase organic matter decomposition rates and soil pH, and induce nutrient release (Duchesne and Wetzel, 1999; Scheuner et al., 2004), which may have a positive effect on tree growth and stand productivity in paludified forests. Moreover, in order to improve black spruce establishment and growth in cutovers, site preparation techniques could be used to better improve regeneration sites (Lafleur et al., 2011). In paludified stands, ditching is an efficient technique to dry the forest soil (Roy et al., 2000) and scarification may reduce the SOL thickness (Duchesne and Wetzel, 1999), however these mechanical methods often lack the biological and chemical effects of wildfire (McRae et al., 2001).

Prescribed burning after clearcut (CCPB), the application of fire for ecosystem management purposes, has been used in the boreal forest after harvesting to prepare microsites for tree planting (Granström, 2001; McRae et al., 2001), but CCPB is now rarely used in Canada in a forestry setting due to its operational challenges (McRae, personal communication). However, the inherent properties of CCPB as a site preparation technique to emulate some of the effects of wildfire in an ecosystem based management framework are attractive (Bergeron et al., 2007; Nesmith et al., 2011; Ryan et al., 2013). CCPB can enhance microbial activity leading to higher decomposition rates of the SOL (Duchesne and Wetzel, 1999; Pietikainen and Fritze, 1995), increase soil pH, and induce a release of nutrients (Scheuner et al., 2004). Prescribed burning is also used to control competing vegetation (McRae, 1998), but the fire must be severe enough to burn the roots and prevent re-sprouting (Fernández et al., 2013). The effects of prescribed burning on soil and vegetation suggest that it could be an effective technique to control paludification and increase black spruce regeneration and growth (Certini, 2005; Ryan et al., 2013). Numerous studies have investigated the short term impacts of CCPB, but these studies were not conducted on deep organic soils like those found in paludified cutovers. Consequently long term studies of the impacts of CCPB are lacking, as are studies on deep organic sites.

Our study, using a retrospective approach, compared the effects of CLAAG, CC and CCPB on black spruce stands with deep soil organic layers (SOL) in the Clay Belt region of eastern Canada, a region prone to paludification due to its cold climate and poorly drained landscapes (Lefort et al., 2002). We hypothesized that, compared to CLAAG, CC and CCPB (1) reduce SOL depth and increase organic matter decomposition level rates, pH and carbon nitrogen ratio, (2) reduce *Sphagnum* spp. and ericaceous shrub cover, and (3) increase black spruce height and growth rate as well as stand density. We expected a stronger effect of CCPB than CC on the nutrient availability and pH of the SOL because of the biochemical effects of fire, and a stronger effect of CCPB than CC on understorey vegetation because prescribed burning removes forest floor plant species. The effects of CCPB should lead to a greater black spruce growth rate in burnt stands. With this study, we seek to illustrate the efficiency of applying prescribed burning in paludified black spruce cutovers to preserve and potentially improve stand productivity.

2. Methodology

2.1. Study region

This study was conducted in the Northern Clay Section, also called the Clay Belt, of the Boreal Forest Region (Rowe, 1972), Ontario, Canada. The Clay Belt is a large physiogeographic region characterized by clay deposits from proglacial lakes Barlow and Ojibway (Vincent and Hardy, 1977) with a low topographic relief. At the nearest weather station (Kapuskasing, ON) the mean annual temperature is 1.3 °C with an average of 829 mm of annual precipitation (Environment Canada, 2013). Vegetation in the Clay Belt region is characterized by extensive black spruce forests on uplands and lowlands, alternating in the latter position with extensive forested peatland and sphagnum peat bogs (Rowe, 1972). Forest floor cover is typically composed of mats of feathermosses (e.g. *Pleurozium schreberi*) and *Sphagnum* spp, as well as ericaceous shrubs (e.g. *Rhododendron groenlandicum* (Oeder) [Kron and Judd] and *Kalmia angustifolia* (Li.)).

2.2. Selection of sites

Retrospective studies rely on a rigorous selection of sites to ensure the similarity of the initial conditions of the studied sites to establish the nature and direction of the change in site characteristics, following disturbance (Dyck and Cole, 1994). We used two approaches to evaluate the similarity of the initial conditions before treatment: archival data and permanent site features that could not be affected by the type of harvest treatment (Appendix A). Forest industry archive data, Ontario Ministry of Natural

Resources and Fire Services data on prescribed burns were studied to select potential sites based on the initial stand conditions with respect to age, species composition and density (Arnup, 1987). The permanent site features that we used were mineral soil texture and drainage, which influence understorey vegetation dynamics, to evaluate the pre-harvest stand conditions. We described the mineral soil texture and moisture regime in the field following Taylor et al. (2000). In addition, we tallied the stumps in each site to estimate pre-harvest stand density (Appendix A).

To compare mineral soil texture and moisture regime we used a chi-square test on the contingency table of the treatments (Scherrer, 1984) and the number of stumps using generalized linear models. Comparisons of initial conditions proxies (mineral soil texture, moisture regime, and the number of stumps) among sites confirmed the similarity of sites prior to disturbance (Appendix A).

Site selection resulted in eight sites for the CLAAG and CCPB treatments, and six sites for the CC treatment for a total of 22 sites with the following selection criteria: slope inclination <3°, average SOL >20 cm over clay mineral soil, presence of *Sphagnum* spp. and Labrador tea (*R. groenlandicum*) in the understorey vegetation. Based on forest inventory and archive data, the pre-harvest stands were dominated by mature black spruce with at least 80% black spruce canopy cover, and were over 120 years old at time of harvest. According to the North East Ontario forest ecotype classification (Taylor et al., 2000), they were classified as ecosites 8, 9p, 11, 12, 13p, i.e. black spruce stands on moist mineral soil to deep fibric organic soil, with abundant *Sphagnum* spp., feathermosses and ericaceous shrubs.

2.3. Sampling

Fieldwork was conducted during the summers of 2006, 2007 and 2008. Within each site, we characterized the SOL profile, understorey vegetation and black spruce dendrometry in three 400 m^2 circular plots per site. Plots were established randomly in areas representative of the stand and were located 50 m or more from any roads, and at least 30 m from each other.

2.3.1. Soil Organic Layer

We characterized the SOL profile using the Ontario Ministry of Natural Resources protocol (Taylor et al., 2000). Within each 400 m^2 plot, we dug three pits in the SOL down to the mineral soil or to a maximum depth of 130 cm. In each pit, we measured the depth of the SOL and described the decomposition level at a 20 cm depth using the von Post index (VP20; Pepin et al., 1992). The von Post index is a semi-quantitative scale graduated from 1 (least decomposed) to 9 (most decomposed) used to evaluate the degree of humification of peat (Carter, 1993).

In each pit, a sample from the organic layer (around 20–30 cm deep, where the bulk of the root system was found) was collected and kept frozen at −20 °C until laboratory analyses. Organic layer samples were sieved at 4 mm to remove coarse woody debris and roots. Sub-samples were dried at room temperature and pH determined in distilled water and in KCl solutions (Carter, 1993). Total C and N contents were determined on a CNS analyzer (Leco Corporation).

2.3.2. Forest floor vegetation

We visually estimated the percent cover of *Sphagnum* spp., and percent cover of dominant ericaceous species (*K. angustifolia* L. and *R. groenlandicum*) in four circular subplots (4 m^2) per plot. As there were other understorey plant species such as herbaceous species, percent cover of *Sphagnum* spp. and ericaceous species did not always sum up to 100%. The subplots were systematically placed 2 m apart on the north-south axis of each plot.

2.3.3. Stand height and density

We measured a minimum of 50 black spruces taller than 50 cm per plot. Tree measurements included: height (*H*) and the last three years' apical growth. We noted the proportion of the plot covered by the 50+ black spruce in order to estimate the density of black spruce. We were interested in the dominant tree layer, thus we analyzed black spruce growth on the black spruces higher than the 75th percentile of sample height distribution.

2.3.4. Black spruce growth

Within each 400 m^2 plot, we randomly selected one dominant black spruce stem for growth analyses, dominance being determined based on height (>75th percentile of height distribution). Hence we selected 3 dominant stems per site for a total of 66 stems; 24 stems in CLAAG sites, 18 stems in CC sites and 24 stems in CCPB sites. Stem cross sections were collected at 0, 0.3, 0.6, 1, 2, and 3 m and every meter above for stem analyses. The cross sections were sanded using a progression of sand paper grit sizes (180, 300, 600). We measured tree ring width using high resolution imagery coupled to the dendrometry software Windendro (Regent Instruments Inc). Growth curves were then interpolated using WinStem software (Regent Instruments Inc). Pre-established stems presented characteristic slow growth unsuitable for crossdating before stand harvest and growth release. Thus growth analyses were done only for the years following stand harvest.

2.4. Statistical analysis

We performed comparisons of the treatment means using generalized linear mixed models (Pinheiro and Bates, 2000; Zuur et al., 2009) followed by a Least Square Deviation multiple comparison test. We used mixed models with "*site*" as a random effect to control for the intra-site correlation and to avoid pseudo-replication.

Quantitative continuous variables (e.g. organic soil depth and tree height) were analyzed using linear mixed models. Interval-scale variables (proportional and percentage data) were analyzed using generalized linear mixed models using a binomial distribution (Zuur et al., 2009) and the ordinal variable (VP20) was analyzed using a cumulative link mixed model (Venables and Ripley, 2002). We log transformed C:N ratio and relative growth rate in order to respect model assumptions of homoscedasticity and normal distribution of residuals.

We calculated the black spruce current relative growth rate (*RG*) using Eq. (1).

$$RG = \frac{I}{H} \quad (1)$$

where *I* is the total apical growth of the last three years of growth and *H* is the tree height. For each plot, we calculated black spruce density by dividing the number of trees measured by the surface of area sampled.

We analyzed the growth curves using a nonlinear least square regression model. We used the logistic growth curve with four parameters to model black spruce growth (Eq. (2)).

$$h_t = int + \frac{Asym}{1 + \exp\left(\frac{Xmid - t}{Scal}\right)} \quad (2)$$

where h_t is the tree height at time *t*, *int* is the intercept, *Asym* is the asymptote of the logistic curve, *Xmid* the inflection point and *Scal* the scale of the curve, which is the distance on the horizontal axis between the inflection point an 0.73 times the asymptote (Pinheiro and Bates, 2000).

Statistical analyses were performed with R software version 2.4.1 with the packages "MASS", "lme4", "nlme", and "multcomp" (Hothorn et al., 2008; R Core Team, 2013; Venables and Ripley, 2002). The logistic growth curve was fitted using the nlsList procedure with a self-start function of the "nlme" package (Pinheiro and Bates, 2000).

Most of the variables we studied were likely to change with time since disturbance (*TSD*). Therefore, we used a backward selection strategy to select the best model: we built all our models to include both *TSD* as a covariate and all the interactions between *TSD* and the treatments. We used a log-ratio test to assess if interaction of treatment and *TSD* was necessary (Vuong, 1989). If the effect of *TSD* was not important, we ran the model with "treatment" as the only explanatory variable. The *TSD* covariate was scaled prior to analyses to avoid correlation of parameters estimates (Schielzeth, 2010).

3. Results

3.1. Time since disturbance effect

Stands were 13–32 years old, averaging 22 years and were typical of paludified stands with deep acidic organic soils, extensive *Sphagnum* spp. mats and relatively small trees (Table 1).

Overall, time since disturbance was not important in regression analyses for the organic layer characteristics and for vegetation cover, but it was significant for black spruce relative growth. In addition, the interaction effect of *TSD* and treatment was significant for stem density (Table 2).

3.2. Comparison of soil organic layer characteristics

Multiple comparisons indicated that SOL depth did not differ significantly among treatments (Fig. 1 left panel).

Decomposition level of the organic layer at 20 cm (VP20) had a lower probability of being higher than 4 in CLAAG sites than in CCPB sites, as indicated by multinominal logistic regression (Table 3), meaning that at a depth of 20 cm SOL in CLAAG sites was less decomposed than in CCPB sites. VP20 was not significantly different between CLAAG and CC sites, nor between CCPB and CC sites.

The pH of the organic layer in CCPB sites was marginally higher than in CLAAG and CC sites ($p = 0.10$, Fig. 1, middle panel). Multiple comparison analyses on the log transformed CN ratio revealed no significant differences among treatments (Fig. 1 right panel).

3.3. Comparison of vegetation cover

CLAAG sites presented the highest cover of *Sphagnum* spp., CCPB sites had a significantly lower *Sphagnum* spp. cover than CLAAG ($p < 0.05$), and CC sites had an intermediate level of *Sphagnum* spp. cover (Fig. 2 left panel).

Multiple comparisons revealed no significant difference in ericaceous shrub cover among treatments, although the mean cover and the variability of cover in CCPB sites were lower (Fig. 2 right panel).

3.4. Comparison of stand height, apical growth and density

Stand height was not significantly different between CLAAG and CC sites but was marginally greater in CCPB sites than in CC sites ($p = 0.09$, Fig. 3 left panel).

The relative apical growth decreased with TSD (Table 2). Relative apical growth was not significantly different among treatments, although it appeared higher in CCPB sites (Fig. 3 right panel).

Black spruce density varied with time, and this effect varied among treatments (Table 2, Fig. 4). While black spruce density was constant with time in CLAAG and CC sites, it increased in CCPB sites (TSD slope = 0.15 stems m^{-2} ± 0.08 SD, $p = 0.06$ Fig. 4).

3.5. Black spruce individual growth

Individual growth curves showed that 12/24 of the stems collected in CLAAG sites were established before harvesting, and 6/18 of the stems collected in CC sites were also pre-established while only one stem out of 24 collected in CCPB sites was pre-established. This translated into higher intercepts for CLAAG and CC growth curves than CCPB but the differences were not significantly different (0.33 m, 0.43 m and 0.00 m respectively, Fig. 5).

The asymptote parameters were not significantly different among treatments (Fig. 5). The scale of the logistic curve was marginally lower for stems collected in CCPB and CC sites than in CLAAG (6.41 years ± 1.07 SE, 5.33 ± 0.82 SE and 9.02 ± 1.60 SE, respectively) and the inflection point of the logistic curve was lower for stems collected in CCPB sites than in CLAAG and CC sites (12.42 ± 0.60 SE, 14.35 ± 0.40 SE and 15.27 ± 0.58 SE, respectively), meaning that the growth rate was higher for stems collected in CCPB sites compared to CLAAG and CC sites (Fig. 5). As their growth rate was higher, stems in the CCPB sites were able to eliminate the height advantage of the pre-established CC and CLAAG stems by 15 years post-disturbance (Fig. 5).

4. Discussion

In this retrospective study, we compared the effects of three harvesting techniques, CLAAG, CC and CCPB, on paludification and regeneration of black spruce in the Canadian Clay Belt region. Compared to CLAAG and CC, SOL in CCPB sites was more decomposed and less acidic, which supports the hypothesis that prescribed fire has chemical effects on SOL that do not occur with harvest alone. Additionally, CCPB reduced *Sphagnum* spp. cover compared to other treatments, supporting the hypothesis that CCPB on paludified cutovers controls the expansion of *Sphagnum* spp. mats. Our results for black spruce height, growth, and density also suggest that CCPB increased black spruce growth compared to

Table 1
Mean and standard deviation of response variables for each treatment.

Treatment		*TSD* (year)	SOL (cm)	VP20	pH	CN	sph (%)	eri (%)	*H* (cm)	*RG*	Stem density (s.ha^{-1})
CLAAG	Mean	23.63	77.64	2	4.10	42.00	59.38	20.99	208.56	0.05	15854.72
	sd	6.35	29.94	1–4	0.64	19.93	15.62	11.60	149.24	0.02	6071.06
CC	Mean	22.83	57.83	3	3.97	48.60	45.53	20.86	198.52	0.06	10754.76
	sd	3.42	20.23	1–9	0.95	25.14	20.20	11.34	130.40	0.03	6014.48
PB	Mean	19.17	62.08	3	4.55	44.83	25.79	17.36	215.08	0.07	9807.54
	sd	4.83	37.03	1–9	0.91	25.18	27.72	17.62	144.91	0.03	8027.22

CLAAG = Careful logging around advanced growth; CC = clearcut; CCPB = clearcut followed by prescribed burning; *TSD* = time since disturbance; SOL = soil organic layer depth; VP20 = von Post index at 20 cm depth (mode and range); CN = carbon nitrogen ratio; sph = *Sphagnum* spp.; eri = ericaceous shrubs; *H* = black spruce height; *RG* = relative growth.

Table 2
Results of Log Likelihood ratio test to select for inclusion of time since disturbance (*TSD*) in the models. See Table 1 for variable names descriptions. Bold values indicate that *TSD* is meaningful variable based on model likelihood.

	SOL		*VP20*		*pH*	
Model	logLik	*p*	logLik	*p*	logLik	*p*
Treatment	−921.440	–	−282.720	–	484.270	–
Treatment + *TSD*	0.095	0.758	−282.720	0.934	489.500	0.827
Treatment + *TSD* + Treatment × *TSD*	2.232	0.328	−282.500	0.800	499.940	0.941
	logCN		*Sph*		*eri*	
Model	logLik	*p*	logLik	*p*	logLik	*p*
Treatment	−58.356	–	−790.830	–	−616.950	–
Treatment + *TSD*	−58.001	0.420	−790.200	0.264	−616.610	0.409
Treatment + *TSD* + Treatment × *TSD*	−58.068	1.000	−789.360	0.432	−616.550	0.944
	H		*RG*		Stem density	
Model	logLik	*p*	logLik	*p*	logLik	*p*
Treatment	−35196.160	–	−2553.800	–	−699.460	–
Treatment + *TSD*	−35193.130	**0.014**	−2542.900	**0.000**	−696.220	**0.011**
Treatment + *TSD* + Treatment × *TSD*	−35192.980	0.862	−2542.000	0.415	−690.620	**0.004**

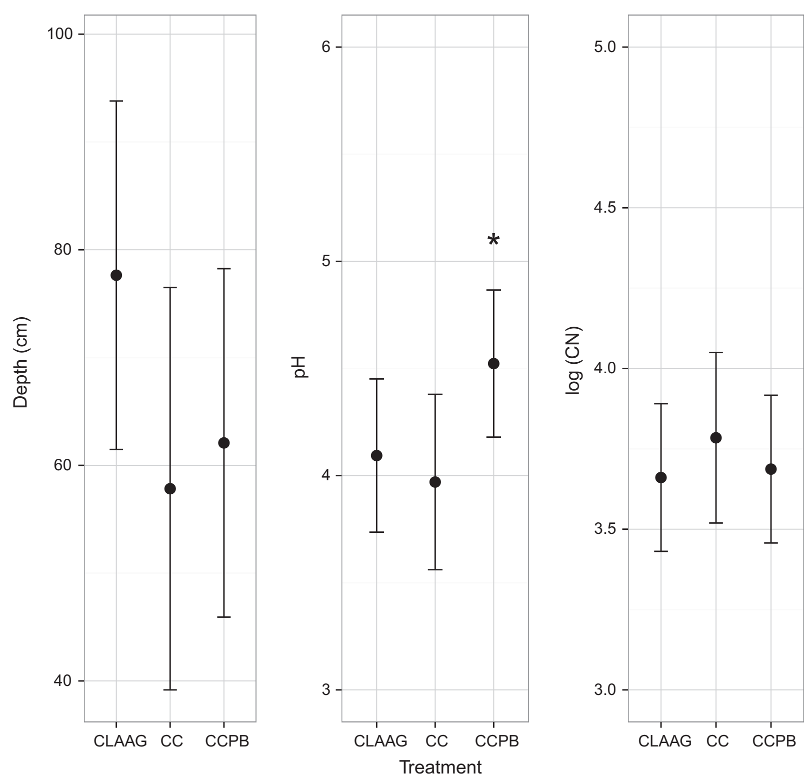

Fig. 1. Estimated mean and 95% confidence intervals of soil organic layer depth, soil organic layer pH and CN ratio (log scale to respect model assumptions) in three treatments: careful logging around advanced growth (CLAAG), clearcut (CC) and clearcut followed by prescribed burning (CCPB). Star indicates marginal difference with other treatments (alpha = 0.1).

the other treatments, presumably because of fire effects on SOL and forest floor vegetation. Our study demonstrates the potential of prescribed burning as a forest management tool to control paludification of black spruce boreal forest and increase stand productivity.

4.1. Effects on the organic layer

We found that prescribed burning after harvest affected the quality rather than the quantity of the soil organic layer. We found no effect of treatment on SOL depth. We expected few or no differences between CLAAG and CC because, while CC can compress the organic layer and create ruts, it does not affect the depth of the organic layer at the stand scale (Groot, 1998). By contrast we were surprised to find no difference of SOL thickness between CCPB and the other treatments. However, fires on deep SOL sites may only burn the surface because of the humidity of the peat which hinders organic soil smouldering (Miyanishi and Johnson, 2002; Terrier et al., 2014); consequently a retrospective study such as ours would not detect an effect because litter and organic matter accumulation could have subsequently eliminated the effects of low severity fire. These results indicate that prescribed burning in

Table 3
Coefficient estimation and standard error of multinominal logistic regression on von Post index classes measured at 20 cm depth for each treatment: careful logging around advanced growth (CLAAG), clearcut (CC), and clearcut followed by prescribed burning (CCPB). Bold coefficient estimates are significantly different from CLAAG estimates based on 95% confidence intervals. Coefficient estimates represent the probability (on the logit scale) and indicate that it is unlikely that CLAAG VP20 had a value of or more than 4 (logit (−1.74922) = 0.14, hence 14% probability). The high standard deviations for index 5–9 in the CLAAG treatment were due to a lack of observations in those classes of decomposition at 20 cm depth in the CLAAG sites.

VP20 index	CLAAG		CC		CCPB	
	coef	sd	coef	sd	coef	sd
2	0.083353	0.288927	0.40549	0.456436	**2.351592**	**0.740072**
3	−0.13974	0.30574	0.223143	0.474345	**1.946042**	**0.75599**
4	−1.74922	0.54174	−0.98085	0.677013	**1.252945**	**0.801839**
5	−17.3475	1219.269	−0.98084	0.67701	1.386484	0.790625
6	−17.3475	1219.269	0.117789	0.485915	0.916481	0.836712
7	−17.3475	1219.269	−1.38628	0.790571	−0.69299	1.224788
8	−17.3475	1219.269	−0.98073	0.676983	0.000184	1.000043
9	−17.3475	1219.269	−0.69312	0.612371	0.000184	1.000043

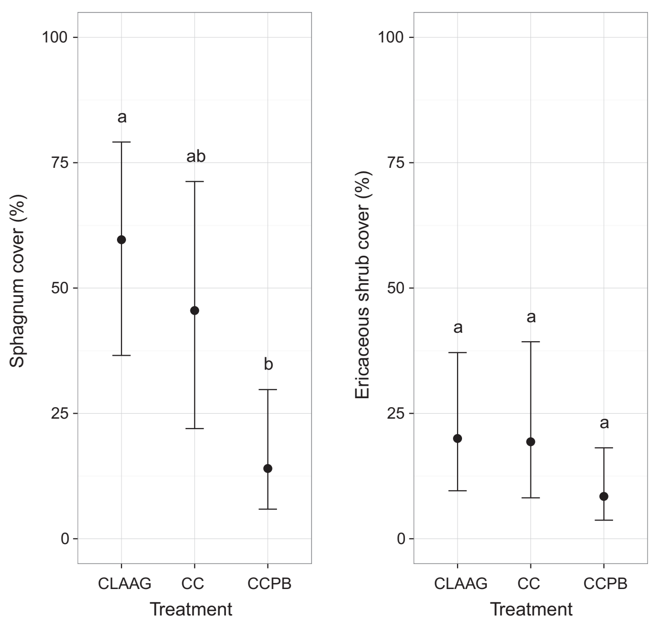

Fig. 2. Estimated mean and confidence intervals (95%) of sphagnum mat and ericaceous shrub cover in three treatments: careful logging around advanced growth (CLAAG), clearcut (CC) and clearcut followed by prescribed burning (CCPB); different letters indicate significant differences ($p < 0.05$).

paludified cutovers is of low severity and does not consequently reduce significantly SOL thickness in the long term.

Despite this, we found that CCPB had a positive impact on the decomposition level of SOL with more advanced humification (von Post index) and a slightly higher SOL pH compared to CLAAG and CC sites. Prescribed burning increases the decomposition rate of SOL through its chemical effects (Kranabetter and Macada, 1998; Certini, 2005). By combustion of slash and the surface of the forest floor, prescribed burning induces a pulse of exchangeable cations, which decreases soil acidity. Also, the burnt surface increases soil temperatures (DeBano, 2000). These changes to SOL chemistry and temperature conditions increase the rate of microbial activity, like nitrification, for several years (Pietikainen and Fritze, 1995; Ste-Marie and Paré, 1999; Zimmermann and Frey, 2002). However, we found no difference in the C:N ratio among treatments. The period during which there is a significant effect of prescribed burning on soil chemistry is highly variable: part of the SOL nitrogen is volatilized during fire, while the increase in availability of nutrients after fire is short and nitrogen availability is only increased during a few years (Certini, 2005). This could explain why our study conducted more than a decade after treatment did not detect a difference in SOL chemistry other than an increase in pH. Thus, the effect of prescribed burning on deep organic soil did not decrease SOL depth but modified SOL chemistry, while clearcut or careful logging had less impact on SOL. Although we did not have the information about the timing of harvest, we believe that the low impact of CC might be due to the harvesting season, which has a great effect on harvesting severity on SOL (Lafleur et al., 2010). Clearcut during winter may be equivalent to a careful logging practice because of the snow pack protecting established regeneration, and the frozen SOL is less impacted by machinery. Therefore some CC sites harvested in winter might have been less impacted by soil compaction during CC treatment, and consequently are more similar to CLAAG sites.

4.2. Effects on forest floor vegetation

We found that CCPB sites had less *Sphagnum* spp. cover than CC and CLAAG treatments while ericaceous shrub cover presented no significant difference among treatments. These findings support the hypothesis that prescribed burning can control *Sphagnum* spp. expansion on cutovers, but not the expansion of ericaceous

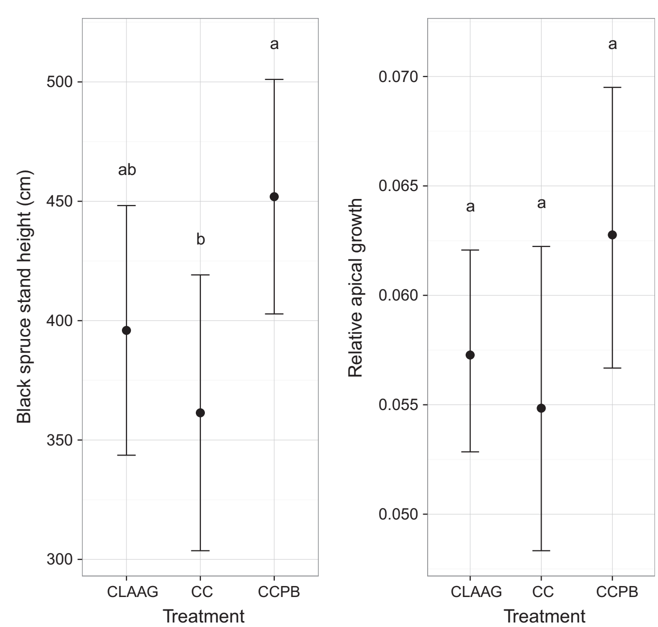

Fig. 3. Estimated mean and confidence intervals (95%) of black spruce height (cm) and vertical apical growth in three treatments: careful logging around advanced growth (CLAAG), clearcut (CC) and clearcut followed by prescribed burning (CCPB); different letters indicate significant differences ($p < 0.05$).

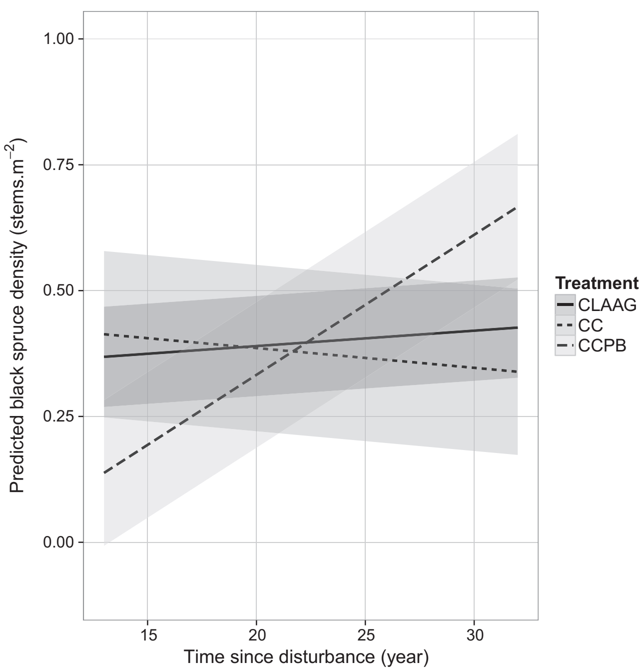

Fig. 4. Predicted black spruce density since harvesting in three treatments: careful logging around advanced growth (CLAAG), clearcut (CC) and clearcut followed by prescribed burning (CCPB); greyed areas are 95% confidence intervals of predictions.

shrubs. Our results are consistent with studies of post-wildfire forest floor succession in forested peatland areas dominated by *Sphagnum* spp. (Kuhry, 1994), where fire reduces *Sphagnum* spp. cover. In CC sites, *Sphagnum* spp. cover was not different compared to

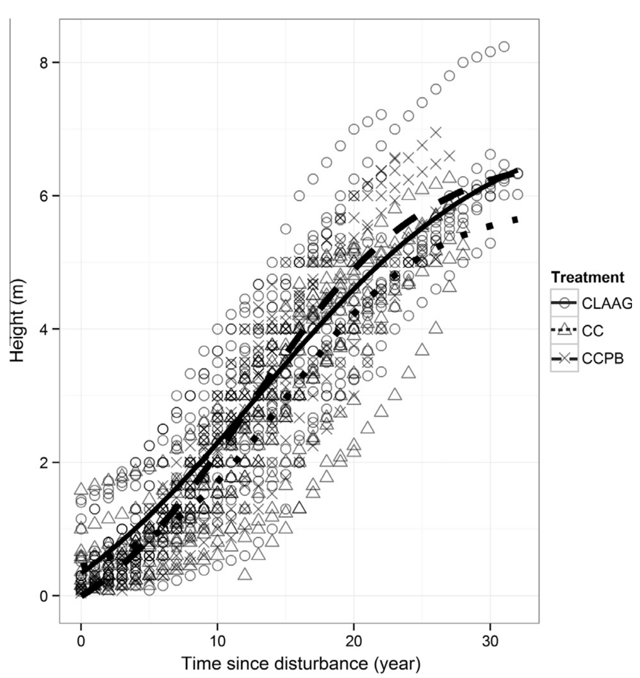

Fig. 5. Modeled black spruce growth with time in three treatments: careful logging around advanced growth (CLAAG, $n = 24$ stems), clearcut (CC, $n = 18$ stems) and clearcut followed by prescribed burning (CCPB, $n = 24$ stems); dots are data measurements indicating height of individual stems over time. Circles are CLAAG stems data and the solid line is the modeled growth curve. Triangles are CC stems data and the dotted line the modeled growth curve. Crosses are CCPB stems data and the dashed line the modeled growth curve.

CLAAG sites, which can be explained by the fact that *Sphagnum* spp. have the ability to regenerate from vegetative fragments (Rochefort and Lode, 2006), suggesting that light mechanical disturbances might not prevent *Sphagnum* spp. from spreading on cutovers as prescribed burning does (Fenton and Bergeron, 2007). However there was a non-significant trend indicating that *Sphagnum* spp. might recolonize the forest floor after CCPB, while leaving enough time for black spruce seedlings to establish on the burnt cutovers.

We found no difference in ericaceous cover among treatments. While high severity fires can burn ericaceous shrubs and notably their root systems, prescribed burning on wet sites such as those studied here may not burn the SOL deeply enough to destroy the roots system from which new shrubs can sprout (Mallik, 2003). Although our results demonstrate that low severity prescribed burning cannot prevent ericaceous shrub colonization in the long term, an initial control of ericaceous species is favorable for seedling establishment and could have increased stand regeneration (Thiffault and Jobidon, 2006). It is possible that a survey conducted one to five years following prescribed burning would have detected a short term reduction of ericaceous shrub cover, allowing a better regeneration of black spruce. Therefore, prescribed burning on paludified cutovers seems to be severe enough to prevent *Sphagnum* spp. expansion, but more severe prescribed burning might be needed if ericaceous shrub control is a specific objective of the site preparation treatment.

4.3. Effects on stand height, density and growth of dominant black spruces

We found that stands originating after prescribed burning were marginally taller than stands originating from CLAAG and CC. Also, the relative growth rate tended to be higher in CCPB than in CLAAG and CC sites. Finally, we found that black spruce density increased with time in CCPB sites, while in CLAAG and CC sites density remained constant over time, although the latter showed a great variability, presumably because of contrasting effects due to season of harvesting (Lafleur et al., 2010). Our results support our hypothesis that prescribed burning increases black spruce stand height and growth compared to CC and CLAAG. Our findings are consistent with studies indicating that fire increases stand productivity and tree growth (Chen and Wang, 2006; Chrosciewicz, 1976; Kranabetter and Macada, 1998). Prescribed burning effects on SOL and forest floor vegetation, as well as the low density after disturbance, might allow black spruce to grow in better conditions than in cutting only sites. We presume that the observed increase of pH and of the decomposition level improved tree nutrition in burnt sites (Certini, 2005; Thiffault et al., 2008). Further, the release of competition from *Sphagnum* spp. and ericaceous shrubs for the first years might have provided better growth conditions for black spruce seedlings and saplings. *Sphagnum* spp. is a poor growth substrate because it causes water retention at the surface of the organic soil (Bisbee et al., 2001; Lavoie et al., 2007) and its scaffolding effect on stems can suffocate small seedlings and reduce sapling growth (Malmer et al., 2003; Nguyen-Xuan et al., 2000). In addition to competition for resources, ericaceous shrubs, such as *K. angustifolia*, have the ability to inhibit black spruce growth by releasing phenolic allelochemical compounds (Inderjit and Mallik, 2002; Yamasaki et al., 2002). Finally, low stand density at the early stage of development might have helped the black spruce to grow faster because of reduced light and nutrient competition with neighbors.

We found that growth curves of dominant trees in CCPB sites were steeper than in CC and CLAAG sites (Fig. 5). In addition to the site variables discussed above, the establishment from sexual seedlings in cutovers with a site preparation could have led to higher growth rates in CCPB sites. A large proportion of trees in CLAAG and CC sites (50% and 33% respectively) were established before the time of harvest (Morin and Gagnon, 1992), confirming the efficiency of careful logging and the protection of the established regeneration by the snow in the case of winter CC (Lafleur et al., 2010). Those pre-established trees had a head-start compared to trees on CCPB sites (Fig. 5). However, most of the stems on CLAAG and CC sites were layers (Renard S., unpublished data), i.e. stems from low hanging branches that produce adventitious roots when in contact with SOL. Layers have a lower growth rate than seedlings, especially when site preparation is used (Prévost and Dumais, 2003). We found that the faster growth of black spruce on burnt sites reduced the pre-established advantage to the point that after 15 years, dominant trees were of similar size in each treatment, a notably shorter period than what was observed by Lussier et al. (1992). Notably, we were surprised by the high proportion (one third) of pre-established dominant black spruces in the CC sites. This could indicate that some CC harvesting was done during the winter when snow protected the pre-established regeneration. Using a more severe mechanical treatment (such as a summer clearcut) might improve black spruce growth in a similar fashion as observed with prescribed burning (Lafleur et al., 2010). While the exact causal pathway by which prescribed burning increased black spruce growth remains unknown, we suggest that the chemical and biological effects of fire described above might cause that positive effect on black spruce growth.

5. Implications for forest management

Over the last decades, the forest management paradigm has shifted from a focus on goods production to a focus on ecosystem management (Fenton et al., 2009; Franklin et al., 2002). Under that new paradigm, forest management seeks to emulate natural disturbance processes in order to keep the natural variability of structure and functions of ecosystems, and forest biodiversity (Gauthier et al., 2008). We believe, faced with the specificities of boreal black spruce forests in the Clay Belt region and the results of this retrospective study, that the use of prescribed burning should be considered as a preparation technique to control paludification after harvesting. Despite the obvious challenges of public health and forest fire control, the use of fire in forest management has been shown to be efficient in numerous cases (McRae et al., 2001; Weber and Taylor, 1992) and we advocate that prescribed burning should be considered as a management tool for forest managers to keep natural processes such as the chemical and biological effects of fire within the managed forest ecosystem.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.09.037.

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