Forest Ecology and Management 375 (2016) 172–181

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Silviculture to sustain productivity in black spruce paludified forests

Benoit Lafleur [a,b,*], Sébastien Renard [a,1], Cécile Leroy [b], Nicole J. Fenton [a], Martin Simard [c], Sylvie Gauthier [d], David Paré [d], Alain Leduc [b], Nelson Thiffault [b,e], Yves Bergeron [a]

[a] Institut de recherche sur les forêts and Chaire industrielle CRSNG-UQAT-UQAM en aménagement forestier durable, Université du Québec en Abitibi-Témiscamingue, 445 boul. de l'Université, Rouyn-Noranda, QC J9X 5E4, Canada

[b] Centre d'étude de la forêt, Université du Québec à Montréal, 141 Avenue du Président-Kennedy, Montréal, QC H2X 1Y4, Canada

[c] Département de géographie, Université Laval, Québec, QC G1V 0A6, Canada

[d] Ressources naturelles Canada, Service canadien des forêts, Centre de foresterie des Laurentides, 1055 du P.E.P.S., P.O. Box 3800, Québec, QC G1V 4C7, Canada

[e] Direction de la recherche forestière, Ministère des Forêts, de la Faune et des Parcs du Québec, 2700 Einstein, QC G1P 3W8, Canada

ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form 23 May 2016
Accepted 25 May 2016

Keywords:
Boreal forest
Foliar nutrition
Forest fire
Forested peatlands
Logging
Prescribed burning

ABSTRACT

Fire is considered the major disturbance in boreal forests. Nonetheless, in several areas logging has become the primary driver of forest dynamics. In many areas of the boreal forest, stands may undergo paludification (i.e. the accumulation of thick, poorly decomposed organic layers over the mineral soil) in the prolonged absence of fire, which reduces forest productivity. Whereas high-severity fires (HSF) may restore forest productivity by burning the soil organic layer (SOL), low-severity fires (LSF) mainly burn the soil surface and do not significantly reduce SOL thickness. In the Clay Belt region of eastern Canada, an area prone to paludification, forest stands have historically been harvested by clearcutting (CC), but concerns about the protection of soils and tree regeneration lead to the replacement of CC by careful logging (CL). Whereas CC disturbs the SOL and is thought to favor tree growth, CL has little impact on the SOL. Furthermore, it has been suggested that prescribed burning after clearcut (CCPB) could also be used to control paludification. Using a retrospective approach, this study sought to understand how CC, CL, and CCPB compare to LSF and HSF with respect to soil properties, SOL thickness, vegetation ground cover, tree nutrition, and stand height in paludified black spruce stands of the Clay Belt region. HSF led to significantly taller trees than CL and LSF, but did not differ from CC and CCPB. Foliar N was significantly higher in HSF and CCPB sites relative to CL and LSF, with an intermediate value in CC sites. Ground cover of *Rhododendron groenlandicum* was significantly lower in HSF and CC sites relative to LSF, with intermediate values in CL and CCPB sites. *Sphagnum* spp. ground cover was significantly lower in HSF and CCPB sites relative to CL, with intermediate values in CC and LSF sites. High-severity fire sites had a significantly thinner SOL than the four other disturbances. Finally, regression tree analysis showed that SOL thickness represented the best predictor of tree height, whereas segmented regression showed that tree height was negatively correlated to SOL thickness and revealed a cut-off point *circa* 23 cm, which suggests that tree growth is impeded beyond this threshold. These results support the idea that management strategies intending to regenerate paludified forests should primarily aim at reducing organic layer thickness, either through mechanical disturbance or combustion.

1. 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 eastern Canada. Historically, black spruce stands have been harvested by clearcutting because it was thought to be 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 Canada replaced clearcutting by careful logging, whose objectives are to protect soils and natural tree regeneration (Harvey and Brais, 2002). More specifically, careful logging consists of logging all merchantable trees with machinery

* Corresponding author at: Institut de recherche sur les forêts and Chaire industrielle CRSNG-UQAT-UQAM en aménagement forestier durable, Université du Québec en Abitibi-Témiscamingue, 445 boul. de l'Université, Rouyn-Noranda, QC J9X 5E4, Canada.

E-mail address: benoit.lafleur@uqat.ca (B. Lafleur).

[1] Present address: Parc Canada, 1340 Rue de la Digue, Havre-St-Pierre, QC G0G 1P0, Canada.

http://dx.doi.org/10.1016/j.foreco.2016.05.037
0378-1127/

traffic restricted to parallel trails that cover approximately 25–33% of the logged area. Trails are separated by "protection strips" in which only merchantable stems are logged, leaving pre-logging tree regeneration (Harvey and Brais, 2002).

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 (i.e. to the transformation of productive closed-crown forests on dry mineral soil into unproductive forest on organic soil), such as parts of the Clay Belt of northeastern Ontario and northwestern Quebec, 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 (Simard et al., 2007; Viereck et al., 1993). Furthermore, 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, directly limit tree growth (Inderjit and Mallik, 1996; Mallik, 1987; Thiffault et al., 2013). Studies conducted in northeastern Canada have 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 (Lafleur et al., 2010; Simard et al., 2009; Thiffault and Jobidon, 2006). 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.

Fire is considered the major natural disturbance in the boreal forest of eastern Canada (Bergeron et al., 2001; Payette, 1992). Forest fires are spatially variable, and soil burn severity varies greatly within and among fires (Johnstone and Chapin, 2006; Miyanishi and Johnson, 2002). In paludified black spruce forests, soil burn severity has significant consequences for tree regeneration (Greene et al., 2007; Johnstone and Chapin, 2006) and growth (Johnstone and Chapin, 2006; Simard et al., 2007), and for the structure, composition and productivity of forests (Lecomte et al., 2006a,b; Simard et al., 2007; Viereck, 1983). High-severity soil burns consume most of the organic forest floor (Dyrness and Norum, 1983; Greene et al., 2005) and promote the establishment of productive stands on mineral soil (Dyrness and Norum, 1983; Simard et al., 2007). In contrast, low-severity soil burns leave the forest floor almost intact, which provides a "head start" to the development of thick organic layers (Fenton et al., 2005; Shetler et al., 2008; Simard et al., 2007). In this context, prescribed burning (i.e. the application of fire for ecosystem management purposes) has been proposed as a means to reduce the thickness of the soil organic layer (SOL; Certini, 2005; Renard et al., 2016), control competing vegetation (McRae, 1998; Wiensczyk et al., 2011), release nutrients locked-up in recalcitrant organic matter, and favor tree regeneration and growth (Certini, 2005; Renard et al., 2016; Ryan et al., 2013; Siren, 1955). In the European boreal forest, prescribed burning was widely used after harvesting to prepare microsites for tree planting, but it is currently rarely used in Canada in a forestry setting due to its operational challenges. However, the inherent properties of prescribed burning as a site preparation technique to emulate wildfire in an ecosystem based management framework are attractive (Bergeron et al., 2007; Nesmith et al., 2011; Ryan et al., 2013). The effects of prescribed burning on soil and vegetation suggest that it could be a potential technique to control paludification and increase black spruce regeneration (Certini, 2005; Ryan et al., 2013). Numerous studies have investigated the short term impacts of prescribed burning that increase SOL temperature and decomposition (Duchesne and Wetzel, 1999; Pietikainen and Fritze, 1995), and could favor black spruce regeneration, notably through a reduction of competing vegetation (McRae, 1998). But these studies were not conducted on deep organic soils like those found in paludified cutovers, neither were they long term studies.

Using a retrospective approach, this study sought to understand how current (careful logging, CL) and former (clearcutting, CC) forest harvesting methods and potential site preparation techniques (prescribed burning, PB) compare to both low- and high-severity fires (LSF and HSF, respectively) with respect to soil chemical properties, SOL thickness, competing vegetation (i.e. ericaceous shrubs) and bryophyte ground cover, tree nutrition, and stand height in paludified black spruce stands of the Clay Belt region of northeastern Ontario and northwestern Québec (Fig. 1). To do so, we this study combined data from four different studies conducted in the Clay Belt region that each independently looked at the effects of CL, CC, CCPB (clearcut followed by prescribed burning), LSF, and/or HSF on soil properties and tree growth. It was hypothesized that because of greater soil disturbance due to compaction and/or combustion, CC and CCPB would reduce the thickness of the SOL, increase soil pH and nutrient availability, decrease the ground cover of competing vegetation, and promote stand growth compared to CL. It was also hypothesized that clearcutting would promote stand growth at a level comparable to that of high-severity soil burns. This study sought to identify the silvicultural treatments most likely to reproduce the growth patterns observed after high-severity soil burns and useful to maintain or restore forest productivity in paludified black spruce stands. In parallel, this study sought to identify, at the tree level, the variables that explain differences in tree height.

2. Methods

2.1. Study area

Located in the Canadian Boreal Shield Ecozone, the Clay Belt of northeastern Ontario and northwestern Québec (Fig. 1) is a large (125,000 km^2) physiographic region characterized by clay deposits (Vincent and Hardy, 1977). While the southern part of the study area is covered by thick (>10 m) glaciolacustrine clay and silt deposited by the glacial Lake Ojibway, 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). Soils of the study area are mostly classified as Gleysols and Luvisols (Soil Classification Working Group, 1998). Nonetheless, organic deposits (i.e. a surficial deposit consisting of a SOL > 30 cm thick) are found in many locations in both the southern and northern parts of the study area. According to local weather stations, from 1981 to 2010, the average annual temperature was 1.3 °C in Kapuskasing (49°24′N; 82°28′W), Ontario, whereas it was 0.0 °C in Joutel (49°28′N; 78°18′W), Québec (Environment Canada, 2015). During the same period, the average annual precipitation was 830 mm and 909 mm in Kapuskasing and Joutel, respectively, with 30% falling during the growing season, whereas the average number of degree-days (>5 °C) was 1430 in Kapuskasing and 1240 in Joutel. In both locations, the frost-free season lasts about 100 days, with frost occasionally occurring during the growing season.

The study area is dominated by black spruce-feathermoss forests that vary in density and height. Occasional stands of jack pine