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Key ecosystem attributes and productivity of boreal stands 20 years after the onset of silviculture scenarios of increasing intensity

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ABSTRACT

Ecosystem-based management, now a dominant forestry paradigm, implies reducing the gap between variability of natural and managed forests (i.e. ecological distance) to reconcile ecological issues with production of socioeconomic services. Here, we tested whether a trade-off exists between conserving key ecosystem attributes of natural forests and maintaining and/or increasing merchantable wood production at the stand scale in humid boreal stands. Using 20-y data from an experimental design comparing silviculture scenarios of increasing intensity, (i) careful logging around advance growth (CLAAG); (ii) CLAAG followed by pre-commercial thinning; (iii) plantation followed by mechanical release; and (iv) plantation followed by chemical release, we examined plant community composition, stand structure and the quantity and the quality of snags. We also assessed timber productivity by comparing scenarios in terms of conifer and merchantable (diameter at breast height > 9 cm) tree dimensions. We used data from stands originating from a spruce budworm outbreak as a baseline to understand scenario impacts on variability of key attributes and productivity. Our results showed increasing differences in these attributes between natural and managed stands with increasing silviculture intensity: the diameter structure became more homogenized, light demanding species richness and abundance increased and the quantity and the quality of snags decreased. Therefore, our results showed that the ecological distance from naturally disturbed stands was lower after CLAAG than after the other silviculture scenarios. However, CLAAG favored an increase in the density of deciduous trees and a decrease of conifer snag density that have the potential to affect resilience of mature stands. Pre-commercial thinning resulted in crop trees reaching larger diameter than following CLAAG only and in the decrease of birch tree density, with no effect on deciduous regeneration density $\geqslant$ 60 cm in height. We measured higher basal area of merchantable trees in plantations than in stands originating from natural regeneration scenarios, with mechanical and chemical release scenarios resulting in similar crop tree productivity. Globally, our study confirmed a general antagonism between the impacts of silviculture on key ecosystem attributes and forest productivity, posing a challenge for reconciling ecological issues with the production of socioeconomic services. At the stand level, results support that retention forestry could emulate natural disturbances by conserving biological legacies during harvest in humid boreal forests. Further research is needed to determine retention parameters to achieve expected wood production while maintaining variability of key attributes in humid boreal forests.

1. Introduction

While conservation of intact areas is necessary to deal with some biodiversity issues (e.g. Ray et al., 2015), adapting the management of the remaining forest matrix is essential to maintain ecosystem diversity and processes (Seiferling et al., 2012; Kareiva and Marvier, 2012). Over the past two decades, ecosystem-based management has thus become the dominant forestry paradigm in many countries (e.g. Butler and Koontz, 2005). Under this paradigm, forest managers aim at reducing the gap between variability of natural and managed forests (i.e. ecological distance) to reconcile ecological issues with production of socioeconomic services

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(Cardinall et al., 2004). Efforts to increase fiber production are, however, generally coincident with an increase in the intensity of silviculture, mainly due to plantations (Fu et al., 2007; Park and Wilson, 2007), which has a significant potential of conversion of natural forests to artificial ecosystems (Brockerhoff et al., 2008; Barrette et al., 2014). Hence, there is an apparent antagonism between maintaining variability of natural forests and increasing management intensity to favor merchantable wood production of desired species.

Extending over approximately 12.1 million km^2, the boreal biome is widely used for industrial forestry (Saucier et al., 2015). In terms of timber resources only, boreal forests worldwide support more than one million direct jobs in the forestry sector (Burton et al., 2010). This pressure has inevitable effects on boreal forest ecosystems; ecosystem-based management have thus been implemented in northeastern Canada (Gauthier et al., 2008). While many studies have shown a positive link between diversity and forest productivity (Forrester and Bauhus, 2016; Liang et al., 2016), production is often considered from an ecosystem perspective (e.g. aboveground biomass; Paquette and Messier, 2011) rather than from a forest management perspective. Many studies have reported on the short-term impacts of silviculture treatments on crop tree growth or plant community diversity after harvesting in temperate and boreal ecosystems (see review by Wagner et al., 2004). To our knowledge, few have assessed the effects of forest management on both the production from a forest management perspective and the ecological distance between managed and natural forests (but see Bell, 2015). To support the successful implementation of ecosystem-based management, there is a need to investigate the combined mid-term effects of silviculture scenarios of increasing intensity on merchantable wood production and variability of key ecosystem attributes at the stand level.

Humid boreal forests typical of northeastern America offer a particular challenge regarding ecosystem-based management of regenerating second growth stands. Balsam fir (*Abies balsamea* (L.) Mill.) is the dominant tree species of this ecosystem. It establishes understory seedling banks that survive decades under low light conditions until the opening of the canopy that typically follows cyclic insect outbreaks (Leblanc and Bélanger, 2000; Parent and Ruel, 2002). This natural disturbance dynamics supports the use of careful logging around advance growth (Thiffault et al., 2015). When fir advance growth is deficient, regenerating sites can, however, become dominated by northern hardwoods (e.g. white birch; *Betula papyrifera* Marsh.), a dynamic that favors the development of deciduous stands at the expense of conifer dominated stands (Déry et al., 2000). For such stands, reducing intra- and interspecific competition through pre-commercial thinning (PCT) became one of the most frequently applied silviculture treatments in the province of Quebec (Canada) during the 1990s (Thompson and Pitt, 2003). Although it may or may not enhance merchantable volume per hectare (depending on initial stand density), this treatment enables redistributing the site growth potential to a limited number of desired crop trees (Pothier, 2002; Pitt and Lanteigne, 2008). PCT generally increases species richness of ground vegetation cover and understory layers as it decreases canopy closure (Lindgren et al., 2006; Bataineh et al., 2014), but nonlinear responses to site fertility and light availability make it hard to predict understory responses to the treatment (Thomas et al., 1999). Thinning can also homogenize stand structure and composition (Puettmann et al., 2012). Furthermore, the establishment of spruce plantations (mainly black spruce; *Picea mariana* (Mill.) BSP) involving site preparation and one or more vegetation management treatments (either mechanical or chemical) is also common in this ecosystem. This practice raises concerns regarding variability of key attributes compatible with ecosystem-based management of fir-dominated forests (Hartley, 2002).

In this context, there is a need to assess silviculture scenarios along a gradient of intensity and balance their potential impacts on variability of key ecosystem attributes of natural forests with the benefits they can produce regarding productivity of desired crop species. It is crucial to test whether a trade-off exists between conserving key ecosystem attributes of natural forests and maintaining and/or increasing merchantable wood production at the stand scale. We thus report on a 20-y study assessing the impacts of silviculture scenarios of increasing intensity on stand productivity as well as on stand composition, structure and snags, i.e. three key ecosystem attributes of natural forests. We compared the variability of stand productivity, composition, structure and snags between managed stands and control stands. With globally distributed emissions of CO_2 and land use, we can nowadays consider that forests untouched by human activities no longer exist anywhere (Winter et al., 2010). We therefore used second growth stands with the maximum time past since management was abandoned (Winter, 2012) as a control baseline to assess the ecological distance between managed and 'natural' forests. These natural stands are regularly affected by spruce budworm outbreaks (*Choristoneura fumiferana* (Clem.)), the dominant natural disturbance that has driven forest species composition in this region over the last century (Boucher et al., 2016). We hypothesized that an increase in intensity of management (defined by the number of treatments and their objectives; Bell et al., 2008) concentrates environmental resources to desired crop species. Based on this hypothesis, we predicted that more intense scenarios would result (i) in a modification in plant community composition with an increase in heliophilous species at the expense of sciaphilous species, (ii) in a more homogenized stand structure, (iii) a decrease in snag density and quality and (iv) an increase of merchantable conifer wood production than less intense scenarios. Globally, we therefore predicted that at the stand scale, the ecological distance between managed and natural forests and the merchantable wood production would both increase with increasing silviculture intensity.

2. Materials and methods

2.1. Study area

We conducted this experiment on sites located in *Forêt Montmorency* and *Parc de la Jacques-Cartier* (47°16′–47°21′N; 71°01′–71°19′W), both located about 80 km North of Québec City (Québec, Canada) (Fig. 1). Vegetation in this region is typical of the balsam fir–white birch bioclimatic domain described by Saucier et al. (2009). Mature forests growing on mesic sites are typically dominated by balsam fir, black spruce and white birch. The region presents a boreal per humid climate with a mean annual temperature of 0.5 °C and mean annual precipitation of 1583 mm, of which about two-thirds fall as snow (weather station n° 7042388 located at 47°19′N; 71°09′W, Environnement Canada, 2015). The region is also characterized by a hilly landscape with an elevation ranging from 600 to 1100 m, and by soils covered by acidic glacial tills. Spruce budworm outbreaks constitute the main natural disturbances in our study area whereas wildfires are not frequent because of the high precipitation regime (Leblanc and Bélanger, 2000).

Only natural disturbances shape the forest landscape within *Parc de la Jacques-Cartier* since the last historical clear-cut harvests that occurred during the 1940s. Indeed, the *Parc* was classified as a conservation zone in the early 1980s and hence, forest stands within its limits have not been submitted to silviculture activities since then. Stands we selected within the *Parc* experienced a single spruce budworm outbreak between 1974 and 1986 (Fig. 2).