Journal of Environmental Management 225 (2018) 346–355

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Does time since fire drive live aboveground biomass and stand structure in low fire activity boreal forests? Impacts on their management

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ARTICLE INFO

Keywords:
Boreal forests
Live aboveground biomass
Stand structure
Time since fire
Low fire activity
Forest management

ABSTRACT

Boreal forests subject to low fire activity are complex ecosystems in terms of structure and dynamics. They have a high ecological value as they contain important proportions of old forests that play a crucial role in preserving biodiversity and ecological functions. They also sequester important amounts of carbon at the landscape level. However, the role of time since fire in controlling the different processes and attributes of those forests is still poorly understood. The Romaine River area experiences a fire regime characterized by very rare but large fires and has recently been opened to economic development for energy and timber production. In this study, we aimed to characterize this region in terms of live aboveground biomass, merchantable volume, stand structure and composition, and to establish relations between these attributes and the time since the last fire. Mean live aboveground biomass and merchantable volume showed values similar to those of commercial boreal coniferous forests. They were both found to increase up to around 150 years after a fire before declining. However, no significant relation was found between time since fire and stand structure and composition. Instead, they seemed to mostly depend on stand productivity and non-fire disturbances. At the landscape level, this region contains large amounts of biomass and carbon stored resulting from the long fire cycles it experiences. Although in terms of merchantable volume these forests seemed profitable for the forest industry, a large proportion were old forests or presented structures of old forests. Therefore, if forest management was to be undertaken in this region, particular attention should be given to these old forests in order to protect biodiversity and ecological functions. Partial cutting with variable levels of retention would be an appropriate management strategy as it reproduces the structural complexity of old forests.

1. Introduction

North American boreal forests are shaped by disturbance regimes, most particularly wildfires (Brandt, 2009; Johnson, 1992; Payette, 1992). Successional patterns are strongly determined by fires, notably fire intervals and fire severity. With an increasing time since the last fire, stand biomass and organic layer accumulate for a certain period of time, stand composition changes from mainly shade intolerant species to a higher proportion of shade tolerant species (Paré and Bergeron, 1995; Ward et al., 2014) and stand structure shifts from an even-aged structure to a more irregular one (Bouchard et al., 2008). A stabilization of the aboveground biomass is generally observed between 75 and 90 (Bouchard et al., 2008; Paré and Bergeron, 1995) to 150 years after a fire (Garet et al., 2009; Gauthier et al., 2010; Harper et al., 2005), depending on the region under study.

In North American boreal forests, fire activity decreases from west to east (Zhang and Chen, 2007). For instance, the North Shore region of Quebec, eastern Canada, experiences fire cycles reaching 785 years (Bouchard et al., 2008; Portier et al., 2016), while they could be as short as 90 years in the Taiga Plain of western Canada (Zhang and Chen, 2007). In the absence of fire, stands can become older than the mean longevity of tree species (Boucher et al., 2006; Kneeshaw and Gauthier, 2003). Their dynamics gradually become driven by non-fire disturbances associated with gap dynamics, such as insect outbreaks and windthrows (Blais, 1983; Girard et al., 2014; Pham et al., 2004; Waldron et al., 2013), or simply by senescence mortality. Consequently, such stands are characterized by complex age structures as new cohorts

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https://doi.org/10.1016/j.jenvman.2018.07.100
Received 16 April 2018; Received in revised form 27 July 2018; Accepted 29 July 2018
Available online 06 August 2018

establish below older ones (Boucher et al., 2006; De Grandpré et al., 2008).

Over the last few years, the Romaine River region in eastern Quebec has been opened for the forest industry, and close to 280 km^2 of forests have been flooded for hydroelectric production. In the context of such economic development, areas experiencing long fire cycles present substantial challenges. First, they contain an important proportion of old forests that are highly complex ecosystems playing a crucial role in preserving biodiversity and ecological functions (Bergeron and Fenton, 2012; Kneeshaw and Gauthier, 2003). Second, boreal forests contain a large share of the global terrestrial carbon pool (Bradshaw and Warkentin, 2015; de Groot et al., 2013; IPCC, 2014). In the context of climate change, the importance of keeping this carbon stored is widely recognized (IPCC, 2014). A large portion of this carbon is released into the atmosphere by fires (Bond-Lamberty et al., 2007; de Groot et al., 2007) but areas subject to low fire activity can store large amounts at the landscape level (Luyssaert et al., 2008).

Contrary to areas subject to short fire cycles that are relatively well documented (Harper et al., 2002; Rapanoela et al., 2015), forest attributes and dynamics of long fire cycle areas are still poorly known. Yet, live aboveground biomass and merchantable volume, as well as composition and structure characteristics of such regions would be valuable information for forest managers. Moreover, if forest live aboveground biomass and merchantable volume generally increase with time since the last fire (Harper et al., 2005; Lecomte et al., 2006; Paré and Bergeron, 1995), this relation is still poorly understood in boreal forests subject to long fire cycles. Similarly, the role of fire versus non-fire disturbances in changes in structure and composition of these ecosystems needs to be further studied, especially when forest management is involved. Finally, estimating carbon stocks is crucial for a better appreciation of the consequences of developing commercial forestry, as well as for simulating alternative scenarios using forestry as a mean to mitigate climate change (e.g. reforestation or intensive management in unproductive sites).

The goal of our study was to characterize the live aboveground biomass, merchantable volume, structure and composition of a fire-scarce region in the Romaine River area of Quebec, Canada, and to establish the relation between these attributes and the time since the last fire. Our study was based on field inventory data that was also used to extrapolate live aboveground biomass and merchantable volume to the entire study area at the scale of forest stands. Overall, this study intended to improve our understanding of the dynamics of low fire activity areas to help build appropriate forest management strategies in such regions.

2. Material and methods

2.1. Study area

The Romaine River is located in the eastern North Shore region of Quebec, eastern Canada, north of the St. Lawrence River. This region has recently been opened to economic development for hydroelectric energy and forest products (MFFPQ, 2013a). In particular, a portion of the forested landscape has been flooded permanently to produce electricity. The entire region is mainly characterized by a very low fire activity with rare but large fires. Fire cycles range from ~200 years in the north to ~8200 years in the south (Gauthier et al., 2015). Our study area is centered on Romaine River and is entirely located within the spruce-moss bioclimatic domain, except for the northernmost portion that lies in the spruce-lichen domain (MFFPQ, 2013b). It covers 72,681 km^2 and stretches between latitudes 50°N to 53°N, and between longitudes 66°W to 60°W (Fig. 1). This region is the one of the wettest in eastern Canada, with total mean annual precipitation ranging from 754 mm to 1108 mm. Mean annual temperature varies from −4.2 °C to 3.3 °C (means of weather data extracted at the forest-stand level over the 1971–2000 period - Leboeuf et al., 2012). The topography is

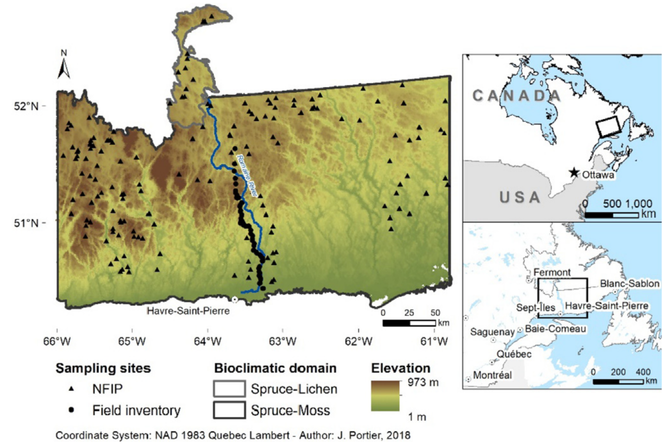

Fig. 1. Map of study area in the eastern North Shore region of Quebec, Canada, showing the location of sampling sites, elevation profile and bioclimatic domains.

variable throughout the study area with flat, sea level areas in the south along the St. Lawrence River, gradually transiting to a highly fractured relief to the north, rising to nearly 1000 m of elevation (Fig. 1). The southern half of the study area mainly sits on bedrocks with very thin mineral soil, while the northern half is largely dominated by thick till deposits. If, as in the rest of the boreal zone of Quebec, black spruce (*Picea mariana* (Mill.) B.S.P.) is the most represented tree species in the coniferous boreal forests of the North Shore region, long fire cycles and high precipitation make it possible for a significant proportion of balsam fir (*Abies balsamea* (L.) Mill.) to develop in these forests (Bouchard et al., 2008; De Grandpré et al., 2000). Some other tree species, such as trembling aspen (*Populus tremuloides* Mich.), white birch (*Betula papyrifera* Marsh.) and white spruce (*Picea glauca* (Moench) Voss) can also be found in smaller proportions.

2.2. Field data and basal area calculation

The field campaign was conducted in 2014 along a 160-km-long road near Romaine River (Fig. 1). The road was divided into 32 consecutive 5-km-long by 750-m-wide cells (Portier et al., 2016). In each cell, two points located at a minimum distance of 100 m from the road were randomly generated. These points were used as sampling plots for the estimation of tree basal area (BA) and organic layer thickness. One out of two plots per cell was used for time since fire estimation. In the northern section of the road, a lower number of plots were sampled because of access issues (total number of field plots = 54). In addition, 164 plots from the Northern Forest Inventory Program (NFIP; 2005 to 2009) of the Ministère des Forêts, de la Faune et des Parcs du Québec (MFFPQ) were added to the field dataset (Fig. 1). Our field protocol was adjusted to match that of the NFIP in order to obtain data of the same kind. Both datasets could therefore be combined without further compatibility testing. In total, time since fire data was available for 200 plots: 44 field plots (Portier et al., 2016) and 156 inventory plots from the NFIP. Fire history was conventionally reconstructed using dendrochronology. In each stand, the time since the last fire was inferred from the age of 10 dominant trees (Arno and Sneck, 1977; Johnson and Gutsell, 1994). If this method allows the reconstruction of up to 350 years of fire history, time since fire estimates become less precise as they increase (Cyr et al., 2016; Portier et al., 2016). When a stand is older than the oldest tree on-site, assessing a precise stand age becomes impossible. In these cases, a minimum time since fire was attributed to the stand (Cyr et al., 2016; Portier et al., 2016).

In the 54 field plots, BA was assessed per species from the center of the plot using a factor-two wedge prism that selects trees meeting a certain size-distance threshold (Bruce, 1955; Paré et al., 2013). The BA