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A comparative study of long-term stand growth in eastern Canadian boreal forest: Fire versus clear-cut

Arnaud Fourrier *, David Pothier [1], Mathieu Bouchard [2]

Center for Forest Research (CEF), Department of Forest Sciences, Laval University, Québec, QC G1K 7P4, Canada

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ABSTRACT

Clear-cutting and fire are the two main disturbances affecting the boreal forest of eastern Canada. These two disturbance types exert different effects on forest dynamics, which can have major implications in terms of economic and ecological sustainability. This study compared the long-term effects of these two disturbance types on stand composition, stand density, and merchantable volume on eastern Canadian mesic boreal forests dominated by black spruce and balsam fir. We used 157 permanent sample plots (PSP), 41 of which originated from fire and 116 were from clear-cuts. Model selection with finite-sample corrected Akaike Information Criterion (AICc) was used to understand which factors had the greatest influence on relative stand density and merchantable volume. Our results indicate that merchantable volume was positively influenced by stand density, which in turn was primarily influenced by disturbance origin, with post-cutting stands being denser than post-fire stands. These results indicated that an increase in stand density is an important mechanism through which disturbance acts upon merchantable volume. We also found differences in forest composition between stand-origin categories, with balsam fir being more abundant post-clearcutting; this was likely because advance regeneration was mainly composed of balsam fir, whereas post-fire stands are dominated by black spruce. Differences in merchantable volume between post-fire and post-clearcut stands become non-significant with time, likely because of higher tree growth and lower mortality in the dominant canopy of clearcut-origin stands. Overall, the results indicate that stand origin is an important determinant of stand composition and stand yield, but that the latter effect tends to disappear after a few decades. The higher balsam fir content generally observed in naturally regenerated, clear-cut origin stands could have potentially negative economic and ecological impacts at the landscape scale, which may call for mitigation strategies.

1. Introduction

Boreal forest is the most extensive forest ecosystem worldwide, in that it covers 11% of the Earth's terrestrial surface (Kuusela, 1992). Moreover, the boreal forest biome represents the largest terrestrial reserve of carbon (Shugart et al., 1992). In the last few decades, many studies have documented natural disturbances processes in boreal forest ecosystems, in order to maintain these processes as much as possible through forest management (Johnson et al., 1998; Bergeron et al., 2002; Harvey and Brais, 2002). Wildfire is the principal agent of natural disturbance in the boreal forest (Bonan and Shugart, 1989; Viereck, 1983), but over the last century, at least in Canada, the area clear-cut has increased substantially (Brumelis and Carleton, 1989; Hart and Chen, 2006). The higher rate of clear-cut compared to fire is particularly obvious in parts of the boreal forest where the fire cycle (i.e., the time needed to entirely burn an area equivalent to the study area) is longer than the clear-cut rotation age (i.e., the age at which forest is to be harvested). Understanding differences in stand growth and compositional trajectories between clear-cutting and fire is important for a better understanding of the effects of management activities on natural ecosystems, and to improve management tools such as timber supply models.

Although fire and clear-cutting are both stand-replacing disturbances, they have different effects in terms of stand dynamics (Haeussler and Kneeshaw, 2003; Johnson et al., 2003). Fires leave an abundance of dead trees and some patches of residual unburned live trees, which create structural heterogeneity at the stand and landscape levels (Johnson et al., 1998). Patches of live trees may act as source habitats for plant species with poor dispersal capabilities (Dettki et al., 2000), whereas dead trees, snags and decaying logs provide an important habitat for a range of specialized plant species (Bradbury, 2006). In comparison, traditional clear-cutting generally results in removal of all merchantable trees, the felling

* Corresponding author. Tel.: +1 (418) 656 2131x2792.
E-mail addresses: arnaud.fourrier.1@ulaval.ca (A. Fourrier), David.Pothier@sbf.ulaval.ca (D. Pothier), Mathieu.Bouchard@mrn.gouv.qc.ca (M. Bouchard).
[1] Tel.: +1 (418) 656 2131x12908; fax: +1 (418) 656 526.
[2] Tel.: +1 (418) 643 7994; fax: +1 (418) 643 2165.

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of most non-merchantable tree species, and the retention of few dead and live standing trees (Haeussler and Kneeshaw, 2003). Severe fires also generally eliminate advance regeneration and consume much of the surface organic matter layer, thereby producing suitable mineral seedbeds for regeneration (Johnson, 1992), whereas clear-cuts often maintain advance regeneration and the understory plants (Rees and Juday, 2002), especially when the ground is snow-covered during harvesting operations (Nguyen-Xuan et al., 2000; Reich et al., 2001).

While equal wood volume yields from stands originating from fire and clear-cutting can be observed when their compositions are similar (Reich et al., 2001; Ruel et al., 2004), differences in species composition can markedly affect wood production, regardless of the disturbance being considered (Reich et al., 2001). If different disturbances induce different patterns of species succession, we can expect differences in stand production between these two types of disturbance. In eastern Canada, late-successional species may represent much of the regeneration in clear-cut stands, particularly when careful logging practices that protect advance regeneration and soil are used (Morin and Gagnon, 1991; Pothier et al., 1995; Parent and Ruel, 2002). In contrast, stands originating from fire are expected to be mostly composed of pioneer species that have established after the disturbance (Bergeron, 2000; Bouchard et al., 2008). Stand density and initial size of the recruited trees following disturbance could also have important implications in terms of wood production (Seedre and Chen, 2010).

It is important to compare forest productivity that is associated with both types of stand-replacing disturbance to accurately predict volume increases and to insure sustainable forest management over the long-term. Hence, the main purposes of this study are: (1) to compare stand-level wood production in clearcut-origin and fire-origin stands over the long term on a large territory; (2) to examine if potential differences can be explained by stand characteristics such as relative stand density or forest composition; and (3) to examine the implications of these findings for sustainable forest management in boreal forests.

2. Materials and methods

2.1. Study area

The study area covered most of the North Shore region, a provincial administrative district in eastern Québec, Canada. The study area covered 62,962 km^2 and extended northward from the north shore of the Saint Lawrence River to 51°N (Fig. 1). It is located on the Canadian Shield, which is composed mostly of Precambrian rocks that are covered by glacial till of various thicknesses and by fluvioglacial deposits. According to 30-year meteorological records at two different locations along the river (1971–2001, Environment-Canada, 2012), the climate is boreal humid, with mean annual precipitation varying from 1014 to 1156 mm and mean annual temperature ranging from 0.8 to 1.5 °C. Further inland, the climate is expected to be colder and drier (Proulx, 1987). Forests in this region are dominated by black spruce (*Picea mariana* (Mill.) BSP) and balsam fir (*Abies balsamea* (L.) Mill.), with minor components of jack pine (*Pinus banksiana* Lamb.), white or paper birch (*Betula papyrifera* Marsh.), and trembling aspen (*Populus tremuloides* Michx.). Other species that were present in lower proportions include white spruce (*Picea glauca* (Moench) Voss) and eastern larch or tamarack (*Larix laricina* (Du Roi) K.Koch), together with yellow birch (*Betula alleghaniensis* Britt.) and red maple (*Acer rubrum* L.) in the southern portion of the North Shore region. In this region, fire is the major natural stand-replacing disturbance, with a relatively long mean return interval that ranges from 250 to 500 years along a west–east longitudinal gradient (Bouchard et al., 2008). Mesic sites tend to be dominated by black spruce and hardwood pioneers after fire, with a gradual increase in balsam fir content that can occur when the initial post-fire cohort begins to die some 100 years or more after the stand-initiating fire (Bouchard et al., 2008). In pre-industrial conditions, fire was the only disturbance capable of creating patches of mortality larger than several tens of km^2 across the whole region. Other types of natural disturbances are widespread, but are of relatively secondary importance in terms of landscape-scale forest composition; stand-replacing windthrows (defined as severe mortality that is incurred over areas >5 ha) have affected a mean 0.0255% of the area per year, which is equal to a cycle of about 3900 years (Bouchard et al., 2009), while severe spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks have historically affected only the southern part of the study area, with a corresponding cycle of about 9200 years over the entire study area (Bouchard and Pothier, 2010). Prior to 1900, anthropogenic disturbances were mainly restricted to selective logging of large trees along major rivers. Clear-cut logging (defined as removal of at least 75% of the original dominant canopy cover) began in the early 1920s, i.e., during the pulp and paper industry boom (Frenette, 1996). Early clear-cuts occurred mostly in the southern part of the region and were gradually expanded northward away from the main rivers with the progressive development of the road network, particularly after the 1950s (Bouchard and Pothier, 2011). Even today, however the northern and eastern sectors of the North Shore region have not experienced extensive forest management (Bouchard et al., 2008) such as 57% of the forest stands are overmature (MRNFP, 2004).

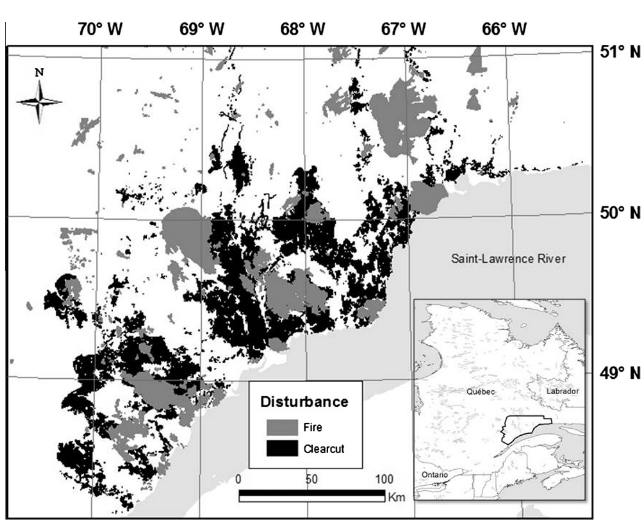

Fig. 1. Location of study area and large scale distribution of fires (1921–1976) and clear-cuts (1932–1990).

2.2. Disturbance maps

A fire history map, which had been constructed by Bouchard et al. (2008), was used to determine stand origin in the eastern part of the territory for the period 1900–2000. For the western part of the territory, a fire map was constructed for the same period by using archival information (aerial photographs and forest maps), which were complemented with ground surveys (dendrochronology); details of the methodology are presented in Bouchard et al. (2008). Maps of clear-cutting history were created using maps found in forest company archives, as well as aerial photographs (between 1930 and 2000) (Bouchard and Pothier, 2011). For the older cuts, for which company archives were scarce, field surveys were conducted using dendrochronological methods to confirm the year in which clear-cutting had occurred at different points