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Tree community structural development in young boreal forests: A comparison of fire and harvesting disturbance

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ABSTRACT

Although natural disturbance-based management systems support the use of clearcut harvesting as a means of emulating fire disturbance in boreal forest, there are continual concerns and uncertainties over the degree to which clearcutting alters forest ecosystem dynamics relative to wildfire. Here, we sampled 56 and 47 post-fire and post-harvest stands, respectively, to examine early tree community structural development in young boreal mixedwood forests in central Canada. We find that tree species diversity is higher immediately following clearcut harvesting compared with stand-replacing crown fire. We attribute this primarily to protection of advanced regeneration, suitable regeneration substrates, and propagule availability of shade-tolerant conifer species following harvesting compared with fire. Although both disturbances promoted early successional species, harvesting resulted in higher regeneration densities of late-successional conifers (*Picea mariana* (Mill.) and *Abies balsamea* (L.) Mill.). Vertical height structure variation was higher after fire than harvesting, likely a result of spatial heterogeneity in burn severity. Although tree heights, corrected for stand age, did not differ between disturbances for *Populus tremuloides* Michx. and *Pinus banksiana* Lamb., they were shorter for *Betula papyrifera* Marsh. and taller for late-successional conifers following harvest. Higher tree species richness, regeneration densities, and tree heights of late-successional conifer species indicate that clearcut harvesting can potentially accelerate succession in boreal mixedwood forests; however, harvesting can reduce height structural variability. Furthermore, leaving *Betula papyrifera* to satisfy the policy requirement for green tree retention can negatively affect its post-harvest regeneration and growth.

1. Introduction

Historically, wildfire is the dominant natural disturbance driving forest ecosystem dynamics across the world's forest (Attiwill, 1994; Bonan and Shugart, 1989; Bond-Lamberty et al., 2007). However, corresponding with worldwide trends in natural resource consumption (Foley et al., 2005), millions of hectares of forests are now harvested annually (Food and Agriculture Organization, 2010), leading to a significant shift in forest disturbance regimes globally. In North America, approximately one million hectares of boreal forest are clearcut each year, with the majority of harvested areas being left to regenerate naturally (Canadian Council of Forest Ministers, 2005). Although 'natural disturbance-based management' systems support the use of clearcut harvesting as a means of emulating fire disturbance in boreal forest (Bergeron et al., 2002; Lieffers et al., 1996), there are continual concerns over the degree to which clearcutting alters forest ecosystem dynamics relative to wildfire (McRae et al., 2001; Kuuluvainen and Grenfell, 2012); in particular, growing use of 'full-tree' clearcut harvesting, in which most trees on site are felled, transported roadside and processed, with branches and foliage either burned on site or removed for bioenergy (Thiffault et al., 2011).

In the boreal mixedwood forests of North America, both crown fire and clearcutting tend to shift tree community composition toward higher abundance of shade-intolerant, deciduous species, i.e., *Populus* spp. and *Betula papyrifera* Marsh. (Bergeron, 2000; Peters et al., 2006; Chen et al., 2009), primarily due to their abundant light-weight wind-dispersed seed, prolific vegetative reproduction, and fast growth; particularly in stands where these species formed a significant component of the pre-disturbance community (Greene et al., 1999; Caners and Kenkel, 2003; Ilisson and Chen, 2009a). However, the differential effects of crown fire and clearcutting on plant community structural diversity are less well known (Rees and Juday, 2002; Haeussler and Bergeron, 2004; Simon and Schwab, 2005).

Crown fires tend to kill most vegetation in affected stands, promoting young even-aged communities of fire-adapted tree species, e.g., *Populus* spp., *Betula papyrifera*, *Pinus banksiana* Lamb., and *Picea mariana* (Mill.) B.S.P. (Johnson, 1992). However, within and

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among crown fires, burn severity can vary substantially, resulting in scattered patches of surviving trees (Kafka et al., 2001; Jayen et al., 2006;), including less fire-adapted species, (e.g., *Abies balsamea* (L.) Mill. and *Picea glauca* (Moench) Voss), that contribute to overall community diversity (Burton et al., 2008). Surviving patches of trees coupled with variable effects of burn severity on soil germination beds (Johnstone and Kasischke, 2005; Johnstone et al., 2010) may further contribute to heterogeneity in tree regeneration structure (the horizontal and vertical distribution of tree biomass) throughout the stand (Wang, 2003; Greene et al., 2004; Haeussler and Bergeron, 2004).

Clearcut harvesting is considered to promote the abundance of shade-intolerant, deciduous species by stimulating root and stump sprouts, but can have a negative effect on regeneration of fire-adapted conifers through lack of thermal energy required to open serotinous and semi-serotinous cones (McRae et al., 2001). Conversely, protection of advanced regeneration (seedlings and samplings established prior to harvest), seeds, and vegetative propagules, which would normally be consumed under crown fire conditions, can promote the abundance of shade-tolerant tree species (Nguyen-Xuan et al., 2000; Harvey and Brais, 2002; Simon and Schwab, 2005; Ilisson and Cshen, 2009b). Protection of adanved regeneration, coupled with skid trail creation and soil disturbance from operation of heavy machinery, may in fact result in higher heterogenity of tree regeneration structure than that following wildfire (Nguyen-Xuan et al., 2000; Harvey and Brais, 2002; Buckley et al., 2003).

In this paper, we examine early tree community structural development following crown fire and clearcut harvesting in the boreal mixedwood forest of central Canada. Specifically, we sought to test whether tree species diversity, evenness, and vertical height structure significantly varied according to disturbance type and we explore underlying causal mechanisms.

2. Materials and methods

2.1. Study area

Our study was conducted in the boreal forest north of Lake Superior and west of Lake Nipigon in the Upper English River (B.11) Forest Region (Rowe, 1972), approximately 150 km north of Thunder Bay, Ontario (48° 22′ N, 89° 19′ W, 199 m elevation) (Fig. 1). Average annual precipitation for Thunder Bay (1971–2000) is 712 mm and average annual temperature is 2.5 °C (Environment Canada, 2011). This region is part of the boreal mixedwood forest, with upland forests consisting primarily of mixtures of trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) B.S.P.), and balsam fir (*Abies balsamea* (L.) Mill.), with small components of white spruce (*Picea glauca* (Moench) Voss), tamarack (*Larix laricina* (Du Roi) K. Koch), and balsam poplar (*Populus balsamifera* L.). Fire is the most common natural stand-replacing disturbance in the study area, with a mean fire-return interval of approximately 100 years (Senici et al., 2010). The last spruce budworm (*Choristoneura fumiferana* Clem.) epidemic peaked in 1986 and collapsed approximately 10 years later (Paul Poschmann, personal communication), causing significant mortality of balsam fir and *Picea* spp. trees. Soils on upland sites are relatively deep glacial tills of the Brunisolic order (Soil Classification Working Group, 1998).

2.2. Sampling design

Field data collection took place in the summer of 2007. To facilitate sampling, a wide range of pre-disturbance stand compositions in an area of approximately 800 km^2 were selected using forest inventory maps. Pre-disturbance stand ages ranged from 70 to 150 years since fire (Senici et al., 2010). As most tree species that form the post-disturbance cohort recruit within 5–10 years after disturbance (Gutsell and Johnson, 2002), we selected both post-fire and post-harvest stands ranging from 6 to 12 years old in an effort to capture early forest ecosystem dynamics (Swanson et al., 2011).

Implementing a well-balanced design to study the effects of natural disturbances can be challenging (Parker and Wiens, 2005). In our study area, there was one large fire that occurred during the decade of interest (1992–2001) (Senici et al., 2010). This fire was ignited on 30 April 1999, was brought under control on 15 May 1999, and was extinguished on 13 July 1999 by the Provincial Fire Suppression Program. Throughout the 2-month burn period, fire intensity varied with changing weather conditions, resulting in a 26,400 ha burn area and a wide range of stand types and conditions. The entire burn area was left to regenerate naturally without salvage logging. Post-harvest sites in our study area were created from full-tree clearcut harvesting that took place between 1995 and 2001. Trees were felled and dragged roadside for processing, with branches and foliage burned in piles. Post-harvest stands were left to regenerate naturally with no site preparation, seeding, or competition control. However, due to limitations in harvest site availability, we included seven stands that had received spot planting (<300 seedlings per ha) of black spruce. Planted trees were easily recognizable as they were planted in rows with equal spacing. We avoided sampling these areas and did not include any planted trees in our analysis (Ilisson and Chen, 2009b). Furthermore, sample plots were allocated at least 250 m from unburned or uncut forest stand edges to control for potential edge effects from undisturbed areas. Resulting post-fire and post-harvest stands ranged in age from 6 to 12 years old in 2007.

To help control for confounding effects of different site edaphic conditions, we followed an ecological classification approach (Taylor et al., 2000) by selecting only mesic sites on mid-slope positions with well-drained glacial moraine soils >50 cm thick. Soil moisture regime class was confirmed for each stand by examining its topographic position and texture of the soil profile, dug to the underlying parent material (Taylor et al., 2000).

In an effort to represent the wide range of pre-disturbance forest compositions on the same dominant site type (i.e., mesic sites) after disturbance, we used stratified random sampling, aided by pre-disturbance forest resource inventory and aerial photos, to capture various species compositions of the six dominant tree species, *Populus tremuloides*, *Betula papyrifera*, *Pinus banksiana*, *Picea mariana*, *Picea glauca*, and *Abies balsamea.* For each of the six study species and disturbance origins, we attempted to sample at least five random replicates of each of the commonly occurring forest stand types on mesic sites in the region (Taylor and Chen, 2011), but actual species compositions were used in our analysis. Every effort was made to intersperse stands by selecting stands from different road accesses, resulting in at least 50 m distance between the nearest plots (most of them over 200 m). In total, we sampled 56 post-fire stands and 47 post-harvest stands.

2.3. Field measurements

In each selected stand, pre-disturbance stand structure and composition was determined within a 20 × 20 m main plot, in which we only measured trees that would have been alive before fire or harvest. Live and dead trees at the time of fire were separated according to charring signs on the wood. Live trees killed by fire typically shed their charred bark within a few years, leaving only bare wood that weathers and turns gray. Alternatively, trees that are dead at the time of fire have dry wood and bark that burn, leaving a snag or log with clearly charred wood (Boulanger and