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Characterizing residual structure and forest recovery following high-severity fire in the western boreal of Canada using Landsat time-series and airborne lidar data

Douglas K. Bolton [a,*], Nicholas C. Coops [a], Michael A. Wulder [b]

[a] Integrated Remote Sensing Studio, Department of Forest Resources Management, Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada

[b] Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, British Columbia V8Z 1M5, Canada

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ABSTRACT

Post-fire regrowth is an important component of carbon dynamics in Canada's boreal forests, yet observations of structural development following fire are lacking across this remote and expansive region. Here, we used Landsat time-series data (1985–2010) to detect high-severity fires in the Boreal Shield West ecozone of Canada, and assessed post-fire structure for >600 burned patches (>13,000 ha) using airborne light detection and ranging (lidar) data acquired in 2010. We stratified burned areas into patches of dense (>50% canopy cover) and open (20–50% canopy cover) forests based on a classification of pre-fire Landsat imagery, and used these patches to establish a 25-year chronosequence of structural development for each class. While structural attributes were similar between dense and open patches during the first ten years since fire (YSF), canopy cover (cover above 2 m) and stand height (75th height percentile) were significantly higher ($p < 0.001$) for dense patches by the end of the chronosequence (20–25 YSF), suggesting that differences in site productivity were driving patches towards pre-disturbance structure. Our results suggest that growing space remained in stands at the end of the chronosequence, and therefore stem exclusion was not yet reached, as canopy cover was significantly lower ($p < 0.001$) for patches at 20–25 YSF (mean = 41.9% for dense, 18.6% for open) compared to patches with no recorded burns (mean = 63.3% for dense, 38.6% for open). The lasting impact of high-severity fire on structure was further confirmed by estimates of stand height, which were approximately half as tall for patches 20–25 YSF (4.9 m for dense, 4.2 m for open) compared to patches with no recorded burns (9.8 m for dense, 7.7 m for open). Additionally, we assessed the structural complexity of burned stands using measures of canopy roughness (i.e., rumple) and the distribution shape of lidar returns (i.e., skewness and kurtosis), which provided evidence of young, even-aged structure once a new overstory was formed. As forest inventories are not routinely conducted across Canada's northern boreal, the fusion of Landsat time-series and airborne lidar data provides powerful means for assessing changes in forest structure following disturbance over this large forested area.

1. Introduction

An average of two million hectares of forests is burned annually across Canada, with the boreal region accounting for 88% of the documented burned area between 1959 and 1997 (Stocks et al., 2002). These fires lead to significant changes in forest structure, with direct carbon emissions from fire across Canada estimated at 27 Tg carbon year^{-1} (Amiro, Stocks, Alexander, Flannigan, & Wotton, 2001). In the absence of active fire suppression, the northern boreal of Canada is dominated by large, stand-replacing crown fires, typically started by lightning strikes (De Groot et al., 2013; Stocks et al., 2002; Wooster, 2004). As the majority of these northern forests are unmanaged and not subjected to routine forest inventory (Gillis, Omule, & Brierley, 2005), a strong characterization of the impacts of these fires on forest structure is lacking. Additionally, due to the large extent of the northern boreal and the limited access to these forests (Andrew, Wulder, & Coops, 2012), quantifying the structural response to a range of fire events is difficult through field measurement alone.

Landsat data has been used extensively to detect and describe forest disturbances at regional scales for decades (e.g., Cohen et al., 2002; Schroeder, Wulder, Healey, & Moisen, 2011; Vogelmann & Rock, 1988). The change in the normalized burn ratio (NBR) between Landsat images, for example, has been used to detect fires and estimate burn severity (Hall et al., 2008; López García & Caselles, 1991; Soverel, Perrakis, & Coops, 2010). The opening of the Landsat archive in 2008, along with advances in cloud screening (Zhu & Woodcock, 2012) and atmospheric

* Corresponding author. Tel.: +1 604 822 6592; fax: +1 604 822 9106.
E-mail address: doug.k.bolton@alumni.ubc.ca (D.K. Bolton).

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correction (Masek et al., 2006), has led to a drastic increase in the volume of Landsat data used in disturbance detection studies, both spatially and temporally (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). By developing approaches to analyze dense time-series of Landsat images (e.g., Hermosilla et al., 2015; Huang et al., 2010; Kennedy, Yang, & Cohen, 2010; Zhu, Woodcock, & Olofsson, 2012), it is now possible to reconstruct the history of forest disturbances over the Landsat data record. For example, Goodwin and Collett (2014) processed thousands of images across 20 Landsat scenes to map fire history in Queensland, Australia from 1986 to 2013.

While Landsat is well-suited to detect and describe fires, the lack of three-dimensional information limits our ability to assess the structural response of forests using Landsat data alone. To address this issue, recent attempts have relied on a fusion of Landsat time-series and light detection and ranging (lidar) data, which together provide the means to detect disturbances and quantify their impact on forest structure (Kane et al., 2014; Pflugmacher, Cohen, Kennedy, & Yang, 2014; Wulder et al., 2009). Kane et al. (2013) differentiated the structure of forests following varying levels of burn severity in Yosemite National Park using Landsat data to determine burn severity and airborne lidar to assess structural response. The regeneration of vegetation following disturbance can also be tracked through the fusion of Landsat time-series and lidar data. For example, Lefsky, Turner, Guzy, and Cohen (2005) used Landsat to determine stand age and airborne lidar to assess biomass accumulation and forest productivity in western Oregon. Alternatively, Goetz, Sun, Baccini, and Beck (2010) used spaceborne lidar data acquired by the Geoscience Laser Altimetry System (GLAS) to assess vegetation regrowth following fire over large areas of Alaskan boreal forests.

A range of structural attributes can be estimated from airborne lidar data that are of interest in aboveground biomass and habitat characterization research, such as canopy cover, stand height, and stand structural complexity (Kane, McGaughey et al., 2010; Lefsky, Hudak, Cohen, & Acker, 2005). While estimates of canopy cover and stand height can be estimated directly from a lidar point cloud, structural complexity is often inferred as the variability in return height (Zimble et al., 2003) or the variation in maximum height across the canopy surface (Kane, McGaughey, et al., 2010). In addition, a number of studies have demonstrated the value of lidar data for characterizing forest successional stage (e.g., Falkowski, Evans, Martinuzzi, Gessler, & Hudak, 2009; Kane, Bakker et al., 2010, 2011; Van Ewijk, Treitz, & Scott, 2011). For example, Falkowski et al. (2009) distinguished six stand development stages with over 95% accuracy in northern Idaho, using a range of lidar metrics that described vegetation height and canopy cover. Using lidar metrics to assess successional stage provides powerful means for assessing forest response to disturbance.

In the summer of 2010, transects of small-footprint airborne lidar data were collected across the Canadian boreal, with a total length of approximately 25,000 km. This lidar dataset provides an opportunity to assess the structural response of forests to a range of fire events. Using this dataset, Magnussen and Wulder (2012) developed a relationship between canopy height and time since fire for 163 fires that occurred from 1942 to 2007, which were recorded in the Canadian National Fire Database (CNFDB), a compilation of historical fire data from fire management agencies across Canada. As most fire perimeters in the CNFDB are generalized and can contain a mosaic of burned and unburned forest patches, Magnussen and Wulder (2012) required a statistical approach based on maximum expected growth to separate burned, regenerating vegetation from unburned vegetation within the fire perimeters. Using Landsat time-series data to delineate burned areas in place of the CNFDB would facilitate a more precise assessment of post-burn structure.

In this analysis, we detect high-severity burned patches from 1985 to 2010 using Landsat time-series data across 40 million ha of Canada's Boreal Shield West ecozone, and assess the structural response to these fires using airborne lidar transects. By sampling patches that burned over a 25-year period, we construct a 25-year chronosequence of structural development to address the following questions:

*Do lidar metrics capture residual forest structures (*e.g., *snags, surviving trees) as well as tree regeneration during the first 25 years since fire (YSF)?*

High-intensity crown fires, which dominate the Canadian boreal, leave little to no live tree cover in the immediate years following fire (Heinselman, 1981; Viereck, 1983). Before regenerating trees begin to form an overstory, lidar metrics will capture and relate to residual structures such as snags (i.e., standing dead wood) or trees that survive the fire. As tree growth is restricted to short growing seasons (Bonan & Shugart, 1989) and tree establishment can take a number of years following fire in the boreal (Johnstone et al., 2004), we do not expect an overstory to begin forming until at least ten years after fire (e.g., Gralewicz, Nelson, & Wulder, 2012).

How does structure at the end of the chronosequence compare to structure in patches with no record of burning?

In particular, we are interested in observing if stands reach crown closure by the end of the chronosequence (20–25 YSF), and how estimates of stand height, an indicator of aboveground biomass, compare to stands with no record of burning. Harper et al. (2002) found that canopy cover was highest in eastern boreal stands from 50 to 100 YSF, while stand height peaked from 75 to 150 YSF, suggesting that structure at the end of the chronosequence will remain significantly different than in patches with no recorded burns. Additionally, we expect stand structure to be less complex at the end of the chronosequence compared to stands with no record of burning, as canopy breakup and gap filling (Chen & Popadiouk, 2002) lead to more complex canopies in older boreal stands (Brassard, Chen, Wang, & Duinker, 2008).

Does canopy cover prior to fire relate to stand development post-fire?

Site-level conditions and pre-fire stand composition have been shown to strongly influence stand development following fire in boreal forests (e.g., Boucher, Gauthier, & De Grandpré, 2006; Greene et al., 2007; Harper, Bergeron, Drapeau, Gauthier, & De Grandpré, 2005; Johnstone & Chapin, 2006). As structural measurements prior to fire are not available, we will classify burned patches into open (20–50% canopy cover) and dense (>50% canopy cover) forests using pre-fire Landsat imagery. We expect newly established trees to grow faster in patches classified as dense prior to fire, as these sites are likely more productive. However, it is unclear the degree to which structural differences between dense and open patches will be detectable with lidar during the first 25 YSF.

By addressing these questions, we intend to develop improved techniques for assessing structural response to fire and provide an improved characterization of the impacts of fire on forest structure in the Canadian boreal.

2. Methods

2.1. Study area

The Boreal Shield is the largest Canadian ecozone, spanning from Newfoundland in the east to Saskatchewan in the west (Ecological Stratification Working Group, 1995). The ecozone is dominated by coniferous species, such as black spruce (*Picea mariana*), white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*), which are capable of tolerating the long, cold winters of this ecozone. Broadleaf species, such as trembling aspen (*Populus tremuloides*) and white birch (*Betula papyrifera*), are more abundant towards the southern portion of the ecozone (Ecological Stratification Working Group, 1995; Farrar, 1995). As the Boreal Shield spans a wide range of climatic and ecosystem conditions from east to west, the ecozone is often divided into east and west compartments for analysis (Stinson et al., 2011; Stocks et al., 2002). The percent annual area burned between 1959 and 1997 was more than five times higher in the Boreal Shield West (0.76%) compared to the Boreal Shield East (0.15%, Stocks et al., 2002), mainly due to drier conditions in the west and a higher probability of lightning strikes (Brassard &