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Characterizing boreal forest wildfire with multi-temporal Landsat and LIDAR data

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ABSTRACT

Wildfire is an important disturbance agent in Canada's boreal forest. Optical remotely sensed imagery (e.g., Landsat TM/ETM+), is well suited for capturing horizontally distributed forest conditions, structure, and change, while Light Detection and Ranging (LIDAR) data are more appropriate for capturing vertically distributed elements of forest structure and change. The integration of optical remotely sensed imagery and LIDAR data provides improved opportunities to characterize post-fire conditions. The objective of this study is to compare changes in forest structure, as measured with a discrete return profiling LIDAR, to post-fire conditions, as measured with remotely sensed data. Our research is focused on a boreal forest fire that occurred in May 2002 in Alberta, Canada. The Normalized Burn Ratio (NBR), the differenced NBR (dNBR), and the relative dNBR (RdNBR) were calculated from two dates of Landsat data (August 2001 and September 2002). Forest structural attributes were derived from two spatially coincident discrete return LIDAR profiles acquired in September 1997 and 2002 respectively. Image segmentation was used to produce homogeneous spatial patches analogous to forest stands, with analysis conducted at this patch level.

In this study area, which was relatively homogenous and dominated by open forest, no statistically significant relationships were found between pre-fire forest structure and post-fire conditions ($r<0.5$; $p>0.05$). Post-fire forest structure and absolute and relative changes in forest structure were strongly correlated to post-fire conditions (r ranging from −0.507 to 0.712; $p<0.0001$). Measures of vegetation fill (VF) (LIDAR capture of cross-sectional vegetation amount), post-fire and absolute change in crown closure (CC), and relative change in average canopy height, were most useful for characterizing post-fire conditions. Forest structural attributes generated from the post-fire LIDAR data were most strongly correlated to post-fire NBR, while dNBR and RdNBR had stronger correlations with absolute and relative changes in the forest structural attributes. Absolute and relative changes in VF and changes in CC had the strongest positive correlations with respect to dNBR and RdNBR, ranging from 0.514 to 0.715 ($p<0.05$). Measures of average inter-tree distance and volume were not strongly correlated to post-fire NBR, dNBR, or RdNBR. No marked differences were found in the strength or significance of correlations between post-fire structure and the post-fire NBR, dNBR, RdNBR, indicating that for the conditions present in this study area all three burn severity indices captured post-fire conditions in a similar manner. Finally, the relationship between post-fire forest structure and post-fire condition was strongest for dense forests (>60% crown closure) compared to open (26–60%) and sparse forests (10–25%). Forest structure information provided by LIDAR is useful for characterizing post-fire conditions and burn induced structural change, and will complement other attributes such as vegetation type and moisture, topography, and long-term weather patterns, all of which will also influence variations in post-fire conditions.

1. Introduction

Wildfire events play an integral role in the ecological functioning of Canadian boreal forests (Bergeron et al., 2004; Parisien et al., 2006), impacting carbon emissions (Amiro et al., 2001; Stocks et al., 2002), plant reproduction (Johnstone & Kasischke, 2005; Johnstone & Chapin, 2006), forest succession (Harper et al., 2005; Lecomte et al., 2006), wildlife habitat quality (Dawson & Bartolotti, 2006), hydrology (Yoshikawa et al., 2003), and soil nutrient cycling (Zasada et al., 1992). Researchers have hypothesized the existence of a positive feedback loop between global warming and forest fires: global warming will extend the fire season in the boreal forest, increasing the likelihood of forest fires and further contributing to greenhouse gas emissions (Balshi et al., 2007; Gillett & Weaver, 2004; Kasischke et al., 1995; Soja et al., 2007; Stocks et al., 1998).

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Climate change scenarios produce an expectation of an increased likelihood of longer fire seasons with more frequent large, high intensity fire events (Flannigan et al., 2005a; Tymstra et al., 2007). It has been projected that increasing concentrations of CO_2 in the atmosphere could result in a 74–118% increase in the average annual area burned in Canada by the end of the 21st century (Flannigan et al., 2005b). Bond-Lamberty et al. (2007) assert that the impacts of climate change have yet to be realized in Canada's boreal forest region. Existing data indicates that the number of forest fires recorded in Canada have increased steadily over the past eight decades to approximately 8000 fires per annum in the 1990s, while the annual area burned has fluctuated substantially over this same time period (Stocks et al., 2003). Average fire suppression costs in Canada range from $300 to $500 million dollars annually (Flannigan et al., 2005b).

Due to broad ecological, social, and economic implications, there is much interest in characterizing forest fire fuels (Arroyo et al., 2008; Mutlu et al., 2008), forest fire behaviour (Pastor et al., 2003), and post-fire recovery (Shatford et al., 2007) for forest fire management. Post-fire conditions are often described in the context of fire intensity and fire or burn severity (Lentile et al., 2006a). Fires burn with varying intensities (*i.e.*, energy released per unit length of flame front, per unit time), depending on fuel load, fuel moisture, wind speed, and topographic constraints (*i.e.*, slope steepness and aspect) (Wright & Bailey, 1982). Fire or burn severity are measures used to characterize the degree to which the ecosystem is impacted by a fire (DeBano et al., 1998; Neary et al., 2005; Ryan, 2002) and incorporate both short- and long-term effects (Key, 2006; Key & Benson, 2006; Lentile et al., 2006a). To date, relatively few studies have used remotely sensed data, specifically LIDAR and optical imagery, to directly investigate the impact of wildfire on vertical forest structure (French et al., 2008).

The goal of this study was to relate variations in remotely sensed measures of post-fire effects to measures of pre- and post-fire vertical forest structure. The first objective was to evaluate whether LIDAR can be used to detect changes in vertical forest structural characteristics associated with wildfire. The second objective was to characterize the relationships between the vertical forest structural information afforded by discrete return profiling LIDAR data collected pre- and post-fire, with the horizontal information on pre- and post-fire vegetation location, type, and post-fire effects provided by Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery acquired pre- and post-fire. This included examining post-fire forest structure, as well as absolute and relative changes in forest structure in the context of varying post-fire effects. The third objective was to determine the influence of pre-fire forest structure on post-fire effects.

2. Background

2.1. Post-fire effects

No common definition of fire or burn severity exists (Jain et al., 2004; Key & Benson, 2006) and both terms have been used interchangeably in the literature. Lentile et al. (2006a) suggest the use of the more generic term "post-fire effects" and distinguish between fire and burn severity as a function of time: fire severity is a measure of immediate post-fire effects such as direct vegetation consumption and mortality as a result of the fire, whereas burn severity is a measure of the longer term consequences of fire. There is often temporal overlap between these two assessments of severity (Lentile et al., 2006a).

For a given area, variation in vertical and horizontal forest structure and composition, and the attendant variation in fire intensity, result in variations in post-fire effects. Post-fire effects can range from partial consumption of vegetation cover with little soil exposure and, or light char/ash deposition, to complete consumption of vegetation cover with high soil exposure and heavy char/ash deposition (Rogan & Franklin, 2001; White et al., 1996). Severity can be a qualitative or quantitative assessment of the ecological effects of a fire that integrates the various phenomenological characteristics of a fire-altered landscape (*i.e.*, the physical, biological, and chemical manifestations of combustion on vegetation) (Pyne et al., 1996). Knowledge of severity provides a vital source of information to understand the impact of fire on ecological functions and as a means to characterize the intensity of past, current, and future fire events (Epting et al., 2005; van Wagtendonk et al., 2004).

The assessment of post-fire effects considers ecosystem conditions prior to the fire, and the amount of aboveground vegetation and forest floor fuel consumed by the fire. Ecosystem conditions prior to the fire are characterized by vegetation type and structure, and by forest floor composition, with the latter being influenced by soil type, depth, bulk density, and inorganic content. The amount of fuel consumed (aboveground vegetation and forest floor) is dependent on fuel characteristics such as fuel load, bulk density, horizontal and vertical distribution of vegetation, fuel moisture, and weather. Wildfires are typically more severe when temperatures, wind speeds, and fuel loads are high, and humidity and fuel moisture are low. Post-fire effects can differ for aboveground vegetation and soil/forest floor. In boreal forests, a low intensity surface fire can create high soil/forest floor burn severity if a large amount of surface fuels have accumulated and are consumed, while a high intensity crown fire in an area with moist soil/forest floor conditions can lead to a high aboveground burn severity, but to a low soil/forest floor burn severity (DeBano et al., 1998; Dahlberg, 2002; Graham et al., 2004). Thus different soil surface burn severity levels can occur in combination with different aboveground vegetation burn severity levels, rendering the application of a composite burn severity index challenging under certain conditions (Kasischke et al., 2008).

Forest structural attributes such as canopy bulk density and canopy base height are associated with aboveground vegetation burn severity. Tree canopy base height has been highlighted as one of the most important factors for crown fire initiation in conifer forests in the inland western United States (Jain & Graham, 2007). Information on vertical forest structure is therefore important when studying aboveground burn severity, because vertical continuity and bulk density of fuels from the ground to the crown increases the likelihood of crown fire occurrence and spread rate, respectively (Monleon et al., 2004); however, high canopy bulk densities and low canopy base heights alone do not necessarily lead to a fast spreading crown fire with a high aboveground burn severity (Hall & Burke, 2006).

Mapping of post-fire effects is necessary for management of post-fire recovery and timber salvage (Miller & Yool, 2002) and aids in predicting and understanding rehabilitation and succession processes (Turner et al., 1998). Assessment of post-fire effects in the field is a subjective process using tools such as the Composite Burn Index (CBI) field protocol (Key & Benson, 2006) which was designed to be correlated with remotely sensed estimates of burn severity (Lentile et al., 2006a). The CBI protocol is used to calibrate and validate burn severity maps produced from remotely sensed data (Hall et al., 2008; Key & Benson, 2006) and assesses average post-fire effects (quantity of fuel consumed, degree of soil charring, degree of vegetation rejuvenation) over a square 30 m by 30 m plot, which is then matched to the severity measured from remotely sensed data. Burn severity is typically classified into broad damage classes (e.g., low, moderate, high) (Diaz-Delgado et al., 2004; DeBano et al., 1998; Isaev et al., 2002; Mitri & Gitas, 2008; Patterson & Yool, 1998; Robichaud, 2000), although there is an important variation in these classifications across regions and vegetation types (Lentile et al., 2006a). Assessment of post-fire effects using remotely sensed data are dependent on spatial, temporal, and radiometric considerations, and the complex interactions of these factors (Key, 2006).

2.2. Normalized Burn Ratio (NBR), delta NBR (dNBR), and Relative dNBR (RdNBR)

A wide variety of remotely sensed data sources have been used to map areas impacted by fire at regional (Röder et al., 2008), national (Goetz et al., 2006), continental (Masek et al., 2008; Pu et al., 2007), and