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Boreal Shield forest disturbance and recovery trends using Landsat time series

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ABSTRACT

Monitoring forest recovery following disturbance is important for both forest management as well as assessing possible climate change impacts on forest dynamics. To do so, an improved understanding of forest recovery processes and their relationship to remotely sensed spectral measures of recovery is required. Our objective in this research is to develop and apply a methodology for using Landsat time series to characterize forest recovery using spectral recovery trajectories. We focus our efforts in the Canadian Boreal Shield ecozone where a known geographic east to west distinction in disturbance regimes remains to be quantified. Results show that forest recovery following a stand replacing disturbance is detectable and quantifiable using a dense Landsat time series of spectral reflectance. All Tasseled Cap indices were found to capture an element of forest recovery following disturbance, with Wetness offering additional information on increasing vegetation structure and complexity. Tasseled Cap component trajectories of recovery show clear differences in both disturbance detection and forest recovery across the east and west Boreal Shield sections. The Cohen's d similarity metric indicated large differences (d > .08) in Wetness and Greenness-based spectral recovery trajectories when comparing the two Boreal Shield sections with the East Boreal Shield having markedly more above average recovery (+2 std. dev. from the mean) than the West. Based on our spectral recovery results, we also observe that forest recovery varies over the entire ecozone and is different between the east and west Boreal Shield forests.

1. Introduction

While variable based upon definitions, Canadian boreal forests represent about 30% of global boreal forests (Brandt, Flannigan, Maynard, Thompson, & Volney, 2013; NRCan, 2014). Wildfire is the primary disturbance agent in boreal forests, though insect infestation, windthrow, harvest, ice and snow related damage are all additional factors that can also occur with varying spatial pervasiveness and severity (Brandt et al., 2013; Johnson, 1996; Payette, 1992. Long-term averages indicate that wildfire occurs over approximately 2,000,000 ha per year in Canada (Stocks et al., 2002) with the most common being stand replacing crown and severe surface fires (Heinselman, 1981). This fire regime has led to boreal tree species being well adapted to these fire disturbances, and often depending on fire to release the growing space from constraints imposed by the overstory (Brandt, 2009; Bonan & Shugart, 1989; Oliver & Larson, 1990). As a consequence the boreal forest is a patchwork of forest structures, types, and ages, which is critical to maintaining the diversity and sustainability of the Canadian boreal zone (Bonan & Shugart, 1989; Heinselman, 1981).

The Canadian boreal can be stratified into ecozones which provide a spatial framework of ecologically homogenous units delineating distinct areas based on biophysical factors (Ecological Stratification Working Group, 1996; Wiken, 1986). The Boreal Shield ecozone is the largest unit stretching from Newfoundland into northern Saskatchewan with much of the area inaccessible and in a wilderness state. Despite the reported homogeneity of this ecozone, studies have suggested that the ecozone could be split along an east/west divide based on a number of distinct factors. Kurz, Apps, Webb, and McNamee (1992) suggested the ecozone be split due to differing ecoclimatic conditions. Kull et al. (2006) split the ecozone citing colder and drier climes in the western section than the east. To characterize fire in the Canadian boreal forest, the ecozone was divided into eastern and western sections by Stocks et al. (2002). Likewise, citing differing climatic patterns and forest processes, Andrew, Wulder, and Coops (2012) divided the Boreal Shield into two separate sections to aid their analysis of protected areas in Canada's boreal zone.

As a result of differing levels of accessibility (Andrew et al., 2012), large areas of the Canadian Boreal Shield are not subject to direct anthropogenic influences with up to 35% and 40% of the forested east and west Boreal Shield ecozone sections not subject to any forest management practices (Shvidenko & Apps, 2006; Wulder, Campbell, White, Flannigan, & Campbell, 2007). Thus the Boreal Shield can be further

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divided into two management zones: a generally southern managed portion that enjoys a relative wealth of descriptive data, and a generally northern unmanaged section that is less well characterized. The different management zones create a divide in forest information, which leaves a large part of the ecozone uncharacterized. The lack of spatially explicit forest information for more than a third of the ecozone is a problem when assessing both current and future climate change (Price et al., 2013). Increased productivity in temperature limited predominantly eastern boreal areas (Boisvenue & Running, 2006), and increased quantity and severity of wildfire disturbances in drier western boreal areas (Flannigan, Logan, Amiro, Skinner, & Stocks, 2005) is expected, highlighting the need for disturbance mapping and monitoring of the subsequent return of vegetation.

Remote sensing technology has demonstrated the capacity to monitor large areas and can offer marked insights into how different regions are potentially changing, both in terms of pressures on disturbance regimes as well as the subsequent recovery (Beck & Goetz, 2011; Berner, Beck, Bunn, Lloyd, & Goetz, 2011; Pickell et al., 2014; Powers, Hermosilla, Coops, & Chen, 2015; Xu et al., 2013). To date, emphasis has been placed on mapping forest disturbance using remote sensing technologies (Eidenshink et al., 2007; Guindon et al., 2014; Steyaert, Hall, & Loveland, 1997). Although forest disturbances are well characterized by remote sensing (Kasischke et al., 2011; Loboda et al., 2012; Potapov, Hansen, Stehman, Loveland, & Pittman, 2008; Wulder et al., 2009), explicit monitoring of post disturbance forest conditions for signals of recovery using a remotely sensed time series of imagery is a relatively recent phenomenon (Chen et al., 2011; Gitas, Polychronaki, Mitri, & Veraverbeke, 2012; Griffiths et al., 2014; Kennedy et al., 2012; Schroeder, Wulder, Healey, & Moisen, 2011). Forest recovery has typically been defined as the reestablishment of forest biomass, or canopy structure, following disturbance (Oliver & Larson, 1990), making it a process rather than a state, and therefore observable using time series of remote sensing data (Hermosilla, Wulder, White, Coops, & Hobart, 2015; Huang et al., 2010; Kennedy et al., 2012; Zhu, Woodcock, & Olofsson, 2012). It is increasingly understood that characterization of the spectral recovery as observed from remote sensing of a recently disturbed forest can aid in identifying and monitoring the progression of the stand towards successful reestablishment and maturation (Schroeder et al., 2011). Interestingly, Frolking et al. (2009) identified the need for remote sensing approaches to examine the characterization of forest recovery to provide forest managers with valuable information such as successional state (Shatford, Hibbs, & Puettmann, 2007) as well as informing on regional or temporally varying recovery trends.

Forest recovery has been monitored using image based time series using a variety of approaches. The most common, used with varying success, is to develop a time series of a given spectral index which is then related to biophysical parameters at a range of spatial scales (Chu & Guo, 2013). Griffiths et al. (2014) assessed variability in forest recovery both spatially and temporally across political jurisdictions in the Carpathian by defining spectral recovery as a combination of pre-disturbance spectral index values and the spectral magnitude of the disturbance. Kennedy et al. (2012) defined spectral recovery as a ratio of the magnitude of the disturbance event to spectral conditions five years post disturbance and illustrated recovery differences between public and privately owned lands in the Pacific Northwest of the United States. In the same study Kennedy et al. (2012) showed that drier areas experienced slower recovery as opposed more moist areas across management regimes, ownership, and political lines. Thus meaningful information about forest recovery across large areas can be derived from remote sensing imagery based time series, providing useful data and facilitating decisions about forest recovery by managers and researchers alike.

Landsat time series analysis offers an effective approach to monitor large forested areas (Hermosilla et al., 2015; Huang et al., 2010; Zhu et al., 2012) like the Boreal Shield ecozone for disturbances and can enable characterization of the subsequent vegetative recovery (Kennedy, Yang, & Cohen, 2010). In this research we compare and contrast spectral forest recovery trajectories following forest disturbance across the east and west sections of the Boreal Shield ecozone by developing and then applying a methodology using Landsat time series imagery. To meet this objective we examine stand replacing disturbances and the subsequent spectral signals of recovery by constructing spectral trajectories of recovery. These trajectories are then compared to nominally undisturbed forested signals, and the extent and recovery rate trends examined and compared across the ecozone.

2. Study area

The Boreal Shield ecozone (Fig. 1) is generally characterized by rolling and hilly topography with many small lakes, streams and rocky outcrops. A precipitation gradient exists with higher amounts (1000 mm) in the coastal east and less (400 mm) in the more continental west (Ecological Stratification Working Group, 1996; Urquizo, Bastedo, Brydges, & Shear, 2000). July average maximum temperatures are 13 °C for both sections, however the east typically has less severe winters with January average minimum temperatures of −1 °C compared to the west with −20 °C (Ecological Stratification Working Group, 1996; Urquizo et al., 2000). The Boreal Shield ecozone is dominated by forests of black (*Picea mariana*) and white spruce (*Picea glauca*) with the more southerly portions having a wider mix of broadleaf treed vegetation such as white birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*) as well as an array of needle leaf species such as white (*Pinus strobus*), and red (*Pinus resinosa*) and jack pine (*Pinus banksiana*) (Ecological Stratification Working Group, 1996). As discussed, fire and harvest are the primary agents of stand replacing forest disturbances (Bergeron, 2000; Bergeron et al., 2004), with fires occurring more often over larger areas in the west than the east (Stocks et al., 2002). Less common are disturbances caused by insect infestations, wind and storm related damage, and disease (Urquizo et al., 2000).For the purpose of this study we follow the division of the Boreal Shield ecozone established by Kull et al. (2006), who cited the colder and drier climate in the west resulting in differing forest processes. As depicted in Fig. 1 the ecozone can be divided by southern managed zone, where commercial forestry activities are present, and a northern largely unmanaged (non-commercial) zone.

3. Methods

3.1. Data

3.1.1. Landsat

The Landsat World Referencing System (WRS-2) acquisition grid (185 × 185 km) was used to create a stratified random non overlapping sample of Landsat scene footprints within the Boreal Shield ecozone (Healey, Yang, Cohen, & Pierce, 2006; Kennedy et al., 2010; Masek et al., 2013; Tucker et al. 2000, Wulder and Seeman, 2001). Scenes were required to be at least 50% within the Boreal Shield ecozone, with portions outside of the ecozone clipped from further analysis. The Earth Observation for Sustainable Development of Forests (EOSD) land cover dataset was used to mask water bodies and to define areas of forest cover within the selected Landsat scenes (Wulder, Ortlepp, White, & Maxwell, 2008). Deciduous, coniferous, and mixed forested type classes from the EOSD were collapsed into one category to create a binary forest layer, which was then used as a second filter to ensure that scenes were dominated by forest cover (>80%). The scenes were further filtered by forest management zone, removing any scene that was not at least 50% within one management zone or another; if a scene covered both management zones, it was clipped to the portion within the largest management zone. Scenes were then randomly selected from the final candidate pool, while minimizing differences in total area as possible. Out of a possible 185 scenes covering the Boreal Shield ecozone, a