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Analyzing spatial and temporal variability in short-term rates of post-fire vegetation return from Landsat time series

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A B S T R A C T

The disturbance and recovery cycles of Canadian boreal forests result in highly dynamic landscapes, requiring continued monitoring to observe and characterize environmental change over time. Well-established remote sensing methods capture change over forested ecosystems, however the return of forest vegetation in disturbed locations is infrequently documented and not well understood. Landsat time-series data allows for both the capture of the initial disturbance and the ability to monitor the subsequent vegetation regeneration with spectral vegetation indices. In this research, we used three spectral recovery metrics derived from an annual Landsat-based per-pixel Normalized Burn Ratio time series to determine trends in the short-term rates of spectral recovery for areas disturbed by wildfire (1986–2006), as assessed using a series of 5-year post-disturbance windows to observe forest recovery trends. Our results indicated that rates of spectral forest recovery vary over time and space in the Taiga and Boreal Shield ecozones. We found evidence that post-fire spectral forest recovery rates have accelerated over time in both the East and West Taiga Shield ecozones, with a consistent, positive, and significant trend measured using a Mann-Kendall test for monotonicity and Theil-Sen slope estimation. Over the analysis period (1986–2011), relative rates of spectral forest recovery increased by 18% in the Taiga Shield East and 9% in the Taiga Shield West. In contrast, spectral forest recovery rates in the Boreal Shield varied temporally, and were not consistently positive or negative. These results demonstrate that post-fire spectral recovery rates are not fixed over time and that spectral trends are dependent upon spatial location in the Canadian boreal. This retrospective baseline information on trends in spectral recovery rates highlights the value of, and continued need for detailed monitoring of vegetation regeneration in boreal forest ecosystems, particularly in the context of a changing climate.

1. Introduction

Climate and disturbance are the two most important factors that shape the Canadian boreal landscape (Brandt et al., 2013). First, climate primarily controls where and which tree species grow and adapt in forested areas, with annual tree growth limited by short growing seasons and severe winters (Gauthier et al., 2015). Second, disturbances drive change in the boreal, particularly fires, which occur frequently over large areas, and are critical for many ecosystem functions (Stocks et al., 2002). As a result of the interplay between climate and disturbance, Canadian boreal forest ecosystems are a mosaic of patches with varying age, structure, biodiversity, productivity, and species composition (Weber and Flannigan, 1997). Thus, boreal tree species have adapted to frequent disturbance by utilizing multiple post-disturbance recovery methods, which occur over relatively long periods of time. This post-disturbance recovery period is 1) a critical time to monitor the reestablishment and health of boreal forests (Gauthier et al., 2015), and 2) highly susceptible to changes in climate. Any disruption of the recovery process can in turn impact the essential ecosystem goods and services provided by boreal forests (Brandt et al., 2013; Gauthier et al., 2014; Gauthier et al., 2015).

Boreal forests are expected to be altered extensively by a changing climate (Brandt et al., 2013; Price et al., 2013; Gauthier et al., 2014; Gamache and Payette, 2004). Currently, boreal ecosystems are undergoing alterations in phenology (Lemprière et al., 2008; Colombo, 1998), productivity (Nemani et al., 2003; Jarvis and Linder, 2000), and disturbance (Stocks et al., 1998; Flannigan et al., 2000; Flannigan et al., 2005; Johnstone et al., 2010), all attributed to changes in climate. With

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respect to altered disturbance characteristics, a changing climate has had mixed effects on forest recovery as well. For example, three key tree species within the Canadian boreal forest have shown divergent responses to a changing climate. Black spruce (*Picea mariana*) dominated systems showed an increase in growth under cooler and wetter conditions (Girardin et al., 2016; Brooks et al., 1998), while jack pine (*Pinus banksiana*) ecosystems displayed increased growth with warmer temperatures and increased spring precipitation (Brooks et al., 1998). Additionally, white spruce (*Picea glauca*) trees have reacted positively to warmer spring temperatures with increased annual growth, but also negatively to much warmer summers with decreased annual growth (Wilmking et al., 2004) that is likely caused by a lack of available moisture (Barber et al., 2000; D'Orangeville et al., 2016).

Spatially extensive temporal trends describing increasing or conversely decreasing vegetation quantity and vigor have been found occurring across the Canadian boreal using coarse (100–1000 m) grained remotely sensed data. Both increasing and decreasing spectral trends have been detected occurring over Canadian boreal forests over time (Pouliot et al., 2009) dependent on location, and those trends are well correlated with trends found at coincident smaller spatial resolution (30 m) data (Olthof et al., 2008). However, some of the spectral trends found at coarse scales have also been shown to be influenced by the inter-instrument calibration, sensor drift, and preprocessing steps (Alcaraz-Segura et al., 2010). Moreover, coarse spatial resolution studies can fail to capture the fine scale mosaicked nature of the boreal forest landscape and are often in disagreement with research done at finer spatial scales (Alcaraz-Segura et al., 2010; Fraser et al., 2011; Wulder et al., 2010). In contrast to known issues with inter-instrument calibration of broad-scale sensors (Alcaraz-Segura et al., 2010), finer spatial resolution Landsat data (30 m) has fewer inter-sensor calibration issues (Markham and Helder, 2012; Vogelmann et al., 2016), although issues regarding inter-sensor calibration of certain spectral wavelengths are noted to exist (Sulla-Menashe et al., 2016; Ju and Masek, 2016).

Finer grained medium spatial resolution (30–100 m) remotely sensed data have also shown some broad spectral trends derived from time series of spectral indices, and importantly have been previously tied to physical properties of forests (Pouliot et al., 2009, McManus et al., 2012, Chu and Guo, 2013, Fraser et al., 2014a, 2014b). For example, the Normalized Difference Vegetation Index (NDVI) is a spectral index that has often been used to examine active photosynthetic vegetation quantity and is linked to forest condition changes over time at broad spatial scales (Cuevas-González et al., 2009; McManus et al., 2012; Turubanova et al., 2015). While some have found a widespread NDVI derived trend of increasing vegetation over time that is associated with a thickening canopy (Myneni et al., 1997, Slayback et al., 2003, Olthof and Latifovic, 2007), Goetz et al. (2005) found that Canadian boreal forests experienced a negative trend between 1981 and 2003 related to reductions in vegetation abundance (Beck and Goetz, 2011; Bi et al., 2013). Often applied more commonly in fire severity studies, the Normalized Burn Ratio (NBR) spectral index and its change over time have been linked to forest structural properties (Wulder, 1998, Epting et al., 2005, Schroeder et al., 2011), and may be more suitable than NDVI for forest recovery tracking (Pickell et al., 2016; Buma, 2012).

Detailed and annual forest recovery information over large areas can be derived from fine spatial resolution wall-to-wall remotely sensed datasets, principally due to free and open data access, data storage, and processing capacity (Kennedy et al., 2014). The United States Geological Survey maintains the Landsat data archive and provides an ideal data set for boreal-wide research that offers a well-calibrated data record initiated in 1972 with complete spatial coverage in fine detail (Wulder et al., 2012; White and Wulder, 2014). Larger areas and longer time periods of spectral data can now be used to inform on the finely detailed process of forest recovery, especially after the wildfire-caused stand replacing disturbances that are typical of the Canadian boreal. For example, Pickell et al. (2016) used Landsat time series analysis across a range of forested boreal bioclimatic zones and observed differing spectral forest recovery rates for each zone. Likewise, Frazier et al. (2015) examined spectral forest recovery using Landsat time series data and found a relationship between spectral recovery differences related to distinct forest recovery processes across two ecozones.

In summary, while research has indicated that boreal forest recovery rates vary spatially (Schroeder et al., 2007; Frazier et al., 2015) and temporally (Chu and Guo, 2013), changes in the post-disturbance forest recovery rates over time has been less well examined (Ju and Masek, 2016; Goetz et al., 2006). In this study, we examine boreal forest recovery rates following wildfire during a period of changing climate to determine how recovery rates have changed over a 26-year long period, both temporally and spatially. We focus on the Boreal and Taiga Shield ecozones as representing nearly half of the Canadian boreal zone, ensuring a wide array of boreal forest conditions and fire severities are considered. The 3,013,995 km^2 study area and wall-to-wall mapping offer the ability to compare all observed forest fire disturbances and their subsequent recovery. To do so we: 1) use multiple spectral forest recovery metrics derived from Landsat time series data to inform on different aspects of post-fire spectral recovery; 2) detect trends in post-fire spectral forest recovery rates first at a 100 km cell spatial unit to visualize detailed trend patterns; 3) understand broad environmental change by using ecozone analysis units to detect spectral recovery rate trends; and, (4) determine if statistically significant trends in spectral recovery rates exist over time. Significant results are then discussed in relation to the disturbance and recovery regimes of Canadian boreal forests, as well as the benefits and limitations of spectral forest recovery metric approaches used in this study.

2. Materials and methods

2.1. Study area

Our study area covers the forested boreal areas with the Canadian Boreal Shield and Taiga Shield ecozones (Fig. 1; Ecological Stratification Working Group, 1996, Brandt, 2009). For scientific analyses and due to differences in climate and disturbance regimes, the Boreal Shield and Taiga Shield ecozones are often divided into eastern and western sections (Andrew et al., 2012; Bolton et al., 2015). Eastern sections generally experience a less harsh winter and more annual precipitation when compared to the western counterparts (Kurz et al., 1992; Kull et al., 2006; Frazier et al., 2015). Both western ecozone sections experience more forest fires (Stocks et al., 2002); forest harvesting occurs in all ecozones, and insect infestations play a larger role in eastern than western disturbance regimes (Brandt et al., 2013). Forest fires have affected 25,039,523 ha or 9.9% of the study area between 1985 and 2010 (White et al., 2017). When combined together, these two ecozones account for 49% of the Canadian Boreal zone (Brandt, 2009).

The West and East Boreal Shield ecozones are dominated by forests and characterized by many small lakes and streams interspersed between rocky outcrops with rolling and hilly topography. A precipitation gradient exists varying from higher (1000 mm per year) amounts in the coastal east, and lesser (400 mm per year) in the continental west. January mean temperatures are − 20 °C and − 1 °C in the west and east showing a pronounced colder west to warmer east temperature gradient (Urquizo, 2000), and the mean annual temperature is approximately 3 °C. Boreal Shield forests are dominated by black and white spruce stands, with southerly portions having a wider mix of broadleaf and coniferous species, i.e. white birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), white (*Pinus strobus*), red (*Pinus resinosa*) and jack pine (Ecological Stratification Working Group, 1996).

Located north of the Boreal Shield Ecozones, the Taiga Shield Ecozones are physically divided by Hudson Bay. The topography is marked by rolling uplands punctuated by rocky outcrops, and glacial moraines and eskers. Differences in temperature and precipitation