



A nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series



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ABSTRACT

In the context of complex demands on forest resources and climate change, synoptic and spatially-explicit baseline data characterizing national trends in forest disturbance and subsequent return of vegetation (and eventual return to forest) are increasingly required. Time series analyses of remotely sensed data enable the retrospective generation of baseline data depicting both forest disturbance and recovery, enabling a more holistic examination of forest dynamics. In this research, we utilize the outputs of the Composite2Change, or C2C, algorithm that leverages the extensive Landsat archive to produce annual, gap-free, surface reflectance composites to date and label disturbance types and to characterize vegetation recovery over the >650 million ha of Canada's forested ecosystems. From 1985 to 2010, 57.5 Mha or 10.75% of Canada's net forested ecosystem area (exclusive of water) were disturbed by either wildfire or harvest, representing an annual rate of disturbance of approximately 0.43% per year. Wildfire accounted for 2.5 times more area disturbed than harvest. On average, wildfire disturbed 1.6 Mha annually and had greater inter-annual variability with a standard deviation of 1.1 Mha, compared to the 0.65 Mha disturbed annually by harvesting ($\sigma = 0.1$ Mha). Herein, we defined a longer-term measure of spectral recovery (the number of years it took for a pixel to attain 80% of its pre-disturbance Normalized Burn Ratio or NBR value), which indicated that harvested areas are recovering more consistently over time relative to areas disturbed by wildfire, with 78.6% of harvested areas requiring ≤ 10 years to recover, compared to only 35.5% of wildfire areas. A shorter-term (5-year) measure of spectral recovery, also based on the NBR, indicated that vegetation in wildfire areas returned more rapidly than harvested areas; however, when the magnitude of the disturbance was incorporated into the metric, with magnitude typically larger and more variable for wildfire areas, harvested areas were found to be recovering more rapidly on average in the short-term. Overall, <1% of the areas disturbed by wildfire and harvest were identified as non-recovering by all three spectral measures of recovery used in our analysis. Regionally, trends in disturbance and recovery largely echoed trends found at the national level, although the relative amounts and rates of wildfire or harvest varied by ecozone. Time series Landsat composites provide an opportunity to characterize relative trends in disturbance and recovery at a national scale, by disturbance type and ecozone, in a spatially explicit manner and at a level of spatial detail that is relevant to both forest management and science.

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1. Introduction

Forest disturbance and recovery represent important ecological processes that strongly impact regional and global forest carbon budgets (Pan et al., 2010; Hicke et al., 2012). Climate change will alter the frequency and intensity of disturbances (Dale et al., 2001), as well as the rate and efficacy of forest regrowth following disturbance (Anderson-Teixeira et al., 2013). In this context of rapid and complex change, baseline information that characterizes historic trends in forest disturbance and recovery over large areas can be valuable reference information

for understanding present and future forest dynamics (Cohen et al., 2016). Time series of remotely sensed data, especially Landsat data, offer opportunities to retrospectively generate baseline information on forest disturbance and recovery trends (Frolking et al., 2009) over regions (Kennedy et al., 2012; Griffiths et al., 2014; Potapov et al., 2015), continents (Masek et al., 2008; Lehmann et al., 2012), and the globe (Hansen et al., 2013). The need for this capacity to generate nationally synoptic baseline information is particularly acute in countries such as Canada, which has a large forested area (representing ~10% of global forests), much of which is difficult to access, and where management responsibility is not primarily vested with the federal government, but mainly with multiple provincial and territorial governments and to a lesser extent, private land owners (Wulder et al., 2007).

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Given the disparate jurisdictional responsibilities for forest management in Canada, national datasets summarizing the location and extent of forest disturbances such as wildfire and harvest have historically been compiled from a variety of multi-jurisdictional data sources. For wildfire these national data are spatially explicit (Stocks et al., 2002), but there are no comparable national spatially explicit data for forest harvesting (Masek et al., 2011). Likewise, there are no national or jurisdictional spatially-explicit data sets in Canada that characterize recovery following disturbance. Disturbance monitoring with remotely sensed data has been exhaustively demonstrated (Hansen and Loveland, 2012), and the characterization of post-disturbance recovery has emerged in the applications community (Frolking et al., 2009; Chu and Guo, 2014), enabled by the availability of time series analysis methods and data, particularly Landsat data (Banskota et al., 2014). Remotely sensed data have been used to characterize vegetation regrowth and recovery following wildfire (e.g., Gitas et al., 2012; Chu and Guo, 2014) and less commonly, following harvest (Schroeder et al., 2007; Madoui et al., 2015). Correct attribution of forest disturbance type (i.e., to wildfire or harvest) has important implications for monitoring of recovery for forest management (Schroeder et al., 2011) and carbon accounting (Seedre et al., 2011). Furthermore, recovery trends associated with wildfire and harvesting are expected to vary regionally (Bartels et al., 2016), with implications for the sustainability of management practices and long-term functioning of forest ecosystems.

Unlike wildfire and harvest, which are typically discrete, episodic events (in both space and time), vegetation recovery post disturbance is a process rather than a state, and as such manifests as the initial re-establishment of vegetation at a site through to the full return of forest structural characteristics that were present pre-disturbance (e.g. LePage and Banner, 2014). In the context of this study, and following on the definition of Bartels et al. (2016), we define recovery as the re-establishment and regrowth of vegetation at a site following a stand replacing disturbance, specifically wildfire and harvesting. In an ecological or silvicultural context, this often implies the re-establishment of forests over time, and can be quantified by measurements of canopy cover, height, basal area, and stem density, among others. These measurements are typically acquired via ground measurements (e.g., Bartels et al., 2016), but indicators of recovery, such as vegetation height and density, can also be measured using airborne laser scanning data (e.g., Magnussen and Wulder, 2012; Slesak and Kaebisch, 2016). As noted by others, spectral recovery, as measured with a time series of optical satellite data, is not a direct measure of forest recovery (Kennedy et al., 2012; Griffiths et al., 2014) and must therefore be interpreted in the context of a priori expectations of recovery, which are typically derived from ground plot measurements. However, as demonstrated in Bartels et al. (2016), it is difficult to characterize national trends in post-disturbance recovery for a nation as large and diverse as Canada on the basis of ground plot measurements alone. Thus, information from remotely sensed data can provide a useful framework for assessing relative rates and changes in spectral recovery that provides a national assessment of trends. These trends can be related to available ground observations, and can form the basis for additional sampling and investigations to further relate spectral measures of recovery to ecological and silvicultural understanding of the recovery process (Gómez et al., 2011; Kennedy et al., 2012). Moreover, considering both the depletion (disturbance) and accrual (regrowth) of vegetation provides a more holistic framework for understanding forest change in the context of long-term forest monitoring and carbon accounting.

The objective of the study presented herein was to demonstrate technical capacity and to characterize national trends in stand replacing forest disturbance caused by wildfire and harvest, and subsequent recovery, for the period 1985–2010 for Canada's forested ecosystems (~650 Mha), using information derived from Landsat time series data. Previous studies that have characterized national trends in disturbance and recovery in Canada have either focused on wildfire exclusively and have used substantially coarser spatial resolution remotely sensed data

(i.e., Advanced Very High Resolution Radiometer or AVHRR 1- and 8-km data) (Amiro et al., 2000; Hicke et al., 2003; Goetz et al., 2006), or have been sample-based (Frazier et al., 2015; Pickell et al., 2016). Moreover, previous studies that have used Landsat time series data to characterize annual trends in disturbance and recovery have not considered such a large area, nor have they distinguished by disturbance type (Kennedy et al., 2012; Griffiths et al., 2014). In this context, the unique contribution of this work is to use a wall-to-wall time series of Landsat data (with a 30 m spatial resolution) to characterize national spatial and temporal trends in both disturbance and recovery, and to distinguish these trends by disturbance type (wildfire and harvest). By leveraging recent advances in image compositing capability and the holdings of the Landsat archive, we generated a synoptic, consistent national baseline of stand-replacing forest disturbance and recovery and characterized important regional variations in the disturbance and recovery trends observed. These baseline data provide unprecedented reference information against which present and future trends in disturbance and recovery can be assessed.

2. Methods

2.1. Study area

Approaching one billion hectares in area, Canada is a large nation with a gradient in ecosystem productivity that is influenced by latitude and precipitation (Hofgaard et al., 1999). Forested ecosystems represent approximately 65% of Canada's land area (~650 Mha; Wulder et al., 2008). Ecozones represent broadly defined ecological units characterized by “interactive and adjusting abiotic and biotic factors” (Ecological Stratification Working Group, 1996). The Boreal and Taiga Shield ecozones have large west-east extents and are often split into their western and eastern components to reflect differences in ecoclimatic conditions between these regions (Stocks et al., 2002; Frazier et al., 2015). We have likewise split these two ecozones into their western and eastern components (Fig. 1A), resulting in twelve ecozone units for our assessment of national trends in disturbance and recovery.

These ecozones represent a broad range of forest conditions in Canada and may be differentiated by the relative abundance of forests, the productivity and growing conditions in these forests, and the degree of forest management and human population density within the ecozone (Table 1).

Canada's managed forest zone is found primarily in the southern extent of Canada's forested ecosystems (Stinson et al., 2011). These managed forest areas contain forest tenures for harvesting, and also have more intensive fire suppression relative to the unmanaged forest areas. Some ecozones, such as the Atlantic and Pacific Maritime ecozones have 100% of their ecozone area within the managed forest, whereas the Taiga Cordillera has 0% of its area within the managed forest zone. The Boreal Shield East and West have 68% and 62% of their areas, respectively, within the managed forest zone (Table 1). Although the eastern and western components of the Boreal Shield have similar growing season length, the Boreal Shield East is characterized by greater precipitation in the growing season (509 mm) and greater productivity (average 10-year GPP = $0.881 \text{ Kg C m}^{-2} \text{ yr}^{-1}$), whereas the Boreal Shield West, which is dominated by fire, is notably drier, and receives less precipitation in the growing season (365 mm) and has lower productivity (average 10-year GPP = $0.763 \text{ Kg C m}^{-2} \text{ yr}^{-1}$) (Table 1).

2.2. Data

2.2.1. Composite2Change (C2C) outputs

Using the Composite2Change or C2C algorithm, annual, cloud-free, Landsat surface reflectance image composites with a 30 m spatial resolution were developed for Canada for 1984 to 2012 using a best-available-pixel (BAP) compositing algorithm (Hermosilla et al., 2016).

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