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Characterization of aboveground biomass in an unmanaged boreal forest using Landsat temporal segmentation metrics

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ABSTRACT

Canada is dominated by forested ecosystems which are subject to various inventory and management practices, with more northern boreal forests subject to neither. Our objectives were to measure the capacity of temporal trajectory metrics for estimating selected forest attributes in a northern Canadian boreal forest context using Landsat imagery and investigate the importance of different types of temporal trajectory metrics. Results indicated that Wetness was the best Tasseled Cap (TC) component for aboveground biomass estimation (R^2 = 50%, RMSE% = 56%), and the combination of simple and complex metrics from all TC components produced the highest R^2 (62%) and lowest RMSE% (49%). Using a similar combination of variables, other forest attributes were estimated equally reliably with lower RMSE% values. The most important temporal trajectory metrics were simple and described TC component values at each point of change in the temporal trajectory, however the most important variables overall were environmental variables.

1. Introduction

Boreal forest comprise 27% of the world's forest cover (FAO, 2001), and in northern latitudes represent areas where human intervention has been minimal and ecosystem processes generally remain undisturbed (FAO, 2006). With the exception of Scandinavia, much of the global boreal forest does not have forest inventory level data or is not regularly monitored (Wulder et al., 2007). While much of this boreal forest area is in Russia, approximately 88% of the North American boreal is found in Canada (Brandt, 2009). In Canada, provincial and territorial resource management agencies hold forest stewardship and management responsibilities, which include implementation of inventory and monitoring programs. Forest stands that are located in the southern boreal forest are typically subject to inventory on a periodic basis (often a 10 year cycle) to support forest management and planning goals to meet a range of sustainable forest management objectives. These managed forests are generally where most of the human populations reside, road access is greater, and vegetative productivity is higher. In contrast, Canada's northern boreal forests are subject to more limited and spatially focused management activities and as a consequence, inventory and monitoring programs receive less emphasis. As a result, the condition and state of the unmanaged northern forests are not as well characterized and understood when compared to the southern managed forests (Andrew et al., 2012).

Managed and unmanaged areas of Canadian boreal forests are subject to a range of disturbances. Fire, harvests, insect outbreaks, and disease are all agents of boreal forest disturbance (Volney and Hirsh, 2005), each with variability in intensity and scale through time and by region (Brassard and Chen, 2008). Of these, fire is the most notable in severity and extent over the boreal forests (Bond-Lamberty et al., 2007). Therefore, in boreal ecosystems fire intensity largely determines the subsequent recovery and regrowth of vegetation (Johnstone and Chapin, 2006; Johnstone and Kasischke, 2005, Payette et al.,1992). Although the location and extent of fires is tracked by a number of agencies (Stocks et al., 2002; de Groot et al., 2007), the subsequent recovery from these disturbances is only monitored through the re-occurring inventory practices in southern Canadian boreal forests and not northern Canadian boreal forests.

Despite their remoteness, information on northern Canadian boreal forests is still necessary, both to meet regional information needs and to support national and international reporting requirements (Wulder et al., 2004a). In response to this need and in partnership with the provinces and territories, Canada has

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implemented a National Forest Inventory (NFI). The NFI is a sample based system based upon a national network of 2 × 2 km aerial photo plots on a 20 km grid. The photo plots are calibrated against, and supported by, an integrated network of ground plots (Gillis et al., 2005). For some larger Canadian jurisdictions, the NFI can provide a sufficient sample to provide reliable statistical estimation of a variety of important forest attributes used for monitoring and reporting purposes.

While the sample based NFI can provide a statistically robust opportunity for reporting, capturing of change across the landscape spatially, is also of value for management, planning, and scientific purposes. Aboveground biomass, for example, is often used to quantify forest carbon stocks and is a critical component for accurate carbon accounting (Goetz et al., 2005; Pacala et al., 2007). In the southern managed forests where inventorying practices occur more regularly and forest information is abundant, aboveground biomass can be estimated much more easily than in northern boreal forests. To augment this paucity of spatial information in the northern boreal, remote sensing techniques offer potential solutions to the remoteness and difficulty of access as well as the high costs of establishing and maintaining ground plots (Wulder et al., 2007). This type of remote sensing based characterization includes: (1) the capture of changes in forest stand condition over time and; (2) the prediction of aboveground biomass and its components for a range of applications, including the replication of some forest inventory attributes to improve understanding of and quantification of national carbon dynamics.

Optical remote sensing has been demonstrated as an ideal data source to characterize forest disturbance and subsequent forest regrowth (Kennedy et al., 2010, 2007; Huang et al., 2010; Zhu and Woodcock, 2012). Landsat data are found useful for remote sensing supported change detection applications due to consistent and accurate geometry, calibrated radiometry, and analysis ready products provided through a free and open access archive since October of 2008 (Wulder et al., 2012a,b; Woodcock et al., 2008). The thirty meter spatial resolution of Landsat also allows for capture and characterization of forest composition and change information that is applicable to management, planning, and science activities.

There is a long history of estimating aboveground biomass in forests using single date Landsat imagery. Frazakas et al. (1999) utilized Landsat Thematic Mapper bands 1–5, and 7 to estimate aboveground biomass in Sweden. Hall et al. (2006) used Landsat Thematic Mapper bands 3, 4, 5, and 7 to derive estimates of canopy cover and stand height, which were subsequently used to predict biomass in Alberta, Canada. Labrecque et al. (2006) utilized Landsat bands, numerous vegetation indices, band ratios, and Tasseled Cap components to estimate aboveground biomass in Newfoundland, Canada, demonstrating that Tasseled Cap components were the most correlated of the variables tested. Due to the use of many different spectral variables, there is no broad consensus on which bands or indices should be used to estimate aboveground biomass and other forest attributes from Landsat data.

The ready availability of Landsat data that are now freely available from the United States Geological Survey (USGS) archive has led to the development of many new applications with a shift towards multitemporal and increasingly pixel-based analyses (Hansen and Loveland, 2012; Wulder et al., 2011), aimed at an improved understanding of landscapes and their dynamics over time (Kennedy et al., 2010). Large amounts of Landsat data are routinely processed to achieve multiple goals: compositing algorithms based on the selection of the best available pixel (Hansen and Loveland, 2012; Roy et al., 2010); tracking forest disturbance through time (Huang et al., 2010, Zhu and Woodcock, 2012); or to map forest carbon stocks and changes (Pflugmacher et al., 2012; Powell et al., 2010). Common to many of these approaches is the derivation of information from spectral changes in Landsat reflectance over time at the same location in what are broadly known as temporal trajectory methods (Kennedy et al., 2010). All of these temporal trajectory methods emphasize characterizing disturbance events from abrupt changes in the Landsat spectral responses over time, with reduced emphasis on the recovery of the vegetation after a disturbance event. This capture of forest recovery events is crucial for carbon accounting measures, as both deforestation and afforestation are critical components for those accounting systems (Kurz, 2010).

Few studies have successfully incorporated the use of temporal trajectory methods for aboveground biomass estimation. Powell et al. (2010) used a large number of spectral indices and environmental variables to estimate aboveground forest biomass in Arizona and Minnesota over a 20+year time series. Results showed that aboveground biomass change estimation was improved when using temporal trajectories as opposed to using single date imagery. Pflugmacher et al. (2012) found that the use of temporal trajectory metrics produced higher correlations than variables created from single date imagery. They found that temporal trajectory metrics could reliably estimate relative aboveground biomass in Douglas-fir forests in Oregon.

Previous studies have shown that temporal trajectory methods aid in forest attribute estimation over conventional methods which rely on a single date of optical imagery (e.g., Pflugmacher et al., 2012; Powell et al., 2010). The primary objective of this study was to measure the capacity of temporal trajectory metrics for estimating selected forest attributes in a northern Canadian boreal forest context. A secondary goal was to investigate the importance of different types of temporal trajectory metrics in the estimation of these forest attributes. To do so we: (1) acquired, normalized, and composited a dense stack of Landsat images of a northern boreal study area; (2) subjected the composited Landsat stack to temporal segmentation using Landtrendr; (3) calculated a number of simple and complex temporal trajectory metrics and constructed variable sets based on each Tasseled Cap component; and (4) created random forests models of LiDAR derived above ground biomass with the variable sets. To develop an improved understanding of which temporal trajectory metrics had the most predictive power we then compared R^2, RMSE% and importance values from the developed models for aboveground biomass. By selecting and then combining the most important variables from previous models, a new and final variable group was created which was then used to estimate aboveground biomass, stem biomass, stem volume, basal area, and Lorey's mean height. We review the R^2, RMSE% and mean importance values from these results and lastly we conclude with a discussion on the ability of temporal trajectory metrics and the importance of types of temporal trajectory metrics for forest attribute estimation.

2. Methods

2.1. Study area

The 29,067 km^2 rectangular study area is defined by a Landsat image footprint (path 54, row 18 of Worldwide Reference System II) in northeast British Columbia and southeast Yukon Territory and encompasses portions of four ecoregions (Fig. 1). The Liard Basin ecoregion covers the central 77% of the study area, and is characterized by low rolling hills (elevation 600–1200 m) separated by wide flat areas. Rainfall is evenly distributed throughout the year totaling approximately 500 mm, with a drier period between February and May that partially coincides with the cold season. Winter and summer temperatures average −25 °C and 12 °C, respectively. Surrounding the Liard Basin are three ecoregions with mountainous terrain, high plains, and plateaus that can reach elevations