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Sources of bias and variability in long-term Landsat time series over Canadian boreal forests

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ABSTRACT

A variety of evidence suggests that the boreal forests of Canada are responding to climate change. Specifically, several studies have inferred that widespread browning trends detected in time series of the Normalized Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) reflect the response of boreal forests to longer growing seasons, increased summer drought stress, and higher frequency of fires. Data from the Thematic Mapper (TM5) and Enhanced Thematic Mapper Plus (ETM+) sensors onboard Landsat 5 and 7, respectively, span essentially the same time period as the AVHRR record, but provide data with substantially higher radiometric and spatial fidelity, and by extension, a much improved basis for evaluating decadal-scale trends in spectral vegetation indices such as the NDVI. However, detection of trends, which are often subtle, requires careful attention to ensure that artifacts associated with the quality and stability of inter- and intra-sensor calibration do not lead to spurious conclusions in results from time series analyses. In this paper, we use time series of TM5 and ETM+ images for fifteen sites distributed across the Canadian boreal forest zone to explore if and how sensor geometry and inter- and intra-sensor calibration affect trends in spectral vegetation indices derived from multi-decadal Landsat time series. To do this, we created annual cloud-free composites for each Landsat spectral band based on peak summer NDVI at each site from 1984 to 2011 using all available TM5 and ETM+ data. To distinguish trends arising from long term climate change from those related to disturbance, we isolated areas within each site that were undisturbed during the Landsat record, and used these locations to analyze sources of variance in time series of red reflectance, near-infrared (NIR) reflectance, the NDVI, and the Enhanced Vegetation Index (EVI). Our results highlight the challenges involved in distinguishing trends in surface properties from data artifacts caused by undetected atmospheric effects, changes in sensor view angles, and subtle radiometric differences between the TM5 and ETM+ sensors. In particular, differences in sensor view geometry across adjacent overlapping Landsat scenes cause vegetated pixels in the eastern portion of Landsat scenes to have higher reflectances in the red and NIR bands (by 5 and 6 percent, respectively) than pixels in the western portion of scenes. While this effect does not significantly change NDVI values, it does affect EVI values. We also found modest, but potentially significant, differences between the red band reflectance of each sensor, with TM5 data having 14 percent higher red reflectance on average for vegetated pixels, which can introduce spurious trends in time series that combine TM5 and ETM+ data. More generally, the results from this work demonstrate that while the 30+ year Landsat archive provides unprecedented opportunities for studying changes to the Earth's terrestrial biosphere over the last three decades, care must be taken when inferring trends in these data without considering how sources of variance unrelated to surface processes affect the integrity of Landsat time series.

1. Introduction

The Earth's surface has warmed over the past 60 years at roughly 0.12 °C per decade (Stocker et al., 2013). Climate warming has been most pronounced over Northern Hemisphere land areas during the winter and spring months (Hansen et al., 2006; Wang, Price, & Arora, 2006; Piao et al., 2008), and has been linked to longer growing seasons and changes to vegetation phenology and productivity (Piao, Friedlingstein, Ciais, Viovy, & Demarty, 2007; Kim, Kimball, Zhang, & McDonald, 2012; Xu et al., 2013; Jeganathan, Dash, & Atkinson, 2014; Stow et al., 2004; Beck & Goetz, 2011), thermokarst dynamics (Smith, Burgess, Riseborough, & Mark Nixon, 2005), and forest dieback events (Allen et al., 2010; Michaelian, Hogg, Hall, & Arsenault, 2011). Boreal forest ecosystems are especially vulnerable to climate change because air temperatures exert strong control on boreal ecosystem function (Bonan, 2008) and continued warming has the potential to trigger a variety of climate feedbacks, including increased rates of ecosystem

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respiration (Angert et al., 2005), enhanced fire regimes (Flannigan, Logan, Amiro, Skinner, & Stocks, 2005; Wotton, Nock, & Flannigan, 2010; de Groot, Flannigan, & Cantin, 2013), and melting permafrost (Anisimov, 1996; Schaefer, Zhang, Bruhwiler, & Barrett, 2011). Because boreal forests are geographically remote and extensive, monitoring and characterizing changes to the structure and productivity of these forests is challenging. Remote sensing therefore provides a critical source of information related to how this important biome is responding to climate change.

Recent decades have witnessed an enormous increase in the volume of Earth-observation data from satellite-borne sensors that are available for climate change research. Several studies using the Normalized Difference Vegetation Index (NDVI), which is widely used as a proxy for primary productivity, have suggested that productivity has decreased across large regions of the North American boreal forest over the last 30 years (Tateishi & Ebata, 2004; Goetz, Bunn, Fiske, & Houghton, 2005; Beck & Goetz, 2011; Bi, Xu, Samanta, Zhu, & Myneni, 2013; Guay et al., 2014). Most of these studies are based on the Global Inventory Modeling and Mapping Studies (GIMMS) data set (newly released as version 3G), which provides 30 years of NDVI observations from the Advanced Very High Resolution Radiometer (AVHRR) at 8-km spatial resolution (Tucker et al., 2005; Pinzon, Brown, & Tucker, 2007; Pinzon & Tucker, 2014). The GIMMS data sets are based on maximum value NDVI composites for 15-day periods and have been pre-processed to correct for clouds and atmospheric contamination, view angle effects, and changes to AVHRR sensor characteristics and calibration. Because observed changes in GIMMS NDVI time series over boreal forests are subtle and small in magnitude (Guay et al., 2014), differences or refinements to methods that are used to generate AVHRR NDVI data sets can affect results from time series analyses. For example, the geographically extensive decreasing NDVI trends ("browning") observed across boreal North America in the GIMMS 3G data set were not detected in previously available AVHRR NDVI data sets (Slayback, Pinzon, Los, & Tucker, 2003; Olthof & Latifovic, 2007; Pouliot, Latifovic, & Olthof, 2009; Alcaraz-Segura, Chuvieco, Epstein, Kasischke, & Trishchenko, 2010). More generally, challenges involved in cloud screening and atmospheric correction (Fontana et al., 2012), lack of on-board calibration (Gutman, 1999; Tucker et al., 2005), the use of blended time series from different AVHRR sensors (Tucker et al., 2005; Pinzon & Tucker, 2014), natural and human disturbances (Goetz et al., 2005), and geolocation errors (Roy, 2000) all introduce uncertainty to AVHRR time series.

In contrast to data from the AVHRR, the Landsat archive provides well-calibrated (Markham & Helder, 2012) and precisely geolocated (Lee, Storey, Choate, & Hayes, 2004) time series of remote sensing observations that span essentially the same time period as the GIMMS 3G data set (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). The Landsat 4 and 5 missions (from 1982 to 2011) carried the Thematic Mapper sensor, which included six spectral bands designed for land cover and vegetation characterization at much finer spatial (30-m) resolution and with better radiometric resolution and calibration relative to the AVHRR sensors (Markham, Storey, Williams, & Irons, 2004). The Landsat 7 mission (launched in 1999) included the Enhanced Thematic Mapper Plus (ETM+) sensor, which has improved radiometric stability and geodetic accuracy relative to the Thematic Mapper (Masek, Honzak, Goward, Liu, & Pak, 2001). Most recently, Landsat 8 was launched in 2013 and includes the Operational Land Imager (OLI), which extends and improves upon the Landsat legacy of Earth-observation science (Irons, Dwyer, & Barsi, 2012).

While a number of recent studies have used Landsat data to study long-term trends in vegetation indices in high latitude regions, these studies have generally used fewer than ten images for a single Landsat path/row and have largely focused on greening trends in tundra ecosystems (Neigh, Tucker, & Townshend, 2008; Pouliot et al., 2009; McManus et al., 2012). In this paper, we investigate a more general set of issues related to compiling and analyzing much denser Landsat time series (i.e., 150 to 300 images per scene) in support of long-term change studies in Canadian boreal forests. The purpose of the work is to explore sources of variability that influence detection of long-term trends in time series of vegetation indices derived from Landsat data. To do this, we selected fifteen locations distributed across the Canadian boreal forest where Landsat acquisitions overlap according to the Worldwide Reference System (WRS2), and downloaded all available TM5 and ETM+ data corresponding to peak-summer conditions (approximately July 1st to September 1st) for each of these locations. After extensive exploration of the data, we identified three critical questions for our research:

1. Are red and near-infrared (NIR) surface reflectances and derived spectral vegetation indices sufficiently stable over the 30-year Landsat record to support long-term trend analyses?
2. Do within-scene variations in sensor view geometry affect red and NIR surface reflectances and vegetation indices derived from Landsat data?
3. Can reflectances from the TM5 and ETM+ sensors be combined into a single time series, or do sensor-specific differences introduce artifacts in the data?

Results from our analyses show that while the radiometric and calibration qualities of the TM5 and ETM+ sensors are exceptionally high relative to the AVHRR sensors, time series of Landsat surface reflectances and spectral vegetation indices include sources of variability that are unrelated to changes in surface properties, which therefore need to be taken into account in time series analyses that exploit the deep and rich record of terrestrial observations provided by the Landsat archive.

2. Data and methods

2.1. Study area

The boreal zone of North America extends from Alaska to Newfoundland, encompasses 627 million ha, and is defined by climate regimes that support cold-tolerant tree species (Brandt, 2009). In this work we focus on the boreal forests east of the Canadian Rocky Mountains, using fifteen sites that encompass a range in forest types, disturbance regimes, and climates (Fig. 1; Table 1). Specifically, we selected locations where two or more adjacent Landsat WRS2 paths overlap each other. This strategy doubled (or in some cases tripled) the number of available Landsat images and compensated for the relatively low frequency of Landsat acquisitions at higher latitudes (Ju & Roy, 2008). The fifteen sites included in our analysis were selected according to two main criteria. First, most of the sites included a substantial proportion of 8-km AVHRR pixels with statistically significant browning trends in peak-summer NDVI based on the GIMMS 3G data set during the period 1982–2012. To identify AVHRR pixels with browning trends, we followed the same procedure as (Beck & Goetz, 2011) and (Guay et al., 2014), where we first selected the maximum NDVI value for each AVHRR pixel from all July and August observations for each year between 1982 and 2012. We then used results from the Theil–Sen trend estimator (implemented in the *zyp* package in R; (Bronaugh & Werner, 2013)) at each pixel to identify regions with widespread and statistically significant browning ($\alpha = 0.05$). Second, the sites were selected to encompass the diverse range of climate zones, forest types, and disturbance histories that are found in the Canadian boreal forest zone (Fig. 1). To do this, we used climate regimes (available at http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html), land cover derived from Landsat data circa 2000 (Wulder et al., 2008), and fire disturbance history from the Canadian Large Fire Database (LFDB; (Stocks et al., 2002)).

2.2. Landsat time series data

The analyses we describe below use time series of peak-summer "greenness" metrics derived from Landsat TM5 and ETM+ surface reflectance data that were screened for both transient (atmospheric