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Landscape variability of vegetation change across the forest to tundra transition of central Canada

Mitchell T. Bonney[a,*], Ryan K. Danby[a,b], Paul M. Treitz[a]

[a] Department of Geography and Planning, D201 Mackintosh-Corry Hall, 68 University Avenue, Queen's University, Kingston, Ontario K7L 3N6, Canada
[b] School of Environmental Studies, Queen's University, Kingston, Ontario K7L 3N6, Canada

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ABSTRACT

Widespread increases in the productivity of tundra ecosystems and static trends – or even declines – in boreal ecosystems have been detected since the early 1980s using coarse-scale remote sensing. However, intermediate-scale Landsat studies have shown that these changes are heterogeneous and may be related to landscape and regional variability in climate, land cover, topography and moisture availability. In this study, a Landsat Normalized Difference Vegetation Index (NDVI) time-series (1984–2016) was examined for an area spanning the transition from sub-Arctic boreal forest to Low Arctic tundra in central Canada. This was supplemented by analyses of relationships with a suite of environmental variables and in situ measurements of bulk vegetation volume. Results show that NDVI trends were generally positive (i.e. increasing) across the study area but were smallest in the forest zone and largest in the northern tundra zone. More than one-quarter (27%) of un-masked pixels exhibited a significant ($p < 0.05$) trend and virtually all (99.3%) of those pixels exhibited an increasing, or “greening”, trend. Greening pixels were most common in the northern tundra zone and the southern ecotone zone. Random Forest modeling of the relationship between NDVI and environmental variables indicated that the magnitude and direction of trends varied across the forest to tundra transition. Areas that experienced larger increases in NDVI include: (i) areas where summer temperatures increased; (ii) areas exhibiting predominantly shrub and forest cover; and (iii) locations closer to major drainage systems, further from major lakes, and at lower elevations. Ground validation in the central portion of the study area reveals a strong relationship ($R^2 = 0.79$) between vegetation volume and NDVI for non-tree functional groups and that alder (*Alnus crispa*) shrublands and open spruce (*Picea mariana* and *P. glauca*) woodland with shrubby understories were most likely to exhibit greening. These findings indicate that the largest positive and more significant NDVI trends were associated with increased productivity in shrub-dominated environments, especially at, and north of the treeline in localities with favorable growing conditions. Smaller and less significant NDVI trends in boreal forest environments south of the treeline were likely associated with long-term successional change following disturbance rather than the variables analyzed here.

1. Introduction

The Earth has experienced climate warming since the late 1800s, especially at high latitudes where warming has been significantly greater than the global average (Serreze and Barry, 2011; IPCC, 2013). A range expansion of broadleaf shrubs in Low Arctic and sub-Arctic ecosystems, as well as an increase in their growth and productivity, has been connected to this warming trend and is projected to continue in these tundra and forest-tundra environments (Myers-Smith et al., 2011). However, the intricacies of shrub expansion are not fully understood, with studies indicating that it has been heterogeneous, and that landscape-scale variability can influence the magnitude of vegetation change at high latitudes (Ropars and Boudreau, 2012; Frost et al., 2014). For example, disturbances (including changes in caribou herbivory) and growth along riparian corridors are key contributors to the heterogeneity of shrub expansion (Tape et al., 2012; Zamin and Grogan, 2013). Differences in land cover, topography and moisture availability have been noted as possible controls on shrub expansion and other vegetation changes.

While shrub growth and expansion has been widespread, treeline advance has been mixed; advancing in some locations but remaining static elsewhere (Harsch et al., 2009). Treeline advance has not occurred at the same rate as shrub expansion because boreal tree seedlings grow more slowly (MacDonald et al., 1998; Gamache and Payette,

* Corresponding author at: Department of Geography, 3359 Mississauga Rd, University of Toronto Mississauga, Mississauga, Ontario L5L 1C6, Canada.
E-mail addresses: mitchell.bonney@mail.utoronto.ca (M.T. Bonney), ryan.danby@queensu.ca (R.K. Danby), paul.treitz@queensu.ca (P.M. Treitz).

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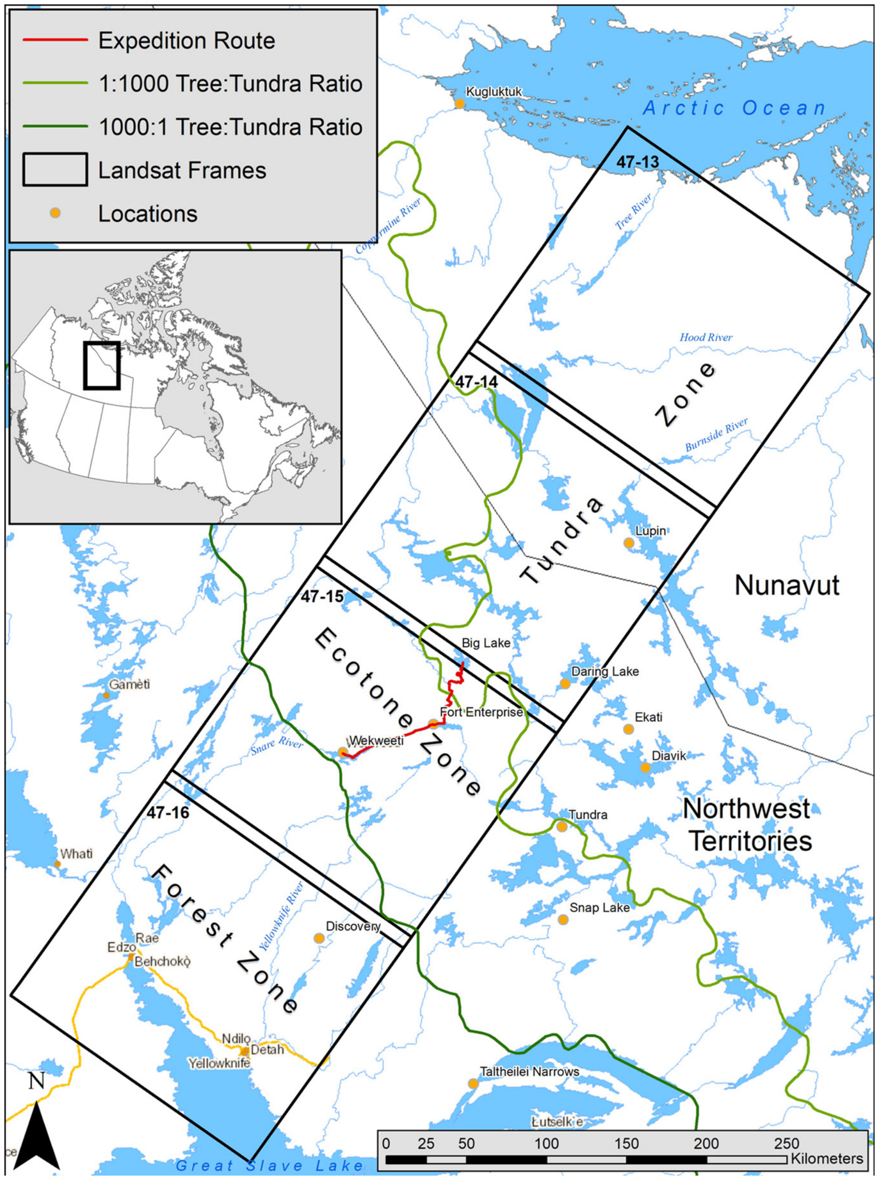

Fig. 1. The four Landsat frames used in this study. Numbers in the upper corner of each frame represent the Worldwide Reference System path-row. Basemap provided by the Government of the Northwest Territories (GNWT) Centre for Geomatics.

2005). However, there have been observations of accelerated height growth, patch infilling and small advances of treeline in certain locations (Gamache and Payette, 2005). Decreases in forest productivity have also been observed in some continental boreal ecosystems (Lloyd et al., 2011; Berner et al., 2011). This has been frequently attributed to higher drought stress during summer as temperatures increase (Barber et al., 2000). Overall, boreal forests appear to be responding to a combination of climate changes and disturbance-recovery dynamics (Girard et al., 2008; Sulla-Menashe et al., 2018).

Satellite remote sensing has allowed for quantification of these changes over multiple spatial and temporal scales. Coarse spatial resolution data from the Advanced Very High-Resolution Radiometer (AVHRR) have been regularly used to monitor vegetation changes at continental scales and has provided evidence of widespread increases in tundra productivity as well as decreases in some continental boreal forests (Pouliot et al., 2008; Verbyla, 2008; Beck and Goetz, 2012; Epstein et al., 2012; Guay et al., 2014). Landsat data have also been widely used at landscape and regional scales for this purpose (Olthof et al., 2008; Fraser et al., 2011; McManus et al., 2012; Raynolds et al., 2013; Ju and Masek, 2016; Edwards and Treitz, 2017). However, Landsat-derived vegetation changes have only recently been explicitly linked to landscape-level variation and drivers of change in northern environments using quantitative methods (Frost et al., 2014; Sulla-Menashe et al., 2018).

Changes in remotely-sensed vegetation indices over time provide limited information on the actual magnitude of physical vegetation change unless verified on the ground. Ground validation has demonstrated a relationship between vegetation biomass measurements and remote sensing vegetation indices in tundra environments (Jia et al., 2003; Laidler et al., 2008; Epstein et al., 2012). There is also the opportunity to quantify vegetation biomass in tundra and boreal forest environments using airborne laser scanning (Korhonen et al., 2011; Pope and Treitz, 2013; Greaves et al., 2016). However, the remote aspect of northern field research means that this approach is often not practical, especially when travelling long distances and with limited carrying capacity (e.g., canoe travel). Field methods that do not require excess equipment, such as bulk volume estimates from vegetation height measurements, can still play an important role in quantifying tundra and forested environments.

Relative to comparable regions, including interior Alaska and