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Mapping forest growth and decline in a temperate mixed forest using temporal trend analysis of Landsat imagery, 1987–2010

Chris J. Czerwinski *, Douglas J. King, Scott W. Mitchell

Carleton University, Department of Geography and Environmental Studies, Geomatics & Landscape Ecology Lab, Ottawa, Canada

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A B S T R A C T

Forest management seeks sustainability for a diverse set of goals, including economic objectives, provision of ecosystem services, and provision of a variety of possible land uses. It is important to quantify, map and monitor forest dynamics resulting from natural and anthropogenic processes over time periods appropriate to the temporal scale of change as well as to land management goals and decision making. This paper presents temporal trend analyses of temperate mixed forest dynamics in Gatineau Park, Québec, Canada, using a time series of Landsat 5 TM scenes. Several vegetation indices were first evaluated as indicators of field measured vegetation abundance parameters such as leaf area index, canopy openness, DBH, and basal area. Of these, Tasseled Cap Wetness (TCW) provided the best relationships (e.g., $r = 0.81$ against LAI) and it differentiated between coniferous, mixed and deciduous forests. Thirteen clear sky 5 TM scenes from the growing seasons of 1987 to 2010 were relatively calibrated and assembled into an image time-series. TCW applied to the image time-series followed by Theil–Sen and Contextual Mann–Kendall trend analysis detected subtle and gradual field-verified forest change. Gradual and abrupt forest decline or regrowth periods were identified; over the full period, 641 ha (1.8% of the park) exhibited statistically significant growth, and 689 ha (1.9%) exhibited decline. Mapping the timing, location, magnitude, and duration of forest change will help inform land management policy and actions within Gatineau Park and such methods may be applied in other similar forests.

1. Introduction

As a result of natural and human-induced disturbances and seasonal and successional dynamics, the structure and composition of a forest are constantly changing (Spies, 1998) at a range of scales in space and time (He et al., 2011). Understanding forest patterns, trends and rates is essential for their preservation and may help to assess the effectiveness of different management approaches (Paolini, Grings, Sobrinos, Munoz, & Karszenbaum, 2006).

Abrupt land cover conversions, such as a forest fire or clear cut, can often be detected using imagery of appropriate spatial resolution before and after the event (Gómez, White and Wulder, 2011). However, mapping and monitoring subtle vegetation dynamics such as longer-term decline, or growth, can require images from more than two dates, introducing additional challenges (He et al., 2011). This is mostly because variance in image data may be related to atmospheric variability, sensor calibration variability, image alignment, image processing or other environmental factors that can reduce the ability to detect image characteristics related to ecologically relevant change (Song, Woodcock, Seto, Lenney, & Macomber, 2001).

In the past, remotely detecting change was often limited by data availability, but using the Landsat satellite archive, which has recently become freely available, community-level forest monitoring has become increasingly feasible, and at a scale and cost that are meaningful from a management perspective. While bi-temporal change detection techniques provide valuable information about a landscape, if there is a wide interval between image dates, it can be difficult to interpret the timing or duration of a change detected. Early trend analysis using Landsat data often evaluated image calibration techniques, and found that for most applications, relative methods produce more temporally consistent time-series (Coppin & Bauer, 1994; Song & Woodcock, 2003). The challenge for forest trend analysis using remote sensing includes reducing the effects of the atmosphere, topography, phenology, and view angle (Song, Woodcock, & Li, 2002). Recent studies have confirmed that a Landsat image time series is capable of detecting subtle and abrupt inter-annual forest changes. Vogelmann, Tolk, and Zhu (2009) examined the Santa Fe National forest in New Mexico using a Landsat 5 TM image time-series comprised of 8 inter-annual image dates ranging from 1988 to 2006. Spectral trends starting in about 1995 showed a distinct increase in the short wave infrared/near infrared index, which they found to be highly correlated with canopy greenness and tree mortality. Severe tree mortality in their semi-arid study area was known to be a combined result of insect defoliation and drought. Powell et al. (2010) used Landsat data to model over 20 years of forest dynamics in both Arizona and Minnesota. Through

* Corresponding author.
E-mail addresses: c.j.czerwinski@gmail.com (C.J. Czerwinski), Dougj.King@carleton.ca (D.J. King), Scott.Mitchell@carleton.ca (S.W. Mitchell).

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comparative efforts of several modeling approaches, they showed that no single modeling approach yielded the best results, and concluded that modeling errors are difficult to overcome at the pixel level (i.e. single date classification). They pointed out however, that the consistency of a Landsat image time series makes the relative changes potentially accurate, and recommended a linear approach to modeling ecological change.

1.1. Study area and research context

Gatineau Park (Fig. 1) is located in southern Québec, just north of Ottawa, Ontario within the Great Lakes-St. Lawrence Forest Region of the Canadian Shield (Pisaric, King, MacIntosh, & Bemrose, 2008). This 36,131 ha area comprises remnants of the Laurentian Mountains, now evident as rolling hills of igneous and metamorphic rock overlain by glacial deposits mostly comprised of till with pockets of clay in some stream valleys (NCC, 2005). The park's forests are a mix of deciduous and coniferous temperate and northern species. In the southern portion, sugar maple (*Acer saccharum*) dominates, however, pockets of American beech (*Fagus grandifolia*), trembling aspen (*Populus tremuloides*), and red oak (*Quercus rubra*) can be found. Other less dominant deciduous species include red maple (*Acer rubrum*), American basswood (*Tilia americana*), ironwood (*Ostrya virginiana*), white ash (*Fraxinus americana*), black ash (*Fraxinus nigra*), white birch (*Betula papyrifera*), and black cherry (*Prunus serotina*). In the northern part of the park, mixed and coniferous forests are more abundant, and include species such as the eastern white pine (*Pinus strobus*), eastern white cedar (*Thuja occidentalis*), eastern hemlock (*Tsuga canadensis*), white spruce (*Picea glauca*), and black spruce (*Picea mariana*).

Before 1960, mining and forest harvesting were common in the park and in the surrounding region (NCC, 2005). Subsequently, park management has favored conservation and recreation over industry, although multi-lane roads as well as house construction have continued to be permitted in various park locations. Forest change has also occurred in various areas of the park due to natural disturbances such as ice storms (King, Olthof, Pellikka, Seed, & Butson, 2005) and insect defoliation events (Louis, 2008). Ice storms, also known as glaze events, involve large amounts of freezing rain, which can cause significant damage to trees. A particularly large event occurred in the temperate regions of eastern North America in 1998. A long term research study was established in the park to model ice storm damage (King, Olthof, Pellikka, Seed and Butson, 2005) and subsequent composition and structure dynamics using high resolution airborne and satellite imagery. Related projects have mapped canopy deadwood distribution (Pasher & King, 2009), and developed multivariate models linking structural attributes to image derived variables (Pasher & King, 2010, 2011). However, no attempt has previously been made to map temporal trends in forest dynamics across the whole park on a time scale relevant to longer term management goals.

1.2. Research goal and objectives

The goal of this research was to identify and map gradients of forest ecosystem change throughout Gatineau Park over a period of about two decades, which corresponds well with the park's planning cycle. In this research, a change in vegetation abundance was considered to include changes in live green biomass resulting from either anthropogenic or natural factors. The research objectives were to:

1) Identify an appropriate image-derived vegetation index for use in temporal trend analysis based on evaluation of relationships for a variety of such indices with field measured estimates of vegetation abundance;
2) Map the location, direction (increase or decrease), timing and magnitude of spectral change within Gatineau Park's forests; and
3) Determine which vegetation communities are changing, the magnitude of change, and the inferred agents of change.

Landsat 5 Thematic Mapper (TM) imagery was used as described below because: i) it represents the most appropriate remotely sensed archival database for the required multi-decadal temporal scale; ii) the temporal archive is complete, meaning imagery has been acquired every 16 days over the whole period, and the archive is free (both of these in contrast to higher resolution satellite imagery); iii) the whole park is imaged within one scene, and; iv) the nominal ground pixel size of 30 m was deemed appropriate for forest patch level analysis while minimizing spatial variance in reflectance associated with tree species and micro site differences that would be present in higher resolution imagery. Objective 1 was addressed using field and Landsat 5 TM data from the growth season of 2010. For objective 2, the relationships identified in objective 1 were used to aid interpretation of trends extracted from the Landsat image time series. Objective 3 was addressed using corroborating evidence from field work and ancillary data available for the time period of this study.

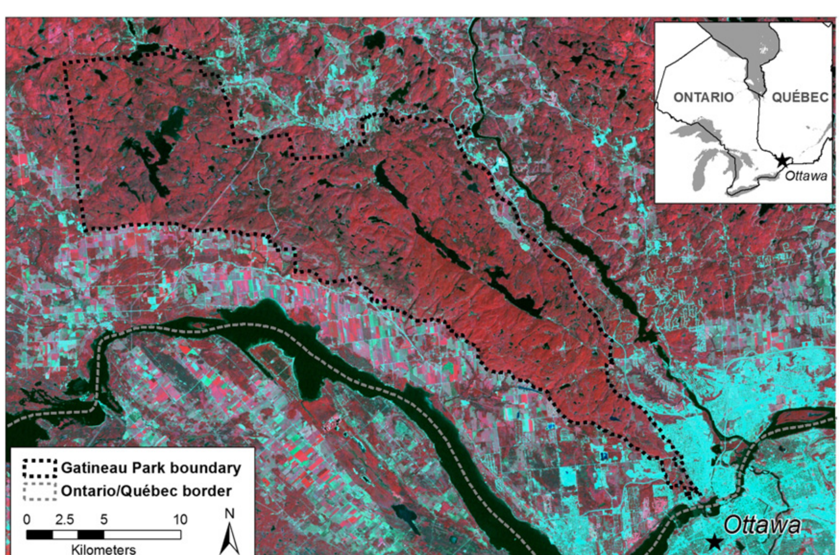

Fig. 1. Location of Gatineau Park, Québec, near Ottawa, Ontario, Canada. Shown using a color infrared composite of a Landsat 5 TM image acquired on August 9, 2004.