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FOREST CHANGE DETECTION AND MAPPING IN GATINEAU PARK, QUÉBEC, 1987 TO 2010 USING LANDSAT IMAGERY

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ABSTRACT

Forest management seeks to balance sustainable economic yields with maintenance and enhancement of a diversity of ecosystem services. Forest change from natural and anthropogenic factors needs to be studied and monitored over time periods appropriate to the time scale of change, whether abrupt or gradual. This paper presents analysis of forest change in Gatineau Park, Québec, by integrating ground-based measurements with Landsat imagery. Thirty-three 90 x 90m field plots were surveyed with respect to vegetation quantity (e.g., LAI, canopy openness, DBH, basal area), health and age during the 2010 growth season, and thirteen near-anniversary Landsat Thematic Mapper (TM) 5 scenes from 1987 to 2010 were relatively calibrated and assembled into an image time-series. Regression of the 2010 Landsat data and various vegetation indices against the field data showed that Tasseled Cap Wetness (TCW) was the most robust predictor and it differentiated between coniferous, mixed and deciduous forests. While several image variables detected abrupt forest change, TCW applied to the image time-series also detected subtle and gradual change using Mann-Kendall trend analysis ($p<0.05$). Landsat time-series and the change analysis techniques evaluated in this research are applicable to other large forested areas. The results of this study will aid the revision of the Gatineau Park Master Plan, which is currently underway.

Keywords: Landsat Time-series, Forest Change, Empirical Modelling, Temporal Trend Analysis, Gatineau Park

INTRODUCTION

As a result of natural and human-induced disturbances, and seasonal and successional dynamics, forests are constantly changing (i). Monitoring to detect change is a process whereby a difference in the state of an object or phenomenon is identified through observations made at different points in time (ii). This can be a difficult task if ground-based data are the only observations available; remotely sensed data are often preferred since they are spatially extensive and can be frequently acquired (iii). Ground-based observations, however, continue to provide valuable information, so, they are often integrated with remote sensing techniques for model development, validation, and quality control (iv). Abrupt land cover conversions can generally be easily detected using imagery before and after the event (iii), but modelling subtle land cover modifications, which often occur as vegetation decay, minor damage, and progressive growth, continues to challenge the remote sensing community (iv). This is because errors related to atmospheric variability and image alignment, can make it difficult to distinguish between image characteristics related to ecologically relevant change and noise from the sensor, environmental effects and data processing (v). Multi-temporal remote sensing has been demonstrated as a means to detect changes that would otherwise remain undetected using two image dates (vi); this will help inform environmental decision making, and evaluation of the effectiveness of management strategies (iv).

The main premise for optical remote sensing as a tool for monitoring forested landscapes is that changes in forest surface components are often manifested as changes in surface reflectance, which in turn determine image brightness. However, the precision with which change can be detected is largely dependent on the ability to reduce radiometric errors (vii). Atmospheric effects are significant sources of error since gases and aerosols scatter, refract or absorb radiant energy (viii). While absolute atmospheric corrections strive for estimates of true surface reflectance, relative methods match band-specific image histograms across time using a master image to normalize the other images. To reliably detect change, a ‘common’ radiometric scale between image dates is most important, and so, relative image calibration methods are often preferred (ix).

In the past, remotely detecting change was often limited by data availability, but now that the Landsat satellite archive is freely available, community-level forest monitoring has become increasingly feasible, and at a scale that is meaningful from a management perspective (x). Recent studies (vi, x) have confirmed that a Landsat image time-series is capable of detecting subtle and abrupt inter-annual forest changes, however, conclusions suggest that ground-based data are necessary to corroborate evidence of change, and that a calibrated image time-series is in most cases mandatory(iv).

This research was designed to remotely detect changes in vegetation quantity, which was considered to include changes in live green biomass, and was assumed to be a result of anthropogenic and natural factors. Sudden or gradual spectral differences across time may be related to changes in vegetation quantity. The research objectives were to determine:

1) Statistically significant relationships between ground-based estimates of vegetation quantity and Landsat TM5 satellite imagery;
2) The location, magnitude and direction of spectral change within Gatineau Park’s forests;
3) The specific vegetation communities being impacted, and estimate the magnitude of these impacts in terms of vegetation change based on the relationships developed in Objective 1.

METHODS

Study Area and Rationale

Gatineau Park, Québec, is located north of Ottawa, Ontario, in an area that was historically exploited for its resources (Figure 1). It was officially created in 1938, and is now managed by the National Capital Commission (NCC). Due to historical logging, more than half of GP is dominated by deciduous stands (xi); mixed and coniferous forests are concentrated in the northern parts of the park. One hundred and eighteen of the park`s species are listed as endangered or rare (xii); forest degradation may further challenge their habitat requirements.

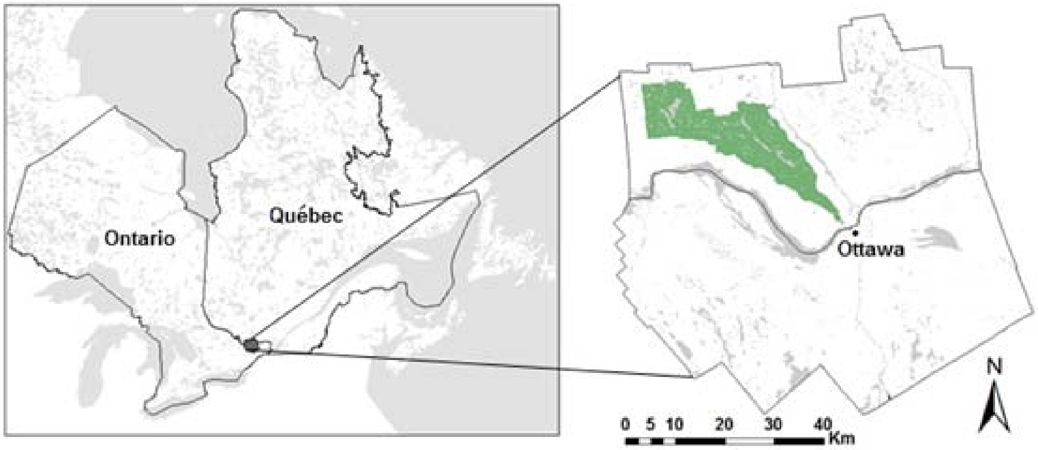

Figure 1: Gatineau Park (green), situated within the National Capital Region of Canada.

The park receives about 1.7 million visitors a year. Consequently, it is used intensively for recreational purposes; regional development and pollution pose additional threats. Several natural disturbances in the last 30 years have also occurred within the park. The ice storm of 1998 is one example that affected the southern regions of the park (xiii). Prior to and during the field season of this research, portions of the forest were severely defoliated by various insects. First hand observations were made in 2010 during the field work of this study, and maps of historical events were provided by the Quebec Ministry of Natural Resources and Wildlife (QMNRF). Based on this recent history, it is clear that the park is highly dynamic. The ecology of the area may benefit from a spatially explicit monitoring system, since current methods are primarily field-based (xii). The notion of a variety of stressors has initiated the revisions being made to the *Gatineau Park Master Plan; a*mendments will be based on research conducted during the period of 2005 to 2015 (xii). This research is the first to remotely assess forest change over a significant time period for the park as a whole, and at a scale relevant to its management.

Field data

The ground-based data for this research were collected from thirty-three 0.8 ha plots (90m x 90m) during leaf-on summer conditions in 2010. Plots were strategically selected to capture the existing range of vegetation composition, quantity and structure, but also to assess spectral trajectories associated with forest growth or deterioration. Prior to site selection, image differencing of 1987 and 2007 normalized difference vegetation index (NDVI) images helped to identify areas within the park that may have changed during the last 20 years. This method required on-the-ground confirmation, but it served as an effective tool for locating suitable sampling locations. Hemispherical photographs acquired at 1.5m height were used to estimate leaf area index (LAI) and canopy openness using methods described in (xi), and included the LX clumping index described in (xiv). The average from five locations in each plot was used. In addition, nine circular subplots (8m radius) within each plot were used to measure the mean and variability of DBH, basal area, age (using tree cores) and number of stems (for all trees with a DBH > 10cm); tree species was also noted. Transects were used to evaluate the proportion of saplings > 2m. Principal Components Analysis (PCA) was used to eliminate data redundancy and to select field variables for use in empirical modelling against the image data (xv).

Geospatial data

Based on preliminary tests, and recommendations within the literature, a relative atmospheric correction, known as the pseudo invariant feature, or PIF method, was used to calibrate the 13 near-anniversary, relatively cloud-free, Landsat TM5 scenes. Dark (i.e. lake) and bright (i.e. quarry) statistically stable PIFs, common to all image dates, were delineated. Their average pixel values were used to match band-specific image histograms to a master image, to ensure that all images were radiometrically comparable, using:

$$DN_{1i} = m_i DN_{2i} + b_i \qquad (1)$$

where m_i and b_i are constants used to transform the reflectance distribution for the i^{th} band of date 2 to an equivalent distribution represented by date 1 (xvi). The absolute average of the standard error of the slopes of 5 independent PIFs was used to determine the minimum spectral trajectory that could be considered ecologically significant, and not an error within the image data. Since a linear calibration was used, errors were assumed to be associated with the remaining non-linear atmospheric effects, and will be referred to as the 'noise floor' hereafter. Image alignment errors were considered negligible for imagery with 30m pixels, since each image showed a horizontal offset of less than 1m when compared to the master image.

Preliminary tests used NDVI imagery, because of its known relationships with vegetation quantity measured on the ground. However, where biomass is high, NDVI can be susceptible to saturation, and where it is low, NDVI can be affected by a strong background signal. Therefore, other spectral vegetation indices (SVI) such as the enhanced vegetation index (EVI) were considered since it is said to be resistant to atmospheric influences and the effects of forest structure. It incorporates blue reflectance information to reduce signal noise and uncertainties; for sensors without a blue-band, EVI2 can be used (xvii). Brightness, greenness and wetness features of the Tasseled Cap transformation were also evaluated since they are often considered robust indictors of forest dynamics (xviii). Other published SVIs were evaluated, but are not discussed here since they were not well related to the field data.

The pixels representing coniferous, mixed and deciduous forests (hereafter referred to as functional groups) were stratified using a digital map that was created in 1992 by the Quebec Ministry of Mines and Forests (QMMF). This map delineated homogenous forest patches based on age and species composition, and was useful for modelling dynamics within these groups. The NCC also provided spatial data describing the roads, trails, recreational facilities, and beaver monitoring sites within the park. Along with the insect defoliation maps provided by the QMNRF, these ancillary datasets were intended to corroborate evidence of change, determined through the remote sensing techniques used.

Modelling the spatial and temporal dynamics of Gatineau Park

Relationships between image-based SVIs and field measurements of vegetation quantity were developed through regression of 2010 Landsat data against the field data. These relationships were used to evaluate each image variable as a linear surrogate of vegetation quantity and helped to aid interpretation of forest trends extracted from the calibrated image time-series. Change was modelled using mathematical operations at the pixel level. Abrupt changes between image dates were mapped using image differencing and statistical thresholds. Subtle and gradual forest trends were inferred using a Mann-Kendall (MK) analysis, which tests for a slope of zero in a variable across a time series. Based on the slopes of all possible bi-temporal iterations in the forward direction, it computes for each pixel, the mean slope and the probability of a monotonic trend for data ordered in time (xix). The entire time-series (1987 to 2010) of the most effective SVIs were analyzed, as well as three separate 11 to 13 year intervals, representing the beginning, middle and end of the available range (1987 to 1999, 1994 to 2004, and 1999 to 2010). These intervals were selected so that each temporal window included a similar number of years and remotely sensed observations (13, 11 and 11 years; n = 6, 7, and 7 respectively). The intention was to highlight the timing of an event, and describe its dynamics in greater detail.

RESULTS

Several relationships existed between the field and image data, and the plots established in deteriorating or growing forests were associated with statistically significant spectral trajectories (Figure 2). This showed that ecologically relevant spectral trajectories could be extracted from the image time-series, and that the calibration process was successful. PCA showed that the first 4 PCs accounted for 83% of the total variance within the ground-based dataset. Live and dead mean dbh and total basal area, as well as mean age, the abundance of tree saplings > 2m, canopy openness and LAI were highly loaded on these PCs. These field variables were regressed against the selected SVI extracted from the 2010 Landsat scene. EVI2 and TCW formed the majority of the statistically significant relationships, which improved when the data were stratified into the three functional groups.

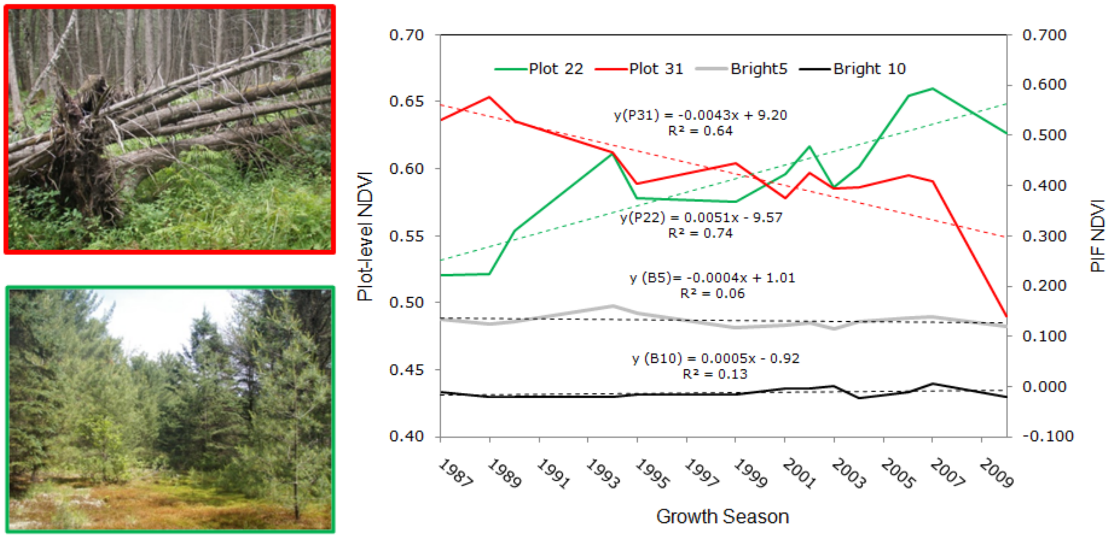

Figure 2: Example NDVI plot-level time trajectories for a deteriorating (red) and growing (green) forest. PIF locations (Bright 5 and Bright10), appear relatively stable over time.

Field data showed that coniferous forests generally have higher LAI values, especially compared to deciduous forests. TCW showed the same trend for coniferous and deciduous plots, while EVI2 showed the opposite. Figure 3 shows a scatter plot that describes the apparent strong positive relationship between TCW and LAI, using all thirty three plots (R^2 value of 0.65). The strength of this relationship was considerably stronger than the other SVIs (R^2 values all < 0.32). The utility of TCW was further emphasized when viewing it as a temporal indicator of vegetation quantity. It described similar trends for plots with known growth or deterioration, such as plot 22 and 31 shown for NDVI in Figure 2, but TCW showed less noise when compared to NDVI and EVI2. Trends appear to be linear for most of the plots that show distinct trends.

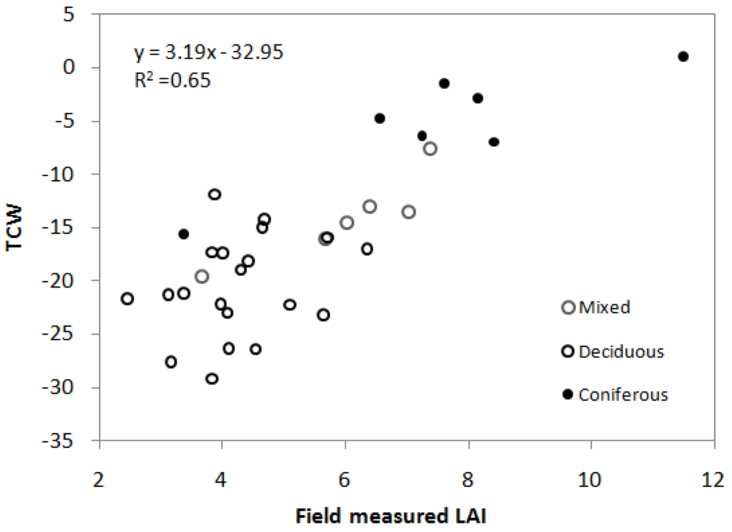

Figure 3: Relationship between plot-level TCW and LAI. Data points are stratified by functional group, and the linear regression equation provided was derived using all 33 plots.

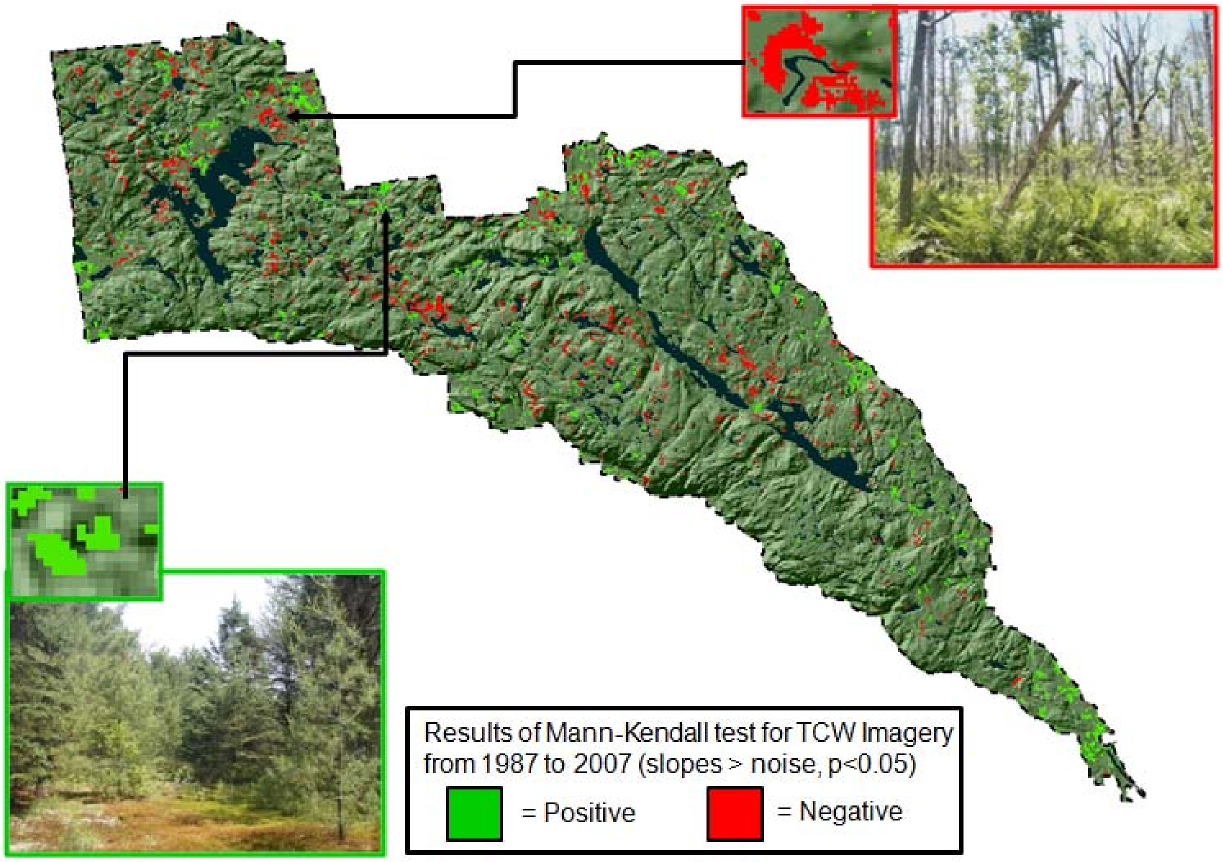

Figure 4: Significant positive and negative Mann-Kendall trajectories (slope > noise floor, p<0.05) determined for the TCW image time-series using imagery from 1987 to 2007.

TCW and EVI2 were both capable of detecting abrupt events, such as the insect defoliation event of 2010, or the development of a 4 lane road completed in 2007. However, subtle and gradual changes were highlighted best by the TCW image time-series. For both image variables, the Mann-Kendall test was applied to the entire time-series; however, the image representing 2010 was removed from the analysis because insect-induced damage caused extremely anomalous data for large proportions of the park. TCW highlighted many regions in the park known to be located in growing or deteriorating forests (Figure 4), but EVI2 maps were for the most part not useful. Many regions that were highlighted using the entire TCW time-series were also highlighted by one of the three intervals (beginning, middle and end), which helped to understand the timing and dynamics of the subtle changes within the park.

CONCLUSIONS

Although still in progress, this research shows that a Landsat image time-series can be used to detect both subtle and abrupt changes in vegetation quantity, and that Tasseled Cap Wetness is an effective indicator of such change. The remote sensing techniques evaluated in this research are applicable to other forest landscapes of a similar scale. Given that Landsat imagery is free, a spatially explicit monitoring system can be implemented for forest management, but local knowledge of the landscape is important. Additional field work and other sources of corroborating evidence (i.e. defoliation maps) will help to verify the changes detected remotely, and the reliability of the methods used. Stratifying the pixels identified as changing into coniferous, mixed and deciduous forests, as well as by the magnitude of change, will help prioritize forest management strategies in Gatineau Park.

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