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Forest Structure Change Detection in the Fundy Model Forest with Threshold Maps Based on the Landsat TM Wetness Index

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SUMMARY

We considered the use of Landsat TM imagery in detecting forest changes in the Fundy Model Forest, a large, multi-jurisdictional forest management unit in southeastern New Brunswick. Our objective was to report the total area of forest cover and the total area of forest disturbance or *change in forest structure* in each year for which suitable Landsat image data were available (1984, 1985, 1986, 1992, 1997, 1999). The approach was based on changes that could be detected as differences in the enhanced wetness difference index (EWDI) documented in earlier research. In this paper, wetness difference values in known change areas were used to determine an appropriate threshold separating forest structural change from areas of no change. The average annual change on the landscape was approximately 3068 ha in each year of the 16 year

interval, with apparently declining mean annual change from the mid-1980s to the late 1990s. The maximum annual change was more than 7000 ha; this occurred in 1985-1986. In the late 1990s, the annual change detected was approximately 3500 ha. The estimates of total annual change (almost 50 000 ha) as a percentage of the total Fundy Model Forest land base (more than 400 000 ha) suggest that approximately 12% of the total land area experienced a change in forest structure; annually, this is equivalent to a rate of change between 0.75 and 0.81%. Since the available productive forest land (approximately 240 000 ha) represents approximately 60% of the total land base, the true estimate of forest structure change is probably closer to 20% in the time interval studied, which translates into a rate of change of approximately 1.3% annually.

INTRODUCTION

Understanding the spectral conditions in forest disturbance areas may be important in determining the types of changes that can be routinely observed by satellite remote sensing instruments and current data processing methods. This may lead to greater appreciation of the appropriate role of satellite remote sensing technology in monitoring forests in a wide range of ecological settings (Franklin 2001). For example, Peterson and Nilson (1993) developed the concept of *successional age trajectories* of forest reflectance. Measurements of reflectance were calibrated with field observations of forest stand age such that different successional conditions – that is, succession approximated with different ages of stands, a surrogate for successional development – could be predicted from the reflectance measurements (Nilson and Peterson 1994). Forest stands were then ‘monitored’ to determine if the reflectance deviated significantly from the expected reflectance for a forest stand at that successional stage of development.

The successional interpretation of reflectance could be coupled with an understanding of the spectral response to disturbance, perhaps caused by harvesting and silviculture (Varjö 1996), or some natural phenomena, such as forest decline (Ardö 1998), or defoliating insect activity (Riley 1989). For example, a clearcut area should have a large change in spectral response compared to an undisturbed or partially-harvested forest stand; in turn, those changes would be large and occur over a short time interval compared to the changes due to natural successional development of a stand.

Generally, the problem of assessing the correspondence between the actual areas treated and the original planning has been quite poorly addressed (Mitchell 2001). If areas scheduled for a treatment such as clearcutting did not show a large difference between observed reflectance and the model predictions, then perhaps a field investigation would be necessary to determine if the area indeed had been harvested as planned. On the other hand, areas that showed large differences in spectral response that were not predicted by the successional/reflectance model and also were not scheduled for treatment (e.g., harvesting) would be of interest and high priority for a field investigation. The management implications of these ideas suggest that imagery be acquired periodically, over the same stands, to determine if there is a difference between the expected reflectance (from the successional age trajectory model or the forest harvesting/silvicultural model coupled with a growth model) and the observed reflectance (Jupp and Walker 1997).

Reflectance models, while improving in accuracy and reliability (Woodcock *et al.* 1997, Battaglia and Sands 1998, Peddle *et al.* 2000), remain inaccessible to many image analysts in forestry applications (Franklin 2001). Rather than use a reflectance model, a reasonably simple strategy would be to acquire imagery periodically of the same stands to compare the actual reflectance observed at different times. Then, the emphasis would be on the creation of a decision rule that could suggest if the changes between successive image acquisitions were significant; the well-known problem of '*optimum thresholds*' for change detection (Fung and LeDrew 1988). This change detection idea is not new but has, perhaps, received insufficient attention in the literature (Cohen and Fiorella 1999); there continues to be a paucity of good, practical examples of satellite remote sensing imagery used in detection of silvicultural (Olsson 1994, Kiedman 1999) and partial harvest forest changes (Franklin *et al.* 2000a). Issues arise from a host of radiometric, geometric, and image analysis processes; the goal is to provide accurate and reliable information on forest structure change, disturbances, and forest loss or depletion (Cohen *et al.* 1998).

To address this issue in one forest environment in Canada, we acquired six Landsat Thematic Mapper images (sequential, non-anniversary) covering a 16 year time interval from 1984 to 1999 of the Fundy Model Forest in southeastern New Brunswick. The objective was to study changes in forest condition and Landsat TM spectral response attributable to different disturbances ranging from clearcutting to partial harvesting and silvicultural treatments. The rationale for examining this approach was the desire on the part of the Fundy Model Forest managers to understand the changes in total area of forest cover and the total area of forest disturbance – *change in forest structure* – in each available time interval in the series of image dates.

DATA COLLECTION AND PREPROCESSING

Landsat TM images were acquired (path 9, row 28) on September 18, 1984, September 21, 1985, August 23, 1986, August 10, 1988, August 7, 1992, September 6, 1997, and September 12, 1999. These images represent the best imagery in the archive for the months of August and September in which the Fundy Model Forest was relatively cloudfree; a few very small areas of cloud and cloud shadow were identified by thresholding bright areas and shadows supplemented with manual digitizing on-screen. Those areas were removed from the analysis with no effect on the image processing results. The images were solar-zenith angle (illumination) and atmospherically-corrected using a standard-atmosphere, model-based atmospheric correction routine (Richter 1990). The image data were geometrically registered to the UTM NAD27 projection with 40 GCPs points at key road intersections dispersed throughout the scene with less than 0.5 pixel RMSE. Cubic convolution resampling algorithm was used to resample the images with a 25 m output grid.

The TM Tasseled Cap transformation (Crist and Cicone 1984, Crist 1985, Horler and Ahern 1986) was used to concentrate the required ‘change’ information in a single channel - the TM wetness index (Collins and Woodcock 1996, Cohen *et al.* 1998, Franklin *et al.* 2000a). The difference in the wetness index for two dates was enhanced (Franklin *et al.* 2001) to emphasize the forest differences of interest, hypothesized to be much larger than the ‘noise’ created by residual differing radiometric and atmospheric properties between images in the time series. For example, earlier we found that partial harvest forest conditions could be detected with greater than 70% accuracy in the 1992-1997 time period in stands stratified by species composition (Franklin *et al.* 2000a). This enhanced wetness difference index (EWDI) was used in all subsequent digital change detection analysis.

ANALYSIS METHODS

We interpreted normal colour composite satellite image and the EWDI in areas of known forest change to identify empirically the appropriate thresholds to apply to the imagery of the entire Fundy Model Forest. In normal colour composite satellite imagery, areas disturbed by clearcutting, partial harvesting or silvicultural treatments were usually brighter than in the undisturbed areas. This was typically most pronounced in the conifer stands, but occurred in hardwood and mixedwood stand as well. The largest increase in the brightness of the bands was found in the clearcut areas, followed by the shelterwood, seed tree, and partial harvesting treatments (Table 1). Areas that were substantially cleared of standing biomass (e.g., clearcuts, shelterwood cuts, partial cuts with legacy patches) appeared as a bright red tone in the enhanced wetness index difference imagery. The largest difference in wetness was found in the clearcut areas, followed by shelterwood and seed tree cuts, partial harvesting with legacy patches, and precommercial thinning. Annual change imagery were able to provide differences between silvicultural treatments that were not apparent in imagery acquired with a multi-year time step. Those imagery, however, were able to provide differences in most of the partial harvest, shelterwood, seed tree, and all of the clearcut, areas (Franklin et al. 2000a).

The threshold differences were used to develop a map. This process is illustrated graphically for the 1984-1985 image pair in Figures 2 and 3 for two small regions: 1) Hayward Brook subarea, and 2) Bay of Fundy subarea. The final results of the image thresholding process for these two subareas – the accumulated changes – are shown for all the available image pairs in Figures 4 and 5, respectively. The GIS data were used to 'mask' all non-forest areas from the change detection procedure; obviously, since the GIS forest cover data were a static layer (compiled in 1993 from 1988 photography) some minor error may have been introduced in this masking process (i.e. areas that were changed in the 1984-1985 scene that were not changes to forest cover, but occurred in agricultural or wetland areas for example, may have 'escaped' the mask).

To summarize, the analysis was based on the following three steps:

1. For each of the available image dates in sequence, the EWDI was created and thresholded to a bitmap which then contained only the changes that exceeded the threshold and could be verified on the ground. These changes included clearcuts, seed tree cuts, shelterwood cuts and partial harvest areas; if the imagery were annual, then also included were some silvicultural treatments such as plantation cleaning, precommercial thinning, strip cuts, two-pass cuts, and commercial thinning.

2. The determination of the threshold required an iterative process of adjustment; particular attention was paid to the location and distinctiveness of new roads, for

example. Known road construction may be used to gauge the effectiveness of the threshold in presenting the changes; for example, if the road were to ‘bloom’ then the threshold was too low; if the road were to ‘disintegrate’ the threshold was too high.

3. The earlier change detection work provided a useful sample of areas that had changed that could also be consulted in the thresholded imagery for ‘preservation’ or ‘extinction’ (Franklin *et al.* 2000a,b, 2001). The changes were accumulated into a single map data layer that could be used to reflect the total area of change in forest structure experienced over the available time interval (1984-1999).

RESULTS AND ANALYSIS

The final map of forest structural changes detected in forest areas of the Fundy Model Forest is contained in Figure 6. The average annual change on the landscape was approximately 3068 ha over the 16 year interval, with apparently declining mean annual change from the mid-1980s to the late 1990s (Figure 7). The maximum annual change was more than 7000 ha in 1985-1986; the minimum annual change was less than 2500 ha in each of the years from 1986 to 1992. This low estimate of change is almost certainly an artifact of the six year time interval between the 1986 and 1992 TM images in which changes of lesser severity (e.g., some partial cutting, thinning) could not be distinguished. In the late 1990s, the annual change was approximately 3500 ha.

These estimates of total annual change (almost 50 000 ha) as a percentage of the total Fundy Model Forest land base (more than 400 000 ha) suggest that approximately 12% of the total land area has experienced a change in forest structure; annually, this is equivalent to a rate of change between 0.75 and 0.81%. Since the available productive forest land (approximately 240 000 ha) represents approximately 60% of the total land base, the true estimate of forest structure change is probably closer to 20% in the time interval studied, which translates into a rate of change of approximately 1.3% annually.

This level of change is probably on the high end of the annual forest structure change or disturbance rates that have been reported in other jurisdictions in a variety of temperate forests throughout the world. Great care must be taken in comparing rates of change in forests; typically, *rates of forest loss* are reported rather than changes in forest structure. For example, in a large forested area on the border of China and North Korea, 1972 and 1988 Landsat imagery were classified into forest and non-forest classes (Zheng *et al.* 1997). Much of the change detected was a result of clearcutting; partial harvesting had increased in this area after 1980 as a result of government policies encouraging selective harvest over clearcutting, but the classification scheme did not show many of those areas as changes. The method was unable to distinguish natural and human disturbances. The reason given was that there were not enough training data for use in the classification procedure. The annual rate of forest cover loss was –0.73% over the 16 yr period for the study area, a comparable rate to that reported by Spies *et al.* (1994) in the US Pacific Northwest for a similar period.

In British Columbia, Sachs *et al.* (1998) reported a large region of the interior forests to be in the early stages of fragmentation. Their analysis was based on the classification of Landsat imagery acquired in 1975 and 1992. Human disturbance was shown to have affected 8.4% of the forest structure in a large study area outside protected areas between 1975 and 1992. Mature and older conifer forest area decreased more than 10%, accompanied by decreases in mean conifer patch size and the percentage of interior forest area. The annual rate of change was estimated to be 0.49% per year. This was thought to be at the low end of the range of disturbance rates for managed, temperate forests (Sachs *et al.* 1998). Forest disturbance rates by harvesting and burns were computed by Hansen et al (2001) in a similar analysis in the Revelstoke area; 1975 and 1997 imagery were used to detect an approximately 6% reduction in the area of forest stands with old growth (mature) characteristics. For the total area of land, the annual rate of change was estimated at 0.09% over the 22-year period. If only the productive forest land base were used in the estimates, the annual rate of forest structure change detected in the satellite imagery was approximately 0.25%.

Many of the cited studies indicated higher rates of forest change outside protected areas and were designed to detect ‘forest fragmentation’ processes. Increased forest fragmentation can be interpreted in landscape metrics developed from satellite image classification and change maps (Franklin *et al.* 2000c). Typically, fragmentation resulting from human disturbance activities can be interpreted by considering areas inside and adjacent to forest reserves where known (very low) levels of activity occur in the time period of interest (e.g. Zheng *et al.* 1997, Sachs *et al.* 1998). This trend is also apparent in the Fundy Model Forest change detection map (Figure 6). The large, intact ‘white’ area in the bottom right (southeast corner) of the map comprises Fundy National Park; only a few small changes occurred inside the park boundary compared to the areas adjacent to the park but within the Model Forest. These small areas of change inside the park represent a number of small human disturbances (e.g., road widening) and natural disturbances – such as beaver pond flooding, tree blowdown, and insect defoliation – that are likely also present but undistinguished from other changes in the larger mapping product.

Several new map products can be suggested based on the results of forest structure change achieved in this study:

- First, all changes are not equal over space: the earlier studies have shown that changes can be mapped at the level of light, moderate and severe changes to forest canopies (Franklin et al 2000a,b); these structural differences could be preserved in the reporting of changes if different thresholds were applied and the changes in each time period were not aggregated.

- Second, all changes are not equal over time: the mapped changes need to be considered in the context of forest disturbance and regrowth. Note that change in forest structure is not equivalent to ‘forest loss’ or ‘forest depletion’. For example, many forest clearcuts and partial harvests in the 1984-1985 period at a later date were probably changes that should ‘fade’ from the change detection map rather than persist on a cumulative change map; thus, there could be a change map that shows only those changes where an actual change in permanent land cover has occurred. Even a change from a forest to a clearcut could continue to be represented as a ‘young forest’; the structure of that forest changed but the dominant characteristic continues to be forest.

- Third, the changes can be reported in several ways with access to the comprehensive forest inventory GIS database (Franklin et al. 2000b). Two different strategies might be used that would reveal patterns of interest over time: 1) examination of changes within homogeneous management units (e.g., stand polygons and ‘blocks’), and 2) a large-area compilation of changes by ownership, species groupings, or ecological strata.

CONCLUSION

We interpreted Landsat TM imagery acquired in 1984, 1985, 1986, 1992, 1997, and 1999 for distinctive patterns associated with forest structure changes known to have occurred as a result of silvicultural and harvesting operations. Critical to our interpretation is the Tasseled Cap enhanced wetness difference index (EWDI – see Franklin *et al.* 2001). The EWDI is based on an emerging understanding of differences in stand structure caused by partial harvesting and silvicultural practices. This interpretation can form the basis of the development of a forest change monitoring tool.

In the Fundy Model Forest, over the 16-year time series of imagery, the average annual forest structure change on the landscape was approximately 3068 ha. The total annual change (almost 50 000 ha) as a percentage of the total Fundy Model Forest land base (more than 400 000 ha) suggest that approximately 12% of the total land area experienced a change in forest structure; annually, this is equivalent to a rate of change between 0.75 and 0.81%. Since the available productive forest land (approximately 240 000 ha) represents approximately 60% of the total land base, the true estimate of forest structure change is probably closer to 20% in the time interval studied, which translates into a rate of change of approximately 1.3% annually. This could be considered at the high end of the range of reported forest structure change rates for managed, temperate forests.

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Table 1. Forest disturbances used to develop thresholds in the enhanced wetness difference index (EWDI) for the detection of changes in the Fundy Model Forest, New Brunswick.

- Light (e.g., plantation cleaning, precommercial thinning)
- Moderate (e.g., strip cutting, plantation thinning, selection cut, shelterwood cut, release cut, group selection cut)
- Severe (e.g., clearcut, partial cut with residual value, seed tree)

Figure 1. Study area in the Fundy Model Forest in southeastern New Brunswick.

Figure 2. Graphical Illustration of the Enhanced Wetness Difference Index (EWDI) and thresholding procedure: Hayward Brook subarea.

Figure 3: Graphical Illustration of the Enhanced Wetness Difference Index (EWDI) and thresholding procedure: Bay of Fundy subarea.

Figure 4. Accumulated change in forest structure for the Hayward Brook subarea.

Figure 5. Accumulated change in forest structure for the Bay of Fundy subarea.

Figure 6. Accumulated change in forest structure for the entire 400 000 ha Fundy Model Forest including Fundy National Park (bottom right corner).

Figure 7. Compilation of total area of forest change detected with images in the time series.