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Interpretation, Classification, and Digital Update of Partial Harvest Forest Stand Conditions Using Annual Differences in Tasseled Cap Transformations of Landsat Thematic Mapper Imagery: A Study in the Fundy Model Forest

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Executive Summary

The detection and update of clearcut and partial harvesting activity in forest polygons of New Brunswick's Fundy Model Forest over a one-year period (1997-1998) is described with the Tasseled Cap transformation of two Landsat Thematic Mapper images. Field data were collected based on a preliminary classification of changes into three classes – light, moderate and severe. Training areas were organized by severity of disturbance and dominant forest type (softwood, hardwood, mixedwood). Visual analysis of training areas using colour composites and an enhanced wetness difference image display technique revealed the level of separability that existed among these training areas and created examples of change classes that could be detected with these methods. B-distance separability measures were generated; high separability was found across the classes (1.88) and a supervised classification was implemented. Proportional change in stand basal area was regressed on the change in spectral response measured in each stand; reasonable levels of correlation were found and a procedure to estimate the degree of disturbance within each change class is described.

A computer program, called the polygon update program (PUP), was written in ArcInfo Macro Language (AML) to facilitate the integration of the satellite image classification of landscape change into the GIS-based forest inventory. The code accepts user-defined attributes and retains a unique polygon identifier, *polyid*, as a variable while converting the vector GIS files to overlay the satellite image in a common grid format. Image classification data are read in and a rule-base is invoked to determine the correspondence between the attributes of the gridded-polygons in the GIS and in the image classification. The program summarizes changes within polygons according to the previously-documented logic of polygon decomposition. A flag can be written to an attribute table to indicate the amount of change detected (i.e. the number of pixels in the change classes of the image classification with that *polyid* in the GIS grid format). A graphical user interface is provided. An example is provided in an Appendix to this report to illustrate the polygon update for forest inventory; the update is summarized by *polyid*, species codes, and area of each forest stand for which changes were detected in three classes (light, moderate, severe).

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Introduction

Forest inventories are used increasingly to support a sustainable forest management planning framework which may require a wide range of information in addition to traditional stand descriptions of volume, age, diameter and height class, and species composition. For example, determining the amount of forest depletion across different management regimes may be critical in understanding sustainable forest management options for a given landbase (Goodenough et al 1998, Hall 1999). More frequent updates of information on changes in forest condition may be required as part of the forest inventory. A Canadian emphasis on criteria and indicators of sustainable forest management has created an entirely new reporting objective for forest inventories (Canadian Council of Forest Ministers 1997), and the information demands will continue to increase with this new articulation of forest management objectives (Boyce and Haney 1997).

The role of satellite remote sensing in regional landscape change detection (Woodcock et al 1997, Cohen et al 1998) and mapping (Wolter et al 1995, Lillesand 1996) may become increasingly important as a source for GIS updates of forest inventories in multijurisdictional settings (Lowell and Edwards 1996). However, there continues to be a paucity of good, practical examples of change detection in forestry such that the user community can readily appreciate the benefits of satellite remote sensing in the task of GIS updating and reporting or monitoring entire landscapes (Franklin et al 2000a, 2000b). For example, very few studies have addressed the issues of silvicultural change and partial harvest change detection (Olsson 1994, Franklin et al 2000a, b) even though these types of forest disturbance may be increasing in importance relative to clearcutting in many forest regions of Canada.

We acquired Landsat Thematic Mapper images from 1992, 1997 and 1998 in the Fundy Model Forest of southeastern New Brunswick to study changes in forest condition and spectral response attributable to different disturbances ranging from clearcutting to partial harvesting to silvicultural treatments. Earlier, we reported that the accuracy of partial harvest change detection using Landsat imagery acquired in 1992 and 1997 approached 71% over a full range of change conditions in southeastern New Brunswick (Franklin et al 2000a). We used the TM Tasseled Cap transformation (Crist and Cicone 1984, Crist 1985) and classified the 1992 and 1997 brightness/greenness/wetness difference images. Three classes related to the level or amount of disturbance were used: light change (e.g. plantation thinning), moderate change (e.g. shelterwood cut), and severe change (e.g. clearcut). One of the main sources of error in the classification was attributed to the wide range of change conditions in the five-year image period within each class. For example, clearcuts at the beginning of the five-year period were significantly different in spectral response when compared to more recent clearcuts, but were placed in the same training area for the severe change class. Clearcuts in softwood stands appeared different when compared to clearcuts in mixedwood stands. Differences over the five-year time period in the partial harvest classes were also difficult to classify because of high variability; for example, some hardwood stands that were subjected to a selection cut early in the five-year period resembled undisturbed forest five years later because opening the canopy sometimes stimulated growth of an exuberant understory. Group selection cutting in hardwood stands, a moderate level of disturbance, appeared significantly different than a moderate disturbance in a softwood stand (e.g. strip cutting or precommercial thinning).

Annual change detection was considered an appropriate strategy to eliminate some of the classification error and uncertainty caused by high variability within some of the change classes. In this paper we address this issue by considering annual change detection with the 1997 and 1998 Landsat TM images. We briefly describe the use of TM Tasseled Cap transformations, image differencing, and supervised classification for the one-year update period from 1997 to 1998. An extensive field program designed to collect information on the forest stand conditions before and after the disturbance was implemented. With these data we attempted to understand better the physical basis for changes in the brightness/greenness/wetness data for each treated stand. Subsequently, greater detail in the classification scheme was possible.

Study Area

This study was conducted in the Fundy Model Forest (FMF), located on the north shore of the Bay of Fundy, New Brunswick, Canada (Figure 1). The Fundy Model Forest is a 420000 hectare working forest with several towns and villages, industrial freehold land (J.D. Irving, 17%), Crown Land (15%), Fundy National Park (5%) and many small private wood lots accounting for approximately 63% of the land base. In order to determine if the forest practices now in effect on this landbase are sustainable, a reporting and monitoring tool for indicators of sustainability (such as the percent area of forest disturbance by human factors) must be developed and applied to all land ownerships and forest community types.

The study area is in the Canadian Acadian Forest Region (Rowe 1972) and contains merchantable timber in complex coniferous, deciduous and mixed-wood forest stands. Upper slopes and ridges are mostly occupied by northern tolerant hardwoods, such as sugar maple (*Acer sacharum*), yellow birch (*Betula alleghaniensis*) and beech (*Farus grandifola*). Most common on lower slopes are conifer stands composed of balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), white spruce and black spruce (*Picea mariana*). Mixed-wood stands are frequently found on mid slopes. Frequent harvesting in the area has encouraged the growth of red maple (*Acer rubrum*), trembling aspen (*Populus tremuloides*) , bigtooth aspen (*Populus grandidentata*), and paper birch (*Betula papyrifira*). Jack pine (*Pinus banksiana*) frequently occurs on areas with sandy soil, and both red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) are found in hardwood and mixed-wood stands. Other species occurring in the region are white ash (*Fraxinus americana*), eastern white cedar (*Thuja occidentalis*), red oak (*Quercus rubra*) and eastern hemlock (*Tsuga canadensis*).

The heavily glaciated terrain dominated by poor drainage systems and thin, generally nutrient-poor soils of this region are capable of producing complex forest stands with numerous species in the overstory; four or more are common. Vegetation re-growth after disturbance is often quick and vigorous in most of this region.

Data Collection and Processing

Field Data

As part of a software development effort (Appendix I; Franklin et al 2000b) a three-class supervised classification of change areas was produced after two field visits in June 1999 and used to generate a selection of random sample stands to be visited in the field in August 1999. Each area of change in that preliminary map had an equal chance of selection, but during the field sampling areas adjacent to the selected stand which could easily be observed or measured were also included in the sample. A total of 36 stands were sampled in the field during August 1999 by a crew trained in timber and stump cruising techniques. An additional 23 stands were observed, but not surveyed. Often these were 'drive-by' assessments, but each of these stands were placed unambiguously into one of the classes for use as a test data set in an assessment of classification accuracy independent of the training of the classifier.

The first task of the field crew was to identify the type of harvesting or silvicultural treatment by examining the stumps and disturbance pattern (e.g. selection cut of softwood trees from a hardwood stand, or a group selection cut within a hardwood stand, plantation thinning or cleaning, etc.). Some interpretations based on prescription reports from the ownership and the GIS data were necessary; for example, white pine shelterwood cuts typically remove all of the merchantable stems except white pine; usually about 14m2/ha residual basal area remains in such treatment areas. This was interpreted as a severe change on the image, though clearly different from a standard clearcut in this area. Commercial thinning treatments were interpreted as either a moderate or light change; often approximately 30% of the stand basal was removed for these areas, but typically the actual canopy change in these mature stands was not large. Pre-commercial thinning in plantations, however, often resulted in a significant reduction in growing biomass, resulting in a larger spectral difference which could be interpreted as a moderate change. Thinning might range from removal of volunteer fir and hardwood from a conifer plantation (and therefore quite patchy), to a systematic removal of up to one-sixth of the stems in a regular pattern.

Depending on harvesting or silvicultural identification for each stand, one of two field protocols was implemented. The first protocol required the crew to survey a line 200 metres long and two metres wide; all trees and stumps within this area were measured. The stand basal area before (using the trees and the reconstruction of stump diameters) and after (current standing trees) harvesting or silvicultural treatment was calculated. The second protocol was used in areas in plantations; stand volume could be calculated before and after the treatment using stem counts.

Figure 2 shows the initial classification prediction (described in Franklin 2000a,b) of the class of change and the measured basal area removed. Our field measurements of the proportion of basal area removed by harvesting were not particularly well related to the initial classification into three disturbance categories. On average there was no difference in proportion removed between light and moderate disturbance classes primarily because a substantial number of stands were erroneously assigned to the light disturbance category in that preliminary classification procedure. It appears that some predominantly hardwood stands with hardwood removals sustained higher levels of cut than predicted by the initial classification. From this compilation it was determined that the initial classification was not reliable when separating light and moderate change classes although there appeared to be a significant difference in basal area removed in these two classes and in the severe change class. Therefore, the field determination of class for each site was used in the training and classification process.

Landsat TM Digital Image Data

Landsat TM imagery acquired September 6, 1997 was 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. A second scene acquired August 8, 1998, was registered to the UTM NAD27 projection with less than 0.2 pixel RMSE using 24 ground control points at key road intersections dispersed throughout the scene. A cubic convolution resampling algorithm was used to resample both images with an output 25 m grid.

The Landsat TM images were atmospherically corrected using the methods described by Richter (1990) and coded by PCI as part of the EASI/PACE software package. First the ground visibility was determined for each scene. The program then used this estimate of the ground visibility, the type of atmosphere and the aerosol type, together with an average elevation constant, calibration coefficients, image acquisition date and the solar zenith angle, to calculate the reflectance from the image DN values.

Image processing consisted of the TM Tasseled Cap transformation and subsequent image enhancement and classification. The Tasseled Cap transformation creates brightness, greenness and wetness indices, which are linear combinations of TM bands 1 through 5 and band 7 (Crist and Cicone 1984, Crist 1985). Several studies have indicated that differences in these dimensions are highly related to differences in forest canopies caused by harvesting or insect activity (e.g. Cohen et al 1998). Interpretation of the new brightness/greenness/wetness image space can be simplified compared to interpretation of the six original reflectance bands. For example, brightness is a positive linear combination of all six reflective TM bands, and responds primarily to changes in features that reflect strongly in all bands (such as soil reflectance). Greenness contrasts the visible bands with two infrared bands (4 and 5), and is directly related to the amount of green vegetation in the pixel. Wetness is a contrast between bands 5 and 7 (negatively weighted) and the other bands. Wetness is a term that has been applied to this component because of the strong relationship between reflectance in bands 5 and 7 and moisture content of vegetation and soils.

The final image processing step was to convert the brightness/greenness/wetness indices from each of the two dates (1997 and 1998) to a difference image for each component. Simple image subtraction was used because the high degree of confidence in the geometric correction of the imagery enabled a near-perfect overlay of the image data and the minimum area of change of interest was several pixels in size.

Methods

Three basic methods were applied in this paper to understand and illustrate the possibilities of annual change detection with Landsat imagery for the 1997-1998 time period:

1. Visual analysis and interpretation of change imagery;
2. Supervised classification based on maximum likelihood decision-rules;
3. Regression analysis of field and spectral data within each change class.

First, a visual analysis of the image data in areas of change was conducted. Standard image display functions were used to help in image interpretations; the wetness index was the most important single variable in detection and classification of change in the 1992-1997 study (Franklin et al 2000a; see also Cohen et al 1998), and was therefore selected for use in the current presentation of visual image interpretation.

One powerful display option – called the enhanced wetness difference image – was obtained by examining the 1998 wetness index through the blue and green colour guns of the display, and the 1997 wetness index through the red colour gun. The resulting areas of change as a result of harvest treatments – which are much brighter in the 1997 wetness index compared to the 1998 wetness index because of the decreased reflectance in the shortwave infrared bands in the earlier image – appear in this type of display in various shades of red (more change) and pink (less change). If a reduction in wetness – or an increase in shortwave infrared reflectance and a decrease in near infrared reflectance – occurred between the two dates then the image display would show a pink or red colour in that stand. A positive change in wetness – perhaps as a result of increased growth in an older clearcut or plantation – would appear as an increased blue tone in this type of display. All of the imagery in this paper are shown in the standard colour composite and the wetness difference images and have been subjected to a linear enhancement applied to the entire database prior to display.

Second, a supervised classification of the changes was generated using the difference in the Tasseled Cap transformation indices as discriminating variables. The visual analysis of composite imagery and the earlier supervised classification was used to stratify the study area into change and no-change areas. As mentioned, change areas were considered in three categories – light, moderate, severe – but without details on the type of stand (such as dominant species). A random sample of 36 sites of these areas was generated and visited in the field during August 1999. A field crew trained in timber and stump cruise techniques collected the field data – counts of stems and stumps. Based on these field data and field identification of silvicultural treatment (e.g. clearcut, partial cut, plantation thinning, commercial thinning, and so on), each area visited on the ground was categorized into one of nine change classes:

- Changes to a Softwood Stand
  - Light (e.g. plantation cleaning, precommercial thinning)
  - Moderate (e.g. strip cutting, plantation thinning, selection cut, shelterwood cut)

    - Severe (e.g. clearcut, partial cut with residual value, seed tree)
- Changes to a Hardwood Stand
    - Light (e.g. plantation cleaning, precommercial thinning)
    - Moderate (e.g. strip cutting, plantation thinning, group selection cut)
    - Severe (e.g. clearcut, partial cut with residual value, seed tree)
- Changes to a Mixedwood Stand
    - Light (e.g. plantation cleaning, precommercial thinning)
    - Moderate (e.g. strip cutting, release cut, selection cut, group selection cut)
    - Severe (e.g. clearcut, partial cut with residual value, seed tree)

The training data for these classes were compiled by identifying the stand surveyed in the field and extracting the image data for the area of the stand with reference to the image display and the GIS forest stand boundaries. An attempt was made to select only those pixels that coincided with the area surveyed on the ground (e.g. 200m survey line would yield 8 or 9 pixels). Care was taken to keep training areas to a minimum size rather than extract larger areas which might include pixels not treated in the same way as the pixels surveyed on the ground.

Third, the field data and the spectral information extracted from the satellite imagery for the areas surveyed in the field (as closely as could possibly be identified to the pixel level) were subjected to a regression analysis to determine the relationship between the proportion of basal area removed by harvesting and the differences in the 1997 and 1998 Tasseled Cap transformation data.

Results

Visual Analysis of Change Classes

A series of examples comparing the wetness index in 1997 and 1998 is contained in Figures 3-12. In the first part of each example change location (used later in classification training) a normal colour composite extracted from the 1997 TM image (top) and the 1998 TM image (bottom) is shown. In the second part of each figure an 'enhanced wetness difference image' is shown for the exact same example change location. The enhanced wetness difference image display contains the 1997 wetness data displayed through the blue and green colour guns of the monitor and the 1998 wetness data displayed through the red colour gun.

Interpretation, followed by classification, of the colour composites and the different 'shades of red' in these enhanced wetness difference images was used to determine the degree of harvesting that was conducted within the various polygons. For example, 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 since the difference in wetness values between 1997 and 1998 was very high (i.e. high wetness caused by low reflectance in bands 5 and 7 in 1997, low wetness caused by high reflectance in bands 5 and 7 in 1998) This is illustrated in Figure

3a-b for a white pine stand, Figure 4a-b for a hardwood stand, and Figure 9a-b for a mixedwood stand.

In Figure 3a the colour composite shows the typical change in reflectance in a normal colour composite of a white pine stand caused by removal of the canopy. The changes in colour are associated with clearcutting in the long patch in the centre of the image; the patch near the bottom of the image and the patch near the left hand side appear with less disturbed (red) pixels, and with more green, darker pixels. These areas are shelterwood cuts with occasional wildlife patches or legacy patches, and are distinct from the clearcut (Franklin et al in press). In Figure 3b the enhanced wetness difference index shows the different shades of red that correspond to the white pine clearcut area and the two white pine shelterwood cuts. Many more pixels in the shelterwood areas appear in neutral gray or white tones indicating greater residual biomass, and less disturbance or change from 1997 to 1998. The hardwood clearcut and clearcut with seed trees shows a similar pattern in Figure 4a-b.

A hardwood selection cut shows a completely different spectral response in the normal colour composite (Figure 5a) and the enhanced wetness difference index (Figure 5b). A group selection cut attempts to mimic a gap-replacement stand dynamic with small but completely cleared areas linked through undisturbed forest. In this tolerant hardwood (primarily hard maple and yellow birch) example, the small grouped-areas, generally smaller than one or two pixels, are very difficult to interpret in the colour composite, but nevertheless show as a distinct speckle pattern in the enhanced wetness difference image. This pattern is a direct result of the differences in canopy structure in the cleared areas although some residual variation due to the geometric registration may also contribute to the pixel differences from 1997-1998.

A softwood two-pass cut will remove up to 40% of the standing volume with the second pass usually conducted after 10 years. Volume after this first pass will be a minimum of 18m2/ha in the residual stand, often in patches or perhaps strips (if a mechanical harvester was used). In Figure 6a-b a distinctive pattern generated by this treatment is apparent in a white pine stand. The two-pass cut on the right hand side appears less distinct than the area on the left hand side of the main road, which appears to have been a white pine shelterwood/seed tree cut. A large white spruce plantation on the right hand side of the image was thinned in the fall of 1997; note the deeper red tone in the enhanced wetness difference index. Visually, the change in wetness index in the thinned plantation appears greater than the change in wetness index for the softwood two-pass harvesting treatment.

Commercial thinning will typically remove about 30% of the standing volume often leaving the canopy essentially intact; single stems and a few stems in small areas may be removed, but few or no large gaps in the canopy resulting from uneven cutting would be created. In Figure 7a-b, this treatment was applied to a white pine/red pine stand, and the resulting image patterns in the colour composite and the enhanced wetness difference image appear distinctly different from patterns generated by clearcutting, shelterwood, and hardwood selection cutting. The change in wetness index for the commercial thinning areas may be similar to the change in wetness index in the area of the plantation thinning and also in the area of the two-pass softwood cut. Averaged over a larger area, the change in wetness might resemble that of the hardwood group selection cut, although the spatial patterns would remain distinct. However, it is interesting to note that the thinned area within the larger clearcut (Figure 8a-b) can be seen as a distinct level of change different from the surrounding clearcut, much more similar to the other, larger commercial thinning shown in Figure 7a-b.

A hardwood strip cut colour composite and enhanced wetness index difference is shown in Figure 10a-b. This area was harvested mechanically, with 100% of the volume removed in 25 metre wide strips separated by narrow undisturbed areas, perhaps 10 metre wide. The strips were angled away from the road but appeared unevenly cut with heavy disturbance to the understory. On the imagery this resulted in a greater change of wetness between 1997 and 1998 than in the softwood strip cut (see Figure 11a-b). Here a black spruce stand was treated but with an average of 35% of the volume removed. The undisturbed areas between the strips were wider than in the hardwood strip cut example.

Figure 12a-b contains a clear example of the detectability of change on the 1997-1998 Landsat image data obtained over a 12 year old red pine plantation which was (pre-commercial) thinned and cleaned (removal of volunteer fir and hardwoods) just prior to the 1998 image acquisition. The cuttings were left on site. The resulting differences in wetness between 1997 and 1998 are significant and can be visually interpreted, even though the actual amount of cutting appeared during the site visit to be quite small.

The interpretation and field data enabled the logical grouping of the different types of harvesting and silvicultural treatments into a nine-class classification scheme within the earlier three mutually exclusive, exhaustive classes (light, moderate and severe). The first level of change that could be detected in the imagery visually included the plantation (pre-commercial) thinning and cleanings, and commercial thinnings; these were grouped into a light disturbance class (Figure 7, 8, 12). A second level of change, called a moderate disturbance class (Figure 5, 6, 10, 11) included the group selection cuts, some heavy thinnings, strip cuts and some light shelterwood cuts. A final class, called severe disturbance, was comprised of the clearcuts, heavy shelterwood cuts, and seed tree cuts (Figure 3, 4, 9). Each of these disturbance categories could be assigned a forest type based on the dominant species thereby creating the nine-class scheme organized by softwood, hardwood and mixedwood stand types.

In the earlier paper (Franklin et al in press) we examined the brightness/greenness/wetness differences between clearcuts and partial cuts between 1992 and 1997 and found that the differences were sometimes reduced by regrowth in the affected areas over that five year period. However, the image differences were used to drive a successful classification of partial cuts and clearcuts on the five-year (1992-97) interval imagery. Since the image differences between 1997 and 1998 are greater and more consistent from one type of change to another, this approach can be used to generate classification products that can show greater detail in the class structure than was possible in the earlier work.

Supervised Classification of Change Classes

Table 1 contains the signature separability statistics for the training areas for the eight classes surveyed in the field and visually interpreted in the colour enhancements. Note that these training areas were the result of the preliminary classification verified in the field and reorganized into the nine-class scheme based on forest type. Average separability is good (1.88) and indicates that overall the nine classes spectral differences based on the field sites appear distinct. The lowest B-distance was obtained in the mixedwood light and moderate classes (1.32); these two were subsequently merged into a single mixedwood light/moderate class for the classification process. Separability between the mixedwood light class and the mixedwood severe class was also not high (1.73) but this categorization was retained in the analysis with the expectation that perhaps a single mixedwood change class could be classified and mapped in the study area.

Separability, as measured by the B-distance statistica, was reasonably high among and between the hardwood and softwood change classes. However, separability was not high between mixedwood severe and softwood severe change classes (1.47); this result could be expected given the similar natural variability in such stands originally softwood or mixedwood following treatment such as seed tree cutting and clearcutting. Separability was also not high between softwood moderate and mixedwood severe (1.60) presumably because of the natural similarity in stand composition before and after treatment.
In general, the final supervised classification map was found to correspond very well with the known distribution of changes in the various ownership files (crown land, freehold, private woodlots). Using the 23 'drive-by' stand assessments as a guide, there were not any errors in classification; that is, each of these stands were unambigously confirmed by the classifier as a member of the class that they originated from based on the field assessment. This sample is small and biased, however, there were no errors of omission, leading to a producer's accuracy of 100%. Based on this limited sample, no areas of change observed in the field were not mapped by the procedure described in this paper.

Regression Analysis of Proportional Change

Figure 13 contains three graphs showing simple linear relationships between changes in reflectance and changes in basal area. Coefficients of linear equations are given in Table 2. Harvesting reduced wetness and increased brightness but had little effect on greenness. There was no change in wetness when approximately 45% or less of the initial basal area was removed as can be seen in Figure 13a, and from the intercept of the linear relation (Table 2). This limits the utility of wetness as an indicator of change due to partial harvest. A linear change in brightness over the entire range of change due to harvesting (Figure 13) gives brightness an advantage over wetness as a predictor of proportional cut. However, conditional variance was greater for the equation using change in brightness than for the equation using change in wetness. Moreover, there were decreases in brightness at low levels of change and increases in brightness at high levels of change, and that requires some explanation before using changes in brightness to predict change in basal area.

Changes in reflectance were significantly related to proportional removal of basal area for TM bands 1, 2, 3, 5 and 7, but not for band 4 (graphs not shown; Table 2). Values of the y-intercept were greater than 0.25 (meaning more than 25 % of initial basal area removed at x=0) for bands 3, 5 and 7, limiting their utility for predicting proportional cut. The y-intercept for the equation using change in band 2, was not significantly different from zero, and a linear relation existed over the entire range of proportional cut, but the change in reflectance varied only from 5 to 16. This comparatively small change in reflectance due to harvesting for band 2 may limit its value for predicting proportional cut.

There was a high level of correlation (r=0.92) between Δbrightness and ΔTM2, so there would be no gain from using both to predict proportional cut in a multivariate regression. No trend exsited when residuals were plotted against initial basal area. However, when residuals were plotted against final basal area a tendency existed to underestimate cut with small residual basal area and overestimate cut with larger residual basal areas. This result suggests that using additional information from the later image might improve prediction of proportional cut. Unfortunately, none of the TM bands from the 1998 image were sufficiently correlated to final basal area to be useful as predictive variables. Multilinear regression using Δbrightness and Δwetness in combination with final basal area produced much more precise predictions than corresponding simple regressions (Table 2). Standard errors of estimate were 0.12 – 0.13 for the multilinear regression equations. Note that inclusion of interaction terms did not improve regression statistics.

Conclusion

In this paper examples of forest changes detected on 1997 and 1998 Landsat TM images of the Fundy Model Forest are illustrated and interpreted to reveal the level of detail that can be expected in annual change detection procedures. These examples are shown in colour composites and an enhanced wetness index difference which was used to interpret and confirm the field grouping of the detected changes into three classes (light, moderate, severe change) each within three covertypes (softwood, hardwood, mixedwood). These classes were mapped using standard supervised classification with 100% producer's accuracy (based on a small, limited test sample) following generation of reasonably high B-distance separability measures (average separability was 1.88) with the Tasseled Cap transformation of two Landsat Thematic Mapper images. Proportional change in stand basal area was regressed on the change in spectral response measured in each stand; reasonable levels of correlation (e.g. R-square of .67) were found. These results may lead to a procedure to classify changes annually and estimate the degree of disturbance within each change class.

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List of Tables and Figures

Table 1. Signature separability (B-distance) for nine classes of change based on training data.

Average Separability: 1.88168
Minimum Separability: 1.32552
Maximum Separability: 2.00000

Separability Matrix:

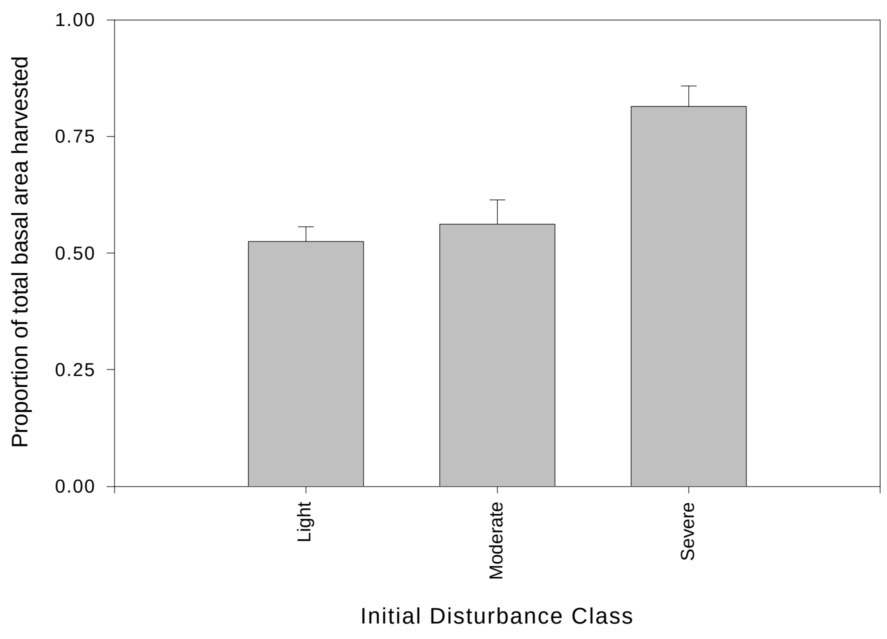
	1	2	3	4	5	6	7	8
2	1.98797							
3	1.98443	1.95770						
4	1.99823	1.99999	2.00000					
5	1.99998	2.00000	1.99998	1.70761				
6	1.99983	1.99998	1.99764	1.99192	1.85837			
7	1.94350	1.99899	1.99862	1.80229	1.66158	1.97011		
8	1.58742	1.76971	1.83083	1.76551	1.60542	1.73848	1.32552	
9	1.99984	1.99997	1.90815	1.99992	1.99190	1.47354	1.99683	1.88862

Note: Change to hardwood class 1,2,3 (light, moderate, severe); Change to softwood class 4,5,6 (light, moderate, severe); Change to mixedwood class 7,8,9 (light, moderate, severe)

Table 2. Regression equations predicting stand basal area change using spectral response in 36 stands surveyed in the field in August 1999.

Equation for predicting proportional change	R^2
0.451 – 0.00967 x Δwetness	0.58
0.574 + 0.0159 x Δbrightness	0.47
0.335 + 0.017 x Δband7	0.58
0.351 + 0.00833 x Δband5	0.58
0.272 + 0.0212 x Δband3	0.53
0.060 + 0.0608 x Δband2	0.51
-0.123 + 0.0349 x Δband1	0.36
0.577 - 0.00831 x Δwetness – 0.00555 x finalba	0.67
0.699 + 0.0136 x Δbrightness –0.00681 x finalba	0.64

Figure 2. Initial classification of three change classes and field measurement of basal area removed.



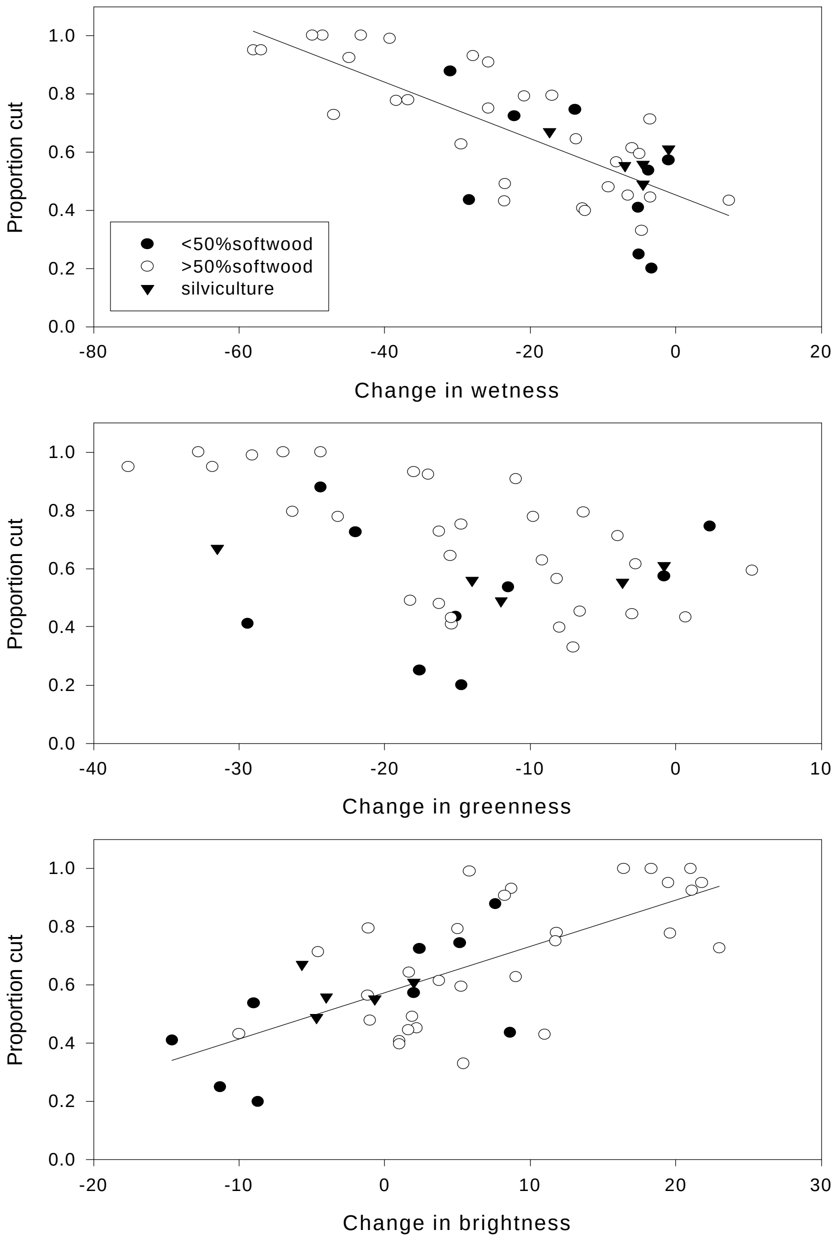


Figure 13. Change in Tassled Cap Transformation Indices and proportional change in basal area measured in the field.

Appendix I: An AML Polygon Update Program (PUP)

There is a long-standing need to simplify and automate the task of forest inventory database updating in an accurate and timely manner (Lowell and Edwards 1996). Attributes in a forest inventory GIS, such as species composition or age class, may change for a wide variety of reasons and at different spatial and temporal scales. An important but difficult task is to keep these attributes current while maintaining accuracy, but accuracy may be compromised by methods traditionally used to update changes in the database (for example, when changes to thousands of polygons are made manually). More commonly, the entire attribute database is 'replaced' periodically rather than attempt to 'update' the inventory. Satellite remote sensing has been shown to be a promising technology upon which future GIS updates may be based (Singh 1989, Olsson 1994, Muchoney and Haack 1994, Sader 1995, Varjo 1996, Royle and Lathrop 1997, Hame et al 1998, Cohen et al 1998).

Wulder (1998) developed the 'polygon decomposition' approach to integrating satellite remote sensing data within a forestry GIS. The basic idea is that satellite remote sensing image pixels located within forest inventory polygons can be used to analyze within-polygon variability. Such internal variability can be important in a number of ways, for example, in the calculation of leaf area index (LAI) from satellite reflectance. The polygonal data can be used to guide the selection of LAI equations based on species composition or forest type. The resulting LAI estimates provide higher accuracy and less uncertainty (i.e. greater confidence) (Franklin et al 1997).

Polygon decomposition can also be considered a foundation for polygon update since the core analysis technique is to determine the relationship between the pixels and the polygons in the two different information sources. The code developed in the LAI polygon decomposition application (Wulder 1998) was not written to specification and was based on three separate software programs and two operating systems. Therefore, a 'user-friendly' approach to polygon decomposition that would have wider applicability was developed and is described in this paper.

A computer program, called the polygon update program (PUP), was written in ArcInfo Macro Language (AML) to facilitate the integration of satellite image classifications of landscape change into a GIS-based forest inventory. The code accepts user-defined attributes and retains a unique polygon identifier, *polyid*, as a variable while converting the vector GIS files to overlay the satellite image in a common grid format. Image classification data are read in and a rule-base is invoked to determine the correspondence between the attributes of the gridded-polygons in the GIS and in the image classification. The program summarizes changes within polygons according to the previously-documented logic of polygon decomposition. A flag can be written to an attribute table to indicate the amount of change detected (i.e. the number of pixels in the change classes of the image classification with that *polyid* in the GIS grid format). A graphical user interface is provided. An example is provided to illustrate the polygon update for forest inventory; the update is summarized by *polyid*, species codes, and area of each forest stand for which changes were detected in three classes (light, moderate, severe). The work was performed on a IBM Pentium II running the NT 4.0 operating system and, with a few file name changes, tested successfully on a Sun workstation under Solaris 2.0.

Software Design

The ArcInfo Macro Language (AML) is a relatively powerful low-level programming language that has the obvious attraction of 1) widespread acceptance and 2) availability among the forestry-GIS community, two key software design criteria for the current programming effort. Therefore, AML was selected as the programming language for the update software. The original programming concept was simple for this project:

> *Develop an AML tool to accept the results of image classification, examine those results with reference to the existing GIS database polygon descriptions, and update the attribute table with flags that would correspond to summary compilations of the percentage area changed within each polygon.*

The process first attempts to place all files on a regular grid using the georeferencing information supplied with each file, but retaining the polygon identifiers and a classification system that is user-supplied. This user-defined system must match that used in the classification of the remotely-sensed data; for example, if species composition were used to generate GIS classes, the species composition in each polygon must be converted to a class variable that matches the classes used in the remote sensing product. In the examples shown here, the GIS variable L1S1 (dominant canopy species expressed in the GIS as Layer 1, Species 1) was used to provide the GIS class structure. Additional classes, such as change classes obtained by remote sensing methods, can then be used uniquely to update these GIS classes. The class variable must be kept simple in order to match the kind of change classes that can be mapped using existing satellite remote sensing systems such as Landsat; in future, as satellite sensors improve and more digital aerial systems are deployed in forestry applications, perhaps more complex classification systems that more closely match the ecological communities on the ground could be used.

In Figure 1 the code logic is presented. The program begins with a sequence of remote calls requesting the names of the files to be used:

1. an ArcInfo coverage (with attribute table), and

2. a remotely-sensed image classification (with or without the original bands and other channels of data).

The ArcInfo coverage is converted to GRID format (an ArcInfo raster-based program), and the image data (in this case, in PCI Easi/Pace .pix format, but could be any supported raster image structure) are imported into a standard GRID format. As mentioned, the classified image and the ArcInfo vector files must be geometrically corrected (a previous task) and must carry the required georeferencing information. These two selected files are combined into a variable called *layer1*. The GRID-converted ArcInfo file maintains three columns of information in each record (i.e. each pixel or raster location); the first column is the record number, the second column is the count (quantity), and the third column is the selected attribute. In the first instance, this selected attribute will be the *polyid* in order to maintain a link to the original vector file and attribute table throughout the procedure. The ArcInfo file is actually converted twice, once with *polyid* as the selected attribute, and the second time with a user-defined attribute.

The program now uses the converted images to build the second layer for analysis (variable *layer2*). This layer contains the data for the classified image and the polygon id's. The algorithm compares the two layers (*layer1* minus *layer2*) and identifies areas that are different based on the occurrence of different user-selected attribute values (i.e. classes). A grid location with *NODATA* in either layer is ignored. If the user-selected attribute value is not changed (i.e. *layer1 - layer2* = 0) the variable *areax* is assigned a 0 value and the next grid location (pixel or record) is examined. If the user-selected attribute value is changed (i.e. layer1 > or < layer2) then *areax* is assigned a positive value equal to the change in class that has been detected. For example, if the spruce-dominant class 6 mentioned above has been changed to a partially-harvested spruce stand (given a different class in the classification system, say class 2), then *areax* would be assigned a value of 4. Since each grid location is geometrically corrected and registered to each other, location is not tracked as the program traverses from pixel to pixel (or record to record). The variable *layer3* contains the change results on a pixel by pixel (or record by record) basis.

The next step in the program is to examine the polygon changes by interpreting *layer3*. Using *polyid* as a guide, the program summarizes the results contained in the variable *areax* with the following equation:

(changed polygon pixel count / original polygon pixel count) * 100

The result is the percent of change that has occurred in that polygon based on the total number of pixels with that *polyid*. For example, if *polyid* 44 originally had 100 pixels of class 3 (spruce), and in the remote sensing image classification 50 of these pixels were classified as a clearcut class (say, class 199) and 20 of the original 100 pixels were classified as a partial harvest class (say, class 56), the result of this *areax* in *layer3* polygon summary would show a 70 percent change. At this point it would not be clear which remote sensing classes were involved in the detected changes, only that the polygon experienced a 70% change in area. The individual details for the class breakdown appear in a final report (a file called *layer3.txt*).

An additional feature of the program is to summarize the characteristics of the changes detected within polygons with reference to data from the specified bands in the remote sensing image. These data are compiled using *ZONALSTATS* which is a call subroutine within the ArcInfo GRID package; essentially this subroutine uses *layer3* as a mask and computes variables under the mask. The general statistics (mean, std. dev., max, min) are based on specified zones or polygons (in this case, corresponding to *layer3*) but the data for these regions are extracted from either the original imagery or the classified image. The results of each statistical summary for each specified data source are written to separate files with the following naming convention *(channel1.txt, channel2.txt,…)*. The original reflectance values could be examined, rather than a class summary of change. Alternatively, if an NDVI variable was computed and used in the image classification then changes in NDVI could be examined within the class changes that were detected for that *polyid*.

The final sections of the PUP code are purely graphical and were designed to allow the user to view the data graphically. For example, in addition to the reported statistics, the user may want to view the spatially-explicit changes in the data by *polyid* or across the entire image data set. And finally, the program supports individual pixel queries (using standard ArcInfo remote calls).

Example Application in Forest Inventory Updating

A test of the PUP code was conducted in the Fundy Model Forest (FMF), located on the north shore of the Bay of Fundy, New Brunswick, Canada. The Fundy Model Forest is a 420000 hectare working forest with several towns and villages, industrial freehold land (J.D. Irving, 17%), Crown Land (15%), Fundy National Park (5%) and many small private wood lots accounting for approximately 63% of the land base. Approximately 243723 ha, including all of Fundy National Park, of this area was cloud free in the two satellite images available and is the subject of this communication.

Upper slopes and ridges are mostly occupied by northern tolerant hardwoods, such as sugar maple (*Acer sacharum*), yellow birch (*Betula alleghaniensis*) and beech (*Farus grandifola*). Most common on lower slopes are conifer stands composed of balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), white spruce and black spruce (*Picea mariana*). Mixed-wood stands are frequently found on mid slopes. Frequent harvesting in the area has encouraged the growth of red maple (*Acer rubrum*), trembling aspen (*Populus tremuloides*), bigtooth aspen (*Populus grandidentata*), and paper birch (*Betula papyrifira*). Jack pine (*Pinus banksiana*) frequently occurs on areas with sandy soil, and both red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) are found in hardwood and mixed-wood stands. Other species occurring in the region are white ash (*Fraxinus americana*), eastern white cedar (*Thuja occidentalis*), red oak (*Quercus rubra*) and eastern hemlock (*Tsuga canadensis*).

The heavily glaciated terrain dominated by poor drainage systems and thin, generally nutrient-poor soils of this region are capable of producing complex forest stands with numerous species in the overstory; four or more are common. Vegetation re-growth after disturbance is often quick and vigorous in most of this region.

Remote Sensing and Geographic Information System (GIS) Data

Since the early 1990's information from all land users in the FMF has been integrated into a GIS data archive. The inventory was conducted in the 1990's based on the standard aerial photointerpretation systems then in place (Gillis and Leckie 1996). Attributes associated with each polygon included estimates of species percent (to the nearest 10 percent), stand age in categories (mature, old growth, young), crown closure (to the nearest 20 percent) and condition or treatment, among many others.

A Landsat TM image acquired September 6, 1997 was geometrically registered to the UTM NAD27 projection with 40 GCPs at key road intersections dispersed throughout the scene. Less than 0.5 pixel RMSE was obtained. A second scene acquired August 8, 1998, was registered to the UTM NAD27 with less than 0.2 pixel RMSE using 24 ground control points, again at key road intersections dispersed throughout the scene. A cubic convolution resampling algorithm was used for both images to determine pixel values in a 25 m grid. An illumination correction was applied during the atmospheric correction of each image. The methods described by Richter (1990) and coded by PCI as part of the EASI/PACE software package were used. First the ground visibility was determined for each scene. The program then used this estimate of the ground visibility, the type of atmosphere and the aerosol type, together with an average elevation constant, calibration coefficients, image acquisition date and the solar zenith angle, to calculate the reflectance from the image DN values.

Image Processing and Classification

Image processing consisted of a simple transformation of the image data using the TM Tasseled Cap transformation (Crist and Cicone 1984, Crist 1985). The resulting 1997 and 1998 brightness, greenness and wetness indices, which are linear combinations of TM bands 1 through 5 and band 7, were used to create a difference image for each component. Simple image subtraction was used because the high degree of confidence in the geometric correction of the imagery enabled a near-perfect overlay of the image data and the minimum area of change of interest was several pixels in size. Three difference images were used in a supervised classification based on the maximum likelihood decision rule. The training data for classes were compiled from areas identified in each of the different land ownership types (crown land, freehold, private woodlots) and visited in the field during August 1999.

Treatment types were used to organize the training data into nine distinct classes of change, recoded into three categories of change: light, moderate and severe. Each candidate training area identified through the treatment records on each ownership type was checked visually in the field to ascertain quantitatively (i.e. change, no change) and qualitatively the condition of the stand before and after treatment and the usefulness of the stand for training the classifier. A field program was designed to collect quantitative site specific information in these training areas (for example, before treatment stand volume by stump cruising techniques), and in other areas not used for training, across the full range of change in the area independent of the image data.

Results

The quantitative survey of 36 sites did not reveal any locations of change in the image that were not also locations of change on the ground. This survey showed a zero error of omission in this classification and, consequently, a 100 per cent correct producer's accuracy assessment. The detailed analysis of the quantitative field data is the subject of a companion communication (Franklin et al, submitted to CJRS). Here we report on the success of the classification products as input to the newly written PUP GIS update procedure. For simplicity of presentation, the remote sensing change classes were recoded into three codes: 199 (severe change), 111 (moderate change) and 56 (light change).

The second part of Figure 2 shows the corresponding portion of the GIS inventory converted to a grid but retaining the dominant species as a class variable to be compared to the remote sensing image classification. In this example, the GIS attribute L1S1 (codes in the species items of the FOREST (poly) layer of the NBLIB library) has been converted according to the system shown in Table 1. A different classification, perhaps including more of the species codes from different layers in the canopy (L1S1 to L1S5, L2S1 to L2S5), or the codes in the species development stage (L1DS1 to L1DS5, L2DS1 to L2DS5), or some other combination, could be used in a more complex change detection exercise.

Tables 2, 3 and 4 contain portions of the main output obtained by the comparison of the classification in the top part of Figure 2 with the polygon attributes in the bottom part of Figure 2 using PUP. Table 2 provides an example listing of changes by *polyid*. Each polygon for which change class pixels exist is summarized by the total number of pixels and the number of pixels in the change classes with that *polyid*. For example, in one polygon with an polyid of 5691, both light (code 56) and severe (code 199) changes were found. The total area of the polygon was 144 pixels; of these, 41 were found in the light change class (21%) and 15 were found in the severe chance class (10%). The original species code for this stand was 16 (PO). Another example is the red maple stand with polyid 10717; of the original 10 pixels in this stand, two were classed as light change (20%) and one was classed as severe change (10%).

Table 3 provides additional information on the characteristics of the reflectance measured in an example change polygon. Only the change pixels for locations listed in Table 2 are examined in Table 3. One balsam fir stand with polygon number 52496 can be interpreted with reference to the maximum and minimum reflectance values and other statistics that might be useful in considering the type and accuracy of the changes that have been detected in this polygon. It is important to note that the change statistics are computed as a proportion of the pixels within the changed stands; areas that have not changed are not included in the analysis since this is a relatively simple GIS operation that could be accomplished independently of the PUP process.

Table 4 contains an example 'roll-up' summary of the changes in this run of the software. The number of stands in each type of change class by species can be totaled by pixel and by area. For example, 424 balsam fir stands were found with changes detected by the remote sensing classification procedure. In these stands some 76882 pixels were found to have changed in roughly equal proportions in the light, moderate and severe change classes. Another type of stand – eastern hemlock – is much smaller in number of stands (only 3) and changes to those stands (approximately 3 ha). Thirty-two tolerant hardwood stands were found to have changed; of these, the majority were light or moderate changes, although the largest area of change was found in the severe class (1055 of 5294 pixels, or approx. 90 ha).

The grand total shown in Table 4 indicates that 2204 stands comprised of all species types were found to have changed between 1997 and 1998 in the satellite image classification. Of the total number of pixels in those stands (an area of approximately 26839 ha), approximately 13% or 3561 ha) represent changes in the light, moderate or severe classes. This percentage of change within stands that have been treated represents a very small percentage of the total area of the image analysis; this 13% of the area in changed stands represents approximately 1.46% of the total land area studied (243723 ha).

Conclusion

A new tool for resource managers – called the polygon update program (PUP) – was written in ArcInfo Macro Language (AML) to facilitate the integration of the remotely-sensed classifications of landscape change into a forest inventory GIS database in New Brunswick. The program requires a georegistered data set comprised of image classification data and an ArcInfo coverage. The program compares user-defined attributes with a unique polygon identifier, *polyid*, to classification data. The program summarizes change class pixels found within polygons. A flag is written to an attribute table to indicate the amount of change detected (i.e. the number of pixels in the change classes of the image classification compared to the total number of pixels in that polygon). Some options to analyze the reflectance characteristics of the detected changes are provided.

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List of Tables and Figures in the Appendix

Table 1. Portion of the GIS Species Code Classification and Change Classes

Species	L1S1 Code	Class
Balsam fir	BF	1
White Birch	BI	2
Black spruce	BS	2
Dead fir	DF	6
Eastern Hemlock	EH	7
Hardwood	HW	9
Intolerant Hardwood	IH	10
Jack pine	JP	11
Red maple	RM	17
Red pine	RP	18
Sugar maple	SM	20
Spruce	SP	21
White Spruce	SW	22
Tolerant Hardwood	TH	23
White Pine	WP	25
.		
.		
.		
Light Change	L	56
Moderate Change	M	111
Severe Change	S	199
.		
.		
.		

Table 2. Portion of the Output Polygon Update Showing Changed Pixels

POLYGON ID	ORIGINAL PIXELS	CHANGE PIXELS	ORIGINAL L1S1*	REMOTE SENSING CLASS	PERCENT CHANGE
3,983	59	33	16	199	55
4,145	149	13	24	111	8
4,391	119	33	17	56	27
4,706	61	49	21	56	80
4,846	243	62	21	199	25
4,931	8	8	21	56	100
4,934	73	73	21	56	100
5,214	162	29	2	199	17
5,470	188	42	9	111	22
5,545	4	4	22	111	100
5,601	82	18	17	56	21
5,691	144	41	16	56	28
5,691	144	15	16	199	10
7,011	115	19	1	199	16
8,973	260	6	1	56	2
8,974	46	6	1	199	13
9,907	105	13	21	199	12
9,909	26	18	11	199	69
9,917	101	93	10	56	92
9,921	141	30	2	56	21
10,717	10	2	17	56	20
10,717	10	1	17	199	10
11,529	134	7	9	56	5
11,529	134	6	9	111	4
15,829	351	24	10	199	6
15,976	169	82	10	56	48
15,989	244	12	10	199	4
16,297	21	11	10	56	52
16,622	53	7	11	56	13
17,110	9	9	2	56	100
17,111	3	3	2	56	100
17,188	56	20	2	56	35
17,219	34	34	2	56	100
34,212	205	69	20	111	33
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.

(*original LIS1 codes in Table 1)

Table 3. Portion of the Output Polygon Update Showing Statistical Summaries

POLYGON ID	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	MAJR	MINR
52,444	102	91,800.0	3	7	4	3.7745	0.6988	4	6	4
52,473	31	27,900.0	3	5	2	3.8710	0.8325	3	4	4
52,484	3	2,700.0	4	5	1	4.6667	0.4714	5	4	5
52,494	5	4,500.0	4	8	4	5.4000	1.3565	5	4	5
52,496	13	11,700.0	5	10	5	6.0000	1.4676	5	7	5
52,498	1	900.0	4	4	0	4.0000	0.0000	4	4	4
52,514	10	9,000.0	3	6	3	4.1000	1.1358	3	5	4
.	.	.	.	.	.	.	.	.	.	.
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Table 4. Example of the Output Polygon Update Showing Changed Pixels by Species Codes and Area

SPECIES	NUMBER OF STANDS	ORIGINAL PIXELS	CHANGE PIXELS	REMOTE SENSING CLASS
Balsam Fir (Species Code 1)				
	157	34444	1965	56 (L)
	227	17812	1230	111 (M)
	153	24626	1551	199 (S)
Subtotal				
	424	76882	4742 (431 ha)	
Black Spruce (Species Code 3)				
	55	6252	1177	56 (L)
	30	2770	333	111(M)
	65	8898	1468	199(S)
Subtotal				
	150	17920	2978 (270 ha)	
Eastern Hemlock (Species Code 7)				
	2	52	2	56(L)
	1	280	34	199 (S)
Subtotal				
	3	332	36 (3 ha)	
Tolerant Hardwood (Species Code 23)				
	11	1317	405	56 (L)
	14	952	101	111(M)
	7	5294	1055	199(S)
Subtotal				
	32	7563	1561 (142 ha)	
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SUBTOTAL ALL SPECIES				
	977	123190	21483 (1953 ha)	56(L)
	517	73110	6939 (630 ha)	111(M)
	709	99528	10761 (978 ha)	199(S)
Grand Total				
	2204	295828	39183 (3561 ha, approx. 13% of the area of stands with change)	