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Remote Sensing Change Detection of Partial Harvest Stands in the Fundy Model Forest

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Executive Summary

This report describes a collaborative project, with participation from the Fundy Model Forest, the University of Calgary, the Canadian Forest Service, the University of Lethbridge, and Parks Canada, to document and apply satellite remote sensing methods in forest change detection in the New Brunswick Fundy Model Forest to support a new monitoring approach that can be applied annually to update a GIS forest inventory database, and which can provide consistent and reliable accuracies in classification of a wide range of landscape conditions. The broad objectives were to:

1. Test and describe a remote sensing change detection method which can provide acceptable classification accuracies across forest stands and treatments;

2. Develop a simple software tool to facilitate remote sensing/GIS integration, and;

3. Test the use of physical models in understanding the changes in reflectance observed in different stands.

In Section I of this report, forest canopy change caused by partial harvesting is detected and classified using multitemporal Landsat Thematic Mapper imagery acquired in 1992 and 1997. A software tool to update GIS polygons through the attribute tables associated with the forest inventory layer has been developed and is discussed in Section II of this report. The original code and some of the screens and menus are reproduced in two Appendices. An experiment to model the TM pixels to describe the conditions that cause reflectance values in partial harvest stands is described using a physically-based geometric-optical model in Section III. The resulting lookup tables in graphical form, together with the full set of change detection polygons and image data used in this study are included as Appendices.

The Landsat TM image data were corrected to reflectance, and geometrically registered to the UTM grid (separately), to each other, and then to the existing forest inventory GIS database. Fifty stands that were originally typed as spruce, fir, pine, tolerant hardwood, intolerant hardwood and mixedwood were selected and sorted by year of partial harvesting treatment. Visual analysis of the colour composite imagery and brightness/greenness/wetness indices together with NDVI and principle components analysis showed the expected pattern of increased brightness, decreased greenness and decreased wetness in most areas of disturbance. The change information was concentrated in one or two of the three principle components retained in the analysis. Areas of interpretation difficulty were resolved with reference to field observations on the amount of vegetation removed during the harvest treatment, and the condition of the understory. A comparison between reflectance observed by the Landsat TM sensor in 1992 and that observed in 1997 revealed the likelihood of successful change detection. Comparisons to undisturbed and clearcut areas were made to show the differences in reflectance that were related to partial harvesting, clearcut and undisturbed conditions. Absolute reflectance differences were significant in the disturbed areas compared to the natural range of variability found in undisturbed forest. The largest differences were recorded in the wetness variable, but brightness and greenness differences were also present in most stands.

A classification hierarchy which included clearcuts and partial harvest stands was devised to test the potential of Landsat TM imagery in an automated GIS update procedure. Clearcuts were mapped with 71% accuracy between 1992 and 1997 using a per-pixel method. The accuracy with which partial harvest stands could be classified using a discriminant function decision rule approached 55% over all the classes, although confusion in the original stand typing of black and white spruce classes may be responsible for much of the error in the final classification. In future work a single spruce class could be used to reduce this source of confusion. Individual stand classification, using the mean brightness/greenness/wetness values in 1992 and 1997 for each polygon in the GIS identified with a partial harvesting treatment, approached 71% accuracy for the complete sample of partial harvests.

The polygon update program (PUP) written in ArcInfo Macro Language (AML) is described to facilitate the integration of the remotely-sensed classifications of landscape change into a forest inventory GIS database in New Brunswick. The code accepts user-defined attributes and retains a unique polygon identifier, *polyid*, as a variable. The image classification data were read in and an overlay procedure was used to determine the correspondence between the attributes of the polygon 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 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) within that polygon boundary. A graphical user interface is provided. In this report, an application of this new code is demonstrated with the detection and update of forest polygons for clearcut and partial harvesting activity in the five-year period with an unsupervised Landsat Thematic Mapper image classification.

Physical models of forest stands provide a powerful image processing tool for the extraction of forest structural information from remote sensing imagery. These models provide the critical linkage between the satellite or airborne image spectral data and the dimension, geometry, composition and density of forest canopies and stands. In this study, we applied these models to the problem of forest change detection of the partially harvested stands. We developed a modified approach to using these models in *"multiple forward mode"* to produce extensive look-up tables of forest structural inputs and their corresponding satellite image spectral response. These digital look-up tables (included in graphical form in Appendix III) were produced for 1992 and 1997 Landsat TM imagery, and sets of quantitative forest structural information were derived for each date. The physical information derived for each date was then compared to provide a quantitative, physical basis to forest change detection.

Model results had a good level of correspondence with independent forest inventory and ground-based plot information, thus providing a mechanism for quantifying both absolute and relative forest structural change. In contrast to the previous remote sensing change detection approach (i.e. using a statistical classifier in a purely empirical framework described in Section I) we have instead provided a physical-structural basis to the analysis. This is potentially of greater and more direct interest to forest managers and forest inventory monitoring needs because the method is less dependent on a statistical summary of change conditions; i.e. the models work with the physical properties of reflectance and the structural changes that can be documented readily (such as stem density before and after treatment) in the partial harvest stands. These methods provide a significant area for future investigation, both in terms of site-specific forest structural information extraction, as well as in the ability to build a longer term forest information resource in the form of easily accessible spectral-structural digital libraries.

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I. Change Detection Using Multitemporal Landsat TM Imagery

Introduction

Monitoring and reporting environmental change in forests is an important information need identified as part of the "*Criteria and Indicators of Sustainable Forest Management*" by the Canadian Council of Forest Ministers (1997). Several local level 'indicator' committees or working groups across Canada have been developing local lists of such indicator elements to be monitored (see Local Level Indicators Working Group 1997, Manitoba Natural Resources 1997, Dempster 1998, McGregor Model Forest 1997). A few generic examples of ecological indicators, among many provided by Goodenough et al (1998) and Hall (1998), would include indicator products listed as the '*area and severity of insect attack*', '*percent canopy cover*', and '*area of forest depletion*'. These information needs require a monitoring and reporting system with a clear scientific base in the use of satellite remote sensing technology.

Numerous studies have shown that the detection of change in forest cover (Cohen et al 1998) and forest canopies (Collins and Woodcock 1996) is possible using Landsat Thematic Mapper imagery (see also Wickware and Howarth 1981, Singh 1989, Muchoney and Haack 1994, Sader 1995, Varjo 1996, Royle and Lathrop 1997, Hame et al 1998, among many others). In general, the methods of change detection should be tailored or suited to the particular type of change that has occurred in the landscape, and might range from simple digital number (DN) matching (Franklin et al 1995) and classification (Franklin and Wilson 1991) to more complex reflectance modelling (Olsson 1994, Adams et al 1995) and area-based analyses (Wulder 1998). In the detection of forest mortality caused by insects, Collins and Woodcock (1996) have suggested that there is strong evidence to support the use of simple DN matching methods; the logic for this approach is based on the fact that single-date TM data are found to be dispersed mainly in three-dimensional brightness/greenness/wetness space, and that measurements of differences in these quantities over time can be a good indicator of vegetation change. Their work suggests that a successful forest canopy change detection methodology requires radiometric correction, and knowledge of the types of changes that are to be detected and their subsequent (expected) spectral response or reflectance patterns.

In many forests, accurate, timely and cost effective knowledge of partial harvesting is essential to the goals of sustainable forest management. Removal of part of the canopy is likely to increase reflectance in the red portion of the spectrum in the short term. Green reflectance will typically decrease following disturbance, but the understory may contribute to an inverse or direct pattern depending on many factors, including the original stand density. Such structural changes to forest canopies are likely to decrease reflectance in the infrared and shortwave infrared portion of the spectrum in a complex manner. In general, one reasonably consistent finding in the various mortality studies (Collins and Woodcock 1996, Franklin et al 1995) and in clearcut mapping (Cohen et al 1998) is that shorter wavelength reflectance tends to increase and longer wavelength reflectance tends to decrease with decreasing amounts of vegetation. There may be less water absorption, and greater shadow fraction following disturbance. Thus, a forest stand subjected to insect defoliation, harvesting, or other mortality would tend to be brighter in the red band, and darker in the green and shortwave infrared bands. Few studies (Olsson 1994) have attempted to detect partial harvesting using these reflectance patterns which may be acquired by Landsat TM images.

The need for a change detection approach that can encompass the types of change created by partial harvest treatments has been created by the increasing use of non-clearcut and partial harvest treatments in forest management. Traditional GIS forest inventory updates occur over years or decades (Gillis and Leckie 1996), but the emerging focus on sustainable forestry has generated a need for annual or even seasonal updates to changing landscapes (Lambin 1996). Many forest management entities have invested in GIS systems and infrastructure; while they are often increasingly proficient in GIS and may have ready access to GIS functionality, this does not necessarily extend to access or proficiency with remote sensing and image processing systems. This suggests that perhaps a simple though robust image processing technique is required; one that could be implemented within a GIS and which takes full advantage of the existence of complete GIS forest stand coverages. Such an approach must be tested in a wide variety of forest conditions and types of change.

In this Section we describe the success of simple DN matching change detection methods in detection of various partial harvest and clearcut conditions using Landsat imagery acquired in 1992 and 1997 over the Fundy Model Forest (FMF). We discuss the visual analysis of imagery in treated and undisturbed areas, and the classification accuracy obtained in a discriminant analysis of pixels sampled from various types of partial harvest stands and clearcuts in this mixedwood region of New Brunswick. This discussion is followed by a presentation of a new software tool to update the inventory (Section II) and an experiment to derive the causal factors in reflectance mapping of change classes with a geometric-optical model (Section III).

Study Area

This study was conducted in the Fundy Model Forest, located on the north shore of the Bay of Fundy, New Brunswick, Canada (Lat. 45 ° 25’ N, Long. 65 ° 50’) (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. For example, a typical clearcut may have saplings well over 1 m tall in 2 to 3 years. The stands selected for this test of change detection methods include some of these recent clearcuts, and partial harvest stands of various descriptions (see below); all have an average elevation of less than 1000m a.s.l., and are characterized by very gentle hills and slopes.

Database Description and Preprocessing

Geographic Information System (GIS) Database

Since the early 1990's information from all land users in the FMF has been integrated into a GIS data archive, which was used to select sample locations and to generate a stand description for this study. The forest inventory was conducted in the 1990's based on the standard aerial photointerpretation systems then in place (see Gillis and Leckie 1996; specific details of this provincial forest inventory are found in NBDNRE manuals). The early inventory used a three species composition delineation for homogeneous stands in different forest communities and ecoregions; a later update used a five species composition delineation for stands. Attributes associated with each polygon include 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.

The GIS database was projected in a locally-optimal New Brunswick Stereographic Projection. Prior to data extraction the database was converted to a UTM NAD27 projection to facilitate overlays on the image data. Although after this processing step the two data types were in the same projection, some minor discrepancies between the vectors and imagery existed. The vectors were resampled, based on road intersections, to fit the TM imagery with less than 0.25 pixel RMSE.

Initially, a sample of all existing GIS polygons in an undisturbed, clearcut and partial harvest condition were extracted. More than 200 polygons in the partial harvest condition were selected (see Figure 1). Visual analysis was used to reduce the number of stands to be visited on the ground and examined in the image database to approximately 60 in total; the criteria for stand selection included size (greater than 2 ha), access (within reasonable walking distance of good roads), dominant species (fir, spruce, pine, hardwoods, mixedwoods), and year of treatment (1992 to 1997 undisturbed, clearcut or partial harvest). Information extracted from the database included species composition (in percent, to the nearest 10), stand age and crown closure (prior to and post harvesting) as well as stand area (in hectares). The final sample discussed in this report is presented in graphical form in Figure 2, which shows the GIS attribute detail on the partial harvest treatments for each stand in the sample described in more detail in the next section. The complete sample of these stands, and the various image processing products examined in each case, are contained graphically in Appendix IV.

<u>Landsat TM Digital Image Data</u>

Landsat TM imagery acquired August 7th, 1992 were geometrically registered to a second geocoded scene acquired September 6th, 1997, with less than 0.2 pixel RMSE using 24 ground control points at key road intersections dispersed throughout the scene. The original image geocorrection was based on a large sample of GCPs (more than 40), again with less than 0.2 pixel RMSE. In both geocorrections, a cubic convolution resampling algorithm was used to determine pixel values in a 30 m grid. To facilitate the integration of the GIS data with the TM imagery both TM scenes were projected to the UTM NAD27 projection.

The two TM images were acquired on different dates, and therefore under different illumination and atmospheric conditions. The image solar zenith angle for August 7th, 1992 was 60° and the solar zenith angle for the September 6th, 1997 image was 45°. To minimize these differences an illumination correction was applied during the atmospheric correction of the two image dates. 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 both scenes. 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 simple transformations of image data within the GIS-selected stand polygons on a pixel-by-pixel basis. The image data were transformed into TM Tasseled Cap brightness, greenness and wetness indices (Crist and Cicone 1984). The red and near-infrared bands were transformed into the normalized difference vegetation indices (NDVI) for each year.   And finally, the first three components in a principle components analysis of the original six reflectance bands (separately for each image) were generated and used to interpret image differences between years and between partial harvest treatments.

Description of the Sample

Two field excursions were conducted in June 1998 (five days) and October 1998 (two days) to visit as many of the partial harvest stands as was possible to confirm the validity of the GIS label and to examine the condition of the canopy and understory. No quantitative measurements were conducted, but a sense of the type of changes and the degree to which these changes might be remotely sensible was obtained.

Figure 2 contains the listing of the GIS data characterizing each of the 50 partially cut and seven clearcut polygons selected for this analysis (see also Appendix IV). Often, numerous individual stand polygons in the original database were merged after the harvesting treatment with a single polygon label (called a cutblock). In the figure, the original inventory polygon labels and the area covered by the stands are shown in the boxes on the left side, and the new polygon label after treatment is given to the right. Only partial harvest stands are shown in this format, and the clearcuts are shown separately in the bottom right corner of the figure. The area sum of the individual polygon from the original inventory may be equal to or slightly less than the area of the relabelled polygon. Some discrepancies are caused by ground features, such as water and roads, which were removed from the analysis. The sample polygon areas varied in size from 2.25 to 92.15 hectares. The number of pixels sampled in the Landsat TM imagery is shown next to the polygon area and is directly related to polygon size.

In the softwood dominated stands, the most common partial harvesting treatments suggested by these data and confirmed during the field visits included removal of red and/or white spruce, jack pine and balsam fir from black spruce stands, removal of the hardwood component from most white pine stands, and removal of black spruce from jack pine stands. In the hardwood dominated stands (both tolerant and intolerant hardwoods) much of the softwood component was removed. The result of these activities was to increase the number of hardwood stands and the number of spruce stands.

Partial harvest practices differed by stand and species, and included removal of a small portion of the stands canopy in a strip (a mechanical harvester) or a (seemingly) random pattern (manual cutting). Typically, it appeared that partial harvesting was designed to remove about one third of the stand basal area; when the species targetted was in the upper canopy, this often resulted in opening the stand canopy, and reducing crown closure by a similar percent (about 30%). In other areas the partial harvesting was patchy, with all trees removed from small areas within stands. The reasons for partial harvesting included merchantable volume removal, precommercial thinning (usually in plantations), shelterwood cutting, habitat enhancement (legacy patches), release cutting (to open the canopy to encourage understory development), and treatments for stand improvement or conversions.

One extreme example of partial harvesting can be very similar to a clearcut but with a number of undisturbed areas, or legacy patches, randomly distributed in the larger area. Figure 3 shows a field example of this type of treatment, and Figure 4 shows the appearance of this stand in the imagery (bands 2,3,4 colour composite). Clearly, the pink tone of the area on the imagery following treatment is a result of the remaining vegetation reflecting highly in the infrared yet displaying lower brightness values than a more complete clearcut area. It is interesting to note the very different reflectance pattern in the larger clearcut just to the west of the legacy cut in Figure 4; the area shows a significant increase in green reflectance as a result of the growth of the jack pine planted in 1992 (the year of the first image).

Clearcuts are areas harvested for all merchantable timber and often leaving completely open stands with perhaps a few remnant or seed trees scattered throughout the area. In some cases the clearcuts had already been replanted, such as the young forest to the west of the legacy partial cut shown in Figure 4. In Figure 5 an area harvested by clearcutting in 1995 is shown. This forest area was originally dominated by several spruce stands with a minor fir component and some hardwood in the canopy. The new clearcut shows very little red absorption and is highly reflective in all bands. Adjacent to the new clearcut is an older area, harvested in 1988 and planted with white spruce. A significant change in colour can be noted as the regeneration trees grow in the five years between image dates, although even in 1992 the area shows significant green reflectance. The road into that clearcut area is more visible in the 1997 scene as the vegetation surrounding the road increased leaving the contrast between road and young forest more distinct.

Methods

Visual and Statistical Analysis of Image Data

A set of visual analyses was conducted to determine the spatial extent of changes within the GIS polygons and to examine the reflectance patterns following different types of partial harvest treatments in different types of stands. Comparisons of zoom-up imagery permitted an initial inspection of the direction of reflectance change and the differences that might be predictable in different types of stands and treatments. The original colour composites of these images were examined, together with the differences in brightness/greenness/wetness imagery, NDVI imagery and the first three principal components. A statistical analysis of these stands consisted of mean reflectance comparisons, and the development of correlation coefficients between reflectance measured in 1992 and in 1997.

The absolute differences in mean percent reflectance were calculated by subtracting the 1992 imagery from the 1997 imagery on a per pixel basis and then averaging for each polygon. Reflectance in the six bands and the brightness/greenness/wetness and NDVI values were tested using the Student's paired t-test and a significance level of 95% (0.05). These tests were repeated and interpreted at several levels of a hierarchical classification of stands. Correlation was used to show that the multitemporal data were related within the polygons; for example, in undisturbed areas the correlation would be higher between the 1992 and 1997 imagery than in either clearcuts or partial cuts. The correlation between reflectance values of a polygon subjected to clearcutting should be close to 0, and would increase as the amount of cutting was decreased.

Classification of Partial Harvest Stands

Classification was of considerable interest in this study because of the need to update the GIS database. One of the optimal methods in which such an update might be accomplished is to integrate a remote sensing classification within the organization of the landscape provided by the vectors in the forest inventory GIS (see Wulder 1998, and Section II and Appendices I and II). In this study, discriminant functions were used first to test the classificatory power of the remote sensing data on the polygonal data sampled from the GIS; both per-pixel and stand-level classifications were tested.

Discriminant functions were derived at several levels of a classification hierarchy (shown in Figure 6). The idea here is to separate classes of partial cuts, starting at the 1st and continuing to the 3rd hierarchical level which represent increasing levels of generalization for the dominant species in the resulting stands. A stepwise statistical discrimination was used to suggest, in an exploratory analysis, which variables were more useful in distinguishing between various partial cut classes (results not shown here). The seven clearcuts were combined to form the clearcut class and the pixel values representing the undisturbed forest were treated as an independent class.

The first level of the classification structure assumed that each polygon was an independent class, and the polygon description was based on the 1997 polygon label. At the second level, GIS polygons that consisted of the same dominant and codominant species in the post-harvest stand descriptions were grouped to form nine distinct classes (mixed Black Spruce, pure Black Spruce, mixed Intolerant Hardwood and Spruce, mixed Tolerant and Intolerant Hardwood, pure Jack Pine, mixed Spruce and Hardwood, mixed Spruce and Softwood, pure Tolerant Hardwood, and pure White pine). The 10th class at this level of the hierarchy consisted of the pixels sampled from the clearcut polygons, and the 11th class consisted of pixels sampled from the undisturbed forest. The third and final level of the hierarchy showed six dominant species classes (Black Spruce, Intolerant Hardwood, Jack Pine, Spruce, Tolerant Hardwood, White pine) , as well as the clearcut class and the undisturbed forest class. Thus, from level one to three the classes were reduced from 51 classes to 11 classes to 8 classes. The described hierarchical merging structure is shown in Figure 6.

Results

<u>Visual Interpretation of Stand Differences</u>

Over 50 individual forest stands across the Fundy Model Forest were examined in the image data set and many were visited in the field. Two representative examples of the change in stand appearance caused by partial harvesting are shown in Figures 7 and 8, and Figures 9 and 10, for stands dominated by spruce and tolerant hardwood, respectively. Initial comparisons of these figures to the legacy cut in Figure 4 and the clearcut in Figure 5 show the differences in reflectance observed between the various levels of disturbance.

In Figure 7 the spruce stand assemblage (nine different stands all containing spruce or fir as the dominant conifer) had been partially harvested and assigned a label as a dominant spruce stand in the 1995 cutblock. In 1992 the area was a homogeneous, dark green in the colour composite; in 1997 this area appears significantly brighter and more variable. It is quite apparent that the new road cuts into the partial harvest area which extends to the north and south, and that parts of the original spruce stand have been left undisturbed in the southern part of the image area. Certain areas to the west of the main stand appear to have been originally hardwood stands and appear much brighter in the 1997 image. This pattern of reflectance is similar to the tolerant hardwood partial harvesting pattern observed in Figure 9 (discussed later), however, these areas were not visited in the field during this study.

Figure 8 shows this same spruce stand in the three dimensions of brightness, greenness and wetness, and the differences using simple image subtraction to emphasize the spectral reflectance changes between 1992 and 1997. The brightness values (Figure 8a) show that the stand has higher reflectance in 1997, and lower greenness (Figure 8b) in 1997. This is the expected pattern in disturbance areas since it is related to the removal of vegetation from the canopy resulting in decreased red absorption and decreased green reflectance. The difference in wetness is quite dramatic (Figure 8c). In 1997 the stand displays a decrease in reflectance in the shortwave infrared bands which contribute most of the information in the wetness index. Again, this is the expected pattern suggested, for example, by Cohen et al (1998) in their work in mapping forest clearcuts in Oregon.

The principle components analysis (Figure 8d) confirm that there are differences in reflectance before and after this spruce stand has been subjected to partial harvesting practices. As Collins and Woodcock (1996) found, the second principle component (when all six brightness/greenness/wetness indices are input to the analysis) could be named the *'change component'* since the maximum information related to changes between the two image dates appears to be well represented in that component image. The area is quite distinctly outlined in at least the first two components, however, and the third component appears to show those hardwood stands in the western portion of the image have changed. More analysis is required to determine the effectiveness of these components in description and delineation of changed forest stands.

The NDVI image (Figure 8e) appears to conform to the logic that would be expected for an area where the forest canopy has been reduced. In earlier work NDVI has been shown to be related to leaf area index (LAI) to the extent that LAI is related to the absorbed photosynthetically active radiation (APAR) (see Bonan 1993). In the present study the 1997 NDVI values are lower than the 1992 values since the leaf area (presumably) has been reduced. Since the NDVI image is a single variable there may be more uncertainty in the interpretation of change areas compared to the interpretation of the multidimensional brightness/greenness/wetness variables or principle components.

In Figure 9 the tolerant hardwood stand assemblage (six different stands all containing tolerant hardwood as a major component of the canopy, but with various amounts of spruce or fir as the dominant or co-dominant conifer) had been partially harvested and assigned a label as a dominant tolerant hardwood stand in the 1995 cutblock. In 1992 the area was a fairly heterogeneous, light shade of green in the colour composite; in 1997 this area appears significantly brighter and more variable. The actual area of the partial harvest appears much larger than the stand boundaries extracted from the GIS for this study; during the field visit the stand was clearly processed for the removal of the softwood component and the western edge of the stand was more obvious. The understory, quite dense and in at least two layers in places, was responding well to the opening of the canopy. All of the stumps in the area appeared to be red spruce. The areas to the north and east of the partial harvest stand appeared to be older cutovers that now contain significant regeneration; during the field visit it was determined that these areas are vigorous and healthy conifer plantations, very dense and growing extremely well. In the 1997 image these areas appear spectrally very similar to an undisturbed forest.

Figure 10 shows this same tolerant hardwood stand in the three dimensions of brightness, greenness and wetness, and the differences obtained using simple image subtraction to emphasize the spectral reflectance changes between 1992 and 1997. The brightness values (Figure 10a) show that the stand has higher reflectance in 1997. However, the difference in greenness is minor (Figure 10b). This is probably related to the emergence of the very dense understory. The brightness difference is the expected pattern in disturbance areas since it is related to the removal of vegetation from the canopy resulting in decreased red absorption. Again in this example, the difference in wetness is quite dramatic (Figure 10c). In 1997 the stand displays a decrease in reflectance in the shortwave infrared bands which contribute most of the information in the wetness index.

The principle components analysis (Figure 10d) confirm that there are differences in reflectance after this tolerant hardwood stand has been subjected to partial harvesting practices. Again, the second principle component (when all six brightness/greenness/wetness indices are input to the analysis) could be named the *'change component'* since the maximum information related to changes between the two image dates appears to be well represented in that component image. The larger treatment area is quite distinctly outlined in the second and third components, unlike the earlier spruce example which showed more distinct changes in the first two components. In the tolerant hardwood image (Figure 10d) and in the spruce image (Figure 8d) the third component appears to show the hardwood stands which have changed. This third component also appears to show the regenerating clearcuts in the vicinity of the tolerant hardwood stand quite distinctly. Again, more analysis is required to determine the effectiveness of these components in description and delineation of changed forest stands.

The NDVI image (Figure 10e) does not appear to show the change in the canopy as well as in the spruce example where the understory was less exuberant. Here, it appears that the harvesting has not reduced the leaf area of the stand much even though the forest canopy has been reduced through the removal of the softwood component.

Statistical Analysis of Stand Differences

Table 1 contains a listing of the reflectance differences, and the differences in brightness, greenness, wetness and NDVI variables for each of the stands subjected to partial harvesting treatments in the sample. The second and third parts of the table show the differences aggregated by the classification hierarchy shown in Figure 6. This information is shown to allow the statistical confidence of these tests to support the differences in stand reflectance interpreted in the preceding section which are shown as absolute reflectance change in Table 1.

All of the reflectance bands show absolute reflectance change between the 1992 and the 1997 imagery of the sampled polygons, regardless of dominant-codominant species types.   In general the largest differences are in TM bands 5 and 7 (most apparent in the wetness index), followed by band 3 (red absorption band) and band 4 (infrared band). The wetness index is statistically different (at the 95% confidence level) for all but one stand. However, that stand has some of the largest differences found in the brightness and greenness values in the sample.   The NDVI differences are statistically significant in most of the polygons illustrating the sensitivity of this measure to the changing canopy leaf area and also to the structural differences generated by the partial harvest treatments.

Using these absolute reflectance differences in a Bhattacharyya distance separability test showed that statistical separability was high in virtually every polygon (table not shown) when the means were tested across the temporal scale rather than within one image. In other words, the original stands were different after treatment. A partial harvest stand of spruce, for example, might not be distinguishable from another partial harvest stand of spruce, but would be quite different from partial harvest stands of pine or tolerant hardwood, and would be very different from an undisturbed stand of spruce or pine or tolerant hardwood.

Another way to show differences in the stands before and after treatment is to examine the correlation between reflectance sampled within the polygon from the first image to the second image (Table 2). In an undisturbed forest, the correlation coefficient between the pixels in that set of polygons in 1992 and 1997 ranged between 0.68 and 0.77 for the brightness/greenness/wetness measures, and was 0.40 for the NDVI statistics. This reflects the fact that even an undisturbed forest would have some changes related to physiology (perhaps some mortality by insects or competition, wind damage, new growth, etc.), and some changes related to the remote sensing imagery themselves (e.g. shadow fraction, sensitivity of the sensors to radiant flux, residual atmospheric differences, etc.). However, the partial harvest stands show a considerable difference in the correlation between the 1992 and 1997 pixels within the various polygons. For the brightness/greenness/wetness measures the correlation coefficient ranged from 0.11 to 0.34, and was 0.27 for the NDVI statistic. Similar coefficients were computed for the aggregated samples.

The conclusion that may be drawn from this result is simple and straightforward:

Forest stands that were subjected to partial harvesting are different in reflectance measured before and after the treatment, compared to the natural range of variability expected in an undisturbed environment and compared to the differences measured in areas that were clearcut.

The amount of difference that can be detected in reflectance measurements appears to be well within the range of partial harvest treatments applied in southeastern New Brunswick. Although no quantitative measures of basal area or crown closure were obtained in this study, field visits to various stands appeared to confirm that the partial harvest treatments affected at least 30% of the basal area or crown closure, and in most cases this was enough change to be detected by Landsat TM sensors up to five years after the treatment was applied.

Classification Accuracy

One goal when remotely sensing the conditions of forest canopies is to enable a reporting mechanism to be systematically applied to existing databases; in essence, an update procedure for the GIS. Many ideas and aspects of this issue have been reported in the literature to accomplish this task to various degrees of automation and accuracy. Classification is often considered an optimal approach because the classes can be readily defined and the error underlying the output quantified (Cohen et al 1998). Classes can also be used to refine the development of regression equations between reflectance and biophysical parameters such as crown closure or basal area, and this approach can permit still further detail to be extracted from the relatively coarse resolution and low dynamic range of the satellite imagery (see Section III). Therefore, based on the successful visual and statistical interpretation of the partial harvest polygons, and their separation from undisturbed forests and clearcuts, a clear idea of the classification accuracy that could be expected in an automated update procedure for the GIS-based forest inventory was sought in this study. If this accuracy is acceptable, further effort might be warranted in optimizing the classification approach to achieve the highest possible accuracy and the most effective use of resources to achieve that accuracy.

Discriminant functions comprised of the original reflectance bands and various combinations of those bands and the derived indices were generated and tested using an indpendent sample of polygons from the partial harvest coverages (Table 3). The first test used all the pixels in the polygon and attempted to classify individual pixels into one of the partial harvest polygons based solely on spectral reflectance. The second test grouped the polygons into the second level of the hierarchy shown in Figure 6; and the third test grouped the polygons into the third level of the hierarchy shown in Figure 6. In all these tests individual pixels were classified into one of the groups, and the accuracy is expressed as the percent of these pixels that were classified into the group from which they originated.

At the first level the partial harvest stand classification accuracy obtained was 28%, and the clearcuts were 71% accurate; the undisturbed forest class was 65% correct using this per-pixel methodology in a previous study (see Franklin et al 1997). These latter two results (clearcut and undisturbed forest classification accuracy) are considered reasonable (with these methods and data). Further work on clearcuts and forest community classification (reported in Franklin et al 1997) showed that stand-level accuracies improved, but these classes are not the focus of this study and are not further discussed here.

The partial harvest stand classification accuracy (less than 30%) using a per-pixel methodology appears reasonable since many pixels would not uniquely belong to a polygon labelled partial harvest with a certain stand composition after treatment. However, the accuracy is much better than would be expected given a random distribution of pixels into 50 partial harvest classes, and this encouraging result is interpreted to mean that:

- there is good reason to proceed to the next level of the hierarchy in the test, and

- there is good reason to believe that an optimal classification technique could be the basis for a successful automated update procedure.

The second part of Table 3 shows the classification confusion matrix for the merged polygons, where the merging was accomplished with reference to the species composition (dominant, co-dominant) after the final treatment of the stand (see Figure 6).

Two sets of class percentages are shown; the first is the per-pixel method, the second is the stand-level classification result.

In the per-pixel method the classification accuracy for partial harvest stands was 42%, and ranged from a low of 24% to a high of 60%. This means that up to 60% of the pixels from a stand labelled partial harvest were actually placed in that class using a discriminant function comprised of brightness/greenness/wetness variables from 1992 and 1997. Confused pixels within such stands, especially in the mixed spruce and fir classes, appear reasonable; high accuracy was not expected in those instances. At the third level those confusions are sorted out by merging the various softwood classes, and a final classification accuracy of 55% over all the partial harvest classes was achieved. Again the black spruce stands exhibited the lowest accuracy (35%); the jack pine and white pine classes obtained the highest levels (70%). The black spruce was confused with the white spruce class, although the white spruce class was confused with most other classes as well.

This may not be as troubling as it appears; there may even have been more inaccuracies in the original GIS stand typing than in the classification of the image data reported here. A follow-up field program may be required to completely understand the difficulties in classification that are reported in the spruce classes. In future work a single spruce class could be used to reduce this source of confusion. And finally, it is important to note that this accuracy was achieved using a relatively primitive statistical classifier (see Foody 1996, Cihlar et al 1998) dealing with limited training area information and without other more complex modifications (for example to the input variables or the decision rule). The 55% overall classification accuracy level indicates the promise of still higher accuracy with a purpose designed system, rather than with only the simple hypothesis testing procedures involved in this initial study.

The second set of statistics in Table 3 show the stand-level results (using the mean reflectance value for each polygon and assuming that this value can be used to classify the entire area included in the polygon boundary). This resulted in an overall classification accuracy of 67% for the partial harvest stands at level two of the hierarchy (eight partial harvest classes). At level three (six partial harvest classes), this improved slightly to 70.7%. One obvious conclusion that may be drawn from these stand-level or polygonal classification accuracy results is that the potential accuracy for an optimal classification technique in this environment appears to justify further effort in developing an automated update procedure for the GIS using these multitemporal TM data (see discussion below and Section II).

In Section III of this report a ‘physically-based’ approach is described to enable greater insight into the optimal methods of change detection in these stand conditions.

Possible GIS Update Procedure

The fact that partial harvest stands and clearcuts can be detected and classified accurately, and with relatively simple, robust classification decision rules and non-complex input variables, leads to a discussion of a possible operational system of updating GIS forest inventories with such remote sensing classification products. An operational update procedure would require and be largely based on:

- the capability of providing radiometrically and geometrically correct remote sensing data sets,
- ready access to the GIS vector coverages, and
- the capability of deriving brightness/greenness/wetness values for classification input.

One of the major stumbling blocks in any such update project has always been the definition of an ‘*acceptably homogeneous area’* on an aerial photograph which, primarily through digitizing and field logistics, then becomes the de facto standard for organizing the landscape into forest stands (Lowell and Edwards 1996). In our experience, these ‘*acceptably homogeneous areas’* rarely translate comfortably between GIS vectors and remote sensing image data (Franklin et al 1997, Wulder 1998). Traditionally, if a user accepts the GIS vectors ‘without error or uncertainty’ then the remote sensing data cannot be used to update the GIS since the remote sensing data do not conform to the vector-imposed organization of the landscape (we do not refer here to the technical difficulties in converting raster to vector, and vice versa, most of which were resolved several years ago). The remote sensing approach is to organize the landscape on a raster, or possibly on a segmented or classified version of this raster grid.

To update the GIS an intermediate step is required, and the attribute tables that accompany the GIS vectors seem to be the ideal meeting ground for a new tool to operate. In essence, the updating procedure would be to ensure that within the GIS polygon an understanding of the distribution of classes has been obtained; where that distribution of classes reveals a possible, logical change, then the GIS attribute tables could be accessed and new entries made. These entries can then be mapped using the conventional mapping functionality of the GIS, and the remote sensing data are constrained to providing input to a series of rules concerning the threshold at which the distribution warrants an update flag.

In Section II of this report such a tool is described together with an application to Fundy Model Forest change detection.

Summary

Forest canopy change caused by partial harvesting was examined using multitemporal Landsat Thematic Mapper imagery acquired in 1992 and 1997 in New Brunswick. In summary, we found, through visual and statistical analysis of the colour composite imagery, that brightness/greenness/wetness indices together with NDVI and principle components analysis showed the expected pattern of increased brightness and decreased greeness and wetness in most cases of clearcutting and partial harvest stands, and the concentration of change information in one or two of the three principle components. Absolute reflectance differences were significant between 1992 and 1997 imagery in partial harvest stands, compared to the natural range of variability expected in a natural, undisturbed forest. The largest differences were recorded in the wetness variable, but brightness and greenness differences were also present in most stands. These differences were less than those observed in clearcuts.

Moderate classification accuracy in per-pixel and stand-level classifications were obtained using discriminant functions comprised of the brightness/greenness/wetness variables in 1992 and 1997. The accuracy with which individual pixels within polygons labelled as partial harvest stands could be classified using a discriminant function decision rule approached 55% over all the partial harvest classes, and an attempt to classify polygons in their entirety using the mean reflectance of all pixels in that polygon resulted in a classification accuracy in the range of 68-71%.

II. A Polygon Update Program Based on Remote Sensing

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, wildlife habitat issues are of increasing concern in sustainable forest management, and therefore new and better information on habitat may be required from the forest inventory. A new Canadian emphasis on criteria and indicators of sustainable forest management has created an entirely new reporting objective for forest inventories, and the information demands continue to increase with this new articulation of forest management objectives (Canadian Council of Forest Ministers 1997).

To ensure that the forest inventory is able to satisfy these and other demands for information, more powerful and adaptive geographical information systems (GIS) 'update' procedures are required. 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, Wulder, 1998). 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 data current while maintaining accuracy. The GIS database 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 database is 'replaced' periodically rather than attempt to 'update' the inventory.

The role of satellite remote sensing, already prominent in landscape change detection (Cohen et al 1998) and mapping (Lillesand 1996), may become increasingly important as a source for GIS updates of the kind envisioned for forest inventories

(Wolter et al 1995, Woodcock et al 1997). To test this idea in an operational forest management example, multitemporal Landsat Thematic Mapper images were acquired in the New Brunswick Fundy Model Forest, and used to detect changes over the five-year period from 1992 to 1997 (see Section I). A brightness/greenness/wetness transformation was used to isolate areas of change. A classification of image data into a number of landscape-change classes, such as clearcuts, partial harvest, and roads, was developed. Limited field checking determined that the resulting classification was realistic and could be used to determine area estimates of forest operations, including clearcutting and partial harvesting. A method of transferring the changes detected on the satellite image classification to the forest inventory geographical information system (GIS) was required to enable these calculations and others for the forest area under management.

In an earlier study, Wulder (1998) developed a *'polygon decomposition'* approach based on the integration of georeferenced remote sensing and GIS data. The original application was designed to use the information contained in the forest inventory GIS to permit a more accurate remote sensing image analysis to proceed. The basic idea was that satellite remote sensing image pixels located within forest inventory polygons could be used to analyze within-polygon variability. Such internal variability can be important in a number of ways. For example, the calculation of leaf area index (LAI) from satellite reflectance was found to be more accurate if the original stand characteristics were considered (Franklin et al 1997). The polygonal data were used to guide the selection of equations in the LAI calculation, higher accuracy and less uncertainty (i.e. greater confidence) would result. The code developed in that application was not written to specification and was based on three separate software programs and two operating systems.

The success of that application has generated additional needs in the integration of remote sensing and GIS, most notably in the update of changes detected on satellite imagery that can be used to keep the GIS database current. A 'user-friendly' approach to polygon decomposition that would have wider applicability was developed and is described in this Section. The program is written in Arc Macro Language (AML) (see

Appendix 1) which is part of the ArcInfo software package. The work was performed on a IBM Pentium II running the NT 4.0 operating system.

Software Design

Many large-scale GIS projects currently use ArcInfo as the software of choice, and in Canadian forest inventory work, ArcInfo is one of the dominant GISs. Unfortunately, ArcInfo offers no high-level programming option, and the raster-based GRID program within ArcInfo is not well-developed (essentially unchanged since 1985). However, the Arc Macro Language (AML) is a relatively powerful low-level programming language that has the obvious attraction of widespread acceptance and 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 earlier programming effort (Wulder 1998) required a major effort to run the different procedures in different operating environments, and there was a need for some proficiency in C (a high-level programming language). Since we needed to reduce the complexity of the update operation to the simplest functionality (defined earlier), the original Wulder (1998) programming concept was simplified for this project:

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

Two flowcharts illustrating the software concept are contained in Figures 11 and 12. Conceptually, 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 classes, the dominant species in each polygon must be converted to a class variable that matches the classes used in the remote sensing product. Additional classes, such as change classes, can then be used uniquely to update the GIS classes.

In Figure 13 the code logic is presented. The AML listings for the polygon update program – called PUP – are contained in Appendix I. The program uses a menu-driven interface (graphics for some of the screens are contained in Appendix II). 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. This second attribute should correspond to the classification system that has been imposed on the polygonal dataset (i.e. species composition classes, age classes, density classes, or some other classification system that is targetted for update). And, this second attribute should match the numbering of classes in the remotely-sensed image classification (i.e. if spruce-dominant stands were labelled class 6 in the GIS dataset, then spruce-dominant stands should be class 6 in the remote sensing dataset; a simple recode step might be necessary if these two systems do not match).

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 6 (spruce), and in the remote sensing image classification 50 of these pixels were classified as a clearcut class (say, class 3) and 20 of the original 100 pixels were classified as a partial harvest class (say, class 2), the result of this *areax* in *layer3* polygon summary would show a 70 percent change. At this point it would not be clear which 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 Polygon Update Program Application

An unsupervised classification of the 1992 and1997 Landsat TM images was used to create change classes to test the PUP code. Figure 14 contains a map of the image classification showing classes which have been interpreted as clearcuts, older clearcuts (i.e. showing significant regrowth), and partial cuts (see Section I). The older clearcut class was necessary because of the relatively long (five year) time interval between the two remote sensing image acquisitions. The remote sensing change classes were arbitrarily assigned the codes 77 (clearcut), 110 (older clearcut) and 190 (partial cut). The second part of Figure 14 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 4. A different classification, perhaps including more of the species codes (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 5 and 6 contain portions of the main output obtained by the comparison of the classification in the top part of Figure 14 with the polygon attributes in the bottom part of Figure 14. Highlighted in Table 5 is one polygon (number 52496) with a significant change detected as a clearcut. Of the 72 original pixels labelled as balsam fir, 13 were found to be a member of the clearcut class in the remote sensing layer. This is reported as an 18% change to this polygon. Table 6 provides some additional information on the characteristics of the reflectance measured in this polygon. The same 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 change that have been detected in this polygon.

Summary

A new tool for resource managers – called the polygon update program (PUP) – has been written in ArcInfo Macro Language (AML) to facilitate the integration of 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 (such as dominant species codes) with a unique polygon identifier, *polyid*, to image 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.

III. Quantifying and Modelling Forest Structural Change

Introduction

A key component of remote sensing change detection is providing forest managers with an ability *to quantify the amount of structural change in forest stands* that may result from partial harvesting activities. This would represent a significant step forward because virtually all of the previous work (including that presented in Section I of this report) in forest change detection using remote sensing have generally provided only:

- a statistical indication of change in spectral response, and/or
- a spatial description of changes in landcover patterns.

A truly quantitative, physically-based change detection capability has yet to be fully demonstrated. The basic idea is to obtain structural information first from imagery in the form of estimates of conditions such as stems/ha, crown closure and width, and then compare those predicted observations to quantitative structural information obtained from subsequent image dates. The ability to provide quantitative physical descriptions of forest structure, and to apply this with high precision over different time periods represents a more direct information source of potentially greater interest to the forestry community that simple statistical comparisons of reflectance data as has been the common approach in the past (and in Section I).

Previous work has successfully demonstrated a capability to obtain physical information on forest stands as an improvement over statistical and empirical methods (Peddle et al 1997, 1999). However, we have yet to apply these methods to forest change detection.

In this Section, we develop a different approach to using forest canopy reflectance models for detecting and quantifying forest change set within a complex of forest management strategies in which a variety of harvesting practices have been applied over different time periods. We begin by describing the basis of physical scene modelling, with an emphasis on the different modes of usage which provide various options to forest image analysis and inventory. Following this, a new approach developed for this forestry context is described in which the conventional modes of reflectance modelling have been extended and modified to suit the information and validation needs of this work.

This approach is then tested in a focused experiment involving the modelling of forest stands which have been subjected to partial harvesting. Spectral measurements of individual forest components of canopy and ground vegetation were obtained under sunlit and shadowed illumination using a field spectroradiometer. Near simultaneous measurements of incident irradiance were also acquired using a reference panel of known spectral properties. The target and irradiance spectra were input to a reflectance processing software package (Peddle et al, 1999) to compute surface reflectance values for use with the satellite reflectance values and the canopy reflectance model. These physical and spectral forestry measurements provided a basis for both specifying model inputs and also for performing a baseline validation of model output results, as described in the following sections.

The results from a comparison of modelled forest structural information extracted from satellite imagery acquired before and after the partial harvest are compared with inventory data and ground measurements of forest structure. Perspectives on future directions of this work are then summarised, with an emphasis on field measurement needs to provide more extensive validation of these methods, as well as insight into operational modes of use.

Reflectance Modelling

Remote sensing imagery provides spatial information on the magnitude of reflected radiation from the Earth's surface. These image data have been related directly to surface phenomena such as land cover through image analysis and classification. However, more detailed and complex information such as the physical structure of forests cannot be obtained directly and instead requires more sophisticated analytical methods.

Geometric optical reflectance models provide a powerful basis for understanding the interactions of solar radiation with forest stands as a function of the physical dimensions and structure of forest canopies. These models characterize forest structure and vegetation spectral response with respect to sun-sensor-surface geometry. The model simulates the spectral information that would be obtained from a sensor viewing a forest canopy from above. From this perspective, a forest stand is comprised of the canopy, the shadows cast by the canopy, and the background forest floor material. Trees are represented in the model as discrete objects (e.g. three-dimensional ellipsoids) which cast shadows onto adjacent crowns and the forest floor, in a similar way as occurs in nature. The spectral properties of these individual components of a forest stand are required as input to the model. The physical dimensions of these modelled trees can be varied, from which the corresponding remote sensing signals are derived. These 3-D discrete objects (modelled trees) together with the spectral component properties are distributed over an area equivalent to the instantaneous field of view (IFOV) of an airborne or satellite sensor (i.e. pixel spatial resolution). Within the IFOV, different magnitudes of tree densities can be modelled.

The model permits a full range of illumination angles to be simulated according to the range of possible solar positions for a given area. Similarly, the viewing angle of the remote sensing instrument can be varied. Terrain variations such as different slopes and aspects are also accounted for in these models. Based on these inputs - sun position at the time of image acquisition, view angle (which is often nadir with satellite imagery), the spectral properties of forest stand components.

In this Section, the Li-Strahler (1992) Geometric Optical Mutual Shadowing (GOMS) model was used, as its spheroid representation of tree crowns has been shown in previous work (Peddle et al 1999) to be superior to other crown geometrical forms such as cylinders and cones (Jasinski; Li and Strahler 1985, Hall et al., 1995, 1996). The GOMS model also provides extended capabilities to deal with complex crown shadowing created over a gradient of stand densities at higher solar zenith angles which characterise northern forests, as well as being suitable for use in more regional scale contexts in which classification and biophysical estimation have been merged (Hall et al., 1997; Peddle et al 1997).

The model can be used in either forward or inverse mode. In forward mode, the model produces as output the pixel reflectance values in each spectral band, together with a set of scene fractions (%sunlit canopy, %sunlit background and % shadow within individual pixels). As inputs in forward mode, the model requires estimates of tree dimensions, stand density, and the set of spectral component reflectance values. In inversion mode, the model provides as output the physical descriptions of forest stands (tree height, horizontal and vertical crown radius, stand density, and tree height distribution). The required inputs are the satellite or airborne pixel value, and the spectral properties of the individual stand components, as well as the sun and view positions. In the next section, we describe a modified approach to using these models which achieves some of the broader goals of model inversion while preserving the diversity of output possible through forward mode simulation.

Methods and Experimental Design

As the goal of this study is to provide quantitative forest structural information, the modelling framework is necessarily set in the context of model inversion since that mode provides physical descriptors of tree stands based on the satellite image and forest spectral inputs described above. However, in this initial work we are also interested in providing a more comprehensive account of both the range and variability of model results for the purpose of model validation and to enable comparative analyses of actual versus modelled satellite reflectance values with respect to the physical descriptors of interest. Further, we are interested in developing a framework for providing forest managers with a remote sensing-based resource information base for monitoring forest change due to events such as a variety of harvesting and stocking strategies, fire, ecosystem stress such as insect defoliation and disease, normal tree mortality, and possibly even longer term impacts from climate variability and change.

Model inversion of remotely sensed imagery represents a powerful forestry tool as it provides a way of deriving physical information from digital remote sensing imagery. These inversion results are obtained as singular values of canopy structure at site and pixel specific scales (i.e. for a given pixel, the model computes a single value for each of horizontal and vertical canopy radius, tree height, density, and height distribution). However, for our initial objectives, inversion model results are less well suited for studying the variability of model outputs within a more comprehensive model validation context. Accordingly, we have designed a different approach which provides a proper basis for model testing set in the context of an inversion mode solution.

This different approach to forest reflectance modelling was achieved by running these models in what we call “multiple forward mode” (MFM). In standard forward mode, the user must provide input values specifying several physical descriptors of the forest canopy dimension and form (Table 7). The model computes a corresponding pixel value based on these physical inputs and the spectral component measurements. In multiple forward mode, the requirement for specific physical dimension and form inputs is relaxed since only a range of values must be entered. For example, instead of specifying pixel or stand-specific values for crown radius and tree height, the user need only specify a range of values and a model increment. The model is then run multiple times in forward mode for each possible combination of physical canopy descriptors where, for a given physical input, all values are considered throughout the range with respect to the increment step specified.

The end product is a larger number of output satellite pixel values which we store in a look-up table for subsequent forest information query, search and retrieval (a graphical form of this table is shown in Appendix III). When sorted by output pixel values, the look-up table essentially stores a composite of the different physical forest canopy structural values which may exist in nature to produce a common spectral response. For example, a higher density forest stand with a smaller canopy radius may produce a similar overall reflectance as a slightly lower density stand comprised of larger radius crowns set within a different tree height regime. These MFM look-up tables (M-LUT) are first computed over the full range of specified forest structure values. Then, for a given satellite image pixel reflectance value, the M-LUT is searched for all modelled reflectance values which match that satellite image reflectance value, and the corresponding physical inputs to the MFM model are extracted. Typically, there will be multiple occurrences of the same pixel value in the M-LUT: depending on the nature of the study, if these need to be resolved this can be achieved using a variety of approaches or by more sophisticated expert decision rules.

The purpose of the MFM approach is not to replicate what might otherwise be achieved using model inversion (i.e. the derivation of a single set of physical values), and so the stringent requirement for rigorous tie-breaking criteria is unnecessary. Instead, it is intended to characterise the variability of physical structural information as a function of candidate satellite pixel reflectance values. When used this way, the MFM method represents a wealth of information for both forest inventory analyses which could be suitable for longer term access and use, as well as a resource for improving our understanding of forest canopy spectral response as a function of stand structure in a more detailed analysis.

In terms of forest image analysis and reflectance modelling, this MFM approach has several advantages:

- Unlike model inversion in which one set of physical values is derived for a given satellite pixel value, with MFM there is a set of physical outputs produced appropriate for developing a higher level of image understanding through follow-on analyses of look-up table products;

- Unlike standard forward mode where specific physical parameters are required, in MFM only a range is required and this is easily provided from baseline inventory (GIS) data, field knowledge, reports, published literature, or even general estimates in which case a wider, more inclusive range is recommended to ensure proper model coverage;

- It is possible to test a wide range of structural inputs, or, similarly, test a very focused range of values in which several parameters are held constant (e.g. testing the effect of changing tree height on modelled spectral response).

This may be of particular interest in partial harvest or other studies in which specific forestry objectives may be evaluated within a highly controlled experimental framework. Alternatively, specific forestry field test plot conditions can be simulated for different remote sensing or stand structural conditions. Evidently, these models provide substantial power and flexibility to the analyst, and here we have extended that power to suit the needs of a particular forestry application.

Results

Model Inputs and Simulation

For this experiment, several red spruce stands were selected for the model look-up table analysis. These stands correspond to the area shown in Figure 7 and 8. Based on knowledge of the area and forest GIS inventory data, a set of input ranges was determined for parameterising the geometric optical reflectance model. The structural variables input to the model in MFM mode, which also constitute the look-up table outputs, are listed in Table 7. The ranges selected for those inputs are listed in Table 8. Endmember spectra were obtained from field spectroradiometer measurements, which were processed to reflectance (Peddle et al., 1999) and converted to TM values using a linear spectral response function. Direct measurements of red spruce canopy were used for the sunlit canopy endmember, while measurements from fern and alder were integrated to produce the sunlit background endmember. The shadow endmember was processed from TM pixel values obtained over areas deemed representative of deep shadows that would be found in forest stands, as in previous studies elsewhere (Hall et al., 1995, 1996; Peddle et al., 1999).

New software was written to enable multiple runs of the reflectance model in MFM mode. Using this model interface software, the model was run once in forward mode for each possible combination of all model inputs, for a total of 39,204 entries in each forest structural look-up table (product of all N values in Table 8). The terrain, solar zenith angle and solar azimuth values used in the model runs for each date are shown in Table 9. The solar zenith and azimuth angles correspond to the solar position at the time of each Landsat TM image acquisition in 1992 and 1997. Since the solar positions were considerably different, separate model runs were generated for each date, resulting in two look-up tables being used in this study. This was necessary since the model computes the physical structural values with reference to the illumination and viewing conditions present at the time of satellite image acquisition.

Model Outputs

As a first analysis of the model results, we compared the range of model outputs with the range of satellite reflectance values found within the red spruce study area. As shown in Table 10, the range of modeled values is in good correspondence with the satellite image values. This close correspondence in the range of modeled versus actual reflectance values represented a positive first result, indicating that the model performance is appropriate for the environment being studied. We would expect the model results to lie outside the range of satellite values, and this was the case. This is because the model is simulating a large range of possible physical/structural situations, some of which may not actually be present in this particular part of the satellite images.

Some of the modeled results produced for the two forest structural look-up tables have been summarised in graphical form and are contained in Appendix III. These graphs illustrate relationships between physical structural attributes and modeled satellite image spectral response. With the large number of combinations of input variables tested, there are many different types of physical-spectral relationships that can be studied with these model outputs. Here, we present graphically and discuss a relatively small portion of the wealth of results these models have produced in this experiment.

The functional relationship between stand density and modeled reflectance as illustrated in Appendix III shows greater variability in satellite reflectance at lower stand densities. As density increases, spectral reflectance values increase and have lower variability. These graphs (1992, 1997) were useful in determining the range of stand densities that are possible for individual TM satellite spectral reflectance values. Modeled reflectance values were then plotted as a function of horizontal crown radius, from which we found reflectance values were more variable at lower crown radii, with this variability decreasing as larger forest canopies were modeled. Reflectance values at those larger canopy radii were less variable, and increased in comparison to smaller trees. Similar plots were produced for vertical crown radius and also stand height. In the latter case, we found the variability of reflectance was rather large over a range of stand heights, however, the lower and upper limits of reflectance with respect to stand height showed significant differences as stand density changed. This tree height information was quite useful in interpreting, and indeed stratifying, the results generated from other parts of the look-up table with respect to tree height and stand density.

Modelled Differences in Physical Forest Structure for Quantifying Partial Harvest Change

To test the use of these large look-up tables, we created a focused experiment at three sites within the red spruce study area. These sites were chosen to test areas where different levels of change were evident as a result of partial harvesting. The satellite pixel reflectance values were first extracted from each site, representing the differences in spectral response for the same location over the two dates. For each site, the look-up tables were consulted to determine ranges of forest structural attributes that would give rise to the satellite image pixel reflectance values found at each date. These ranges were initially determined with references to the graphs produced in Appendix III, however for future studies this would necessarily be done digitally through a software look-up table program that would search the look-up table and provide the same (if not much more) information than was determined in these results.

For each site, the limits of stand density possible given the satellite spectral response were determined for each year, and then a range of stand densities were evaluated where for each stand density value, the corresponding horizontal crown radius, vertical crown radius, and stand height values were determined for each image date (pre/post harvest). These results provide a way to quantify physical forest stand attributes based on the satellite image reflectance values, and to compare the forest structural information over the different dates. As a result, a capability has been created to quantify physical structural change based on multi-date satellite imagery.

The results from the analysis of these three sites are summarised in Tables 11, 12 and 13. These tables were derived with reference to the look-up table entries and the graphics plotted in Appendix III. Site 1 had the greatest spectral change over the 5 year period (6% reflectance increase from 1992 to 1997 - see Table 11). Horizontal crown radius was chosen as the attribute of interest in terms of studying structural change, both at different stand densities and over different image dates. As above, however, we note that there are many other possible forest structural attributes (and combinations of attributes) that can be extracted and studied in a similar way as the results shown here. In 1992, prior to the partial harvesting treatment the maximum stand density was determined in these model runs to be 40%, with horizontal crown radius values decreasing from 3.0 to 2.0m as stand density increased. If we consult stand height in the structural look-up table (see graphics provided in Appendix III), we also see that beyond a stand density of 40%, the modeled reflectance values no longer match the satellite TM value for the full range of tree heights. This further illustrates the computed stand density constraint, and also shows how different ways of accessing the look-up tables can be used effectively to increase our understanding of individual or multiple physical structural attributes.

For a given stand density, the crown radius values shown in the Table were determined by consulting the appropriate set of stand density entries in the structural look-up table (graphed in Appendix III), and then determining the range of crown radius values that produced the satellite reflectance value of interest from the image. For example, with reference to the graph “Horizontal Crown Radius at 20% Density (1992)”, for a 1992 satellite reflectance value of 0.15 (15%), the crown radius values that have a modeled reflectance value of 0.15 are included in the set of candidate forest structural results. With reference to the graph, the Landsat TM satellite reflectance value is first identified on the y-axis, and using a line drawn perpendicular to that axis, all crown radius values plotted which intersect that line are determined as being possible physical attributes that could produce that satellite value with respect to the range of other structural parameters used in the modeled runs. In the above example, for a TM value of 0.15 this line intersects a crown radius of both 2.0m and 2.5m; hence the range identified for the 20% density entry for 1992 in Table 11.

The same procedure is used for any date or structural parameter of interest. For 1997, following the partial harvest treatment for this red spruce stand, a larger range of input stand densities was modelled for the satellite reflectance value for this site. Again, the crown radius values decreased with increasing stand densities, however, the absolute crown radius values were greater than those modeled in 1992 at a given stand density. Of course, with the partial harvesting done between the image dates, the stand density will be significantly different, and so the actual crown radius values obtained for each date would be dependent upon that determination. These differences in stand density could also be modeled, either instead of, or in conjunction with, the horizontal crown radius values obtained here. It is also possible to utilise the model through multiple queries to enable first the stand density value to be determined, and then based on that modeled result, use that to flag the correct dimension value (e.g. first use the model to determine the stand density was 30% post-harvest, and then access a different part of the look-up table to derive a horizontal crown radius of 2.5m). Either way, the end result in terms of change detection is a set of physical values associated with each image date, from which the structural differences can be determined by simple subtraction of the physical values obtained for each date.

We note that, in some cases, there is a range of values output for a given entry (e.g. 2.0 - 2.5m crown radii for 20% stand density in 1992). This is because there are more than one set of physical inputs that may provide the satellite image reflectance value. As additional attributes are specified, or as other methods to increase the precision of table entry identification are determined, this range would be reduced or eliminated. However, in absence of these more sophisticated processing strategies, we also note that the individual ranges identified here are rather small (usually on the order of 0.5m), and in many cases exact values are provided, particularly at higher stand densities. This illustrates the usability of these model look-up tables for obtaining first-order forest structural information, and for quantifying change in physical terms.

In Table 12, the results for site 2 are shown. Here, there is a larger range of stand densities modeled for the pre-harvest satellite image value, with a range from 10% to 60%. This is consistent with the results from the independent tree height results, in which stand densities greater than 60% did not match the satellite reflectance value. Crown radius varies inversely with stand density, with an overall range of 3.5m radius at 10% density, to 2.0 m radius at 60% density. In 1997, with a slightly greater TM satellite value of 0.22, crown radius varies from 4.0m to 2.0m, and over a larger range of possible stand densities (10%-90%).

Similarly, for Site 3 (Table 13), the model has provided a physical basis for quantifying structural change over a range of stand densities. Again, we see the separate set of tree height modeled results serving to validate the range of stand densities over which the model determined candidate values for the overall result.

Future Modelling Research

For future work, the following needs have been identified:

1. Greater precision and accuracy of satellite image atmospheric correction to surface reflectance values is required. At present the model outputs are not used to their full extent since their precision is substantially greater than the precision of satellite reflectance values. Use of the 6s atmospheric correction model is recommended.

2. Identification of a set of forest stands which capture the entire range of variability inherent to the area caused by partial harvest treatments is recommended, together with a field program designed to yield quantities for model input. This will facilitate additional analysis, model testing and validation leading to model inversion studies with a greater operational focus.

3. Endmember acquisition: additional spectral data are needed within the above identified stands to capture the variety of spectral properties in different forest species and background components. This can be obtained either by field measurement using a spectroradiometer or through the use of higher spatial resolution image endmembers from an airborne image data set (e.g. casi). In the latter case, spatial resolutions should be greater than 1m.

4. Field plots: for the stands identified, additional forest mensuration may be needed to fill any gaps in existing inventory data. Field measurements would be coordinated with model input requirements. A sufficient sample size to allow model testing and independent validation would be required. This could be achieved within the areas identified in step 2.

Summary

These modelling results have demonstrated a number of interesting and new ways to use canopy reflectance models in forest remote sensing studies. By using a new multiple forward mode look-up table approach, we have provided a wealth of quantitative, physical information which relates satellite spectral response to forest structure. The inputs to this mode of model usage are even more streamlined than standard forward or inverse mode methods. This is because only a simple range of stand dimensions is required on input, unlike the more rigorous requirement for actual measurements of stand attributes when run in forward mode. Compared to model inversion, the method provides a more comprehensive characterisation of the full range of possible forest structural arrangements which give rise to satellite spectral response values. Further, the production of these look-up tables through forward-mode runs of the model is also substantially more efficient computationally compared to model inversion.

In terms of the change detection application presented here, an ability has been demonstrated to not only quantify forest structural information for single dates, but also to apply these over multiple dates and quantify structural change in terms of differences in forest stand dimension and canopy geometry. There are also many different ways in which these models can be run, and a large variety of possible forest outputs produced. These models provide a powerful image processing tool which elevates remote sensing image analysis beyond the empirical/statistical approaches which have characterised many forest remote sensing studies to date. Although the details and complexities of the modelling algorithms may be of less concern to the forester and remote sensing user alike, the results these models generate are of far greater interest as they provide the type of information foresters require, with outputs that are readily understood. This has not always been the case in previous forestry remote sensing studies.

The ability to obtain these physical structural results over larger areas and multiple dates represents significant and fertile ground for further investigation. The fact that good first results have been shown for a complex partially harvested area within a mixed forest in eastern Canada lends further evidence to the breadth of application and capabilities possible using these methods.

Further, we have developed expertise using these models over various scales in other studies elsewhere. For example, in a regional scale study as part of the BOREAS project, an evidential reasoning image classifier (Peddle, 1995) was successfully coupled with canopy reflectance models (Peddle et al., 1997) for regional scale predictions of biophysical variables such as biomass, productivity and leaf area index. That classifier has also been used in a complex multi-temporal mixed forest overstorey-understorey classification (Hall et al.,1999). These spectral modelling methods have also been used with high spatial resolution imagery in areas of complex, high relief terrain in the Canadian Rocky Mountains (Peddle and Johnson, 1999). From these studies, and in particular from the modelling work completed here, we conclude that these models provide a critical linkage between remote sensing spectral response, image analysis, and forest structure and change, and that this context is likely a more workable framework of greater interest and relevance to the forestry community.

IV. Conclusion

This collaborative study has attempted to document and apply satellite remote sensing methods in forest change detection in the New Brunswick Fundy Model Forest to support a new monitoring approach that can be applied annually to update the existing GIS forest inventory database. The work is based on a combination of remote sensing image analysis and field work, with contributions by researchers and technicians at the Fundy Model Forest, the University of Calgary, the Canadian Forest Service, Parks Canada, and the University of Lethbridge.

The broad objectives were to:

1. Test and describe a method which can provide consistent and reliable accuracies in classification of a wide range of landscape conditions;

2. Develop a simple software tool to facilitate remote sensing/GIS integration, and;

3. Test the use of physical models in understanding the changes in reflectance observed in different stands.

The following conclusions flow from the remote sensing work conducted in the Fundy Model Forest and are organized in this presentation by the three main areas of activity (i.e. Change Detection, Software Development, Physically-based Models of Forest Change).

Change Detection

- The Landsat TM 1992 and 1997 image data were corrected to reflectance, and geometrically registered to the UTM grid (separately), to each other, and then to the existing forest inventory GIS database with sufficient accuracy (using commerciallyavailable methods) to enable pixel-by-pixel comparisons and polygon summaries to be made over the five-year interval;

- Visual analysis of the colour composite imagery and brightness/greenness/wetness indices together with NDVI and principle components analysis showed the expected pattern of increased brightness, decreased greenness and decreased wetness in most areas of disturbance;

- The change information was concentrated in one or two of the three principle components retained in the analysis;

- Areas of interpretation difficulty could be resolved easily with reference to field observations on the amount of vegetation removed during the harvest treatment, and the condition of the understory;

- Comparisons to undisturbed and clearcut areas showed the differences in reflectance that were related to partial harvesting, clearcut and undisturbed conditions;

- Absolute reflectance differences were significant in the disturbed areas compared to the natural range of variability found in undisturbed forest;

- The largest differences were recorded in the wetness variable, but brightness and greenness differences were also present in most stands;

- Clearcuts were mapped with 71% accuracy between 1992 and 1997 using a per-pixel method;

- The accuracy with which partial harvest stands could be classified using a discriminant function decision rule approached 55% over all the classes;

- Individual stand classification, using the mean brightness/greenness/wetness values in 1992 and 1997 for each polygon in the GIS identified with a partial harvesting treatment, approached 71% accuracy for the complete sample of partial harvests;

Software Development

- A polygon update program (PUP) written in ArcInfo Macro Language (AML) can be used to facilitate the integration of the remotely-sensed classifications of landscape change into the forest inventory GIS database;

- The program can summarize changes within polygons according to the previously-documented logic of *polygon decomposition*;

- An update flag, 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) within that polygon boundary, can be used to track changes in the landscape;

- In one example program run, a polygon with an original stand description (L1S1 species code) that showed a dominant spruce canopy was detected with an 18% change which corresponded well with field observations of the partial harvest condition for this stand;

Physically-based Models of Forest Change

- Physical models of forest stands provide a powerful image processing tool for the extraction of forest structural information from remote sensing imagery by providing critical spectral data and the dimension, geometry, composition and density of forest canopies and stands;

- A modified approach to using these models in *"multiple forward mode"* can be used to produce extensive look-up tables of forest structural inputs and their corresponding satellite image spectral response;

- Model results had a good level of correspondence with independently-derived forest inventory and ground-based plot information, thus providing a mechanism for quantifying both absolute and relative forest structural change from 1992 to 1997;

- The method is less dependent on a statistical summary of change conditions; i.e. the models work with the physical properties of reflectance and the structural changes that can be documented readily (such as stem density before and after treatment) in the partial harvest stands;

- These methods provide a significant area for future investigation, both in terms of site-specific forest structural information extraction, as well as in the ability to build a longer term forest information resource in the form of easily accessible spectral-structural digital libraries.

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Figures

Figure 1: Location of the study area in southeastern New Brunswick and stands used in the study.

Figure 2. GIS species composition and sample size based on the 1994 and 1997 inventories.

Figure 3. Field photograph of a clearcut with legacy patches (an extreme version of partial harvest treatment).

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Figure 12. Conceptual Flowchart of Data Analysis Steps in the Polygon Update Program.

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Figure 14. Example Change Detection in Fundy Model Forest

- **(a) Remote sensing image classification showing three change classes**
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Appendices

Appendix I. AML Code Listings for the Polygon Update Program

Appendix II. Representative Menus and Screens for the Polygon Update Program

Appendix III. Reflectance Model Output for Sample Stand Conditions

Appendix IV. Superset of Change Detection Polygons and Remote Sensing Imagery