MULTITEMPORAL LANDSAT TM DATA FOR STAND-BASED MANAGEMENT IN NORTHERN US FOREST ECOSYSTEMS

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ABSTRACT

Multitemporal Landsat Thematic Mapper (TM) imagery was processed and forest canopy change information was extracted over a 415 km^2 area in north central Minnesota. The study covered two-, four-, and six-year disturbance monitoring cycles. At the pixel level, the detection of canopy depletion and increment dynamics over the six-year interval was 94% accurate. The stand-based accuracy was 714 out of 759 (also 94%). Here change was detected in at least 50% of the total number of pixels that made up the individual stands. This paper specifically discusses the information content of multitemporal multispectral satellite data from the perspective of traditional stand management. Cross-verification using contingency matrices and geographical information system (GIS) modeling, combined with intensive field verification, has shown that the majority of the so-called "change classification errors" were not errors at all, but a powerful source of substand information that can significantly impact sustainable resource management. While the digital disturbance monitoring methodology as developed for this study does not perform its task at the stand level, stand data on change can be readily extracted with the additional benefit of explicit substand information being made available to the resource manager.

1. INTRODUCTION

Forest management requires up-to-date and accurate information. The forest cover, however, is continuously changing, where change is defined as "an alteration in the surface components of a vegetation cover" (Milne, 1988) or as "a spectral/spatial movement of a vegetation entity over time" (Lund, 1983). The rate of change can be viewed as either dramatic and/or abrupt, as exemplified by large-scale tree logging; or subtle and/or gradual, such as growth of standing volume. Some canopy modifications are human-induced, including deforestation for land-use conversion, while others have natural origins resulting from, for example, insect and disease epidemics.
Traditionally, data actualization has come from detailed field reports. The cost of implementing such ground-based assessment activities is high and continues to rise, as does the demand for more and better information. Hence, emphasis has shifted from repetitive ground inventories towards methods that efficiently facilitate a continuous or short-term periodic revision of existing forest resources data bases. These methods commonly involve the detection and the monitoring of changes or disturbances in the

forest canopy via remote sensing technology. They can lead to considerable reductions in overall management costs since detailed assessment efforts in the field can be concentrated exclusively on those areas that are found to be changed or disturbed.

Satellite-based remote sensing tools such as the Landsat Thematic Mapper (TM) offer synoptic (across-track swath of 185 km) and repetitive (16 day repeat cycle) data acquisition capabilities in those regions of the electromagnetic radiation spectrum that differentiate the biophysical characteristics of vegetation features (e.g., the visible, near-infrared and middle-infrared). The sensor therefore has the potential to detect, identify, and map disturbances that are important from the perspective of the forest resource manager.

Forest cover disturbances as seen by a digital sensor are affected by spatial, spectral, thematic and temporal constraints. This makes digital change detection an intricate task to perform. A photointerpreter analyzing, for example, large-scale color infrared (CIR) aerial photography will almost always produce more accurate results for a higher degree of precision (Edwards, 1990). However, visual change detection is difficult to replicate; that is, different interpreters produce different results. Manual detection also incurs substantial data acquisition costs. Most digital change detection methods that have proven to be consistent are based on per-pixel classifiers and change information contained in the spectral domain of the imagery (Teuber, 1990). Generally, statistical decision rules are derived from a descriptive change model and constitute the backbone of the approach. Change is depicted at the pixel (picture element) level as defined by the spatial resolution (size of the pixel) of the sensor. For example, the TM has a pixel resolution of 30m, which results in canopy disturbances being assessed over 30m x 30m cells, where the cell is considered a homogeneous entity.

Forest resource managers traditionally have always conversed in terms of "stands", where the stand is a land parcel defined as having a homogeneous condition with respect to specific management objectives. Stand, however, is not synonymous with "cover type". The latter is a broader designation emphasizing species composition and some other ecological parameter such as, for example, crown closure. Stand can be alternatively defined as the lowest level of a forest resources classification system where the forest is subdivided into areal units on the basis of spatial patterns that affect resource use and natural processes (Bailey et al., 1978).

While remote sensing technology performs relatively well where the monitoring of natural processes is concerned, it does so at the resolution of the sensor. Although many attempts have been made to simulate stand delineation via image segmentation techniques (Edwards, 1990) and convolution filtering (Coppin and Bauer, 1992), they have met with varying degrees of success. The adequate incorporation of decisions on resource use (unit size, unit delineation, condition for unit definition, etc.) still requires the active intervention of an operator/analyst with in-depth resource management knowledge.

This paper discusses a case study in north central Minnesota where the synergism of forest canopy change information, as derived from Landsat TM imagery, and actual forest stand data is investigated from a resource management angle. Whereas the loss of the stand concept from the digital evaluation process is an undeniable drawback, the process nevertheless provides information at the substand (pixel) level. The main objective of the research was to analyze the value of this substand information from the perspective of the resource manager who is accustomed to dealing with stands only.

2. METHODS

2.1. Study area

The study site was located in the southwestern corner of Beltrami County in north central Minnesota. Geomorphologically, the area is part of the northern glacial till plain. The bedrock is crystalline and the landscape is nearly level to gently rolling. Soils are loamy and have developed on calcareous till resulting in a generally high water holding capacity and in good drainage. The southernmost tip of the study site belongs to the Bagley Outwash Plain, where soils are much sandier, have gravel substrata, and also have a much lower water retention capability. The local climate is continental with wide extremes in temperature from summer to winter. The yearly precipitation ranges from 563 to 640 mm, with half of it falling in the form of rain during the summer and the other half as snow.
The area is characterized by a predominant, although not continuous, forest cover encompassing the intricate mixture of tree species and vegetation types that is typical of Northern Minnesota. Major tree species include aspen (*Populus spp.*); birch (*Betula spp.*); balsam fir (*Abies balsamea*); jack pine (*Pinus banksiana*), red pine (*Pinus resinosa*); white pine (*Pinus strobus*); black spruce (*Picea mariana*); white spruce (*Picea glauca*); tamarack (*Larix laricina*); and northern hardwoods (*Fraxinus nigra, Quercus rubra, Tilia spp., Acer spp.*, etc.). Both the Beltrami County and the Minnesota Department of Natural Resources (DNR) forest lands have been under active management since at least the early 1980's. Data from the 1981 management forest inventory were available in three formats : section overlays with stands delineated by photo interpretation of 1:15,840 black and white infrared 1981 aerial photography and updated in the field; original field tally sheets; and compiled township forest stand maps. For county lands, forest plantation records and data on timber sales and other management interventions, although not complete, were available for the last decade. No such records were found for state, federal and private lands.
To test the temporal cycles for inventory updating suggested by Gregory et al. (1981) and Park et al. (1983), forest cover disturbances over two, four, and six year intervals were studied. From the management perspective, this covered both short and long periods and allowed us to determine the system's self-consistency, i.e. whether the recorded changes over six years were similar to the sum of the recorded changes over two and four years. This temporal resolution required the selection of a site that had the relevant reference data available. The elongated shape (9.6 km x 43.2 km) and the size (about 41,500 hectares) of the study area (Figure 1) were dictated by the available multitemporal aerial photography. The latter set consisted of color (four flight lines) and CIR (one flight line) 35mm positive transparencies (slides) for May 1984, CIR slides (all flight lines) for May 1986, and CIR slides (all flight lines) for early October 1990.

2.2. Generation of stand-based information

The available 1981 township stand maps lacked the cartographic precision required to adequately meet the research objectives. Moreover, their information classes were not directly relevant to the forest management practices of the area, and were, in some cases, not detailed enough, too detailed, or even incorrect.

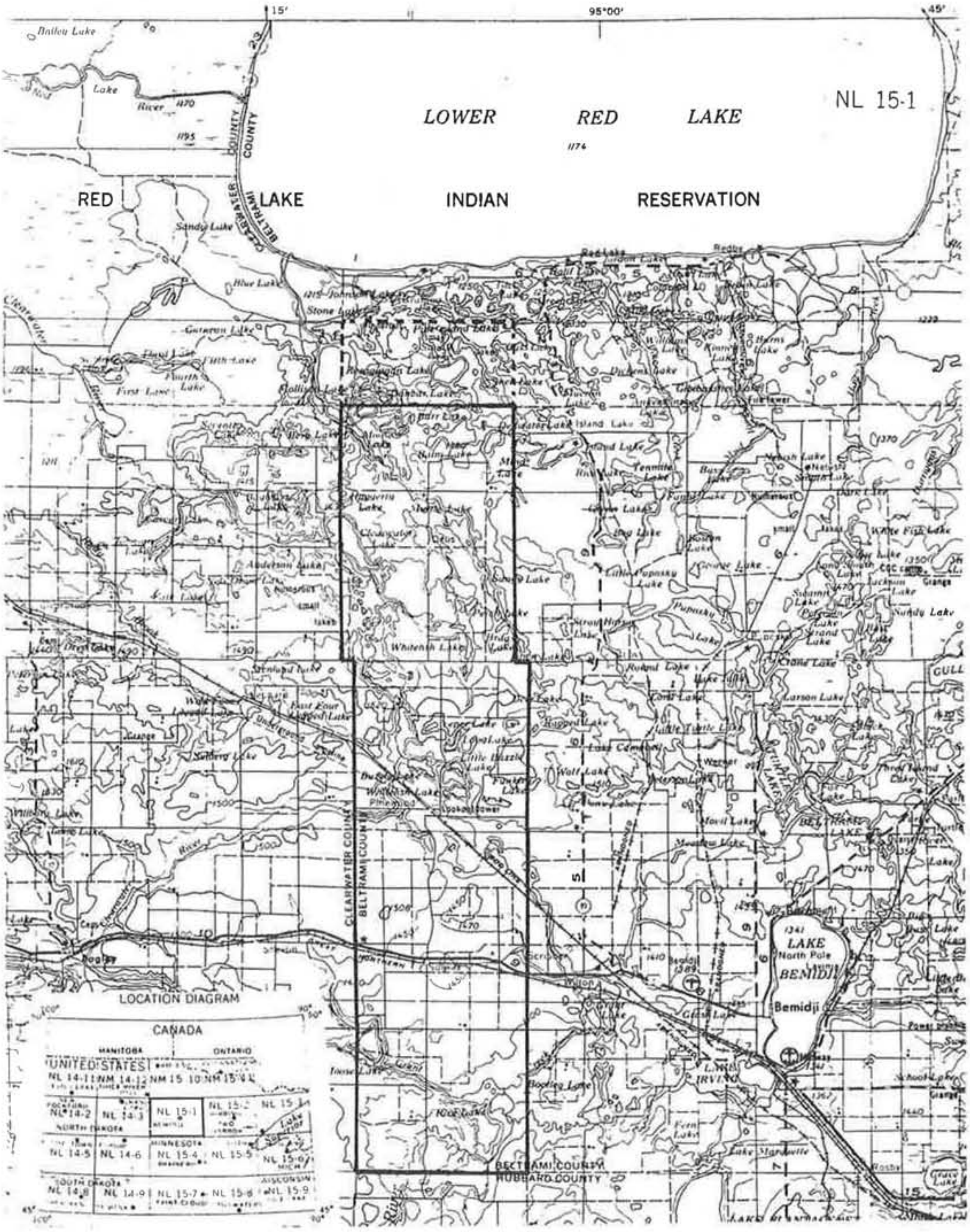

Figure 1. Study area in Northern Minnesota (original map USGS 1:250,000 - NL 15-1)

A multitemporal data generation procedure was developed based on a proven design (Coppin et al., 1986) but adapted to the available information sources for the study area. The procedure incorporates various steps :

1. The creation of an accurate, stable map base.

2. 1981 forest type reclassification into management categories in which the categories reflect the threshold zones important for management planning.

3. Cover type identification, stand delineation, and change information extraction (canopy depletion, canopy increment, storm damage, and no change) from the aerial photography (enlarged via projection from a nominal scale of around 1:100,000 to 1:15,840), from the 1981 reclassified stand maps, from ancillary data sources, and from management knowledge.

4. Data transfer to the map base.

5. Polygon digitizing in a vector environment with subsequent transformation into raster format (same cell size as TM data : 30m x 30m).

In the final data base all non-public lands were masked out. A total of 3,715 stands were mapped in 1984 and subsequently monitored for change. Two hundred twenty nine stands were classified as changed over the two-year interval, 465 over the four-year interval, and 759 over the six-year interval. Note that damage from the 1985 storm could not be differentiated anymore from other depletion events over the four- and six-year periods. The distribution of these canopy disturbances over the stand cover types is summarized in Table 1.

2.3. Generation of pixel-based change information

A brief summary of the digital change detection procedures developed for this study is presented here. Interested readers are referred to Coppin and Bauer (1993) for a detailed technical description.

The multi-date (1984, 1986, 1990) satellite TM imagery necessary to support this research was not obtained on a specific anniversary date, but within an anniversary window. The July-August window was selected taking into account the following criteria : monthly percent cloud cover, based on the examination of the Landsat imagery available for the area of interest since 1980; phenological stability of forest cover; seasonal soil moisture content; and sun angle effects. The acquisition window was centered a bit later than the date the forest vegetation is seasonally fully mature. From an operational standpoint, this led to increased flexibility because it permitted the actual acquisition dates to be chosen from a satellite overpass either somewhat later or earlier than that of the true anniversary date in the driest, most cloud-free period of the year.

Preprocessing of the satellite images prior to change detection processing and analysis had as its unique goals the establishment of a more direct linkage between data and biophysical phenomena, the removal of data acquisition errors and image noise, and the masking of contaminated (e.g., clouds) and/or irrelevant (e.g., urban land cover) scene fragments. Preprocessing routines encompassed, in chronological order of execution, calibration to exoatmospheric reflectance, scene rectification, atmospheric correction, and interpretability enhancement via vegetation index generation.

TABLE 1

Distribution of the change events over the original forest cover types (from stand-based assessment)

Change classes[2]		Total area (hectares)	Distribution (%) over the forest cover type groups[1]							
			1	2	3	4	5	6	7	8
Two years	1	259	50	29	11	1	2	1	5	1
	2	439	3	56	-	41	-	-	-	-
	4	165	7	87	1	5	-	-	-	-
Four years	1	736	29	56	4	7	1	1	-	2
	2	838	16	38	-	41	-	3	1	1
Six years	1	1229	38	41	6	5	7	1	1	1
	2	817	4	49	1	31	1	14	-	1

[1]Cover type groups are: (1) aspen/birch/balm of Gilead, (2) jack pine, (3) balsam fir, (4) red pine/white pine/Scotch pine/white spruce, (5) hardwoods, (6) tamarack/cedar/black spruce, (7) ongoing or finished clearcuts, and (8) grass and brush.
[2]Change classes are: (1) active canopy depletion, (2) active canopy increment, and (4) storm damage.

Calibration of the six reflective TM bands followed the algorithms proposed by Markham and Barker (1987). Scene rectification was carried out independently for each image via a second-order polynomial warp function using a common set of ground control points (GCP's) and yielding an overall residual mean square error of less than a quarter pixel. The atmospheric correction procedure combined two major components : atmospheric normalization and transformation to ground reflectance. A statistical regression approach based on spatially well-defined, temporally stable features (deep lake; mature, even-aged pine stand; flat roof; gravel surface; concrete slab) was used to normalize the satellite data over time. Subsequently, a dark-object subtraction technique to adjust for atmospheric scattering was applied and reflectances were transformed into vegetation indices (VI's).

Converting canopy spectral reflectances into VI's combines the ability of the VI's to considerably reduce the data volume for processing and analysis with their inherent capability to provide information not available in any single band. The VI's values furthermore have a semi-continuous nature. This characteristic is preferred over the discrete values resulting from vegetation classification operations, especially when considered as input values to multitemporal change models (Sader, 1988). Seven of the most widely used VI's were computed for each scene : brightness, greenness, and wetness (Kauth and Thomas, 1976); a modified normalized difference vegetation index (TM4/[TM4 + TM3]); the near-infrared over green (TM4/TM2) and near-infrared over mid-infrared (TM4/TM5) band ratios; and the red (TM3) band.

Actual change detection was carried out using two different algorithms; standardized image differencing and pairwise principal component analysis :

$$change\ indicator = (VI_{time1} - VI_{time2}) \ / \ (VI_{time1} + VI_{time2})$$

$$change\ indicator = PC_2(VI_{time1}, VI_{time2})$$

This resulted in 2 x 7 or 14 change feature data sets for each of the three time intervals of interest (two, four, and six years). Data redundancy was diminished via feature selection with Jeffries-Matusita divergence measures to a level of six features (Swain, 1978). Next, a supervised classification algorithm using the maximum-likelihood decision rule was implemented for change information extraction. Change classes were identical to those defined for the stand-based approach : canopy depletion, canopy increment, storm damage, and no change. Finally, a 4x4 majority filter was passed over the classified imagery to approximate the way cover type units were delineated on the aerial photography.

2.4. Cross-referencing of stand versus pixel information

To appropriately assess the correspondence between the digital change detection results and the stand-based change information (further referred to as "the accuracy of pixel-based versus stand-based data"), complete enumeration, discrete multivariate statistics derived from contingency tables (Story and Congalton, 1986), and raster-based geographical information system (GIS) modeling tools were utilized. First, Kappa coefficients of agreement (Hudson and Ramm, 1987) were computed for each time interval,

where larger Kappa values indicate higher accuracy.
Second, the relationships between digital change detection results and descriptive stand parameters (dominant tree species, stand development stage, and canopy closure class) were analyzed in a GIS environment. Classification inconsistencies are not expected to be randomly distributed, but usually display a systematic occurrence in space and are likely to be preferentially associated with certain categories (Campbell, 1981). The GIS models developed to examine such trends had two categorical data layers as input : stand-based information (type, development stage, crown closure) and error analysis results of the pixel-based digital change detection (error types, e.g., omission storm damage). The models created new spatial data layers where the individual pixel values no longer had a descriptive information content, but exclusively depicted the cell's position in a two-dimensional matrix, cross-referencing (row versus column) the two categories being investigated.
Third, aspects such as the frequency of occurrence of particular inconsistencies between pixel-based change information and stand data (further referred to as "errors") in stands with specific spatial characteristics (size, shape, and spatial complexity) were evaluated.
It was initially assumed that errors may have arisen more frequently in polygons (representing the spatial delineation of the forest stand) of particular sizes, shapes, locations, and arrangements. Errors also were presumed to have a specific spatial relationship to the polygons in which they occurred. For example, they may tend to arise at the edges of the polygons. To examine such aspects, descriptive stand parameters such as polygon area, shape index (SI = perimeter^2/area), and a spatial complexity factor, embodied by number of nodes belonging to the polygon boundary in vector format, were computed for each individual forest stand and cross-referenced against the error information. Edge or boundary pixels were considered as a separate category.

3. RESULTS AND DISCUSSION

Due to residual instability of the platform/sensor combination, we were unable to correct for a within-pixel shift in the multitemporal TM imagery. This phenomenon slightly degraded the change detection capabilities at the change / no change edges, reducing the accuracy of a satellite-image-derived areal assessment of the change events somewhat. Because this limitation is inherent to the digital change detection methodology, it was decided to implement a two-pronged approach to the cross-referencing of pixel-based versus stand-based data. From a map-derived contingency matrix where all edge pixels had been eliminated using a 3x3 boundary filter, overall accuracy, average class accuracy and Kappa coefficients of agreement were calculated for each disturbance period. These parameters were thought to adequately reflect the thematic correspondence between pixel-based and stand-based information. The coefficient of areal correspondence, on the other hand, quantifies the spatial correspondence for all pixels, and as a consequence represents a measure of cartographic correspondence. It was computed from a contingency matrix encompassing all pixels.
Table 2 summarizes the cross-referencing at the pixel level of the digital change detection results versus the rasterized stand data, where the latter are considered to represent the "truth" against which the accuracy is assessed. The slightly lower values of the areal correspondence coefficients as compared to the overall accuracy figures effectively indicate that misclassification is greater at the edges of the stand polygons.

TABLE 2

Pixel-based change detection accuracy (versus stand data)

Time interval	Overall accuracy	Average class accuracy	Kappa coefficient	Areal correspondence coefficient
2 years	97%	79%	0.76	93%
4 years	96%	90%	0.83	89%
6 years	94%	91%	0.82	87%

Kappa values signify that the digital change classification is, for example, 76 % (Kappa = 0.76) better than would be expected if the pixels were randomly assigned to the change classes of interest.

Part of the discrepancy between stand data and classified imagery can be attributed to the presence of stands that were either incorrectly evaluated as disturbed, or mistakenly omitted from the change domain. A detailed examination of the pixel-based classification outcome at the individual stand level resulted in the following results, that are valid for all change events :

1. All disturbed stands smaller than one hectare and totally surrounded by undisturbed forest cover (n = 33) were not detected.

2. All unchanged stands smaller than one hectare and completely encircled or largely surrounded by disturbed forest cover (n = 24) were misclassified and clumped together with the nearest change event.

3. There was no statistically significant relationship between the size, shape and spatial complexity parameters of these "smaller than on hectare" erroneously classified stands. For example, the best R^2 for a linear model between size and shape was only 0.13.

4. Three larger unchanged stands that had a distinct elongated form, were wedged in between disturbed forest cover, and ranged in size from 1.0 to 2.6 hectares, were also misclassified as changed.

While these results are revealing, the complementary character of pixel- and stand-based change information and its relevance to forest management can be much more explicitly illustrated by an analysis of the "error" structure of the final digital change classification versus the original descriptive stand parameters. The classification error types that occurred at the pixel level are summarized in Table 3. The distribution of those errors over the original stand classes explicitly unveiled the complementary relationships (Tables 4, 5, and 6). However, while examining these tables, it is important to interpret the frequency numbers relative to the total area of the error type (column 2), and to realize that area figures do not embody spatial continuity, but merely depict the total number of pixels for which the digital change classification was inconsistent with the stand data.

TABLE 3

Error types as defined for the error structure analysis

Error code	Description
for two-, four-, and six-year periods:	
1	omission active canopy depletion
2	omission active canopy increment
3	commission active canopy depletion
4	commission active canopy increment
5	classified active canopy depletion for active canopy increment
6	classified active canopy increment for active canopy depletion
for two-year period only:	
7	omission storm damage
8	commission storm damage
9	classified active canopy depletion for storm damage
10	classified active canopy increment for storm damage
11	classified storm damage for active canopy depletion
12	classified storm damage for active canopy increment

In combination with intensive field investigations, the following observations were made :

1. Errors across change events (types 5, 6, 9, 10, 11, 12) were minor, except for the classification of storm damage as active canopy depletion. Storm damage, however, invariably entails active canopy loss. It was also visually verified that young pine plantations, always categorized as active canopy increment subjects at the stand level, encompassed segments that had degraded because of changing microsite conditions (fungal attacks, flooding, competition with shrubs and grasses, etc.). For such stands, pixel identification as canopy depletion represented a first source of substand information.

2. Failure to detect change events as reported in the stand data (types 1, 2, 7) was the most common source of error over the two-year interval (52% of the total error), but represented only 36% and 35% of the error for the four- and six-year periods respectively. The trend appeared reversed for the overall commission error (types 3, 4, 8) with 41% for two years, 57% for four years, and 59% for six years. A detailed study of the canopy in 100 randomly chosen 2x2 pixel blocks that were classified under these error types confirmed that the digital disturbance monitoring methodology was capable of detecting canopy changes as they gradually became more notable in the stand, while the stand-based assessment did not allow for this temporal differentiation.

3. The inefficiency of the system in detecting some of the active canopy increment phenomena (type 2) occurred primarily in regenerating conifer stands with low stand density, and in young aspen regeneration. Although pine plantations were automatically classified as canopy increment during stand data generation, tree growth on some of the poorer sites in the study area was verified as actually being stagnant. Furthermore, while texture and the third dimension in the stereoscopic aerial photography made it possible to monitor aspen regeneration in its earliest phases, the digital disturbance monitoring methodology could not detect it after the first or second year of sucker growth. Here the digital approach was clearly inferior. It was also found that the few pixels of aspen regeneration that were digitally classified over the four- or six-year period in the active canopy increment group, covered areas where there had been limited stand development during the regeneration phase.

4. The digital methodology detected active canopy depletion events in many merchantable or over-mature aspen and jack pine stands when the stand data reflected no such changes. Most of these type 3 errors were proven to represent local dieback phenomena within these stands. It was further confirmed that this error type included localized insect infestations in young aspen stands, where the events were not detectable or significant enough on aerial photography to warrant a new stand delineation.

5. The majority of type 1 pixels belonged to merchantable and over-mature aspen and jack pine stands. It was substantiated that they essentially portrayed hardwood and brush clumps smaller than 1/4 hectare that were left untouched during clearcut and/or highgrading operations.

6. As part of the stand data generation procedure, most older jack pine and aspen stands were invariably categorized (and this largely for economic reasons) as merchantable and well-stocked even while exhibiting some evidence of incomplete crown closure in the aerial photography. Field visits repeatedly corroborated that in these stands the vegetative canopy was locally expanding or still developing, either among the dominant crowns (jack pine lateral crown extensions) or in the understory in the form of regeneration or secondary species growth (e.g., balsam fir under aspen). It is evident that this canopy expansion contributed to the spectral/radiometric signature of the particular pixels, resulting in the detection of active canopy increment (error type 4).

7. The section of the study area that was subjected to a major storm causing serious windfall in July 1985 exhibited a very heterogeneous spatial pattern leading to fragmentation of the original (1984) stands. Typically, stands classified as storm-damaged, and to a lesser extent those not classified as such but still located in the periphery of the storm track, depicted varying degrees of coarseness in the texture of the aerial photography. As a consequence, the digital change detection methodology, ignorant as it was of stand boundaries, appropriately detected some pixels in storm-damaged stands as unchanged (error type 7) and some in surrounding stands as storm-damaged (error type 8). Although it was impossible to field-verify this assertion (by 1989 the direct effects of the storm were no longer visually apparent), experience in the assessment of storm damage with aerial photography at the stand level largely supports this observation.

TABLE 4

Error distribution for disturbance monitoring over the two-year period

Error type	Total area(ha)	Percent of total error	Distribution (%) over: cover types[1]								development stages[2]				density classes[3]			
			1	2	3	4	5	6	7	8	1	2	3	4	1	2	3	4
1	87	16	53	21	13	4	7	-	2	-	-	-	75	25	27	48	-	25
2	136	25	5	67	-	29	-	-	-	-	95	3	2	-	92	8	-	-
3	101	18	34	27	8	13	6	9	1	2	16	6	63	15	37	44	4	15
4	91	16	19	54	1	15	3	5	1	2	46	5	31	18	51	29	2	18
5	11	2	1	25	-	74	-	-	-	-	98	1	-	1	66	33	-	1
6	6	1	-	56	-	-	-	-	29	15	-	-	18	82	-	18	-	82
7	58	11	11	78	2	9	-	-	-	-	9	-	78	13	-	87	-	13
8	26	5	5	87	1	5	-	2	-	-	3	-	65	32	6	60	2	32
9	28	5	2	90	-	8	-	-	-	-	8	1	88	3	-	97	-	3
10	3	1	-	100	-	-	-	-	-	-	-	-	97	3	-	97	-	3
11	2	-	3	45	28	-	-	-	21	3	-	-	68	32	-	68	-	32
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[1]Cover type groups are: (1) aspen/birch/balm of Gilead, (2) jack pine, (3) balsam fir, (4) red pine/white pine/Scotch pine/white spruce, (5) hardwoods, (6) tamarack/cedar/black spruce, (7) ongoing or finished clearcuts, and (8) grass and brush.
[2]Development stages are: (1) regeneration, (2) immature, (3) merchantable, and (4) over-mature.
[3]Density classes are: (1) understocked, (2) well-stocked, (3) to be thinned, and (4) the same over-mature group from above.

TABLE 5

Error distribution for disturbance monitoring over the four-year period

Error type	Total area(ha)	Percent of total error	Distribution (%) over cover types[1]								development stages[2]				density classes[3]			
			1	2	3	4	5	6	7	8	1	2	3	4	1	2	3	4
1	35	15	51	30	5	6	3	4	-	1	1	5	65	29	44	27	1	28
2	185	21	25	42	-	29	1	2	-	1	89	2	9	-	48	51	1	-
3	288	32	32	33	3	13	5	3	1	-	13	7	61	19	25	52	4	19
4	224	25	25	29	4	12	5	19	4	2	26	6	55	13	39	46	3	12
5	34	4	18	18	-	60	-	-	-	3	100	-	-	-	32	68	-	-
6	30	3	24	63	4	3	-	-	2	4	2	1	61	36	53	11	-	36

[1]Cover type groups are: (1) aspen/birch/balm of Gilead, (2) jack pine, (3) balsam fir, (4) red pine/white pine/Scotch pine/white spruce, (5) hardwoods, (6) tamarack/cedar/black spruce, (7) ongoing or finished clearcuts, and (8) grass and brush.
[2]Development stages are: (1) regeneration, (2) immature, (3) merchantable, and (4) over-mature.
[3]Density classes are: (1) understocked, (2) well-stocked, (3) to be thinned, and (4) the same over-mature group from above.

TABLE 6

Error distribution for disturbance monitoring over the six-year period

Error type	Total area(ha)	Percent of total error	Distribution (%) over: cover types[1] 1	2	3	4	5	6	7	8	development stages[2] 1	2	3	4	density classes[3] 1	2	3	4
1	226	21	45	25	7	5	13	3	1	1	8	2	70	20	31	49	-	20
2	156	14	6	25	2	27	-	38	-	2	77	3	8	12	97	3	-	-
3	513	47	48	19	3	9	12	9	-	-	13	8	67	12	34	52	2	12
4	135	12	19	44	4	17	4	12	-	-	14	10	51	25	22	50	3	25
5	25	2	4	9	-	67	6	-	9	6	87	-	13	-	81	19	-	-
6	29	3	44	40	1	9	1	3	2	-	33	3	32	32	10	58	-	32

[1]Cover type groups are: (1) aspen/birch/balm of Gilead, (2) jack pine, (3) balsam fir, (4) red pine/white pine/Scotch pine/white spruce, (5) hardwoods, (6) tamarack/cedar/black spruce, (7) ongoing or finished clearcuts, and (8) grass and brush.
[2]Development stages are: (1) regeneration, (2) immature, (3) merchantable, and (4) over-mature.
[3]Density classes are: (1) understocked, (2) well-stocked, (3) to be thinned, and (4) the same over-mature group from above.

Out of a total of 759 stands reported in the stand data as having been affected by disturbance events over the six-year period, the digital change information completely missed only 45 (all pixels that made up the stand classified as no change). Stand size was the limiting factor, as these 45 stands were all smaller than one hectare. Shape and spatial complexity, on the other hand, did not play a significant role in change detectability at the stand level. In the other 714 stands (94%), change was detected in varying proportions (at least 50%) of the total number of pixels that made up the individual stands. Results are comparable for the four-year interval and slightly inferior for the two-year period, which points to an optimal revisit cycle somewhere between four and six years.

4. CONCLUSIONS

As a first conclusion, one may state that a digital monitoring methodology such as the one introduced here is capable of consistently detecting management-relevant changes in forest stands. The methodology is being experimentally implemented in a new state-wide phase I forest inventory design for Minnesota, jointly proposed by the United States Forest Service North-Central Forest Experiment Station and the Minnesota Department of Natural Resources, and known under the acronym AFIS, or Annual Forest Inventory System (Hahn et al., 1992).

While not always capable of delineating forest canopy disturbances exactly as they are traditionally depicted at the stand level, pixel-based change information was shown to contribute a significant amount of substand information that is extremely valuable to the forest manager. However, because of the unavailability of an analytical evaluation tool for the textural domain and due to sensor resolution limitations, the TM-based digital methodology also lost some information that is customarily extracted from aerial photography Examples of this are monitoring of the early development of aspen regeneration after initial crown closure and detection of wildlife openings (0.5 hectares).

Pixel-based change information as generated from TM imagery via the described methodology demonstrated its potential to effectively contribute to the sustained management of forest resources, especially when pre-change stand-based information is already available. Moreover, the system is self-consistent for the four change classes under consideration (canopy depletion, canopy increment, storm damage, no change). For this study site and for the time intervals of interest (2, 4, and 6 years), it provided the following substand information in combination with the actual location of the change event within the stand (at the pixel scale) : localized small-scale dieback, whatever the origin (disease, flooding, insects, etc.); establishment, survival, and growth problems in conifer plantations before canopy closure; trespasses in neighboring stands after clearing/logging operations; and locality-specific storm damage or lack thereof.

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