Ross F. Nelson
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Detecting Forest Canopy Change Due to Insect Activity Using Landsat MSS

A vegetative index difference (VID) transformation most accurately delineates forest canopy change.

Abstract: *Multitemporal Landsat multispectral scanner data were analyzed to test various computer-aided analysis techniques for detecting significant forest canopy alteration. Three data transformations–differencing, ratioing, and a vegetative index difference–were tested to determine which best delineated gypsy moth defoliation. Response surface analyses were conducted to determine optimal threshold levels for the individual transformed bands and band combinations. Results indicate that, of the three transformations investigated, a vegetative index difference (VID) transformation most accurately delineates forest canopy change. Band 5 (0.6 to 0.7 μm) ratioed data did nearly as well. However, other single bands and band combinations did not improve upon the band 5 ratio and VID results.*

Introduction

Foresters have traditionally relied on aerial photography, aerial sketchmapping, and ground sampling techniques to maintain and update their forest inventory records. These inventory techniques, though effective, are cumbersome, and catastrophic events can quickly change the quantity and condition of the wood resources available. Fire, wind throw, ice, and insect damage may profoundly affect a manager's decisions concerning harvesting, silvicultural, and pest control practices in his district. Change detection techniques which quickly and accurately delineate forest canopy alteration can provide the information necessary to make intelligent management decisions.

Satellite data may be used to detect gross forest canopy alterations. Numerous studies have shown that broad cover types, such as conifer, hardwood, agricultural areas, water, etc., may be consistently and reliably classified using satellite data (Fleming and Hoffer, 1977; Gregg *et al.*, 1979; and others). Satellite remote sensing, however, does have limitations and various studies have demonstrated an inability to consistently and accurately identify tree species, crown density differences, or age class differences (Ernst and Hoffer, 1979; Gregg *et al.*, 1979; and others). These characteristics of a forest stand may be critically important in terms of an assessment of the impact of canopy change within a forest.

Due to these limitations, some researchers have suggested that Landsat data may best be utilized as the first stage in a multistage sampling design (Heller, 1978; Smith, 1979), where the delineation of broad cover types is all that is necessary. Similarly, temporal Landsat data should be useful for monitoring significant levels of forest canopy alteration, as only change versus unaltered areas need to be delineated. Once change areas are identified, finer resolution systems and ground observations could be used to provide the details necessary for making intelligent management decisions.

This investigation assesses the capability of Landsat data and computer-aided analysis techniques to provide such first stage change information. Three data transformation techniques referred to as differencing, ratioing, and vegetative index differencing (VID) were analyzed to deter-

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mine which provided the best delineation of forest canopy alteration. Thresholding (density slicing) techniques were used to discriminate changed and unchanged areas. In addition, the three data transformation techniques were evaluated using various band combinations and threshold levels to determine which combination(s) of bands, threshold levels, and transformation techniques maximized change classification accuracy.

LITERATURE REVIEW

Digital change detection aproaches may be characterized by (1) the data transformation procedure (if any), and (2) the analysis techniques used to delineate areas of significant alterations. A tabular breakdown of a variety of change detection approaches is given in Table 1, along with references to those who have used that particular approach. The purpose of the table is twofold. First, it is a concise, if incomplete, summary of the change detection work done to date. Second, it gives the reader an idea of the number of approaches available for digitally detecting land-cover alterations. Many of the approaches presented in the table but not discussed below are reviewed by Nelson (1982).

Of the many transformations available, three were selected for study—differencing, ratioing, and vegetative index differencing. The difference transformation was selected (1) because it is the most widely used transformation, hence it serves well as a comparative index, and (2) because various authors have found the classification accuracy resulting from this transformation to be as good or better than that obtained using more sophisticated approaches. The ratio transformation was investigated to determine the impact of a mathematical operand on the same data sets (i.e., is it inherently better to subtract or divide data?). The vegetative index difference was studied to see if a remote sensing measure directly related to canopy closure performed better than relative reflectance comparisons (i.e., differencing and ratioing).

A four-band differenced image is produced from an eight-band multitemporal data set by subtracting the pixel value in a particular band at time one from the corresponding value at time two. The transformation is, perhaps, the most fundamental approach to accentuating spectral, hence land-cover, change.

Stauffer and McKinney (1978) reported change classification success using differenced data to detect urban encroachment in Austin, Texas. Toll *et al.* (1980) investigated three change detection procedures for delineating the urban/rural boundary: Image differencing, principal components transformation prior to differencing, and a delta classification (comparison of two independent land cover classifications). They found that image differencing produced the highest classification accuracies. Ingram *et al.* (1981) found that a simple image differencing and thresholding approach produced urban change results for the Denver, Colorado area that were as good as much more sophisticated approaches. Robinove *et al.* (1981) used Landsat MSS and thresholding techniques to monitor arid land conditions in southwestern Utah. In this study the researchers differenced albedo images (ratio of reflected to incident radiation in the 0.5 to 1.1 μm region) to determine terrain characteristics. They successfully delineated various spectral changes shown to be a function of soil moisture condition. They warned that such a data transformation is probably more useful in arid environments than in more humid regions, because the presence of appreciable vegetation spectrally confuses the moisture issue.

Ratioing is similar to image differencing in that both approaches compare relative reflectance measurements at two different times. However, grey levels are divided rather than subtracted to produce the transformed four-band image. Data ratioing has not been as intensively investigated as image differencing. Todd (1977) ratioed band 5 pixel values from two different years to determine urban change in Atlanta, Georgia. Only ratios to the low side of the mean were considered changed (threshold approach). He then classified the most recent MSS data set to determine the type of change that had occurred. His overall evaluation indicated that 91.4 percent of all land-use and land-cover change was correctly identified (areal, or per pixel accuracy). This included 78 percent of the total number of change areas (polygonal accuracy). Accuracies decreased when attempts were made to identify the types of change. Todd noted that omission and commission errors occurred, for the most part, in relatively small areas.

The vegetative index difference (VID) in this study, (Band 7/Band 5, time 1)–(Band 7/Band 5, time 2) for a given pixel, is fundamentally different from the first two transformations in that remote sensing measurements directly related to green biomass are compared. Landsat bands 5 and 7 are well situated for monitoring green vegetation; the 0.60 to 0.70 μm region (band 5) is centered on the chlorophyll absorption wavelengths of a green canopy, and the 0.80 to 1.10 μm reflective infrared region is highly reflected by vegetation due to the internal structure of the leaf (Tucker and Maxwell, 1976). The ratios of the reflectance measurements in the red wavelengths to those in the photographic IR are sensitive to the amount of green leaf biomass being sensed (Tucker, 1979). Comparing the 7/5 ratio between dates would provide an avenue for

TABLE 1. CHANGE DETECTION RESEARCH CATEGORIZED BY (1) THE DATA TRANSFORMATION USED (IF ANY) AND (2) THE ANALYSIS TECHNIQUE USED TO DETECT CHANGE

	Two Dates Analyzed Simultaneously								
		Transformed Data							
Analysis Technique Used to Detect Change	Raw Data	Difference	Ratio	Vegetative Index Difference	Regression	Greenness-Brightness	Principal Components	Correlation	Delta-Classification 2 Dates Analyzed Ind. Raw Data
S.D. Threshold (Density Slice)		Stauffer and McKinney (78) Toll *et al.* (80) Ingram *et al.* (81) Robinove *et al.* (81) Jensen and Toll (82) *	Todd (77) *	Angelici *et al.* (77) Banner and Lynham (81) *	Ingram *et al.* (81) Burns and Joyne (81)		Byrne and Crapper (80) Toll *et al.* (80)	Coiner (80)	
Supervised	Banner and Lynham (81) Williams and Haver (76) Burns and Joyce (81)	Anuta and Bauer (73)							Gordon (80) Wickware and Howarth (81)
Modified Supervised		Anuta (74)							Colwell *et al.* (80)
Spectral	Weismiller *et al.* (77)	Anuta and Bauer (73) Weismiller *et al.* (77) Barthmaier *et al.* (80)							Swain (76) Weismiller *et al.* (77) Joyce *et al.* (80) Riordon (80) Burns and Joyce (81)
Spectral-Spatial						Malila, 1980 Colwell *et al.* (80)			
Layered	Weismiller *et al.* (77)								
Visual Interpretation	Colwell *et al.* (80)								

Note 1. *'s mark the techniques tested in this study.
2. Not all techniques are listed; the permutations are numerous.

deciding whether or not a vegetation canopy has been significantly altered. Two studies have investigated this change classification approach. Angelici *et al.* (1977) demonstrated a capability to assess nonurban to urban change. Banner and Lynham (1981) used a vegetation index difference transformation and thresholding to delineate forest clearcuts. They compared the VID approach with a supervised classification approach using multitemporal MSS band 5 data. They found the VID method less effective for delineating clearcuts. Banner and Lynham suggest that the sensitivity of the near infrared wavelengths to the vegetation within the clearcut boundaries resulted in higher classification error rates for the VID approach. Though the band 7 sensitivity may limit the VID in the context of clearcut delineation, that sensitivity may be exploited to define areas defoliated by the gypsy moth.

The thresholding approach for discriminating changed from unchanged areas was chosen for this study on the basis of simplicity. The intuitive and procedural lack of sophistication of thresholding makes it operationally appealing. A greyscale value at time one is compared to the corresponding value at time two; large deviations from the mean indicate change. A number of researchers have used this technique in conjunction with many different data transformations to detect urbanization, deforestation, and desertification (see Table 1). In this study, threshold limits were defined to maximize change detection accuracy. The Landsat data were processed to define only two forest conditions, change or no change.

MATERIALS

19 July 1976 (2544-15001) and 27 June 1977 (2887-14520) Landsat scenes obtained over Harrisburg, Pennsylvania (path 17, row 32), were geometrically corrected, registered, and resampled to a 50-metre grid. A 286 line by 217 sample subsection corresponding to the Wertzville, Pennsylvania 7-1/2 minute USGS quadrangle map was chosen for analysis. The quadrangle encompasses mountainous areas which are heavily forested (predominantly oak-hickory). These forests were not defoliated in 1976, but were extensively damaged by the gypsy moth caterpillar in 1977. The 27 June 1977 data set was obtained during the peak defoliation period, which occurs from mid June through early July.

Color infrared aerial photography obtained 24 June 1977 over the entire quadrangle was available at a scale of 1:48,000. These airphotos (see cover photo) were used to delineate areas of heavy (60 to 100 percent leaf removal) and moderate (30 to 60 percent leaf removal) defoliation. Acetate film was laid atop the photos and the defoliated areas were outlined. This information was transferred to the 7-1/2 minute quad map using a Zoom Transfer Scope. The defoliation boundaries were then digitized from the quad map using the HP-3000 Geographic Entry System (Stauss *et al.*, 1978). The defoliation information and the Landsat data were registered to within 0.5 pixels in the line and sample directions.

The digitized defoliation information was combined with a Landsat derived forest/nonforest mask to form the ground reference image (GRI) to which all change detection products were compared. The forest/nonforest mask was generated from the 19 July 1976 "healthy" Landsat data set. Training statistics were extracted in a supervised manner for forested areas only, and were input to a Bayesian classifier. The classifier generated a confidence map that assigned to each pixel the probability that the pixel belonged to the forest class. This confidence map was then density sliced to separate the forested and nonforested areas. A stratified random sample of 230 pixels (115/strata) indicated that the mask's accuracy was 89.95 percent ± 5 percent at the 95 percent level of confidence.

Combining the forest/nonforest mask with the digitized defoliation information resulted in a four class ground reference image (GRI): non-forest, heavy defoliation, moderate defoliation, and healthy forest (see Figure 1). Any discrepancies between the defoliation data and the forest/nonforest mask were rectified in favor of the mask. In other words, if the defoliation information showed that a given pixel was moderately defoliated, but the mask showed it as nonforest, then the mask was assumed correct (i.e., that pixel would be non-forest in the GRI). The Interactive Digital Image Manipulation System (IDIMS) software (Electromagnetic Systems Laboratory, 1978) was used to manufacture the GRI.

IDIMS was also used to generate the transformed data sets from the raw multitemporal Landsat data. In addition, the image processing system was used to generate change images from these transformed data sets using thresholding techniques. The specific processes involved are explained.

The change products resulting from the thresholding of the transformed data were compared to the GRI to assess the accuracy of the change classification. The accuracy evaluations were done using a software package called ASSESS2. ASSESS2 compares two-byte images and quantitatively evaluates their similarity. One of the two images is designated the ground reference image (in this case, the GRI); the other, the classified image, is compared to the former. The software evaluates the accuracy of classification on a per pixel basis (Chaiken, 1979).

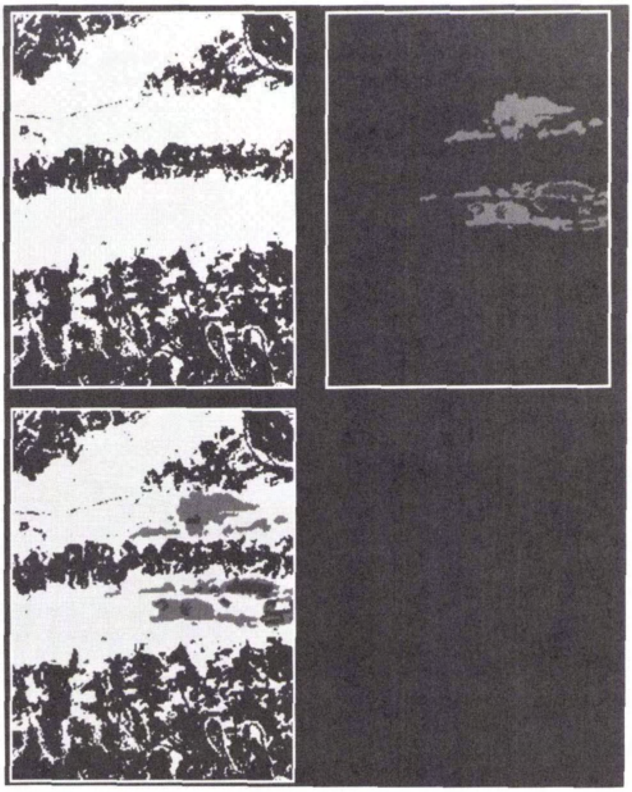

FIG. 1. The ground reference image was manufactured by combining the forest/non-forest mask and the digitized defoliation information.

upper left: forest/nonforest mask,
white—forest,
black—non-forest,
upper right: digitized defoliation information,
light grey—moderate defoliation,
dark grey—heavy defoliation.
lower left: ground reference image (GRI),
colors as noted above.

PROCEDURES

Three transformed data sets were produced from the 1976-1977 multitemporal Landsat data:

(1) *Difference:* A four-band differenced data set was produced by subtracting the 1977 pixel values within a particular band from the corresponding pixel values in the 1976 data set; that is,

$$D_{ijk} = X_{ijk,1976} - X_{ijk,1977} + 127$$

where

i = line coordinate,
j = sample coordinate,
k = band number (4-7),
X = greylevel value for that pixel,
D = differenced value, and
127 = constant added to produce a non-negative image assuming a dynamic range of 128 greylevels.

The differenced image values, then, may range from 0 to 254, with an expected mean of 127 if there is (1) no land cover change between the two dates, and (2) viewing conditions are identical with respect to illumination and atmospheric considerations.

(2) *Ratioing:* Again, an eight-band image was reduced to a four-band ratioed image, where the ratioed bands are manufactured thusly:

$$R_{ijk} = \frac{X_{ijk,1977}}{X_{ijk,1976}}$$

where all terms are as previously defined, and R = ratioed value of the given pixel.

Note that the differenced image is a byte, or discrete, image. The ratioed image is a real image with an expected mean of 1.00 for a given band given identical viewing conditions. The potential range of this image is 0.00 to positive infinity.

(3) *Vegetative Index Difference (VID):* A one-band image was produced, using four of the eight bands of the multitemporal data set, as follows:

$$DR_{ij} = \underset{\text{(healthy)}}{\frac{X_{ij7,1976}}{X_{ij5,1976}}} - \underset{\text{(defoliated)}}{\frac{X_{ij7,1977}}{X_{ij5,1977}}} + C$$

where

- i,j have been previously defined;
- 7,5 refers to the band numbers, 5 (0.60 to 0.70 μm), 7 (0.8 to 1.1 μm); and
- C is an arbitrary constant added to produce a non-negative real image.

In the case of the data used for this study, $C = 4.0$. The potential range of this image is 0.00 to positive infinity.

Two factors should be noted concerning the characteristics of these data transformations. First, the differenced image is a four-band byte, or discrete, image; the ratio and VID images are real, continuous images. Second, the difference and ratio transformations result in images which basically compare relative brightness measures at time 1 and at time 2 for a particular wavelength. The VID image is a comparison of remote sensing measurements directly related to green biomass at time 1 and 2.

This study was designed to define parameter levels for the transformation which maximized the accuracy of delineating defoliated areas. In order to meet that objective, an appropriate accuracy measure had to be selected. A combined classification accuracy was calculated and then maximized. The combined accuracy is merely the average of the average (per class) classification accuracy and overall (per pixel) accuracy. The combined figure was used in order to overcome the inherent biases of the other, more standard accuracy measures. Due to the fact that there was much more healthy forest than defoliated forest, average accuracy tended to favor lower thresholds, thresholds that would call an inordinate amount of area "change." Conversely, the use of overall classification accuracy would result in threshold levels that were too high. For instance, if the threshold were set at infinity (i.e., no change found), the overall accuracy would be 88.32 percent because healthy forest accounted for nearly 9/10ths of the forest cover in this area. The combined accuracy figure dampens these biases; hence, it was the metric used to measure quantitatively the goodness of a particular threshold level for a given band.

An empirical study was conducted to determine that optimal standard deviation threshold which produced the highest change classification accuracy for a particular transformed band. Because the loss of forest canopy produces a predictable spectral shift,* and because the study was concerned only with that alteration due to gypsy moth activity, outliers to only one side of the band mean were noted as change. For instance, for a given threshold level, only pixels to the low side of the threshold would be noted as change in a visible difference band; conversely, only pixels to the high side of the mean would be noted as change in an infrared differenced band. The relationship between change classification accuracy and threshold for a given transformed band was studied by generating change images for thresholds ranging from 0.00 to 2.50 standard deviations (sd), at 0.25-sd intervals. Thresholds every 0.05 sd around the initial empirical maximum were then tested. In this manner, the threshold value which resulted in the maximum classification accuracy could be determined within 0.05 standard deviations.

As noted previously, the difference and ratio data are four-band images. Thus, additional analyses were necessary to determine if various band combinations could improve detection capabilities. A sequential simplex design was used to explore the combined accuracy response surface for various band combinations. The purpose of this portion of the experiment was to explore the response surface of these multiband images in order to maximize the accuracy for any particular band combination. These maximized accuracies were compared to determine (1) if additional bands provided additional information and (2) which band combination best characterized forest canopy alteration due to gypsy moth defoliation.

A simplex design is one in which the experimenter mathematically brackets a "guessed at" maximum with different treatment combinations so that the response surface around that maximum can be explored. "Sequential" refers to the fact that the outcome of previous treatment combinations are used to establish new treatment combinations. The experimental approach is such that the investigator mathematically "steps" across the response surface to the maximum yield or response. The logic and mathematics of the approach may be found in Anderson and McClean, 1974, pp. 362-367; these pages are reproduced in Nelson (1982), Appendix A.

The best two and best three bands, as well as all four bands for the difference and ratio images were considered in the multiband analysis. Any given band was rated best or worst for a particular trans-

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* Forest canopy loss results in an increase in the visible reflectance (due to a loss of chlorophyll) and a decrease in the near infrared reflectance (due to a loss of reflective intracellular surfaces).

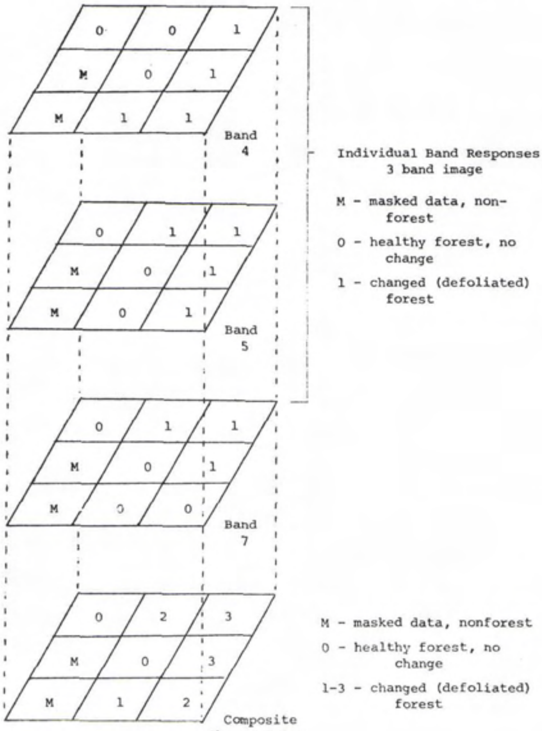

FIG. 2. Construction of a change image-multiband analysis. A pixel is considered changed if any of the bands involved note change. The composite change image is compared to the ground reference image.

formation based on the highest change classification accuracy attained in the empirical study. A composite change image was produced for a given band combination by adding the change/no-change results for the individual bands (see Figure 2). A pixel was considered changed if any of the bands found it changed.

RESULTS

ANALYSIS OF INDIVIDUAL BANDS

The individual bands of the various transformed images were investigated to determine which bands best classified defoliated areas as change. The following facts should be considered:

(1) The study is primarily quantitative. The sole measure of the capability of a given technique to accurately classify defoliation as change is the combined accuracy figure. No visual or qualitative judgements were involved in the selection process.

(2) No sampling error was involved in these accuracy assessments; the assessment included all of the forested pixels as defined by the forest/non-forest mask.

(3) Nonforest areas were masked; thus, any changes in the non-forest area were *not* considered in the accuracy figure.

(4) Only one side of the population distribution of a given band transformation was considered for detecting alterations due to gypsy moth defoliation. Tests were done where outliers on both sides of the mean were considered over a range of thresholds. The results from these tests were compared to the results when only one side was considered. In all bands tested (the four difference and the four ratio bands) the accuracy of the one-sided approach was higher than the highest accuracy when both sides of the mean were considered. Comparison of the one-sided and two-sided results showed that the healthy class was flagged as change significantly more often in the two-sided approach.

Table 2 presents the best individual band performances for the difference, ratio, and vegetative index difference images.

The VID image produced the highest combined change classification accuracy, closely followed by the ratio band 5 image. Within a multiband image (difference or ratio), the order of MSS band utility was 5, 7, 4, 6. In other words, the red band (MSS5) discriminated forest canopy change the best, and the first near infrared band was least useful. Differenced data, in general, produced slightly lower accuracies than the ratioed data. This slight decrease may be due to the discrete nature of the differenced data, which makes it relatively insensitive to response surface evaluation. This insensitivity may be noted in Table 2 where the optimal threshold for the differenced bands encompass relatively wide range of numbers. Changes in the sd threshold produce a real number which, when rounded, results in an identical byte threshold. Hence, a relatively wide range of sd thresholds will result in exactly the same change/no change classification.

Although the VID image performed only half a percent better than the best ratio band, further analyses indicated that the VID threshold/classification accuracy response was much more stable over a wider range of threshold levels, hence it may ultimately be more useful (Nelson, 1982).

The best single band to use to detect forest canopy change is the VID transformation (see Table 2). However, combinations of bands of the difference or ratio images may perform better than any of the individual bands. To investigate this possibility, a sequential simplex design was used to explore the various band combinations.

MULTIBAND ANALYSIS

The results of the sequential simplex experiment are given in Table 3. The thresholds listed are, theoretically, the treatment levels that will yield the maximum response (highest combined

TABLE 2. HIGHEST CHANGE CLASSIFICATION ACCURACY FOUND FOR THE INDIVIDUAL BANDS OF THE DIFFERENCE, RATIO, AND VEGETATIVE INDEX DIFFERENCE IMAGES

		Best Standard Deviation	% Correct Classification Accuracy							
			Ground Reference Class							
Image	Band	Threshold	Healthy[1]	Moderate[2]	Heavy[3]	Change[4]	Avg[5]	Over[6]	Comb[7]	Band Rank
Dif.	4	0.85-1.25	89.3	29.2	77.1	37.5	63.4	83.3	73.3	8
	5	0.35-0.60	83.4	49.2	97.1	59.1	71.2	80.6	75.9	3
	6	0.95-1.05	95.6	7.4	72.7	20.1	57.8	86.8	72.3	9
	7	0.45-0.65	89.7	30.1	93.0	42.3	66.0	84.2	75.1	5
Ratio	4	1.20-1.25	91.3	29.0	67.9	36.6	63.9	84.9	74.4	6
	5	0.65	85.9	49.4	96.6	58.6	72.2	82.7	77.5	2
	6	0.85	96.2	6.5	72.0	23.9	60.1	87.2	73.7	7
	7	0.25	91.3	25.6	92.6	38.7	65.0	85.1	75.1	4
VID		1.00	89.8	40.6	96.8	51.6	70.7	85.3	78.0	1

[1] % correct classification of healthy forest as unchanged, sample size = 31,067 pixels.

[2] % correct classification of moderately defoliated forest as changed, sample size = 3307 pixels.

[3] % correct classification of heavily defoliated forest as changed, sample size = 801 pixels.

[4] % correct classification, change (defoliated) areas. Change = (no. of change pixels in moderate defoliation + no. of change pixels in heavy defoliation)/(total no. of mod. and heavy pixels in ground reference image).

[5] Average classification accuracy = (% correct change + % correct no change)/2.

[6] Overall classification accuracy = total no. of correctly classified pixels/total no. of pixels.

[7] Combined accuracy = (Avg. + Over)/2.

accuracy) for a particular band combination. In actuality, these treatment levels may be viewed as approximations (i.e., close to the maximum) to the optimal treatment levels. Follow-on work showed that small improvements in classification accuracy (up to one half of a percentage point) could be expected if a micro-response surface investigation around the simplex maximum was conducted.

COMPARISON OF ALL APPROACHES

Comparison of the results of the single and multiband analyses for the three images show that (1) the VID transformation produced the highest combined classification accuracy; (2) the red channel, band 5, classifies gypsy moth defoliation more accurately than any other single untransformed channel or channel combination; (3) additional bands do not improve the discriminatory capability of differenced or ratioed data; and (4) ratioed data provided consistently more accurate results than did the differenced data. Table 4 describes the best performance for each of the three images.

A visual representation of these images and the ground reference information is given in Figure 3. The differences between the accuracies are in fact, very small (i.e., on the order of tenths of a percent). The VID, however, seems to reduce the speckle or false alarm problem encountered in the difference and ratio images.

CONCLUSIONS AND DISCUSSION

The following conclusions concerning the use of Landsat data for detecting and monitoring gypsy moth defoliation may be drawn from the literature review and the results of the study:

(1) A vegetative index transformation (such as the 7/5 ratio) classified defoliation slightly more accurately than a strict comparison of relative al-

TABLE 3. RESULTS OF THE SEQUENTIAL SIMPLEX EXPERIMENT TO DETERMINE OPTIMAL THRESHOLD LEVELS FOR BANDS USED IN COMBINATION

		Standard Deviation Threshold Level				% Correct Classification						
Image	Channel Comb.	Band 4	Band 5	Band 6	Band 7	Hth	Mod	Hvy	Change	Avg	Over	Comb.
Dif.	5, 7	0.47	1.70			83.0	49.9	97.1	59.1	71.1	80.3	75.7
Dif.	5, 7, 4	0.49	1.05	1.40		81.6	52.5	97.6	61.3	71.4	79.2	75.3
Dif.	5, 7, 4, 6	0.41	0.95	1.33	1.22	81.2	52.5	97.6	61.3	71.2	78.9	75.1
Ratio	5, 7	0.65	0.54			85.2	49.5	97.1	58.8	72.0	82.1	77.1
Ratio	5, 7, 4	0.95	0.93	1.19		86.7	44.6	94.4	54.3	70.5	82.9	76.7
Ratio	5, 7, 4, 6	0.59	0.65	1.50	1.07	83.4	52.0	97.2	60.9	72.1	80.8	76.5

TABLE 4. BEST CLASSIFICATION PERFORMANCE FOR DIFFERENCE, RATIO, AND VID IMAGES

Image	Band(s)	sd Thresh	Hth	Mod	Hvy	Chng	Avg	Overall	Combined
Difference	5	0.35-0.60	83.4	49.9	97.1	59.1	71.2	80.6	75.9
Ratio	5	0.65	85.9	49.4	96.6	58.6	72.2	82.7	77.5
VID	—	1.00	89.8	40.6	96.7	51.6	70.7	85.3	78.0

bedo measurements, i.e., the difference or ratio transformations. The vegetative index difference transformation has the added advantage of reducing four of the eight channel data set to one channel. The difference and ratio transformations reduce eight channels to four.

(2) Concerning differenced *or* ratioed data in the context of this study:

- Band 5 was the most useful single band for discriminating canopy alteration.
- Band 7 was the second most useful channel, band 4 third, and band 6 was the worst.
- In all cases, additional bands did not improve change classification performance. Note, however, that the composite change image was manufactured using a logical "or" operation; i.e., if any of the bands noted a pixel as changed, that

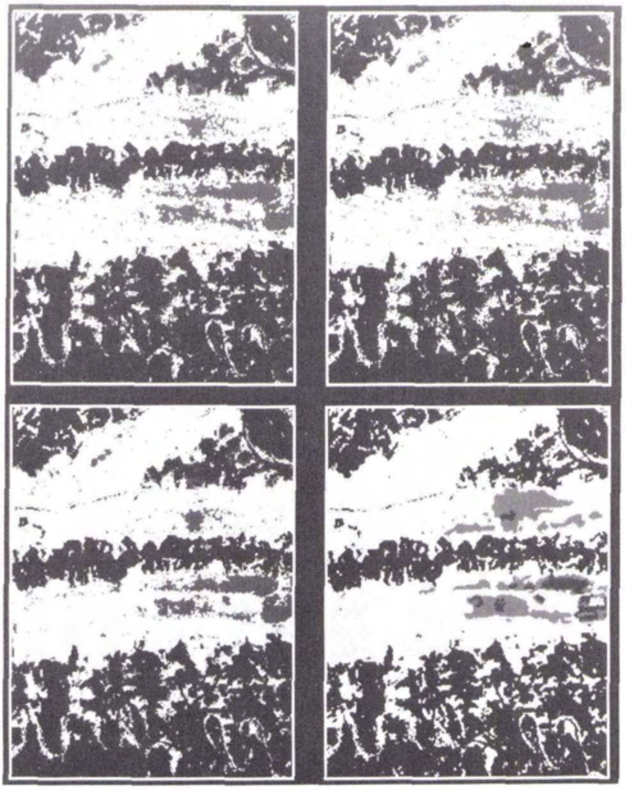

FIG. 3. The best difference, ratio, and vegetation index difference images.

upper left: difference image, band 5
upper right: ratio image, band 5
lower left: vegetative index difference

black—nonforest
white—healthy forest
grey—changed (defoliated) forest

lower right: ground reference image

black—nonforest
white—healthy forest
light grey—moderate defoliation
dark grey—heavy defoliation

pixel was considered changed in the composite image (see Figure 2). Additional bands may improve change classification accuracy if a logical "and" operation is performed; i.e., a pixel is noted as changed in the composite image only if it is noted as changed in all of the bands. This logical "and" approach was not investigated.

- The ratio image produced consistently higher accuracies than the difference image. Though both compare relative reflectance measurements obtained on two different dates, the ratio calculation produced a real number image. The discrete nature of the difference image makes it relatively insensitive to adjustments in the standard deviation threshold level for a particular band.

(3) Optimal threshold levels (based on maximizing combined accuracy) were low, on the order of 0.50 to 1.00 standard deviations. One cannot associate these levels with a certain percentage of the population (via the Empirical Rule) due to (1) the non-normality of the data (Nelson, 1982), and (2) the fact that the standard deviations calculated for each band were inflated estimates of forest variability. The variation in each band was calculated using both forest and nonforest digital values. It is expected that the sd thresholds would be larger if the spectral variability for each band could have been calculated considering forested pixels only.

(4) The low threshold levels were due, in part, to the non-normality of the transformed and untransformed data. The Kolamagorov-Smirnov D statistic and the Fisher g_1 and g_2 statistics were calculated for the various data sets to test for normality, skewness, and kurtosis, respectively. Most of the data sets were leptokurtic (spiked) and skewed. The direction of the skew was in part a function of the data band being considered—whether it was a visible or infrared channel—and of the transformation involved, if any. See Nelson (1982) for a comprehensive coverage of the statistical characteristics of the data sets.

(5) A combined accuracy figure, the average of the average and overall accuracies, had to be generated and analyzed. This criterion, though in itself meaningless, did combine the characteristics of average and overall accuracy into a variable for which an optimal threshold could be defined. The combined accuracy class weights were midway between the weights associated with average and overall accuracy. Such a criterion may be useful wherever there is a need to maximize classification accuracy.

(6) The moderate defoliation class was responsible for the fairly low combined classification accuracies (below 80 percent). Healthy forest and heavy defoliation may be correctly classified typically 85 and 95 percent of the time, respectively; moderate defoliation rarely got above 50 percent. Moderately defoliated areas exhibit abominable classification accuracies regardless of the data transformation used. Major increases in the classification accuracy of moderate defoliation come at the expense of healthy forest. Evidently there is little spectral difference between those forested areas that have lost little or no leaf canopy and forests which have had 30 to 60 percent of the canopy removed.

To summarize, only three of a multitude of data transformations were tested, but the results are clear. If one is searching for a specific type of change, use a data transformation that highlights differences in the cover types being checked. In the case of hardwood forest canopy biomass changes, a vegetative index is the best of the three tested. Data transformations to detect change, however, are not always called for. Many have found differences in the band 5 response adequate for delineating urban boundaries. Flood or coastal zone surveys might do well to study band 7 responses at different times to detect obvious changes in, for instance, the sizes or shapes of barrier islands or large river systems. The point is, tailor the data transformation to the specific type of change being investigated.

Second, utilize information concerning the spectral characteristics of the type of change being studied. For instance, in this project, only values to the high side of the mean of the VID data were considered as change due to gypsy moth defoliation. Low values might indicate (among other things) an increase in the biomass being sensed; such phenomena were of no interest in this study. Hence, the spectral shifts of a particular type of land-cover alteration are consistent and predictable; use that information to detect the change.

This research project has re-emphasized the fact that computer-aided analysis of Landsat MSS data is capable of accurately delineating healthy forest and heavily defoliated forest. Moderate defoliation causes problems; none of the change detection techniques tested accurately classified this cover type. It is unfortunate that this particular cover type class causes such problems because it is the one cover type in which foresters and entomologists are most interested. The areas that were moderately defoliated this year will probably be heavily infested next year. These areas, where the trees are still relatively healthy and there is a good breeding population of moths, deserve the most attention in terms of data collection and suppression efforts. These areas cannot at present be reliably delineated using Landsat MSS data.

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For further information please contact

Jeremiah Eck AIA
Graduate School of Design
Harvard University
George Gund Hall
48 Quincy Street
Cambridge, MA 02138
Tele. (617) 495-9340