Reprinted from

Symposium on Machine Processing of Remotely Sensed Data

June 27 - 29, 1979

The Laboratory for Applications of
Remote Sensing

Purdue University
West Lafayette
Indiana 47907 USA

IEEE Catalog No.
79CH1430-8 MPRSD

A FORESTER'S LOOK AT THE APPLICATION OF IMAGE MANIPULATION TECHNIQUES TO MULTITEMPORAL LANDSAT DATA

DARREL L. WILLIAMS
NASA/Goddard Space Flight Center

MARK L. STAUFFER, K. C. LEUNG
Computer Sciences Corporation

ABSTRACT

Registered, multitemporal Landsat data of a study area in central Pennsylvania were analyzed to detect and assess changes in the forest canopy resulting from insect defoliation. Images taken July 19, 1976, and June 27, 1977, were chosen specifically to represent forest canopy conditions before and after defoliation, respectively. Several image manipulation and data transformation techniques, developed primarily for estimating agricultural and rangeland standing green biomass, were applied to these data. The applicability of each technique for estimating the severity of forest canopy defoliation was then evaluated. All techniques tested had highly correlated results. In all cases, heavy defoliation was discriminated from healthy forest. Areas of moderate defoliation were confused with healthy forest on northwest (NW) aspects, but were distinct from healthy forest conditions on southeast (SE)-facing slopes.

I. INTRODUCTION

One primary objective of an ongoing research effort at NASA's Goddard Space Flight Center (GSFC) is to evaluate, modify, and develop image manipulation and processing techniques that facilitate the use of remotely sensed image data to assess forest damage resulting from major insect infestations. This paper presents a forester's evaluation of several image manipulation techniques that have been applied to multitemporal Landsat data for this discipline-specific application.

The technique-evaluation phase of this project has dealt primarily with the analysis of Landsat multispectral scanner (MSS) data of central and eastern Pennsylvania. The hardwood forests in this region have been infested throughout the past decade by epidemic populations of a defoliating insect commonly known as the gypsy moth. Several investigators have experimented with both manual and digital analysis of Landsat image data of this area for mapping defoliated forest lands. To clarify the temporal dynamics and remote sensing obstacles associated with monitoring a forest infested with gypsy moths, the moths' life cycle and feeding habits are described briefly, and the previous investigations are reviewed.

II. BACKGROUND

A. GYPSY MOTH LIFE CYCLE

The gypsy moth causes tree damage in its caterpillar stage by devouring foliage. This feeding begins shortly after the caterpillars hatch from their egg masses, generally in early May in Pennsylvania. Initially, these caterpillars are small and incapable of devouring vast amounts of foliage, so defoliation is usually not noticeable until early or mid-June. By late June and early July, the heaviest defoliation has taken place: The caterpillars have continued to molt and have nearly reached full size. In mid-July, the caterpillars molt for the last time and go into the pupal stage. After about 10 days, they hatch into moths and immediately mate. The females then lay their fertilized eggs in masses containing 75 to 800 eggs. This step completes the moths' one generation per year, since they overwinter in the egg stage.

If defoliation is complete, trees may remain bare as late as early August; in general, though, by mid-July hardwood trees that had about 60 percent or more of their foliage removed begin to refoliate. Studies indicate that hardwoods suffering less than 60 percent loss of foliage do not refoliate, and evergreens cannot refoliate. Thus, it should be apparent that the life cycle and feeding habits of the gypsy moth and other forest insects must be carefully considered before selecting or scheduling aerial surveillance to correspond with peak levels of damage-related activity.

CH1430-8/79/0000-0368$00.75 © 1979 IEEE

B. PREVIOUS LANDSAT INVESTIGATIONS ON DEFOLIATION

The temporal and synoptic coverage provided by Landsat makes it an ideal survey medium for monitoring widespread phenomena such as insect-related damage in forested areas, and a few Landsat investigators have reported varying degrees of success in delineating gypsy moth defoliation. Rohde and Moore (1974) showed that gypsy moth defoliation can be delineated by manual interpretation of Landsat color composite images.[1] However, they were not able to quantify degrees of defoliation accurately and relied on conventional photo interpretation clues, such as uncalibrated brightness and tonal changes, to distinguish heavy and light-moderate levels of defoliation from undefoliated areas.

Williams (1975) used a digital analysis approach to derive relative statistics and to map areas of heavy defoliation and healthy forest in eastern Pennsylvania.[2] A spectral signature descriptive of moderate defoliation was artificially derived by averaging the healthy forest and heavy defoliation signatures. Classification results using all three signatures were subjectively analyzed and found to be representative of actual ground conditions.

Talerico et al. (1978) reported on a quantitative photographic approach for delineating various levels of insect defoliation by applying advanced photometric calibration techniques to aerial photography and Landsat imagery.[3] They concluded that Landsat data were not only more economical, but also better than high altitude film for mapping defoliation.

Johnson (1978) analyzed Landsat digital data of eastern Pennsylvania using an interactive digital image analysis system and a modified-supervised approach to develop training statistics.[4] Johnson's work also demonstrated that forest canopy defoliation could be identified and mapped from satellite data, but he concluded that additional research was needed, since defoliation severity levels could not be reliably identified because of errors of commission. Williams and Stauffer (1978) recently reported the creation of a multitemporal Landsat data set representing forest canopy conditions "before" and "after" defoliation.[5] They suggested that the application of certain image manipulation techniques and procedures to the multitemporal data set should lead to a reduction in commission errors when levels of defoliation are delineated. Accurate delineation of defoliation levels is necessary for identifying population foci and monitoring population dynamics from year to year, thus permitting earlier and more intelligent application of control measures that may minimize large-scale outbreaks of insect infestation.

III. APPROACH

A. RESEARCH OBJECTIVE

The primary objective of the current research at GSFC is to develop a procedure for accurately identifying and quantifying intermediate levels of defoliation that could be used instead of the typical supervised classification procedure. The user community, which consists mainly of state and federal agencies, would like accurate information on three levels of defoliation: (1) heavy, or 61 to 100 percent of the leaf canopy removed; (2) moderate, or 31 to 60 percent of the leaf canopy removed; and (3) light, or 5 to 30 percent defoliated. The approach taken in this project was to develop an index value, based on the Landsat spectral responses, that would measure the severity of defoliation. Two considerations prompted this approach. First, the derivation of a continuous-valued index indicative of defoliation was thought to be superior to obtaining discrete output, which would result from a typical classification procedure. Secondly, the difficulty and subjectiveness in selecting training areas for varying degrees of defoliation was thought to limit the application of a classification procedure.

B. LINEAR DISCRIMINANT ANALYSIS

The initial approach taken to derive an index value was the application of Fisher's Linear Discriminant Analysis (LDA). LDA is a standard method for reducing the dimensionality of a classification problem by projecting the n-dimensional data onto a single line. This line is chosen in such a way that different classes are well separated--i.e., it maximizes the interclass separation over the intraclass variances.

If the mean spectra for healthy forest and severely defoliated areas are labeled as M_1 and M_2, Fisher's linear discriminant defines a line W as

$$W = S^{-1}(M_1 - M_2) \qquad (1)$$

where S is the sum of variance-covariance matrices of all samples used in obtaining the means. The projection onto this line can be used as a measure of the severity of insect defoliation. A natural way of defining a forest index (FI) for a cell with radiance X is

$$FI = f(W \cdot X) \qquad (2)$$

in such a way that

$$\begin{aligned} f(W \cdot M_1) &= 1 \\ f(W \cdot M_2) &= 0 \end{aligned} \qquad (3)$$

The lack of quantitative moderate defoliation ground measurements prevents the use of any form for f(W · X) other than a linear relationship. The result is

$$FI = \frac{W \cdot (X - M_2)}{W \cdot (M_1 - M_2)} \quad (4)$$

One interesting consequence of this formulation is that the computed quantity is somewhat insensitive to the particular atmospheric condition prevalent at the time of Landsat overpass. This feature makes comparison between different Landsat scenes easier. Two processes contribute to this insensitivity. First, the formula is constructed solely from differences between spectral signals. Thus, for an area where atmospheric haze and backscattering contributions are relatively uniform, these factors will not appear in the signal difference. Secondly, the atmospheric transmission coefficient that affects the total amount of surface radiance transmitted through the atmosphere will not contribute to FI. It is obvious from the definition of FI that this quantity is invariant under a simple transformation of scaling all spectra by some constant. Thus, LDA provides an attractive way of looking at forest defoliation.

C. VEGETATIVE INDEXES

In addition to testing LDA, this study also evaluates several other techniques. Recently, many procedures have been described in the literature that relate Landsat spectral measurements to various vegetation density indicators, such as standing green biomass or leaf area index. These techniques have been developed primarily for agricultural and rangeland applications and are collectively referred to as Vegetative Indexes (VI). Thus far, these indexes have had limited application to other disciplines. The problem of estimating defoliation is essentially a problem of estimating the remaining green biomass or leaf area index of the forest canopy. The application of VI's may provide a useful approach to the specific problem of defoliation estimation and to forestry applications in general.

The various VI techniques tested are briefly outlined in the following discussion. Comprehensive descriptions can be found in the associated references. Comparisons of several VI's for agricultural and rangeland applications can be found in Richardson and Wiegand (1977) and Tucker (1978).[6,7]

Ratio Vegetative Index (RVI). This index is computed as the IR-to-red ratio. When applied to Landsat MSS data, it is computed as:

$$MSS7/MSS5 \quad (5)$$

Numerous researchers have used this ratio for a variety of applications.

Difference Vegetation Index (DVI). This index value is calculated as the difference between IR and red reflectance. It is computed for Landsat MSS data as:

$$MSS7 - MSS5 \quad (6)$$

Richardson and Wiegand (1977) calculate a DVI as:

$$DVI = 2.40 \times MSS7 - MSS5 \quad (7)$$

Here MSS7 is multiplied by the slope of a linear equation, which represents the soil background line defined by MSS5 and MSS7, so that a DVI of 0 indicates bare soil.[6]

Transformed Vegetative Index (TVI). Rouse et al. (1974) and Deering et al. (1975) have used a TVI as an estimate of standing green biomass and relative greenness.[8,9] This ratio is computed as:

$$TVI = \sqrt{\frac{MSS7 - MSS5}{MSS7 + MSS5} + 0.5} \quad (8)$$

They also compute a TVI6 by substituting MSS6 values for MSS7 in Equation (8).

Green Vegetation Index (GVI). Kauth and Thomas (1977) developed a linear transformation of the four Landsat variables, which they interpret to indicate green vegetation.[10] The GVI is derived from the following transformation:

$$GVI = -0.29 \times MSS4 - 0.56 \times MSS5 + 0.60 \times MSS6 + 0.49 \times MSS7 \quad (9)$$

Perpendicular Vegetative Index (PVI). In an effort to distinguish the response of green vegetation from the response contributed by background soils, Richardson and Wiegand (1977) developed an index value based on the perpendicular distance of an unknown response from a line that represents the response of bare soil background.[6] They compute the PVI as:

$$PVI = SOIL5 - MSS5 + SOIL7 - MSS7 \quad (10)$$

where SOIL5 is the MSS5 soil background response and SOIL7 is the MSS7 soil background response. These quantities are computed as follows:

$$SOIL5 = 0.851 \times MSS5 + 0.355 \times MSS7 \quad (11)$$

$$SOIL7 = 0.355 \times MSS5 + 0.148 \times MSS7 \quad (12)$$

A PVI6 can also be computed on the basis of MSS6 response values instead of MSS7. The soil background intersection then becomes:

$$SOIL5 = -0.498 + 0.543 \times MSS5 + 0.498 \times MSS6 \quad (13)$$

$$SOIL6 = +2.734 + 0.498 \times MSS5 + 0.457 \times MSS6 \quad (14)$$

D. ADDITIONAL CONSIDERATIONS

The transformations involving ratio-based computations can be applied directly. For those indexes incorporating a linear transformation (i.e., GVI, PVI, PVI6), the coefficients have been developed for agricultural applications and deal with the specific problem of soil background response. Initially, the transformations developed for the rangeland and agricultural applications were applied to the test data. In the future, it may be appropriate to consider modifications of these techniques to deal specifically with the response of the forest floor.

IV. DATA

The Landsat MSS data used in this study was collected on July 19, 1976, and June 27, 1977. The primary area of interest is a 30- by 30-km subimage near Harrisburg, Pennsylvania. The study area is in the Ridge and Valley province and has a forest cover primarily of oak and hickory.

The July 1976 and June 1977 data were selected to provide near-anniversary coverage of the area during both non-defoliated and defoliated seasons. The primary area of interest experienced no appreciable defoliation in 1976. During the summer of 1977, several thousand acres of forest in this area suffered varying degrees of defoliation. These images were registered to each other and resampled to 1-acre cells.

To support this investigation, the Forest Pest Management Division (FPMD) of the Pennsylvania Department of Environmental Resources provided color aerial photography at a scale of 1:48,000 collected on June 23, 1977. FPMD personnel interpreted these aerial photographs and plotted the boundaries of heavily defoliated and moderately defoliated areas on USGS 7.5-minute quadrangle maps.

V. ANALYSIS

As indicated earlier during the literature review, a factor that has made the accurate delineation of defoliation confusing has been errors of commission. These have been of two types: subtle errors of misclassification between two adjacent levels of defoliation, or gross errors of misclassifying defoliation pixels into areas of non-forest land cover. For example, the terrain effects (i.e., slope and aspect) on spectral response often cause confusion between moderate levels of defoliation on southeast facing slopes (i.e., sunlit) and light defoliation on northwest facing slopes (i.e., shaded). Since reflectance in the near IR spectral regions decreases as defoliation levels increase, the shaded areas of light defoliation are confused with areas of sunlit moderate defoliation.

In the more extreme case of commission error, the spectral signatures developed by training on heavily defoliated areas are similar to the spectral characteristics of certain non-forest cover types in the mid-to-late June Landsat imagery. Consider, for example, corn fields with corn stalks only 10 to 30 cm high in June. The surrounding bare soil largely cancels out the vegetative reflectance from the small corn stalks, thus creating an average reflectance similar to a heavily defoliated forest canopy.

Since the most disturbing errors are those of misclassification between totally unrelated cover types, the confusion between heavy defoliation and other types of land use (i.e., cropland) was the first item addressed in this study. A variation of a layered classifier was used to reduce the potential for errors of commission. By performing a simple two-category classification of forest and other for the non-defoliated 1976 Landsat data, it was possible to create a mask of forest versus non-forest. A standard procedure of training site selection and classification was used to generate the forest/non-forest map. The results of this classification were only subjectively evaluated, and no measure of absolute accuracy was obtained.

The forest/non-forest classification was used to generate a 1/0 binary mask, which was applied on a cell-by-cell multiplication to the 1977 defoliated data set to eliminate all non-forest cells. This approach reduces errors of commission with unrelated cover types, since the majority of all non-forest land has been removed from the data set.

From an operational standpoint, the mask can be applied to the raw data as a pre-processing step to reduce subsequent processing time, or it can be applied as a post-processing step. Throughout this project, we elected to apply the mask as a post-processing step, primarily to allow the LDA and VI techniques to be evaluated for other features within the image, particularly agricultural and urban areas.

To evaluate each technique, a series of training sites was selected using the color IR aerial photography and associated maps provided by the FPMD personnel. The training sites were carefully selected to provide representative statistics for the three major categories of interest: healthy forest, moderate defoliation, and heavy defoliation. The training sites for healthy forest were further categorized on the basis of their slope and aspect differences, generally NW or SE aspects.

The defoliated areas could not be categorized easily according to slope and aspect. Within the heavily defoliated areas, the slope and aspect variation was not sufficient to categorize the test sites further on the basis of aspect differences. The areas of moderate defoliation delineated on the color IR photography appeared to encompass a wide variety of canopy conditions, which made it difficult to select equivalent areas of moderate defoliation that could be used to evaluate slope and aspect variations.

The standard multivariate statistics--mean, covariance, and correlation--were calculated for each training site. Table 1 shows the mean spectral response for each test site. Initially, the mean signature vectors and covariance matrices for the 15 healthy forest and 9 heavy defoliation test sites were used to compute the coefficients for the linear discriminant transformation. Based on the pooled statistics for these test sites, the following linear transformation was derived:

$$\begin{aligned} LDA(ALL) = &-1.94 \times MSS4 - 4.64 \times MSS5 \\ &- 0.87 \times MSS6 + 2.42 \times MSS7 \end{aligned} \tag{15}$$

Based on the subsequent analysis of the results obtained using this transformation, a second linear discriminant transformation was derived using only the statistics for healthy forest on SE aspects and the six heavy defoliation test sites that were consistently grouped together. This resulted in the following discriminant function, a linear discrimant index (LDI):

$$\begin{aligned} LDI = &-2.58 \times MSS4 - 7.28 \times MSS5 \\ &+ 0.88 \times MSS6 + 3.59 \times MSS7 \end{aligned} \tag{16}$$

This transformation was found to maximize the separation of heavy defoliation and healthy forest. The results of this transformation were compared to those based on the discriminant function calculated using all the healthy and heavy training sites. A correlation coefficient of 0.99 was calculated, indicating that the transformations are similar. (Throughout the subsequent discussion of the results, we will refer only to the results obtained using the LDI.)

The LDI and each of the VI's were tested using the mean values obtained for each training site. The results of each technique could only be subjectively evaluated, since no quantitative ground measurement of defoliation was available that could be used as an independent variable for comparison purposes.

Table 1. Mean Spectral Responses. These are derived from the training sites selected to represent the forest canopy conditions of interest in the June 27, 1977, Landsat image.

TRAINING SITES	LANDSAT MEAN DIGITAL COUNTS			
	MSS4	MSS5	MSS6	MSS7
HEALTHY FOREST				
SE ASPECT				
SITE 1	16	13	70	40
SITE 2	15	12	66	38
SITE 3	15	12	63	36
SITE 4	15	12	65	38
SITE 5	16	12	70	41
SITE 6	16	12	65	37
SITE 7	16	13	64	37
NW ASPECT				
SITE 1	15	12	56	31
SITE 2	14	11	50	27
SITE 3	15	12	48	26
SITE 4	15	12	56	31
SITE 5	15	12	57	32
SITE 6	15	12	58	33
SITE 7	16	13	56	31
VARIABLE TERRAIN	16	13	61	35
MODERATE DEFOLIATION				
SITE 1	16	13	58	32
SITE 2	17	14	57	31
SITE 3	17	15	54	28
SITE 4	16	14	56	30
SITE 5	16	13	58	32
SITE 6	16	13	53	29
SITE 7	15	12	58	33
SITE 8	16	13	57	32
HEAVY DEFOLIATION				
SITE 1	18	21	39	19
SITE 2	18	19	42	20
SITE 3	18	21	38	19
SITE 4	19	23	40	20
SITE 5	20	24	40	19
SITE 6	19	23	40	19
SITE 7	19	22	40	19
SITE 8	18	19	43	21
SITE 9	18	17	48	24

VI. RESULTS AND DISCUSSION

Table 2 shows the results of applying the various indexes. To evaluate the results more easily, the data presented in Table 2 were scaled from 0 to 100 and are shown in Table 3. Values near 0 represent areas of heavy defoliation, while values near 100 typically represent areas of healthy forest. The magnitude of the numbers provides a relative measure of the forest canopy condition.

Table 2. Results of Applying the Vegetative Indexes to the Training Site Data Presented in Table 1.

TRAINING SITES	VEGETATIVE INDEXES							
	RVI x 10	DVI	TVI	TVI6	GVI	PVI	PVI6	LVI
HEALTHY FOREST								
SE ASPECT								
SITE 1	31	84	101	109	49	32	40	73
SITE 2	31	80	100	108	47	30	38	67
SITE 3	29	74	99	108	44	28	35	57
SITE 4	30	79	100	108	46	30	37	64
SITE 5	32	85	101	109	50	33	40	75
SITE 6	29	76	99	108	45	29	37	57
SITE 7	28	75	99	108	44	29	36	55
NW ASPECT								
SITE 1	26	63	97	107	38	24	30	36
SITE 2	23	54	95	105	32	20	26	21
SITE 3	22	58	93	105	30	19	24	12
SITE 4	25	62	96	106	37	24	30	33
SITE 5	26	65	97	107	39	25	31	40
SITE 6	26	67	97	106	39	25	32	39
SITE 7	24	63	95	105	37	24	30	27
VARIABLE TERRAIN	26	70	97	106	41	27	33	39
MODERATE DEFOLIATION								
SITE 1	25	65	96	106	38	25	31	33
SITE 2	21	59	93	105	36	22	30	15
SITE 3	18	52	89	103	32	20	27	−4
SITE 4	21	58	93	105	35	22	29	14
SITE 5	23	62	95	106	38	24	31	24
SITE 6	21	56	93	105	34	21	[illegible]	13
SITE 7	26	66	97	107	39	25	[illegible]	40
SITE 8	24	63	96	106	38	24	31	31
HEAVY DEFOLIATION								
SITE 1	8	24	66	89	15	9	12	−99
SITE 2	10	29	72	93	19	11	15	−74
SITE 3	8	24	66	88	15	9	11	−99
SITE 4	8	24	65	88	15	9	12	−106
SITE 5	8	22	62	86	14	8	11	−119
SITE 6	8	23	64	87	15	9	11	−109
SITE 7	8	23	65	88	15	9	12	−106
SITE 8	11	32	75	94	20	12	17	−67
SITE 9	14	41	81	98	26	15	21	−42

The similarity of the techniques is apparent if we compute the correlation coefficients between the results for each of the indexes. These coefficients are shown in Table 4. In each case the correlation between techniques is significant at the 0.01 level. The high correlations between the LDI and the other VI's suggests that there is little difference between the LDI and the other indexes. This sample indicates that there is no significant difference between any of the indexes. If an independent measure of defoliation was available, we would expect that the correlations obtained between each index and that variable would be similar, although not necessarily significant.

Since the various techniques tested were highly correlated, the results concerning the discrimination of defoliation will be discussed in general terms. The study showed that each index tested, LDI and VI's, consistently separated heavy defoliation from both moderate

Table 3. Results of Applying Linear Scaling Factors to the Data Presented in Table 2. The scaled values range from 0 to 100, where values near 0 represent the heaviest levels of defoliation and values near 100 indicate healthy forest.

TRAINING SITES	VEGETATIVE INDEXES							
	RVI	DVI	TVI	TVI6	GVI	PVI	PVI6	LVI
HEALTHY FOREST								
SE ASPECT								
SITE 1	98	97	99	100	98	97	99	98
SITE 2	95	91	98	98	91	91	91	95
SITE 3	89	82	95	96	82	82	83	91
SITE 4	93	89	97	97	89	89	88	94
SITE 5	100	100	100	99	100	100	100	100
SITE 6	87	85	95	96	87	85	88	90
SITE 7	85	83	94	94	85	83	85	89
NW ASPECT								
SITE 1	74	64	89	90	65	64	67	79
SITE 2	64	49	83	85	51	49	52	72
SITE 3	57	44	79	81	44	44	46	67
SITE 4	71	62	88	89	64	62	65	78
SITE 5	77	68	90	91	68	68	69	81
SITE 6	75	70	89	90	70	70	71	81
SITE 7	66	64	85	84	63	64	64	75
VARIABLE TERRAIN	74	75	89	89	75	75	76	81
MODERATE DEFOLIATION								
SITE 1	71	67	87	88	68	67	69	78
SITE 2	57	58	79	81	61	58	64	69
SITE 3	44	47	69	72	51	47	54	59
SITE 4	56	56	78	81	59	56	62	68
SITE 5	63	63	83	85	66	63	69	74
SITE 6	57	52	79	81	54	52	57	68
SITE 7	77	69	90	90	69	69	70	82
SITE 8	69	64	86	87	65	64	67	77
HEAVY DEFOLIATION								
SITE 1	3	2	9	11	3	2	4	10
SITE 2	10	10	25	30	12	10	15	23
SITE 3	3	1	8	8	1	1	1	9
SITE 4	2	3	7	6	3	3	3	6
SITE 5	0	0	0	0	0	0	0	0
SITE 6	1	1	4	4	1	1	1	5
SITE 7	1	1	5	7	2	1	3	6
SITE 8	13	15	31	35	17	15	19	26
SITE 9	24	28	48	51	32	28	35	39

Table 4. Matrix of Correlation Coefficients Between the Vegetative Indexes. These values are computed on the basis of the results summarized in Table 2.

VEGETATIVE INDEXES	VEGETATIVE INDEXES							
	RVI	DVI	TVI	TVI6	GVI	PVI	PVI6	LVI
RVI	1.00							
DVI	0.99	1.00						
TVI	0.97	0.96	1.00					
TVI6	0.96	0.95	0.99	1.00				
GVI	0.99	0.99	0.96	0.96	1.00			
PVI	0.99	1.00	0.96	0.95	0.99	1.00		
PVI6	0.98	0.99	0.97	0.96	0.99	0.99	1.00	
LVI	0.99	0.98	0.99	0.99	0.98	0.98	0.98	1.00

defoliation and healthy forest. In all cases, the index values tended to increase as the severity of defoliation decreased. Table 2 shows this general trend.

Three of the nine heavily defoliated test sites have consistently higher index values than the others, indicating less severe defoliation. The color IR photography and the Landsat enhancement show that these areas were not as severely defoliated as the others; according to the photointerpreter's criteria, however, the areas were mapped as ones of heavy defoliation.

The problem unresolved by any technique tested is the accurate delineation of moderately defoliated areas. Examination of the unscaled (Table 2) or scaled (Table 3) output provides an insight into the nature of this confusion.

Consider first a comparison of healthy forest on southeast (SE) aspects with healthy forest on northwest (NW) aspects. Regardless of the index used, the values derived for SE aspects are consistently higher than those for NW aspects. For Landsat data, this result is expected, given the differential illumination resulting from varying slope and aspect. However, that such differences exist after the application of RVI, TVI, and TVI6 is unexpected. Such ratio-based techniques are generally assumed to reduce the impact of slope and aspect differences on reflectance. For each ratio-based index tested, as well as all other indexes, the SE and NW aspect training sites remain separable, which in this context is unacceptable. In this case, the ratio techniques do not appear to resolve fully this problem. It is possible that environmental factors associated with variations in slope and aspect, such as moisture differences and subtle changes in species composition, are responsible for the differences noted between NW and SE aspect slopes and that the ratio techniques have, in fact, removed slope- and aspect-induced variations. This problem warrants additional study, but is beyond the scope of this paper.

For the sample data, the confusion between moderate defoliation and healthy forest occurs exclusively with healthy forest on NW aspects. This question has proven difficult to resolve. One possible source of confusion is the selection of training sites for moderate defoliation. This selection remains a problem in this application, as it does in a classification procedure. The training areas for moderate defoliation were selected on the basis of the photointerpreted results obtained from the FPMD. Throughout the analysis, these results were the standard against which the computer-derived results were compared. (Absolute accuracy of the photointerpreted results is not implied.) The areas delineated as ones of moderate defoliation on the color IR photography appeared to exhibit only slight tonal variations compared to areas of healthy forest. Also, based on a subjective evaluation of the photography, areas of moderate defoliation appear to encompass a broader range of canopy conditions than do areas of heavy defoliation.

To clarify the confusion between moderate defoliation and healthy forest, it would be desirable to obtain a more detailed evaluation of defoliation levels for the area. This information would allow a better assessment of the computer-derived results; it would also permit evaluation of the defoliation level at which confusion with healthy forest can be expected. Without detailed, quantitative ground truth information, the results of the procedures can only be subjectively evaluated.

VII. SUMMARY AND RECOMMENDATIONS

The initial objective of deriving a continuous-valued index that indicates severity of defoliation was accomplished using a variety of techniques. The similarity of the results obtained using the linear discriminant index (LDI), which was derived for application to a specific problem, and those obtained from the various VI's indicates a general applicability of the VI's to problems other than those encountered in agriculture and rangelands. Of particular interest is the application of the GVI, PVI, and PVI6 transformations to this problem without coefficient modification. Results indicate that the coefficients, although developed specifically for soil/crop interactions, are not limited to those applications.

As expected, the discrimination of heavy defoliation and healthy forest was accomplished using all the techniques tested. Accurate delineation of moderate levels of defoliation, however, remains a difficult problem. The gross errors of commission between defoliation and unrelated land cover types were substantially reduced through the use of a forest/non-forest mask developed from a non-defoliated data set. However, accurate delineation of moderate defoliation from healthy forest has not been resolved. It became apparent as this project progressed that the available ground truth information would not be sufficient to answer the questions that arose concerning the confusion between moderate defoliation and healthy forest. Given the ability to derive a continuous-valued index, it would be desirable to establish the relationship between this index and the severity of defoliation. Since moderate defoliation did not fall into the range of values midway between healthy and heavy, the relationship may be non-linear. Without detailed, quantitative, ground truth information, such evaluations cannot be made.

Based on the results, an approach that may resolve the confusion between moderately defoliated areas and healthy forest is the application of techniques that correct or compensate for the spectral variations resulting from topographic differences. Since the confusion between moderate defoliation and healthy forest occurs with healthy forest on NW aspects, the ability to compensate for the effects of slope and aspect may reduce this confusion. Several approaches to the problem are being investigated. One approach, described by Cicone et al. (1977), is to model the terrain using input from digital terrain tapes.[11] These data are used to derive slope and aspect values, which are used to compute the effect of terrain on observed radiance. Other techniques that use the 1976 image as a base against which the 1977 defoliated image is compared are also being investigated. The question of terrain corrections warrants additional research, not only for this project, but for remote sensing applications in general.

VIII. REFERENCES

1. W. G. Rohde and H. J. Moore, "Forest Defoliation Assessment with Satellite Imagery," Proceedings of the Environmental Research Institute of Michigan, Ninth International Symposium on Remote Sensing of the Environment, 1974, vol. II, pp. 1089-1104.

2. D. L. Williams, "Computer Analysis and Mapping of Gypsy Moth Defoliation Levels In Pennsylvania Using Landsat-1 Digital Data," Proceedings of the NASA Earth Resources Survey Symposium, Technical Session Presentations, 1975, vol. 1-A, pp. 167-181.

3. R. L. Talerico et al., "Quantifying Gypsy Moth Defoliation," Photogrammetric Engineering and Remote Sensing, 1978, vol. 44, no. 11, pp. 1385-1392.

4. G. R. Johnson, "Mapping Hardwood Forest Defoliation by Digital Analysis of Satellite Data," Proceedings of Remote Sensing of Earth Resources (F. Shahrokhi, Editor, University of Tennessee Space Institute), 1978, vol. VII, pp. 139-158.

5. D. L. Williams and M. L. Stauffer, "Monitoring Gypsy Moth Defoliation by Applying Change Detection Techniques to Landsat Imagery," Proceedings of the American Society of Photogrammetry, Symposium on Remote Sensing for Vegetation Damage Assessment, 1978, pp. 221-229.

6. A. J. Richardson and C. L. Wiegand, "Distinguishing Vegetation From Soil Background Information," Photogrammetric Engineering and Remote Sensing, 1977, vol. 43, no. 12, pp. 1541-1552.

7. NASA, Goddard Space Flight Center, Technical Memorandum 79620, Red and Photographic Infrared Linear Combinations for Monitoring Vegetation, C. J. Tucker, 1978.

8. NASA, Goddard Space Flight Center, Type III Final Report, Monitoring the Vernal Advancement and Retrogradation (Greenwave Effect) of Natural Vegetation," J. W. Rouse et al., 1974.

9. D. W. Deering et al., "Measuring Forage Production of Grazing Units From Landsat MSS Data," Proceedings of the Environmental Research Institute of Michigan, Tenth International Symposium on Remote Sensing of the Environment, 1975, pp. 1169-1176.

10. R. J. Kauth and G. S. Thomas, "The Tasseled Cap--A Graphic Description of the Spectral Temporal Development of Agricultural Crops as Seen by Landsat," Proceedings of the Laboratory for Applications of Remote Sensing, Symposium on Machine Processing of Remotely Sensed Data, June 29-July 1, 1976, pp. 4B-41 - 4B-51.

11. Environmental Research Institute of Michigan, Contract No. NAS9-14988, Investigation of Techniques for Inventorying Forested Regions, NASA Final Report, Cicone et al., 1977.

Darrel L. Williams is an Environmental Physical Scientist with the Earth Resources Branch at NASA's Goddard Space Flight Center. He recently accepted the role of Assistant Project Scientist for Landsat-D. Mr. Williams received B.S. and M.S. degrees in forest resources from Pennsylvania State University. His research has involved digital image processing of remotely sensed data as applied to the agriculture/forest/range discipline. He is a member of the American Society of Photogrammetry and the Society of American Foresters.

Mark L. Stauffer is a member of the technical staff of Computer Sciences Corporation's System Sciences Division, supporting Landsat investigations under NASA contract. Since 1973, his research has involved computer processing of multispectral scanner data. His current activities are directed toward development of remote sensing techniques for natural resource applications. He received his B.S. degree in forest resources from Pennsylvania State University and is a member of the American Society of Photogrammetry and the Society of American Foresters.

K. C. Leung received his Ph.D. in experimental physics from the University of California at Berkeley. After working for several years as a research physicist at UCLA, he joined Computer Sciences Corporation to work in satellite data analysis and image applications. His current interest is in using remote sensing technology for earth resources observations.