Progress Toward Improving Aerial Defoliation Survey Methods by Using Electronic Imagers

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ABSTRACT: The results of work toward developing a capability for operational airborne surveys of current-year spruce budworm defoliation with a linear array imager are described. The objectives were to (1) determine whether the MEIS sensor data could provide defoliation classifications acceptable to the New Brunswick Department of Natural Resources and Energy; (2) demonstrate high data acquisition rates over a significant portion of the province of New Brunswick; (3) investigate the feasibility of rapid visual classification with a quick-look data display; and (4) further define the scientific and technical problems to be solved for an operational annual defoliation survey. MEIS data were acquired on four 225-km long east-west flight lines across the province. Training and verification data consisted of small homogeneous evaluation forest patches classified by visual interpretation of oblique 35-mm photographs which were acquired from a small aircraft flying between 150 and 250 m above the ground. The MEIS data were classified using the maximum-likelihood decision rule. Classification accuracies were adequate to meet the need of the Department with most errors consisting of confusion between adjacent defoliation classes. Visual interpretation of enhanced images was found to be too slow and uncertain for operational use. Scientific problems which remain to be overcome include determination of the most cost-effective spatial resolution, development of a reliable method for correcting the radiometric variations caused by large off-nadir viewing angles, and development of reliable methods for correcting for variable atmospheric path radiance and transmission. Technical problems which remain to be overcome include development of a wide swath sensor, development of operational geometric corrections, and development of a high throughput image classification system.

INTRODUCTION

IN AREAS OF Canada which are dependent on the forest resource, a stable, long term supply of wood is one of the most important goals of forest management, because economic and social stability of many small towns depends heavily on employment in the forestry sector. In New Brunswick, 41 percent of the economy is based on forestry, but the goal of ensuring a stable wood supply has been severely complicated by the unpredictable effects of the spruce budworm (*Choristoneura fumiferana* (Clem.)). The New Brunswick Department of Natural Resources and Energy has sought to mitigate the effects of the spruce budworm through an annual survey of current-year defoliation. The purposes of the annual survey are to define areas of insect outbreaks and to estimate the effects consecutive outbreaks may have on the wood supply, and to provide an information source for the management of a multi-million dollar aerial insecticide spray program. For the latter, the annual assessment of current defoliation provides an estimate of insect populations used to evaluate the effectiveness of the current year's spray program, and to help determine areas of high risk which require protection in the following year. Even greater benefits from improved insect damage mapping are projected when stand level damage information can be used for improved timber supply forecasts (MacLean, 1988) and harvest scheduling (Erdle, 1989).

The visual defoliation survey relies on the fact that feeding debris (dead foliage and frass, or insect fecal matter) is caught in webs spun by the insect which gives defoliated trees a reddish brown appearance for approximately two weeks in late June to early July each year, before wind and rain knock the red-brown material from the trees.

Lightly defoliated trees have less red-brown discoloration, and the discoloration is usually more concentrated toward the tops of the trees than in the case of heavily defoliated trees. In addition to current defoliation, trees which have been heavily defoliated in the past have a greater proportion of bare branches. This effect, called cumulative defoliation, gives these trees a gray appearance from the air.

The traditional survey method, called aerial sketch mapping, involves teams flying in small aircraft at low altitudes (200 to 400 m above ground) along predetermined flight lines, and recording and mapping all areas of current defoliation into three broad categories: light, moderate, and severe. The classification is based on a visual estimate of the amount of reddening on susceptible trees, and whether the reddening is concentrated near the top or extends down the crown (see Table 1).

The aerial sketch mapping technique suffers from two major shortcomings: the defoliation estimates are subjective, making it difficult to inter-calibrate the classifications of the different teams, and it is not possible to map the defoliation in detail. Whereas it would be desirable to map the defoliation level of each susceptible stand to predict the effects of defoliation on the stand's growth, only large (several hundred hectares or larger) areas can be sketched, an even then the mappers can only position the boundaries very approximately because of the oblique view at low altitude and because of the brief time the defoliated area is in sight. Because of these limitations, the foresters responsible for the annual defoliation survey have always been eager to try new methods to determine the amount of defoliation and insect population levels.

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TABLE 1. DESCRIPTION OF CLASSES EMPLOYED IN SPRUCE BUDWORM DEFOLIATION ASSESSMENT

The descriptions of the current defoliation classes (numbers 2 through 5) below is the one currently employed by the annual visual survey in New Brunswick. Similar classifications are used in the other eastern provinces and in the northeastern United States for spruce budworm damage assessment. Classes 1 and 6 were added to test for potential confusion with the current defoliation classes.

1. Previous: Stand of spruce and/or fir with 75 percent or more trees showing serious to severe cumulative defoliation from previous years' feeding. Generally recognizable by gray appearance of the trees caused by bare and lichen-covered branches. In most cases these areas consist primarily of dead trees.

2. Severe: Stand of spruce and/or fir with 50 percent or more trees showing very distinct reddish brown discoloration, generally extending the full length of the live crown, although often concentrated at the top.

3. Moderate: Stand of spruce and/or fir with 75 percent or more trees showing reddish brown discoloration over the full crown but less distinct than in the case of severe defoliation. Alternatively, a stand of spruce and/or fir with 25 to 50 percent of the trees showing severe defoliation intermixed with conifers showing little to light discoloration.

4. Light: Stand of spruce and/or fir with some discoloration visible but not enough to classify the stand as severely or moderately defoliated.

5. Healthy: Stand of spruce and/or fir with no evidence of current defoliation (red discoloration) and little evidence of previous defoliation (less than 10 percent dead trees or gray branches in live trees).

6. Deciduous: A stand of predominantly deciduous trees. While this class is not generally indicated on defoliation surveys, it was important to identify for this project to determine whether there was confusion between deciduous stands and any of the conifer defoliation classes.

Satellite images were investigated to supplement or replace current efforts. The first attempts were made to use Landsat Multispectral Scanner (MSS) data to detect insect damage. Low spatial resolution, poor spectral characteristics, and restricted acquisition time contributed to limit the use of satellite data for insect damage mapping (Beaubien and Jobin, 1974; Nelson, 1983). Studies investigating the use of airborne MSS data have shown moderate success for forest damage assessment (Teillet *et al.*, 1981). Better results were obtained by Leckie and Gougeon (1981) and Leckie and Ostaff (1988), who were able to classify four levels of current defoliation with higher resolution airborne scanner data. By 1983, the Canada Centre for Remote Sensing (CCRS) had developed an 8-channel linear "pushbroom" array imager called MEIS (Multi-detector Electro-optical Imaging Sensor) which offered the promise of greatly improved spatial, spectral, and radiometric resolution compared to mechanical airborne multispectral scanners (McColl *et al.*, 1984). MEIS was tested in 1983 and found to provide considerable promise for detecting spruce budworm defoliation (Ahern *et al.*, 1986). A complete review of the factors affecting defoliation assessment using airborne data has been done by Leckie (1987) to help understand and quantify the problems of digital insect mapping and explore solutions.

Because of the promising results obtained with MEIS in the 1983 experiment, further development for mapping current spruce budworm defoliation seemed warranted and a joint project was undertaken between CCRS and the New Brunswick Department of Natural Resources and Energy.

OBJECTIVES

There were four objectives of this study:

(1) To determine whether the MEIS multispectral linear array sensor could provide data enabling the classification of cumulative defoliation and at least three levels of current defoliation (healthy to light, moderate, and severe) to an accuracy satisfactory for the requirements of the New Brunswick Department of Natural Resources and Energy (see Table 1 for a list of the desired classes). This accuracy requirement is provisionally specified as a classification of 80 percent of the pixels to within plus or minus one defoliation level of the correct class. However, it is important to avoid misclassifying SEVERE and MODERATE levels of defoliation as LIGHT or HEALTHY, because protection plans are currently based on the areas classified as having moderate or severe defoliation.

(2) To demonstrate a data acquisition rate sufficient to cover all of New Brunswick in three to four days.[1] This is the typical amount of clear weather available during the two-week period when the red-brown feeding debris, indicative of current defoliation, is usually retained on the tree.

(3) To investigate whether a newly developed quick-look data display could be used as a rapid means of mapping spruce budworm defoliation from MEIS imager data.

(4) To further define the scientific and technical problems which must be solved to produce a system for operational annual current defoliation surveys

STUDY AREA

Although overwintering larval surveys provide some capability to predict defoliation levels before the feeding begins, we decided it would be more reliable to select the study area using information from the visual defoliation survey after feeding was completed. Based on reconnaissance flights with small aircraft, we picked an area centered approximately 60 km north of Fredericton for MEIS data acquisition (Figure 1).

The study area has a low to moderate relief and is covered by mixed softwood-hardwood stands. Balsam fir (*Abies balsamea* (L.) Mill.) and spruce (*Picea* spp.) are the predominant softwood species. Hardwood stands, primarily mixtures of aspen (*Populus tremuloïdes* Michx.) and birch (*Betula* spp.), are also abundant. The landscape mosaic is comprised of vegetation patterns that are relatively small in size and heterogeneous in composition resulting primarily from extensive human disturbances. The study area was chosen on the basis of the actual stand defoliation status provided by the annual survey while it was still in progress, with a final confirmation based on a survey flight which showed that cumulative defoliation and a full range of current defoliation were present in a study block 120 km east-west by 30 km north-south.

MEIS DATA ACQUISITION

MEIS data (Table 2) were acquired at an altitude of 9800 m above ground level (AGL) following four of the visual survey flight lines across the east-west extent of the province of New Brunswick. Immediately following data acquisition, the MEIS data were enhanced and displayed on an on-board quick-look display (Till *et al.*, 1986) and compared with the survey results to identify a portion of the data for which low altitude photography would be obtained. This photography, to be interpreted in terms of the actual defoliation conditions, was needed for calibration and verification of the MEIS data.

The instantaneous field of view of the MEIS imager was 6.9 m by 6.9 m, and the swath width was approximately 7 km. The area covered was 5584 km^2 or 558 400 ha, in a flight of 1.93 hours, resulting in a data acquisition rate of 289 300 ha/h.

CALIBRATION/VERIFICATION DATA

Following the definition of the study area, two forms of calibration/verification data were obtained (Table 2). The first consisted of 1:16,000-scale normal color aerial photographs obtained

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[1] The Province of New Brunswick is nearly rectangular in shape, approximately 200 km east-west, by 300 km north-south. It has a forest area of 6.3 Mha, nearly the entire area of the province.

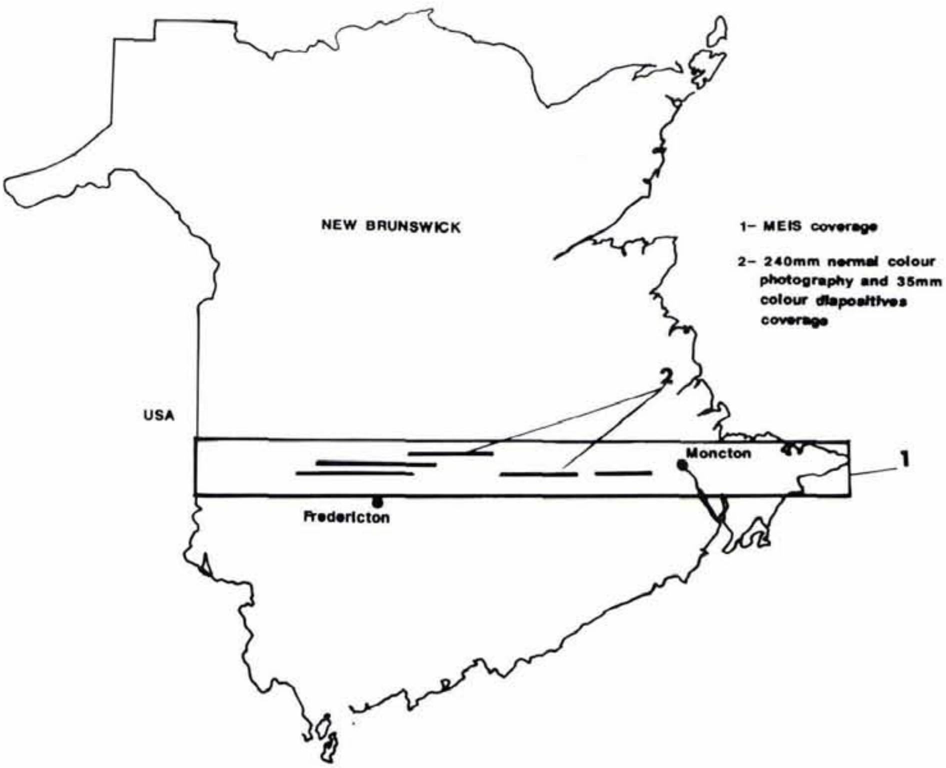

FIG. 1. Map of New Brunswick showing areas of MEIS coverage and coverage by 240-mm normal color photography and 35-mm oblique diapositives.

TABLE 2. DATA SOURCES

Sensor	Bandpasses (nm) center	Bandpasses (nm) width	Altitude AGL(m)	IFOV (MEIS) scale (film)	Purpose	Coverage Latitude	Coverage Longitude
MEIS II pushbroom scanner 24.6-mm lens (8 bands)	1: 480 2: 548 3: 590 4: 675 5: 698 6: 710 7: 746 8: 776	32 32 38 39 13 15 17 37	9 800	0.7 mrad (resampled)	Evaluation of Electro-Optical Sensor	45°55′ to 46°10′	63°30′ to 67°45′
Wild RC-10 151-mm lens Aerocolor film type 2445	blue: green: red:	360-435 525-560 610-665	≈ 2 400	1: 16 000	Track recovery Verification of MEIS (unsuccessful for verification)		
Minolta 35-mm 50-mm lens Ektachrome 200 film	blue: green: red:	410-485 525-585 620-660	≈ 150 to 250	≈ 1: 5 000	Training and verification of MEIS data		

Data acquisition dates: Wild RC-10 08 July 1986
MEIS II 10 July 1986

from the CCRS Falcon aircraft with a Wild RC-10 camera. The second consisted of 670 frames of oblique (45 degree incidence angle) 35-mm diapositives obtained with a 50-mm lens on Ektachrome 200 film from an altitude of 150 to 250 m above ground level (AGL). The oblique photography was intended to provide images as similar as possible to the view of an observer in the defoliation survey. Because of the small area covered by each 35-mm photo, locating them was challenging. The photo aircraft closely followed the spruce budworm survey flight lines. Because of the low altitude of the photo aircraft, the photos were located within 250 to 300 m of the visual survey flight lines.

The 35-mm photos were obtained in groups with each member containing at least 10 percent overlap with its neighbors. The first and last photos in a group included distinctive features (such as roads, houses, water bodies) to help locate the position of the group.

The sample of forest conditions covered by the evaluation patches is very representative of the province as a whole. The sample contained numerous examples of all of the classes of interest (Table 1) occurring in stands of balsam fir and white spruce of varying ages and densities. Black spruce stands of varying density were also present but not defoliated. This is typical for New Brunswick. Deciduous stands consisted primarily of closed canopies of yellow birch and trembling aspen. The forest in the study area is more heterogeneous than that found in the northern part of the province and thus presented a realistic challenge for image classification.

An initial inspection of the 35-mm oblique diapositives showed that they were of excellent quality and a trained spruce budworm survey observer could use them to define the six classes of interest (Table 1): deciduous stands, conifers with cumulative defoliation, conifers with negligible defoliation, and conifers with light, moderate, and severe current defoliation. However, as noted above, the study block is generally quite heterogeneous, and mixing of two or three classes was common. Areas of relatively homogeneous conditions were delineated on magnified images of the diapositives. These areas were called evaluation patches and served as ground truth. A total of 613 evaluation patches were identified and visually classified by one of the authors (Patterson). The use of large-scale 35-mm air photos has been shown to provide spruce budworm assessments comparable to those obtained with ground surveys (Mc Carthy *et al.*, 1983), although perfect agreement cannot be expected.

The 1:16,000-scale normal color photographs, while of good quality, were found to be unreliable for distinguishing current from cumulative defoliation because of the poor color differentiation between these two types of defoliation. Also, different amounts of current defoliation could not be reliably distinguished. We attribute the inability of these photographs to distinguish defoliation classes to the contrast-reducing effects of the atmosphere. A further complication comes from the near-nadir viewing geometry. Similar findings were reported by Ashley *et al.* (1976). The oblique perspective and larger scale of the 35-mm photographs allowed more of the crown to viewed. On the other hand, the normal color photography was invaluable for locating the evaluation patches on the MEIS data. Its high spatial resolution helped us to find corresponding features on the 35-mm diapositives. Nonetheless, only 291 of the original 613 evaluation patches were located on both the 1:16,000-scale photographs and on the MEIS images.

DATA ANALYSIS AND RESULTS

Two approaches were used to investigate the potential of the MEIS pushbroom imager data. A flow chart describes the various steps for each approach (Figure 2). First, we chose a simple technique which is the visual interpretation of normal color images, displayed directly from the high density digital tape to the on-board quick-look system (Till *et al.*, 1986). The second approach involves digital image analysis on the CCRS Landsat Digital Image Analysis System (LDIAS) (Goodenough and Menard, 1988).

VISUAL INTERPRETATION APPROACH

In 1986, the Canada Centre for Remote Sensing had just acquired a device capable of enhancing and displaying three-band color composite images from the eight-band MEIS data on the aircraft in real time for quality control during data acquisition. This display, called Alice, can also enhance and display data played back in real time or one-half real time from the high density digital tapes recorded during a flight. The experiment team wanted to investigate the feasibility of using the Alice display in conjuction with an experienced defoliation observer to determine whether the observer could sketch-map defoliation from an enhanced MEIS image scrolling on the display screen in a manner analogous to the airborne sketch mapping method. We expected this approach would allow the interpreter to map the positions of defoliated areas more accurately than he or she can in the difficult conditions on board an aircraft at low altitude. Furthermore, interpretation by a single observer would eliminate differences in classification standards between observers. Such an approach, if feasible, would enable a defoliation survey to be carried out with MEIS data without the massive ground processing system which would otherwise be necessary to perform geometric and radiometric corrections of the data and subsequent multispectral classification.

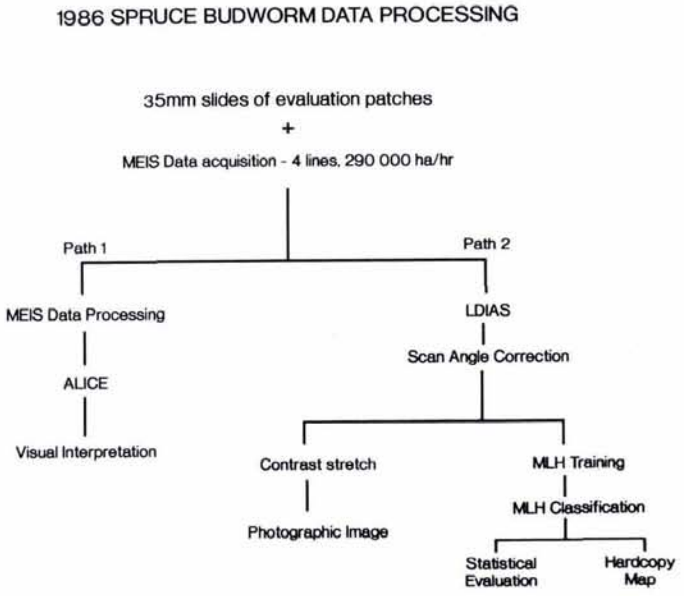

FIG. 2. Processing steps used in the analysis of the data acquired for this project.

Normal color images were created by displaying the 480-nm band in blue, the 548-nm band in green, and the 675-nm band in red. A linear contrast stretch was determined over an area of known defoliation status which displayed the different vegetation classes of interest. This contrast stretch was then applied to the entire flight line to insure consistent color balance and brightness over the whole scene.

We first carried out a familiarization period with image interpretation from the Alice screen, and training of the interpreter (Patterson). Training consisted of comparisons between the images on the Alice screen and the 35-mm slides of selected evaluation patches displayed on a Kodak Ektagraphic 460 desktop projector, until the interpreter was comfortable with the correspondence between the appearance of the various defoliation classes on the 35-mm slides and on the Alice display of MEIS data.

Then, without reference to the 35-mm slides, the interpreter scrolled the MEIS imagery on the Alice display and found the evaluation patches from their positions on the 240-mm photographs. He classified each patch into one of the six desired classes (Table 1). A confusion matrix of the patch classes from the Alice display of MEIS data versus the patch classes from the 35-mm slides was constructed (Table 3).

The exercise with the Alice display provided a number of important insights to direct our future research and development efforts:

(1) Sketch mapping from Alice in real time or one-half time was far too demanding for the interpreter to keep up with the display. The reason was the great amount of detail visible on the display and the desire to classify defoliation on an individual-stand basis. The interpreter must locate, interpret, and draw approximately 100 times as many polygons as are currently drawn in the visual survey. This implies that a conventional image analysis system, which analyzes images on a frame by frame basis, rather than by scrolling, is probably a better approach. (It is inconvenient to

stop the display frequently, and frequent stopping endangers the high density tape which is the first generation, archival data medium.)

(2) The classes HEALTHY, PREVIOUS, and DECIDUOUS seemed to be potentially separable from the three classes of current defoliation. The confusion among classes seemed to be amenable to relatively straightforward improvements. The two most important improvements were to include the near infrared band to increase the separation between the DECIDUOUS class and other classes, and to correct the digital data for the substantial change in radiance caused by the wide scan angle of the MEIS data (± 20 degrees about nadir). The latter correction was expected to improve the separability between the PREVIOUS, LIGHT, and HEALTHY classes.

(3) The visual image interpretation used color information almost exclusively. Shape, context, and texture, which are cues where human interpretation is still markedly superior to numerical methods, did not play a major role in distinguishing the different defoliation classes.

(4) Digital image classification has a potential advantage of being less subjective than visual interpretation.

Based on this experience, we concluded that conventional digital classification is a more promising approach to processing MEIS data for spruce budworm damage assessment than visual interpretation of enhanced images.

DIGITAL ANALYSIS

Because of their large off nadir scan angles, airborne multispectral imagers are affected by substantial variation of radiance with off-nadir view angle, especially when viewing towards or away from the sun (Staenz *et al.*, 1981; Leckie, 1987). Because this problem, not correctable on the Alice display, has been identified as one of the main sources of error during the visual analysis, a correction was applied to each flight line as the first step in digital analysis (Figure 2). We used an LDIAS program (NEWSCN) that computes the along-track average digital signal level for five equally spaced columns in a user-defined homogeneous region in the image. In our case, this region included closed canopy forests of hardwood, mixedwood, and softwood, but essentially no cleared areas or water. NEWSCN corrects the data by fitting a second-order polynomial to the five average values and then using an additive correction to remove the linear and quadratic contributions from the imagery. After correcting the data with NEWSCN, radiometric variations, about a constant value, ranged from negligible to 8.9 percent, with an average for the eight channels of 4.8 percent.

Next, a linear contrast stretch was applied to the data and natural color transparencies were produced on a Color-Fire 240 digital image recorder. These images were used for illustrative purposes to help understand the causes of inter-class confusion (see below).

The principal analysis path used maximum-likelihood (MLH) classification of the eight-band MEIS data, followed by the calculation of confusion matrices comparing the classes assigned by the MLH classifier with the classes of the evaluation patches assigned by visual interpretation from the 35-mm slides.

Much of the success of the MLH classifier depends on the choice of the training areas. The statistical description of the population distribution of each class in feature space derived from the training areas must be representative of the distribution of the class as a whole. Ideally, then, the training area for each class should be picked randomly from the entire sample of the class. We used a subset of our evaluation patches to generate training statistics. The heterogeneity of many stands in our study area prevented us from picking the training areas randomly. Rather, we had to select training areas which were somewhat more homogeneous than the typical situation. In addition, we also picked the largest possible training areas to minimize errors caused by uncertainties in the precise location of our evaluation patches.

Once the training areas were defined for each of the classes in Table 1, the statistical representation (mean digital signal level and covariance matrix) was computed. A per-pixel maximum-likelihood classification was then carried out for the entire study area. Next, a confusion matrix was computed by comparing the class assigned to each pixel by the maximum-likelihood classifier with the class assigned to the evaluation patch the pixel was in.

The resulting confusion matrix is shown in Table 4. The mean correct classification is 72 percent. The classes "previous" and "deciduous" are generally well classified and do not represent important sources of confusion with the healthy and various current defoliation classes. In the case of the healthy and current defoliation classes, the majority of pixels are within one class of the class assigned to the evaluation patch. One-class errors in evaluation patch classification come mainly from inhomogeneities and from interpreter subjectivity. One-class errors in the maximum-likelihood pixel classification arise from the spectral similarity of adjacent classes and the difficulty of

TABLE 3. CONFUSION MATRIX SHOWING THE NUMBER OF PATCHES CLASSIFIED BY VISUAL CLASSIFICATION OF THE 35-MM OBLIQUE AIR PHOTOS (COLUMNS) AND BY VISUAL INTERPRETATION FROM THE ALICE DISPLAY (ROWS). THE NUMBER IN PARENTHESES IS THE PERCENT OF THE TOTAL OF THAT COLUMN.

Class from Alice Interpretation	P	S	M	L	H	D
Previous	47 (72%)	2 (9%)	5 (22%)	14 (53%)	27 (46%)	7 (22%)
Severe		4 (17%)				
Moderate		7 (31%)	3 (13%)	1 (4%)		
Light	3 (5%)	4 (17%)	6 (26%)	4 (16%)		1 (3%)
Healthy	9 (14%)	2 (9%)		2 (8%)	23 (39%)	10 (30%)
Deciduous	2 (3%)	1 (4%)	4 (17%)	5 (19%)	4 (7%)	13 (39%)
Unclassified	4 (6%)	3 (13%)	5 (22%)		5 (8%)	2 (6%)
Total number of patches	65	23	23	26	59	33

TABLE 4. CONFUSION MATRIX SHOWING THE NUMBER OF PIXELS CLASSIFIED BY VISUAL CLASSIFICATION OF THE 35-MM OBLIQUE AIR PHOTOS (COLUMNS) AND BY A PER-PIXELMAXIMUM-LIKELIHOOD CLASSIFICATION (ROWS). THE NUMBER IN PARENTHESES IS THE PERCENT OF THE TOTAL OF THAT COLUMN.

Class from per-pixel MLH classification	P	S	M	L	H	D
Previous	150 (85%)	55 (12%)	13 (3%)	80 (9%)	32 (2%)	
Severe	2 (1%)	236 (51%)		9 (1%)	15 (1%)	
Moderate	4 (2%)	116 (25%)	354 (84%)	152 (17%)	330 (21%)	
Light	12 (7%)	28 (6%)	17 (4%)	536 (60%)	314 (20%)	
Healthy	9 (5%)	18 (4%)	38 (9%)	98 (1%)	849 (54%)	12 (2%)
Deciduous				9 (1%)	32 (2%)	524 (98%)
Unclassified		9 (2%)		9 (1%)		
Total number of pixels	177	462	422	893	1572	586

finding representative training areas. The New Brunswick Department of Natural Resources considers classification within one class as being of satisfactory accuracy. The accuracy reported in Table 4 indicates that an operational system based on MEIS technology can probably meet their requirement. They are particularly encouraged by the fact that the MLH classification classifies every pixel within a stand individually, allowing for further refinement of the description of damage to a stand. For example, it should be possible to independently determine the proportions of healthy conifers, currently defoliated conifers, previously defoliated conifers, and deciduous trees within each stand. This offers the potential of more sophisticated forest management at the individual stand level.

Despite these encouraging results, we wanted to investigate the sources of confusion between the adjacent classes of healthy and current defoliation. To do this, photographic enhancements were projected onto a map made from the MLH classification at a scale of 1: 25,000, allowing a comparison to be made between the enhanced MEIS data, the MLH classification, and the appearance of selected evaluation patches on the oblique 35-mm slides.

This examination of misclassified patches indicated two important sources of error. (1) Even with our attempts to pick homogeneous evaluation patches, considerable within-patch variation was observed. Some patches clearly showed areas of two classes mixed together, and a few showed three classes. The classification of these with the 35-mm slides was into the class having the greatest area, but these patches posed difficulties for the classification of the MEIS data. (2) The exact location of the evaluation patches on the MEIS images was very difficult, and some misregistration certainly remained which would lower the classification accuracy. Even with the correction for view angle induced radiometric variations, the edge of the image looking away from the sun direction appeared to have residual radiometric variations. This portion of the scene was not used for the classification trial, but this variation would have to be corrected in an operational system.

From this evaluation, we concluded that future investigations should consider a more comprehensive classification scheme which might permit mixtures of classes and more than one level of previous defoliation. More precise, quantitative definitions of the classes would benefit both future developments of remote sensing technology and the incorporation of the results of an improved defoliation survey into forest growth forcasts. An operational system would have to include accurate geometric correction of the airborne data, particularly if small training areas must be used, and for accurate registration to existing forest inventory maps. Finally, all of the researchers felt that higher spatial resolution would make the MEIS data more interpretable by locating small features for geographic control and by decreasing the problem of mixed pixels in heterogeneous patches. The cost implications of increasing the spatial resolution mean that this problem warrants careful study to identify the optimum resolution to achieve the minimum cost consistent with satisfactory accuracy.

CONCLUSIONS

We have reached a number of conclusions which are important for the development of an operational system to perform annual current-year defoliation surveys.

(1) A per-pixel maximum-likelihood spectral classification based on eight-band spectral radiances achieved an average classification accuracy of 72 percent for six classes relevant to an annual defoliation survey, with the majority of misclassifications of healthy and current defoliation classes being to adjacent classes. This level of accuracy, coupled with greatly superior spatial resolution and positional accuracy compared to the current visual survey, indicates that an operational sensor based on MEIS technology could enable yearly assessments of defoliation at the stand level. When used as input to timber growth models, this information could decrease the ±25 percent uncertainty level in wood supply forecasts (MacLean, 1988).

(2) We have demonstrated that data can be acquired at a rate of nearly 290,000 ha/hr during a three-hour flight. At this rate, it would be possible to cover the entire province of New Brunswick in approximately 12 flights, or four days at three flights per day. We feel this is more clear weather than one can realistically expect during the two-week period during which the current-year defoliation is clearly visible. An improved sensor has been proposed by CCRS and Forestry Canada which will increase the data acquisition rate three-fold (through an increase in swath width) and ensure that the needs of the annual survey can be met. It is apparent from our experience that a high altitude, high speed aircraft is essential for this task.

(3) A test of visual interpretation of enhanced images showed that shape, texture, and context, which are characteristics where human interpretation usually outperforms computer classification, are not important clues to severity of defoliation on the 7-m resolution ALICE display. Considerations of objectivity, convenience, and fatigue led us to conclude that conventional digital classification is a more promising approach to processing MEIS data for spruce budworm damage assessment than visual interpretation of enhanced images.

RECOMMENDATIONS

In this investigation we have shown that the MEIS linear array imager is capable of mapping current and previous year spruce budworm defoliation with classification accuracies adequate to meet the needs of the New Brunswick Department of Natural Resources and Energy. However, a great deal more research and development are needed to create an operational system which could provide a cost-effective annual survey. Research is needed to determine:

(1) The most cost-effective spatial resolution;

(2) A reliable method for correcting the very significant radiometric variations caused by large off-nadir viewing angles (these will increase with the wider field of view required for the operational system); and

(3) A reliable method for correcting for the variable atmospheric path radiance and transmission which will be encountered in operational use of the proposed system.

Technology developments are needed in three key areas:

(1) Development of a wide swath sensor, capable of imaging a 15-km or greater swath from an altitude of 10 km. With a 15-km swath, it would be possible to acquire data over the entire province of New Brunswick in six flights of three hours each.

(2) Development of operational geometric corrections capable of removing the effects of aircraft attitude and altitude variations, and ultimately capable of removing distortions induced by terrain elevation variations. These corrections are necessary to allow the results to be transferred into a geographic information system containing the province's forest inventory information.

(3) Development of a high throughput image classification system including rapid designation of training areas, and large volume classification. These are necessary to meet the operational requirement of having the final mapping completed within four months of data acquisition.

These are challenging problems. Progress has been made in all of them, but much more progress will be necessary, particularly with regard to efficient processing of the very large data volumes generated by a wide-swath airborne imager.

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