# THE USE OF AIRBORNE MULTISPECTRAL SCANNER DATA FOR THE DETECTION AND MAPPING OF INSECT DAMAGE IN THE JARRAH FOREST

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# EXECUTIVE SUMMARY

## Research Objective

To evaluate remote sensing for mapping the extent and severity of insect damage in jarrah forests, using data collected by a 24 channel airborne multispectral scanner.

## Study Area

Data was acquired in October-November 1989 at Proprietary Block, near Collie, which had high insect infestation levels.

## Findings

- Within jarrah-dominated areas in the study site:
  - (a) the areal extent of canopy infestation was successfully mapped using the remotely sensed data.
  - (b) the severity of damage in broad classes (low, medium, severe) was also detectable, and reliably mapped.
- The important discriminating information was found to be in the infra-red and thermal spectral regions. Visible wavelengths do not alone provide sufficient information for mapping insect damage.
- Spatial resolution of 20 m appears adequate for reliable mapping, given the high spectral quality of the data used in this study.
- Different forest community types within the study area were spectrally distinct. This indicates the potential for mapping forest community types with spectral data.
- The ephemeral nature of the insect damage problem indicates that timing of data acquisition is critical.
- The identified spectral bands and resolution indicate that TM satellite data (7 bands, 30 m resolution) may be useful if cloud and smoke conditions permit data acquisition.

## Recommendations

The positive findings of this pilot study indicate that remotely sensed data could form the basis of an operational monitoring system. Specific recommendations are made in this report on steps to be taken to move towards the implementation on operational system. The recommendations include an integrated program of field mapping and image processing, and an evaluation of TM satellite data.

## PREAMBLE

This report describes the methods and findings of a study which analysed remotely sensed data to detect and map insect-damaged areas in the Northern Jarrah Forest of Western Australia. The report presents the details of the study which related ground information and airborne multispectral scanner data for an area east of Collie that was severely damaged in 1989. Discrimination of insect damaged areas was the primary aim of the study but the results presented here have wider application in the general area of forest condition mapping. The 1989 work followed earlier studies of the spectral characteristics of forest components (Hick, and others, 1989).

The research program has been a collaborative effort between the WA Department of Conservation and Land Management (CALM) and the Commonwealth Scientfic and Industrial Research Organisation (CSIRO) W.A. Remote Sensing Group.

## 1.0 INTRODUCTION

### 1.1 The Insect Damage Problem

Infestations by Jarrah Leaf Miner, *Perthida glyphopa* affect over 500,000 ha of valuable jarrah forests (*Eucalyptus marginata*) of the South-West of Western Australia, the damage in lost wood growth is estimated at around 170,000 cubic metres each year. The insects, when feeding, reduce the green material of jarrah leaves, in some cases by more than 60%.

Jarrah is attacked by the leafminer annually (Mazanec, 1989). When larval population density is high and extensive foliar damage occurs, stands can appear `red-brown' in September-October. Such damage was first observed in the woodland type of jarrah on the coast as early as 1914 (Newman and Clark, 1926), and then in the inland forest east of Manjimup in the 1950's. It spread rapidly and at present the area of forest and partly cleared land on which jarrah is being damaged stretches from south of Collie to the west of Manjimup, Denmark and north of Albany and is estimated at approximately 20,000 km square. The boundary of the obviously damaged forest does not define the area where the leafminer occurs at high population density. The latter is difficult to detect by inspection, especially in a recently invaded forest. Damage may only become visible several years after initial attack. The foliar damage caused by the feeding larvae usually does not kill the jarrah tree (Mazanec, 1978).

Larvae begin to feed in June, with serious damage being caused only in late September - October. The heavily damaged leaves, which tend to be a minority, are shed within a week after most of their photosynthetic tissue has been destroyed, but those damaged to a lesser degree are retained until their replacement during November-January, the time of the annual flush of leaf growth for Jarrah. The tree usually has living leaves, however, in years preceded by a low rainfall in June - September leaf replacement is poor, many branchlets die off and crown damage results. This is a characteristic feature of jarrah forest attacked by the leafminer (Mazanec, 1978).

## 1.2 The Rationale for Multispectral Remote Sensing

Knowledge of the location, extent and severity of insect infestation is a necessity to efficient or effective forest management. Seasonal variation should be known to enable effective control strategies to be developed.

Ground-based methods are not well suited to estimation of areal extent of insect damage, since intrinsically they provide point or line transect samples. Areal estimates from ground sampling are labour intensive, expensive and may be liable to large errors. These difficulties are increased by the nature of the insect infestation problem as its effects are ephemeral and sporadic in their distribution.

Satellite data from sensors with fixed, broad spectral bands can provide routine broad-scale synoptic coverage, subject to suitable (cloud-free) weather conditions. Airborne Multispectral Scanner (AMSS) flights which can be conducted at specific times with narrow, selectable bands can provide greater flexibility in temporal coverage, as well as higher spectral and spatial resolutions.

Remotely sensed data are relatively inexpensive when compared with ground survey. If the multi-spectral data can reliably identify the damaged areas, then remote sensing may offer an attractive complementary approach to mapping forest condition. Field work and verification could be directed with broadscale forest condition information obtained from the image data.

## 1.3 Physical Principles of Spectral Response of Damaged Leaves

There are well known relationships between plant material and their reflectance spectra. Insect damage affects the green canopy materials, reducing chlorophyll levels within the canopy and exposing more cellulose-dominated damaged leaves, understorey debris and soil.

This study relies on the interaction of differing forest components with incoming radiant energy and the modification to reflected energy, at measurable wavelengths. Elvidge (1989) gives detailed information on the reflectance spectra of green and dry plant materials; Hick et al (1987). Important spectral regions for discrimination of materials are the visible (400-700 nanometres wavelength), the near infrared (NIR, 700-1200nm) and the shortwave infrared (SWIR, 1200-2500nm). The longer thermal wavelengths also carry significant information relating to temperature and transpiration. Features in the visible portion of the spectrum are associated with leaf pigmentation and chlorophyll content. Absorption features in the NIR and SWIR are associated with cell structure and water absorption.

Figure One shows sample spectra of healthy and insect-damaged jarrah leaves, and of dry cellulose powder. Absorption features can be readily seen. The notable spectral features of damaged leaves are the absence of the green peak and the red-infrared steep-edge, lower infrared and SWIR features relating to cellulose and water content.

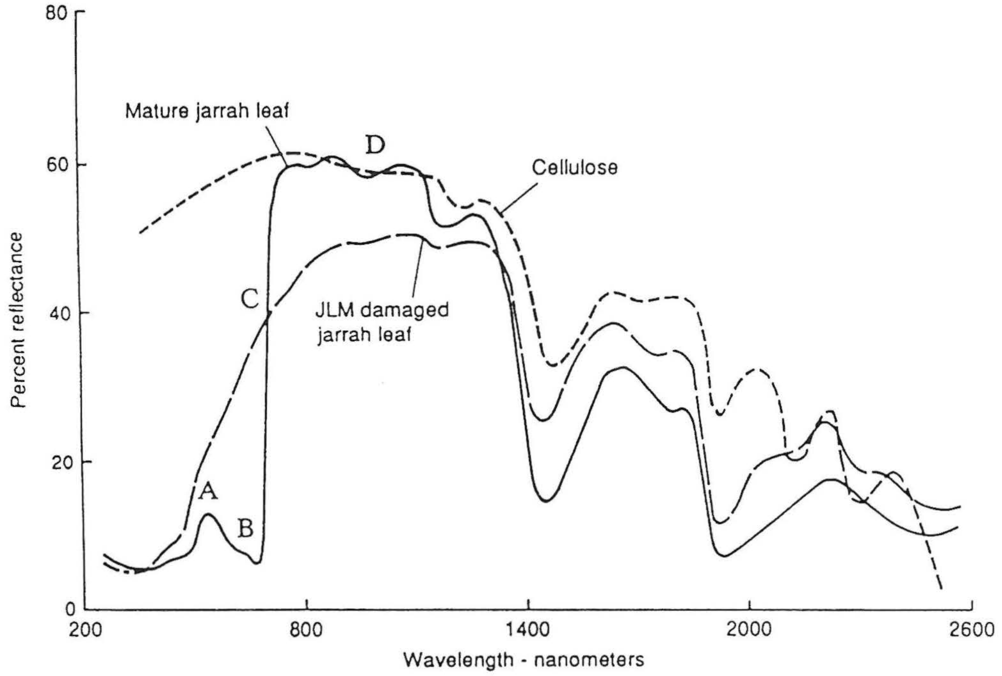

Figure One. Sample laboratory spectra for damaged and undamaged jarrah leaves, and cellulose powder. (A - green peak, B - chlorophyll absorption, C - infrared edge, D - infrared plateau)

## 1.4 Unmixing

Spectral sensors measure the mean integrated response of an area of ground called a picture element or `pixel'. This spectral response is the sum of the components of that pixel, and an understanding of the relationship of the signal to actual forest condition requires the recognition, and unmixing, of these components.

An essential component of "unmixing" studies is an understanding of the spectral responses of the forest components such as leaves of different species (whether healthy or damaged) woody tissue, ground cover and bare soil. The relative effects of shadowing and illumination from the over-storey, mid-storey and illumination from the over-storey, mid-storey and under-storey canopy structures are also important.Previous work (Hick, et al) has examined laboratory spectral signatures of the different forest components with the aim of understanding the physical relationships of forest condition and reflectance, and of developing procedures and identifying spectral-band combinations which may separate these components from the mixed spectral response recorded by a sensor.

## 2.0 DATA AND METHODS

This section describes the data acquisition systems used in the 1989 study, and gives details of the data collection and analysis methods.

### 2.1 Spectra Measurements

Field and laboratory spectra were measured for a range of sample materials. The Geoscan Portable Field Spectroradiometer (PFS) was used concurrently with scanner flights to provide calibration and field spectra. A "cherry-picker" platform enabled the collection of some canopy samples. Insect-damaged and healthy leaves were also returned to the laboratory for detailed spectral analysis on an Hitachi 340 VIS-NIR spectrophotometer. Examples of these spectra are shown in Figure One.

### 2.2 Geoscan AMSS

The Geoscan Airborne Multispectral Scanner (AMSS) is an airborne instrument which records reflected spectral energy in 24 spectral bands (discrete wavelength intervals in the electromagnetic spectrum) (Honey and Daniels 1984). These 24 bands are chosen to cover the visible, reflected infra-red and thermal infrared spectral regions (0.45 - 12.0 microns wavelength), ( see Figure Two below).

The spectral signal is the integrated response over a ground picture element (pixel). The ground resolution depends on the height at which the aircraft is flown. The scanner records perpendicular to the direction of aircraft travel, 768 pixels per scan line, over a field of view of 45 degrees from nadir. Due to the scan angle (90 degrees) and aircraft movement, there can be some geometric distortion in the imagery despite roll, pitch and yaw stabilisation.

The AMSS was flown over the study area on November 1st 1989 at 2 pm. Conditions were suitable with little or no cloud interference The image section comprised 2,471 lines x 768 pixels (See Figure Three). The wavelength intervals of the 24 spectral bands are listed in Table 1. The image covered an area of 7,000ha, which included approx 5,000ha of jarrah forest. The ground resolution gave a pixel size of approximately 5m by 5m.

Table 1: Geoscan AMSS Bands used in data acquisition

| | Band Number | Central Wavelength (microns) | Band width (microns) |
|---|---|---|---|
| VIS/NIR | 1 | 0.522 | 0.042 |
| | 2 | 0.583 | 0.067 |
| | 3 | 0.645 | 0.071 |
| | 4 | 0.693 | 0.024 |
| | 5 | 0.717 | 0.024 |
| | 6 | 0.740 | 0.023 |
| | 7 | 0.830 | 0.022 |
| | 8 | 0.873 | 0.022 |
| | 9 | 0.915 | 0.021 |
| | 10 | 0.955 | 0.20 |
| SWIR | 11 | 2.044 | 0.044 |
| | 12 | 2.088 | 0.044 |
| | 13 | 2.136 | 0.044 |
| | 14 | 2.176 | 0.044 |
| | 15 | 2.220 | 0.044 |
| | 16 | 2.264 | 0.044 |
| | 17 | 2.308 | 0.044 |
| | 18 | 2.352 | 0.044 |
| TIR | 19 | 8.64 | 0.530 |
| | 20 | 9.17 | 0.530 |
| | 21 | 9.70 | 0.530 |
| | 22 | 10.22 | 0.533 |
| | 23 | 10.75 | 0.533 |
| | 24 | 11.28 | 0.533 |

### 2.3 Landsat Thematic Mapper

Satellite data were also considered. Because of their routine and broadscale coverage, satellite data would be ideal for forest monitoring provided that the spectral and spatial resolution are adequate. Landsat Thematic Mapper (TM), which has 30m ground resolution and 7 spectral bands, is the most promising data source. Cloud cover remains a problem for satellite monitoring of ephemeral events. Figure Two shows the spectral band location of the AMSS and TM.

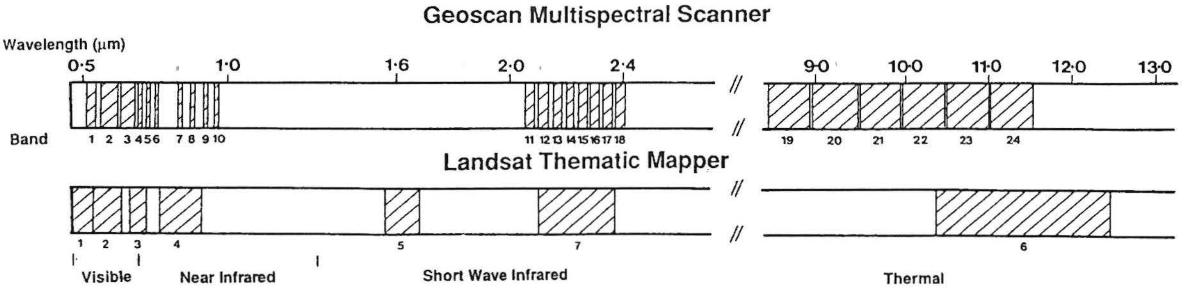

Figure Two. Spectral band locations of the Geoscan Airborne Multispectral Scanner and the Landsat Thematic Mapper

## 2.4 Study Area

The 1989 study concentrated on an area (see Figure Three) of approximately 2,500ha of mixed jarrah forest three km east of Collie ($33^{0}27$'S, $116^{0}12$'E). Heavy infestations occurred in 1989 and the severity of the infestation was mapped.

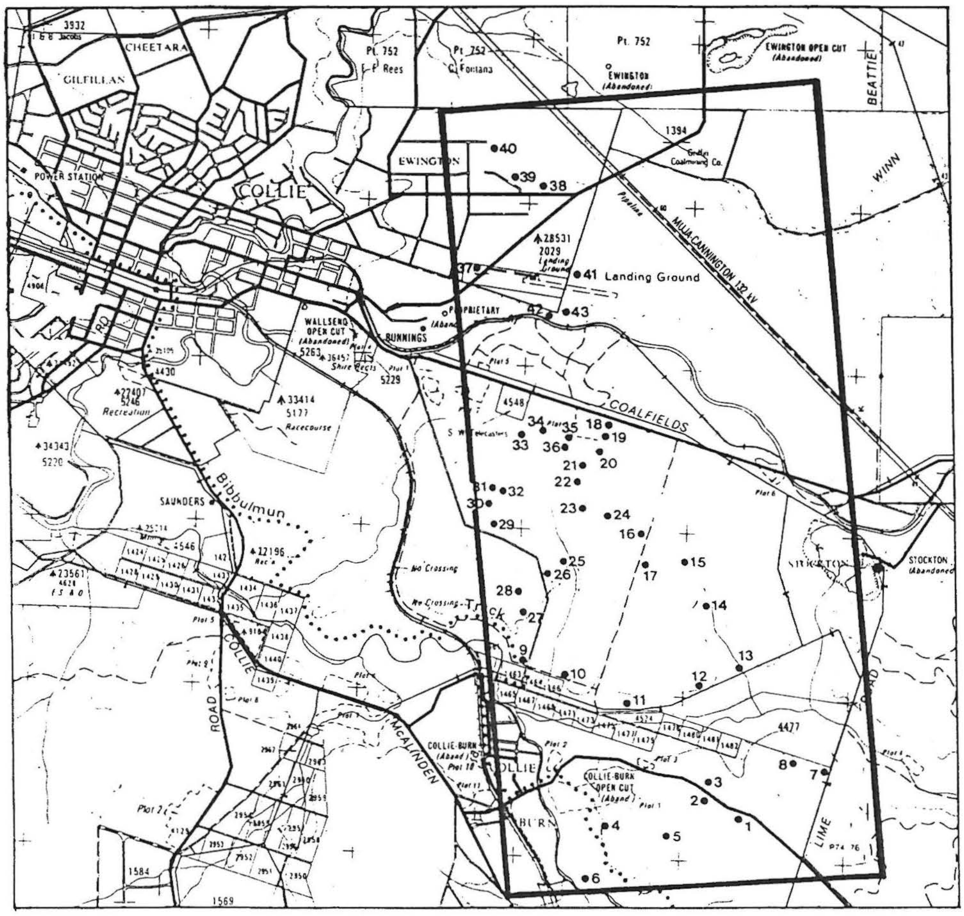

Figure Three: The study area shown located just east of Collie. Numbers within the study area identify the sites which were accurately plotted, described and recorded.

## 2.5 Ground Site Data

Forty-three ground training sites were selected, covering the range of forest conditions encountered in the study area. The size of the sites ranged from 40 x 40 m to 100 x 100 m and were selected alongside existing tracks and other identifiable features, with the locations accurately plotted to enable accurate data extraction from the scanner imagery. Sites were chosen to be reasonably homogeneous with respect to the degree of insect damage, composition and structure (canopy, mid-storey and understorey). Historic site information, such as its burning, logging, past infestations, aspect and landform, were also recorded.

Of the 43 sites, 32 were dominated by jarrah, while the others were dominated by other species such as *E. callophylla, Allocasuarina, Hakea* Sp., and *Banksia* Sp. The insect infestation levels on these sites were recorded as severe, moderate, or light (Table 2).

The important parameters which were recorded for these training sites included the following,

1. Canopy - description and percentage of the dominant tree species and the degree of infestation.

2. Midstorey - description and percentage of the dominant tree species plus the degree of infestation. This level probably caused the most confusion due to the presence of diverse midstorey species within the regenerated jarrah and marri.

3. Lowerstorey - description and percentage of the dominant features included various shrubs, trees and grasses, dead litter, logs, shadow and burnt material.

4. Soil - percentage actually showing and its colour and type.

Table 2. Summary details of 43 ground sites used in the analysis. The column "Class Sites" shows the numbers used in the analysis of jarrah sites.

| Orig. Site | Class. Sites | Canopy | % | Inf | Middle Storey | % | Inf | Lower Storey | % No's | Inf | Soil | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | Jarrah | 0 | L | Poles | 30 | M | Litter | 10 | | Grey sand | 5 |
| 2 | 1 | Jarrah | 10 | L | Poles | 50 | M | Litter | 10 | | Sandy gravel | 5 |
| 3 | 2 | Jarrah + Marri | 10 | L | Poles | 20 | L | Litter + plants | 5 | L | Sandy gravel | 0 |
| 4 | 3 | Jarrah + Marri | 35 | M | Sapling | 20 | M | " " | 20 | L | Sand | 5 |
| 5 | 4 | Jarrah poles | 5 | M | Various species | 45 | M | Litter | 30 | S | Grey sand | 5 |
| 6 | 5 | Jarrah | 40 | S | Jarrah + Banksia | 20 | S | Litter + plants | 20 | L | " " | 0 |
| 7 | 6 | Jarrah | 20 | M | Sapling | 30 | M | " " | 20 | L | " " | 5 |
| 8 | 7 | Sapling | 50 | M | - | - | - | " " | 25 | L | " " | 5 |
| 9 | 8 | Sapling | 30 | S | - | - | - | " " | 20 | S | " " | 0 |
| 10 | 9 | " | 40 | S | - | - | - | " " | 20 | S | " " | 0 |
| 11 | 10 | Jarrah | 20 | S | Various | 25 | S | " " | 40 | - | " " | 5 |
| 12 | 11 | " | 40 | S | " | 25 | S | " " | 49 | - | " " | 5 |
| 13 | 12 | Cleared | 0 | - | occ Blackboy | 10 | - | Grasses | 70 | - | " " | 45 |
| 14 | 13 | Nil | 0 | - | Various | 20 | - | " | 70 | - | " " | 50 |
| 15 | 14 | She-oak | 20 | - | She-oak | 55 | - | Various | 20 | - | " " | 0 |
| 16 | 15 | Saplings | 40 | L | Nil | - | - | She-oak | 25 | - | " " | 0 |
| 17 | 16 | " | 25 | L | Sapling | 40 | L | Various | 30 | - | Brown sand | 5 |
| 18 | 17 | Sapling | 40 | M | " | 5 | M | Litter + plants | 40 | - | Grey sand | 0 |
| 19 | 15 | " | 40 | M | " | 5 | M | " " | 50 | - | " " | 0 |
| 20 | 16 | " | 30 | M | " | 20 | M | " " | 40 | - | " " | 0 |
| 21 | 17 | " | 40 | M | " | 15 | M | " " | 40 | - | " " | 0 |
| 22 | 18 | " | 20 | M | " | 40 | S | " " | 30 | - | " " | 0 |
| 23 | 19 | " | 30 | M | " | 30 | M | Litter | 30 | - | " " | 0 |
| 24 | 20 | - | - | - | " | 60 | M | Litter + plants | 20 | | " " | 0 |
| 25 | | Jarrah | 10 | S | Banksia | 30 | M | " " | 40 | - | " " | 20 |
| 26 | | " | 10 | S | " | 30 | M | " " | 40 | - | " " | 10 |
| 27 | | Jarrah-poles | 10 | M | She-oak | 40 | M | " " | 30 | - | " " | 5 |
| 28 | | Jarrah | 5 | M | Sapling + she-oak | 50 | S | " " | 30 | - | " " | 0 |
| 29 | 21 | Sapling | 20 | S | Sapling | 40 | S | " " | 30 | - | " " | 0 |
| 30 | 22 | - | - | - | " | 50 | M | " " | 40 | - | " " | 0 |
| 31 | 23 | - | - | - | " | 40 | - | " " | 40 | - | " " | 0 |
| 32 | 24 | - | - | - | " | 35 | M | " " | 40 | - | " " | 0 |
| 33 | 25 | Sapling | 30 | M | " | 20 | M | " " | 40 | - | " " | 5 |
| 34 | 26 | " | 15 | M | " | 30 | M | " " | 40 | M | " " | 5 |
| 35 | 27 | " | 15 | M | " | 30 | M | " " | 40 | M | " " | 0 |
| 36 | 28 | " | 15 | M | " | 30 | M | " " | 40 | M | " " | 0 |
| 37 | | Jarrah (burnt) | 15 | - | Saplings (burnt) | 10 | - | Ash, blacken | 50 | - | " " | 40 |
| 38 | 29 | Jarrah | 25 | S | Sapling + she-oak | 25 | S | Litter | 40 | - | " " | 20 |
| 39 | 30 | " | 10 | S | Various | 30 | S | Litter + plants | 40 | M | " " | 5 |
| 40 | | " | 5 | S | J. occ. Marri | 20 | S | " " | 70 | - | " " | 40 |
| 41 | | " | 5 | M | " " | 15 | M | Open (grass) | 60 | - | " " | 50 |
| 42 | 31 | Sapling | 20 | L | Jarrah | 30 | M | Litter + plants | 40 | - | " " | 0 |
| 43 | 32 | Jarrah | 30 | L | Sapling | 30 | M | " " | 30 | - | " " | 5 |

Abbreviations: Inf - level of infestation by leafminer - Light (L), Moderate (M), Severe; J - Jarrah; Saplings + Poles - refer to Jarrah; 1 - Jarrah sites used in the classification analysis.

## 2.6 Statistical Analysis of AMSS Data

The crucial factor in producing spectral maps or enhancements which reliably display forest condition is that the spectral separation of the condition classes is large compared to the variation within classes. If this can be established, then important band combinations which provide the discrimination can be identified and appropriate enhancements produced. A classification mapping approach can also be adopted and pixels can be allocated with confidence to one or other of the classes (or to none).

Canonical variate analysis (CVA) (Anderson, 1958) was used to summarise the class separation between the training site data. Associated routines allow the important discriminating spectral bands to be identified (Campbell 1984; McKay and Campbell, 1982). The CVA analysis summarises the separation between sites in the multivariate (24 bands = 24 dimensions) spectral space. It discovers successive band combinations (vectors) which maximise the site separation. These vectors are referred to as canonical vectors and associated with each is a canonical root - a number which is an index of the separation between sites along that axis. The sum of the canonical roots gives a measure of the overall site separation in all dimensions. The canonical roots form a decreasing sequence. The first CV direction is the single axis which has the greatest separation. Frequently, the site separation in spectral space can be adequately summarised by the first few canonical variates, thus reducing the dimensionality of the data set while maintaining relevant information on site clustering and separation. Band reduction routines are then applied to identify simplified combinations of bands which maintain the separation between groups of sites. The results may be used to identify useful image enhancements, or as input to the allocation procedures.

The allocation procedures calculate two sets of indices for each image pixel - a relative probability of class membership and a typicality for the class. These results are displayed as class maps in different ways to summarise the membership of each class separately, or of several classes together. Note that all the 32 sites used in the analysis were jarrah-dominated. The allocation procedure is applied to the whole image but the class condition labels may only be applied usefully in jarrah areas.

The multivariate discriminant analysis and allocation procedures are incorporated in the A-Image display and analysis system which runs on an Amiga microcomputer.

Prior to analysis, the data were aggregated to a ground resolution of approximately 20 m by 20 m. A correction was applied to adjust for cross-track illumination effects caused by scan angle and atmospheric effects.

## 3.0 RESULTS

### 3.1 Image Enhancement

The 24 band AMSS data were displayed initially on the IVAS 600 image analysis system at CSIRO. Various combinations of raw data bands were displayed and enhanced for visual assessment in the forest areas. An enhancement of bands 3(610-680nm), 7(820-840nm), and 13(2110-2150nm) in Blue, Green and Red appeared to differentiate healthy and insect-damaged forest, at least in some known areas. These bands were chosen because of their known association with chlorophyll and cellulose. The enhancement in Figure Four (a) shows some known insect damaged areas in red. The green areas were known to be associated with light insect infestation. A more rigourous association was then derived from multivariate analyses of the training site data. Figure Four (b) is a mosaic of colour aerial photography covering the study area.

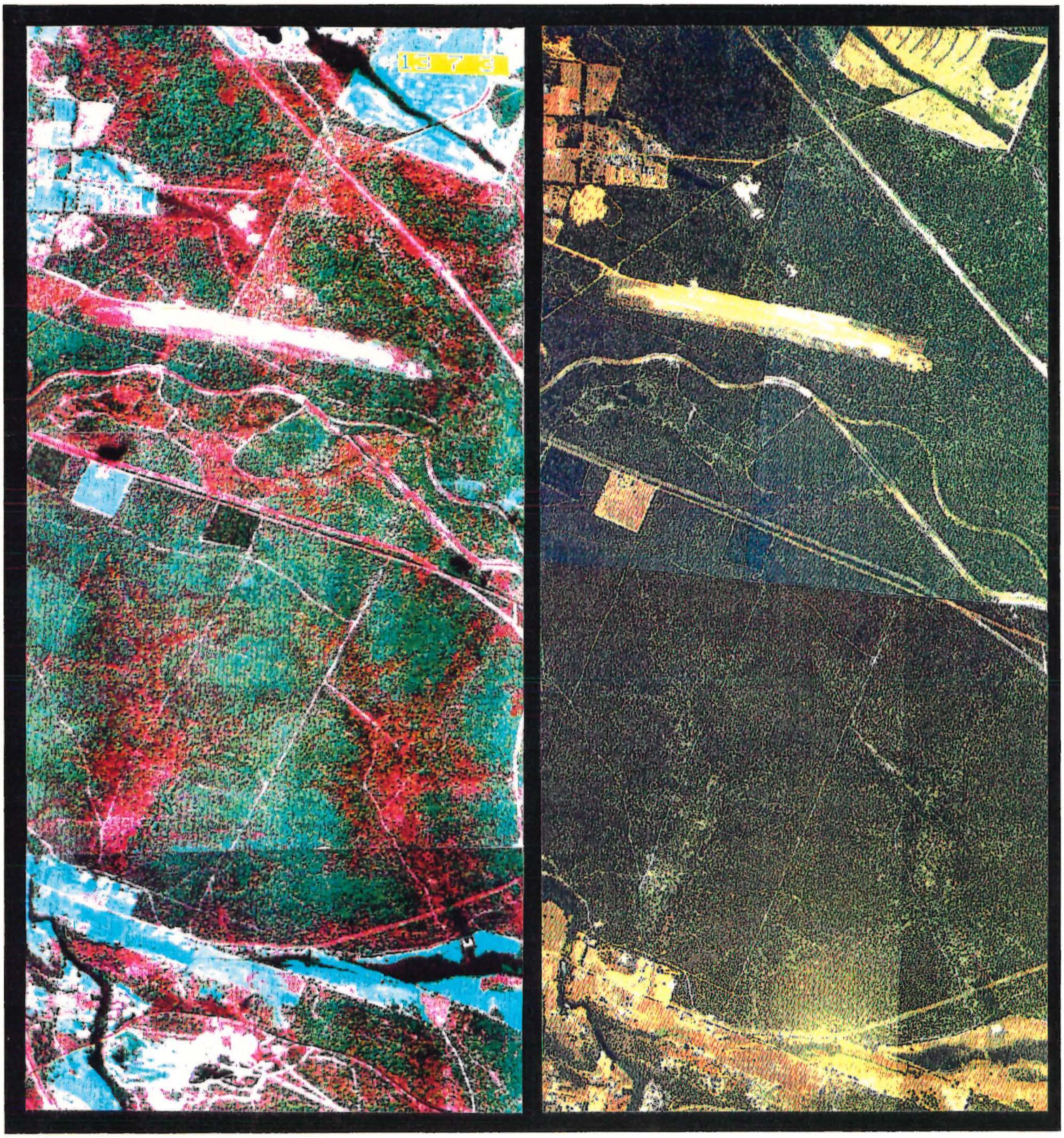

Figure Four. Image enhancement and aerial photography of study area.

(a) Enhancement of bands 3,7,13 in B,G,R appears to discriminate healthy and insect-damaged forest. Insect damage is associated with the red areas.

(b) Mosaic of colour aerial photography.

### 3.2 Spectral Plots of Training Site Data

Individual pixel spectral responses, and site averages, may be qualitatively compared using spectral plots.

Figure Five shows the mean spectral response from three sites; one from each class of insect damage. The pooled within-site standard deviations indicate that the variation within groups is large compared to the separations in any band. The visible and SWIR region clearly separate the severe site, while the thermal region appears to separate the moderate and lightly damaged sites (See Section 3.4).

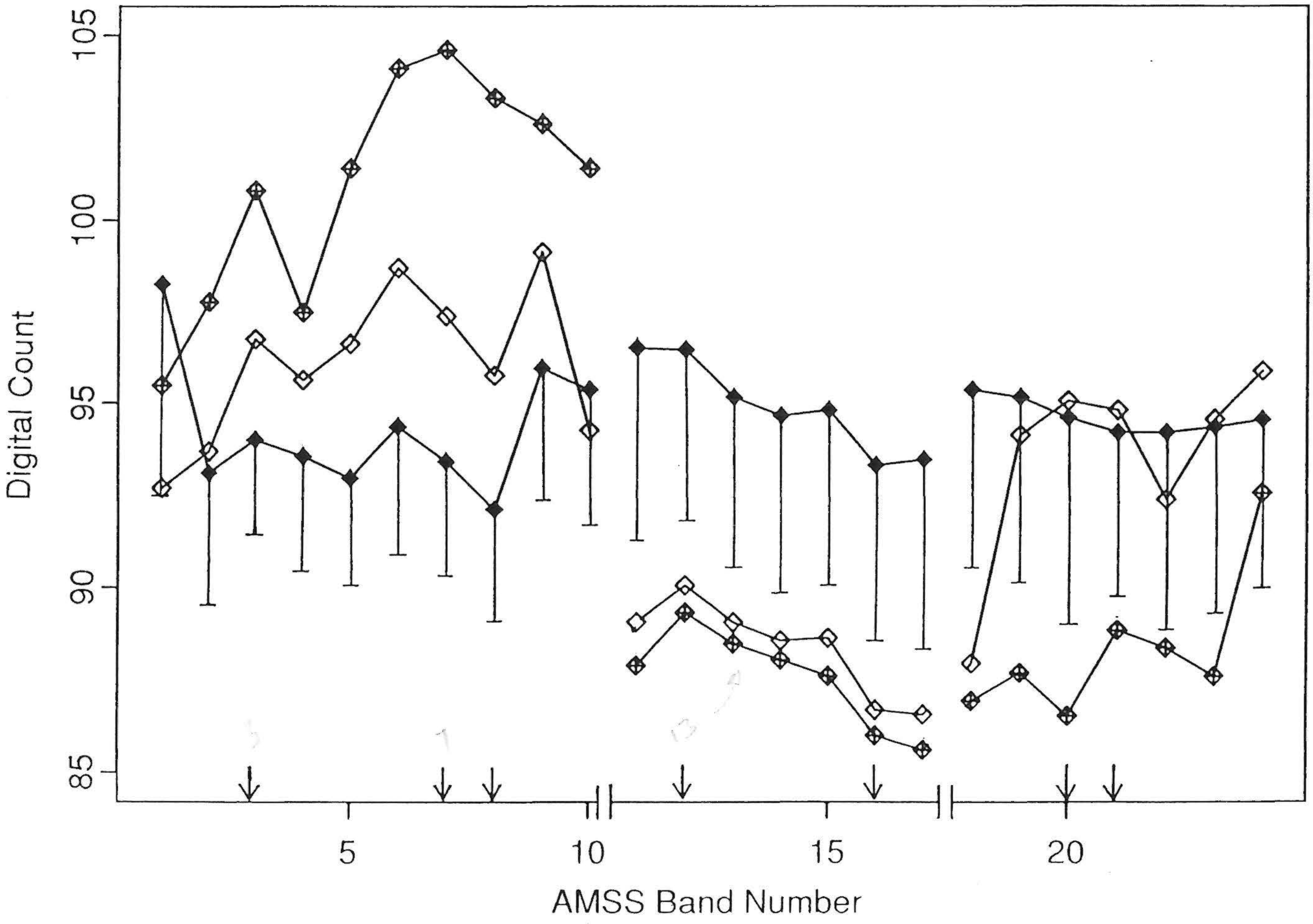

Figure Five. Mean spectral response in digital counts plotted against band number for three jarrah sites with different infestation levels ( light; moderate; severe). Within site standard deviations were approximately 3.5 counts in the VIS/NIR, and 4.5-5.0 counts in SWIR and TIR bands. Arrows on the x-axis indicate the seven bands used in the allocation.

## 3.3 Canonical Variate Analysis - All Sites

### 3.3.1. Aggregation of Sites and Comparison

The nominal five metre data were aggregated to 10m, and 20m ground resolution, producing three image files of the area. The training site data from each of these files were analysed using the CVA discriminant analysis. This was done for two reasons; firstly it was noted that the 5m resolution was perhaps too fine for a forest environment - individual pixels might contain quite different proportions of canopy/understorey/soil and not be representative of the site as a whole, thus increasing within site variation. Secondly, the larger resolution approximates that of satellite scanners. The training sites at each of the three scales cover exactly the same ground area so that the site means are unaffected by the aggregation. The number of pixels is affected and so are the variance estimates. The initial analysis used all 43 sites and 24 spectral bands for 5m x 5m raw data. The sum of canonical roots was 2.3 indicating poor separation overall between sites. One reason for this is the high within-site variability at this scale.

Analysis of the data from the same sites at the 10m x 10m and 20m x 20m aggregated scales gave a sum of roots of 6.2 and 14.3 respectively. Since the site means are unchanged, this increase in separation results from reduction of within site variation at larger pixel sizes. Since the aggregated pixels are averages of the smaller pixels, this effect is expected.

### 3.3.2. Analysis of 20m x 20m Pixels

The sum of roots for the 20m data of 14.3 indicates a reasonable degree of site separation overall at this scale. Hereafter in this report the results refer to this pixel size. The full CVA analysis is found in Appendix II. As the number of sites were later reduced to 32 (Appendix I), the full analysis is only briefly summarised here. An understanding of how this overall spectral separation relates to ground condition is provided by the analysis statistics and the ordination plots.

The first two canonical roots were 5.6 and 2.2 so that 55% of the variation between sites is explained by the first two canonical variate axes (Figure Six). The next four roots are all greater than 0.5 indicating some degree of separation in higher dimensions. However, the ordination on the first two axes indicates why the sites were reduced and re-analysed. Figure Five shows that the greatest separation in the 43 sites was between different forest communities; jarrah poles, she-oak etc. These differences dominate any effects which may be due to insect damage within the jarrah areas. Accordingly, the set of sites was reduced to include only jarrah areas and re-analysed.

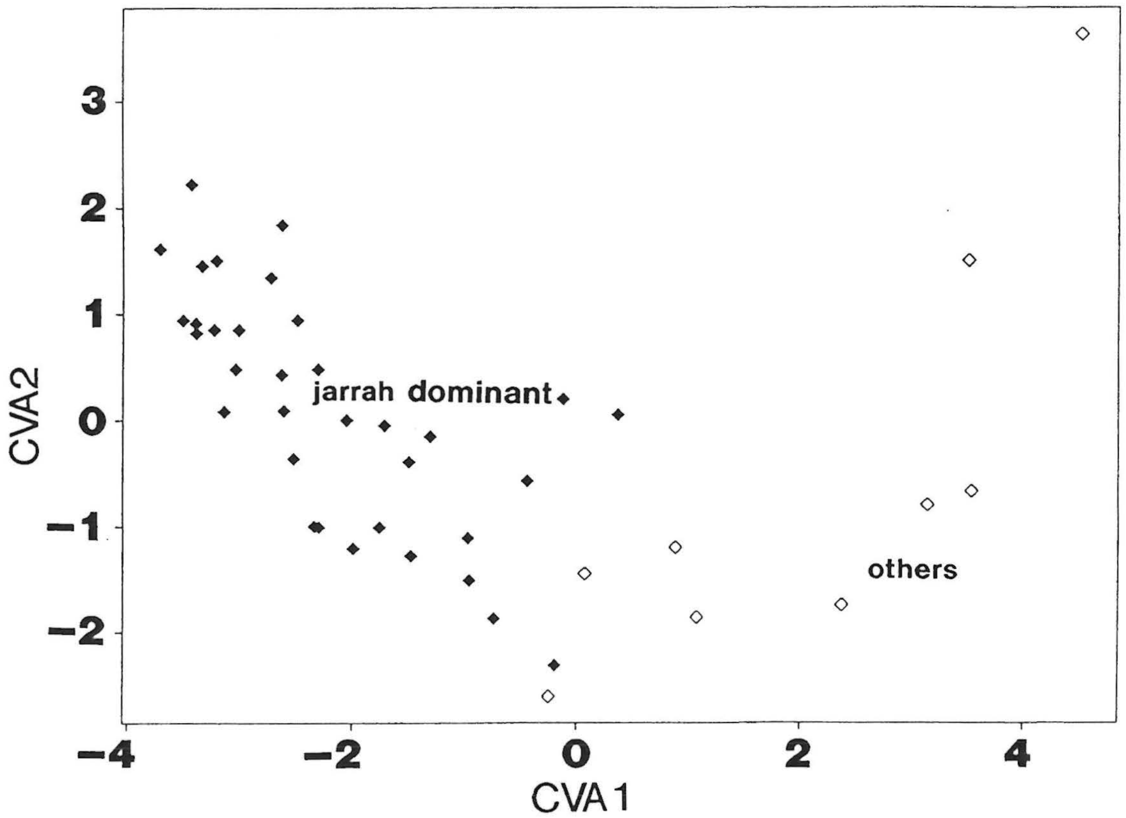

Figure Six. Shows all 43 sites and their degree of separation on the first two canonical variates.

### 3.3.3. Canonical Variate Analysis - Jarrah Sites

The analysis was repeated on the sites which were dominated by jarrah poles (numbered 1-32 in Table 1). The CVA analysis summarises the spectral variation between sites, which correspond to changing conditions within the jarrah forest.

Using all 24 bands and 32 sites, the sum of the canonical roots was 9.6, with the first four roots being 2.7, 1.8, 1.0, and 0.9 respectively. The first two roots account for 66% of the between site variation, ( for full analysis, see Appendix I. ) The ordination of site means indicates a high degree of overall separation. For the purposes of discrimination, a separation of two to three units on Figure Seven may be considered adequate.

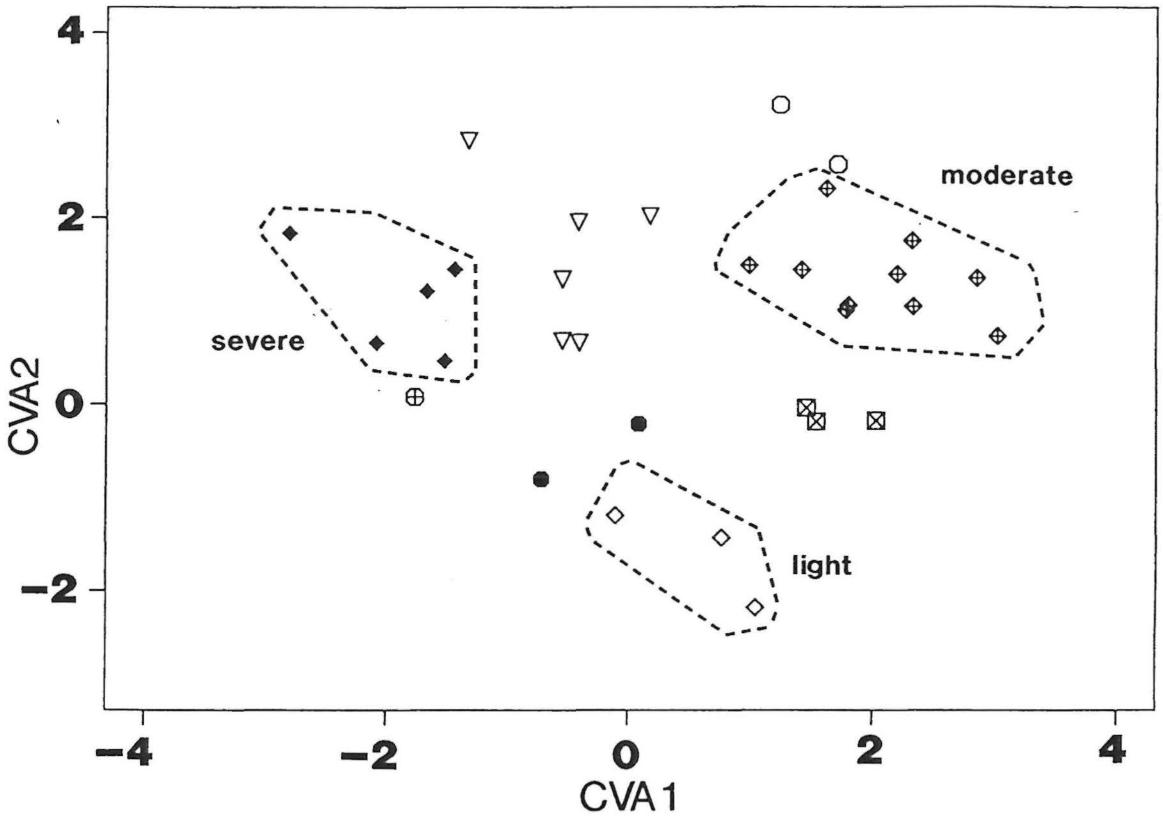

Figure Seven. Shows the separation obtained on the first two canonical axes, when only 32 sites (representing sites that were dominant by jarrah) were used.

The ordination also reveals that there is general clustering corresponding to insect damage severity. The three light infested sites are clustered and separated from the more infested sites on the first CV axis, while the moderate and severe sites are also clustered and separated on the second axis. There is considerable variation between sites within these classes, and some overlap of sites labelled as severely and moderately damaged, notably where casuarina was a component of the forest. Nevertheless, the spectral separation of the broad insect damage classes is evident and forms a basis for producing a damage-class map from the spectral data.

## 3.4 Identification of Important Bands

The interpretation of the spectral separation is simplified if subsets of bands are identified which maintain the observed discrimination. Band reduction procedures were applied to do this. At this point, maintaining overall separation is not the objective; rather, maintaining the separation of insect-damage levels is important. Accordingly, the procedures were directed to contrast the groups of sites, low damage versus medium; low versus severe; and medium versus severe.

It is crucial to maintain separation of the closer sites in these separate classes; accordingly some extreme sites were left out - the contrasted groups comprised:

Light - 3 sites, 2,12,13;
Moderate - 9 sites, 15,16,17,20,22,23,26,27,28;
Severe - 5 sites, 5,8,9,10,29.

For each subset of bands, the analysis calculates a single statistic which summarises the between/within-separation of classes in the nominated contrast. This can be compared to the value for the full 24 bands to assess the loss of information associated with using the reduced set. The best reduced sets of bands can be identified in Table Three. It can be seen that there is little information lost by reducing the 24 available bands to seven. On the basis of these results, a subset of seven bands was used in the subsequent allocation process; the bands used were 3, 7, 8, 12, 16, 20 and 21.

Table Three. Separation index for best discriminating subsets from one to seven bands, for contrast of insect damage levels.

| | Band Subset | Log Ratio | |
|---|---|---|---|
| 1 band | 7 | .689 | 40% |
| 2 bands | 7,12 | .859 | 50% |
| 3 bands | 7,12,20 | 1.308 | 76% |
| 4 bands | 7,8,12,20 | 1.444 | 84% |
| 7 bands | 3,7,8,12,16,20,21 | 1.617 | 94% |
| 24 bands | All 24 bands | 1.723 | 100% |

Discriminating spectral regions can be inferred from this and Table 1. All optimal subsets include bands of the following ranges.

| | | |
|---|---|---|
| Band 3 | wavelengths | 501 - 543 (microns) |
| Band 7-8 | " | 819 - 895 |
| Band 12 | " | 2022 - 2110 |
| Band 16 | " | 2242 - 2286 |
| Band 20-21 | " | 8375 - 9965 |

Thus reflectance differences in these regions detect variations in condition associated with insect damage. Figure Two shows the wavelengths of these bands and those on the Landsat TM sensor.

### 3.5 Definition of Spectral Condition Super-Classes

On the basis of the CVA results and site ordinations, and the noted field condition, training sites were grouped into super classes for the purpose of allocation. The allocation procedure is applied to produce a classification map. The classes are shown in Figure Seven. These classes were tentatively identified with insect damage as follows:

| Super Class | Sites |
|---|---|
| 1. Jarrah light infestation | 2,12,13; |
| 2. Jarrah moderate | 15,16,17,20,22,23,26,27,28; |
| 3. Jarrah severe | 5,8,9,10,29; |
| 4. | 3,14,30,32; |
| 5. Mixed sites of jarrah | 11,18; |
| 6. and other forest species | 1; |
| 7. with varying infestation levels | 21,24. |

Note that all these sites were jarrah-dominated. The allocation procedure is applied to the whole image but the class condition labels may only be applied usefully in jarrah areas.

### 3.6 Allocation

The allocation procedure was applied to the whole image area using the seven super-classes defined above and the reduced set of seven spectral bands. For each pixel, a posterior probability and typicality index are calculated for each class.

Approximately 60% of the image is forest and this area is indicated on the following figures. Figure eight (a) is a seven-class maximum likelihood map of the area. A typicality threshold has been applied so that pixels with a typicality index of less than 2% in all classes are displayed as black.

Areas classified spectrally as Class 1 ("light infestation") appear as green, moderate infestation appear as yellow while the severely damaged areas appear as red. Note that, in general, non-forest areas are atypical, and the forested area is fairly completely classified - that is few areas fall outside the spectral regions covered by the ground sites. Figures eight(b), eight(c), and eight(d) display these classes individually overlaid on an enhancement of the image data.

Exact verification of these results is not possible due to the lack of accurate pixel-by-pixel ground information. However, the patterns and severity of insect infestation have been broadly mapped on the study area, and the classification results are consistent with this known ground information. Several areas had been mapped in detail and the spectral classification results agreed on these also. Note that the classification (and enhancement) results cannot be usefully interpreted except in jarrah forest areas. In fact, the typicality threshold excludes many non-jarrah areas but not all; for example some areas of pine are classified but no interpretation on condition can be made for them.

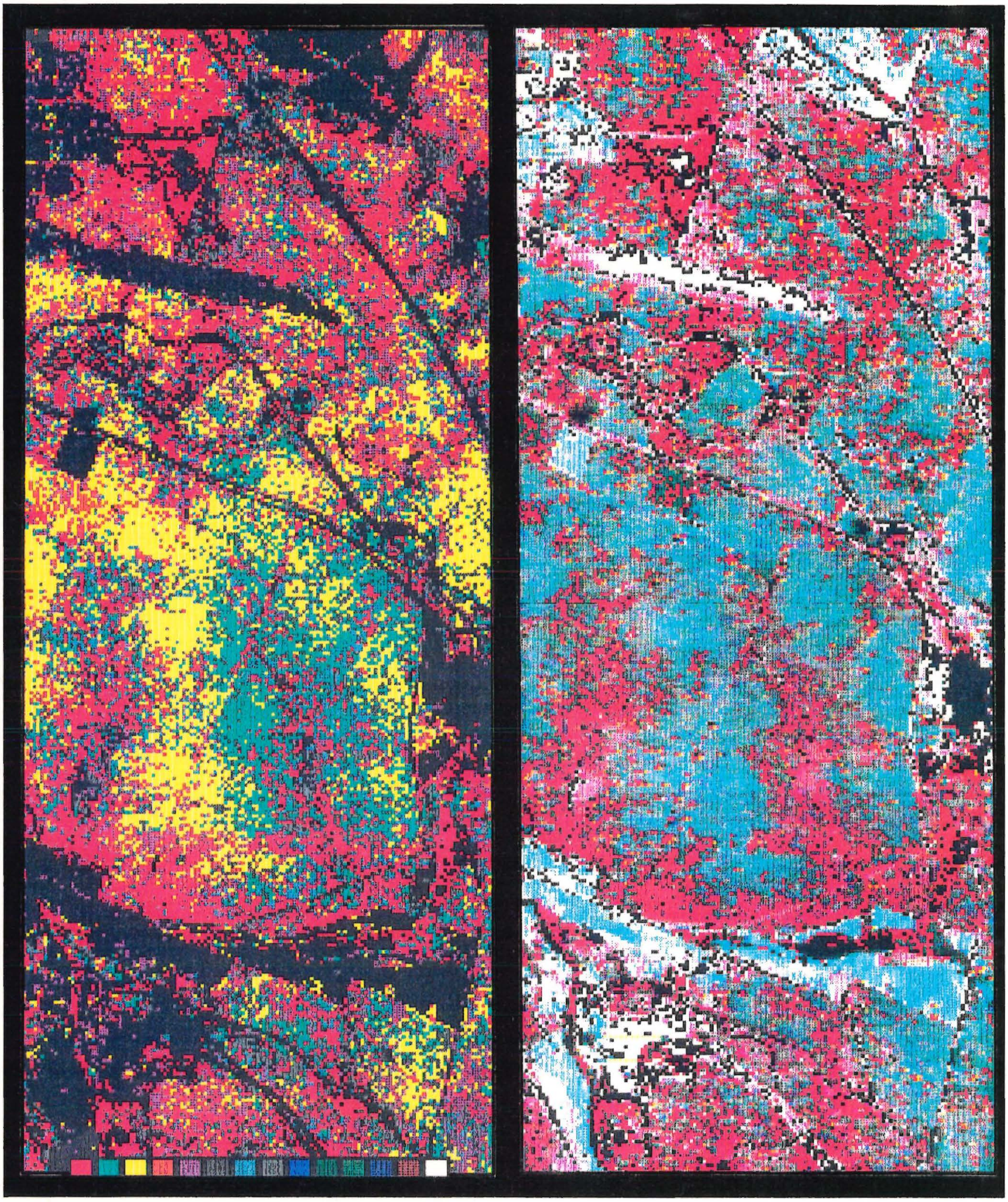

Figure Eight. Image classification and super-classes overlaid onto enhanced image.
(a) Classification of the seven-class maximum likelihood map
(b) Super-class three (severe-red) overlaid on enhanced image.

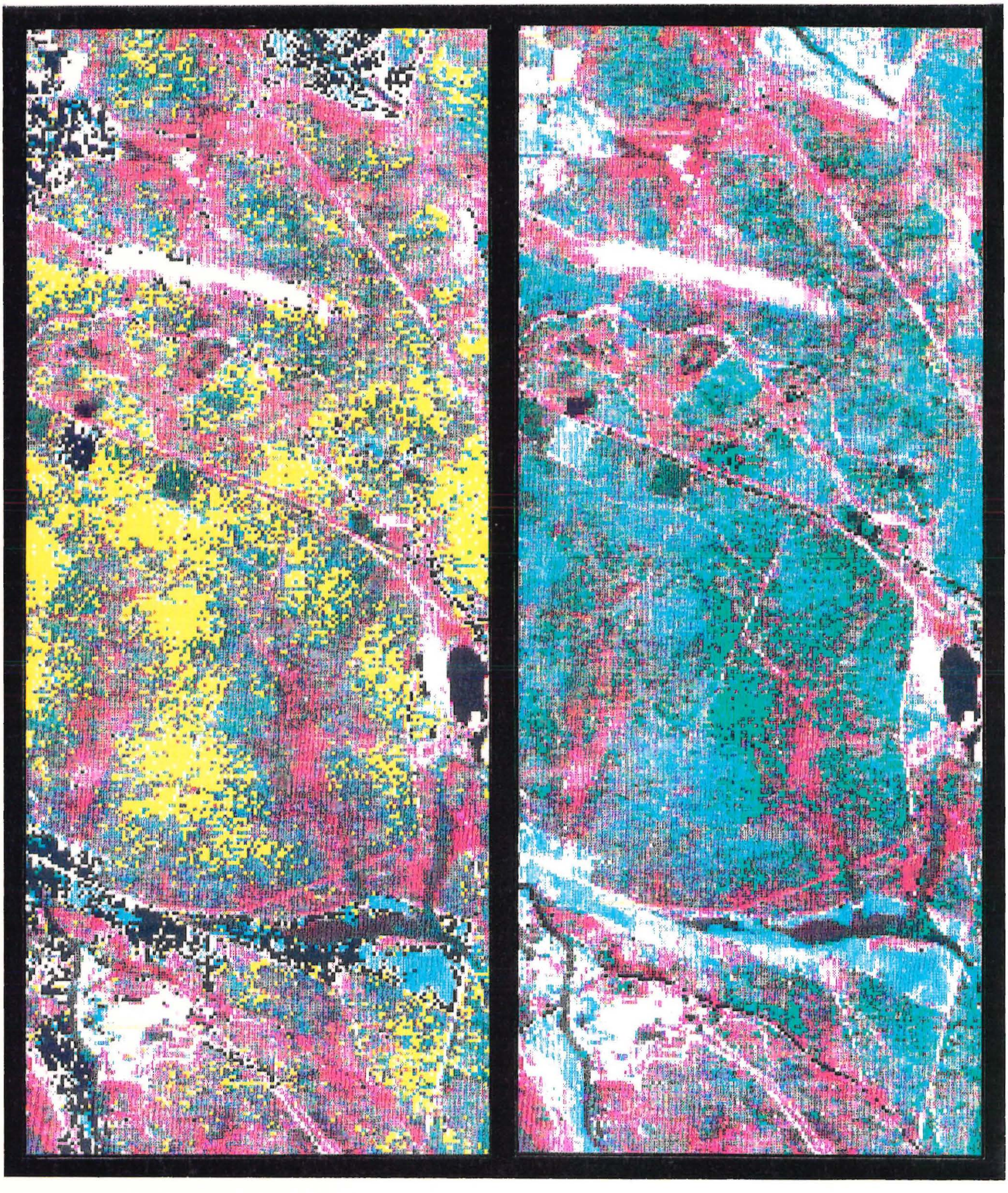

Figure Eight (c) Super-class two (moderate-yellow) overlaid on enhanced image
(d) Super-class one (light-green) overlaid on enhanced image.

## 4.0 DISCUSSION

The results of this study indicate that high-spectral resolution airborne data can provide discrimination of forest types and the extent of damage resulting from insect attack. Spectral bands have been identified in wavelengths known to be associated with chlorophyll and cellulose absorption features which can be identified in leaf materials. Also, the thermal regions of the spectrum are shown to be important, as plant stress and transpiration are known to affect leaf temperatures.

A classifier, derived from the analysis, has proved to be a useful mapping method on the local area from which it was derived. For application to new areas, field verification and local calibration will be required.

The assessment of the accuracy of the allocation maps is limited by the amount of accurate ground information available. Validation of the spectral allocation against accurate ground information must be made before the proportion of correctly labelled pixels for each class and errors of omission and commission can be calculated. Detailed ground information was not available in the 1989 forest study. The ephemeral nature of insect damage means that verification after the event is not always possible. This highlights the difficulties of ground-based mapping methods. In this study, ground identification of healthy and infested areas was made at the time of infestation and the assessment of the classified image was limited to these areas. Enhancements of selected spectral bands provide useful information on forest condition and insect damage.

A combination of field work and image mapping is likely to provide the most efficient information. The statistical analysis confirms that discrimination of insect damage-levels is possible using single pass AMSS data acquired at an appropriate time. The results provide for the use of such data for more widespread mapping of forest condition or insect damage. For the purpose of insect damage detection, a method which is as accurate on a broad scale as the results in this study would be valuable. However, this study does not yet provide a general data treatment which can be routinely applied. Further refinement and verification of band combinations will be required to determine data treatments which will work across the variations in natural forest environments where insect damage occurs. Further work should be conducted to test the reliability of remote sensing methods and determine optimal ways to combine their use with field missions. The accuracy and reliability of the remote sensing methods is likely to be improved if ancillary data, for example soil properties, topography and forest state, is included in the analysis. The analysis of spectral and other information using GIS technology should be investigated.

The important bands identified in this study give rise to consideration of the use of Landsat TM satellite data for the purpose of mapping insect damage. The aggregated airborne data had an effective ground resolution of 20 m, while TM has a pixel size of 30 m. Thermal data from TM has much poorer spatial resolution (120 m), but the other important bands are matched by the broader bands in TM. In addition, TM band 5 is known to carry useful vegetation information. Since TM offers affordable broadscale coverage, the cost in accuracy due to poorer spatial and spectral resolution should be examined. The use of temporal imagery may be vital here. TM also provides the opportunity to compare between years for future and retrospective comparisons. However, weather conditions in the south west provide a significant problem as acquisition of cloud-free images is rare.

The use of multi-temporal data should be considered and tested for mapping of ephemeral events such as insect damage. A pair of before- and after-infestation images should show some consistent change in spectral signature with severity of attack. This should allow removal of the background variation in forest type and condition. Change detection techniques using these images may allow discrimination of insect damage over a wider range of forest types.

In summary, the 1989 insect study using Geoscan AMSS data has shown the usefulness of spectral information for accurately discriminating insect damage in an area of jarrah forest. These results provide a basis for the adoption of a technique to detect and map insect damage in forest. Further research is required to extend the technique and to test the results of this study.

This work has also shown that spectral information may be of value when considering other questions associated with forest management.

## 5.0 RECOMMENDATIONS

For effective use of these preliminary results and extension of the use of spectral data for the insect problem and related studies the following actions are recommended.

1. These results should be presented to relevant field staff for feedback on the value of such results to their work in insect damage and other areas of forest assessment.

2. A "trial" test operation should be carried out in real time in conjunction with field work on previously unmapped area(s). Data should be acquired and processed according to the findings in this report; limited initial validation should provide the basis for refinement of the technique to suite the test areas. Predictive enhancement or classifications should then be produced and checked. Errors should be tabulated and understood. Timeliness is important for this exercise. Processing of data at a field station would be appropriate. The reaction of field staff to the image results should also be assessed.

3. Two-date change imagery AMSS data should be acquired at suitable dates for the test areas covered in (2) above. Using the maps of condition and errors, the effectiveness of change imagery could be established by analysis.

4. TM data search. A detailed search of the TM archive month by month should be conducted to estimate the probability of cloud-free imagery at appropriate times over specified areas, e.g. Collie. Quicklook summaries are not sufficient - the actual area may be cloud-free even if the image as a whole is cloud-affected.

5. TM enhancement and analysis should be undertaken if suitable images are available. If possible their effectiveness should be assessed on the test areas used in (2) and (3) above.

6. Research into the effective integration of ancillary GIS-type data should be undertaken to improve the generality of image-derived results.

Note that a combination of timely field and image data acquisition, analysis and assessment is required for the effective examination of these questions. Image data can be obtained quickly and easily, but suitable field data are more difficult to acquire and crucial to finding improved methods to obtain real information from the image data.

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# APPENDIX I

## Output listing from robust canonical variate analysis