Discrimination of nitrogen fertilizer levels on permanent grasslands from aircraft based imaging spectrometers

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Abstract

This paper describes an experiment, undertaken within the framework of the EISAC programme, to evaluate the potential of airborne imaging spectroradiometry for detecting changes in the spectral response of vegetation associated with controlled applications of nitrogen fertilizer on lowland grasslands. Different levels of fertilizer treatments can be distinguished by the spectral response of the vegetation canopy detected from the airborne data. The use of a linear mixing model for characterising the vegetation community suggests that changes in the spectral response due to different fertilizer levels are mostly influenced by changes in the physical structure of the canopy.

1. INTRODUCTION

Under a natural vegetation canopy, plant litter and organic manure provide the bulk of the nitrogen (N) returning to the soil. In agricultural areas, where harvesting or grazing remove most of the vegetation from the land, the return of N in chemical fertilizers or through the growth of legumes is necessary and used to maintain the soil N supplies for subsequent crops. Of the nutrients applied in a commercial fertilizer, N appears to have the quickest and most pronounced effect on vegetation growth. It tends to encourage above-ground growth and imparts to the leaves a dark green colour. Physiologically, it governs the degree of utilisation of Potassium and Phosphorous, leads to an increase in foliar N concentrations, a strengthening of cell walls and an expansion in cell numbers. Plants receiving insufficient N are stunted in growth and possess a restricted root system. The leaves turn yellow or yellowish green and tend to drop off.

Excess addition of N fertilizer to agricultural areas should be avoided because of its expense, its adverse ecological effects and the risk of elevated levels of nitrates in drinking water due to soil leaching. To minimize the waste of fertilizers and their undesirable side-effects, methods are needed to monitor the condition of crops and grasslands, to give early detection of conditions of nutrient deficiency.

It has been widely reported (Chang and Collins 1983; Banninger 1990) that vegetation under stress, as in the case of nutrient deficiency, exhibits a decrease in reflectance of the near-infrared (NIR) plateau (750-1300 nm), a reduced chlorophyll absorption (680 nm) and a consequent blue shift in the red edge. By relating changes in these wavelengths to biophysical parameters, analysis of canopy reflectance can be used to derive indicators which are responsive to canopy health and vigour. However, the coarse spectral resolution (typically 100-200 nm spectral bandwidths) of recent airborne and satellite sensors can only detect broadband changes in the response of vegetation canopies. Consequently, subtle differences in vegetated surfaces, such as those manifested in the blue shift mentioned above, are overlooked. The recent advent of airborne imaging spectrometers provides high resolution spectral data which allow the detection and identification of more subtle diagnostic spectral features associated with the response of vegetation to stress (Wessman *et al.* 1989).

During the spring of 1989, the Joint Research Centre of the Commission of the European Communities with the

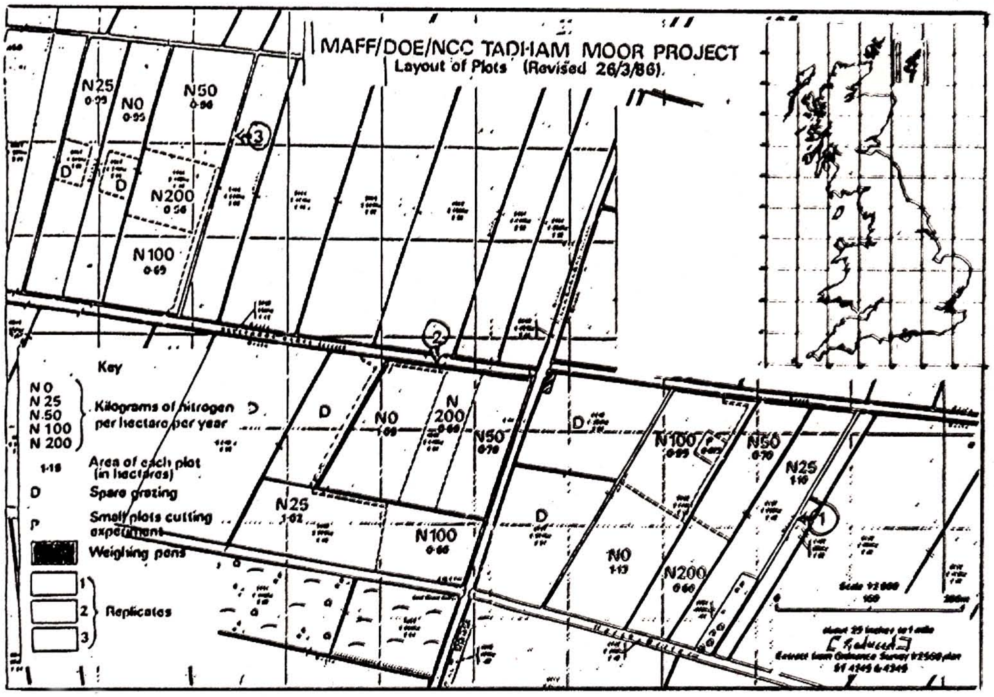


Fig. 1. Location and layout of experimental plots on Tadham Moor, Somerset Levels.

European Space Agency, undertook a European Imaging Spectrometry Airborne Campaign (EISAC) aimed at evaluating the potential of data from imaging spectrometers (IS) for a variety of marine and terrestrial applications (Bodechtel 1990). One of the terrestrial EISAC test sites was a series of experimental plots on the pastures of the Somerset Levels in southwestern England. This paper is concerned with evaluating the potential of data from airborne spectroradiometers over the Somerset site as a means of detecting, identifying and quantifying changes in the nutritional status of permanent lowland grasslands.

2. TEST SITE

The project was carried out as part of a long-term experiment, run by the Institute of Grassland and Animal Production and the Institute of Terrestrial Ecology. The experiment involves a series of treatments, located on 20 ha of unimproved species-rich hay meadows on the low-lying peat moors of the Somerset Levels (Fig. 1). The aim of the Tadham Moor experiment is to identify a level of N application which can be used without reducing species diversity on the peat soils and to estimate the effects of these reduced levels of N fertilizer on agricultural productivity.

In the experiment, N ferilizer is applied at five rates of between 0 and 200 kg per hectare per year to a series of plots in three replicate treatments (plots are referred to as N0 to N200 in the following text). The plots are cut for hay in July and grazed by beef cattle until mid-October. Botanical composition is assessed annually and the productivity af the individual treatments measured in terms of hay yield and beef production.

3. AIRBORNE IMAGING SPECTROMETRY

A series of aircraft overflights of the study area were undertaken in late May 1989 with the Moniteq PMI (Programmable Multispectral Imager) airborne imaging spectrometer as part of the EISAC programme (data from the GER-II were not acquired over the study area due to operational difficulties with the aircraft). The PMI uses four separate cameras to image the whole swath and has two operating modes; full spatial and full spectral (Fig. 2). In spatial mode, PMI data were acquired in eight narrow bandpasses (Table 1), at approximately 1m spatial resolution.

In spectral mode the PMI acquired data in 288 contiguous bands between 430-800 nm, with a 2.6 nm bandwidth. The spectral mode data are acquired using a "push-rake" con-

Fig. 2. PMI spatial mode image of the Somerset Levels. The irregular edges are a result of the roll-correction procedure carried out on the data. Area depicted is approximately 5 km x 1.5 km. North is to the bottom of the image with the experimental treatments in the lower third of the flightline.

TABLE 1
SPECTRAL BANDWIDTHS OF PMI SPATIAL MODE - GEOBOTANY BANDSET

Band	Wavelength Range	Centre Wavelength
0	491.42 - 501.90	496.66
1	546.44 - 556.92	551.68
2	596.16 - 606.61	601.39
3	675.75 - 682.26	679.01
4	708.26 - 714.76	711.51
5	734.22 - 740.70	737.46
6	744.59 - 751.06	747.83
7	784.68 - 789.84	787.26

figuration of the sensor, whereby each image pixel is an average of 8 contiguous detectors across the swath, separated by 32 detectors. The resultant image is composed of eight spectral pixels from each of the four operational cameras. As a consequence, there are unsampled regions between the data strips and the resulting image is compressed and distorted.

Preliminary examination of both spatial and spectral data showed interesting differences in data quality. In comparison with a previous PMI dataset collected in 1988 (Wyatt *et al.* 1990) the spatial mode data from this experiment did not show the marked intercamera differences or intra-camera striping due to non-equalization of detectors. This mis-calibration was still evident in the spectral mode data which again caused serious problems in information extraction. Further processing of these data revealed that problems in the calibration procedure still existed.

Geometrically both spatial and spectral mode data are influenced by the aircraft motion during the flightlines as a result of air turbulence. The spatial mode data from 1989 were subsequently corrected for gross errors in aircraft roll. Previous experience with the PMI (Wyatt *et al.* 1990) demonstrated the need for geocorrected datasets for agricultural studies where extraction of per field information is required. Although substantially improved, the 1989 dataset still included high frequency jitter in the roll axis and gross errors for the pitch and yaw directions. Due to the residual radiometric problems outlined above, the application of roll correction to the

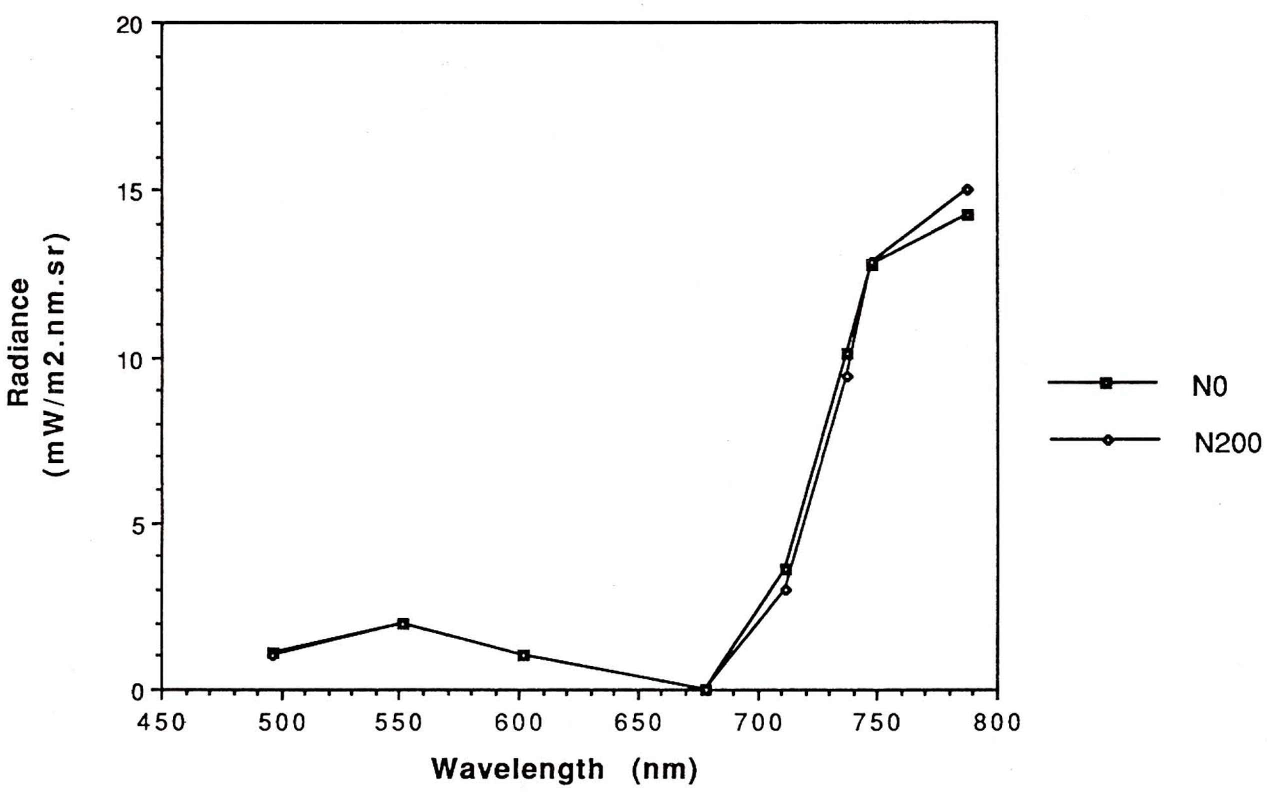


Fig. 3. PMI spatial mode data (geobotany bandset) plotted from average radiance data for the N0 and N200 treatments.

spatial data exacerbated the extraction of information and potential correction procedures.

An intensive programme of ground data collection was planned for the day of the overflight. Ground data collection was concentrated in the central replicates of the experiment (Blocks 1 & 2). Within each individual treatment (N0-N200), a series of sampling quadrats were selected as being botanically representative of each treatment type. Within each of the selected quadrats, in-situ spectral reflectance measurements were acquired from a Geophysical Environmental Research (GER) IRIS Mk IV ground based spectroradiometer (scanning over a wavelength range of 400 -2500 nm). Soil and vegetation samples from each IRIS site were taken and subjected to a variety of analytical tests. In addition, an intesive botanical survey was carried out at the time of the airborne data collection.

4. DATA ANALYSIS

PMI data for both modes were acquired as digital counts and were calibrated to radiance using information supplied with the data. It was possible to clearly identify individual treatments from the spatial mode data and averaged counts were extracted for each treatment. The eight mean radiance values for each treatment were extracted from the geobotany bandset and plotted against wavelength (Fig. 3). Spectral behaviour was observed which was typical of green-leaved vegetation. The different experimental treatments exhibited differential spectral responses around the chlorophyll absorption band at 680 nm with increased separation between treatments in the region of high reflectance at 750-800 nm. Within this red/NIR plateau, highest radiance was displayed by the N200 treatment and lowest values by the N0 plot. This trend was reversed at the shorter wavelengths, where the N200 plot exhibited enhanced absorption. Other treatments showed intermediate effects in both spectral regions. Calibration of the data revealed substantially lower radiances than recorded in 1988 over the same targets which could not be accounted for by the minimal differences in time, date, and weather conditions between the two experiments (Fig. 4).

A major advantage of the PMI is the capability to provide contiguous spectral profiles between 430 - 800nm (Fig. 5).

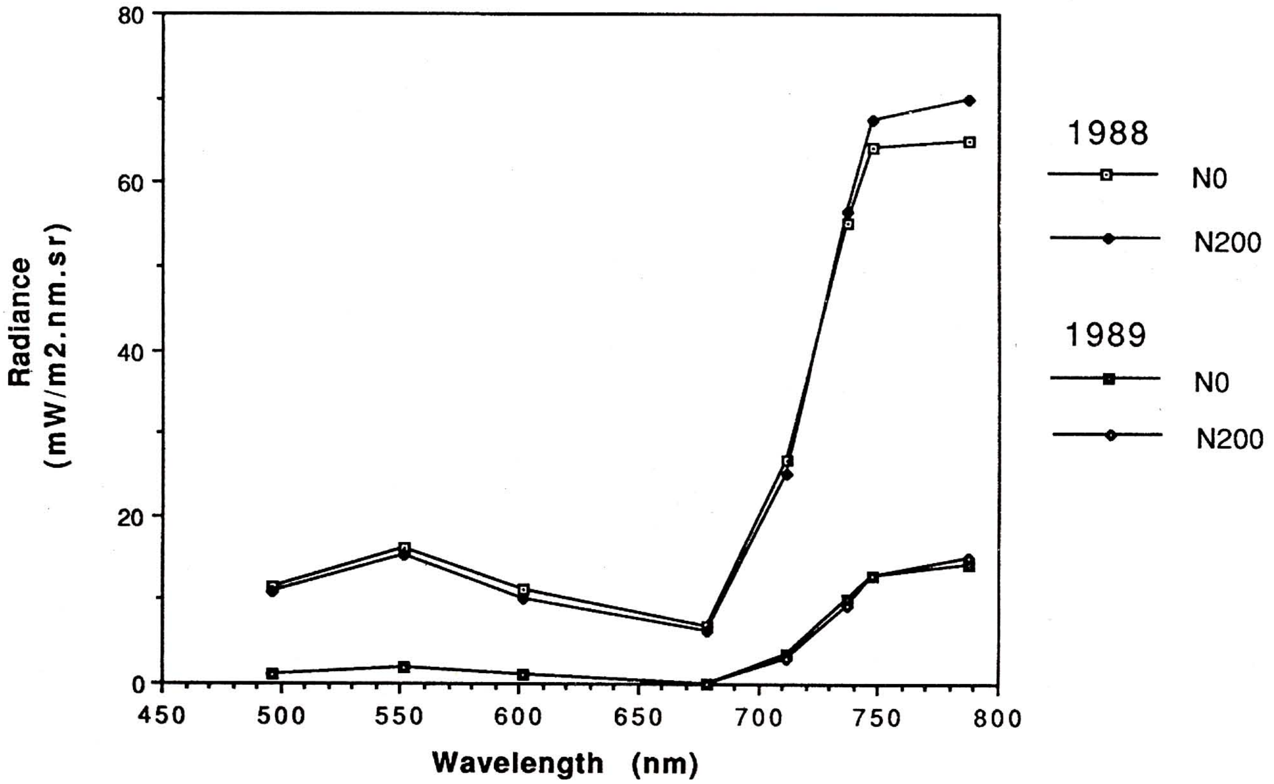


Fig. 4. PMI spatial mode radiance data for N0 and N200 plots from 1988 and 1989 illustrating the effect of sensor calibration on data interpretability.

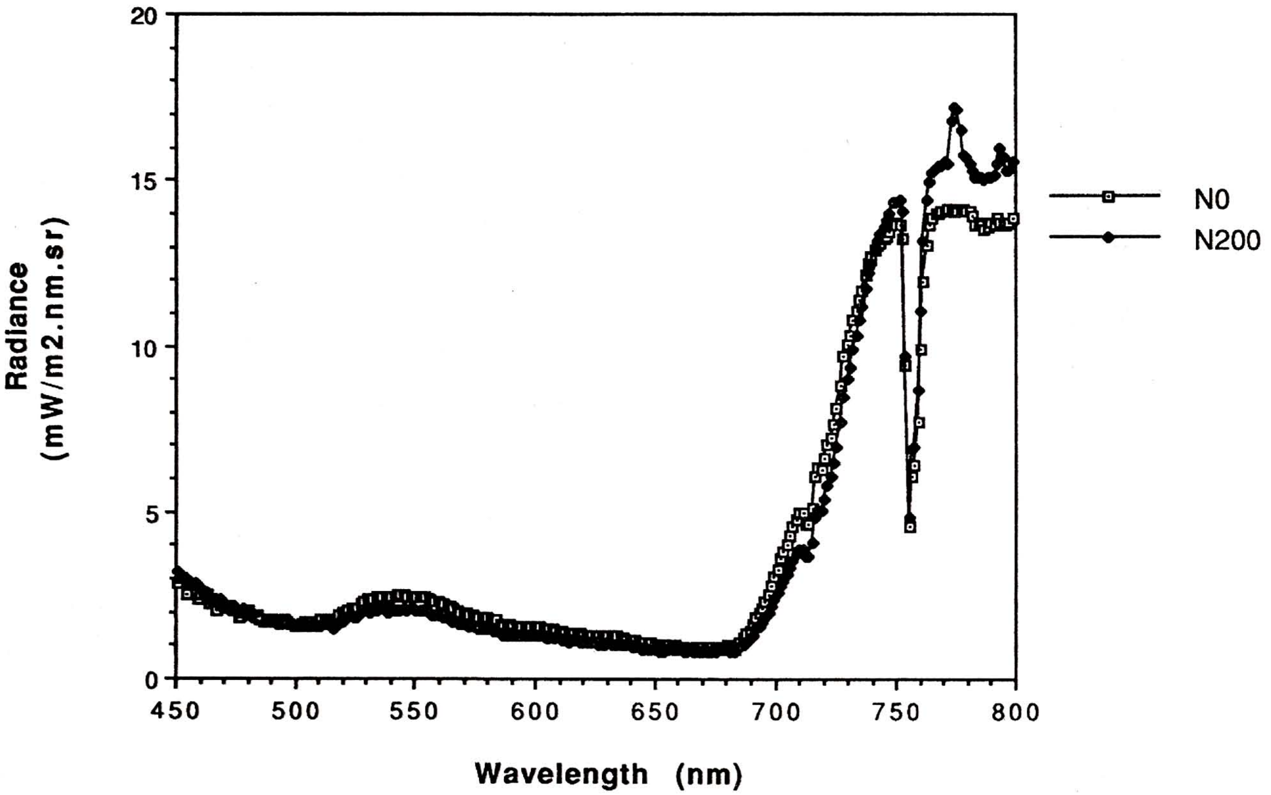


Fig. 5. Vegetation response from PMI spectral mode data as a function of nitrogen fertilizer application.

TABLE 2
RESULTS OF INVERTED GAUSSIAN MODELLING

	PLOT 0	PLOT 200
SHOULDER REFLECTANCE (mW/m^2.nm.sr)	14.28	15.34
REFLECTANCE MINIMUM (mW/m^2.nm.sr)	-0.08	-0.58
WAVELENGTH MINIMUM (nm)	690.96	688.29
SIGMA (Gaussian bandwidth)	27.91	33.18
INFLECTION WAVELENGTH (nm)	718.87	721.47

Similar trends to those observed in the spatial mode data were apparent from data acquired when operating in spectral mode.

4.1 *Red Edge Modelling*

A program was implemented to measure characteristic parameters of the red edge, using an inverted gaussian model (Bonham-Carter 1988). The results of processing calibrated PMI spatial mode data are presented in Table 2.

The model quantifies the observed spectral changes in the height of the NrIR plateau (shoulder reflectance) with changing levels of N application. The inflection wavelength, which marks the position of the red edge, shows a slight increase in wavelength with increased application of N, while there was only a slight shift in the position of the chlorophyll absorption maximum as defined by the wavelength minimum parameter in Table 2. Due to the low radiance levels encountered in the calibrated data the inverted gaussian modelling produced negative reflectance minima for all treatments and inflection wavelengths were higher than in 1988 where equivalent results for N0 and N200 treatments were 712.84 and 714.64 nm respectively.

4.2 *Linear Mixture Modelling*

Linear mixture modelling techniques were applied to a 512 by 512 pixel subscene of the 1989 data containing the treatments in replicate two. The theory of linear mixture modelling, discussed by Drake (1990, this volume), assumes that each photon has only interacted with one component, that each component has a spectral response that is distinct and therefore can be separated from the other components in the mixture, that the number and identity of each component is known. It is possible to determine the number of spectrally distinct components in the mixture and their endmembers using principal components analysis (Smith *et al.* 1985). This method was applied to the subscene and the identity of each component determined from ground reference data. Four image components were defined; active (green) vegetation, dry vegetation, flowering vegetation and a soil component. The endmember spectra of these components are shown in Fig. 6. None of these endmembers are situated in any of the nitrogen plots. The active vegetation endmember came from a field of improved pasture that had been ploughed, reseeded and fertilised; the 'dry vegetation' endmember was located in an area of recently cut hay meadow; the 'flowering vegetation' endmember came from a field dominated by Ranunculus repens (buttercups) and the 'soil' endmember came from an area of peat exposed by cutting.

Estimates of proportional contributions for each component were calculated using a modified form of the classical estimator where the following function is minimised:

$$(\mathbf{X} - \mathbf{Mf})^T \mathbf{C}^{-1} (\mathbf{X} - \mathbf{Mf})$$

where **X** is a pixel vector, **M** a matrix of endmembers, **f** a vector of unknown proportions and **C** a matrix of errors. The proportion f_i of the i^{th} endmember must also satisfy:

$$0 \leq f_i \leq 1 \text{ and } \Sigma_i f_i = 1.$$

(The consequences of applying these constraints are outlined in Settle and Drake (in press)).

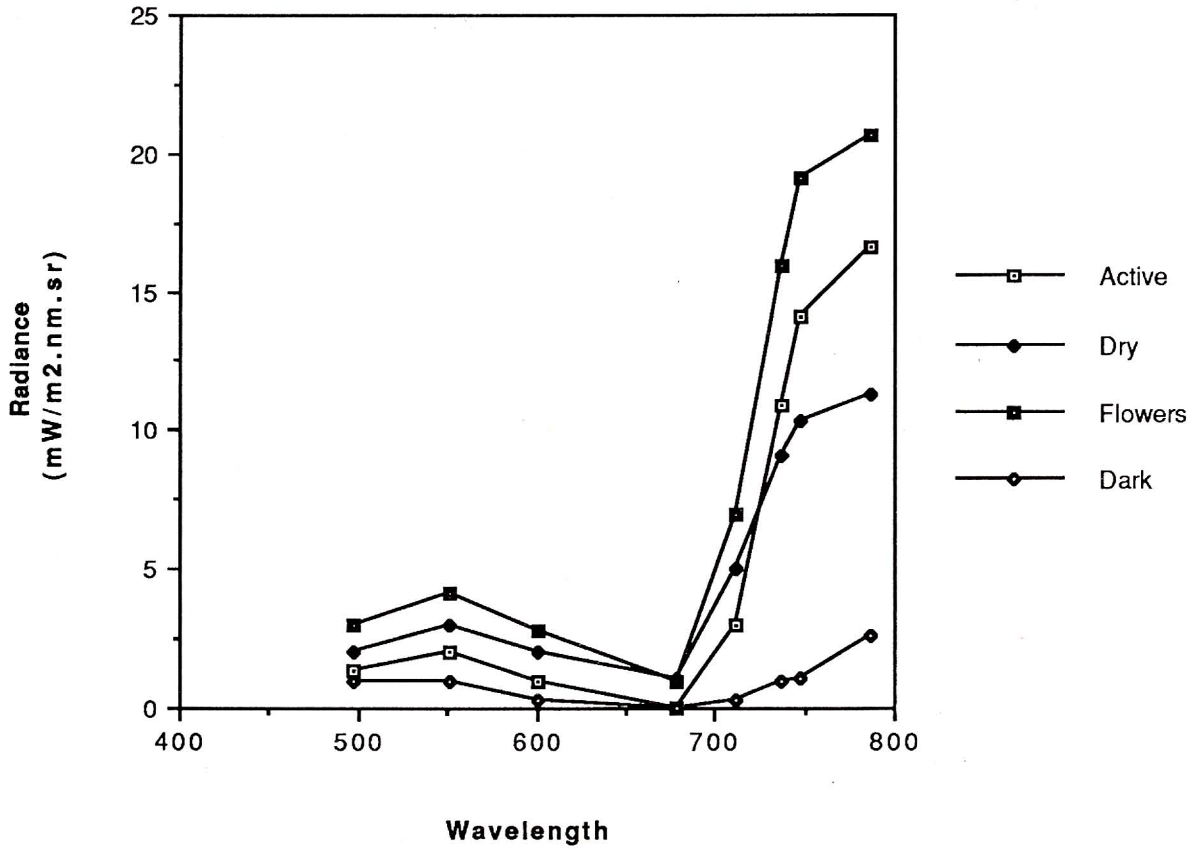


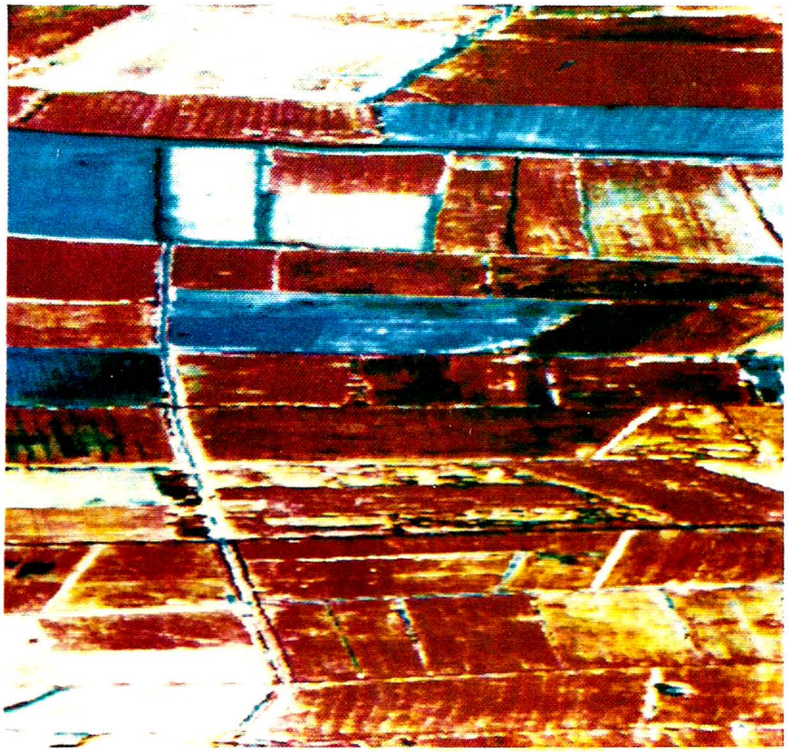
Fig. 6. Spectral profiles of the four endmember components

The results of the mixture modelling are shown in Figs. 7 and 8. Using conventional colour display systems, only the distribution of three components can be displayed unambiguously. However, a method for displaying the distribution of four components has been developed which minimises color ambiguities and provides a key of colours so that the interpreter can relate a particular hue to a particular mixture (Fig. 7ii) and, consequently, the distribution of all the components in one image (Fig. 7iii). In this method, pure pixels are coloured white whilst pixels of 99% purity are coloured, red, purple, yellow and cyan. Each of the four mixture maps is then assigned one of these colours, the intensity of which varies linearly with the proportion. Areas which record the absence of an endmember are depicted in black (Fig. 8).

The distribution of the active vegetation seems to be greatest in fertilized pastures and in those where species composition is largely controlled by farming practices. The dry vegetation mixture map emphasises areas of less active vegetation due either to hay cutting or less active vegetation associated with lack of fertilization. The flowering vegetation mixture map is self explanatory. Large numbers of flowers are found in areas largely unaffected by human interference where species diversity is high. The peat mixture map outlines the areas of peat cutting, however, it is also affected by other components that have a similar spectral response to peat such as water and shade. These three components cannot be separated as they are not spectrally distinct and hence the assumption of a unique spectral response for each component in the image is violated. A more accurate term for this mixture map is 'dark components' as used in the key of Fig. 7.

5. DISCUSSION

Analysis of both PMI spatial and spectral mode data reveal similar trends. In both cases, individual treatments can be differentiated, both in the green spectral region and within the red/NIR plateau. Modelling of the red edge suggests a slight red shift (approximately 2 nm) in the N200 response with respect to that of the N0. Results of similar experiments on vegetation, particularly coniferous forests, indicate that a 5 nm shift is significant for determining physiological stress. The Tadham experiment is designed to study vegetation response resulting from the enhancement of natural levels of



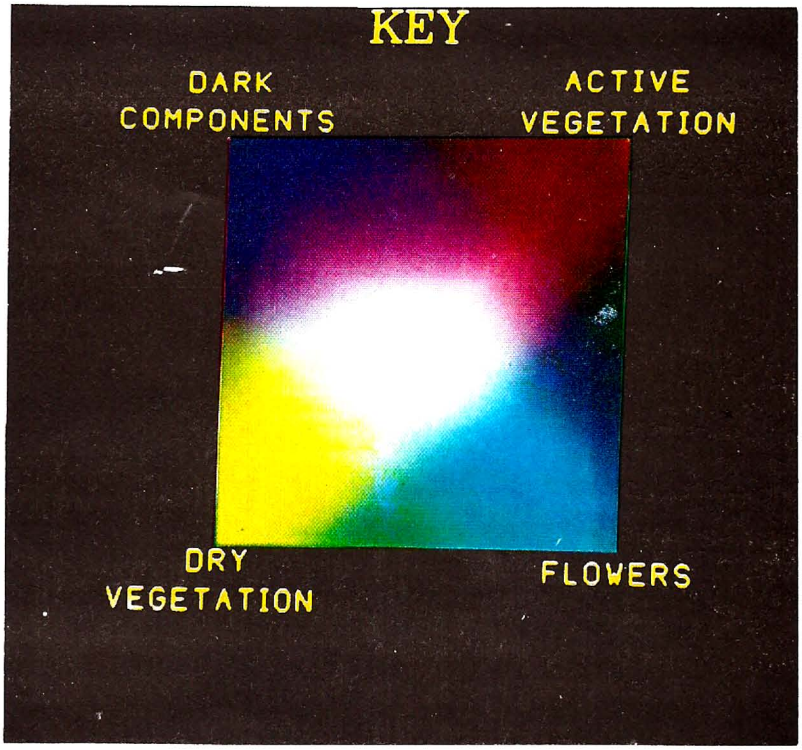


Fig. 7. (i) PMI Spatial mode false colour subscene used in mixing study. The red tones relate to vegetated areas and blues to hay cut fields (see Fig. 8 for guide to experimental plots)

(ii) colour key to Fig. 7iii explain the relationship between hue and endmember proportions

(iii) decomposition image showing distribution of endmembers.

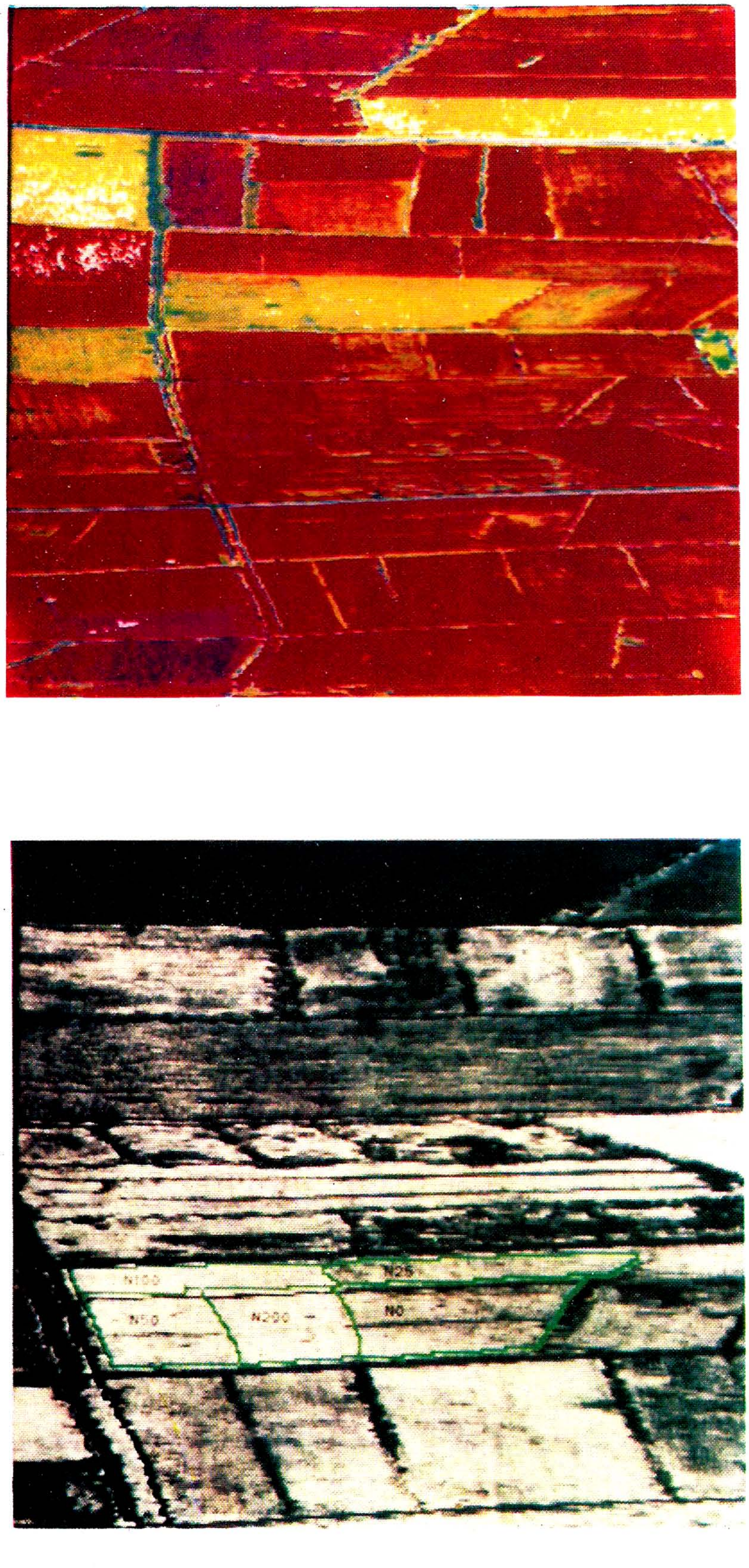


Fig. 8. End member map for active vegetation. Note the marked change in brightness between high and low nitrogen plots.

nitrogen. The change in spectral response due to enhanced nitrogen levels is less than that seen as a consequence of physiological stress. Wyatt *et al.* (1990) suggested that either sub-optimal timing of data acquisition or that enhancement of natural ecosystems by fertilizer applications resulted in such subdued shifts of the red edge. Similar results from the EISAC experiment, which was carried out at an optimal time, implies that these subtle shifts of the red edge are to be expected from fertilized grasslands.

Mixture modelling procedures were used to assess how the distribution of relevant endmembers varied with the application of nitrogen fertilizer. The distribution of the active vegetation in the nitrogen plots is shown in Fig. 8. Although a certain amount of natural variation is evident within each plot the average amount of active vegetation increases with the amount of nitrogen applied. The dry vegetation mixture map exhibits an inverse relationship to that of the active vegetation in these areas. In an attempt to determine what specific biophysical parameters are related to these rather arbitrarily termed image components, a correlation matrix was calculated comparing the average value of each component for each nitrogen treatment to the ground collected in each plot. High correlations are evident between canopy height and active vegetation component (0.908) and between canopy height and the dry vegetation component (-0.931). The grasses are the tallest plant species in the canopy and it is the increase in their height with the application of nitrogen that causes this relationship. There is good correlation between biomass (dry weight) and the active vegetation endmember (0.756) and a similar negative correlation with the dry vegetation component (-0.753). This is due to the increase in the expansive phase of the vegetation growth with the application of more nitrogen, causing a corresponding increase in biomass.

Analysis of the botanical composition indicates that increased fertilizer application leads to a taller, more grass dominated sward. This change in the structure of the canopy has marked implications for the nature of the spectral signature measured by the sensor. Initial comparisons of the mean radiances and endmember maps with simple monocotyledonous-dicotyledonous ratios produce close correlations with the predominantly grass dominated (fertilized) plots. A preliminary explanation for the above mentioned correlations is that, as nitrogen is applied to these soils all the vegetation species become more active. The grasses, however, can utilize the available nitrogen more efficiently than the other species present, with the result that they grow rapidly and outcompete other broadleaved species. The end result of large nitrogen application is an increase in vegetation activity and a reduction in species diversity that produces a canopy where grasses are dominant. Work by Plummer (1990, this volume) supports these findings from analysis of ground-based spectroradiometry of the plots.

There are a number of problems which are specific to the design of the MONITEQ sensor. For certain applications, such as for water quality monitoring, the spatial averaging over eight contiguous pixels that currently operates during the spectral mode acquisition provides satisfactory data. However, where there is a high variability in surface conditions (as in natural vegetation) or where the land parcels are small, it may be preferable to sample a 'purer' spectrum from an individual pixel as opposed to eight. This mode of operating would remove gross uncertainties due to mixed pixels that affect the data at present. Calibration of imaging spectrometers is inherently more complex than conventional line-scanners and wide-band instruments due to the vast number of individual detector elements. Despite the ability to provide contiguous spectral profiles, the problems in detector and inter- camera calibration restrict the utility of these data.

6. CONCLUSION

Despite the radiometric problems encountered with the airborne data, some encouraging results have been obtained. The use of imaging spectrometry has demonstrated our ability to detect the effects of different applications of N fertilizer, with evidence of a shift to red wavelengths of the red edge of spectra recorded from the highest nitrogen treatments (N200) compared with the control (N0). Similarly, significant differences between treatments were observed in reflectance at green and at red/NIR wavelengths. The magnitude of these differences were smaller than expected because the experiment was not observing true "stress" in vegetation but rather the enhancement of a stable ecosystem by the addition of fertilizer. The use of linear mixing models show good promise in mapping the distribution of fertilized pastures. Future work will attempt further to quantify this distribution.

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