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Estimating Green LAI from Multispectral Aerial Photography

A hand-held 35-mm camera provided acceptable results for small (36 m²) study sites.

ABSTRACT: *When choosing a remote sensing technique, there is usually a trade-off between cost and accuracy. For small study sites of a few fields in area, multispectral aerial photography collected with a small format hand-held camera is usually the least expensive source of aerial reflectance data, but with what accuracy can these data be used to estimate green leaf index (green LAI)? To answer this question 12 sets of radiometric and photographic reflectance data were collected, on the ground, at five points on four heathland sites. Data were transformed into the perpendicular vegetation index (PVI) for regression against the green LAI for each of the 60 points. Reflectance data derived from 20 flights of aerial multispectral photography were also transformed into the PVI and were input into the ground based relationship to estimate the green LAI of five areas, within each of the four heathland sites. Accuracy with which green LAI could be estimated was dependent upon the acceptable error of the estimate. At an error of ±0.1 green LAI for the young and mature* Calluna *association and ±1.0 green LAI for the* Pteridium *and* Pteridium/Calluna *associations, accuracies of green LAI estimation were around 74 percent. The accuracy was dependent upon vegetation type and season. For vegetation types with a low spatial variability and therefore a low sampling error, e.g.,* Pteridium, *green LAI could be estimated with an accuracy of 81 percent and, if measurements were restricted to the winter and spring when the canopies were stable, then green LAI could be estimated with an accuracy of 84 percent.*

INTRODUCTION

WHEN CHOOSING a remote sensing technique for a particular application, there is usually a trade-off between cost and accuracy. This is the case when using remotely sensed multispectral data to estimate the green leaf area index (plan area of a green leaf to a given land area) of ecological or agricultural test sites. For such areas, light aircraft multispectral photography can often be the most economical and suitable source of aerial reflectance data (Curran, 1982a). Landsat digital multispectral scanner data are much more expensive and have inferior spatial resolution to multispectral aerial photography. Aircraft multispectral scanner data are most useful for green leaf area index (green LAI) estimates but, at around a hundred times the cost of a multispectral aerial photographic flight (in the United Kingdom), its use is rarely justified on economic grounds. The major disadvantage with multispectral photography is that reflectance data are stored on film in an analog manner, which leads to a decrease in the accuracy of both the reflectance measurement and green LAI estimate.

This paper reports on an experiment which determines the accuracy with which this low cost multispectral reflectance data can be used to estimate green LAI.

ESTIMATING GREEN LAI FROM REMOTELY SENSED MULTISPECTRAL REFLECTANCE DATA

The green LAI of a vegetation canopy is causally related to the radiance of that canopy (Curran,

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1981b). Under the majority of conditions green LAI has a negative relationship with red reflectance and a positive relationship with near infrared reflectance. There are factors that influence reflectance independently of green LAI. These include soil color, the presence of senescent vegetation, the geometric relationship of the Sun to the sensor and canopy, and the phenological stage of the canopy at the time of imaging (Curran, 1980b; Kondratyev and Fedchenko, 1982). When the effects of these factors are minimized, workers have obtained very high correlations between green LAI and both red and near infrared reflectance, for example, Pearson *et al.* (1976), Tucker *et al.* (1979), Tucker *et al.* (1980), and Bauer *et al.* (1980).

These correlations have been high enough to encourage workers to estimate green LAI (or similar measurements of vegetation amount) from remotely sensed reflectance data, as is reviewed by Curran (1983b). This has been undertaken in one of four ways. First, the relative amount of vegetation was indicated without recourse to absolute values (Heilman *et al.*, 1977; Hielkema, 1980). Second, green LAI estimates were made for a limited number of sites of known green LAI, on one or two dates (Colwell, 1974; Barlett and Klemas, 1980; Curran, 1980c; Chance, 1981). Third, the estimated green LAI data were correlated with the observed green LAI data for several sites (Ahlrichs *et al.*, 1978; Pollock and Kanemasu, 1979). Fourth, an estimate was given of the range of green LAI that could be determined at a given probability (Deering *et al.*, 1975).

In this experiment a slightly different approach was taken, with the aim of estimating green LAI within specified margins of error.

STUDY AREA

The study area was Snelsmore common, a heathland in Berkshire, England (Figure 1). The heath is the largest area of its kind in Berkshire and is underlain by lowland plateau gravels of late Tertiary or Quaternary age. The heath vegetation is primarily ling, *Calluna vulgaris* (L.) with some *Erica* spp. in both the dryer and wetter sites. Due to fre-

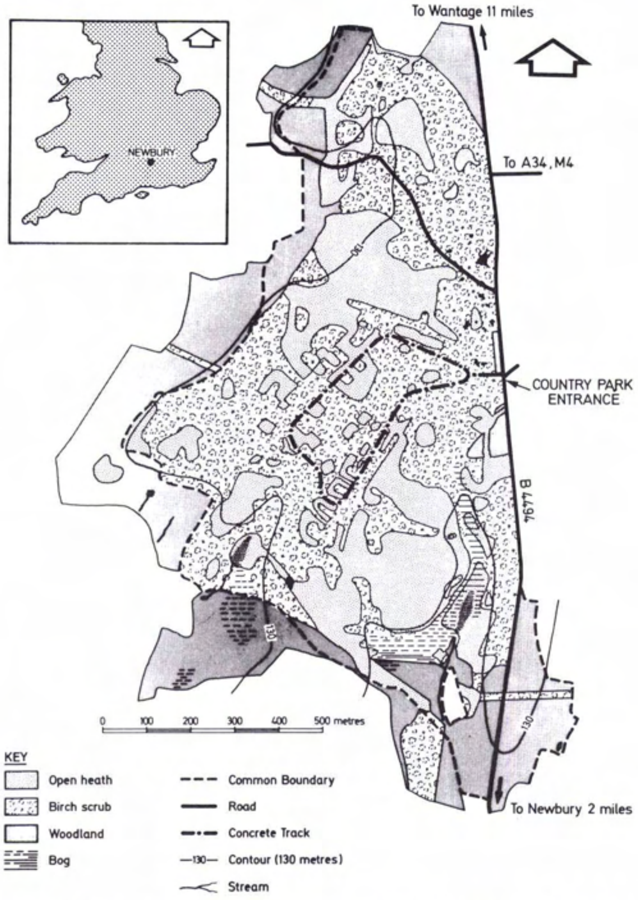

FIG. 1. The location and vegetation cover of Snelsmore Common, Berkshire.

quent burning the heather is of mixed age, has a poorly developed understory, and is being invaded on the dryer and often more badly burnt sites by bracken, *Pteridium aqualinum* (L.). The soil is a thin humus podsol with a surface layer composed of a compact dark humus with bleached sand grains and flint fragments (Curran, 1981c).

Four vegetation associations were chosen for study; they were young *Calluna*, mature *Calluna*, *Pteridium*, and a mixture of *Pteridium* and *Calluna*. These four vegetation associations were continuous over eight environmental site types (see Table 1) which varied in their topographic location and time since last burning (Curran, 1982b). All associations were crossed by bare paths.

The four vegetation associations were chosen to represent two contrasting types of semi-natural vegetation. The young and mature *Calluna* associations represented areas of low and spatially variable green LAI and the *Pteridium* and *Pteridium/Calluna* associations represented areas of high and temporally variable green LAI. The maximum green LAI for the *Pteridium* and *Pteridium/Calluna* areas was over eight times the maximum green LAI for young and mature *Calluna* areas. This can be illustrated by the ratio of spatial to temporal variability for green LAI (coefficient of variation of spatial, green LAI data: coefficient of variation of temporal, green LAI data) which was 1:0.52 for young *Calluna*, 1:0.65 for mature *Calluna*, 1:1.42 for *Pteridium*, and 1:0.96 for *Pteridium/Calluna*.

EXPERIMENTAL METHOD

The experiment consisted of five overlapping stages, the first of which involved the following data: (1) ground radiometric red and near infrared reflectance and/or (2) ground photographic red and near infrared reflectance and (3) green LAI. The data were collected for five 0.2 m^2 points on 12 dates for each of the four vegetation associations as well as the neighboring bare ground. (The spectral bands used are detailed below.) The second stage involved the correction of the reflectance data for the effect of solar elevation, the transformation of the corrected reflectance data into the Perpendicular Vegetation Index (PVI) of Richardson and Wiegand (1977), and the regression of PVI against green LAI for each vegetation association (Graph A, Figure 2). The third stage involved the collection of data on the following: (1) aerial photographic red and near infrared reflectance and (2) green LAI. The data were collected for five 36 m^2 areas at 20 dates for each of the four vegetation associations as well as the neighboring bare ground. The fourth stage involved the correction of the reflectance data for the effect of solar elevation, and the transformation of the corrected reflectance data into the PVI. The PVI was then input in the PVI/green LAI regressions calculated in stage two (Graph A, Figure 2), to estimate the green LAI (Graph B, Figure 2).

TABLE 1. THE FOUR VEGETATION ASSOCIATIONS AND EIGHT SITE TYPES, CHOSEN FOR STUDY ON SNELSMORE COMMON, BERKSHIRE

Vegetation Association	Site No.	Topography	Time since last burn (in years)	Total green LAI range
Young *Calluna*	1	Flat	3	0.13-0.44
	2	Flat	6	0.36-0.63
	3	Flat	6	0.49-0.79
Mature *Calluna*	4	Flat	13	0.17-0.38
	5	Flat	10	0.42-0.69
Pteridium	6	4° slope	unknown	0.0-8.1
Pteridium/Calluna	7	2° slope	5	0.5-1.3
	8	2° slope	5	0.0-6.3

THE COLLECTION OF GROUND DATA FOR THE REGRESSION OF PVI AGAINST GREEN LAI

Sampling. Snelsmore Common was visited on 12 occasions throughout a yearly growing cycle. For each visit, a sample point was generated on an enlarged aerial photograph and, from this random point, random numbers were chosen to produce a random walk (e.g., 28642 represents a walk of 42 paces at a bearing of 286°). The random walk was continued until five points had been visited within

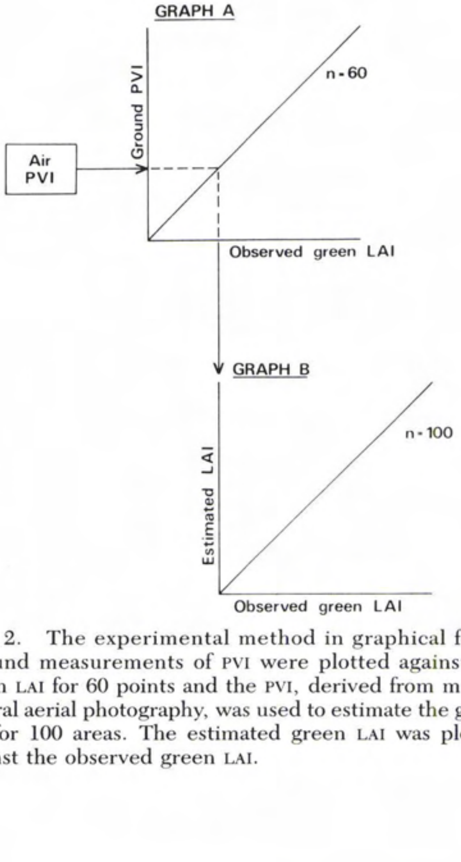

FIG. 2. The experimental method in graphical form. Ground measurements of PVI were plotted against the green LAI for 60 points and the PVI, derived from multispectral aerial photography, was used to estimate the green LAI for 100 areas. The estimated green LAI was plotted against the observed green LAI.

each of the four vegetation associations and five points had also been visited on the bare burnt areas and tracks. At each point three radiometric red and near infrared measurements and/or three photographic red and near infrared measurements were made, and on the vegetated areas three vegetation samples were taken. The data were expressed as one mean red reflectance value, one mean near infrared reflectance value, and one mean green LAI value per random sample point.

Radiometric measurement of red and near infrared reflectance. Radiometric measurements of red (0.62 µm to 0.69 µm) and near infrared (0.78 µm to 0.99 µm) reflectance were made for each sample point on five of the 12 dates using a mast mounted Milton multiband radiometer† (Milton, 1980) from a height of 3.5 metres, atop a step ladder. This gave a field-of-view (FOV) of 1.1 metres within which green LAI was sampled (for discussion, see section on measuring green LAI).

Photographic measurement of red and near infrared reflectance. Photographic measurements of red (0.64 µm to 0.69 µm) and near infrared (0.75 µm to 0.95 µm) reflectance were made for each sample point on eight of the 12 dates using a 35-mm Canon F1† camera with a 100-mm lens. The film was Kodak 2481† infrared monochrome and was alternately filtered into red and near infrared wavebands by Wratten 92† plus Corning 3961† filters and a Wratten 88A filter, respectively (Curran, 1980a). The photographs were taken from a height of 3 metres, atop a step ladder; this produced a maximum usable FOV of 1 metre. Green LAI was sampled from the center of the FOV and, therefore, the effect of fall-off is considered negligible.

As the photographs were taken, light grey and dark grey targets of known reflectance were incorporated into the FOV. The image tone of the vegetation and/or soil and the two targets was measured using a Photolog† densitometer with a 2-mm spot size. As this spot size measures a ground area of only 3 by 3 cm, five measurements were taken close to the photo-center to produce a mean tonal value. Using the targets as standards, the reflectance of the vegetation and/or soil was calculated using the method proposed by Lillesand and Kiefer (1979, pp. 374-375). It has been shown that reflectance determined photographically by this method is directly correlated (r = 0.91 to 0.98, significant at the 1 percent level) to reflectance determined radiometrically (Curran *et al.*, 1981). On the date when both photographic and radiometric reflectance measurements were made, there was a mean reflectance difference of only 0.6 percent and a nonsignificant (1 percent level) variance difference between the two sets of measurements.

Measuring green LAI. At each sample point three 0.02 m^2 (14 by 14 cm^2) quadrats were harvested. The total harvest from all three quadrats was spread out onto a large light colored canvas target (used for the aircraft overflights) and was then photographed along with a scale, using a Kodak 64ASA color transparency film. In the laboratory the transparencies were projected onto a screen covered with random sample points. The number of green contacts per 100 sample points was used to calculate the proportion of the transparency area that was covered with green leaves. This in turn was used to calculate the green leaf area per unit area of ground, or green LAI.

For example, if from the scale it were determined that the area photographed was 1 m^2 and 12 of the 100 photographic sample points touched green leaves, then 0.12 m^2 of green leaves would have been harvested from the 0.06 m^2 sample area. Therefore, the green LAI of the sample area was 0.12 m^2/0.06 m^2 = 2.

GROUND DATA MANIPULATION AND REGRESSION

Correction of red and near infrared reflectance for the effect of solar elevation. For vegetation canopies there is usually a strong positive relationship between solar elevation and near infrared reflectance, and little or no relationship between solar elevation and red reflectance (Duggin, 1977; Curran, 1983a). Correction of reflectance data for the effect of solar elevation has been achieved with blanket normalization functions, e.g., cosine of the solar elevation (Jordan, 1969; Holben *et al.*, 1980), but in this case, where the seasonal effect of solar elevation on the reflectance of *Calluna* and *Pteridium* was unknown, the effect of solar elevation was minimized by avoiding very sunny days, and an empirical approach was adopted to correction.

Avoiding sunny days was not difficult during the field seasons of 1980 and 1981, and as a result all reflectance measurements were made on cloudy or overcast days under conditions of diffuse irradiance. The mean cloud cover during measurement was 6.6 (σ2.4) oktas (Reading University Meteorological Station Records 1980-81).

Even under diffuse illumination, the canopy reflectance did vary with solar elevation. Therefore, the diurnal relationship between reflectance and solar elevation was determined on overcast days in February and June for the associations of young *Calluna*, mature *Calluna*, *Pteridium*, *Pteridium*/*Calluna*, and also bare ground. A discussion of the relationship between solar elevation and reflectance for the mature *Calluna* association is given by Gayler (1981).

For all of the sites, there was no significant deviation in red reflectance from the mean red reflectance (Kolmogorov-Smirnov test (Gregory, 1970)). However, the near infrared reflectance did decrease markedly with solar elevation (Figure 3). Using these diurnal data for each site, the reflectance data were corrected graphically to a solar elevation of 25°, a solar elevation common to both winter and summer

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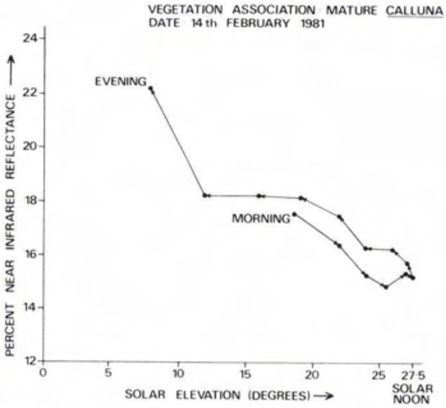

FIG. 3. The relationship between near infrared reflectance and solar elevation for mature *Calluna* (modified from Gayler (1981)).

diurnal measurements. This involved increasing the spring, summer, and autumn near infrared reflectance data by an average of 0.18 percent per 1° increase in solar elevation above 25° and decreasing the winter near infrared reflectance data by an average of 0.15 percent per 1° decrease in solar elevation below 25°. The bare sites required the least and the *Pteridium* site the most correction.

Determining the substrate line. The 120 ground radiometric and photographic reflectance measurements for the bare soil sites were plotted on a graph of red and near infrared reflectance. This gave the substrate (or soil) line discussed by Kauth and Thomas (1976) and Richardson and Wiegand (1977). Near to the origin of the graphs are the dark, peaty, and wet soils and further away from the origins are the light, stony, and dry soils. Upon this line the ground reflectance data for each site were plotted.

A simplified diagram to show the area covered by the data in red and near infrared feature space is given in Figure 4. The young and mature *Calluna* associations with their low green LAI and high shadow area have a low red and near infrared reflectance and are located both near to the origin of the graphs and the substrate line (Figure 4, a and b). The *Pteridium* and *Pteridium/Calluna* associations have a higher green LAI and less shadow area and are therefore located further from both the origins of the graphs and the substrate line (Figure 4, c and d).

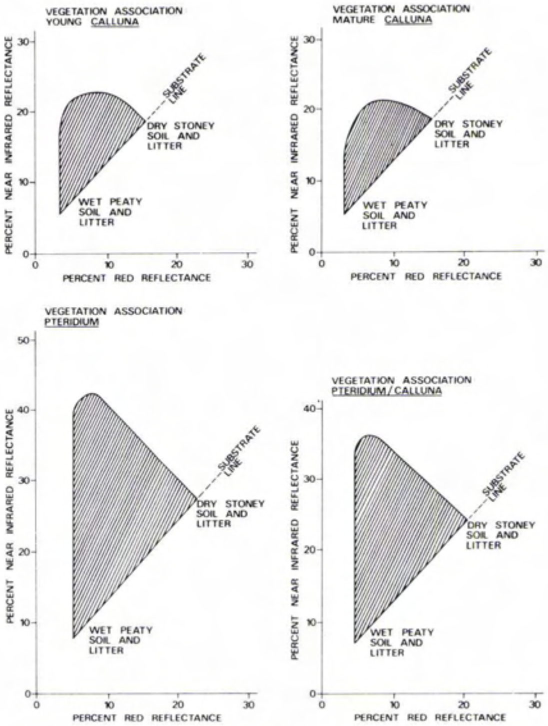

FIG. 4. The red to near infrared reflectance feature space occupied by the four vegetation associations.

Transformation of the reflectance data to the Perpendicular Vegetation Index (PVI). The reflectance of the vegetation canopy varies considerably with variations in soil background reflectance. This is discussed generally by Curran (1980b; 1983b) and specifically for this site by Curran (1981c). The Perpendicular Vegetation Index or PVI (Richardson and Wiegand, 1977) was used to overcome this effect, as the PVI measures the perpendicular distance between the mean vegetation canopy reflectance and the substrate line in feature space (Figure 4); that is,

$$\text{PVI} = \sqrt{(pS_R - pV_R)^2 + (pS_{IR} - pV_{IR})^2} \qquad \text{Formula (1)}$$

where PVI = Perpendicular Vegetation Index,
pS = soil reflectance,
pV = vegetation reflectance,
subscript R = red wavelengths, and
subscript IR = near infrared wavelengths.

Regression of PVI against green LAI. The regression of PVI against green LAI for each of the four vegetation associations is given in Figures 5 to 8. For all vegetation associations, PVI was positively related to green LAI over the green LAI range of 0 to 0.5 for young and mature *Calluna* and over the green LAI range of 0 to 8 for the *Pteridium* and the *Pteridium/Calluna*. These relationships were linear except for *Pteridium*, which had a curvilinear relationship between PVI and green LAI resulting from a low linear correlation between PVI and green LAI at high values of green LAI.

The sample points in Figures 5 to 8 are not evenly spread over the whole range of green LAI. This is due to a bunching of areas of similar green LAI for

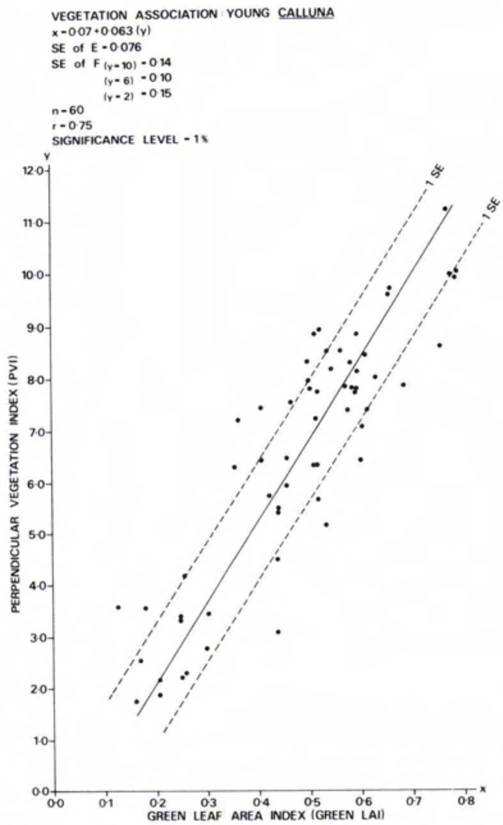

FIG. 5. The relationship between the perpendicular vegetation index (PVI) calculated from ground reflectance data, and the green leaf area index (green LAI) for the young *Calluna* association. SE refers to standard error, E refers to estimate and F refers to forecast.

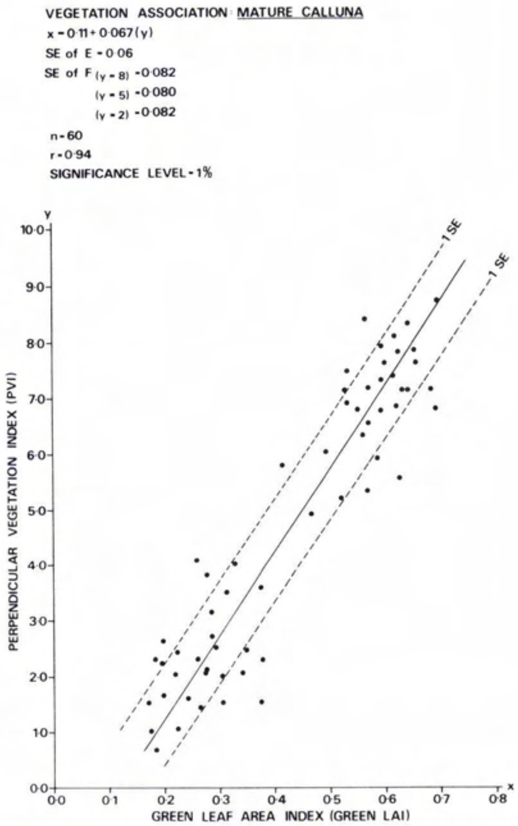

FIG. 6. The relationship between the perpendicular vegetation index (PVI), calculated from ground reflectance data, and the green leaf area index (green LAI) for the mature *Calluna* association. SE refers to standard error, E refers to estimate and F refers to forecast.

each association. For example, mature *Calluna* (Figure 6) had two quite distinct zones (Table 1), one with a mix of both very old and very young *Calluna* and a green LAI maximum of 0.38 and another with just mature *Calluna* and a green LAI minimum of 0.42. The *Pteridium* (Figure 7) was either senescent or was growing up to the full canopy green LAI of around 4.0 in one area and 7.0 in another area.

Therefore, the regression of PVI against green LAI is useful for the whole vegetation association over time rather than for the whole vegetation community at a point in time.

THE COLLECTION OF MULTISPECTRAL AERIAL PHOTOGRAPHY AND GREEN LAI DATA

Multispectral aerial photography. Near vertical 35-mm aerial photography was taken at around 1100 local time, on 20 dates, from June 1980 to August 1981, from either a Cessna 172 or a DeHavilland Chipmunk light aircraft, flying at a height of approximately 600 metres. A Canon F1† camera with 100-mm lens and a Canon AT1† camera with a 50-mm lens were used.

The Canon F1 had the same film/filter combination as was used for ground multispectral photography and the Canon AT1 contained Kodak† color infrared film in order to record general site conditions (Curran, 1981a).

For each image in each waveband, the image tones of sample points were recorded near to the image center using a Photolog† spot densitometer with a 1-mm spot size. Five measurements were taken within each vegetation association, five measurements were taken on bare ground, one measurement was taken on a light toned canvas reflectance target, and one measurement was taken on an area of bare black charcoal. Red and near infrared reflectance were determined using the method outlined in the discussion on ground photographic reflectance data.

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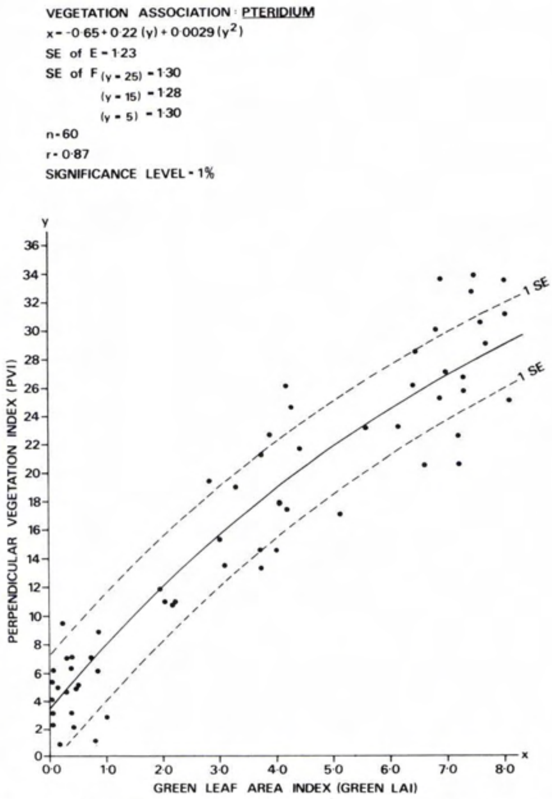

FIG. 7. The relationship between the perpendicular vegetation index (PVI), calculated from ground reflectance data, and the green leaf area index (green LAI) for the *Pteridium* association. SE refers to standard error, E refers to estimate, and F refers to forecast.

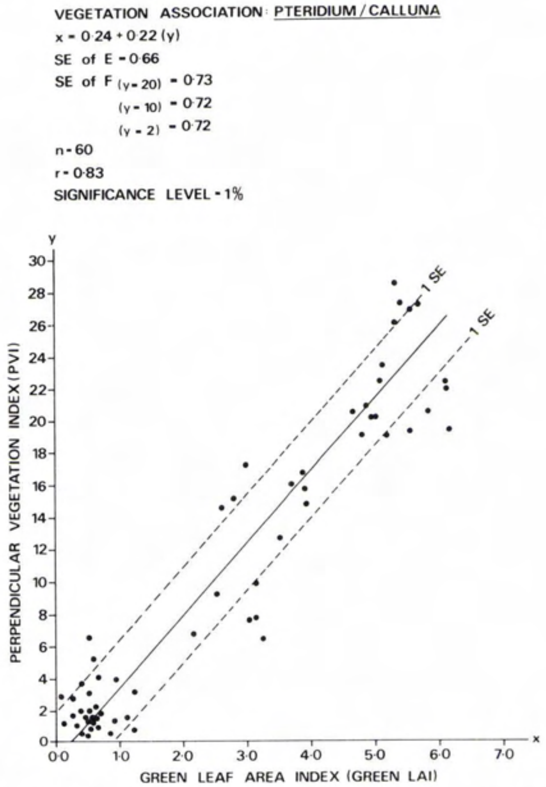

FIG. 8. The relationship between the perpendicular vegetation index (PVI), calculated from ground reflectance data, and the green leaf area index (green LAI) for the *Pteridium/Calluna* association. SE of E refers to standard error, E refers to estimate, and F refers to forecast.

The radiometric accuracy of multispectral aerial photography. All reflectance measurements have a degree of error associated with them. Therefore, prior to reflectance measurements, it is essential to determine if the sensing technique, in this case multispectral aerial photography, had sufficient radiometric accuracy to record the likely changes in reflectance (Duggin, 1981). Therefore, red and near infrared aerial photographs were taken of four ground targets of known reflectance on three occasions during four of the photographic missions.

Two of the targets (white and black) were on the toe and crest of the D log E curve while two of the targets (light grey and orange) were on the straight line portion of the D log E curve. The variation in the recorded reflectance was very similar in both the red and near infrared wavelengths. The two targets on the edge of the straight line portion of the D log E curve had a 2σ for all reflectance measurements ($n = 48$) of ±1.1 percent. The two targets on the straight line portion of the D log E curve had a 2σ for all reflectance measurements ($n = 48$) of ±0.8 percent. Therefore, for the majority of areas under study, a reflectance measurement can be made with an accuracy of better than ±1 percent at the 95 percent confidence limit. This level of measurement accuracy, although not ideal, is adequate to record the seasonal change in reflectance on Snelsmore Common, which is around 11 percent in near infrared and 14 percent in red wavelengths.

Measuring green LAI. Within each of the four vegetation associations, an area of 36 m^2 (6 by 6 m) was sampled by three sample points (0.02 m^2). At each point the vegetation was harvested and the green LAI determined, using the methods discussed previously. The results were presented as the mean green LAI within the sample area.

ESTIMATING GREEN LAI

For each flight the aerial photographic red and near infrared reflectance data were transformed to PVI values for each of the five areas for which green LAI had been sampled within each association. The PVI values were then used to estimate the green LAI of each of these areas by means of the regressions calculated for the ground PVI/green LAI relationship (Figures 5 to 8). For example, on the mature *Calluna* site a PVI of 5.0 would indicate a green LAI of between 0.29 and 0.61 at the 95 percent confidence limit. The mean of the estimated green LAI range was plotted against the observed green LAI for each site (Figures 9 to 12). In all cases this expected green LAI was linearly related to and slightly overestimated the observed green LAI.

Discussion

The accuracy of the estimated green LAI is dependent upon the acceptable error of the estimate, the type of vegetation, and the season. If estimates must be perfect, percent accuracies are going to be near to zero. If very high errors are acceptable for each estimate, e.g., each estimate is ±3.0 green LAI, then accuracies are going to be near to 100 percent. Between these two extremes the actual percentage error will be related directly to the initial standard error of the forecast and the accuracy with which the observed green LAI can be measured. For example, if the green LAI was observed without error on the mature *Calluna* site, then the accuracy with which this green LAI could have been estimated by multispectral photography would have been 68 percent (Gregory, 1970) at an error of 0.08 green LAI at low or high values of green LAI. This is the standard error of the forecast given on Figure 6.

In practice a user will wish to estimate a wide range of green LAI values at a prespecified range of acceptable error. Therefore, the relationship between error range and accuracy is illustrated by means of three possible error ranges that are comparable between the four vegetation associations.

Low error of estimate: this was chosen to represent one eighth of the total green LAI range for each vegetation association and is ±0.05 green LAI for the young and mature *Calluna* and ±0.5 green LAI for the *Pteridium* and *Pteridium/Calluna*. Medium error of estimate: this was chosen to represent one quarter of the total green LAI range for each vegetation association and is ±0.1 green LAI for the young and mature *Calluna* and ±1.0 green LAI for the *Pteridium* and *Pteridium/Calluna*. High error of estimate: this was chosen to represent one half of the total green LAI range for each vegetation association and is ±0.2 green LAI for the young and mature *Calluna* and ±2.0 green LAI for the *Pteridium* and *Pteridium/Calluna*.

An estimate of green LAI can be made with a low error of the estimate to an overall accuracy of 42 percent, at a medium error of the estimate the overall accuracy increases to 74 percent, and at a high error of the estimate the overall accuracy increases to 98 percent (Table 2).

The accuracy of the green LAI estimate varied between vegetation associations due to the problem of sampling. The canopies with a high spatial variability of green LAI, e.g., young *Calluna* proved difficult to sample in a representative way, and this decreased the quality of the reflectance and green LAI data.

The accuracy of estimation also varied with season. The accuracy of the green LAI estimate at a medium level of error (±0.1 green LAI for young and mature *Calluna* and ±1.0 green LAI for *Pteri-*

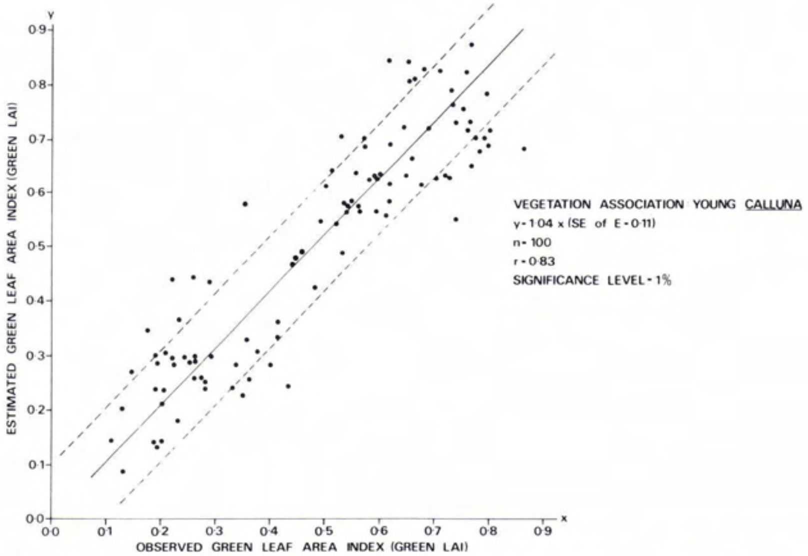

FIG. 9. The relationship between the estimated and the observed green leaf area index for the young *Calluna* association. SE of E refers to the standard error of the estimate.

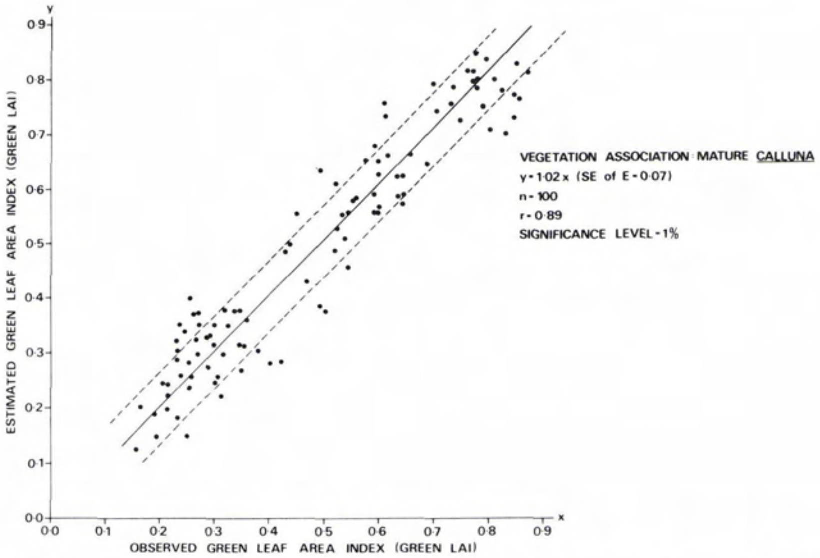

FIG. 10. The relationship between the estimated and the observed green leaf area index for the mature *Calluna* association. SE of E refers to the standard error of the estimate.

dium and *Pteridium/Calluna*) over time is given in Figure 13. The accuracy of the green LAI estimate is highest in the winter and spring, from December to early May, when it is an average of 84 percent. In the Summer and Autumn, from late May to November, the accuracy of the green LAI estimate dropped to an average of 52 percent. The three reasons for this seasonal variation are the flowering of *Calluna* and the growth and senescence of *Pteridium*. In July and August, when *Calluna* is in flower and many of the leaves are hidden by petals, the accuracy of the green LAI estimate drops to 25 percent for the young and mature *Calluna* in comparison to 70 percent for the unaffected *Pteridium* and the little effected *Pteridium/Calluna*. When *Pteridium* is growing in late May and early June and many of the green leaves are either hidden under the *Calluna* or have a similar near infrared reflec-

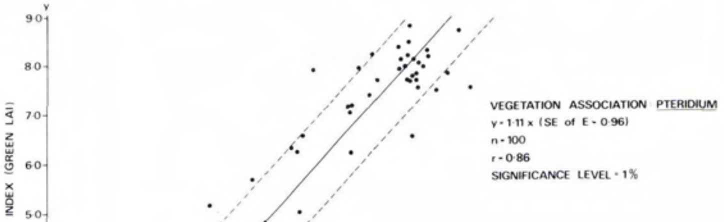

FIG. 11. The relationship between the estimated and the observed green leaf area index for the *Pteridium* association. SE of E refers to the standard error of the estimate.

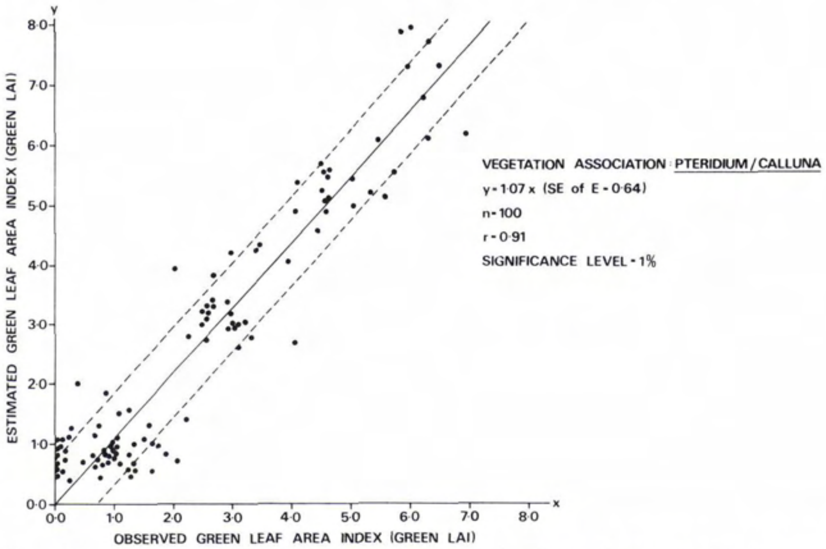

FIG. 12. The relationship between the estimated and the observed green leaf area index for the *Pteridium/Calluna* association. SE of E refers to the standard error of the estimate.

tance to the senescent litter, the accuracy dropped to 50 percent for *Pteridium* and *Pteridium/Calluna* in comparison to 87 percent for the unaffected young and mature *Calluna*. When *Pteridium* is senescing in October and November and green leaves and senescent vegetation are sensed together, the accuracy of the green LAI estimate dropped to 57 percent for the *Pteridium* and *Pteridium/Calluna* association in comparison to 80 percent for the unaffected young and mature *Calluna* association.

TABLE 2. THE RELATIONSHIP BETWEEN THE ERROR OF A GREEN LAI ESTIMATE AND THE ACCURACY OF THAT ESTIMATE. FOR EXAMPLE THE GREEN LAI OF *PTERIDIUM* CAN BE ESTIMATED WITH AN ERROR OF ±1.0, 73 TIMES OUT OF EVERY 100

Vegetation Association	Error of Green LAI Estimate	Percent Accuracy of Green LAI Estimate at given level of error
Young *Calluna*	±0.05 (low)	34
	±0.1 (medium)	62
	±0.2 (high)	92
Mature *Calluna*	±0.05 (low)	41
	±0.1 (medium)	73
	±0.2 (high)	100
Pteridium	±0.5 (low)	39
	±1.0 (medium)	73
	±2.0 (high)	100
Pteridium/Calluna	±0.5 (low)	53
	±1.0 (medium)	89
	±2.0 (high)	98

CONCLUSIONS

- Low cost multispectral aerial photography, combined with a detailed knowledge of the relationship between canopy reflectance and green LAI, was used to estimate the green LAI of four different vegetation canopies.
- The accuracy of the green LAI estimate is dependent upon the acceptable error of the estimate, the efficacy of sampling, and the season of data acquisition.
- At an error of estimate of ±0.1 green LAI for the young and mature *Calluna* and ±1.0 green LAI for *Pteridium* and *Pteridium/Calluna*, green LAI could be estimated with an overall accuracy of 74 percent. At higher levels of error the overall accuracy increases.
- At times of canopy stability in the winter and early spring and at an error of estimate of ±0.1 green LAI for the young and mature *Calluna* and ±1.0 green LAI for the *Pteridium* and *Pteridium/Calluna*, the overall accuracy increased to 84 percent.

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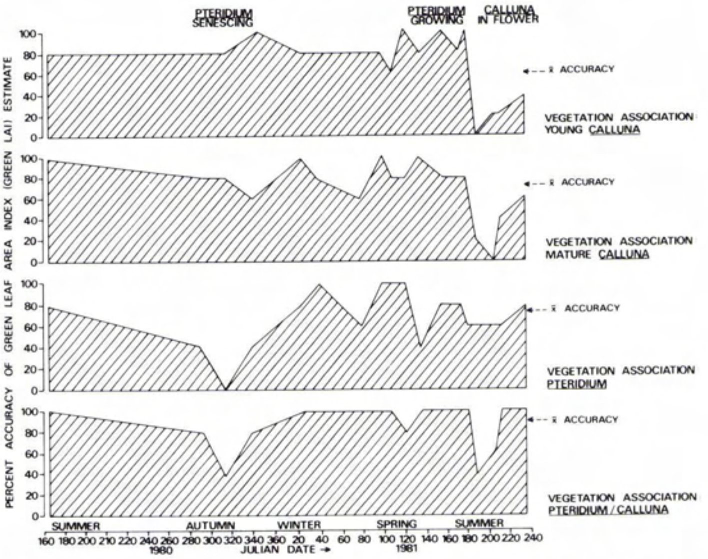

FIG. 13. The effect of season on the accuracy of the green leaf area index estimate. The green LAI estimate is for an error of ±0.1 green LAI for the young and mature *Calluna* and ±1.0 green LAI for the *Pteridium* and the *Pteridium/Calluna*. Note that for the associations containing *Calluna* accuracy drops during flowering and for the associations containing *Pteridium* accuracy drops during times of both growth and senescence.

REFERENCES

Ahlrichs, J. S., M. E. Bauer, M. M. Hixson, C. S. T. Daughtry, and D. W. Crecelius, 1978. Relation of Crop Canopy Variables to the Multispectral Reflectance of Small Grains. *Proceedings of the International Symposium on Remote Sensing for Observation and Inventory of Earth Resources and the Endangered Environment*. Ed. G. Hildebrandt and H. J. Boehnel. International Archives of Photogrammetry, 22: 629-49.

Bartlett, D. S., and V. Klemas, 1980. Quantitative Assessment of Tidal Wetlands Using Remote Sensing. *Environmental Management*, 4: 337-45.

Bauer, M. E., L. L. Biehl, and B. F. Robinson, eds., 1980. *Field Research on the Spectral Properties of Crops and Soils*. Purdue University, Laboratory for the Applications of Remote Sensing, West Lafayette, Indiana: 27-42.

Chance, J. E., 1981. Crop Identification and Leaf Area Index Calculations with Landsat Multitemporal Data. *International Journal of Remote Sensing*, 2: 1-14.

Colwell, J. E., 1974. Grass canopy bidirectional spectral reflectance. *Proceedings of the 9th International Symposium on Remote Sensing of Environment*, University of Michigan, Ann Arbor: 1061-1085.

Curran, P. J., 1980a. Relative Reflectance Data from Preprocessed Multispectral Photography. *International Journal of Remote Sensing*, 1: 77-83.

———, 1980b. Multispectral Remote Sensing of Vegetation Amount. *Progress in Physical Geography*, 4: 315-41.

———, 1980c. Multispectral Photographic Remote Sensing of Vegetation Amount and Productivity. *Proceedings of the 14th International Symposium on Remote Sensing of Environment*, University of Michigan, Ann Arbor: 623-637.

———, 1981a. Remote Sensing, the Role of Small Format, Light Aircraft Photography. *Geographical Papers*, 75 Department of Geography, University of Reading, U.K.

———, 1981b. Multispectral Remote Sensing for Estimating Vegetation Biomass and Productivity. In H. Smith (ed.) *Plants and the Daylight Spectrum*, Academic Press: 65-99.

———, 1981c. The Estimation of the Surface Moisture of a Vegetated Soil Using Aerial Infrared Photography. *International Journal of Remote Sensing* 2:369-78.

———, 1982a. Multispectral Photographic Remote Sensing of Green Vegetation Biomass and Productivity. *Photogrammetric Engineering and Remote Sensing*, 48: 243-250.

———, 1982b. Polarised light as an aid to Vegetation Classification. *Remote Sensing of Environment*, 12: 491-499.

———, 1983a. Problems in the Remote Sensing of Vegetation Canopies for Biomass Estimation. In R. M. Fuller (ed) *Ecological Mapping from Ground Air and Space*, Institute of Terrestrial Ecology, Symposium N° 10 Cambridge U.K.: 84-100.

———, 1983b. Multispectral Remote Sensing for the Estimation of Green Leaf Area Index, *Philosophical Transactions of the Royal Society London Series A*, 309: 257–270.

Curran, P. J., T. J. Munday, and E. J. Milton, 1981. A Comparison Between two Photographic Methods for the Determination of Relative Bidirectional Reflectance. *International Journal of Remote Sensing*, 2: 185-8.

Deering, D. W., J. W. Rouse, R. H. Haas, and J. A. Schell, 1975. Measuring "Forage Production" of Grazing Units from Landsat MSS Data. *Proceedings of 10th International Symposium on Remote Sensing of Environment*. University of Michigan, Ann Arbor: 1169-1178.

Duggin, M. J., 1977. Likely Effects of Solar Elevation on the Quantification of Changes in Vegetation with Maturity Using Sequential Landsat Imagery. *Applied Optics*, 16: 521-523.

———, 1981. The Effects of Irradiance and Reflectance Variability on Vegetation Condition Assessment. Paper presented at *The International Conference on Matching Remote Sensing Technologies and their Applications*. London, England, December 1981.

Gayler, J., 1981. *An Investigation into the Effects of Solar Elevation on the Bidirectional Reflectance of Heather*. Unpublished Project Submitted as Part Fulfilment of B.Sc. Degree, University of Reading, U.K.

Gregory, S., 1970. *Statistical Methods and the Geographer*. Longman, Second Edition.

Heilman, J. L., E. T. Kanemasu, J. O. Bagley, and U. P. Rasmussen, 1977. Evaluating Soil Moisture and Yield of Winter Wheat in the Great Plains Using Landsat Data. *Remote Sensing of Environment*, 6: 313-326.

Hielkema, J. U., 1980. Remote Sensing Techniques and Methodologies for Monitoring Ecological Conditions for Desert Locust Population Development. *Final Technical Report FAO/USAID Development Project on Remote Sensing Applications for Desert Locust Survey and Control*. Food and Agriculture Organisation of the United Nations, Rome, Italy, CGP/INT/349/USA, 63 p.

Holben, B. N., C. J. Tucker, and J. W. Robinson, 1980. Limitations on the Application of a Ground-Based Spectral Technique for Determining Rain Forest Leaf Area Index. *Photogrammetric Engineering and Remote Sensing*, 46: 1555-1561.

Jordan, C. F., 1969. Derivation of Leaf Area Index from the Quality of Light on the Forest Floor. *Ecology*, 59: 663-666.

Kauth, R. G., and G. S. Thomas, 1976. The Tasseled cap, a Graphic Description of the Spectral-Temporal Development of Agricultural Crops as Seen by Landsat. *Proceedings on the Symposium on Machine Processing of Remote Sensing Data*. L.A.R.S. Purdue, IEEE Cat. No. 76, 6.23-7.2.

Kondratyev, K. Ya, and P. P. Fedchenko, 1982. *Spectral reflectivity and recognition of vegetation* [In Russian] Leningrad: Gidrometeoizdat.

Lillesand, T. M., and R. W. Kiefer, 1979. *Remote Sensing and Image Interpretation*. John Wiley and Sons.

Milton, E. J., 1980. A Portable Multiband Radiometer for Ground Data Collection in Remote Sensing. *International Journal of Remote Sensing*, 1: 153-165.

Pearson, R. L., C. J. Tucker, and L. D. Miller, 1976. Spectral Mapping of Shortgrass Prairie Biomass. *Photogrammetric Engineering and Remote Sensing*, 42: 317-323.

Pollock, R. B., and E. T. Kanemasu, 1979. Estimating Leaf-Area Index of Wheat with Landsat Data. *Remote Sensing of Environment*, 8: 307-312.

Richardson, A. J., and C. L. Wiegand, 1977. Distinguishing Vegetation from Soil Background. *Photogrammetric Engineering and Remote Sensing*, 43: 1541-1552.

Tucker, C. J., J. H. Elgin, and J. E. McMurtrey, 1979. Temporal, Spectral Measurements of Corn and Soybean Crops. *Photogrammetric Engineering and Remote Sensing*, 45: 643-653.

———, 1980. Relationship of Crop Radiance to Alfalfa Agronomic Values. *International Journal of Remote Sensing*, 1: 69-76.

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