PAUL J. CURRAN*
Department of Geography
University of Reading
Reading, RG6 2AU United Kingdom

Multispectral Photographic Remote Sensing of Green Vegetation Biomass and Productivity

The role of productivity should be considered in the interpretation of bidirectional reflectance from vegetation canopies.

ABSTRACT: *There is usually a positive relationship between a red to near infrared bidirectional reflectance ratio and the biomass of green vegetation, up to the bidirectional reflectance asymptote of the vegetation. However, bidirectional reflectance is known to vary independently of green biomass due to the effect of the soil background, the presence of senescent vegetation, the angles of sun and sensor, the canopy geometry, and episodic and phenological canopy changes (Curran, 1981). One little studied influence on the relationship between a bidirectional reflectance ratio and green biomass is the effect of productivity, which could theoretically affect red bidirectional reflectance independently of green biomass.*

Using bidirectional reflectance data derived photographically from 22 sets of near vertical aerial photography and 56 sets of oblique ground photography, it was demonstrated that (1) the amount of bidirectional reflectance ratio variance accounted for by green biomass could be increased by around 6 percent with the addition of productivity, and (2) on a pasture site with low green biomass but high productivity the bidirectional reflectance ratio was higher than for a high green biomass pasture site with lower productivity.

While the importance of productivity is suggested rather than proved by the data discussed in this paper, it is clear that the role of productivity should at least be considered in the interpretation of bidirectional reflectance from vegetation canopies.

INTRODUCTION AND OBJECTIVE

THERE IS usually a positive relationship between a red to near infrared bidirectional reflectance ratio and the biomass of a green vegetation canopy (Colwell, 1974). This relationship holds good for a healthy grass crop on a medium toned soil but shows considerable variation with the environment. Bidirectional reflectance is known to vary independently of green biomass due to the effect of the soil background; the presence of senescent vegetation; the angles of sun and sensor; the canopy geometry; and episodic and phenological canopy changes (Curran, 1981). It is to be expected that a variable photosynthetic rate will also affect both vegetation productivity, the absorption of red light, and therefore the red bidirectional reflectance of the canopy without a change in green biomass.

Until now the relationship between the rate of productivity and bidirectional reflectance has received little attention.

THE RELATIONSHIP BETWEEN GREEN BIOMASS AND BIDIRECTIONAL REFLECTANCE

For the majority of vegetation covered scenes, green biomass has a positive relationship to infrared bidirectional reflectance and a negative re-

* Now with the Department of Geography, University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom.

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lationship to bidirectional reflectance in the regions of strong chlorophyll absorbance; within blue, orange, and red wavebands (Tucker and Maxwell, 1976). These relationships hold until the ground surface is covered with vegetation; thereafter, further increases in green biomass result in proportionally smaller changes in bidirectional reflectance. The difference between bidirectional reflectance in the bands of vegetation absorbance and infrared bidirectional reflectance is at a minimum when the amount of green biomass is low and at a maximum when the amount of green biomass is high. This difference can be expressed by a vegetation index; either a bidirectional reflectance ratio or a spectral transform.

The indices used in studies of vegetation and land use are discussed in Curran (1980b). For this study the vegetation index of normalized difference was used: IR − R/IR + R where IR represents near infrared and R represents red. This has been shown to be directly related to the green biomass of grassland up to the asymptote of that particular vegetation type (Tucker, 1977).

THE RELATIONSHIP BETWEEN VEGETATION PRODUCTIVITY AND BIDIRECTIONAL REFLECTANCE

The relationship between a bidirectional reflectance ratio and green biomass is not static because the bidirectional reflectance ratio of a stable stand of vegetation could probably be affected by the productivity of that vegetation. For example: a low green biomass stand of vegetation undergoing a period of active growth (high productivity) would be expected to strongly absorb red light for photosynthesis. This stand would have a greater near infrared to red bidirectional reflectance difference (and also bidirectional reflectance ratio) than a low green biomass stand of similar vegetation, with a slower growth (lower productivity).

The importance of productivity was inferred by Agazzi and Franzetti (1975) who considered that their radiometers were sensitive to the quality of the green biomass rather than the quantity of green biomass. Tucker (1977) tried to separate the relationship between bidirectional reflectance ratios and first, green biomass and second, productivity. He found a high, near infrared divided by a red bidirectional reflectance ratio (indicative of high green biomass) for a site with low green biomass but with a rapid growth rate and presumably, therefore, low red bidirectional reflectance.

This paper attempts to demonstrate the importance of productivity to the relationship between green biomass and a bidirectional reflectance ratio.

Methods for Measuring Bidirectional Reflectance, Green Biomass, and Productivity

The study site was an area of semi-natural vegetation at Shapwick Heath on the Somerset Levels, England (Figure 1). The area has a varied land use and is well instrumented for remote sensing investigations (Curran, 1979a, 1979b). The five sites sampled within the area were mature and young carr woodland, heath bog scrub, *Phragmites* reed bed, and agricultural pasture. From June 1977 to December 1978, 22 sets of multispectral aerial photography were taken of the five sites. At the time photography was taken, green biomass percent cover and productivity were measured.

AERIAL PHOTOGRAPHY

Near vertical 70-mm aerial photography was taken shortly after midday from a Cessna F172 light aircraft, at a height of approximately 600 metres. Twin, bore-sighted Hasselblad EL/M cameras with 80-mm Zeiss lenses and Kodak 2424 infrared monochrome film filtered into red (620 to 680 nm) and infrared (740 to 900 nm) wavebands were used. Sixteen of the 22 flights were flown at the same time as ground photography was taken; only these data were analyzed.

GROUND PHOTOGRAPHY

Oblique 35-mm ground photography was taken from the roof of a Land Rover shortly before midday at a height of approximately six metres. The camera was a motor driven Olympus OM1 with a 50-mm Zuiko lens. The film, a Kodak 2481 infrared monochrome, was filtered into the same red and near infrared wavebands used in the aerial photography.

DENSITOMETRY AND DATA PREPROCESSING

The image tone of sample points was measured using a manual Photolog digital spot densitometer. Ten 1-mm diameter sampling spots were used for each of the five site types. Image tone was re-

FIG. 1. The location of Shapwick Heath.

corded in opacity units, because opacity at a gamma of one has a linear relationship to surface radiance. In order to derive standardized bidirectional reflectance data from the photographic opacity data, a three-step standardization procedure was adopted (Curran, 1980a). Step one, standardize all data to a gamma of one; step two, ratio each opacity value against a spectrally stable scene target; and step three, ratio the wavebands together using the vegetation index of IR − R/IR + R. This technique produces data that are highly correlated to radiometric measurements of bidirectional reflectance (Curran *et al.*, 1981).

MEASURING GREEN BIOMASS

The amount of green vegetation can be measured by the Leaf Area Index (LAI), green biomass, or percent cover. The most useful measurement for remote sensing studies is LAI (Colwell, 1974) because the bidirectional reflectance of vegetation is primarily related to the area of leaves within the canopy. The degree of correlation between bidirectional reflectance and green biomass or percent cover is dependent upon two relationships; first, the relationship between bidirectional reflectance and LAI, and second, the relationship between LAI and green biomass or percent cover. For the vegetation under study, where LAI measurements would have been too time-consuming, green biomass and percent cover were measured; dry green biomass for the low vegetation of *Phragmites*, heath bog, and pasture and percent cover for the tall woodland vegetation of young and mature carr. Because the canopy cover was incomplete for much of the year, there was a linear relationship between LAI, green biomass, and percent cover for the majority of the sites, and, therefore, the term green biomass will be used to refer to the results derived from the measurement of both dry green biomass and percent cover. This is further discussed in Curran (1980c).

Dry green biomass was measured by harvesting, drying, and weighing vegetation (Milner and Elfyn Hughs, 1968) from up to six one-metre-square plots within each site, for each of the 56 ground visits. Percent cover was measured by photographing upwards into the vegetation canopy from the woodland floor, with percentage cover calculated by image sampling using a dot grid. Five or six photographs were taken for each of the 56 ground visits. The range of percent cover and dry green biomass between sites and over time is summarized in Table I. For further discussion refer to Curran (1981).

MEASURING PRODUCTIVITY

Vegetation productivity is a measurement of energy (biomass) accumulation over a specific time period and area (Jones, 1979). There are five conventional methods for recording vegetation productivity. These are harvest green biomass, cover estimate, leaf gasometric, canopy gasometric, and carbon 14 assay (for details of these techniques refer to Curran (1981)). The two gasometric methods can be used to record actual productivity, but they are unsuitable for remote sensing studies because they restrict spatial sampling. The carbon 14 assay method can be used to record the actual productivity of several sites during a remote sensing overflight; however, the laboratory methods associated with this method are laborious. The harvest green biomass and cover estimate techniques which are used in this study enable average, as opposed to actual, productivity rates to be measured at several sites during a remote sensing overflight. The method involves the determination of the average daily increase in green biomass or percent cover in between regular ground measurements of dry green biomass or percent cover. This gave two productivity units: g/m²/day for the low vegetation, and percent cover/day for the woodland (Table 1). At this scale of study there was no collinearity between green biomass and productivity, although this is unlikely to be the case for studies in areas of very low vegetation cover.

TABLE 1. SUMMARY OF GREEN BIOMASS, PER CENT COVER, AND PRODUCTIVITY RECORDED AT FIVE SITES ON SHAPWICK HEATH FROM MAY 1977 TO DECEMBER 1978

	Vegetation Amount				Productivity			
	% cover		Dry green-biomass (g/m²)		% cover/day		g/m²/day	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
mature carr	45.5	35.7			0.41	1.01		
young carr	57.3	32.6			0.36	0.88		
heath bog			141.6	72.2			1.49	2.09
Phragmites			52.9	27.7			0.55	0.92
pasture			94.6	75.4			*	*

* Not measured due to grazing.

Results and Discussion

The Relationship between Green Biomass and the Bidirectional Reflectance Ratio at Shapwick Heath

A regression of the form shown in Equation 1 was used for all sites at ground and air altitudes; that is,

$$\text{Bidirectional Reflectance Ratio} = B_0 + B_1 \text{ (green biomass)}. \quad (1)$$

There was a direct linear relationship between the bidirectional reflectance ratio and green biomass for four of the five sites: *Phragmites*, heath bog, young carr, and mature carr. The correlations for the four sites were significant at the 1 percent level; however, for the two woodland sites this correlation was considerably improved due to the low percent cover values in the winter. The overgrazed pasture site had a low correlation between the bidirectional reflectance ratio and green biomass and will be discussed in a separate section. The regressions are presented in Table 2 and are plotted with the standard error of the estimate in Figures 2 to 5.

The coefficient of determination for the bivariate regression (r^2) indicated that, on average, 46.8 percent of the variance in the ground measurements of bidirectional reflectance and 62.2 percent of the variance in the aircraft measurements of bidirectional reflectance were accounted for by variance in the measure of green biomass. The correlation between the bidirectional reflectance ratio is lower when using the ground photography due to the oblique view that obscures soil bidirectional reflectance (Curran, 1980).

The Relationship between Green Biomass, Productivity, and the Bidirectional Reflectance Ratio at Shapwick Heath

Assuming there are no other changes in a stand of vegetation, an increase in photosynthetic activity will increase productivity and, by increased absorption of red light, will probably increase the bidirectional reflectance ratio. The increase in the bidirectional reflectance ratio, for example at the start of spring, will probably occur without an immediate increase in green biomass. Unless the productivity of vegetation is taken into account, error could be expected in the linear relationship between green biomass and the bidirectional reflectance ratio.

To determine the effect of a seasonally variable productivity rate on bidirectional reflectance, the mean seasonal productivity was related to the deviation from the bivariate regression. The data for the four undisturbed sites were combined and are summarized in Figure 6.

The spread of bidirectional reflectance ratios around the regression line was related to the productivity, with values higher than the regression line in spring, times of high productivity, and below the regression line in autumn and part of winter, times of low or no productivity. To determine if the addition of productivity to green biomass increased the bidirectional reflectance ratio variance accounted for by green biomass alone, a trivariate regression (Equation 2) was used; that is,

$$\text{Bidirectional Reflectance Ratio} = B_0 + B_1 \text{ (green biomass)} + B_2 \text{ (productivity)} \quad (2)$$

There was a direct linear relationship between the bidirectional reflectance ratio and green biomass plus productivity for the four undisturbed sites of *Phragmites*, heath bog, young carr, and mature carr (Table 3). This relationship was at its strongest in the spring and early summer; times of high productivity and fairly high green biomass levels.

The coefficient of determination indicates that, for the four combined sites, green biomass and productivity account for 49.6 percent of the variance in the ground measurements of bidirectional reflectance and 67.3 percent of the variance in the

Table 2. Results of the Bivariate Regression for Four Sites and Two Altitudes

Site	Altitude	$\frac{IR - R}{IR + R} = B_0 + B_1$ (green biomass) B_0		B_1	S.E. of estimate	n	r^2	Significance level of B_1 (T Test)	Significance level of r (F Test)
Mature Carr	Ground	−0.182	+	0.0063	0.230	59	0.454	1%	1%
	Air	−0.311	+	0.0061	0.231	16	0.461	1%	1%
Young Carr	Ground	−0.365	+	0.0078	0.225	56	0.552	1%	1%
	Air	−0.301	+	0.0091	0.174	16	0.757	1%	1%
Heath Bog	Ground	−0.330	+	0.0024	0.225	56	0.439	1%	1%
	Air	−0.431	+	0.0024	0.163	16	0.626	1%	1%
Phragmites	Ground	−0.391	+	0.0070	0.253	56	0.430	1%	1%
	Air	−0.445	+	0.0078	0.179	16	0.643	1%	1%

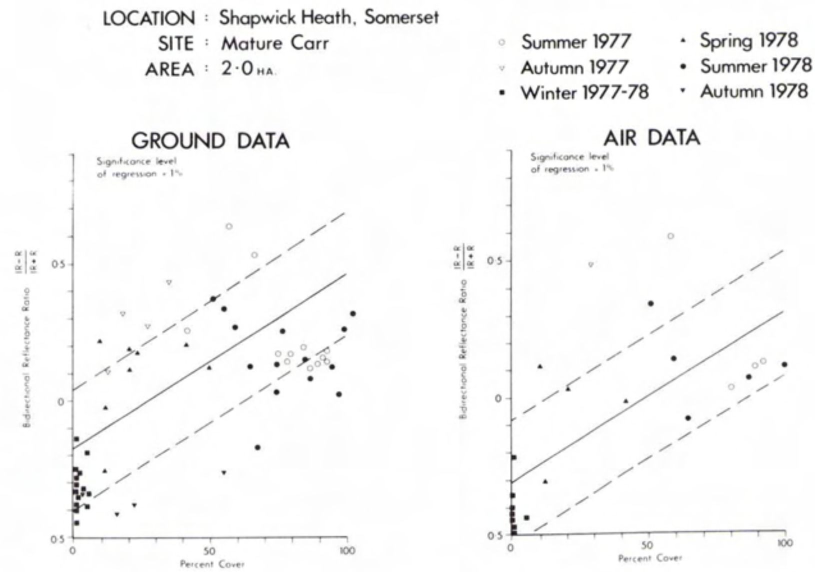

FIG. 2. The relationship between a bidirectional reflectance ratio recorded photographically and the percent cover of mature carr at both ground and aircraft altitudes.

aircraft measurements of bidirectional reflectance. Therefore, around 6 percent additional bidirectional reflectance ratio variance was accounted for by the inclusion of productivity to the bivariate regression, thus indicating the probable importance of productivity.

AN EXAMPLE OF THE NON-STATIC RELATIONSHIP BETWEEN GREEN BIOMASS AND BIDIRECTIONAL REFLECTANCE ON SHAPWICK HEATH

On undisturbed sites there was a linear relationship between the bidirectional reflectance ratio and green biomass plus productivity. To investi-

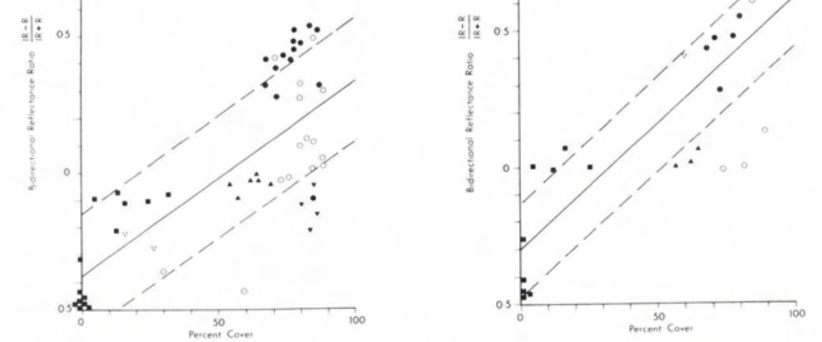

FIG. 3. The relationship between a bidirectional reflectance ratio recorded photographically and the percent cover of young carr at both ground and aircraft altitudes.

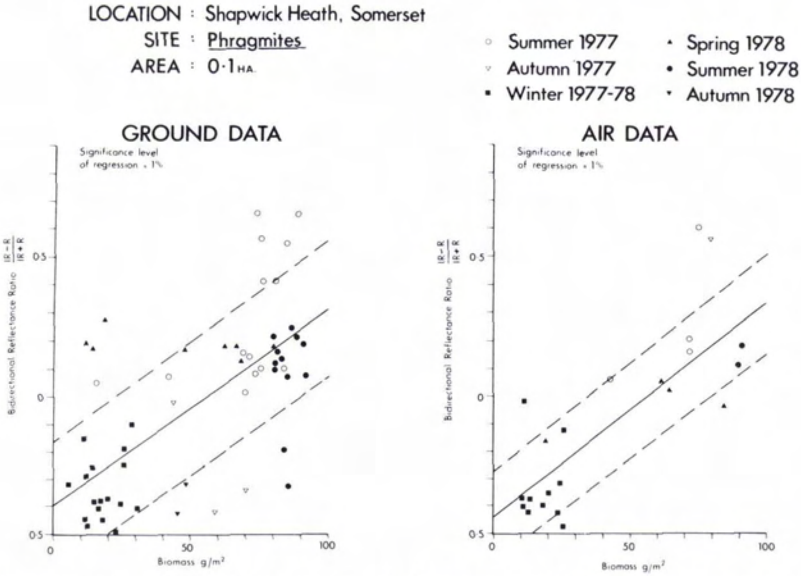

FIG. 4. The relationship between a bidirectional reflectance ratio recorded photographically and the green biomass of *Phragmites* at both ground and aircraft altitudes.

gate this relationship before, during, and after disturbance, bidirectional reflectance ratio values were calculated and dry green biomass recorded for the north and south sections of the pasture site from late 1977, using the methods outlined for the other four sites. The northern two-hectare portion of the pasture was heavily grazed from January to April, 1978; the southern one-hectare portion of the pasture remained undisturbed.

The Somerset Levels are a dairy farming area where it is usual to leave some cattle in the fields to be hay-fed during the winter, at a stocking rate of up to two head per hectare. The northern two-hectare pasture on Shapwick Heath was grazed by 27 large cattle, which resulted in severe poaching and the rapid removal of vegetation cover. This change is summarized in Figure 7.

The green biomass for the two sites decreased from 200 g/m^2 in November to 120 g/m^2 for the ungrazed and 70 g/m^2 for the grazed site in February. For the ungrazed site green biomass remained at a winter low of 70 g/m^2 until spring,

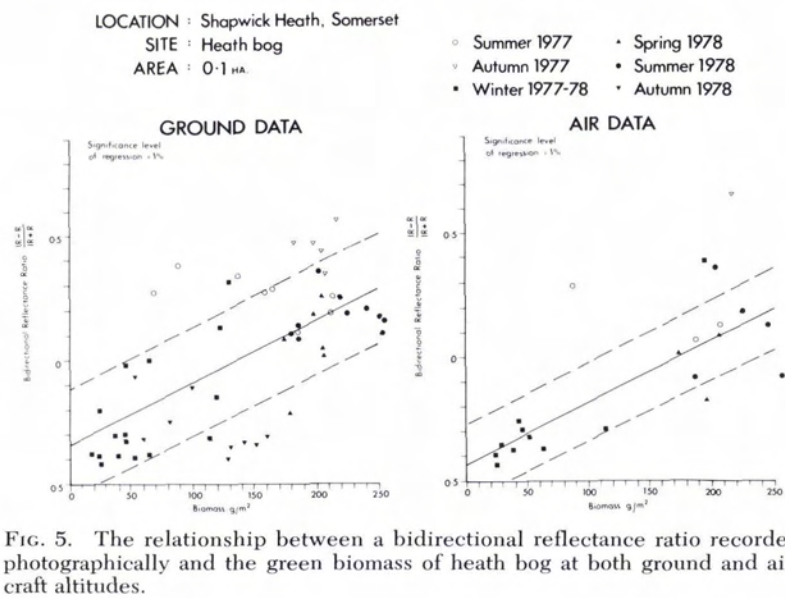

FIG. 5. The relationship between a bidirectional reflectance ratio recorded photographically and the green biomass of heath bog at both ground and aircraft altitudes.

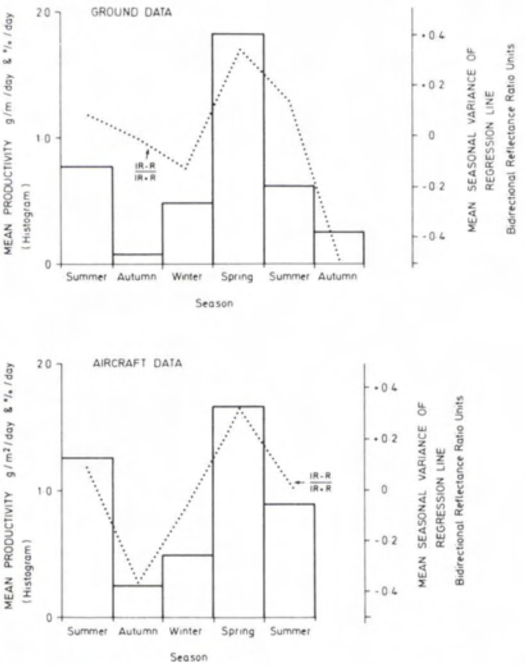

FIG. 6. Deviation of the ratioed bidirectional reflectance data from the bivariate regression line and their relationship to productivity.

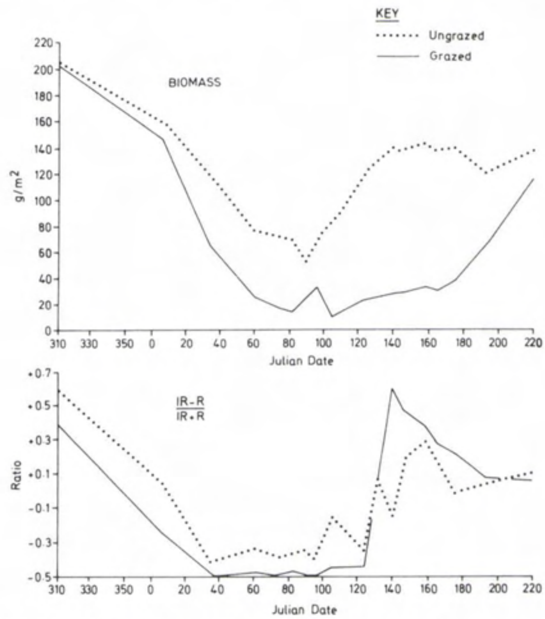

FIG. 7. The temporal trend in green biomass and bidirectional reflectance ratio, for the grazed and ungrazed pasture, where biomass refers to green biomass, ratio refers to bidirectional reflectance ratio, and Julian date refers to the annual day number, e.g., January 20th = 20.

when rapid growth in late April and early May increased green biomass to the early summer level of 130 g/m². For the grazed site, the February low decreased due to grazing, to under 10 g/m² in March and remained at that level until mid-June. The vegetation was so badly damaged that the spring growth burst did not occur immediately after the cattle were removed. Green biomass increased slowly during the spring and rapidly from mid-June to mid-July, by which time there was no obvious difference between the two pastures on aerial photography. In August the grazed and ungrazed pasture had a similar and increasing green biomass of 120 g/m².

If the bidirectional reflectance ratios were responding to green biomass alone, then plots of the bidirectional reflectance ratio would be similar to the green biomass plots for grazed and ungrazed pasture. The bidirectional reflectance ratio plot in both pastures had decreasing values during the autumn and early winter, until February when both the grazed and ungrazed pastures retained a similarly low bidirectional reflectance ratio value.

TABLE 3. RESULTS OF TRIVARIATE REGRESSION FOR FOUR SITES AND TWO ALTITUDES

$$\frac{IR - R}{IR + R} = B_0 + B_1\,(\text{green biomass}) + B_2\,(\text{productivity})$$

Site	Altitude	B_0		B_1		B_2	S.E. of estimate	R^2	Significance level of B_1 (T Test)
Mature Carr	Ground	−0.359	+	0.034	+	0.00225	0.206	0.487	1%
	Air	0.116	−	0.0026	−	0.00202	0.211	0.586	5%
Young Carr	Groud	−0.339	−	0.029	+	0.00793	0.220	0.563	1%
	Air	−0.234	−	0.0501	+	0.0087	0.163	0.752	1%
Heath Bog	Ground	−0.359	+	0.0340	+	0.00225	0.206	0.487	1%
	Air	−0.355	+	0.0523	+	0.0019	0.154	0.708	1%
Phragmites	Ground	−0.407	+	0.0237	+	0.00702	0.251	0.446	1%
	Air	−0.407	−	0.028	+	0.0072	0.160	0.648	1%

In the spring the bidirectional reflectance ratio for the ungrazed site increased towards a summer maximum, but the bidirectional reflectance ratio for the grazed site increased even faster. By May the bidirectional reflectance ratio was considerably higher for the grazed, rather than the ungrazed, pasture and yet the green biomass for the grazed pasture was 10 g/m^2, in comparison with 130 g/m^2 for the ungrazed pasture. By August the bidirectional reflectance ratio and green biomass were similar for the two pastures (Figure 7). It is assumed that the bidirectional reflectance ratio increase after grazing was primarily due to the very high productivity of the vegetation (Curran, 1980). The rate of productivity can be seen in the green biomass increase, which from April to August was 37.4 percent (between flights) for the grazed pasture, and only 9.5 percent (between flights) for the ungrazed pasture. This increased photosynthetic activity (and the absorbtion of red light) in the grazed pasture is thought to explain why the rapid increase in green biomass from April to August is accompanied by a high bidirectional reflectance ratio.

It is suggested that, although the current work on remote sensing of vegetation concentrates on the static relationship between green biomass and bidirectional reflectance, the relationship between a bidirectional reflectance ratio and green biomass is probably not static. If the canopy is undisturbed, any environmental influences that result in an increase in the rate of photosynthesis, and thereby productivity, will probably increase the bidirectional reflectance ratio regardless of the amount of green biomass present on the site. For further discussion refer to Curran (1980c).

Conclusions

Using bidirectional reflectance data derived photographically from 22 sets of near vertical aerial photography and 56 sets of oblique ground photography, it was determined that (1) the amount of bidirectional reflectance ratio variance accounted for by green biomass could be increased by around 6 percent with the addition of productivity, and (2), on a pasture site with low green biomass but high productivity, the bidirectional reflectance ratio was higher than for a high green biomass pasture site with lower productivity.

The influence of productivity on bidirectional canopy reflectance suggested in this paper has yet to be fully tested. If productivity can be proved to have an effect on the relationship between bidirectional reflectance and green biomass and its effect is ignored, then it will be difficult to determine whether a high bidirectional reflectance ratio indicates vegetation with a high green biomass or vegetation with a low green biomass and high productivity.

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