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Sensor Design for Monitoring Vegetation Canopies

Optimization of sensor wavelengths and bandwidths has been investigated based upon the analysis of *in situ* spectral reflectance data collected from experimental plots of blue grama grass.

ABSTRACT: *Optimization of sensor wavelengths and bandwidths has been investigated based upon the analysis of in situ spectral reflectance data collected from experimental plots of blue grama grass. Sensor characteristics have been simulated by integration of spectral data over the region from 0.350 to 1.000 μm. Subsequently, the integrated reflectance values were regressed against the canopy or plot variables (total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content) to determine the relative significance between integrated reflectance and the canopy variables for the various wavelengths and bandwidths simulated. Three spectral regions of strong statistical significance (0.35-0.50, 0.63-0.69, and 0.74-1.00 μm) were identified and found to be persistent both early and late in the growing season. In addition to quantifying the significance of various sensor wavelengths and bandwidths, the additive effects of adjacent spectral regions were also quantified. The results of this work enable quantitative judgments to be made regarding existing and hypothetical sensors and their effectiveness in monitoring green functioning vegetation.*

INTRODUCTION

DESCRIPTION OF RESEARCH UNDERTAKEN

THE RESEARCH was undertaken to evaluate various wavelengths and bandwidths, corresponding to simulated sensors, by integrating narrow bandwidth (0.005 μm) spectral reflectance curves of blue grama grass (*Bouteloua gracilis* (H.B.K.) Lag.) plots. Grass canopies were selected for detailed study because they are morphologically one of the least complex vegetation types. This reduced the variability inherent in the study and allowed for a more meaningful interpretation of the results.

Two data sets, one from June and one from September, were chosen for analysis (Table 1). The June data represented a less advanced phenological state when most of the standing vegetation was alive or green, whereas the September data represented a more advanced phenological state of approximately equal amounts of dry standing live

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and standing dead vegetation. The June data provided a much greater range of plot variables (total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content) which will enable the results of this analysis to be extended to other higher biomass ecosystems.

The data were obtained at the IBP Grassland Biome Pawnee Site on native shortgrass prairie at the Pawnee National Grassland, about 35 miles northeast of Fort Collins, Colorado. Field measurements were made in the Ecosystem Stress Area (ESA) on control, irrigated, and/or nitrogen fertilized plots.

Prairie vegetation is dominated by various species of grasses. One species, blue grama, comprises about 75 per cent of the dry weight of the gramineous vegetation at the Pawnee Site (Uresk, 1971). For this reason, plots of blue grama grass were selected for experimentation purposes.

In situ measurements of spectral reflectance were obtained with the field spectrometer laboratory designed and constructed for the IBP Grassland Biome Program to test the feasibility of spectro-optically measuring the aboveground plant biomass and plant cover (Miller *et al.*, 1976).

Simulation of sensors of different wavelengths and bandwidths was accomplished by integration of the narrow bandwidth spectral reflectance data. Subsequent regression analysis determined the degree of statistical significance, in coefficient of determination (r^2 values) terms, between the integrated reflectances and the plant canopy variable in question. The results of the regression analysis identified regions of high sensitivity and provided a quantitative basis for sensor design. The results clearly show that vegetational remote sensing can be improved in the future assuming, as we do, that grass canopy results are applicable to other vegetation types.

It should be noted that this research addresses only the target spectral factors affecting sensor selection for the $0.35 - 1.00\ \mu m$ region. The trade-offs between bandwidth, spatial resolution, signal/noise ratio, and atmospheric transmission were not considered as they apply to ground, aircraft, and satellite remote sensing of vegetation.

CANOPY PHYSIOLOGY AND REMOTE SENSING

The physiological factors affecting or actually determining reflectance from leaves have been the subject of recent research. Knipling (1970) and Woolley (1971) are excellent references concerning leaf morphology and physiology and the resulting spectral reflectance, transmission, and absorption. Hoffer and Johannsen (1969) have addressed the question of spectral signature analysis for vegetation monitoring. Gausman *et al.* (1973) have investigated biological criteria for sensor selection and found that the spectral wavelength intervals centered around 0.680, 0.850, 1.650, and 2.200 μm provide optimum discrimination of vegetation.

Colwell (1974) investigated grass canopy bidirectional spectral reflectance using computer modeling which was qualitatively validated by field experimental measurements. Interested readers are directed to this work for an excellent treatment of grass canopy bidirectional reflectance where different soil backgrounds, leaf area indices, percent vegetation covers, amounts of live and dead vegetation, solar zenith angles, look angles, and azimuth angles were considered for the wavelengths of 0.55, 0.65, and 0.75 μm (Colwell 1974).

The majority of basic research to date concerning plant physiology and resulting reflectance has been done with leaf spectra measured in the laboratory or with aircraft or spacecraft multispectral imagery of heterogenous vegetation scenes. Little *in situ* canopy spectral data have been collected, although the US/IBP Grassland Biome has collected approximately two thousand spectral curves of prairie scenes.

The results of Tucker (1975) and Tucker *et al.* (1975) report on two of the few ground-based studies of *in situ* measured canopy reflectance for which detailed information is available concerning the biophysical composition of the plant canopy.

Statistical analyses have identified five regions of the spectrum between 0.350 and 1.000 μm where different biological and/or physical processes result in different relationships between canopy reflectance and the amount of vegetation present (Figure 1). The five spectral regions described by Tucker (1975) where different relationships exist include:

(1) The 0.350 to 0.500 μm region (ultraviolet-blue), characterized by strong absorption by the carotenoids and chlorophylls and strong relations between spectral reflectance and the plot variables.

(2) The 0.500 to 0.600 μm region (green), characterized by a reduced level of pigment absorption and hence higher reflectance (the "green" color of healthy vegetation). This spectral region exhibits a weaker relationship between spectral reflectance and the

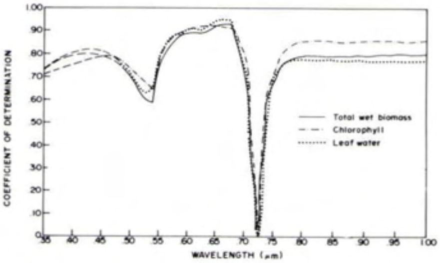

FIG. 1. Spectral coefficient of determination curves for total wet biomass, total chlorophyll, and leaf water content. Note the similarity among these three curves resulting from the regressions between the respective plot variables and spectral reflectance for 35 plots sampled in June 1972.

plot variables because of the reduced level of pigment absorption.

(3) The 0.600 to 0.700 μm region (orange-red), characterized by strong chlorophyll absorption and a strong relationship between spectral reflectance and the plot variables.

(4) The 0.700 to 0.740 μm region, a transition region between strong chlorophyll absorption in the far red and enhanced reflectance in the photographic infrared which exhibits weak relations between spectral reflectance and the plot variables.

(5) The 0.740 to 1.000 μm photographic infrared region, exhibiting high or enhanced reflectance and a strong relationship between spectral reflectance and the plot variables. The term "enhanced reflectance" is used to denote the higher levels of photographic infrared reflectance by healthy vegetation, which result from internal leaf scattering mechanisms in the absence of absorption. The canopy geometry also contributes to the enhancement of photographic infrared reflectance by inter-leaf scattering.

Thus the different relationships exist between spectral reflectance and the sampled plot or canopy variables depending upon the dominant physiological and physical processes in the various spectral regions. Regions of strong absorption can be represented by functions of the form

$$RFL_\lambda = A_\lambda . e^{\beta_{1\lambda} X_i} \tag{1}$$

where

RFL_λ = canopy reflectance at wavelength λ
A_λ = regression derived coefficient at wavelength λ *
e = Napier's number (i.e., ~2.71)
$\beta_{1\lambda}$ = regression derived estimate of β_1 at wavelength λ
X_i = canopy variable i (see Table 1)

or

$$RFL_\lambda = \beta_{0\lambda} + \beta_{1\lambda} X_i^{-1} \tag{2}$$

where

$\beta_{0\lambda}$ = regression derived estimate of β_0 at wavelength λ

The area of reduced absorptance in the green region of the spectrum exhibits some degree of absorptance, albeit to a lesser extent than adjacent regions. The relationship between reflectance and the plot variables can be approximated in this spectral region by either Equation 1 or Equation 2 depending upon the range of plot variable X_i (Tucker, 1975).

The transition from strong pigment absorption in the far red to strong reflection at the lower end of the photographic infrared results in weaker relations between spectral reflectance and the plot variables over this spectral region. Note from Figure 1 that the coefficient of determination approaches zero at the midpoint of the interval (0.72 μm). This effect could be caused by very similar soil and vegetation reflectance characteristics in this interval, i.e., the vegetation could have the same per unit reflectance contribution as the soil background. Thus, there would be little effective discrimination of functioning vegetation. Or because the previously mentioned change from strong absorption to enhanced reflection occurs over a small wavelength interval (~0.040 μm), the spectrometer may introduce a measurement error into this region because of slight wavelength calibration errors. A combination of the two hypotheses is the most logical proposition (Tucker, 1975).

Strong relationships were found between spectral reflectance and the plot variables in the photographic infrared region. The function which best approximated the relationship between spectral reflectance and the plot variables in this region was of two forms, depending upon the range of the plot variables in question:

$$RFL_\lambda = \beta_{0\lambda} + \beta_{1\lambda} X_i \tag{3}$$

and

$$RFL_\lambda = \hat{S}_\lambda(1-\exp(\beta_{0\lambda} + \beta_{1\lambda} X_i)) \tag{4}$$

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* Standard regression notation is used after Draper & Smith (1966).

where

$\hat{S}_\lambda$ = asymptotic reflectance at wavelength λ

Asymptotic spectral reflectance is reached by adding leaf layers or biomass until a stable (i.e., unchanging) reflectance is obtained (see also Gausman *et al.*, 1976; Tucker, 1976).

METHODS AND ANALYSIS

Several thousand curves of grassland vegetation have been collected in the field using the field spectrometer laboratory. A subset of this data base was selected for this experiment. It consisted of the spectral radiances and reflectances of circular 1/4 m^2 plots of blue grama measured in an irrigated area. Thirty-five plots were measured in June of 1972 and 40 in September of 1971.

Immediately after the reflectance measurements were completed, the plot was clipped of all standing vegetation. An aliquot was extracted for chlorophyll analysis and immediately quick-frozen on dry ice (Horwitz 1970). the clipped vegetation was put into a plastic bag, sealed, and placed in an icebox. When the clipped vegetation from four or five plots accumulated, it was transported to the Pawnee Site's laboratory building and stored in a refrigerator.

Laboratory technicians then began processing the clipped vegetation. The first determination made was the total wet biomass weight measurement. After this measurement was completed, the clipped vegetation was transferred to a paper bag and force-air dried at 50°C for 48 hours. Upon completion of the drying cycle, the total dry biomass weight measurement was made. The leaf water content was calculated as simply the difference between the total wet biomass and total dry biomass. The leaf water content represents the water present in the leaf and stem material.

The total dry biomass was then separated mechanically with manual finishing into green and brown fractions, and weighed (Van Wyk 1972). The chlorophyll content was determined for the representative 5 g aliquot after Horwitz (1970). This was then multiplied by the total wet biomass to yield the chlorophyll concentration in mg/m^2 units.

The total wet biomass, total dry biomass, leaf water content, dry green biomass, and dry brown biomass were all expressed in g/m^2 units (Table 1). Per unit area measurements such as the various biomass determinations, leaf water content, and total chlorophyll content will be used in describing the research results. Projected areas of these canopy variables will not be used although simple relationships exist between biomass and leaf area indices.

INTEGRATION OF NARROW BANDWIDTH SPECTRAL CURVES

The narrow bandwidth reflectance data (0.005 μm bandpass) were numerically integrated to approximate a variety of bandwidths. Reflectance values were used such that the results are implicit properties of vegetation.

The integration procedure was carried out in the following fashion:

$$RFL_\Lambda = \left(\sum_{I=1}^{n} RFL(\mathrm{I})^2 \, \Delta\lambda \right)^{1/2} \qquad (5)$$

where

RFL_Λ = reflectance in band from $\lambda(1)$ to $\lambda(n)$
$RFL(I)^2$ = square of reflectance at $\lambda(I)$
$\Delta\lambda$ = 0.005 μm

This method of integration was used to approximate the reflectance integral from the narrow bandwidth (0.005 μm) *in situ* spectral measurements.

Reflectance is a measure of the relative intensity with which electromagnetic waves will be reflected from a surface. The square of reflectance, therefore, is a measure of the relative amount of energy reflected from the surface. Since the sum of narrow bandwidth reflected energies must equal the energy which would be measured in a wide bandwidth system of equal total bandwidth, Equation 5 should provide a valid estimate of reflectance for the wide bandwidth system. This procedure is consistent with the well-known relationships for blackbody radiation and noise intensity, both of which show a linear variation of power or energy with bandwidth. This procedure does assume a constant surface impedance and noncoherent energy across the bands being integrated. The surface impedance probably is not constant, particularly for bandwidths which span from strong absorbing wavelengths to highly reflecting wavelengths, but for a first approximation the results should be reasonably valid. The assumption of noncoherence is certainly valid.

The results obtained with Equation 5 are consistent when the integrated reflectances are regressed against the plot variables and compared to the results of the narrow

TABLE 1. STATISTICAL SUMMARY OF THE BIOPHYSICAL CHARACTERISTICS OF THE SAMPLE PLOTS.
A STATISTICAL DESCRIPTION OF THE VEGETATIVE CANOPY CHARACTERISTICS FOR
(A) THE THIRTY-FIVE 1/4 M^2 SAMPLE PLOTS OF BLUE GRAMA SAMPLED IN JUNE 1972 AND
(B) THE FORTY 1/4 M^2 SAMPLE PLOTS OF BLUE GRAMA SAMPLED IN SEPTEMBER 1971.

Sample	Range	Mean	Standard deviation	Coefficient of variation	Standard error of the mean
		A. June 1972			
Wet total biomass (g/m^2)	52.00–1230.40	339.52	316.94	93.35	50.11
Dry total biomass (g/m^2)	13.04– 528.84	134.07	130.25	97.15	20.59
Dry green biomass (g/m^2)	12.48– 343.36	105.11	93.46	88.93	14.78
Dry brown biomass (g/m^2)	00.16– 185.48	28.96	40.23	138.91	6.36
Leaf water (g/m^2)	38.12– 701.56	205.46	187.83	91.42	29.70
Chlorophyll (mg/m^2)	62.27–2108.06	414.41	515.56	124.41	81.52
		B. September 1971			
Wet total biomass (g/m^2)	70.83– 491.22	261.31	134.40	51.44	21.25
Dry total biomass (g/m^2)	41.50– 337.84	168.55	90.81	53.88	14.36
Dry green biomass (g/m^2)	17.12– 185.04	89.38	50.15	56.11	7.93
Dry brown biomass (g/m^2)	20.40– 186.42	82.41	48.54	58.90	7.68
Leaf water (g/m^2)	28.03– 190.80	92.75	50.93	54.91	8.05
Chlorophyll (mg/m^2)	53.02– 778.97	319.58	238.73	74.70	37.75

bandwidth analyses. The integrated regressed values closely approximate the narrow bandwidth results.

The integrations were carried out in two modes:

(1) Initially the spectral region between 0.350 to 0.800 μm was divided up into 15, 9, 5, and finally 3 equal bandwidths. The spectral reflectances corresponding to each spectral curve were integrated according to Equation 5. Results were punched onto cards along with the six plot variables for subsequent regression screening. Regression screening denotes the use of an algorithm to screen various univarite combinations of variables (Frayer *et al.*, 1971).

(2) A particular bandwidth was positioned at a wavelength of interest; and (a) while holding the lower limit of the band constant, the upper limit was reduced by 0.010 μm steps. Each diminished bandwidth was integrated in the same manner. (b) Then the upper limit of the band was held constant and the lower limit was increased at 0.010 μm steps until the bandwidth was equal to or greater than 0.010 μm. Each interval was integrated and evaluated in an identical manner to (1) above.

REGRESSION SCREENING

Regression screening was used to evaluate the relationship between the various integrated reflectances and the plot variables in terms of coefficients of determination (r^2 values). This was advantageous because the computer program used (FSCREEN) calculates the various r^2 values and then outputs an ordered list of the r^2's (Frayer *et al.*, 1971). Because of the number of bandwidth intervals simulated, the FSCREEN approach allowed for a substantial savings in computer time.

The models given in Equations 1 and 2 were transformed from their original nonlinear form into linear models for regression screening purposes. In each case, the integrated reflectances were regressed against the various plot variables.

To facilitate comparisons between the June 1972 and the September 1971 statistics, the plot variables of total wet biomass, leaf water, and total chlorophyll content were used. Of these sampled variables, leaf water was used principally because it is indicative of the amount of the alive, green, and photosynthetically active biomass present (Tucker *et al.*, 1975).

EXPERIMENTAL RESULTS

EQUAL BANDWIDTH APPROACH

Coefficients of determination for the integrals for five equal bandwidth intervals within the 0.350 and 0.800 μm region were found to closely resemble the continuous narrow band r^2 plots (Figure 2). The same similarity was found when the region was divided into 15, 9, and 3 equal bandwidths (Tucker, 1975).

Figure 2 demonstrates the statistical similarity between the narrow bandwidth (0.005 μm) regression results and the much wider bandwidth results. In fact, it is obvious that integration of the coefficient of determination curves would have produced almost identical results. The only exception to this is seen for the fifth band (0.71 to 0.80 μm) on Figure 2 where the area for that band is larger than the area under the curve. This implies that the random error or noise in the 0.71 to 0.80 μm band did not appreciably degrade the strong infrared relationship between spectral reflectance and total wet biomass. When the interval was made wider (0.65 to 0.80 μm) and began to include more of the strong chlorophyll absorption region, as in the case of the three band simulation, a marked reduction in significance occurred.

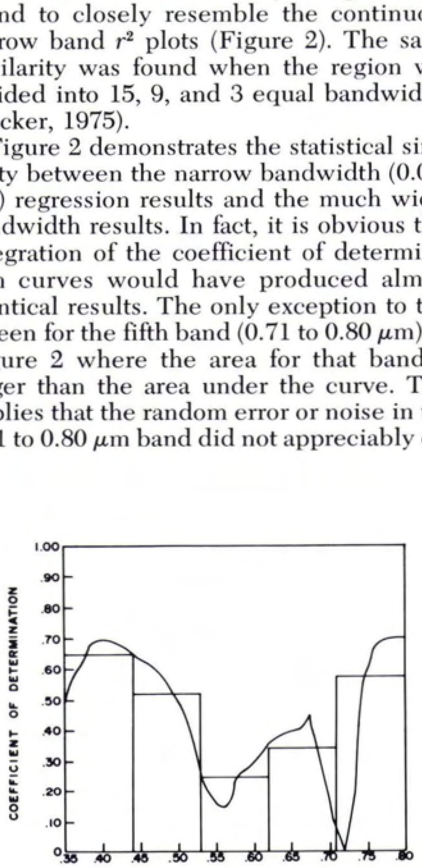

FIG. 2. Comparison between the continuous coefficient of determination curve (0.005 μm bandwidth) and the coefficients of determination resulting from dividing the 0.350 to 0.800 μm region into five equal bandwidth intervals for the September 1971 data. The continuous curve resulted from the series of regressions between spectral reflectance and total wet biomass at ninety-one 0.005 μm intervals. The histograms resulted from the five regressions between integrated reflectance and total wet biomass. Note how the five equal bandwidth intervals closely approximate the area under the continuous coefficient of determination curve.

DECREASING BANDWIDTH APPROACH

The following bands were selected for evaluation by this method:

(1) 0.37 to 0.55 μm (September data only),
(2) 0.50 to 0.68 μm (June and September data), and
(3) 0.60 to 0.78 μm (June and September data).

The spectral estimation of total wet biomass was investigated in the 0.37 to 0.55 μm band. The area of greatest significance was in the ultraviolet region as noted in Table 2. The strong ultraviolet-blue sensitivity which existed between the various plot variables and reflectance in this region has not previously been reported. The possibility that this region shows a strong sensitivity as the growing season wanes is of particular interest for the estimation of grass canopy biomass.

The 0.50 to 0.68 μm band includes the orange-red chlorophyll absorption region. Of particular interest here were the differences between the June and September data sets. Although the total bandwidth of 0.50 to 0.68 μm was the most significant for both data sets (Table 3), the June r^2 value of 0.88 was far greater than the September r^2 value of 0.56. The lowest June r^2 value, 0.65, was higher than the highest September value.

The spectral interval of 0.60 to 0.78 μm was considered in tripartite fashion:

(I) 0.60 to 0.72 μm: absorption + noise.
(II) 0.72 to 0.78 μm: noise + enhanced reflectance.
(III) 0.60 to 0.78 μm: absorption + noise + enhanced reflectance.

This was done to evaluate the effect(s) of pigment absorption, noise, and enhanced spectral reflectance and the combinations of these three effects taken together or two at a time.

One would expect a slight correlation degrading of situation (I) and (II) of the above due to the noise in the 0.70 to 0.74 μm region and a serious correlation degrading of situa-

TABLE 2. INTEGRATED SIMULATION RESULTS FOR THE 0.37 TO 0.55 μm INTERVAL REGRESSED AGAINST TOTAL WET BIOMASS. NOTE THE GREATER SIGNIFICANCE IN THE ULTRAVIOLET REGION. (A) 0.37 TO 0.55 μm; (B) 0.37 TO 0.55 μm. (EVERY OTHER LINE DELETED FOR BREVITY).

Rank	Ordered r^2's	Bandwidth (μm)	Rank	Ordered r^2's	Bandwidth (μm)
(A)	$y = ae^{bx}$		(B)	$y = ae^{bx}$	
1	0.69	0.370–0.420	1	0.52	0.370–0.550
3	0.68	0.370–0.430	3	0.51	0.390–0.550
5	0.66	0.370–0.470	5	0.48	0.410–0.550
7	0.65	0.370–0.460	7	0.46	0.430–0.550
9	0.65	0.370–0.450	9	0.44	0.450–0.550
11	0.64	0.370–0.500	11	0.41	0.470–0.550
13	0.61	0.370–0.520	13	0.35	0.490–0.550
15	0.55	0.370–0.540	15	0.27	0.510–0.550

TABLE 3. ORDERED COEFFICIENTS OF DETERMINATION VALUES RESULTING FROM THE REGRESSIONS BETWEEN INTEGRATED REFLECTANCE INTERVALS AND LEAF WATER CONTENT FOR THE 0.50 TO 0.68 μm REGION. (A) REPRESENTS THE RESULTS FROM THE THIRTY-FIVE PLOTS SAMPLED IN JUNE 1972 AND (B) REPRESENTS THE FORTY PLOTS SAMPLED IN SEPTEMBER 1971. NOTE THE SIMILAR ORDERINGS BETWEEN THE COEFFICIENTS OF DETERMINATION AND ASSOCIATED BANDWIDTHS FOR THESE TWO SAMPLE PERIODS. (EVERY OTHER LINE DELETED FOR BREVITY).

Rank	Ordered r^2's	Integral bandwidth (μm)	Rank	Ordered r^2's	Integral bandwidth (μm)
(A)	$y = a + b/x$		(B)	$y = ae^{bx}$	
1	0.88	0.500–0.680	1	0.56	0.500–0.680
3	0.86	0.500–0.660	3	0.51	0.500–0.660
5	0.85	0.500–0.650	5	0.46	0.500–0.640
7	0.84	0.500–0.620	7	0.43	0.500–0.630
9	0.81	0.500–0.600	9	0.39	0.500–0.550
11	0.76	0.500–0.580	11	0.37	0.500–0.620
13	0.70	0.500–0.560	13	0.35	0.500–0.590
15	0.65	0.500–0.540	15	0.33	0.500–0.570

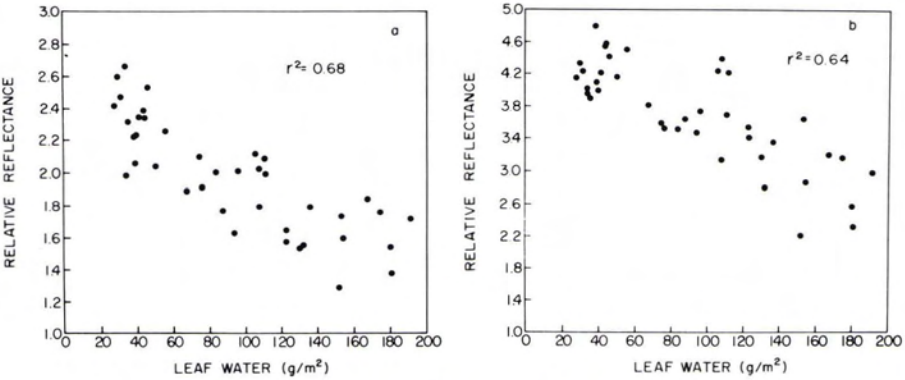

FIG. 3. Relative integrated reflectance plotted against leaf water content for the spectral intervals of (a) 0.37 to 0.50 μm and (b) 0.60 to 0.70 μm (ultraviolet-blue and orange-red absorption regions respectively). These data from the September sampling period indicate the inverse relationship between integrated reflectance and the leaf water content for these regions of strong pigment absorption. Relative reflectance is used because of the unit changes which resulted from integration by Equation 5.

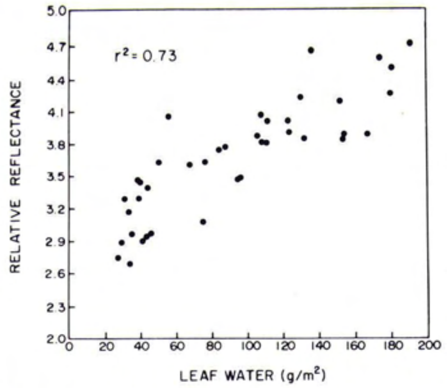

FIG. 4. Relative integrated reflectance plotted against leaf water content for the spectral interval of 0.75 to 0.78 μm (photographic infrared enhanced reflectance). These data from the September sampling period show the direct relationship between integrated reflectance and the leaf water content.

tion (III) resulting from the confounding interaction of pigment absorptance, noise, and enhanced spectral reflectance.

As the upper limit of 0.78 μm remains constant and the lower limit is increased from 0.60 μm toward 0.75 μm in 0.01 μm increments, a marked improvement in r^2 values occurred for both the June and September data sets (Table 4).

PRIMARY EFFECTS

Three primary effects were evident between 0.350 and 1.000 μm and were persistent for both data sets:

(1) Absorption by plant pigments which occurs in the 0.350 to 0.500 μm and 0.600 to 0.700 μm regions (Figure 3). The orange-red and ultraviolet-blue regions of the spectrum showed similar relationships between integrated reflectance and the plot variables. These results identified the greatest sensitivity to be in the 0.37 to 0.46 and 0.67 to 0.69 μm wavelengths, respectively.

There was a decrease in r^2 values in the orange-red region as the upper limit of integration decreased from 0.68 to 0.54 μm (Table 3). This is undoubtedly due to weaker absorption by the chlorophylls as the upper limit of integration moves away from 0.68 μm. This also indicates that the ~0.67 to 0.69 μm region is where maximum chlorophyll absorption occurs in the orange-red.

(2) The photographic infrared region (0.74 to 1.00 μm) showed the enhancement of spectral reflectance by the functioning vegetation present and the strong sensitivity which existed between the functioning biomass and the resulting spectral reflectance (Figure 4). Note the decrease in r^2 values as the lower limit of integration is decreased (Table 4). This is undoubtedly due to the inclusion of random effects (noise) in the 0.70 to 0.74 μm region and the absorption in the 0.60 to 0.68 μm region.

(3) The 0.70 to 0.74 μm portion of the spectrum demonstrated the random effects which occur in this transition region (Figure 5). The regression results from this spectral region indicated nonsignificance when integrated reflectances were regressed against the plot variables.

In addition to the 0.70 to 0.74 μm region of nonsignificance, the green region (0.50 to 0.60 μm) was found to not be significant for the September data set (Figure 5). As the

TABLE 4. ORDERED COEFFICIENTS OF DETERMINATION VALUES RESULTING FROM THE REGRESSIONS BETWEEN INTEGRATED REFLECTANCE INTERVALS AND LEAF WATER CONTENT FOR THE 0.60 TO 0.78 μm REGION. (A) REPRESENTS THE RESULTS FROM THE THIRTY-FIVE PLOTS SAMPLED IN JUNE 1972 AND (B) REPRESENTS THE FORTY PLOTS SAMPLED IN SEPTEMBER 1971. NOTE THE SIMILAR ORDERINGS BETWEEN THE COEFFICIENTS OF DETERMINATION AND ASSOCIATED BANDWIDTHS FOR THESE TWO SAMPLE PERIODS. (EVERY OTHER LINE DELETED FOR BREVITY).

Rank	Ordered r^2's	Integral bandwidth (μm)	Rank	Ordered r^2's	Integral bandwidth (μm)
(A)	$y = a + bx$		(B)	$y = a + bx$	
1	0.82	0.750–0.780	1	0.73	0.750–0.780
3	0.78	0.730–0.780	3	0.66	0.730–0.780
5	0.70	0.710–0.780	5	0.55	0.710–0.780
7	0.58	0.690–0.780	7	0.39	0.690–0.780
9	0.46	0.670–0.780	9	0.23	0.670–0.780
11	0.35	0.650–0.780	11	0.12	0.650–0.780
13	0.26	0.630–0.780	13	0.05	0.630–0.780
15	0.19	0.610–0.780	15	0.01	0.610–0.780

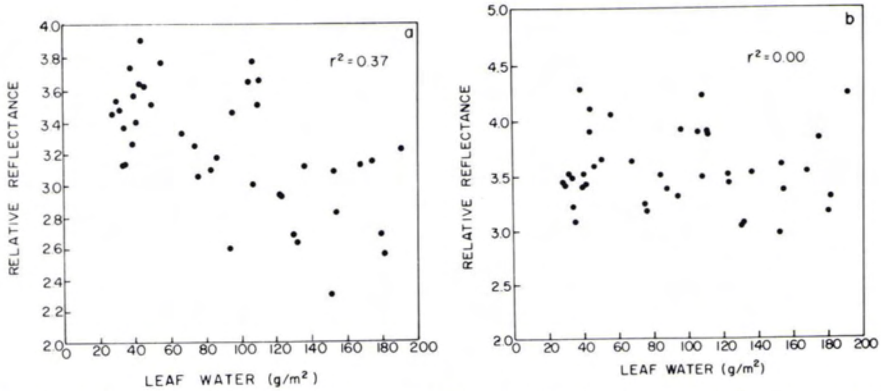

FIG. 5. Relative integrated reflectance plotted against leaf water content for the spectral intervals of (a) 0.50 to 0.60 μm and (b) 0.70 to 0.74 μm transition region. Note the lack of any apparent relationship between integrated reflectance and leaf water content for this wavelength interval for the September sampling period.

growing season wanes, the significance between integrated reflectance in the 0.50 to 0.60 μm region decreases.

COMBINATION OF TWO PRIMARY EFFECTS

The inclusion of the 0.50 to 0.60 μm and 0.70 to 0.74 μm regions (green and transition regions, respectively) of reduced significance with wavelengths showing strong pigment absorption (the 0.350 to 0.500 μm and 0.600 to 0.700 μm regions) demonstrated conclusively (Figure 6) the degrading effect of these regions. Furthermore, the integrals evaluated in Table 4 show the reduction in r^2 values which occur as proportionally more of the 0.70 to 0.74 μm region is included with the 0.74 to 0.78 μm spectral interval of enhanced reflectance. This is also evident when comparing Figures 4 and 7.

COMBINATION OF ALL THREE PRIMARY EFFECTS

Sensor bandwidths were also evaluated where the integrated reflectances encompassed areas of strong pigment absorption, lessened spectral sensitivity, and enhanced near infrared reflectance (0.60 – 0.78μm) (Table 4) (Figure 8). Results of these evaluations demonstrated conclusively that any

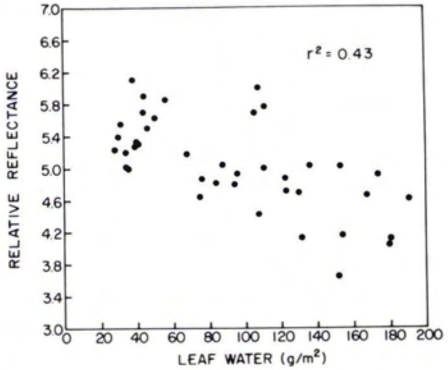

FIG. 6. Relative integrated reflectance plotted against leaf water content for the spectral interval of 0.60 to 0.74 μm. Note the degrading effect upon the relationship between integrated reflectance and leaf water content when the 0.70 to 0.74 μm region of reduced significance is included with the 0.60 to 0.70 μm region of strong absorption (see Figure 3). These data are from the September sampling period.

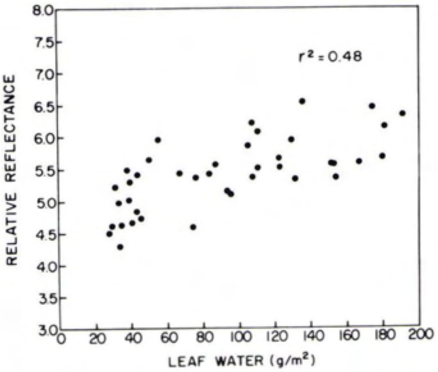

FIG. 7. Relative integrated reflectance plotted against leaf water content for the spectral interval of 0.70 to 0.78 μm. Note the degrading effect indicated by this plot when one compares this figure to Figure 4. The added variability is introduced by the inclusion of the 0.70 to 0.74 μm region into this interval. These data are from the September sampling period.

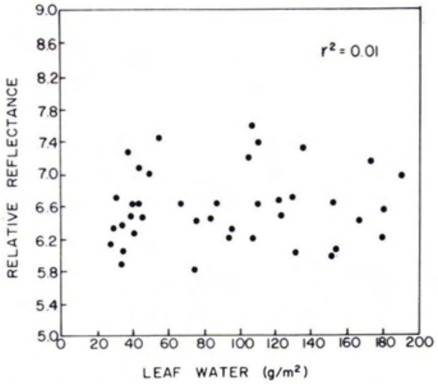

FIG. 8. Relative integrated reflectance plotted against leaf water content for the spectral interval of 0.60 to 0.78 μm. Note the confounding effect which results when a region of absorption, a region of reduced significance, and a region of enhanced reflectance are combined into the same spectral interval. Refer to figures 3, 4, and 5b for the three primary effects included in this figure. These data are from the September sampling period.

sensor bandwidth where absorption and enhanced reflectance both occur was extremely insensitive for spectrally estimating grass canopy vegetational status. Sensors such as this should most certainly be avoided.

INFLUENCE OF TIME OF SAMPLING DURING THE GROWING SEASON

The phenological influence can be inferred from comparisons between early in the growing season data (June) and late in the growing season data (September). The June data showed a higher degree of significance, and sensor wavelength and bandwidth characteristics were not crucial. The September data, however, indicated that as the growing season progresses and the transfer or conversion of live to dead standing vegetation occurs, a lower level of significance existed. Furthermore, sensor wavelength and bandwidth criteria were extremely important.

The September data represented a more complex interaction between incident spectral irradiance and the grass canopy because of the presence of more dead vegetation. The results of the more complex canopy state represented by the September data were therefore the most useful to develop optimum sensor wavelength and bandwidth criteria for remote sensing sensors.

EVALUATION OF LANDSAT CHANNELS

The seven LANDSAT sensors were evaluated by simulating the bandwidths of the various sensors. The utility of the seven LANDSAT Return Beam Vidicon (RBV) and Multi Spectral Scanner (MSS) channels ranged from excellent to poor in terms of optimal channel bandwidths for monitoring grass canopy vegetational status (Table 5). MSS bands 5 (0.60 to 0.70 μm) and 7 (0.80 to 1.10μm) and RBV band 2 (0.58 to 0.68 μm) are well situated to sense blue grama canopy radiances, which in turn were highly related biologically to the canopy vegetational status.

RBV band 1 encompasses the 0.50 to 0.56

TABLE 5. RBV AND MSS COEFFICIENTS OF DETERMINATION RESULTING BETWEEN THE REGRESSIONS OF INTEGRATED REFLECTANCE AND THREE PLOT VARIABLES FOR TWO SAMPLING PERIODS. THE JUNE DATA INCLUDED THIRTY-FIVE PLOTS AND WAS MEASURED FOR THE 0.50 TO 1.00 μm REGION; THE SEPTEMBER DATA INCLUDED FORTY PLOTS MEASURED FOR THE 0.35 TO 0.80 μm REGION.

		Highest r^2 values					
		June (n = 35)			September (n = 40)		
Channel	Bandwidth (μm)	Total wet biomass (g/m²)	Leaf water (g/m²)	Chlorophyll (mg/m²)	Total wet biomass (g/m²)	Leaf water (g/m²)	Chlorophyll (mg/m²)
RBV-1	0.475–0.575	0.72	0.76	0.77	0.32	0.42	0.25
RBV-2	0.580–0.680	0.88	0.91	0.91	0.38	0.62	0.32
RBV-3	0.690–0.800	0.68	0.68	0.68	0.49	0.44	0.41
RBV-4	0.500–0.600	0.77	0.81	0.82	0.26	0.37	0.21
MSS-5	0.600–0.700	0.88	0.91	0.91	0.39	0.65	0.33
MSS-6	0.700–0.800	0.72	0.72	0.71	0.54	0.51	0.45
MSS-7	0.800–1.100*	0.70	0.71	0.75	—	—	—

* The September data was not collected over this region. The June data was, but suffers from a progressively lower signal to noise ratio beyond −0.90 μm and thus is seriously degraded beyond −0.95 μm.

μm region of lessened significance and does not include enough of the blue region to be effective as the growing season wanes. RBV band 3 includes the 0.69 to 0.70 μm region of absorption by chlorophyll, the 0.70 to 0.74 μm region of noise, and the 0.74 to 0.80 μm region of enhanced reflectance. Thus RBV band 3 is degraded by some pigment absorption at its lower wavelengths and by the noise present in the 0.70 to 0.74 μm region.

MSS band 6 is redundant to band 7 and includes the noisy 0.70 to 0.74 μm region. Bands 5 and 7 are well situated for vegetational remote sensing of the blue grama canopy studied. Band 4, however, is placed over the 0.50 to 0.60 μm region of lessened statistical significance and what physiological information is sensed by this band is better sensed by band 5.

It should be noted that MSS 6 has been shown to be of greater utility than MSS 7 for monitoring rangelands by Rouse *et al.* (1974). This has been corroborated by Johnston (1976) for LANDSAT imagery of the Pawnee National Grassland, Colorado. In any event, MSS 6 does include the 0.70 to 0.74 μm transition region of noise and the information that is highly correlated to vegetational density or biomass for this sensor is received in the 0.74 to 0.80 μm region.

We thus feel that MSS 6 and MSS 7 are highly redundant in that the same vegetational information is equally as well sensed over the 0.74 − 1.30 μm. However, sensor detector sensitivities and atmospheric effects make direct comparisons between MSS 6 and MSS 7 difficult to draw.

SUMMARY AND CONCLUSIONS

(1) Simulation-integrations for various sensor wavelength and bandwidths for two sample periods, one early and one late in the growing season, indicated that greater spectral sensitivity existed earlier in the growing season between reflectance and the grass canopy variables.

(2) The spectral regions of 0.37 − 0.50, 0.63 − 0.69, and 0.75 − 0.80 μm were found to be statistically significant, in a regression sense, both early and late in the growing season.

(3) Inclusion of noisy bands (green and transition region) degrade sensor results and should be avoided to optimize vegetational remote sensing.

(4) Inclusion of a bandwidth where orange-red absorption and enhanced reflectance both occur result in a near total degrading of any spectral sensitivity and should be avoided.

(5) Sensor location and bandwidth criteria can be accurately approximated by integration of spectral coefficient of determination curves.

(6) LANDSAT MSS bands 5 and 7 and RBV band 2 are well situated for biological remote sensing.

(7) MSS band 6 is redundant to band 7 (biologically speaking) and is degraded by noise from the 0.70 to 0.74 μm region. However, actual MSS 7 performance may be degraded by sensor characteristics and/or atmospheric effects.

(8) RBV band 3 includes the 0.69 to 0.70 μm region of absorption, the 0.70 to 0.74 μm transition region of noise, and the 0.74 to 0.80 μm region of enhanced spectral reflectance and should be moved to a longer wavelength interval (say 0.75 to 0.85 μm) for better results.

(9) Remote sensing missions concerned with vegetation monitoring could increase the potential information content by including these criteria in system design.

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