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Resolution of Grass Canopy Biomass Classes

The photographic infrared region of 0.750 to 0.800 μm could be used to distinguish three classes or levels of total wet biomass.

ABSTRACT: *Analysis of variance methods have been applied to in situ grassland spectral reflectance data in order to determine the classes or levels of total wet biomass that can be resolved spectrally by a single narrow band measurement. The methodology involved the ground-truth clipping of 40 blue grama grass plots immediately following spectral reflectance measurements at 91 0.005 μm wavelength intervals over the spectral range from 0.350 to 0.800 μm. The 40 plots were measured for total wet biomass and then grouped into classes corresponding to divisions or treatments over the biomass range. The 91 one-way analyses of variance on the spectral reflectances associated with the plots were run at each of the 0.005 μm intervals between 0.350 and 0.800 μm for three, four, and five levels, classes, or treatments. Results indicated that three classes or levels of total wet biomass could be distinguished spectrally by a narrow band measurement. The photographic infrared region of 0.750-0.800 μm was the best spectral region to distinguish three classes or levels, and four or five classes or levels were found not to be spectrally distinguishable, particularly at higher biomass levels.*

INTRODUCTION

RECENTLY THERE HAS BEEN a great deal of interest in applications of remote sensing to resource problems. A portion of this effort has focused on spectral methods to estimate biomass, or the biological weight, of gramineous vegetation (Colwell, 1973; Pearson and Miller, 1973; Tucker *et al.*, 1975; Tucker and Miller, 1977).

Most of the work which has been done to date has simply developed the regression relationship(s) between spectral radiance or spectral reflectance and various plant canopy variables such as chlorophyll, total wet biomass, total dry biomass, leaf water content, and dry green or brown biomass.

In attempting to determine the degree to which classes of total wet biomass can be spectrally resolved by remote sensing techniques, one must refer to the nature of class, level, or treatment resolution in a grass canopy total wet biomass context. Resolution of total wet biomass classes concerns simply the number of wet weight classes of the plant material present on the grassland surface that can be distinguished.

The range scientist could use information about the total biomass available. It would not be necessary to describe very accurately the spatial distribution of this biomass in g/m^2 terms, but rather would be useful and certainly more practical to describe the spatial distribution of three or four biomass class-

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es ranging from low to high quantities.

Based upon the aformentioned biomass estimate, grazing strategies could be formulated to move the herbivores in question. Remote sensing offers the possibility of using spatial and spectral information from rangelands to estimate the amount of forage available. This paper addresses itself to the questions of which wavelengths or wavelength regions between 0.350 and 0.800 μm best distinguish between biomass classes and how many classes can be resolved.

Methods and Analysis

Study Location

The experiments were conducted on native shortgrass prairie at the IBP Grassland Biome Pawnee Site, the field research facility of the Natural Resource Ecology Laboratory, Colorado State University, located on the USDA Agricultural Research Service Central Plains Experimental Range about 55 kilometers northeast of Fort Collins, Colorado. Average annual precipitation of the area is about 31 cm with approximately 80 percent of the precipitation falling during the growing season from 1 May to 30 September. Annual wind velocity averages approximately 10 km/hr and the mean low and high temperatures during the growing season are 8° and 26°C with an average frost-free period of 135 days. 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 (*Bouteloua gracilis* (H.B.K.) Lag.), comprises about 75 percent 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 a field spectrometer laboratory that was designed and constructed for the IBP Grassland Biome Program in order to test the feasibility of spectro-optically measuring the aboveground plant biomass and plant cover (Miller *et al.*, 1976).

Data Used

Forty 1/4 m^2 plots of blue grama grass were sampled *in situ* by spectral radiometric measurement over the 0.350 to 0.800 μm region at every 0.005 μm interval with the mobile field spectrometer laboratory. All measurements were made normal to the ground surface in early September 1971.

Immediately after the reflectance measurements were completed, the plot was clipped of all standing vegetation. The clipped vegetation was put into a plastic bag, sealed, and placed in an icebox. When the clipped vegetation from four or five plots had accumulated, it was transported to the Pawnee Site's laboratory building and weighed (Table 1).

Per-unit area measurements such as total wet biomass will be used in describing the research results. Projected areas of this canopy variable will not be used although a simple relationship exists between total wet biomass and leaf area index. Resource managers of grasslands, for example, use g/m^2 and kg/ha to describe the spatial distribution of vegetation density. Because this effort is ultimately directed toward resource management of grasslands, the per-unit area terms will be used.

Biomass determinations were made on the fresh clipped vegetation and on the vegetation after it had been force-air dried, separated mechanically with manual finishing into green and brown fractions, and weighed (Van Wyk, 1972). The field experiments were not designed with an analysis of variance approach in mind, although the total wet biomass subset of the plot variables was suited to a one-way analysis of variance evaluation. Total wet biomass was selected for study because of the six plot variables (total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content), the number of total wet biomass values were more equally distributed among classes (Table 1).

Analysis of Variance Approach

Treatments, classes, or levels were defined by determining the range of the total wet biomass values and then dividing the range by the number of levels or classes in question (i.e., 3, 4, or 5). The total range of biomass values/number of classes ratio represented the biomass interval of each class and was done for three, four, and five levels, classes, or treatments (Table 1). The various treatments or classes show a varying degree of boundary effects (i.e., data values very close to adjacent treatments).

The spectral reflectance analysis was done by a computer program which accessed the spectral data files, associated the spectral reflectance curve with its respective total wet biomass value, sorted the associated data

TABLE 1. TOTAL WET BIOMASS LEVELS OR TREATMENTS FOR FORTY ¼ M^2 BLUE GRAMMA PLOTS AND ASSOCIATED SPECTRAL REFLECTANCES AT 0.465 μm. THE CLASS RANGES AND NUMBER OF PLOTS INCLUDED IN EACH CLASS ARE INCLUDED FOR THE THREE CLASSES EVALUATED.

		3 treatments			4 treatments			5 treatments		
Plot number	Reflectance at 0.465 μm (%)	Range (g/m^2)	Biomass values	No. in class	Range (g/m^2)	Biomass values	No. in class	Range (g/m^2)	Biomass values	No. in class
10025	7.80	(0.0)	70.80		(0.0)	70.80		(0.0)	70.80	
10024	7.68		73.60			73.60			73.60	
10027	8.23		78.40			78.40			78.40	5
10023	7.75		80.80			80.80			80.80	
10026	7.35		85.60			85.60	10	(100.0)	85.60	
10022	7.73		119.60			119.60			119.60	
10021	6.54		123.60	13		123.60			123.60	
10020	7.35		124.00			124.00			124.00	
10030	7.74		124.00			124.00			124.00	
10019	7.39		124.80		(125.0)	124.80			124.80	
10029	6.79		133.60			133.60			133.60	
10028	8.21		138.00			138.00			138.00	13
10018	7.64	(164.5)	155.20			155.20			155.20	
10017	6.67		174.40			174.40			174.40	
10036	6.52		178.40			178.40			178.40	
10032	6.51		183.60			183.60	11		183.60	
10015	7.13		188.40			188.40			188.40	
10031	6.18		198.80			198.80		(200.0)	198.80	
10043	6.67		226.00			226.00			226.00	
10014	6.32		232.00	12		232.00			232.00	
10039	5.71		248.00		(250.00)	248.00			248.00	4
10001	6.01		296.40			296.40		(300.0)	296.40	
10040	5.04		306.40			306.40			306.40	
10002	7.09		308.00			308.00			308.00	
10038	4.25	(329.0)	328.80			328.80	7		328.80	
10044	5.80		334.40			334.40			334.40	9
10042	5.98		360.00			360.00			360.00	
10041	5.21		368.00		(375.0)	368.00			368.00	
10003	5.26		378.80			378.80			378.80	
10010	6.76		378.80			378.80			378.80	
10008	5.62		393.60			393.60		(400.0)	393.60	
10009	6.69		404.80			404.80			404.80	
10035	4.61		407.20	15		407.20			407.20	
10033	6.02		427.60			427.60			427.60	
10006	5.46		436.40			436.40	12		436.40	
10034	4.10		437.20			437.20			437.20	9
10036	4.87		440.80			440.80			440.80	
10007	5.29		442.40			442.40			442.40	
10005	5.11		450.00			450.00			450.00	
10004	5.96	(492.5)	491.20		(500.0)	491.20		(500.0)	491.20	

first by wavelength and then by total wet biomass values, and then computed the spectral reflectance one-way analysis of variance (AOV) at each of the 91 0.005 μm wavelength intervals between 0.350 and 0.800 μm.

The results at each wavelength interval were displayed in a tabular fashion (Table 2) and the treatment means ± Tukey's Q/2 were plotted on microfilm (Figure 1). Tukey's Q, a studentized multiple range test, was used to detect where significant differences, due to treatments or classes (i.e., divisions or total wet biomass), lay (Snedecor and Cochran, 1967). Tukey's Q is calculated as follows:

$$Q = q(a, Edf) * \mathrm{SQRT}(EMS/\tilde{n})$$

where a =number of treatments
Edf =error degrees of freedom
$q(a, Edf)$ =look up value (Snedecor and Cochran, 1967, p. 568)
EMS =error mean square
$\tilde{n}$ =harmonic mean or $\dfrac{a}{\frac{1}{n_1} + \frac{1}{n_2} + \cdots + \frac{1}{n_a}}$

TABLE 2. SPECTRAL REFLECTANCE ANALYSIS OF VARIANCE TABULAR OUTPUT AT 0.465 μm FOR THREE CLASSES OF TOTAL WET BIOMASS. THE DATA WERE ORIGINALLY ORDERED BY TOTAL WET BIOMASS AND ASSOCIATED SPECTRAL REFLECTANCE VALUES. THE ASSOCIATED SPECTRAL REFLECTANCE VALUES WERE THEN USED FOR THE SPECTRAL ANALYSIS OF VARIANCE. REFER TO FIGURE 1 FOR GRAPHICAL OUTPUT AT THIS WAVELENGTH

Wavelength = 0.465 μm					
Number of Treatments = 3					
Treatment Group		1		2	3
Sample Size		13		12	15
Mean Reflectance (%)		7.55		6.17	5.51
Standard Deviation		0.48		0.83	0.72
Analysis of Variance:	Sum of Sq.	DF	Mean Sq.	F Ratio	P(F > Comp. F)
Between Treatments	29.61	2	14.80	30.72	0.000
Error	17.83	37	0.48		
Total	47.44	39			

with n_i =number of observations in treatment i.

Tukey's Q is a method for testing some or all of the differences between pairs of treatment, class, or level means. The probability that no erroneous claim(s) of significance will be made is ≥0.95 (Snedecor and Cochran, 1967). Referring to Figure 1, for example, we see that the three total wet biomass treatments' or classes' associated reflectance means have been plotted. Tukey's Q has been overplotted to bracket each mean, with $Q/2$ added to and subtracted from each treatment mean. Inspection of Figure 1 indicates that the reflectance mean at 0.465 μm associated with treatment 1 (0.0 to 164.5 g/m^2) is significantly different from treatment 2 (164.5 to 329.0 g/m^2) and also from treatment 3 (329.0 to 492.5 g/m^2) because the plotted brackets (Tukey's Q) do not overlap in the χ dimension. Treatments 2 (164.5 to 329.0 g/m^2) and 3 (329.0 to 492.5 g/m^2) overlap slightly. One should infer that treatments 1 and 2 and 1 and 3 can be distinguished on the basis of their reflectances at 0.465 μm with a probability of ≥0.95. Treatments 2 and 3, however, overlap slightly and could be distinguished from one another for the probability of ≥0.95.

This method of visual inspection will be used to analyze the results of this experiment and relate them to spectral reflectance properties of vegetation canopies. It should also be noted that the words treatments, classes, and levels will be used interchangeably. The more common analysis of variance term is "treatment" although this paper addresses the number of total wet biomass "classes" or "levels" which can be distin-

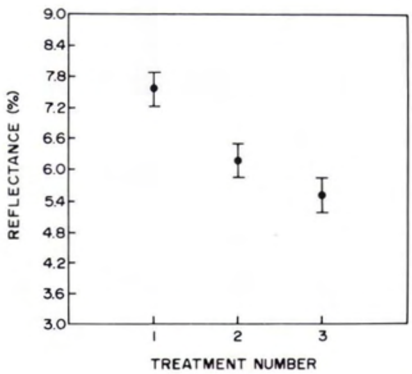

FIG. 1. Spectral reflectance analysis of variance output ploted at 0.465 μm for three total wet biomass classes or treatments. Treatment number 1 = 0.0–164.5 g/m^2, 2 = 164.5–329.0 g/m^2, and 3 = 329.0–492.5 g/m^2. The brackets around each mean represent Tukey's Q. Refer to Table 2 for the tubular output at this wavelength.

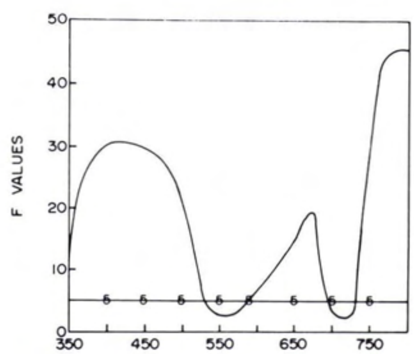

FIG. 2. F values plotted as a function of wavelength for the 91 intervals between 0.350 and 0.800 μm for three total wet biomass classes. The -5- line represents the 0.5% level of significance.

guished from spectral reflectances.

Experimental Results

The analysis was completed for three, four, and five treatments, classes, or levels of total wet biomass by using the associated spectral reflectances. Analyses of variance were calculated at 91 0.005 μm intervals between 0.350 and 0.800 μm. At the conclusion of the 91 separate analyses of variance, corresponding to wavelength intervals, the *F* values were plotted as a function of wavelength (Figure 2). The *F* values, a common statistical indication of significance, were used for the selection of individual wave lengths for more detailed discussion.

The results presented in Figure 2 and the corresponding plot for four and five treatments of total wet biomass were very similar in character but slightly different in magnitude. For this reason, only the *F* values plotted vs. wavelength for three treatments will be presented.

Six wavelength intervals were selected from inspection of Figure 2. These included 0.385, 0.465, 0.550, 0.675, 0.720, and 0.765 μm (Figure 3). The criteria used was to select maxima and minima at several wavelengths between 0.350 and 0.800 μm.

The various wavelengths selected correspond to regions of the spectrum where different physiological or physical processes predominate and thus determine the spectral response of the canopy.

- The near ultraviolet wavelength of 0.385 μm and the 0.465 μm blue wavelength both show the effect of carotenoid and chlorophyll absorption.
- The 0.550 μm green wavelength shows the effect of reduced chlorophyll absorption in this region of the spectrum.
- The red interval of 0.675 μm was selected because this wavelength corresponds to the red region of maximum chlorophyll a and chlorophyll b absorption.
- The region of 0.720 μm was selected because it is a region of transition between strong chlorophyll absorption in the red and enhanced spectral reflectance in the photographic infrared.
- The photographic infrared wavelength of 0.765 μm was selected to represent this region of enhanced spectral reflectance.

In order to avoid an imbalance between figures and text, only the wavelengths of 0.465, 0.720, and 0.765 μm will be presented for four and five treatments or classes (Figures 4 and 5).

Interpretation and Discussion

The interpretation of the results is best accomplished by inspection of Figures 3, 4, and 5. Regardless of the number of biomass classes evaluated (three, four, or five), the trends between spectral reflectance and total wet biomass were the same. The three total wet biomass classes or levels analysis will be examined in detail to explore the relationships involved.

(1) The region of 0.350 to 0.440 μm demonstrated the strong inverse relationships between spectral reflectance in this region and total wet biomass (Figure 3a). The physiological basis for this inverse relationship is the strong chlorophyll and carotenoid absorption which occurs in this region of the spectrum. The spectral absorption is quite strong, giving very low values for the spectral reflectances. There was, however, sufficient contrast between the spectral reflectances in this region associated with total wet biomasses and the dry soil background to result in separation between treatments 1 (0.0 to 164.5 g/m^2) and 2 (164.5 to 329.0 g/m^2) and treatments 1 (0.0 to 164.5 g/m^2) and 3 (329.0 to 492.5 g/m^2). Treatment 2 (164.5 to 329.0 g/m^2) and 3 (329.0 to 492.5 g/m^2) overlapped slightly and thus could not be completely separated by using their associated reflectances at 0.385 μm.

(2) The 0.45 to 0.50 μm region, represented by the interval of 0.465 μm in Figure 3b, is somewhat similar to the 0.35 to 0.44 μm region. A strong inverse relationship also exists between spectral reflectance in this region and total wet biomass. This is due to pigment absorption by the chlorophylls and carotenoids. Absorption at 0.465 μm is predominantly due to the chlorophylls and to a lesser extent to the carotenoids. Less absorption occurs at 0.465 μm than at 0.385 μm, which results in higher levels of reflectance at 0.465 μm than at 0.385 μm. The three classes, levels, or treatments of total wet biomass (0.0 to 164.5 g/m^2, 164.5 to 329.0 g/m^2, and 329.0 to 492.5 g/m^2) can be separated from each other at this wavelength. Treatments 1 and 2 are widely separated using their associated reflectances at 0.465 μm while treatments 2 and 3 are separable using their respective reflectances at this wavelength.

(3) The separation of three levels, classes, or treatments of total wet biomass by using their associated reflectances at 0.550 μm is not possible (Figure 3c). In fact, there is so much overlap between the reflectances associated with the three levels of total wet

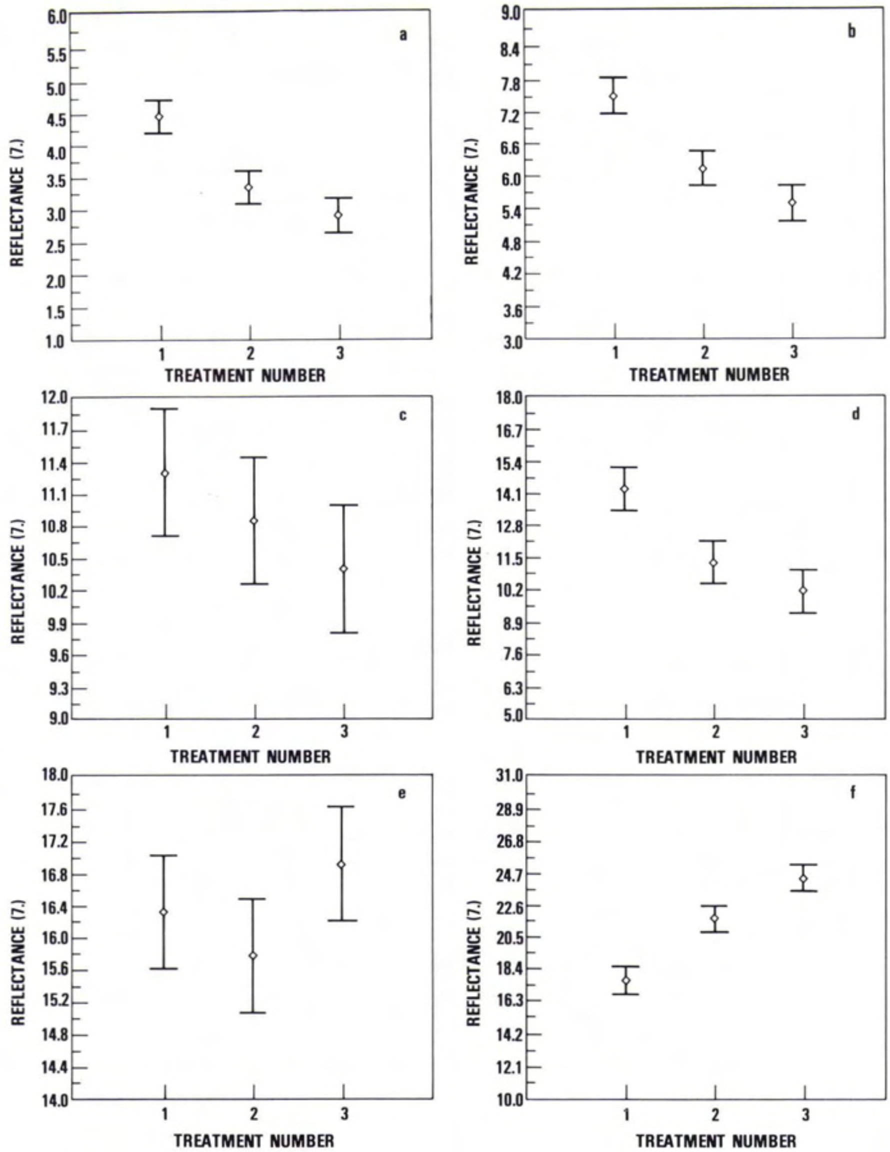

FIG. 3. Treatment means for the spectral reflectances associated with the total wet biomass values for three treatments or classes at six wavelength intervals of interest: (a) 0.385 μm, (b) 0.465 μm, (c) 0.550 μm, (d) 0.675 μm, (e) 0.720 μm, and (f) 0.765 μm. Treatment number 1 = 0.0–164.5 g/m², 2 = 164.5–329.0 g/m², and 3 = 329.0–492.5 g/m². The brackets around each mean represent Tukey's Q.

biomass that class or treatment 1 (0.0 to 164.5 g/m²) cannot be spectrally separated from treatment 3 (329.0 to 492.5 g/m²). We can conclude from Figure 3c that none of the differences between pairs of treatments, classes, or levels are significant at this wavelength. Thus the green region of the spectrum is a poor region to resolve or discriminate levels or classes of total wet biomass using the associated reflectances from this region.

There exists a perceptual chauvinism which assumes that the green region of the spectrum contains very valuable information about vegetation. This may be true to some extent, but the adjacent blue and red regions of the spectrum contain more valuable and direct information about vegetation than the green region. This can be attributed physiologically to reduced pigment absorptance in the green region of the spectrum. Reduced absorption in this region re-

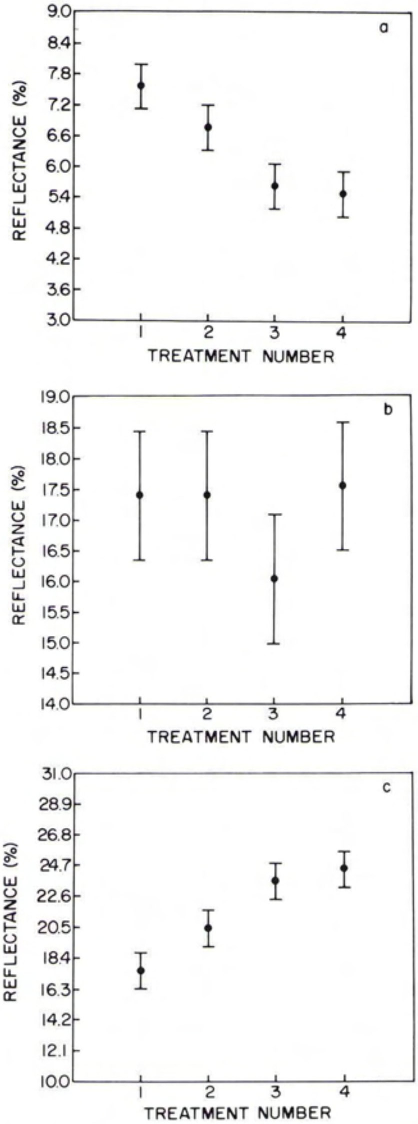

FIG. 4. Treatment means for the spectral reflectances associated witht he total wet biomass values for four treatments or classes at three wavelength intervals of interest: (a) 0.465 μm, (b) 0.720 μm, and (c) 0.765 μm. Treatment number 1 = 0.0–125.0 g/m^2, 2 = 125.0–250.0 g/m^2, 3 = 250.0–375.0 g/m^2, and 4 = 375.0–500.0 g/m^2. The brackets around each mean represent Tukey's Q.

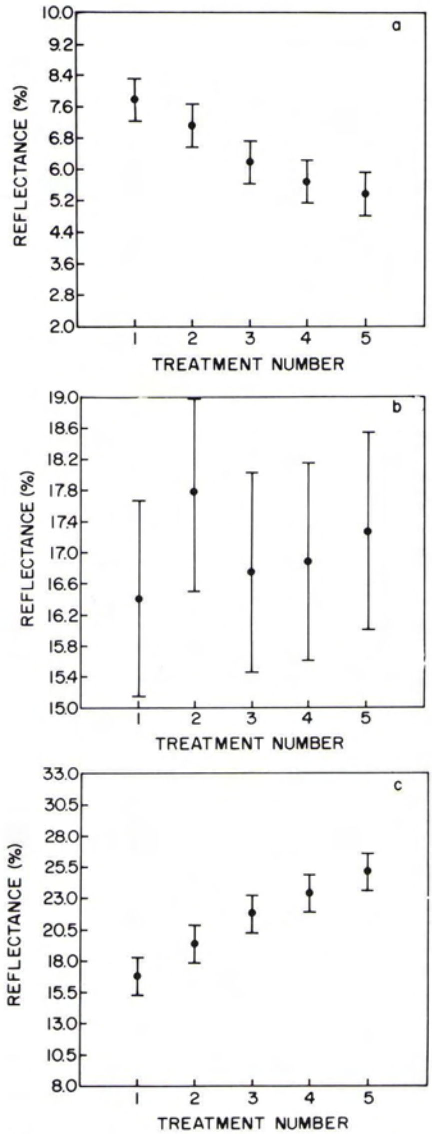

FIG. 5. Treatment means for the spectral reflectances associated with the total wet biomass values for five treatments or classes at three wavelength intervals of interest: (a) 0.465 μm, (b) 0.720 μm, and (c) 0.765 μm. Treatment number 1 = 0.0–100.0 g/m^2, 2 = 100.0–200.0 g/m^2, 3 = 200.0–300.0 g/m^2, 4 = 300.0–400.0 g/m^2, and 5 = 400.0–500.0 g/m^2. The brackets around each mean represent Tukey's Q.

sults in higher levels of reflectance and hence the "green" color of healthy vegetation. Reduced absorption in the green region of the spectrum also means that there is less of a dry soil-vegetation contrast in terms of reflectance in this region. Hence the green region is not a good choice for a spectral region of promise in discriminating levels or classes of total wet biomass. (Refer also to Tucker and Miller, 1977 for a discussion of soil-vegetation contrast(s)).

(4) The wavelength interval of 0.675 μm in the red region of the spectrum exhibits the improvement in reflectance discrimination of total wet biomass classes over the 0.550 μm interval (Figure 3c vs. Figure 3d).

Chlorophyll a and b are at a red region *in vivo* absorptance maxima at ~0.67 to 0.68 μm. Thus, an inverse relationship would be expected between the reflectance at 0.675 μm and total wet biomass. In addition, strong pigment absorption in this spectral region would result in an excellent dry soil-green vegetation reflectance contrast. This in turn would suggest the utility of the 0.675 μm wavelength for total wet biomass reflectance discrimination.

Inspection of Figure 4d indicates that class or treatment 1 (0.0 to 164.5 g/m^2) is separated from treatments 2 (164.5 to 329.0 g/m^2) and 3 (329.0 to 492.5 g/m^2) when using the associated reflectances at 0.675 μm. Treatments 2 (164.5 to 329.0 g/m^2) and 3 (329.0 to 429.5 g/m^2) overlap slightly when using their associated reflectances at this wavelength. Comparing 0.465 and 0.675 μm (Figures 3b and 3d, respectively), we see that 0.465 μm affords better spectral resolution of three classes or treatments of total wet biomass than does 0.675 μm. This results from the fact that there was an approximately equal amount of live and dead vegetation in the canopy. The presence of the dead vegetation degrades the statistical relationships between total wet biomass and reflectance more at 0.675 μm than at 0.465 μm. This phenomena is examined at length in Tucker (1977) for the same data set.

(5) The 0.70 to 0.74 μm region of the spectrum demonstrates the lack of a relationship between spectral reflectance and total wet biomass (Figure 3e). This results from the dry soil background having approximately the same per-unit area reflectance as the vegetation canopy. Therefore it is impossible to distinguish dry soil from amounts of total wet biomass when using reflectance data from this spectral region.

(6) The photographic infrared region of 0.75 to 0.80 μm, however, was well suited for the resolution of total wet biomass classes using their associated reflectances at 0.765 μm (Figure 3f). The direct relationship between biomass and reflectance at this wavelength resulted in all classes or treatments being separated from each of the other two classes. There was no overlap between any adjacent classes or treatments, and 0.765 μm was clearly superior to any of the other five wavelengths examined in Figure 3.

It would be impractical to discuss each of the six wavelengths presented in Figure 3 for four and five classes, levels, or treatments of total wet biomass. Instead, the wavelengths of 0.465, 0.720, and 0.765 μm will be presented and discussed for four and five classes, levels, or treatments of total wet biomass.

The results for four and five classes or levels of total wet biomass showed the lack of separation at higher levels of total wet biomass (Figures 4 and 5). Five levels or classes were clearly not separable when using the associated spectral reflectances (Figure 5). Even the 0.765 μm wavelength would not separate any one class or level from an adjacent one for the five classes, levels, or treatments analysis.

Four classes, however, show somewhat more promise (Figure 4). The 0.765 μm interval demonstrated the greatest utility for resolving classes of total wet biomass by their associated reflectances at this wavelength. Four classes could not be resolved from reflectances, but the first three total wet biomass classes could. Class or treatment 1 (0.0 to 125.0 g/m^2) can be distinguished from class 2 (125.0 to 250.0 g/m^2), class 3 (250.0 to 375.0 g/m^2), and class 4 (375.0 to 500.0 g/m^2). Class or treatment 2 (125.0 to 250.0 g/m^2) can be distinguished from 1 (0.0 to 125.0 g/m^2), 3 (250.0 to 375.0 g/m^2), and 4 (375.0 to 500.0 g/m^2). Class 3 (250.0 to 375.0 g/m^2) but could from classes 1 (0.0 to 125.0 g/m^2) and 2 (125.0 to 250.0 g/m^2).

The most promising inference is that three levels of total wet biomass can be distinguished at 0.765 μm. The three classes would be class 1 (0.0 to 125.0 g/m^2), class 2 (125.0 to 250.0 g/m^2), and class 3 (250.0 to 500.0 g/m^2). Class 3 is in actuality class 3 combined with class 4.

Conclusions and Summary

(1) Analysis of variance indicates that three classes of total wet biomass could be distinguished from their associated spectral reflectances from single narrow band measurements of *in situ* plots.

(2) Four and five total wet biomass classes were not spectrally resolved at higher amounts of total wet biomass when analyzed by these methods.

(3) The photographic infrared region was the best narrow band spectral region to discriminate levels or classes of total wet biomass.

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