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Shortgrass Prairie Spectral Measurements

Statistical analyses of spectral measurement data were used to determine those spectral regions which could be used to identify green biomass, chlorophyll concentration, and leaf water content.

Introduction

K NOWLEDGE OF THE MANNER IN WHICH SOLAR energy interacts with grassland vegetation is necessary in order to interpret remote sensing data from this ecological zone which comprises one-sixth of the world's land area. Grassland vegetation is dominated by various species of grasses which serve as the main state variable for solar energy flow into

craft, and spacecraft could supply the necessary inputs to the biosystem models for estimating the primary productivity and hence determine the state variables of this ecosystem.

Traditional methods for estimating the productivity of rangelands do not lend themselves to application over large geographical areas on a timely basis. These methods in-

ABSTRACT: *Statistical analysis of in situ spectroreflectance data from sample plots of the shortgrass prairie indicates that green biomass, chlorophyll concentration, and leaf water content are directly interrelated to that composite property of the plot called the "functioning green biomass." Correlations between the reflectance and these three measures of the functioning vegetation have been calculated at 91 wavelength intervals of 0.005 µm between 0.350 and 0.800 µm by using computer analysis. These spectrocorrelation results show the spectral regions of the optimum sensitivity for remotely estimating the green biomass, chlorophyll, and leaf water of a prairie surface and substantiate the direct interrelationship betwuen these parameters. Comparisons between spectrocorrelation curves from two sampling periods in the growing season identifying regions of the spectrum between 0.350 and 0.800 µm that are relatively unaffected by increasing amounts of standing dead vegetation and continue to show strong consistent correlations to the amount of functioning green biomass.*

higher trophic levels of this ecosystem. Knowledge of the spatial and temporal status of rangeland vegetation could be used as the basis for more efficient management

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volve the measurement of herbage biomass by several ground sampling techniques. The schemes with the use of biosystem models. Remotely sensed data from the ground, airtechniques most commonly used involve the hand clipping of a known area of vegetation and weighing of the resulting sample. The usefulness of clipping as a sampling method is limited by two characteristics. First, it is a

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slow, tedious, and time-consuming operation. Second, clipping is a destructive sampling procedure which precludes sampling the plot on a repetitive basis.

Several nondestructive sampling methods include the ocular estimation procedure (Pechanec and Pickford 1937), the point quadrant method (Warren-Wilson 1963), the capacitance meter (Van Dyne et al., 1968), the β-attenuation technique (Mitchell 1972), and recently reported spectral methods (Pearson and Miller 1972). The spectral methods of vegetation analysis not only measure herbage biomass on a nondestructive basis but also can be adapted to aircraft and satellite devices to map the spatial distribution over an area in an efficient and economical fashion. The periodic remote sensing measurements of this rangeland vegetation parameter can serve as primary input to management models which truly represents the real, distributed grassland ecosystem. It is difficult to imagine that the necessary spatial information can be measured by the other means noted earlier on a timely basis. This paper reviews the ground based *in situ* field spectrometry in the 0.350 to 0.800 μm region of the spectrum which has been used to develop this approach. The application of the method with ground, aircraft, or satellite-based remote sensors for the spectral measurement of the amount and status of the functioning green biomass in a prairie ecosystem will be reviewed in a subsequent paper.

Materials, Methods, and Equipment

The experimental results reported herein 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. Average annual precipitation of the area is about 31 cm with approximately 80 percent of the precipitation falling during the growing season from May 1 to September 30. Annual wind velocity averages approximately 10 kilometers per hour 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 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 spectroreflectance 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 (Pearson et al., 1975).

Several thousand curves of grassland vegetation have been collected in the field using the field spectrometer laboratory (Tucker et al., in prep.). A subset of this data base was selected for this experiment. It consisted of the spectroradiance and spectroereflectance of circular 1/4 m² plots of blue grama measured in an irrigated area. Twenty-four plots were measured in July and 40 in September of 1971. The vegetation on each plot was clipped *immediately* after the spectroradiometrical measurements. An aliquot was extracted for chlorophyll analysis and immediately quick frozen in the field in dry ice (Horwitz 1970). Biomass determinations were made on the fresh clipped vegetation and on the vegetation after it had been forced-air dried, separated mechanically with manual finishing into green and brown fractions, and weighed (Van Wyk 1972). The vegetational characteristics of the plots were stored on punched cards for subsequent use (Table 1).

The spectral curves were converted from punched paper tape to magnetic tape for analysis on the University's CDC 6400 computer. A computer program associated the spectroreflectance data file with the respective hand sampled plot parameters, sorted the spectroreflectance data by wavelength, and computed the regressions at each of the 91 0.005 μm wavelength intervals between 0.350 and 0.800 μm, regressing the reflectances against each plot parameter in question.

Two regression models were used to approximate the functional relationship between canopy reflectance and the plot parameters sampled. Equation 1 represents a linear model while Equation 2 is a nonlinear model similar to the Beer-Lambert law, and is applicable for regions of spectroabsorption.

$$\text{Reflectance}_\lambda = A_\lambda + B_\lambda(\text{Plot Parameter}) \qquad (1)$$

$$\text{Reflectance} = A_\lambda e^{B_\lambda(\text{Plot Parameter})} \qquad (2)$$

Both regression models were evaluated for each of the 91 0.005 μm intervals. Regression results at each wavelength were very similar although the linear model statistics were slightly more significant than the exponential

TABLE 1.   A STATISTICAL DESCRIPTION OF THE VEGETATIVE CHARACTERISTICS OF THE 40 ¼ m² SAMPLE PLOTS OF BLUE GRAMA SAMPLED IN EARLY SEPTEMBER, 1971 AND USED IN CONSTRUCTING FIG. 1 THROUGH 7.

Sample	Range	Mean	SD	Coef. of Variation	SE of the Mean
Wet total biomass (g/m²)	70.83– 491.22	261.31	134.40	51.44	21.25
Dry total biomass (g/m²)	41.50– 337.84	168.55	90.81	53.88	14.36
Dry green biomass (g/m²)	17.12– 185.04	89.38	50.15	56.11	7.93
Dry brown biomass (g/m²)	20.40– 186.42	82.41	48.54	58.90	7.68
Leaf water (g/m²)	28.03– 190.80	92.75	50.93	54.91	8.05
Chlorophyll (mg/m²)	53.02– 737.00	319.58	238.73	74.70	37.75

model at each wavelength. This implies that for the range of plot parameters sampled in this experiment, the functional relationship between canopy reflectance and the plot parameters can be approximated by the linear model. Greater vegetation density, such as a mid-grass or tall-grass prairie, would require a non-linear model. The regression statistics referred to in the balance of this report resulted from the use of the linear model.

The results of the regressions and the data point scatter at each 0.005 μm wavelength interval are displayed in a tabular fashion and as a microfilm plot (Figure 1). At the conclusion of computing each of the 91 individual spectral relations, the simple, linear correlation values are plotted on microfilm as a spectrocorrelation curve (Figure 2). This curve shows at a glance the sensitivity of the spectroreflectance to the hand sampled plot parameter in terms of correlation values. Spectrocorrelation curves have been determined for dry green biomass, dry brown biomass, chlorophyll, and leaf water.

RESULTS AND DISCUSSION

Strong correlation between spectroreflectance and green biomass occurs in two pigment absorption bands of the visible spectrum and in the photoinfrared region of the spectrum (Figure 2). Spectrocorrelation results for green biomass are based upon the chlorophyll content, the internal structure of the leaves, and the geometrical arrangement of the plant canopy. The relationship between green biomass and chlorophyll was expected because chlorophyll is largely responsible for the "green" color of green biomass. The physiological basis for a high negative spectrocorrelation in the visible region (Figure 2) is due to the absorption of
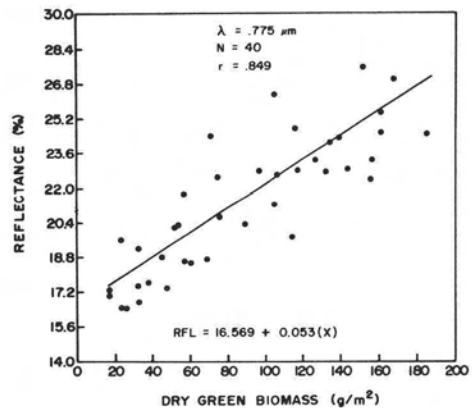

FIG. 1. Simple linear regression of the reflectance at 0.775 μm (0.005 μm spectral bandwidth) against the dry green biomass clipped from 40 ¼ m² *in situ* sample plots of blue grama.
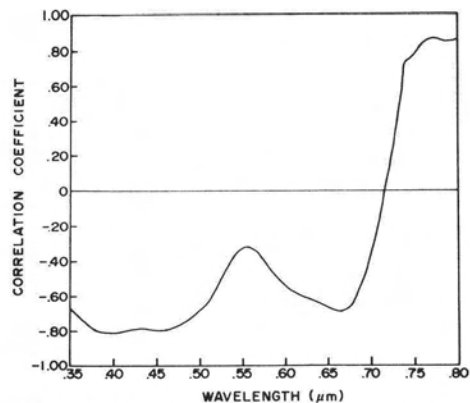

FIG. 2. Simple linear spectrocorrelation curve for dry green biomass constructed by plotting the correlation coefficients (R values) between reflectance and dry green biomass for each of the 91 wavelength intervals.

solar irradiance by plant pigments, predominantly the chlorophylls in the plant canopy (Knipling 1970). This effect is amplified by the geometric layering characteristics of the plant canopy (Woolley 1971). The exact relationship in the field situation between green biomass, chlorophyll, and leaf water, however, was not fully understood prior to this experiment.

Functioning green vegetation maintains proportional amounts of green biomass, chlorophyll, and leaf water in an interrelated fashion. Approximately 70 per cent of the wet weight of green vegetation is water. Leaf water contents at which metabolic activities are not impaired help maintain the chlorophyll concentration by apparently preventing its enzymatic and photo-oxidative breakdown. During active growth and under nonlimiting leaf water potentials, photosynthetically absorbed energy is passed along the pigment system without modifying the chlorophyll molecules. When leaf water decreases, however, the pigment system is no longer capable of transporting all of the captured electrons and photo-oxidation of chlorophyll probably occurs at a rate depending on the leaf water potential (Cleon Ross, personal communication).

Simple, linear spectrocorrelation curves for leaf water, green biomass, and chlorophyll were calculated by using the approach outlined earlier. Spectrocorrelations for these plot parameters are slightly different in magnitude but are identical in character (Figure 3). This situation indicates that these plot parameters are highly interrelated and are measurements of the same biological phenomenon—the amount of the functioning green biomass on the plot. Correlations between the plot parameters have been calculated and support the spectrocorrelation similarities (Table 2). The absence of near perfect correlation between the hand sampled values of dry green biomass, chlorophyll, and leaf water is due to the var-

iability associated with each type of determination. Chlorophyll determinations are the most variable due to the sampling error, dilutions, blendings, and extractions necessary for this laboratory measurement. Dry biomass measurements use machine sorting on a gravity basis with hand finishing to separate the dried vegetation into green and brown fractions. This process is very time-consuming and is prone to technician error. Leaf water measurements only require that the dry weight of the grass clipped from the plot be subtracted from the wet weight measured for that grass in the field. Leaf water determination is thus the least prone to measurement error and shows the highest spectrocorrelation of the three measures of functioning green biomass.

The coefficients of variation for the plot parameters (Table 1) show statistically the variability introduced by the various determinations. Leaf water has the smalllest coefficient of variation, the coefficient of variation for dry green biomass is slightly larger,
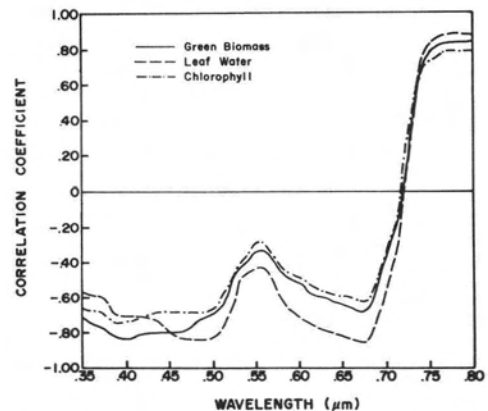

FIG. 3. Simple linear spectrocorrelation curves for the dry green biomass, chlorophyll content, and leaf water for the same 40 *in situ* plots of 1/4 m² of blue grama. Note the similarity in the three curves.

TABLE 2. CORRELATION MATRIX OF THE HAND SAMPLED CHARACTERISTICS OF THE 40 SAMPLE PLOTS DESCRIBED IN TABLE 1. NOTE THE HIGH INTERCORRELATIONS BETWEEN DRY GREEN BIOMASS, CHLOROPHYLL, AND LEAF WATER.

	Total wet biomass	Total dry biomass	Dry green biomass	Dry brown biomass	Leaf water	Chloro-phyll
Total wet biomass	1.00	0.97	0.98	0.84	0.91	0.89
Total dry biomass		1.00	0.95	0.92	0.78	0.88
Dry green biomass			1.00	0.78	0.89	0.88
Dry brown biomass				1.00	0.56	0.70
Leaf water					1.00	0.85
Chlorophyll						1.00

and the chlorophyll coefficient of variation of 75 per cent is 40 per cent larger than either the dry green biomass or leaf water value.

The analysis of the 40 plots sampled in early September and outlined above has been compared with that of 24 plots sampled 8 weeks earlier in July that have approximately equal total dry biomass mean values, standard deviations, coefficients of variation, and standard errors of the mean (Table 3). The data set analyzed from the early part of September (Table 1) represents the more complex vegetational situation containing significant amounts of both dry and green biomass fractions. A comparison of plot statistics for the two dates illustrates that a compositional change occurred in the 8 weeks although the mean amount of total dry biomass was relatively constant (Table 3). The experimental plots contained a dry green to dry brown biomass ratio of approximately 2.5:1 in July during the active growing season, but that by September this ratio had become approximately 1:1. Spectrocorrelation curves for dry green biomass values from the two sampling dates also reflect the change in composition in the vegetation canopy (Figure 4). The two spectral regions of strong pigment absorption have high spectrocorrelations with dry green biomass on both dates as does the photoinfrared spectral region. The remainder of the September spectrocorrelation curve is degraded due to the presence of so much dry brown biomass in the plant canopy. More significant spectrocorrelations exist earlier in the growing season when the ratio of dry green to dry brown biomass is much higher than later in the growing season. The September results represent sampling at a less advantageous time in the growing season although certain spectral intervals continue to be sensitive to the
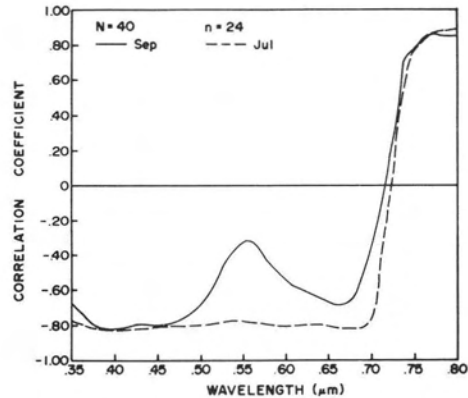

FIG. 4. Simple linear spectrocorrelation curves for dry green biomass taken at two different times in the growing season. Note the consistency in the high negative correlations in the two chlorophyll absorption bands in the blue-violet and red-orange and the high positive correlations in the photoinfrared spectral region.

TABLE 3. A STATISTICAL COMPARISON OF THE VEGETATIVE CHARACTERISTICS OF PLOTS OF BLUE GRAMA SAMPLED 8 WEEKS APART IN JULY AND SEPTEMBER AND USED IN CONSTRUCTING FIG. 5. NOTE THE CONSISTENCY OF THE TOTAL DRY BIOMASS BETWEEN THE TWO SAMPLING PERIODS BUT THAT DRY GREEN BIOMASS HAS BEEN TRANSFORMED TO DRY BROWN BIOMASS.

Vegetative characteristics	July	September
Total dry biomass (g/m²)		
Number of sample plots	24	40
Range	69.32 to 352.40	41.50 to 337.84
Mean	171.36	168.55
Standard deviation	82.36	90.81
Coefficient of variation	48.06	53.88
Standard error of the mean	16.81	14.36
Dry brown biomass (g/m²)		
Number of sample plots	24	40
Range	17.84 to 91.48	20.40 to 186.42
Mean	48.53	82.41
Standard deviation	21.81	48.54
Coefficient of variation	44.95	58.90
Standard error of the mean	4.45	7.68
Dry green biomass (g/m²)		
Number of sample plots	24	40
Range	38.72 to 260.92	17.12 to 185.04
Mean	122.83	89.38
Standard deviation	71.44	50.15
Coefficient of variation	58.16	56.11
Standard error of the mean	14.58	7.93

functioning green biomass regardless of the presence of standing dead vegetation.

Although the spectrocorrelation results are somewhat different in magnitude and character for dry green biomass, chlorophyll, and leaf water, it is apparent from the similarities between the curves and the intercorrelation between the sampled plot parameters that the same biological characteristic is being estimated—the amount of functioning green biomass present in the plant canopy. The spectrocorrelation approach identifies those intervals of the region tested, in this case 0.350 to 0.800 μm, which are sensitive to the plot parameters and indicates as well the relative sensitivity of these intervals as compared to other spectral intervals. These results then can be applied to grassland remote sensing inventories in order to gather spatial data of the productivity of these areas and the changes in it with various management practices, such as type conversions, reseedings, fertilization treatments, and grazing systems.

SUMMARY

Green biomass, chlorophyll, and leaf water are measurements of the amount of functioning green biomass and are highly interrelated in blue grama (*B. gracilis*) plots of the shortgrass prairie. Spectrocorrelation curves for dry green biomass, chlorophyll, and leaf water are very similar. Differences are due to the sampling errors associated with each type of determination. Regions of high negative spectrocorrelation for these sample parameters occur in the two chlorophyll absorption bands of the visible spectrum. These remain relatively constant for functioning green vegetation and are unaffected by increasing amounts of standing dead vegetation on the plot. The near infrared region of the spectrum shows a high positive spectrocorrelation to these three sample parameters and is also unaffected by increasing amounts of standing dead vegetation.

REFERENCES

Horwitz, W. (Ed.), 1970, *Official methods of analysis*, 11th Ed. Association of Analytical Chemists, Washington D.C. pp. 53-55.

Knipling, E. B., 1970, "Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation," *Remote Sensing Environment* 1(3):155-159.

Mitchell, J. E., 1972, "An analysis of the beta-attenuation technique for estimating standing crop of prairie range," *J. Range Manage.* 25:300-304.

Pearson, R. L., L. D. Miller, and C. J. Tucker, 1975, "Design of a mobile field spectrometer laboratory," *US/IBP Grassland Biome Preprint No. 140*, Colorado State Univ., Fort Collins. 16 pp.

Pearson, R. L., and L. D. Miller, 1972, "Remote mapping of standing crop biomass for estimation of the productivity of the shortgrass prairie, Pawnee National Grasslands, Colorado," p. 1357-1381. *In: Proceedings of the 8th International Symposium on Remote Sensing of the Environment*, Univ. Michigan, Ann Arbor.

Pechanec, J. F., and G. D. Pickford, 1937, "A weight estimation method for the determination of range or pasture production," *J. Amer. Soc. Agron.* 29:894-904.

Tucker, C. J., L. D. Miller, and R. L. Pearson, (in prep.), "Grassland spectrometer experimental data: 1971 and 1972," *US/IBP Grassland Biome Tech. Rep.*, Colorado State Univ., Fort Collins. Approx. 100 pp.

Uresk, D. M., 1971, "Dynamics of blue grama within a shortgrass ecosystem," Ph.D. dissertation, Colorado State Univ., Fort Collins. 52 pp.

Van Dyne, G. M., F. M. Glass, and P. A. Opstrup, 1968, *Development and use of capacitance meters to measure standing crop of herbaceous vegetation*, Oak Ridge (Tennessee) National Laboratory, ONRL-TM 2247. 47 pp.

Van Wyk, J. J. P., 1972, "A preliminary report on new separation techniques for live-dead aboveground grass herbage and roots from dry soil cores," *US/IBP Grassland Biome Tech. Rep. No. 144*, Colorado State Univ., Fort Collins. 16 pp.

Warren Wilson, J., 1963, "Estimation of foliage denseness and foliage angle by inclined point quadrats, *Aust. J. Bot.* 11:95-105.

Woolley, J. T., 1971, "Reflectance and transmittance of light by leaves," *Plant Physiol.* 47:656-662.