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ABSTRACT

The application of photographic infrared/red (ir/red) reflectance or radiance ratios for the estimation of vegetation biomass and physiological status were investigated by analyzing in situ spectral reflectance data from experimental grass plots. Spectral reflectance data were collected in June, September, and October. In addition, canopy biological samples were taken for total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content at each sampling date. The normally collected spectral reflectance curves were multiplied by a spectral irradiance function to yield a spectral radiance curve for each plot sampled. Hypothetical red and photographic infrared sensors were simulated by integration of the narrow bandpass (0.005 μm) spectral radiance data for the regions of 0.63 - 0.69 and 0.75 - 0.80 μm, respectively. The integrated red and photographic infrared radiances were subsequently regressed against the various canopy or plot variables to determine the relative significance between the red, photographic infrared, and the ir/red ratio and the canopy variables. Several transformations of the red, photographic infrared, and ir/red ratio were also evaluated. These included the ir + red sum, the ir - red difference, the red/ir ratio, the vegetation index (VI) of (ir-red)/(ir+red), and the transformed vegetation index (TVI) of $\sqrt{VI + .5}$.

Several conclusions were drawn as a result of this analysis which have application to aircraft, satellite, and ground collected ir/red spectral data: (1) The ir/red ratio is sensitive to the photosynthetically active or green biomass, the rate of primary production, and actually measures the interaction between the green biomass and the rate of primary production within a given species type; (2) The ir/red ratio resulted in improved regression significance over the red or the ir radiances taken separately; (3) Only slight differences were found between ir/red ratio, the ir-red difference, the VI, and the TVI; (4) The asymptotic spectral radiance properties of the ir, red, ir/red ratio, and the various transformations were evaluated. It was found for the June data that the red radiance asymptoted at 2 to 3 times lower biomass levels of the canopy variables than the ir radiance. The ir/red ratio, the ir-red difference, the VI, and TVI were found to have similar asymptotic properties which were a function of the red and ir components' asymptotic properties. The ir/red ratio and the various transformations were found to be useful in estimating canopy variable total dry biomass,

for example, up to ~4000 kg/ha. Beyond that level, the ir radiance was more useful by itself; (5) No difference was found for different ir bandwidths when used in the ir/red ratio and the transformations. The regression significance was found to be extremely similar for the different ir bandwidths of 0.75 - 0.80, 0.80 - 0.90, and 0.75 - 0.90 μm when ratioed with the red radiance or used in the various transformations.

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USE OF NEAR INFRARED/RED RADIANCE RATIOS FOR ESTIMATING VEGETATION BIOMASS AND PHYSIOLOGICAL STATUS

INTRODUCTION

The use of near infrared/red ratios for monitoring vegetation biomass and physiological status have recently become common in the remote sensing community. Accompanying this increased usage, however, has been a lack of detailed analysis concerning limitations of the near infrared/red (ir/red) ratios and their application(s) to vegetation monitoring. Quantitative information regarding the ir/red ratio and the constraints involved in the use of this method will enable more advantageous use of this technique. It will also prevent overambitious use of this technique when other methods would be more applicable. This paper will examine ground-collected grass canopy spectra in an attempt to quantify the relationship between the ir/red ratio and properties of the plant canopy in question.

The terms band ratio, channel ratio, and radiance or reflectance ratio all refer to a rationing of two radiances or reflectances. In the field of remote sensing of vegetation, this has usually come to mean a near infrared/red reflectance or radiance ratio. The use, henceforth, in this paper of ir/red ratio is synonymous with band, channel, and radiance or reflectance ratios.

Previous Work

The use of a near infrared/red ratio method for estimating biomass or leaf area index was first reported by Jordan (1969) who used a radiance ratio of 0.800/0.675 μm to derive the leaf area index for forest canopies in a tropical rain forest. This application of the ir/red ratio used the transmitted light at these wavelengths which was sensed on the forest floor (Jordan, 1969). Subsequent work was reported by Pearson and Miller (1972) who developed a hand-held spectral radiometer for estimating grass canopy biomass. The instrumentation aspect of the hand-held radiometer is described in Pearson et al. (1976).

The work of Pearson and Miller (1972) served as a stimulus for other investigators who used, evaluated, and/or modified the near infrared/red ratio for their particular purposes.

Colwell (1973 and 1974) presented a detailed study of bidirectional spectral reflectance of grass canopies. He concluded that the ir/red ratio was effective in somewhat normalizing the effect of soil background reflectance variation(s), was quite useful for estimating biomass, and could possibly be used to determine both the total dry biomass and the live and dead vegetation fractions by simultaneous use of both of ir reflectance and the ir/red ratio. Colwell also cautioned that the ir/red ratios may worsen angular effects rather than alleviate them under certain conditions. Smith and Oliver (1974) have corroborated several of Colwell's (1973 and 1974) conclusions using a stochastic canopy model versus Colwell's use of Suits' (1972) deterministic canopy model.

The ir/red ratio method has been applied to Landsat image analysis of range biomass by Rouse et al. (1973 and 1974), Carneggie et al. (1974), Johnson (1976), and Maxwell (1976), among others.

Carneggie et al. (1974) used a ratio of Landsat MSS7/MSS5 and found that the ratio curves, plotted as a function of time, peaked during the period of greatest forage production. Thereafter, the curves fell off signalling the period of drying following the maximum green period for their California study site. Once the curves had leveled off, Carneggie et al. (1974) concluded that all annual vegetation had dried. The Landsat radiance ratios appeared to provide a valid quantitative method for comparing relative differences in forage production for different grazing regions throughout the annual California grassland, assessed the timing of growth stages, and determined range condition (greeness or dryness) (Carneggie et al. 1974).

Rouse et al. (1973 and 1974) analyzed Landsat MSS data and developed what they referred to as the vegetation index (VI) and transformed vegetation index (TVI). They found that although a simple ratio of MSS7/MSS5 could be used as a measurement of relative greeness, location and cycle deviations would introduce a large error component. The difference of the MSS7-MSS5 radiance values, normalized over the sum of MSS7 + MSS5, was used as an index value and was christened the VI.

$$VI = \frac{MSS7 - MSS5}{MSS7 + MSS5} \quad (1)$$

To avoid working with negative ratio values and the possibility that the variances of the ratio would be proportional to the mean values (i.e. . . . a Possion distribution) the constant of 0.5 was added and a square-root transformation was applied to the VI. This transformation of the VI was likewise christened as the TVI.

$$TVI = \sqrt{VI + .5} \quad (2)$$

The assumption that the distribution of VI is Possion needs to be examined. If the VI is distributed as a Possion distribution, then the square root transformation will tend to make it more normal. If the distribution of VI is, however, Gaussian, log-normal, or log-log in character then the square root transformation is not warranted. This needs to be examined in greater detail to justify the use of the square root transformation. It should be mentioned, however, that the square root transformation is not a drastic transformation.

Inspection of the residuals from VI-biomass and TVI-biomass regressions should help to clarify the applicability of the TVI.

One should note that the theoretical range of values for the VI and TVI ranges inclusively from -1.0 to +1.0 and $\sqrt{-.5}$ to 1.22, respectively. It is surmised that in practice Rouse et al. (1974) found the VI or TVI values ranged from -.5 to 1.0, thus explaining their choice of adding the constant .5 to the VI in equation (2) to avoid working with negative numbers.

The VI and TVI were then applied to Landsat data. MSS bands 6 and 7 were both evaluated as the near infrared band. Rouse et al. (1974) reached several conclusions. Among them were: (1) that Landsat VI and TVI methods could be used to monitor rangelands and wheat crops; (2) the close relationship between green biomass and TVI should allow researchers to follow crop development as ground cover, biomass, and leaf area indices increase; and (3) phenological inferences could possibly be gleaned for certain crops or range types and used to monitor these types of vegetation (Rouse et al. 1974).

Johnston (1976) and Maxwell (1976) also analyzed Landsat imagery using ratio methods. They concluded that the ratio of MSS6/MSS5 was slightly more statistically significant than MSS7/MSS5 and that both ratios were useful in monitoring green biomass. An explanation of the apparent greater utility of MSS6 vs MSS7 for rangeland biomass estimation based upon soil-green vegetation spectral contrasts has been proposed by Tucker and Miller (1977). Interested readers are directed to this reference for further discussion along these lines.

Basic Properties of ir/red Ratio

It is perhaps prudent to briefly review the basic properties of the ir/red ratio before embarking on a detailed analysis of the ratio and various related techniques. As previously stated, the ir/red ratio involved a near infrared radiance or reflectance and a red radiance or reflectance. Each of these components exhibit a different relationship when plotted against biomass for example (Figure 1). The red component of the ratio exhibits the nonlinear inverse relationship between integrated spectral radiance and green biomass while the near infrared component exhibits a nonlinear direct relationship.

The relationship between the 0.63 - 0.69 μm radiance and green biomass results from strong spectral absorption of incident radiation by chlorophyll molecules. It is also apparent that a spectral radiance asymptote is more quickly reached for the 0.63 - 0.69 μm red radiance than the 0.75 - 0.80 μm near infrared radiance (Figure 1). The asymptotic nature of vegetation spectral radiance and reflectance has been reported elsewhere for grass canopies (Tucker, 1977a).

Because the 0.63 - 0.69 μm radiance is inversely proportional to the amount of chlorophyll present in the grass canopy, this component of the ir/red ratio is sensitive to green or photosynthetically active vegetation. It is not sensitive to dead or standing brown biomass.

The 0.75 - 0.80 μm radiance is sensitive to green or photosynthetically active vegetation and, to a lesser extent, the dead or nonphotosynthetically active vegetation. This has previously been suggested by several workers and demonstrated experimentally for grass canopies by Tucker (1977b and 1977c).

The relationship between the 0.75 - 0.80 μm infrared radiance and biomass results from the lack of appreciable spectral absorption in the 0.74 - 1.30 μm region and the high degree of intra- and interleaf scattering in the plant canopy. In the absence of spectral absorption, proportionally more incident spectral radiance escapes from the canopy than is absorbed. Thus the spectral radiance in the 0.74 - 1.00 μm region is said to be enhanced or increased over the level of radiance of the background spectra.

Discrimination of vegetation biomass is strongly dependent upon the soil surface-vegetation spectral reflectance or radiance contrast (Tucker and Miller, 1977). For this reason, some wavelengths are far superior to others for discrimination of green vegetation biomass (Figure 2).

Figure 2 diagrammatically presents the reasons why strong statistical significance has been reported for some wavelength regions and not others. We would expect maximum discrimination of vegetation from the soil-litter background when the curves for the soil and vegetation spectra were the most divergent. Conversely, we would expect minimal discrimination of vegetation from the soil-litter background when the two curves were not divergent. This has shown to be the case by Tucker and Maxwell (1976), Tucker and Miller (1977), and supports the hypothesis of Colwell (1974). Relative spectral statistical

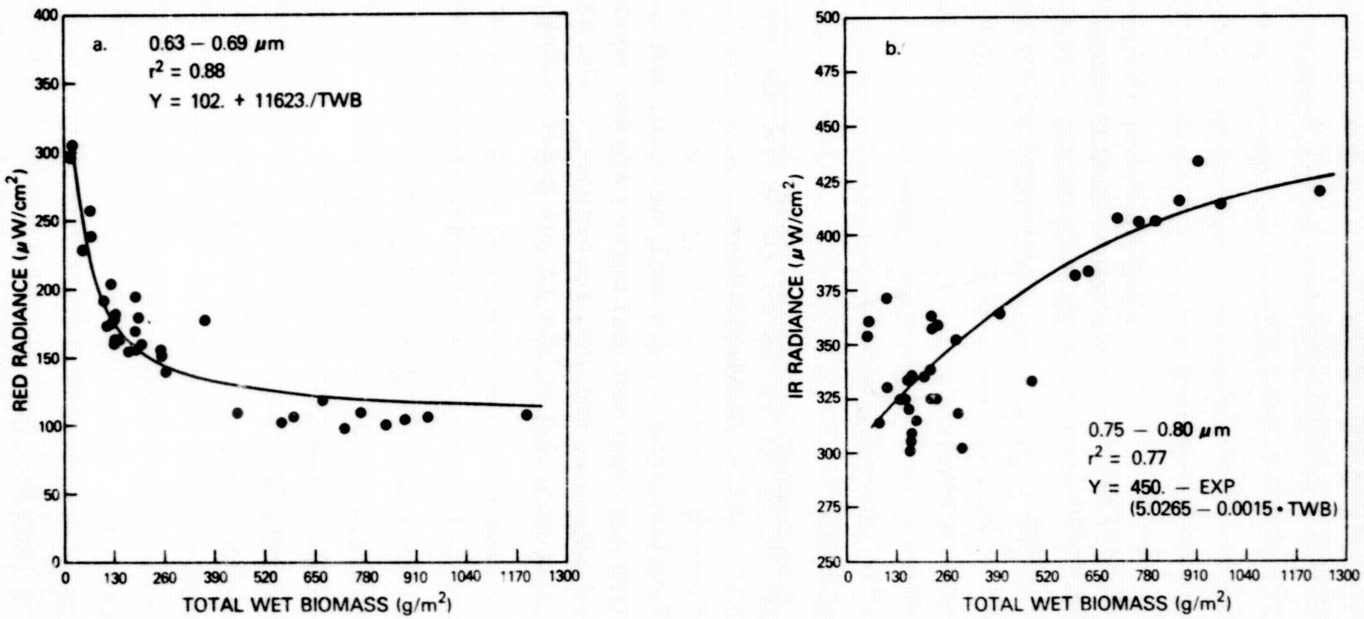

Figure 1. Radiance plotted against total dry biomass for the (a) 0.63-0.69 and (b) 0.75-0.80 μm intervals for the June data. Similar results were obtained for total wet biomass, leaf water content, dry green biomass, and total chlorophyll content for this sampling time.

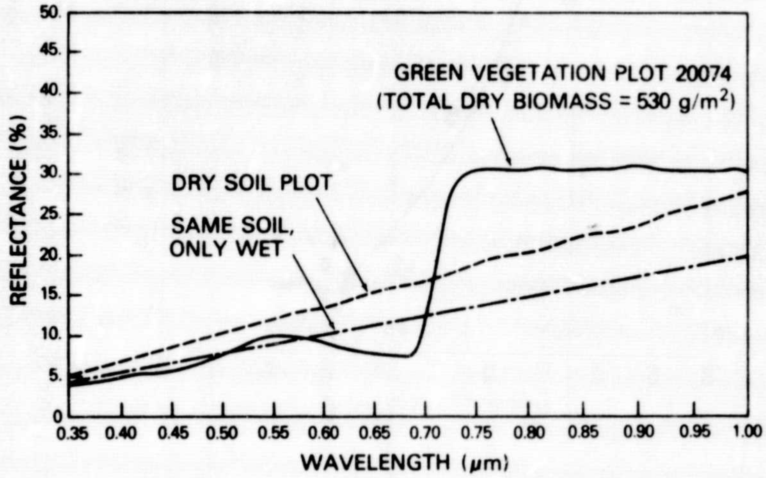

Figure 2. Spectral reflectances for dry soil, wet soil, and asymptotic green reflectance. The dry soil and wet soil curves are the average of five bare soil plots measured when dry and wet, respectively. The asymptotic green reflectance curve is from a plot of blue grama grass having a total dry biomass of 530 g/m ^{2}.

significance between reflectance or radiance and biomass, leaf water, or chlorophyll is dependent upon the background spectra. Colwell (1974) has investigated this in detail and has shown that the situation presented in Figure 2 is valid for light colored soils. That is, the red and near infrared spectral regions give the greatest spectral contrasts for vegetation over a dry soil. When the soil is dark or moist, however, the vegetation-soil contrast for the red is decreased while the vegetation-soil contrast increases for the near infrared region (Colwell, 1974) (Figure 2).

Considering the influence of the background spectra on in situ canopy spectra, Figure 1 represents the influence of various background spectra on the thirty-five plots sampled in June 1972. It can be clearly seen that less variability exists for low levels of biomass (or leaf water, chlorophyll) for the red radiance than for the infrared radiance for the same plots. This has also been previously suggested by Colwell (1974) and demonstrated for experimental data by Tucker (1977a).

Colwell (1974) has suggested that the ir/red ratio tends to normalize or compensate for variations in the soil-litter background spectra and/or variable amounts of bare soil present for a given range of biomass. This is indeed fortuitous and will be examined in detail later in this paper.

In addition, the relationship between primary productivity and green biomass is of interest and importance regarding use of the ir/red ratio. Although the ratio has been reported to be sensitive to green biomass, it is the feeling of the author that it is actually some inference to the amount of primary production occurring. Certainly a relationship exists between the degree of primary production and the green biomass; the green biomass being a result of primary production. The ir/red ratio appears to be sensitive to the interaction between the amount of green biomass and the rate of primary production.

For example, experimental data collected by the author during the summer of 1976 at the Grassland Research Institute, Hurley, Berkshire, United Kingdom showed conclusively the relationship between the interaction of green biomass and the degree of primary product upon the ir/red ratio for perennial ryegrass. When measuring the ir/red ratios of two adjacent swords of ryegrass, one of high biomass and older vegetation and the other of low-medium biomass but experiencing rapid regrowth as a result of recent cutting, the ratios indicated a higher biomass for the two-fold lower biomass but rapidly regrowing sword (Table 1). This was later reconfirmed several times at this study site.

Somewhat similar findings, although expressed differently, have been reported from Landsat data by Carneggie et al. (1974). They reported that

MSS7/MSS5 ratios peaked during the period of greatest forage production. Subsequently, lower MSS7/MSS5 values corresponded to drying out the vegetation following the period of maximum green forage production. These Landsat results appear to support the contention of this paper that the ir/red ratio and related transformations are sensitive to the green biomass – rate of primary production interaction within a given species type.

Table 1

Fresh, Dry, and Ashfree Weights with Associated Ir/Red Ratios from Plots of Perennial Rye Grass. Data Collected at the Grassland Research Institute, Hurley, Berkshire, United Kingdom with Michael Wade in August, 1976.

Plot #	Fresh Weight	Dry Weight	Ashfree Weight	Ir/Red Ratio
U2	201	50	43.0	7.50
U3	158	41	36.4	7.64
D1	89	27	24.3	7.76
D3	154	41	34.4	10.02

*U = Undefoliated, D = defoliated (clipped) 4 weeks prior to measurements.

The work of Carneggie et al. (1974), while not stratified by species types, is encouraging for larger heterogenious ecological situations. Whether or not some inter-species quantitative (or quasi-quantitative) inference can be drawn from remotely sensed red and ir radiance data remains to be seen. The usefulness of inferring estimates of the amount of primary productivity from different vegetation types would be tremendous. This assumes, of course, that inter-species variability does not confuse the relationship between the ir/red ratio and related transformations and the green biomass-rate of primary productivity interaction.

Description of Research Undertaken

The previously reviewed work by other investigators is quite informative for establishing a background of the utility of ir/red ratios for monitoring vegetation biomass. In addition, the simulation modeling work of Colwell (1973 and 1974), and to a lesser extent, Smith and Oliver (1974), gives several hypotheses that could be field verified by a controlled in situ series of spectral measurements coupled with detailed grass canopy sampling.

This study was undertaken to specifically investigate several hypotheses:

Are there advantages in using the radiance difference, VI, or TVI compared to regular ir/red ratios?

Is the distribution of the VI Possion, log-normal, or what?

Do the various ratio techniques tend to reduce background spectra differences as suggested by Colwell (1973 and 1974)?

How well do the various ratios work at different sampling times during the year?

What sampled canopy variables are the most highly correlated with the various ratios?

What are the asymptotic properties of the various ratios?

Does the infrared bandwidth influence the relationship between the sampled canopy variables and the ir/red ratio?

Might some other ratio technique be more useful?

How do the various components of the ratios behave individually and what functional forms do they take with regard to the canopy variables?

Can red or ir radiances be used to determine the total biomass and the live/dead fractions as suggested by Colwell (1973 and 1974)?

In short, this research will examine the various aspects of ir/red ratios and attempt to explain why the ir/red ratio apparently works, give constraints for its usage, and quantify the utility of ir/red ratios for monitoring vegetation.

METHODS AND ANALYSIS

Study Location

The experimental results reported herein were obtained 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 Agriculture Research Service Central Plains Experimental Range 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 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° 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.

Prarie 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. 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 above-ground plant biomass and plant cover (Miller et al., 1976).

Data Used

Thirty-five plots were sampled in June, 1972; forty plots were sampled in September, 1971; and eighteen plots were sampled in October, 1972. All plots were 1/4 m^2 in area and were composed of blue grama grass. They were sampled in situ by spectroradiometric measurement over the 0.350-0.800 μm (September and October) and the 0.350 to 1.000 μm (June) region at every 0.005 μm interval with the mobile field spectrometer laboratory. All measurements were made normal to the ground surface.

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. 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.

The first laboratory 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. 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 2). 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. 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 various per unit area terms used are consistent with accepted range management practices.

The experimental data collected were chosen for this study because analysis of the data would help quantify the changes that occur as vegetation changes from live to dead as the growing season approaches its conclusion. Furthermore, the utility of remote sensing estimation of grass canopies after the growing season has ended could be evaluated in terms of total wet biomass, total dry biomass, leaf water content, dry green biomass, and chlorophyll content.

Because the growing season had ended two weeks prior to the October sampling period, all of the total dry biomass was dry brown biomass. Thus only four canopy variables were sampled at this sampling time.

Integration of Narrow Bandwidth Spectral Curves

The narrow bandwidth radiance curves (0.005 μm bandpass) were numerically integrated to approximate a variety of bandwidths. The radiance curves were obtained in the following fashion. Initially, the spectral curves were represented as reflectances. This was necessary in order to express the reflectance or radiance in a common reference system (reflectance being a surface property independent of illumination). Next, a spectral irradiance curve was obtained for the intensity of solar radiation at sea level with a solar zenith angle of 60° (Dave et al. 1975). At each 0.005 μm wavelength interval between 0.350-0.910 μm, the radiance for each of the experimental plots was obtained by multiplying the spectral reflectance times the spectral irradiance.

Table 2

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, (B) The Forty 1/4 M^2 Sample Plots of Blue Grama Sampled in September 1971, and (C) The Eighteen 1/4 M^2 Sample Plots of Blue Grama Sampled in October, 1972.

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

Table 2 (Continued)

Sample	Range	Mean	Standard Deviation	Coefficient of Variation	Standard Error of the Mean
B. September, 1971					
Wet total biomass (g/m^2)	70.83- 491.22	261.31	134.00	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	14.36
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
C. October, 1972					
Wet total biomass (g/m^2)	49.20-1071.20	370.10	238.20	88.70	77.40
Dry total biomass (g/m^2)	43.60- 696.00	261.10	216.20	82.80	51.00
Leaf water content (g/m^2)	1.20- 373.30	109.00	113.00	103.60	26.60
Chlorophyll content (mg/m^2)	16.40- 502.10	134.20	138.90	103.50	32.70

The experimental data was integrated according to the following criteria: The red band was 0.63 - 0.69 μm, and the ir band was 0.75 - 0.80 μm. This, of course, was dictated in part by the fact that the September and October data only covered the 0.35 - 0.80 μm region. The June data, however, was integrated with ir bandwidths of 0.75 - 0.80, 0.80 - 0.90, and 0.75 - 0.90 μm, respectively. The red band was selected because it corresponds to the proposed Landsat-D thematic mapper red band (0.63 - 0.69 μm) and has been shown to be optimum for monitoring green grass canopies in this region of the spectrum (Tucker, 1977b; Tucker and Maxwell, 1976). The ir band, as previously explained, was dictated by instrumentation considerations and high levels of reflectance characteristic of living vegetation which occur in the 0.74 - 1.20 μm region.

Regression Analysis

A regression approach was undertaken to approximate the relationships existing between the six sampled canopy variables and the spectral reflectance at each 0.005 μm interval. Four regression models were evaluated at each 0.005 μm interval. Standard regression notation after Draper and Smith (1966) will be used and donated as a function of wavelength by the subscript λ.

$$\text{CANOPY RFL}_\lambda = \beta_{0\lambda} e^{\beta_{1\lambda}(\text{plot variable})} \tag{3}$$

where:

$\text{CANOPY RFL}_\lambda$ = normal canopy spectral reflectance at wavelength λ,

$\beta_{0\lambda}$ = estimated value of β_0 at wavelength λ,

$\beta_{1\lambda}$ = estimated value of β_1 at wavelength λ,

e = Napier's number (i.e., ~ 2.72);

plot variable = total wet biomass, chlorophyll, etc. (see Table 2).

$$\text{CANOPY RFL}_\lambda = \beta_{0\lambda} + \beta_{1\lambda} \cdot (\text{plot variable})^{-1}, \tag{4}$$

$$\text{CANOPY RFL}_\lambda = \beta_{0\lambda} + \beta_{1\lambda} \cdot (\text{plot variable}), \tag{5}$$

and

$$\text{CANOPY RFL}_\lambda = \hat{S}_\lambda \left(1.0 - e^{\beta_{0\lambda} + \beta_{1\lambda}(\text{plot variable})}\right) \tag{6}$$

where:

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

Equations (3), (4) and (6) were transformed into linear models prior to regression computation. Regression results indicated that the linear model represented in Equation (5) was best approximated for the September and October data.

Equation (4) was the best approximation for the red radiance from the June data. Equation (6) was the best approximation of the ir radiance, the ratio, difference, VI, and TVI. Results presented in the balance of this section will be for these models and their respective spectral regions.

Six series of regressions betwi en nine radiance variables and each of the six canopy variables were performed. Regression output included the regression derived equation, regression analysis of variance, correlation coefficient (r), coefficient of determination (r^2), residuals, etc. (Dixon, 1974).

It should be noted that the coefficient of determination (r^2) values presented for the many of the June radiance variables are for the transformed data using Equations (4) and (6). Thus, they are approximate although a small amount of transformation error has been introduced for small and large values of the plot variables.

Various Combinations Evaluated

The experimental spectral curves were numerically integrated for the 0.63 - 0.69 and 0.75 - 0.80 μm intervals for all three data sets. A total of nine combinations were evaluated for each of the six canopy variables for June and September and for four of the canopy variables for the October data. The combinations were as follows:

1. red (0.63 - 0.69 μm integrated radiance).
2. ir (0.75 - 0.80 μm integrated radiance).
3. ir/red — i.e., #2/#1
4. red/ir — i.e., #1/#2
5. ir-red — i.e., #2-#1
6. ir+red — i.e., #2+#1
7. VI — i.e., #5/#6
8. (ir+red)/(ir-red) — i.e., #6/#5
9. TVI = (SQRT (#7 + 0.5)) — i.e., $\sqrt{\#5/\#6 + 0.5}$

Experimental Results

The nine spectral variables involving the red radiance, ir radiance, and various ratios, sums, etc. were regressed against the six canopy variables measured for the June and September data and the four canopy variables measured for the October data (Table 2). This resulted in 144 separate comparisons which defies concise presentation. The results of this analysis will be presented for the canopy variable total wet biomass for the June and October data sets. The September results will be presented for the canopy variables total dry biomass and leaf water content.

The rationale for this is simply that the June and October data sets were rather homogeneous with respect to canopy composition. The June data was almost entirely green with little standing dead vegetation present in the canopy. The October data was entirely dead with little if any green vegetation present in the canopy. The September data, however, contained approximately equal amounts of standing live and dead vegetation (Table 2). For this reason, the canopy variables total dry biomass and leaf water content were selected for presentation. It should be noted that the total dry biomass and leaf water contents equal the total wet biomass when added on a plot-by-plot basis. A detailed discussion of the differences between the canopy variables total dry biomass and leaf water content and the resulting canopy spectral reflectance is given in Tucker (1977b).

June Data

Inspection of the regression results between the nine radiance variables and the total wet biomass demonstrated the differences and similarities between the various radiance variables when regressed against total wet biomass (Figure 3). Regression results for all six canopy variables are presented in Table 3. In general, strong statistically significant relationships existed between total wet biomass, total dry biomass, leaf water content, dry green biomass, and total chlorophyll content and eight of the nine radiance variables. The only radiance variable which was not significant in any regression was the sum of the red and ir radiances. The canopy variable dry brown biomass showed a greatly reduced regression significance when compared with the other five canopy variables (Table 3).

The functional relationships between the nine radiance variables and total wet biomass fell into three categories: inverse nonlinear relationships for the red radiance, the red/ir ratio, and the sum/difference; a rather confused scatter relationship for the radiance sum; and a direct nonlinear relationship for the ir radiance, the ir/red ratio, the radiance difference, the VI, and the TVI (Figure 3). The same functional relationship(s) existed between the nine radiance variables and total dry biomass, leaf water content, dry green biomass, and total chlorophyll content as were the case for the nine radiance variables and total wet biomass (Figure 3, Table 3). The functional relationship(s) between the nine radiance

Table 3

Coefficients of Determination for the Simple Regressions Between the Nine Radiance Variables and the Canopy Variables for (A) 35 Plots of Blue Grama Grass Sampled in June, 1972; (B) 40 plots of Blue Grama Grass Sampled in September, 1971; and (C) 18 Plots of Blue Grama Grass Sampled in October, 1972.

Variable # Description	1 RED	2 IR	3 IR/RED	4 RED/IR	5 DIF	6 SUM	7 VI	8 SUM/DIF	9 TVI
(A) June, 1972									
Total Wet Biomass	0.88	.77	.85	.84	.92	.03	.89	.94	.88
Total Dry Biomass	0.80	.75	.80	.72	.89	.03	.84	.96	.84
Leaf Water Content	0.90	.78	.87	.89	.93	.03	.91	.91	.90
Dry Green Biomass	0.82	.76	.86	.73	.93	.04	.91	.88	.90
Dry Brown Biomass	0.32	.61	.56	.26	.66	.01	.58	.22	.58
Total Chlorophyll	0.91	.80	.85	.94	.89	.01	.85	.77	.85
(B) September, 1971									
Total Wet Biomass	.39	.54	.52	.64	.65	.00	.61	.06	.63
Total Dry Biomass	.22	.48	.34	.46	.47	.01	.42	.06	.44
Leaf Water Content	.65	.50	.78	.82	.83	.05	.82	.04	.82
Dry Green Biomass	.38	.57	.54	.64	.66	.00	.62	.06	.63
Dry Brown Biomass	.06	.30	.11	.20	.21	.04	.17	.05	.19
Total Chlorophyll	.33	.46	.42	.54	.55	.00	.51	.03	.52
(C) October, 1972									
Total Wet Biomass	.67	.72	.00	.00	.13	.72	.00	.01	.00
Total Dry Biomass	.66	.71	.00	.00	.13	.71	.00	.01	.00
Leaf Water Content	.68	.73	.01	.00	.13	.73	.00	.02	.00
Total Chlorophyll	.66	.78	.03	.03	.23	.75	.03	.03	.00

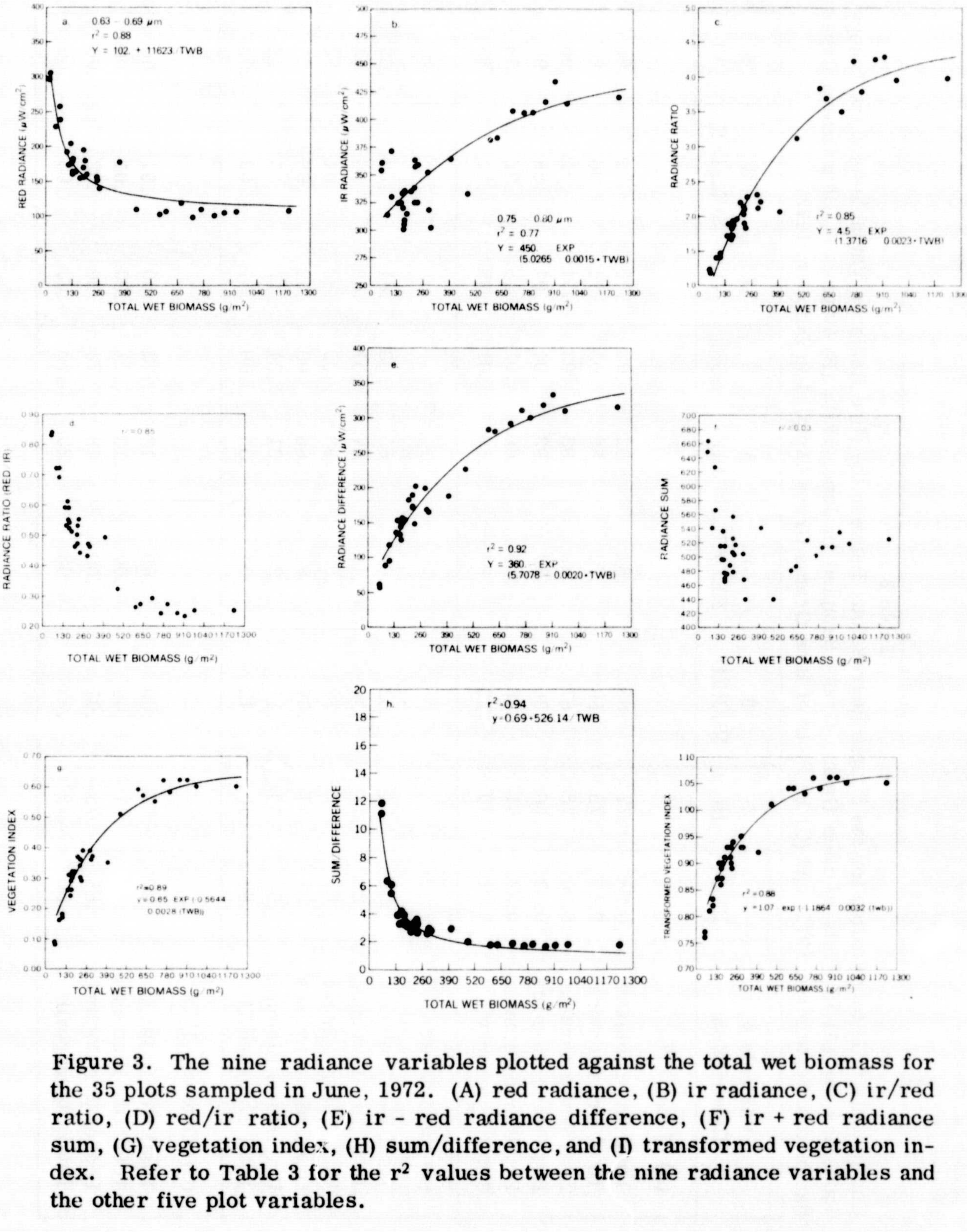

Figure 3. The nine radiance variables plotted against the total wet biomass for the 35 plots sampled in June, 1972. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables.

variables and dry brown biomass were more scattered or random which in turn was expressed in much reduced coefficients of determination values (Table 3).

September Data

The experimental results for the September portion of the analysis were markedly different from the June results. This is most apparent when one compares the tabular results for June and September in Table 3. Without exception, lower levels of regression significance were found for the September results. The September plot variable which was more highly correlated with the radiance variables was the leaf water content (Table 3).

The total dry biomass canopy variable, by contrast, was never significant* with any of the nine radiance variables (Table 3, Figure 4). The comparison between the results for total dry biomass and leaf water content are quite different and were chosen for this reason. In addition, this comparison is of interest from a ground-truth or canopy sampling perspective for grass canopies and possibly for other herbaceous canopies. Most ground-truth sampling of these canopies heretofore has only used the total dry biomass measurement. A related and more detailed companion study has addressed these questions in greater detail and will not be reviewed at length in this paper (Tucker, 1977b). The conclusions of the study, however, indicated that more detailed types of canopy sampling are necessitated by increasing canopy compositional complexity. Thus the comparison between total dry biomass and the leaf water content as they are related to the nine radiance variables.

Regression results between the nine radiance variables and the total dry biomass were not significant in a regression sense (i.e., $r^2 \leq .50$). Regression results between seven of the nine radiance variables and the leaf water content were, however, significant. The radiance sum and the sum/difference were not significant in a regression sense when regressed against leaf water content (Figure 4, Table 3).

The functional relationships between the nine radiance variables fell into three categories as were the case for the June data. The September data was linear for every combination of variables investigated, however. The trends between the radiance variables and the two canopy variables were the same (Figures 4 and 5) and will be discussed together: The functional relationships were:

*The accepted biological "test" of regression significance by r^2 values is observed in this paper. r^2 values less than 0.50 are not considered to be significant.

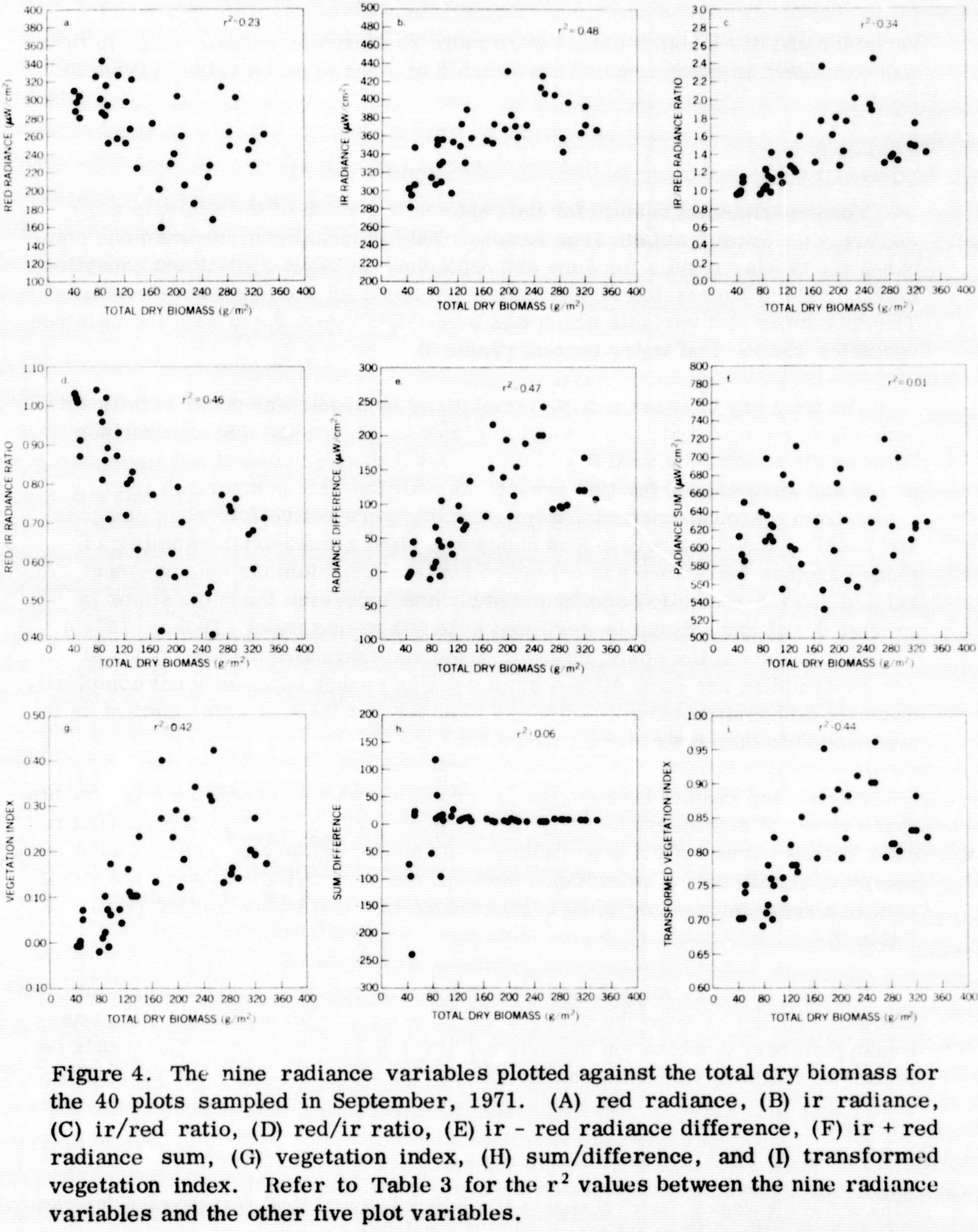

Figure 4. The nine radiance variables plotted against the total dry biomass for the 40 plots sampled in September, 1971. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables.

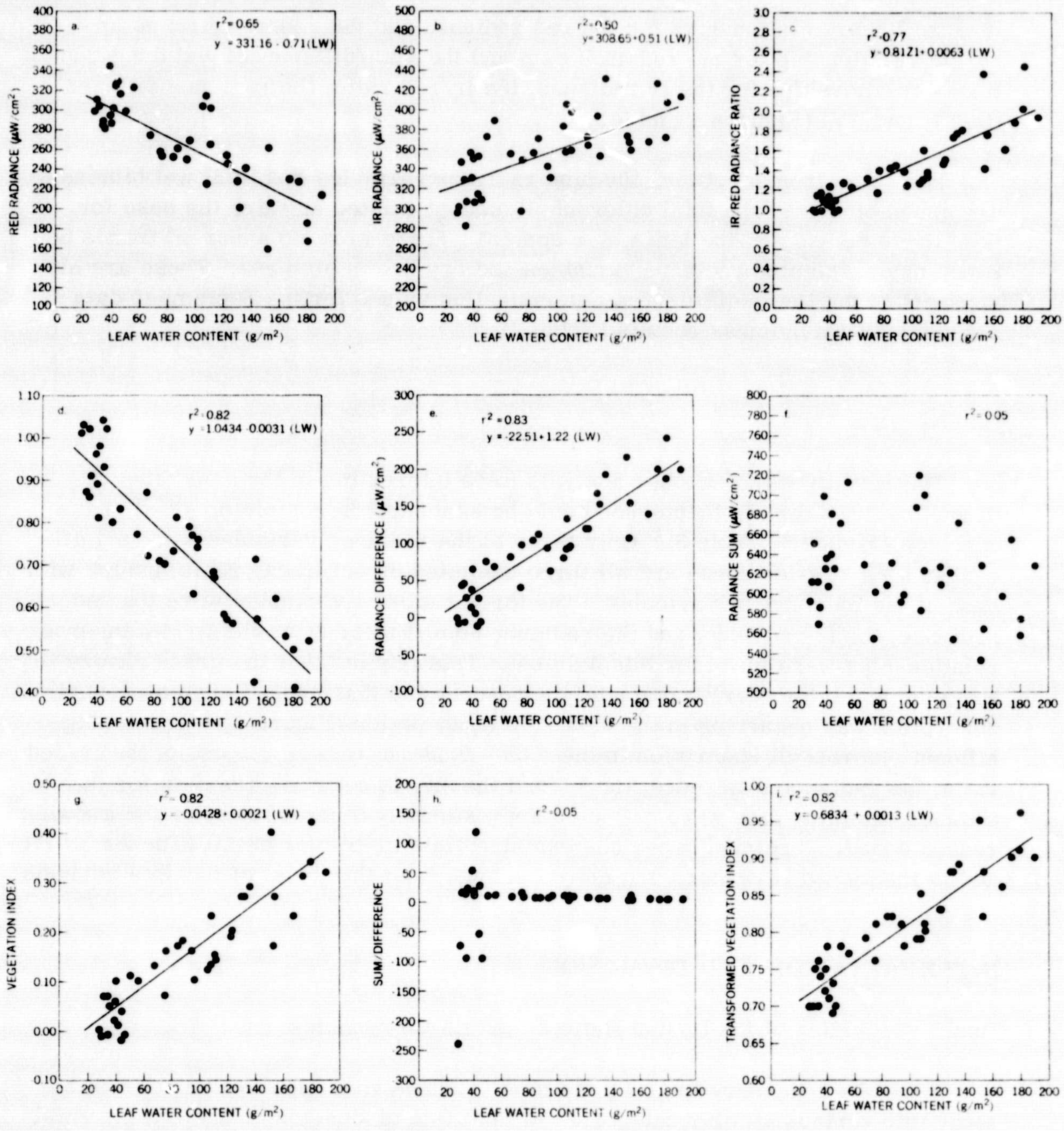

Figure 5. The nine radiance variables plotted against the leaf water content for the 40 plots sampled in September, 1971. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables.

inverse linear relationships for the red radiance and the red/ir ratio; no apparent relationship for the radiance sum and the sum/difference; and the direct linear relationships for the ir radiance, the ir/red ratio, the radiance difference, the VI, and TVI (Figures 4 and 5).

The same trends between the nine radiance variables and total wet biomass, dry green biomass, and total chlorophyll content existed as were the case for total dry biomass and the leaf water content. There were no apparent trends between any of the nine radiance variables and dry brown biomass. These are also apparent in the low coefficient of determination values for the September data set's dry brown biomass results (Table 2).

October Data

The results of the October analysis were interesting in the sense that the use of various ir/red ratio techniques could be evaluated on completely dead grass canopies (Figure 6, Table 3). Only three of the radiance variables were significant in a regression sense and all three exhibited direct linear relationships with each of the four canopy variables. The three radiance variables were the red radiance, the ir radiance, and the radiance sum (Figure 6, Table 3). No inverse relationships were found for this data set. This implies that the grass canopy was completely or nearly completely senescent and that little if any chlorophyll absorption was occurring in the 0.63 - 0.69 μm region (Figure 6). Without significant chlorophyll absorption in the 0.63 - 0.69 μm region, the use of the ir/red ratio, the radiance difference, the VI, and the TVI is negated. The data for the October sampling date were collected approximately four weeks after the growing season ended. A related paper has examined this in greater detail (Tucker, 1977c) and is mentioned if readers are more curious about this facet of the data analysis.

INTERPRETATION AND DISCUSSION

Basic Properties of the Ir/Red Ratio(s) and its Components

It will be necessary to group the nine radiance variables evaluated in this study into various similar categories to facilitate discussion of the experimental results: The red and ir radiance values will be treated separately as they are the basic components for the other seven radiance variables. The ir/red ratio, the red/ir ratio, the radiance difference, the VI, and the TVI will be grouped together because of their similarities; and the radiance sum and the sum/difference will be grouped together.

Red and Ir Radiances

The 0.63 - 0.69 μm integrated radiance exhibits the affect of chlorophyll absorption for the June and September data sets. The October data set exhibits a direct relationship between this radiance and the total wet biomass indicating that minimal if any chlorophyll absorption is occurring for this data set.

The soil-green vegetation contrast is at a local maxima in the 0.63 - 0.69 μm region with green vegetation having a lower return than the exposed soil surface (Figure 2). When the vegetation is no longer green and photosynthetic, a direct relationship exists between the red radiance and the total wet biomass (Figure 6).

The June data exhibited stronger chlorophyll absorption per unit area than the September data which was expressed in the nonlinear inverse relationship between the red radiance and the total wet biomass (Figure 3). The September data, while not nonlinear, exhibited the affect of chlorophyll absorption for this sampling time (Figures 4 and 5). Comparisons between the June and September red radiances indicated that more green biomass was present in June than September (also Table 2). In addition, the grass canopy in question was in a period of rapid growth in June and therefore had much higher levels of primary productivity occurring. The interaction between the greater amounts of green biomass and the higher level of primary production per unit of green biomass resulted in the greater degree of nonlinearity observed for the June data (Figures 3 and 4).

The 0.75 - 0.80 μm infrared radiance, by contrast, exhibited a direct relationship between biomass, leaf water, etc. and the resulting ir radiance for all three sampling periods (Figures 3, 4, and 5). The ir radiance was linearly related to biomass, leaf water, etc. for the September and October data and nonlinearly related to biomass, leaf water, etc. for the June data. The nonlinearity of the June data implies that more scattering was occurring for this sampling period than was occurring in September for plots of comparable total dry biomass values.

It should be noted that the 0.75 - 0.80 μm integrated radiance suffers from instrument induced noise for the $\sim$ 0.79 - 0.80 μm portion of this spectral interval. The instrument used was a grating spectrometer with a grating covering the 0.35 - 0.80 μm region (Miller, et al., 1976). Instrument induced noise was very pronounced on the upper end of the grating interval. The integrated radiances include a strong signal to noise ratio for the $\sim$ 0.75 - 0.78 μm region and a progressively poorer signal to noise ratio as the wavelength approaches 0.80 μm. This should be kept in mind when comparing the red and infrared radiances.

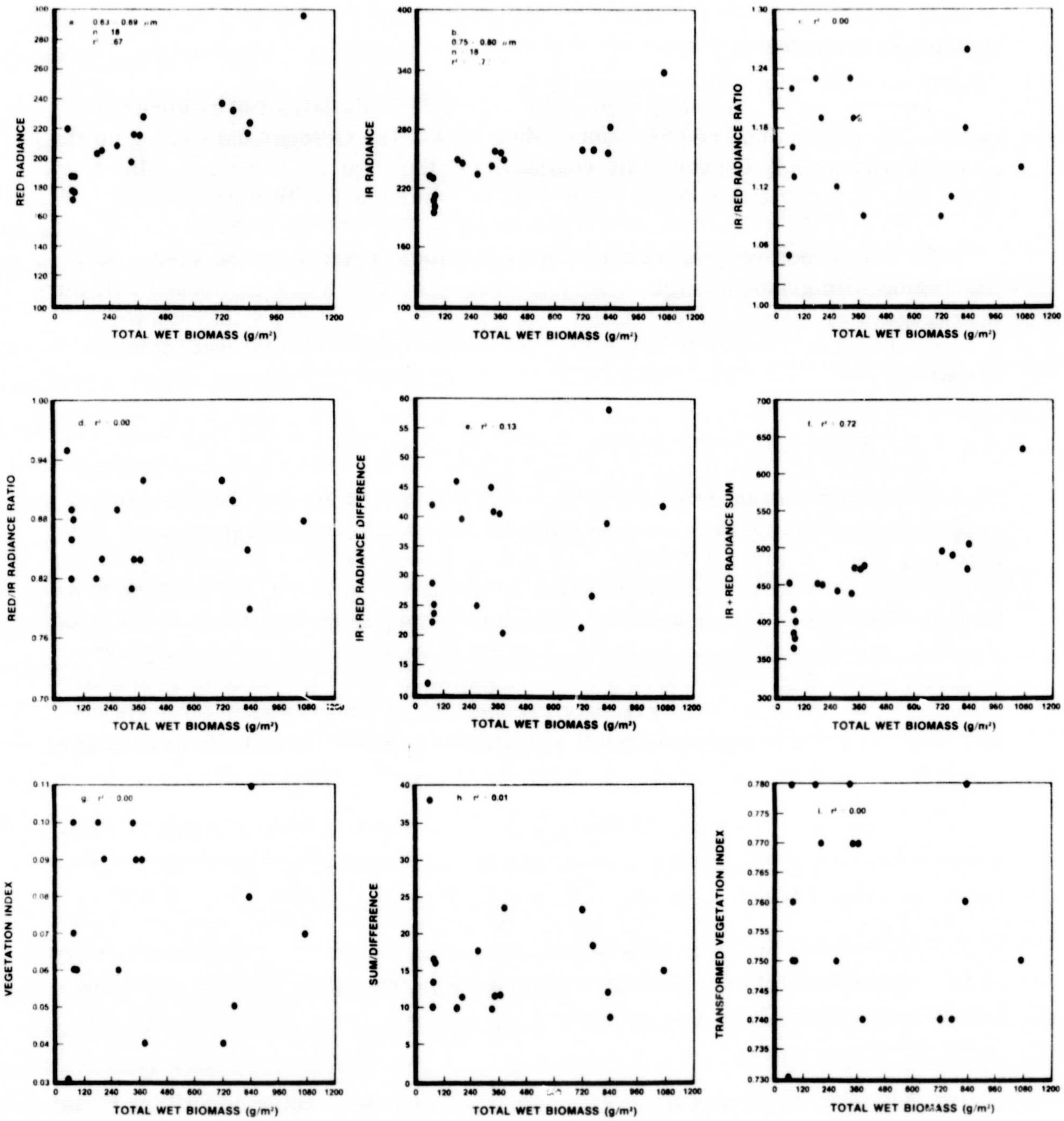

Figure 6. The nine radiance variables plotted against the total wet biomass for the 18 plots sampled in October, 1972. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables.

Ratios, Difference, VI, and TVI

The ir/red ratio, the red/ir ratio, the radiance difference, the VI and the TVI will be discussed together because of their similarities. The ir/red ratio, radiance difference, VI, and TVI all exhibited similar functional trends with respect to the canopy variables (Figures 3 and 4) and had similar levels of regression significance (Table 3). The red/ir ratio, however, exhibits the inverse functional relationship from the ir/red ratio as one would expect.

Perhaps the most obvious observation from the data analysis was the reduction in the data scatter around the regression derived function(s) for the ir/red ratio, the red/ir ratio, the radiance difference, the VI, and the TVI when compared with the red and infrared radiances (Figures 3 and 5). Colwell (1974) was the first to suggest that the ir/red ratio apparently normalized for the background spectra's variability. The data analysis seems to support this especially for the more compositionally complex September data. The radiance difference was the most significant radiance variable when regressed against the plot variables for the June and September data sets (Figures 3, 4, and 5; Table 3). The higher r^2 values for the radiance difference indicated that this radiance variable explained 7% more variability than the ir/red ratio, 3% more than the VI, and 4% more than the TVI for the June data. The corresponding comparison for the September data analysis had the radiance difference explaining 6% more variability thanthe ir/red ratio, and 1% more than the VI and TVI when regressed against the canopy variable leaf water content (Table 3).

It can be concluded that the radiance difference was the most useful for the June sampling period but was only 3% and 4% better than the VI and TVI, respectively. The radiance difference, VI, and TVI were only separated by a 1% difference in explaining additional variability for the canopy variable leaf water content from the September data set. (It should be noted that the r^2 value x 100 equals the percentage of total variability between the two variables which is explained by the regression relationship in question.)

The VI and TVI were found to be extremely similar as one would expect. No analytical advantage was found for using the TVI over the VI. Additional ground-based biomass estimation work by the author indicates that the VI or TVI can be a valuable means for normalizing red and ir spectral radiances for biomass estimation work. The VI and TVI both employ the radiance difference and radiance sum. The radiance difference has been shown to be highly correlated with green vegetation while the radiance sum is not (Figures 3, 4, and 5).

The radiance difference would be expected to maximize the presence of green vegetation. The more green vegetation per unit area present, the lower the spectral radiance return in the red (chlorophyll absorption) and the higher the spectral radiance return in the near or photographic ir (enhanced photographic ir radiance). The radiance difference would be greatest for denser amounts of green vegetation (Figures 3 and 5).

The radiance sum, by contrast, would be expected to be insensitive to the presence of green vegetation. Bare soil would have approximately the same radiance sum value as a heavily green vegetated plot from the same study area (Figure 2).

The VI and TVI, both employing the radiance sum as the denominator, effectively normalize the radiance difference by this division. This in turn is expressed in a high degree of regression significance (Table 3).

The sum/difference radiance variable, however, exhibits a much different functional relationship with respect to the canopy variables. The June sum/difference variable exhibits a highly nonlinear inverse relationship (Figure 3). The transgenerated regression analysis between the sum/difference and total wet biomass resulted in an r^2 value of 0.94 which was the highest of any of the radiance variables for the June data set. Unless one examined the radiance sum/difference plotted against total wet biomass, they would infer that this transformation would be better suited for estimating total wet biomass, total dry biomass, leaf water content, dry green biomass, and total chlorophyll content for the June data. (Figure 3; Table 3). Inspection of the plotted data destroys this statistical inference and underscores the need to inspect the functional relationship(s) between variables. The relationship between the sum/difference and total wet biomass, for example, would be useless for predicting total wet biomass from sum/difference values. This is, unfortunately, a common abuse of applied regression analysis. Many times relationships are reported with high r^2 or R^2 values which have no foundation in biological or physical reality. It is all too common to find data transformed simply to improve the r^2 or R^2 values with little thought given to the reason for the transformation in the first place.

Returning to the subject at hand, the September data analysis indicated an unusual relationship between the sum/difference and the various canopy variables (Figures 4 and 5). This same relationship was found for all six of the canopy variables and the sum/difference radiance value for the September data set. It can be inferred that there is little direct information about vegetative condition present in the sum/difference radiance variable.

Phenological Considerations

The spectral manifestations of grass canopy phenology can be inferred from the three sampling periods used for this study. If we consider the phenological condition of the grass canopy to control the resulting canopy spectral radiance, inspection of variables which quantify the canopy phenology can be related to the resulting red and ir radiances, ratios, etc. Fortunately, this study was designed from a biological perspective. As such, detailed canopy sampling resulted in the six canopy variables measured for the June and September sampling periods. The October data was also sampled in the same way. Because, however, all the total dry biomass was dry brown biomass, it was not necessary to divide the total dry biomass into dry green and dry brown fractions. For this reason there are only four canopy variables for the October data (Table 2).

Phenological development resulted in the gradual accumulation of more standing vegetation in the grass canopy. By September there were approximately equal amounts of standing live and dead vegetation. The October data, representing a post-senescent sampling time, was composed entirely of standing dead vegetation.

Spectral manifestations of grass canopy phenology can be seen by comparing the various radiance variables for the three sampling periods. The June analysis results were more significant in a regression sense, showed the most nonlinearity, and had the highest degree of intercorrelation between the six canopy variables (Tables 3 and 4). Canopy composition at this time was $\sim 80\%$ green vegetation and only $\sim 20\%$ dead vegetation (Table 2).

It should be noted that the June data was collected after a quantity of standing biomass had accumulated in the canopy. If, for example, data would have been collected one month earlier, it would have demonstrated the effects of lower amounts of standing crop green biomass and a much stronger soil background contribution to the composite canopy spectra. Because of less biomass being present at this hypothetical sampling time, earlier in the growing season and hence less percent canopy cover (with associated greater amounts of soil exposed), regression significance would be expected to be lower than the June data, the data more linear than the June data, and the degree of intercorrelation between canopy variables comparable if not higher than the June data.

Regression significance would be lower because of a much stronger soil contribution and associated weaker vegetation contribution resulting from lower amounts of green biomass. The data trends would be more linear because the green vegetational density controls the degree of nonlinearity for the red and photographic ir regions. Intercorrelation between canopy variables would be

Table 4

Correlation Matrix Between the Sampled Plot Variables for (A) 35 1/4 m^2 Plots of Blue Grama Grass Sampled in June, 1972, (B) 40 1/4 m^2 Plots of Blue Grama Grass Sampled in September, 1971, and (C) 18 1/4 m^2 Plots of Blue Grama Sampled in October, 1972.

	Total Wet Biomass	Total Dry Biomass	Dry Green Biomass	Dry Brown Biomass	Leaf Water	Total Chlorophyll
A. June, 1972						
Total wet biomass	1.00	1.00	1.00	0.91	1.00	0.98
Total dry biomass		1.00	0.99	0.94	0.99	0.97
Dry green biomass			1.00	0.88	1.00	0.96
Dry brown biomass				1.00	0.88	0.90
Leaf Water					1.00	0.98
Total Chlorophyll						1.00
B. September, 1971						
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

Table 4
(Continued)

	Total Wet Biomass	Total Dry Biomass	Leaf Water Content	Chlorophyll Content
C. October, 1972				
Total wet biomass	1.00	0.99	0.99	0.94
Total dry biomass		1.00	0.99	0.93
Leaf water content			1.00	0.95
Chlorophyll content				1.00

high because only small amounts of standing dead vegetation would have accumulated in the canopy by this time in the growing season. The role of changing physiological condition(s) as the growing season progresses is not considered per se. These considerations, which may be quite important, are beyond the scope of this paper. (These considerations include changing chlorophyll a to b ratios, diversion of photosynthates from vegetative growth into seed material, different metabolic rates associated with plant growth and development, etc.).

The September analysis results were less significant in a regression sense than the June results, were linear, and had a lower degree of canopy variable intercorrelation than the June results (Tables 3 and 4). Canopy composition at this time was ~ 52% green vegetation and ~ 48% dead vegetation (Table 2).

The October analysis results demonstrated the need for sufficient chlorophyll absorption to occur for the ir/red ratio and related transformations to work. By this sampling time, canopy composition had simplified again as the last of the green vegetation had senesced and all the standing crop was standing dead vegetation. Associated with this phenological condition were direct linear relationships between both the red and ir radiances and each of the four canopy variables sampled at this time. The regression results were not significant, except for three radiance variables, and there was a higher degree of canopy variable intercorrelation than was the case for the September data (Tables 3 and 4).

It should be noted that the "chlorophyll" determination for the October sampling period does not present in vivo chlorophyll a & b. It is thought, instead, that it represents chlorophyll decomposition products for this sampling period. This is apparent when one inspects the linear and direct relationship between the October red radiances and the "chlorophyll" concentrations. Clearly the use of standard chlorophyll determinations to characterize the greenness of grass canopies late in the growing season or after the end of the growing season is cautioned. This may also explain why the canopy variable total chlorophyll did not show higher r^2 values when regressed against the radiance variables for the September data (Table 3).

Canopy composition then directly influences the ir/red ratio and the related transformations studied in this paper. Early in the growing season, as more green biomass accumulates in the canopy, the vegetation first becomes apparent from the composite soil-vegetation background spectra. Plant growth continues which enhances the discrimination of vegetation from the soil background for certain wavelength intervals. This becomes more pronounced as the grass canopy greens up and approaches full canopy cover. When the grass canopy has reached full canopy cover and is experiencing rapid rates of photosynthesis, the ir/red ratio and related transformations show a high degree of nonlinearity when plotted against the various canopy variables. Then, as more and more dead vegetation accumulates in the canopy, the ir/red ratio and related transformations become more linear when plotted against the various canopy variables. This continues until the presence of a preponderence of dead vegetation results in a degrading of the inverse relationship between the red radiance and the plant material present. This may be accompanied by a reduction in the intensity with which near infrared radiances are reflected, but this is not clear from the data at hand. In any event, the utility of the ir/red ratio and related transformations is dependent upon the presence of sufficient green and photosynthetically active vegetation to result in absorption of red irradiance by chlorophyll molecules. When there is no longer sufficient green vegetation to do this, the ir/red ratio, radiance difference, VI, and/or TVI are no longer useful (Table 3).

Asymptotic Properties

The spectral reflectance or radiance of green vegetation against a light colored soil background decreases in regions of absorption and increases in regions of non-absorption as the vegetational density increases until a stable spectral reflectance or radiance is reached. The stable spectral reflectance or radiance is called the asymptotic spectral reflectance or radiance (Tucker, 1977a).

Asymptotic spectral radiance values are of interest because they indicate the range over which changes in the green vegetation present can be monitored by spectral methods. When a spectral radiance asymptote has been reached, increases in the vegetational density are no longer expressed in the resulting canopy spectral radiance.

The June data set was the only situation evaluated herein for which asymptotic considerations were necessary. Asymptotic considerations were necessary because of the June data set's high values for green biomass and the apparent high degree of primary productivity. The interaction between these two variables resulted in a high degree of nonlinearity for the red radiance and, to a lesser extent, the ir radiance (Figure 3).

Inspection of Figure 3 demonstrates the differences in asymptotic properties between the red and ir radiances with respect to total wet biomass. The ir/red ratio, the radiance difference, the VI, and TVI have asymptotic properties which are related to their red and ir components' properties. In general, the red region of the spectrum asymptoted at two- to three-fold lower amounts of total wet biomass, total dry biomass, leaf water content, dry green biomass, and total chlorophyll content when compared with the photographic ir region (Table 5).

Table 5
Levels of Five Canopy Variables Associated with Approximated Asymptotic Spectral Reflectances at 0.680 μm and 0.775 μm for Three NE$\Delta\rho$'s (from Tucker, 1977a)

Criteria	Wavelength (μm)	Total Wet Biomass (g/m^2)	Total Dry Biomass (g/m^2)	Leaf Water Content (g/m^2)	Dry Green Biomass (g/m^2)	Total Chlorophyll Content (mg/m^2)
NE$\Delta\rho$ = 0.15%	0.680	373.8	127.5	255.0	100.0	490.0
	0.775	975.0	435.0	600.0	300.0	1485.0
NE$\Delta\rho$ = 0.20%	0.680	325.0	112.5	220.0	90.0	440.0
	0.775	780.0	345.0	480.0	240.0	1155.0
NE$\Delta\rho$ = 0.25%	0.680	292.5	97.5	200.0	80.0	412.5
	0.775	633.8	285.0	400.0	200.0	880.0

The asymptotic properties of the ir/red ratio, the red/ir ratio, the radiance difference, the VI, and TVI are very similar. The red radiance component has effectively asymptoted at ~ 600 g/m^2 (Figure 3) and any change in the various ratio techniques results from the ir radiance component. It is therefore apparent that red radiance component is more or less constant as vegetational density increases. This could have application in further "normalizing" canopy spectral radiance data from similar canopy types over some large area where variations in spectral irradiational intensity might occur.

Applications of the Various Ratio Techniques

The ir/red ratio, radiance difference, VI, and TVI have definite application(s) to remote sensing of vegetation studies. Although this study has evaluated them and other spectral variables in a canopy variable context, there are definite applications to aircraft and Landsat image analysis.

The most apparent application is to the task of green vegetational density or green biomass monitoring. The various ratio techniques are more useful than either the red or ir radiances separately. Asymptotic properties of vegetation may restrict the application of these techniques to very dense green canopies, represented by several of the June data, but this applies only to very green and vigorous canopies.

The other principal remotely sensed inference which may be extracted concerns the physiological condition of the plant canopy in question. As mentioned earlier, the various ratio techniques are sensitive to the green biomass – degree of primary production interaction within a given species type. For a given plant canopy type of equal green biomass amounts, ratio differences would imply differences in degree of photosynthesis or primary production, other conditions being equal. This could result from some limiting condition such as water availability, nutrients, pathogens, etc.

It should be cautioned, however, that ratio technique differences record the interaction between the green biomass present, the degree of primary production, and other factors such as the background spectra, irradiational conditions, etc. Ratio differences could be due to green biomass differences and not imply the presence of limiting conditions upon primary production. Great care must therefore be taken to attribute observed ratio differences to their respective causative condition(s). This is often difficult because of the interaction(s) between the various abiotic and biotic variables.

Application of the various techniques brings forth the question about which one to use? The data analysis reported herein does not strongly favor one over the others. The radiance difference, VI, and TVI appear to be slightly superior in a r^2 sense to the ir/red ratio. In addition, other ratio data collected by the author during the summer of 1976 from Iceland, Sweden, and the United Kingdom supports this contention and tends to favor use of the VI.

The use of the VI or TVI appears to be superior to the other ratio variables. The difference of the ir-red radiances normalized over the sum of the ir+red radiances appears to minimize the error component as suggested by Rouse et al. (1973 and 1974). The use of the TVI depends upon the distribution(s) of the VI values. Assuming them to always be Poisson regardless of time of year, vegetation type, etc. is perhaps assuming too much.

The data analyses presented herein show no improvement for the TVI over the VI (or the VI over the TVI) for the June and September data sets (Tables 3 and 6). Inspection of the residuals associated with the various regressions between the VI and TVI and the canopy variables indicated that the TVI offers no improvement over the VI as a regression model and vice versa. Considering this, one should evaluate both the VI and TVI and inspect the residuals to determine which spectral variable is more suited for the application at hand. It appears, for this data set, that they are redundant. Additional research into the distributional characteristics of standing crop biomass and the resulting red and ir radiance values is needed.

Evaluation of Different ir Bandwidths

Another aspect of the study was to evaluate the influence of ir bandwidth upon ratio technique applications for estimating the various canopy variables. In addition to the original ir bandwidth of 0.75-0.80 μm, the bandwidths of 0.80-0.90 and 0.75-0.90 μm were evaluated. No differences were found in regression significance among the three ir bandwidths for the June data (Table 6; Figures 7, 8, and 9). The June data was the only one of the three data sets which covered the 0.80-1.00 μm spectral interval. The same evaluation of ir bandwidths could not be made, therefore, for the September and October data sets.

Summary and Conclusions

1. The ir/red ratio, radiance difference, VI, and TVI are sensitive to the photosynthetically active or green biomass, the rate or degree of primary production, and actually measures the interaction between the green biomass and the rate of primary production within a given species type. Sufficient green vegetation must be present in the canopy for the ir/red ratio or the related ratio techniques to be useful.

Table 6

Coefficients of Determination for the Simple Regressions Between the Nine Radiance Variables and the Six Canopy Variables for the 33 Plots of Blue Grama Grass Sampled with the 0.70 - 1.60 μm grating in June, 1972. (A) is for the 0.75 - 0.80 μm bandwidth, (B) is for the 0.80 - 0.90 μm bandwidth, and (C) is for the 0.75 - 0.90 μm bandwidth. Refer also to figures 7, 8, and 9.

Variable # Description	1 RED	2 IR	3 IR/RED	4 RED/IR	5 DIF	6 SUM	7 VI	8 SUM/DIF	9 TVI
(A) 0.75 - 0.80 μm									
Total Wet Biomass	0.90	0.79	0.91	0.83	0.94	0.00	0.92	0.01	0.92
Total Dry Biomass	0.82	0.77	0.88	0.70	0.93	0.00	0.89	0.01	0.89
Leaf Water Content	0.93	0.79	0.92	0.88	0.93	0.00	0.93	0.01	0.92
Dry Green Biomass	0.83	0.78	0.83	0.72	0.93	0.00	0.93	0.01	0.93
Dry Brown Biomass	0.32	0.63	0.65	0.24	0.77	0.08	0.66	0.00	0.66
Total Chlorophyll	0.92	0.79	0.85	0.90	0.91	0.01	0.87	0.12	0.86
(B) 0.80 - 0.90 μm									
Total Wet Biomass	0.90	0.77	0.92	0.86	0.94	0.06	0.92	0.91	0.91
Total Dry Biomass	0.82	0.75	0.89	0.84	0.93	0.05	0.89	0.88	0.89
Leaf Water Content	0.93	0.77	0.92	0.87	0.93	0.06	0.93	0.90	0.92
Dry Green Biomass	0.83	0.75	0.93	0.89	0.93	0.04	0.93	0.90	0.93
Dry Brown Biomass	0.32	0.63	0.67	0.22	0.67	0.08	0.58	0.18	0.55
Total Chlorophyll	0.92	0.78	0.85	0.90	0.91	0.10	0.86	0.76	0.85
(C) 0.75 - 0.90 μm									
Total Wet Biomass	0.90	0.78	0.92	0.87	0.92	0.17	0.92	0.93	0.91
Total Dry Biomass	0.82	0.76	0.89	0.84	0.92	0.16	0.89	0.86	0.88
Leaf Water Content	0.93	0.78	0.92	0.87	0.93	0.17	0.91	0.94	0.91
Dry Green Biomass	0.83	0.76	0.93	0.90	0.90	0.14	0.93	0.88	0.93
Dry Brown Biomass	0.32	0.63	0.65	0.23	0.80	0.18	0.69	0.22	0.64
Total Chlorophyll	0.92	0.78	0.85	0.90	0.91	0.22	0.86	0.85	0.86

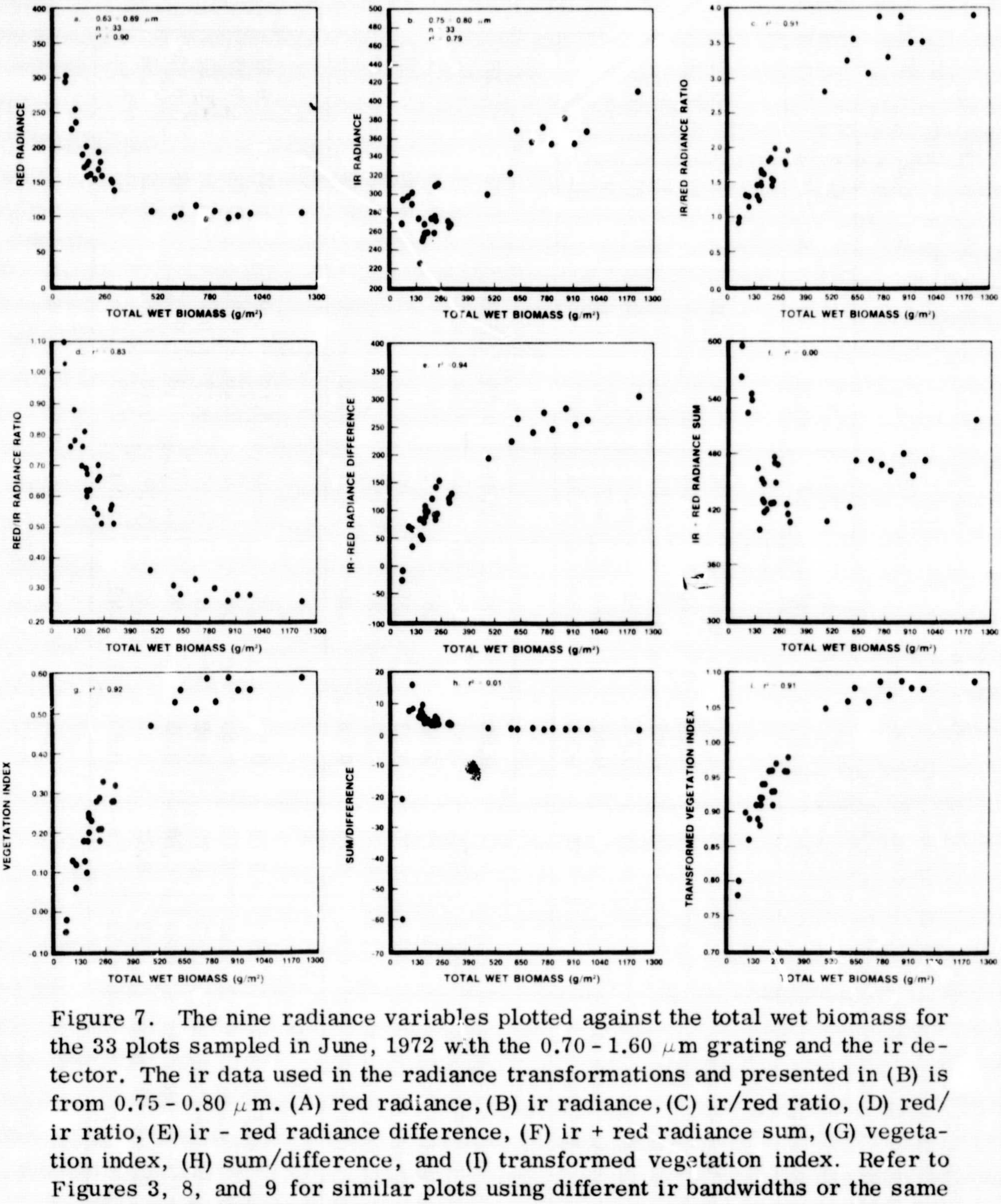

Figure 7. The nine radiance variables plotted against the total wet biomass for the 33 plots sampled in June, 1972 with the 0.70 - 1.60 μm grating and the ir detector. The ir data used in the radiance transformations and presented in (B) is from 0.75 - 0.80 μm. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Figures 3, 8, and 9 for similar plots using different ir bandwidths or the same bandwidth but with the 0.35 - 0.80 μm grating and the visible detector. Refer to Tables 3 and 6 for the tabular results.

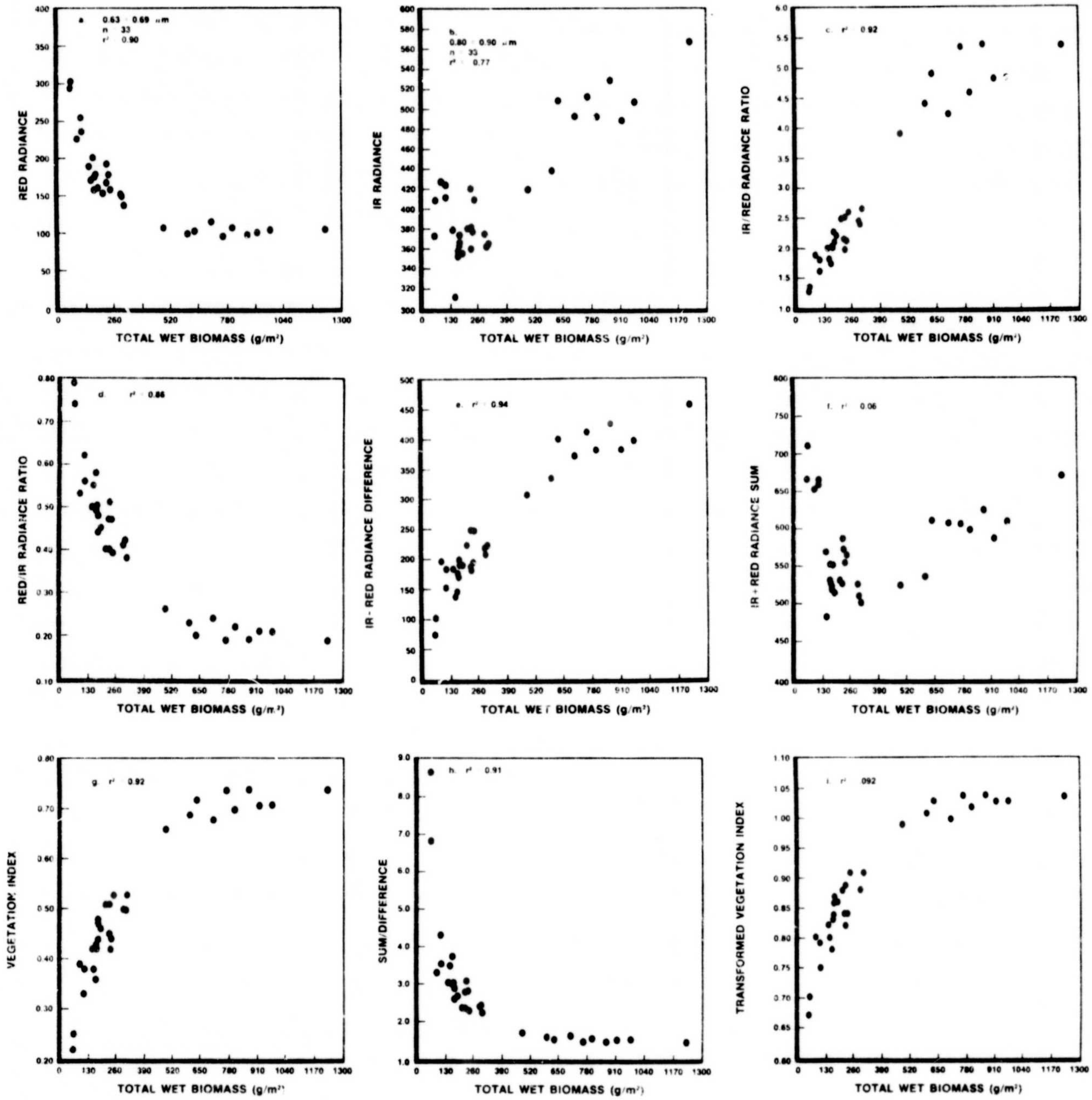

Figure 8. The nine radiance variables plotted against the total wet biomass for the 33 plots sampled in June, 1972 with the 0.70 - 1.60 μm grating and the ir detector. The ir data used in the radiance transformations and presented in (B) is from 0.80 - 0.90 μm. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Tables 3 and 6 for tabular results.

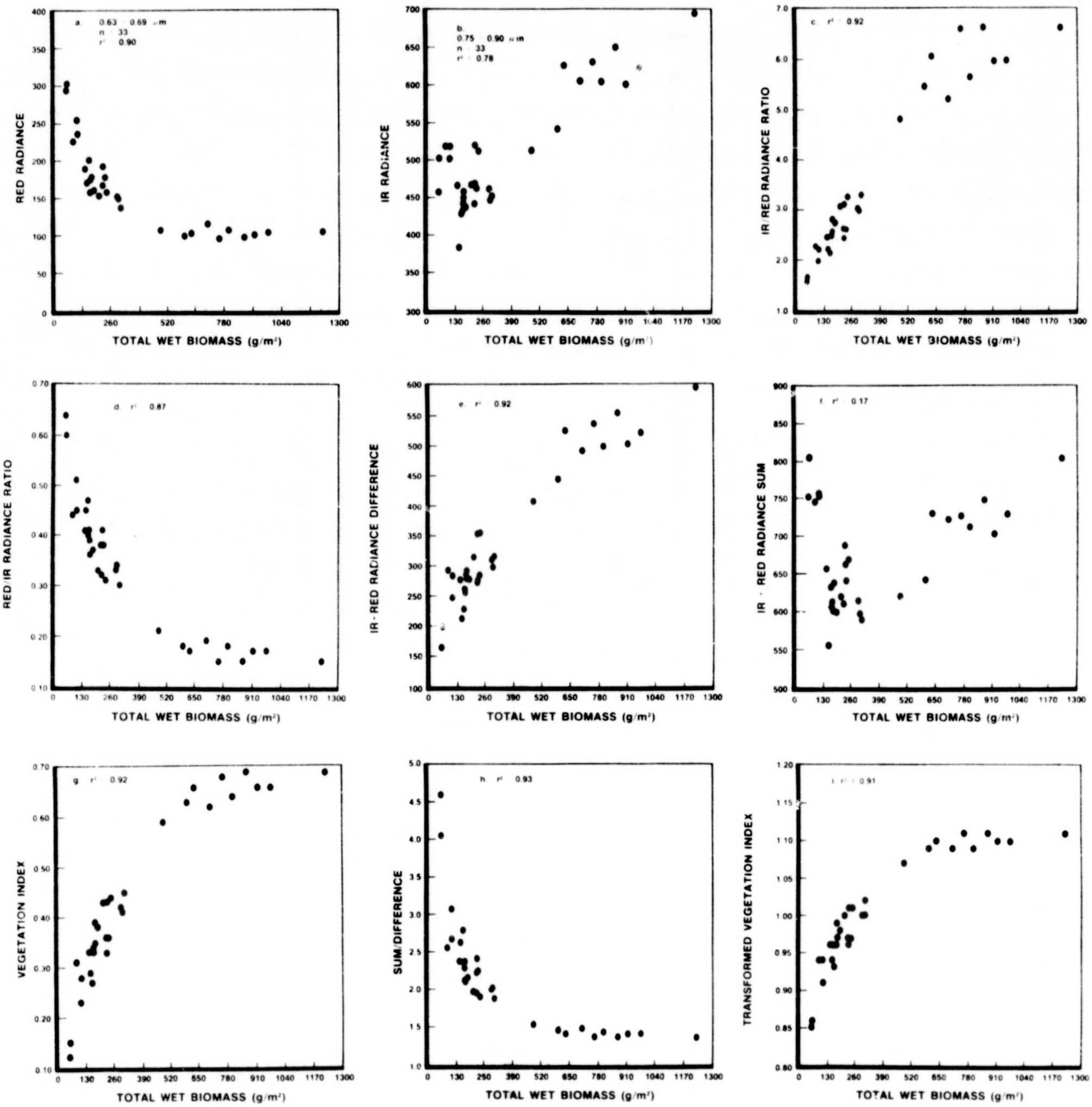

Figure 9. The nine radiance variables plotted against the total wet biomass for the 33 plots sampled in June, 1972 with the 0.70 - 1.60 μm grating and the ir detector. The ir data used in the radiance transformations and presented in (B) is from 0.75 - 0.90 μm. (A) red radiance, (B) ir radiance, (C) ir/red ratio, (D) red/ir ratio, (E) ir - red radiance difference, (F) ir + red radiance sum, (G) vegetation index, (H) sum/difference, and (I) transformed vegetation index. Refer to Tables 3 and 6 for tabular results.

2. The ir/red ratio, radiance difference, VI, and TVI showed improved regression significance over the red or the ir radiances taken separately when adequate amounts of green vegetation were present in the canopy.

3. Only slight differences were found between the ir/red ratio, radiance difference, VI, and TVI when regressed against the various canopy variables. The radiance difference, VI, and TVI were found to be the most useful. No advantage was found for transforming the VI into the TVI.

4. The asymptotic spectral radiance properties of the red radiance, ir radiance, ir/red ratio, radiance difference, VI, and TVI were evaluated for the June data. The red radiance asymptoted at 2 to 3 times lower amounts of the canopy variables than the ir radiance. The ir/red ratio, radiance difference, VI, and TVI were found to have similar asymptotic properties which were a function of the red and ir radiance compnents' asymptotic properties.

5. The regression significance for the different ir bandwidths of 0.75-0.80, 0.80-0.90, and 0.75-0.90 μm was evaluated and found to be extremely similar when ratioed with the red radiance or used in the various transformations.

6. The degree of nonlinearity between the red radiance, ir radiance, ir/red ratio, radiance difference, VI, and TVI and the canopy variables total wet biomass, total dry biomass, leaf water content, dry green biomass, and total chlorophyll content was directly related to the amount of green vegetation present and inversely related to the amount of standing dead vegetation present. The accumulation of standing dead vegetation in the canopy had a linearizing effect upon the red and ir spectral radiances and the canopy variables.

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