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Red and Photographic Infrared Linear Combinations for Monitoring Vegetation

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In situ collected spectrometer data were used to evaluate and quantify the relationships between various linear combinations of red and photographic infrared radiances and experimental plot biomass, leaf water content, and chlorophyll content. The radiance variables evaluated included the red and photographic infrared (IR) radiance and the linear combinations of the IR/red ratio, the square root of the IR/red ratio, the IR – red difference, the vegetation index, and the transformed vegetation index. In addition, the corresponding green and red linear combinations were evaluated for comparative purposes. Three data sets were used from June, September, and October sampling periods.

Regression analysis showed the increased utility of the IR and red linear combinations vis-à-vis the same green and red linear combinations. The red and IR linear combinations had 7% and 14% greater regression significance than the green and red linear combinations for the June and September sampling periods, respectively.

The vegetation index, transformed vegetation index, and square root of the IR/red ratio were the most significant, followed closely by the IR/red ratio. Less than a 6% difference separated the highest and lowest of these four IR and red linear combinations. The use of these linear combinations was shown to be sensitive primarily to the green leaf area or green leaf biomass. As such, these linear combinations of the red and photographic IR radiances can be employed to monitor the photosynthetically active biomass of plant canopies.

Introduction

The use of photographic infrared (IR) and red linear combinations 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 analyses concerning limitations of these data and their application(s) to vegetation monitoring. Quantitative information regarding the various IR and red linear combinations and the constraints involved in the use of these methods will enable more advantageous application of these techniques. It will also prevent overambitious use of these techniques when other methods would be more applicable. This article examines ground-collected grass canopy spectra in an attempt to quantify the relationship between the IR and red linear combinations and properties of plant canopies.

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, 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

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canopy biomass. The instrumentation aspect of the hand-held radiometer is described in Pearson et al. (1976).

Colwell (1973, 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) and was useful for estimating biomass. 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, 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, 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 leveled off, Carneggie et al. (1974) concluded that all annual vegetation had dried.

Rouse et al. (1973, 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 greenness, 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.

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

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 Poisson distribution) the constant of 0.5 was added and a square-root transformation was applied to the VI.

$$TVI = \sqrt{VI + 0.5} \qquad (2)$$

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: (1) 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; (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 versus MSS7 for rangeland biomass estimation in low biomass situations based upon soil–green-vegetation spectral contrasts has been proposed by Tucker and Miller (1977).

Other researchers have also used the VI for LANDSAT analyses. Blair and Baumgardner (1977) monitored several hardwood forest sites using LANDSAT imagery. They used the VI, which they refer to as the "band ratio parameter," and found that the greenwave effect could be monitored for these vegetation types using LANDSAT imagery.

Ashley and Rea (1975) reported how LANDSAT MSS5 and MSS7 data were used to depict phenological change. They also used the VI and found that it increased with foliage development and decreased with senescence. The VI was found to reduce influencing multiplicative effects such as solar elevation differences between overpasses (Ashley and Rea, 1975).

In addition to the above reviewed LANDSAT analyses, Kauth and Thomas (1976) and Richardson and Wiegand (1977) have proposed LANDSAT vegetational analytical methods using, at least in part, IR and red linear combinations.

Richardson and Wiegand (1977) have proposed a departure from the soil backround line with the perpendicular vegetation index (PVI):

$$\text{PVI} = \times\sqrt{(\text{Red}_{\text{soil}}-\text{Red}_{\text{veg}})^2+(\text{IR}_{\text{soil}}-\text{IR}_{\text{veg}})^2}\,, \tag{3}$$

where Red_{soil} is the soil background red reflectance or radiance, Red_{veg} is the vegetation background red reflectance or radiance, IR_{soil} is the soil background IR reflectance or radiance, IR_{veg} is the vegetation background IR reflectance or radiance.

Kauth and Thomas (1976) have developed a technique for transforming LANDSAT MSS information in four-dimension data space using the four MSS bands. From this, a soil brightness index (SBI) and green vegetation index (GVI) were calculated as follows:

$$\text{SBI} = 0.43^*\text{MSS4} + 0.63^*\text{MSS5} + 0.59^*\text{MSS6} + 0.26^*\text{MSS7} \tag{4}$$

and

$$\text{GVI} = -0.29\ \text{MSS4} - 0.56\ \text{MSS5} + 0.60\ \text{MSS6} + 0.49\ \text{MSS7}. \tag{5}$$

Note that all the SBI-independent variable coefficients are positive, while the GVI-independent variables MSS4 and MSS5 are negative. The SBI establishes the data space of soils and the GVI departs from it, in a negative or absorptive fashion with MSS4 and MSS5, approximately the same coefficients for MSS6 for both models, and a positive departure for MSS7. This also follows from Fig. 1.

Deering (1978), in a recent and comprehensive analysis of LANDSAT rangeland biomass monitoring, has reported that the VI and TVI approaches he evaluated using MSS6 were slightly more significant with respect to green biomass than the PVI of Richardson and Wiegand (1977) and the GVI of Kauth and Thomas (1976). In addition, Deering (1978) reported that the denominator of the VI and TVI (i.e., MSS5 + MSS6 or MSS5 + MSS7) were highly correlated ($r \geqslant 0.95$) to Kauth and Thomas' (1976) soil brightness index (SBI).

The majority of IR and red linear combination work has used LANDSAT data. Kanemasu (1974), however, reports on a ground-based reflectance study of crop types where various ratios were investigated. Wheat, sorghum, and soybean plots were monitored periodically during

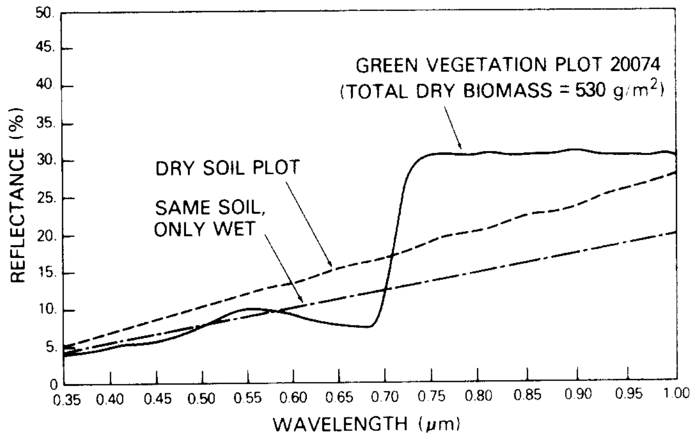


FIGURE 1. Spectral reflectances for dry soil, wet soil, and asymptotic green reflectance. The dry soil and wet soil curves are the average of five bare soil plots measured when dry and wet, respectively. The asymptotic green reflectance curve is from a plot of blue grama grass having a total dry biomass of 530 g/m^2 (from Tucker and Miller, 1977).

the growing season using a spectrometer. Kanemasu (1974) concluded the 0.545/0.655-μm wavebands provided useful information regardless of crop type. For all crops studied, the green/red ratio closely followed crop growth and development and appeared to be more desirable than the near-infrared reflectance as an index of growth. The green/red ratio will be evaluated in this paper also.

Recent works by Nalepka et al. (1977) and Tucker et al. (1979) have used IR and red data to forecast winter wheat yields and monitor agricultural crop vigor and condition, respectively. Nalepka et al. (1977) evaluated various green measures using LANDSAT data and concluded that most are useful but stress that no new information is created. Tucker et al. (1979) monitored several crop types using a hand-held radiometer.

Basic Properties of the IR and Red Radiances with Respect to Green Vegetation

It is perhaps prudent to briefly review the basic properties of the IR and red radiances with respect to green vegetation before embarking on a detailed analysis of the various linear combinations.

The red radiance 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 the chlorophylls. It is 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

(Fig. 2) (Gausman et al., 1976; Tucker, 1977a).

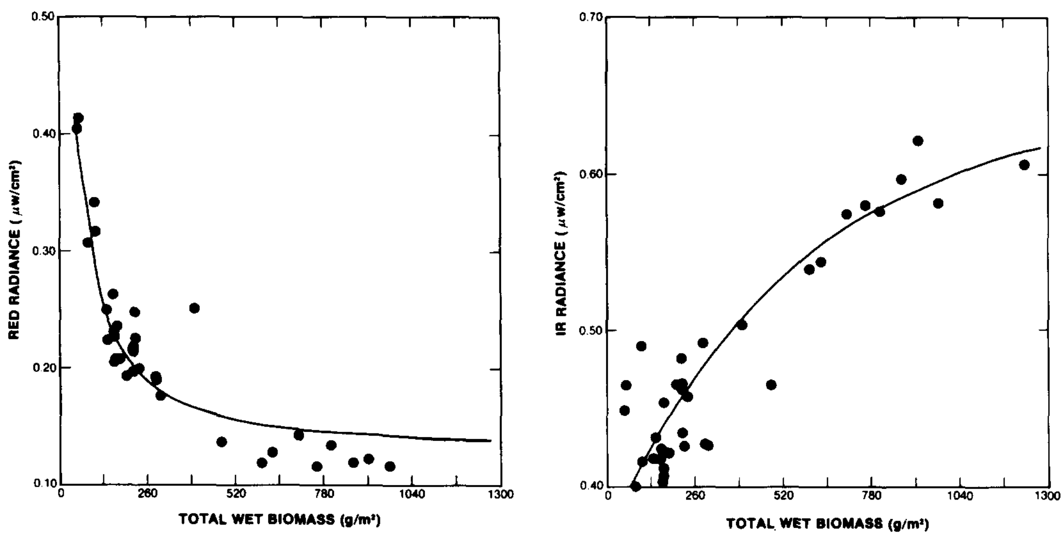
The 0.63–0.69-μm radiance is inversely proportional to the amount of chlorophyll present in the plant canopy and thus is sensitive to green or photosynthetically active vegetation present.

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 (Colwell, 1974; Tucker, 1977b, 1978).

The relationship between the 0.75–0.80-μm infrared radiance and biomass results from the lack of appreciable spectral absorption in the 0.74–1.20-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 0.74–1.20-μm region is said to be enhanced or increased over the level of radiance of the background material.

Discrimination of vegetation biomass is strongly dependent upon the soil surface-vegetation spectral reflectance or radiance contrast (Colwell, 1974). For this reason, some wavelengths are far superior to others for discrimination of green vegetation biomass (Fig. 1).

The green region, by contrast, has a lower soil–green-vegetation reflectance contrast (Fig. 1). This results from the fact that the chlorophylls are slightly absorptive in the green region (absorption



(a) 0.63–0.69 μm
$r^2 = 0.88$
$Y = 0.1233 + 16.7980/X$

(b) 0.75–0.80 μm
$r^2 = 0.86$
$Y = 0.65 - \exp(-1.2680 - 0.0017 \cdot X)$

FIGURE 2. Radiance plotted against total wet 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 dry biomass, leaf water content, dry green biomass, and total chlorophyll content for this sampling time. The total wet biomass was predominantly green and contained little dead vegetation (Table 1).

coefficients~10), while much more absorptive in the red region (absorption coefficients of ~40–90) (Salisbury and Ross, 1969). The relationship between the green radiance and green biomass is similar to the same relationship between the red radiance and green biomass (Figs. 2a and 3).

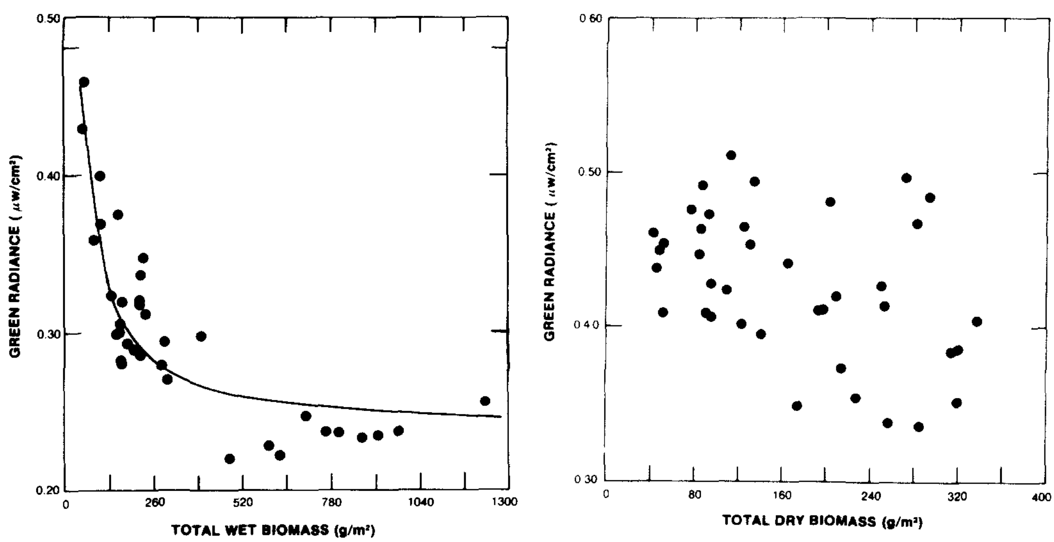
Description of Research Undertaken

The work reported herein examines ground-collected *in situ* spectrometer data, evaluates the green/red ratio method of Kanemasu (1974), and contrasts that with the IR/red ratio method(s) to determine which are superior for the June, September, and October data sets. The utility of the various green vegetation measures using the different IR and red linear combinations are also evaluated.

Methods and Analysis

The data used in this evaluation have all been previously described and are not redescribed in this report. The June and September data sets are described in Tucker and Maxwell (1976), while the October data is described in Tucker (1978).

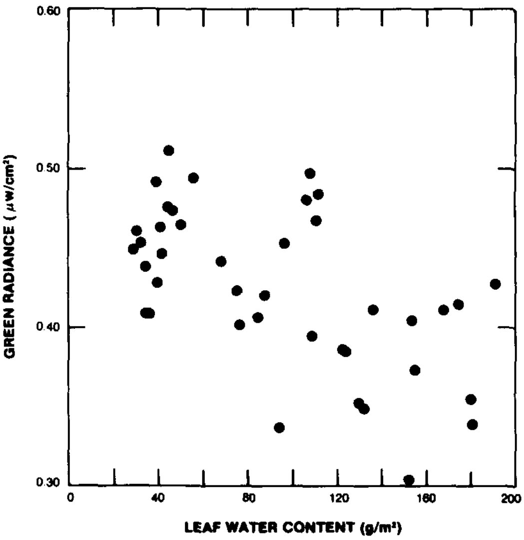
The narrow bandwidth radiance curves (0.005-μm bandwidth) were numerically integrated to approximate three bandwidths: 0.52–0.60 μm for the green, 0.63–0.69 μm for the red, and 0.75–0.80 μm in the photographic infrared. The radiance curves resulted from the product of the spectral reflectance



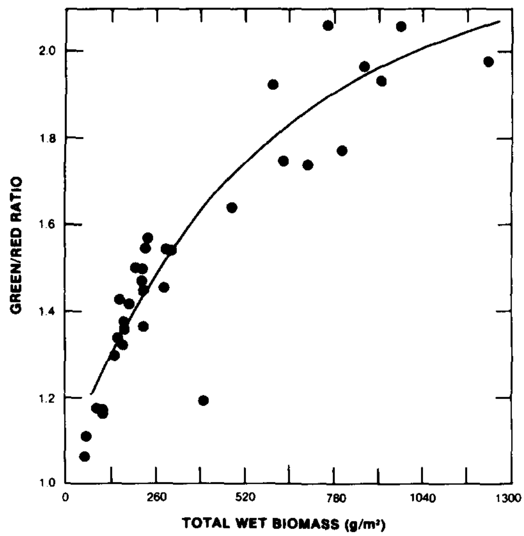
(a) 0.52–0.60 μm
$r^2 = 0.79$
$Y = 0.237 + 12.129/X$
June data

(b) 0.52–0.60 μm
$r^2 = 0.14$
September data

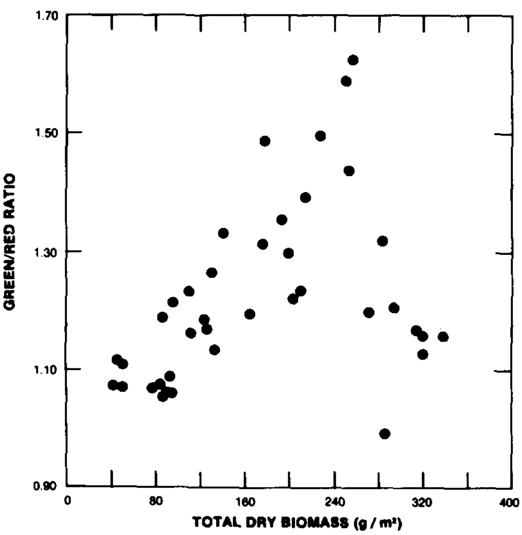
FIGURE 3. Comparisons between the green radiance (0.52–0.60 μm) and the green/red radiance ratio. Refer to Tables 2 and 3 for the r^2 values associated with this portion of the analysis and Figs. 4c, 5c, and 6c for comparisons to the IR/red ratio for the same data sets.



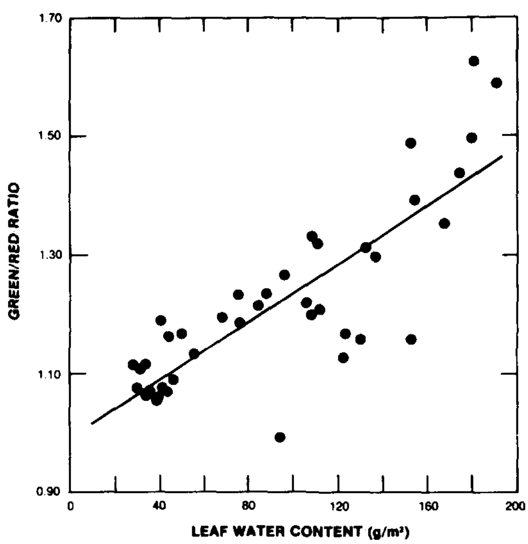
(c) 0.52–0.60 μm
$r^2 = 0.33$
September data



(d) $r^2 = 0.82$
$Y = 2.2 - \exp(0.1081 - 0.0012 \cdot X)$
June data



(e) $r^2 = 0.16$
September data



(f) $r^2 = 0.67$
$Y = 0.9933 + 0.0024 \cdot X$
September data

FIGURE 3. continued.

and a spectral irradiance.

Regression analyses identical to Tucker (1977b) were performed. The various grass canopy variables (Table 1) were regressed against the following IR and red and green and red radiance variables:

1. red radiance (0.63–0.69 μm)
2. IR radiance (0.75–0.80 μm)
3. IR/red
4. SQRT (IR/red)
5. IR − red
6. IR + red
7. (IR − red)/(IR + red)
8. (IR + red)/(IR − red)
9. $\sqrt{(\text{IR-red})/(\text{IR}+\text{red})+.5}$

1. red radiance (0.63–0.69 μm)
2. green radiance (0.52–0.60 μm)
3. green/red
4. SQRT (green/red)
5. green − red
6. green + red
7. (green − red)/(green + red)
8. (green + red)/(green − red)
9. $\sqrt{(\text{green}-\text{red})/(\text{green}+\text{red})+0.5}$

Experimental Results

The nine spectral variables involving the IR–red data and the green–red data were regressed against the six canopy variables measured for the June and September data and the four canopy variables measured for the October data. This resulted in 288 separate comparisons that defy concise presentation. The results of this analysis are presented for the canopy variable total wet biomass for the June and October data sets. The September results are presented for the canopy variables total dry biomass and leaf water content.

The linear combinations of the IR and red data were regressed against the six canopy variables as were the same green and red linear combinations. Without exception, the IR–red linear combinations were more significant in a regression context (Tables 2 and 3; Figure 3).

This supports the majority of LANDSAT analyses that have used IR and red data instead of green and red data for vegetational analyses. In addition, these results show that the IR/red ratio, the square root of the IR/red ratio, the VI, and TVI are sensitive to the photosynthetically active biomass or the green leaf area present in the grass canopy. This is evident from the June data where ~80% of the canopy was green or alive and only ~20% was standing dead vegetation (Table 1). For this data set, the dry brown biomass canopy variable had the lowest r^2 when regressed against any of the nine IR and red radiance variables evaluated (Table 3).

The September data, comprised of ~52% live and ~48% dead vegetation (Table 1), also showed the lowest r^2 values for the dry brown biomass canopy variable when regressed against any of the nine IR and red radiance variables (Table 3).

This confirms quantitatively that the IR/red ratio, the square root of the IR/red ratio, the IR − red difference, the VI, and the TVI are primarily sensitive to the green leaf material or photosynthetically active biomass present in the plant canopy.

The IR − red difference, TVI, VI, square root of the IR/red ratio, and IR/red ratio showed the greatest regression significance for the June and September data sets (Table 3). The IR − red difference can be excluded from further

TABLE 1 Statistical Summary of the Biophysical Characteristics of the Sample Plots. A Statistical Description of the Vegetative Canopy Characteristics for (a) The Thirty-Five 1/4 M^2 Sample Plots of Blue Grama Sampled in June 1972, (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
(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	7.93
Dry brown biomass (g/m^2)	20.40–186.42	82.41	48.54	58.90	7.68
Leaf water (g/m^2)	28.03–190.80	92.75	50.93	54.91	8.05
Chlorophyll (mg/m^2)	53.02–778.97	319.58	238.73	74.70	37.75
(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

consideration because it will not compensate for different irradiational conditions.

A 4% range existed between the IR/red ratio, the square root of the IR/red ratio, VI, and TVI for the June data in terms of explaining greater regression variability. A 6% range existed for the September leaf water content variable and the IR/red, square root of the IR/red, VI, and TVI regressions, respectively (Table 3).

TABLE 2 Coefficients of Determination for the Simple Regressions Between the Nine Green and Red 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. DIF = Green − Red, SUM = Green + Red, VI = DIF/SUM, TVI = SQRT (VI + .5).

				SQRT	"Green − Red"				"Green/Red"
Data	Red	Green	Green/Red	(Green/Red)	DIF	SUM	VI	SUM/DIF	TVI
(a) June ($n = 35$)									
Total wet biomass	0.88	0.79	0.82	0.82	0.42	0.85	0.80	0.81	0.81
Total dry biomass	0.80	0.72	0.75	0.75	0.41	0.78	0.73	0.81	0.75
Leaf water content	0.91	0.82	0.86	0.86	0.42	0.88	0.84	0.79	0.85
Dry green biomass	0.82	0.74	0.85	0.85	0.45	0.79	0.83	0.83	0.84
Dry brown biomass	0.32	0.28	0.46	0.46	0.27	0.31	0.43	0.18	0.45
Total chlorophyll	0.91	0.83	0.78	0.78	0.36	0.89	0.76	0.68	0.77
(b) September ($n = 40$)									
Total wet biomass	0.43	0.22	0.34	0.34	0.30	0.36	0.34	0.07	0.34
Total dry biomass	0.25	0.14	0.16	0.16	0.16	0.22	0.16	0.10	0.16
Leaf water content	0.70	0.33	0.67	0.68	0.57	0.56	0.67	0.02	0.67
Dry green biomass	0.41	0.19	0.37	0.37	0.33	0.33	0.37	0.04	0.37
Dry brown biomass	0.07	0.06	0.02	0.02	0.02	0.07	0.02	0.13	0.02
Total chlorophyll	0.36	0.18	0.29	0.30	0.28	0.30	0.30	0.01	0.31

TABLE 3 Coefficients of Determination for the Simple Regressions Between the Nine Red and IR 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. DIF = IR − RED, SUM = IR + RED, VI = DIF/SUM, TVI = SQRT (VI + .5).

Variable	1	2	3	4	5	6	7	8	9
Description	RED	IR	IR/RED	SQRT(IR/RED)	DIF	SUM	VI	SUM/DIF	TVI
(a) June 1972									
Total wet biomass	0.88	0.86	0.86	0.89	0.89	0.00	0.89	0.94	0.90
Total dry biomass	0.80	0.84	0.80	0.83	0.86	0.00	0.84	0.96	0.85
Leaf water content	0.90	0.86	0.90	0.92	0.90	0.00	0.92	0.91	0.92
Dry green biomass	0.82	0.85	0.88	0.90	0.89	0.00	0.91	0.88	0.92
Dry brown biomass	0.32	0.70	0.52	0.55	0.65	0.01	0.56	0.22	0.57
Total chlorophyll	0.91	0.88	0.86	0.86	0.90	0.00	0.86	0.77	0.85
(b) September 1971									
Total wet biomass	0.43	0.64	0.51	0.56	0.64	0.02	0.61	0.00	0.63
Total dry biomass	0.25	0.52	0.32	0.36	0.45	0.05	0.42	0.00	0.44
Leaf water content	0.70	0.68	0.77	0.81	0.85	0.00	0.83	0.00	0.83
Dry green biomass	0.41	0.66	0.52	0.57	0.65	0.03	0.62	0.00	0.64
Dry brown biomass	0.07	0.28	0.10	0.13	0.19	0.09	0.17	0.00	0.19
Total chlorophyll	0.36	0.52	0.41	0.45	0.55	0.02	0.51	0.00	0.53
(c) October 1972									
Total wet biomass	0.67	0.72	0.00	0.00	0.28	0.72	0.00	0.01	0.00
Total dry biomass	0.66	0.71	0.00	0.00	0.27	0.71	0.00	0.01	0.00
Leaf water content	0.68	0.73	0.01	0.00	0.29	0.73	0.00	0.02	0.00
Total chlorophyll	0.66	0.78	0.03	0.03	0.40	0.75	0.03	0.03	0.00

The October data demonstrated conclusively that the various green vegetation measures do not have applicability to dormant vegetation (Table 3; Fig. 7).

The use of the square-root transformation for the IR/red ratio (Nalepka et al., 1977) and TVI (Rouse et al., 1973, 1974) needs to be examined. Rouse et al. (1973, 1974) suggest that the distribution of the VI is Poisson while Nalepka et al. (1977) suggest that the square root of IR/red ratio is more linear. The data analysis for the June data shows the same functional relationship(s) between the total wet biomass and IR/red ratio and square root of the IR/red ratio with the same asymptotic nature for both plots, respectively. The asymptotic properties of the IR/red ratio, square root of the IR/red ratio, VI, and TVI are very similar as are the respective degrees of regression significance (Table 3; Fig. 4).

Phenological Considerations

The spectral manifestations of grass canopy phenology can be inferred from the three sampling periods used for this study. 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 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 ~80% green vegetation and only ~20% dead vegetation (Table 1).

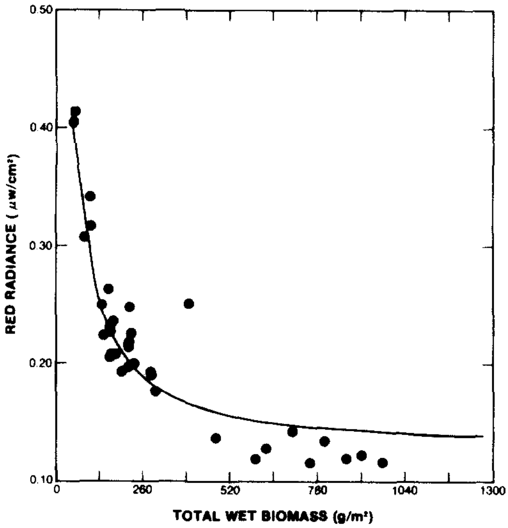
The September analysis results were less significant in a regression sense than the June results, were linear, and had a lower degree of canopy variable intercorrelation than the June results (Tables 3 and 4). Canopy composition at this time was ~52% green vegetation and ~48% dead vegetation (Table 1).

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 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 for the September data (Tables 3 and 4).

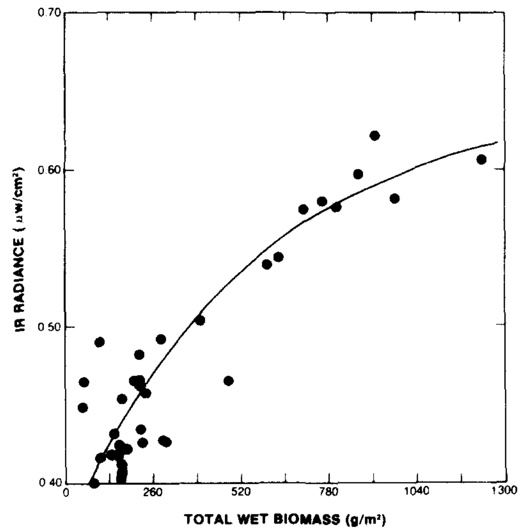
It should be noted that the "chlorophyll" determination for the October sampling period does not present *in vivo* chlorophyll a and b. It is thought to represent chlorophyll decomposition products for this sampling period.

Evaluation of Different IR Bandwidths

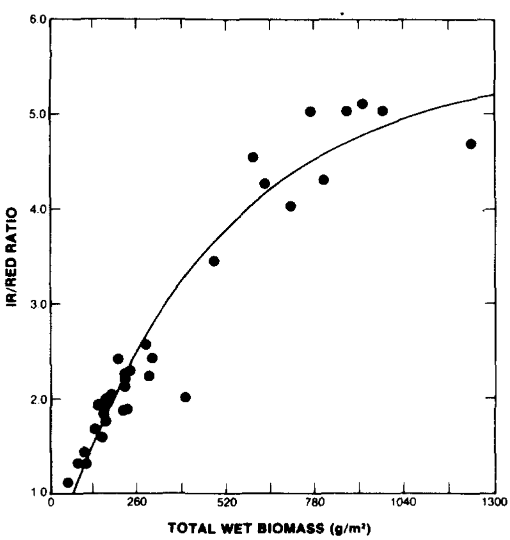
Another aspect of the study was to evaluate the influence of IR bandwidth upon ratio technique applications for



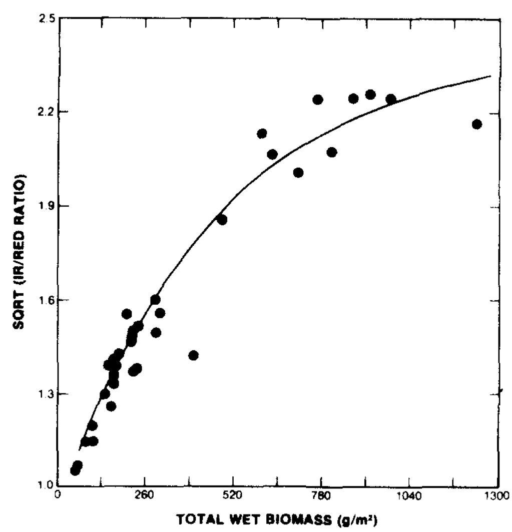
(a) 0.63–0.69 μm
$r^2 = 0.88$
$Y = 0.1233 + 16.7980/X$



(b) 0.75 – 0.80 μm
$r^2 = 0.86$
$Y = 0.65 - \exp(-1.2680 - 0.0017 \cdot X)$

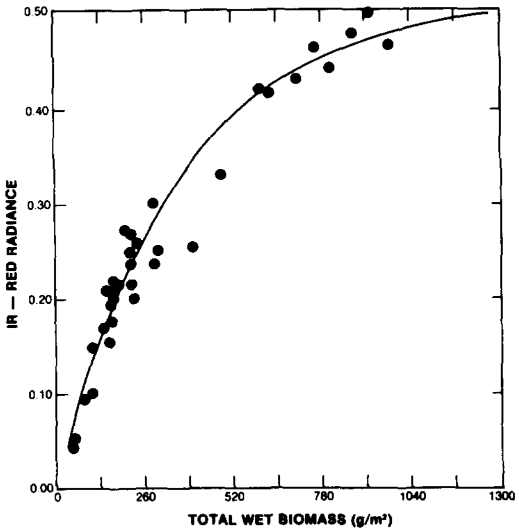


(c) $r^2 = 0.86$
$Y = 5.5 - \exp(1.6641 - 0.0022 \cdot X)$

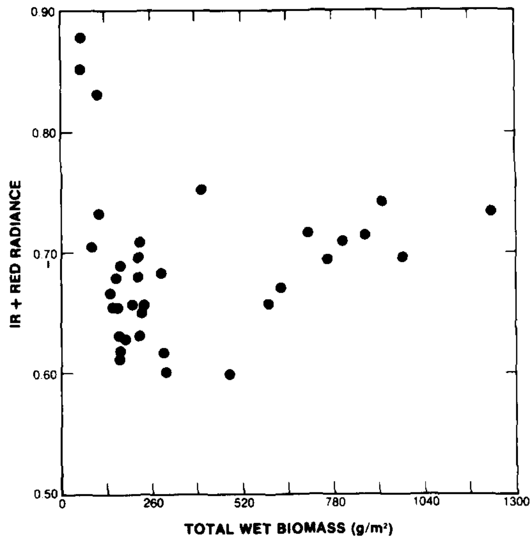


(d) $r^2 = 0.89$
$Y = 2.4 - \exp(0.3926 - 0.00022 \cdot X)$

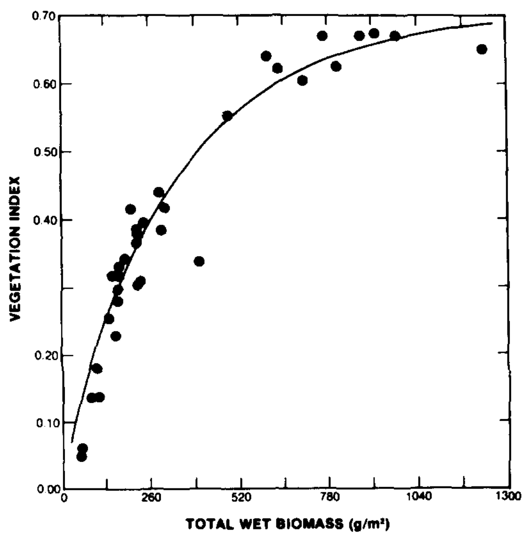
FIGURE 4. The nine radiance variables plotted against the total wet biomass for the 35 plots sampled in June 1972. (a) red radiance, (b) IR radiance, (c) IR/red ratio, (d) square root of the IR/red ratio. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables. Figure continues on next pages.



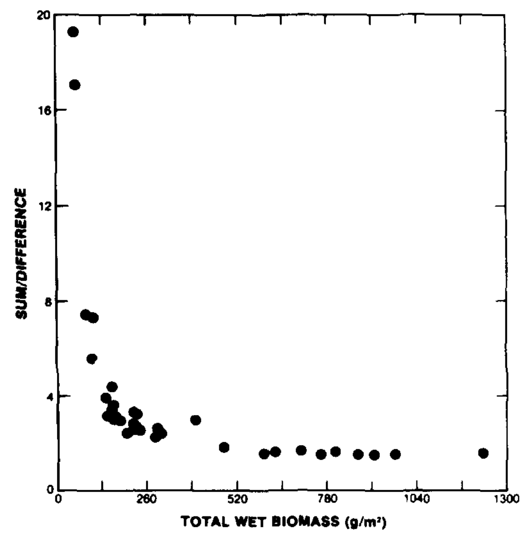
(e) $r^2=0.89$
$Y=0.51-\exp(-0.6713-0.0028\cdot X)$



(f) $r^2=0.00$

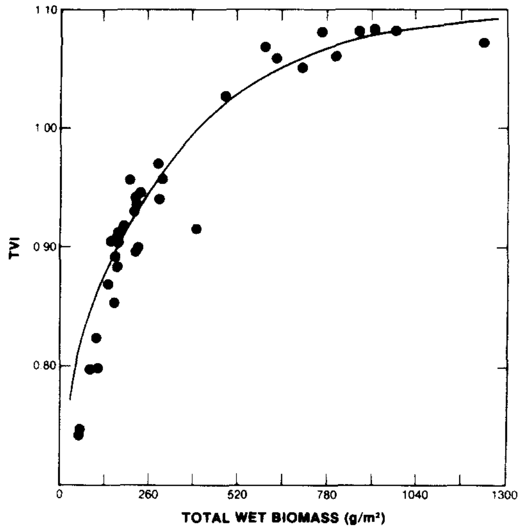


(g) $r^2=0.89$
$Y=0.70-\exp(-0.4207-0.0030\cdot X)$



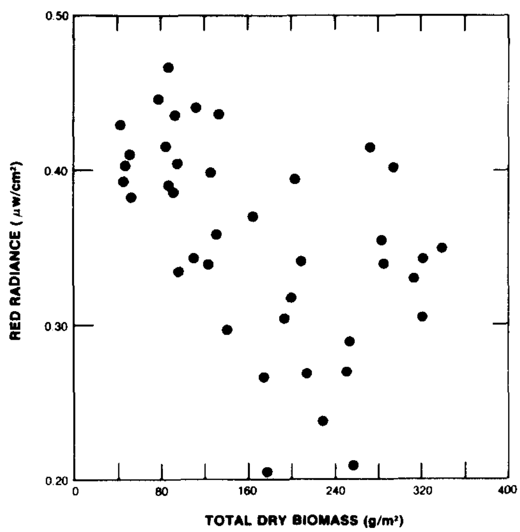
(h) $r^2=0.94$

FIGURE 4. continued. (e) IR−red radiance difference, (f) IR+red radiance sum, (g) vegetation index, (h) sum/difference. Figure continued on next page.

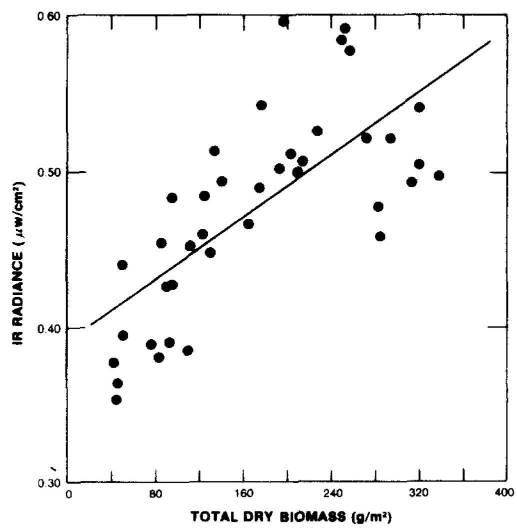


(i) $r^2 = 0.90$
$Y = 1.1 - \exp(-1.1025 - 0.0029 \cdot X)$

FIGURE 4. continued. (i) transformed vegetation index.

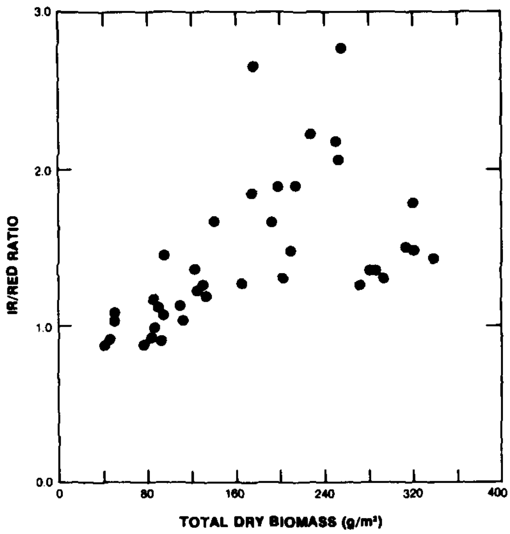


(a) 0.63 – 0.69 μm
$r^2 = 0.25$

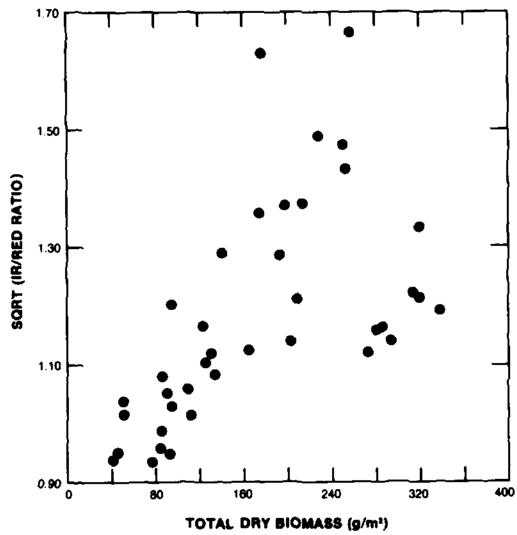


(b) 0.75–0.80 μm
$r^2 = 0.52$
$Y = 0.38906 + 0.00050 \cdot X$

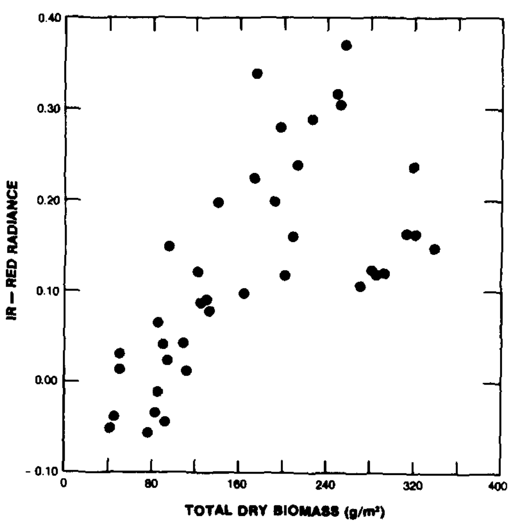
FIGURE 5. The nine radiance variables plotted against the total dry biomass for the 40 plots sampled in September 1971. (a) red radiance, (b) IR radiance, Figure continues on next pages.



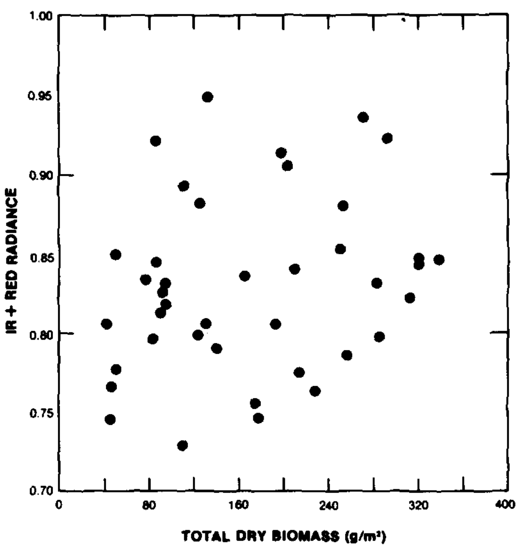
(c) $r^2=0.32$



(d) $r^2=0.36$

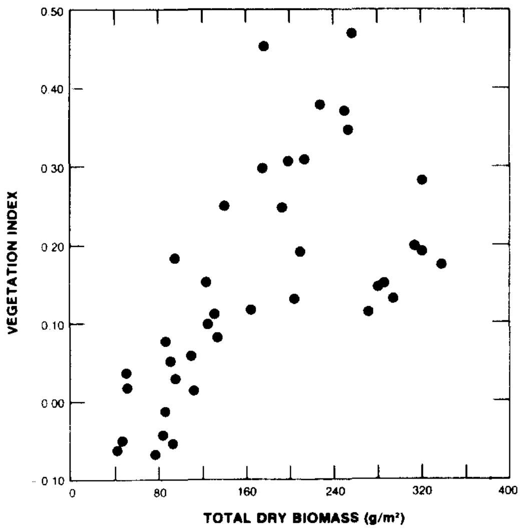


(e) $r^2=0.45$

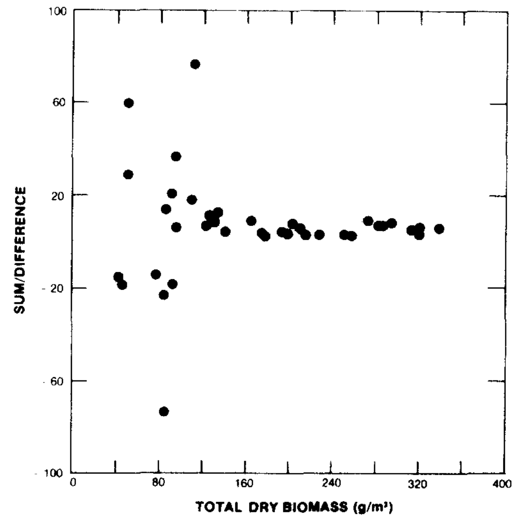


(f) $r^2=0.05$

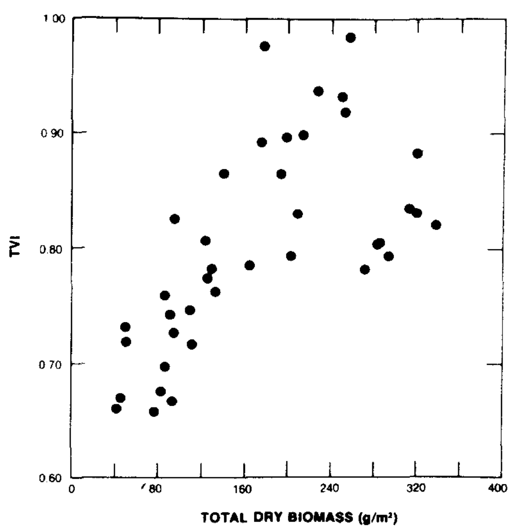
FIGURE 5. continued. (c) IR/red ratio, (d) square root of the IR/red ratio. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables. (e) IR−red radiance difference, (f) IR+red radiance sum. Figure continued on next page.



(g) $r^2 = 0.42$



(h) $r^2 = 0.00$



(i) $r^2 = 0.44$

FIGURE 5. continued. (g) vegetation index, (h) sum/difference, (i) transformed vegetation index.

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
(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

estimating the various canopy variables for the June data. 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.

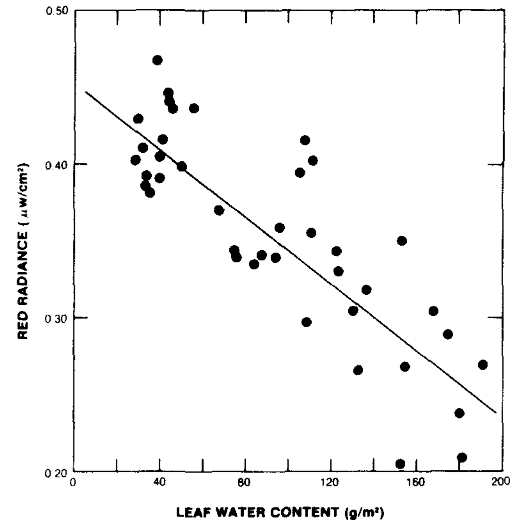
Conclusions

1. The IR/red ratio and related IR and red linear combinations were found to be superior to the green/red ratio and related green and red linear combinations for monitoring vegetation.

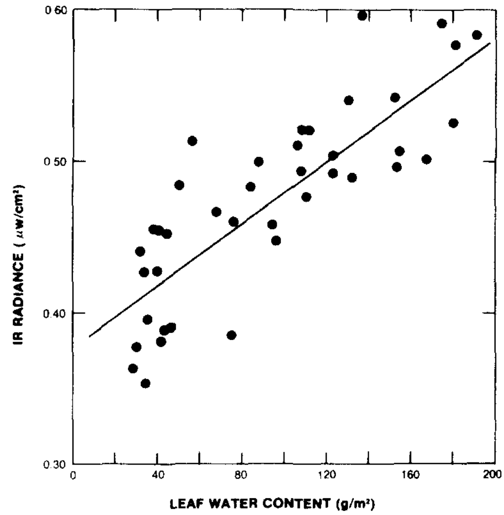
2. The IR/red ratio, square root of the IR/red ratio, IR − red difference, VI, and TVI are sensitive to the amount of photosynthetically active vegetation present in the plant canopy. All were found to be very similar for estimating the photosynthetically active biomass.

3. The asymptotic properties of the IR/red ratio, square root of the IR/red ratio, IR − red difference, VI, and TVI were very similar for high green biomass situations. The square-root transformation did not result in a more linear situation.

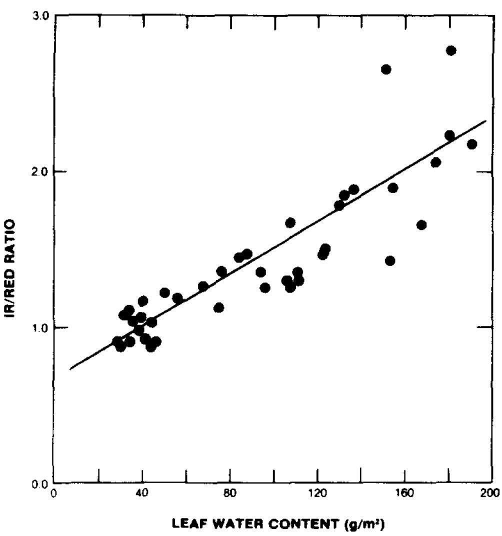
4. The accumulation of standing dead vegetation in the canopy had a linearizing effect upon the various green vegetation measures.



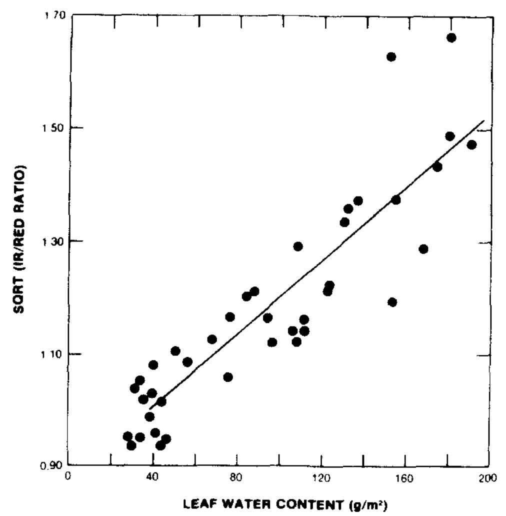
(a) 0.63–0.69 μm
$r^2 = 0.70$
$Y = 0.45534 - 0.00108 \cdot X$



(b) 0.75–0.80 μm
$r^2 = 0.68$
$Y = 0.37860 + 0.00102 \cdot X$

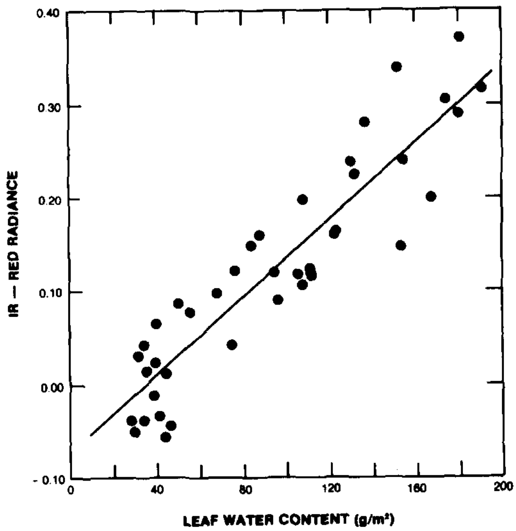


(c) $r^2 = 0.77$
$Y = 0.65945 + 0.00813 \cdot X$

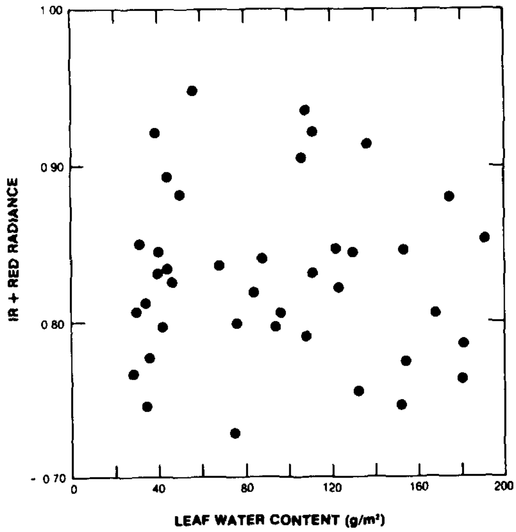


(d) $r^2 = 0.81$
$Y = 0.86788 + 0.00331 \cdot X$

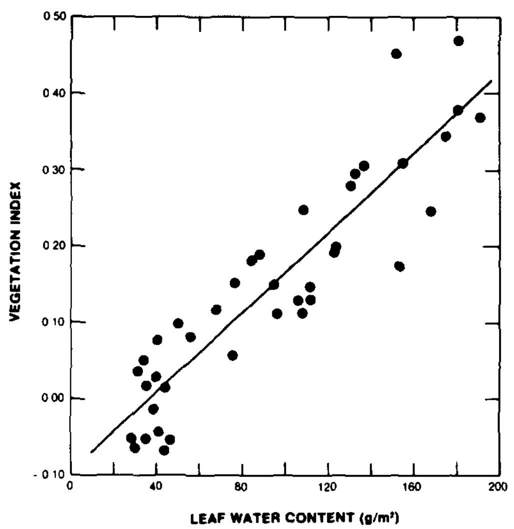
FIGURE 6. The nine radiance variables plotted against the leaf water content for the 40 plots sampled in September 1971. (a) red radiance, (b) IR radiance, (c) IR/red ratio, (d) square root of the IR/red ratio. Figure continued on next pages.



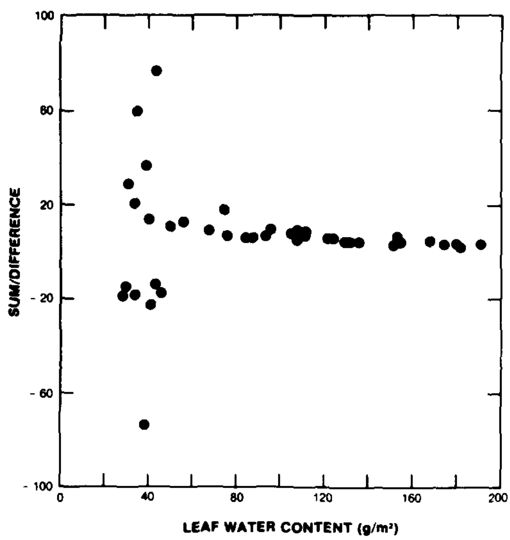
(e) $r^2 = 0.85$
$Y = -0.07673 + 0.00211 \cdot X$



(f) $r^2 = 0.00$

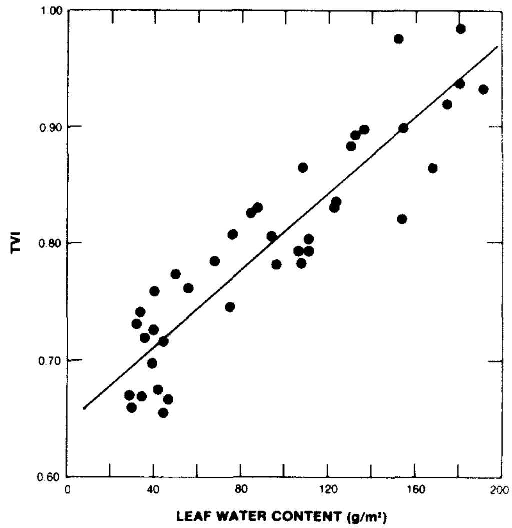


(g) $r^2 = 0.83$
$Y = -0.09752 + 0.00261 \cdot X$



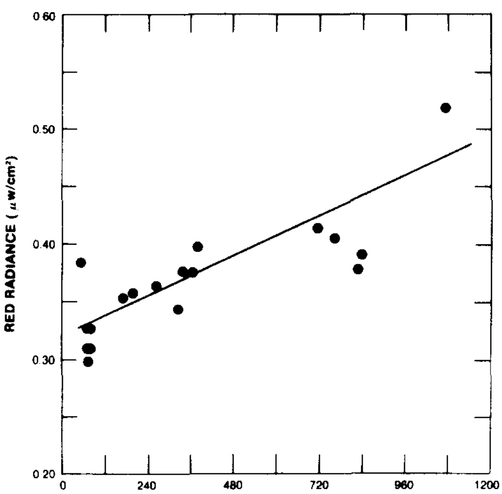
(h) $r^2 = 0.00$

FIGURE 6. continued. (e) IR − red radiance difference, (f) IR + red radiance sum, (g) vegetation index, (h) sum/difference. Figure continued on next page.

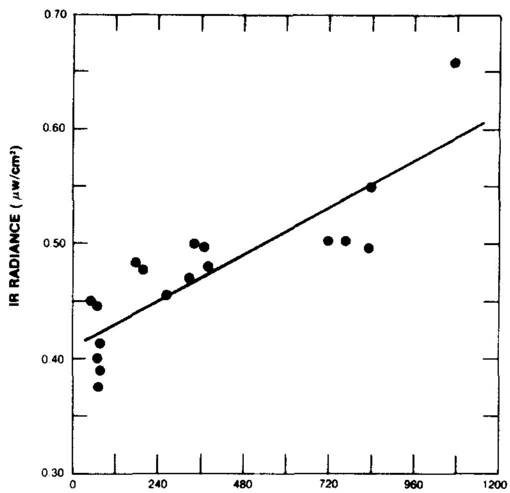


(i) $r^2 = 0.83$
$Y = 0.64843 + 0.00161 \cdot X$

FIGURE 6. continued. (i) transformed vegetation index.

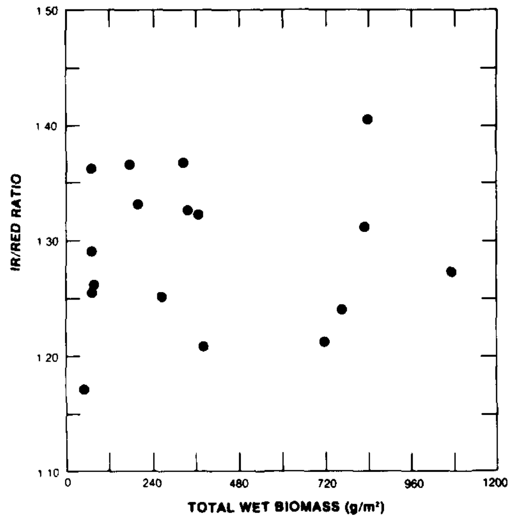


(a) 0.63–0.69 μm
$r^2 = 0.67$
$Y = 0.32159 + 0.00013 \cdot X$

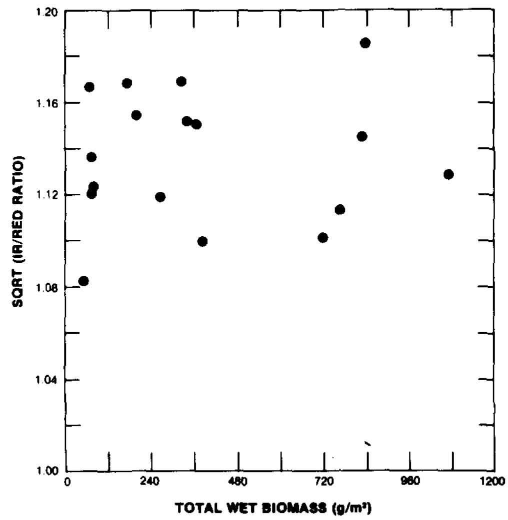


(b) 0.75–0.80 μm
$r^2 = 0.72$
$Y = 0.41285 + 0.00017 \cdot X$

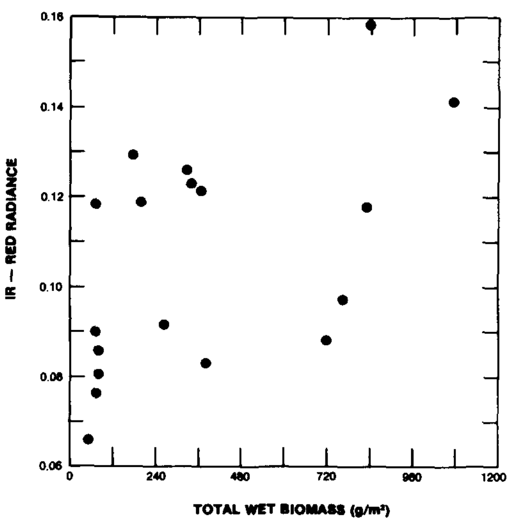
FIGURE 7. The nine radiance variables plotted against the total wet biomass for the 18 plots sampled in October 1972. (a) red radiance, (b) IR radiance. Figure continued on next page.



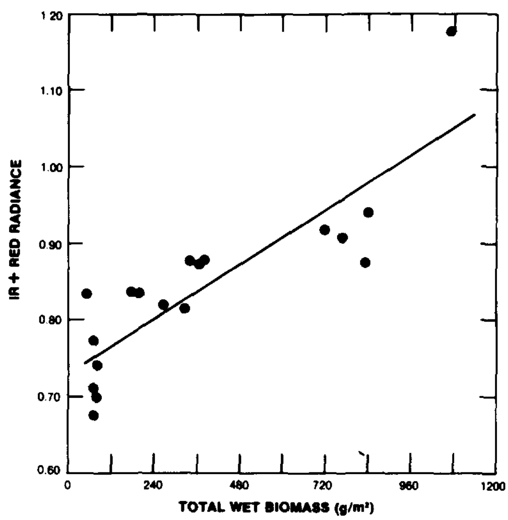
(c) $r^2 = 0.00$



(d) $r^2 = 0.00$

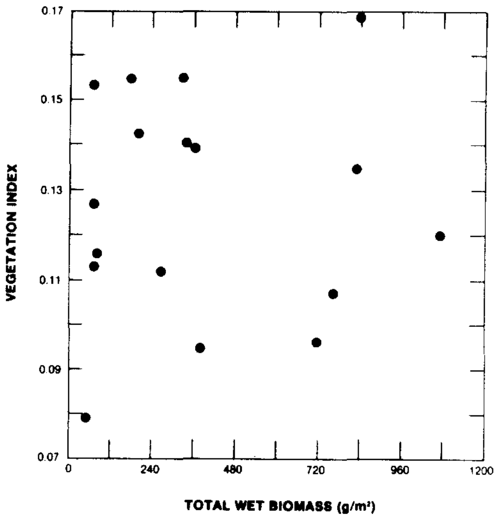


(e) $r^2 = 0.28$

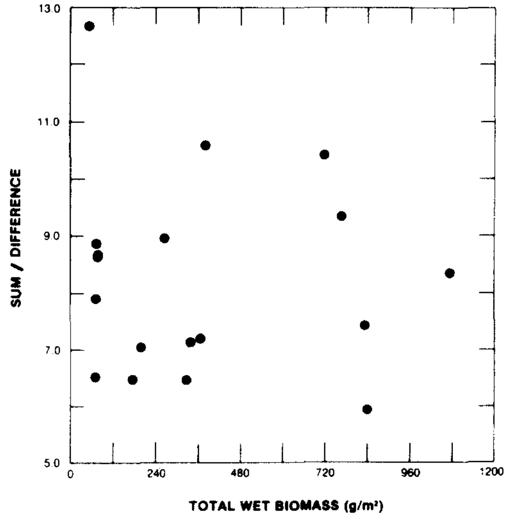


(f) $r^2 = 0.72$
$Y = 0.73444 + 0.00029 \cdot X$

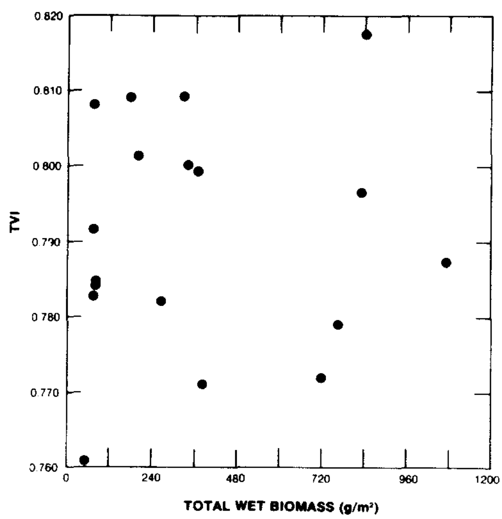
FIGURE 7. continued. (c) IR/red ratio, (d) square root of the IR/red ratio. Refer to Table 3 for the r^2 values between the nine radiance variables and the other five plot variables, (e) IR − red radiance difference, (f) IR + red radiance sum. Figure continued on next page.



(g) $r^2=0.00$



(h) $r^2=0.01$



(i) $r^2=0.00$

FIGURE 7. continued. (g) vegetation index, (h) sum/difference, (i) transformed vegetation index.

5. The regression significance for the different IR bandwidths of 0.75–0.80, 0.80–0.90, and 0.75–0.90 μm were evaluated and found to be extremely similar when used with the red radiance or used in the various linear combinations.

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