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# Relationship of Red and Photographic Infrared Spectral Radiances to Alfalfa Biomass, Forage Water Content, Percentage Canopy Cover, and Severity of Drought Stress

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# RELATIONSHIP OF RED AND PHOTOGRAPHIC INFRARED SPECTRAL RADIANCES TO ALFALFA BIOMASS, FORAGE WATER CONTENT, PERCENTAGE CANOPY COVER, AND SEVERITY OF DROUGHT STRESS *


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# RELATIONSHIP OF RED AND PHOTOGRAPHIC INFRARED SPECTRAL RADIANCES TO ALFALFA BIOMASS, FORAGE WATER CONTENT, PERCENTAGE CANOPY COVER, AND SEVERITY OF DROUGHT STRESS

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## ABSTRACT

Red and photographic infrared spectral data were collected using a hand-held radiometer for two cuttings of alfalfa. Significant linear and non-linear correlation coefficients were found between the spectral variables and plant height, biomass, forage water content, and estimated canopy cover for the earlier alfalfa cutting. The alfalfa of later cutting experienced a period of severe drought stress which limited growth. The spectral variables were found to be highly correlated with the estimated drought scores for this alfalfa cutting.

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# RELATIONSHIP OF RED AND PHOTOGRAPHIC INFRARED SPECTRAL RADIANCES TO ALFALFA BIOMASS, FORAGE WATER CONTENT, PERCENTAGE CANOPY COVER, AND SEVERITY OF DROUGHT STRESS

## INTRODUCTION

Remote sensing techniques have been reported for estimating forage production (Pearson and Miller, 1972; Rouse et al., 1973; Deering et al, 1975; Reginato et al., 1978; and others) and estimating yields of nonforage agricultural crops (Thomas et al., 1967; Hammond, 1975; Morain and Williams, 1975; Colwell et al., 1977; Idso et al., 1977a and b; and others).

Recently, the hand-held radiometer technique for monitoring agricultural crop condition has been reported (Tucker et al., 1979a and b). This new approach allows for the collection of *in situ* radiance data in the visible and near infrared portions of the reflective spectral region (0.4 – 2.5 $\mu$m).

Hand-held radiometers are ideally suited for small-scale experimental purposes. They require only minimal logistic support and the resulting data can be reduced and analyzed on pocket calculators if necessary. Because of their light weight and self-contained battery power supplies, they are extremely mobile and hence can cover a great deal of experimental territory in a small amount of time. These attributes make hand-held radiometers well suited for collection of "ground-truth" data in support of satellite experiments and also for nondestructive collection of crop condition data from crop canopies (Tucker et al., 1979b).

In this paper, we report on an experiment in which a ground-based, hand-held radiometer was used to estimate alfalfa forage yield and related agronomic variables such as crop canopy cover, plant height, and drought stress.

## METHODS AND LOCATION

Two established alfalfa fields located on the U.S. Department of Agriculture's Beltsville Agricultural Research Center were selected for this study. In the first field, fifteen 1- x 4-m plots were designated following the second alfalfa cutting in late June 1977. Three plots were harvested per week for the 5-week period corresponding to the third cutting. In a second field, an additional fifteen 1- x 4-m plots were designated following the third cutting in early August and were harvested, three plots per week, for the 5-week period corresponding to the fourth cutting. Agronomic notes pertaining to average plant height (cm), estimated percent crop canopy cover, and estimated percent drought stress were recorded weekly along with total wet and dry biomass harvested from each of the three plots. Plant heights were measured with a meter stick on three to five plants per plot and an average plant height was determined; percent canopy cover and percent drought stress measurements were visual estimates of the percentage of the ground covered by the leaf canopy and of the percentage of the canopy wilting due to drought stress, respectively. All agronomic variables were measured or estimated by the same observer throughout the study.

Immediately prior to the weekly harvest, four pairs of *in situ* spectral measurements were collected from each plot to be harvested, using a hand-held radiometer (Pearson et al., 1976) configured to measured red (0.65-0.70 $\mu$m) and photographic infrared (0.775-0.825 $\mu$m) (IR) radiances. The red and infrared measurements were used to generate the IR/red radiance ratio and the normalized difference vegetation index (VI) of (IR−red)/(IR+red) after Rouse et al. (1973). All spectral measurements were made between the hours of 1100 and 1500 e.d.t., were normal to the plot, and were taken from a height of approximately 1.5 m above the soil surface. The four pairs of spectral measurements and the two transformations were averaged to account for the spatial variation and the averages were used thereafter in the data analysis.

Prior to recording the radiance values for each experimental plot, a $BaSO_4$ panel was used to make an irradiance reference reading from which an atmospheric correction factor could be calculated. This enabled the data analysis to be performed in both the radiance and in the reflectance modes.

The wet biomass measurements were collected by harvesting the entire 1- x 4-m plot. The fresh weight of the harvested material was recorded. For each plot a sample (approximately 1 kg) of the harvested material was taken, weighed, dried, and reweighed to obtain an estimate of dry matter percentage. The dry biomass production (dry biomass = wet biomass * dry matter percentage) and forage water content (wet biomass – dry biomass) were then calculated and expressed in grams per square meter.

Correlations among all measurements were calculated to quantify the relationships between the spectral variables and the agronomic variables. These analyses were conducted using both the reflectance data (i.e., adjusting for solar intensity) and the uncorrected radiance data. Previous studies by the authors have shown that the IR/red radiance ratio and the radiance VI effectively compensate for irradiational variability (Tucker et al., 1979b). Therefore, the experimental results presented herein will use the radiance data because this is what is measured by satellites. The reflectance data results were identical in terms of statistical significance to those using the radiance data.

## RESULTS AND DISCUSSION

### Third Alfalfa Cutting

Highly significant linear correlation coefficients were found for all the relationships between the four radiance variables and the agronomic variables for the third cutting (Table 1). Several nonlinear significant correlation coefficients were also found. Figures 1 and 2 show the response of the four radiance variables to increasing percent canopy cover and dry biomass accumulation measured over the 5-week growing period. The red radiance generally decreased as percent cover and biomass increased (Fig. 1a and 2a). This was due to increased chlorophyll absorption by larger quantities of vegetation. The photographic infrared radiance, IR/red ratio, and VI increased as percent cover and biomass increased (Fig. 1b, c, d, and 2b, c, d). The opposite slopes for the red and IR spectra with increasing canopy cover and biomass are consistent with previously published reports (Gausman et al., 1976; Tucker, 1977). Similar spectral responses were found for plant height, wet biomass, and forage water content. Plant heights increased from 14 to 48 cm from week 1 to week 5.

The most striking effect for the third cutting was the asymptotic or saturation effect produced by increasing amount of alfalfa canopy, particularly for the red radiance and the VI. Figures 1 and

Table 1

Linear Correlation Coefficients Between Four Spectral Variables and Six Agronomic Variables for the Third Alfalfa Cutting at the Beltsville Agricultural Research Center, Maryland

| Spectral | (n=15) Plant height | (n=15) Estimated canopy cover | (n=15) Wet biomass | (n=15) Dry biomass | (n=15) Forage water content |
|---|---|---|---|---|---|
| | (cm) | (%) | ($g/m^2$) | ($g/m^2$) | ($g/m^2$) |
| Red | -0.89** | -0.82** | -0.84** | -0.81** | -0.85** |
| IR | 0.90** | 0.87** | 0.92** | 0.85** | 0.93** |
| IR/Red | 0.98** | 0.93** | 0.96** | 0.91** | 0.97** |
| Vegetation index | 0.96** | 0.89** | 0.91** | 0.87** | 0.93** |

**Indicates significance at the 0.01 level of probability.

2 show that after vegetative cover reached approximately 50% (week 3-4) little additional spectral response was recorded for increasing canopy cover and biomass accumulation. A similar observation was made for plant height and forage water content. This asymptotic spectral response of the plant canopy with respect to increasing percent cover and associated green leaf density was also reported by Gausman et al. (1976) and Tucker (1977).

It is apparent that the usefulness of spectral data such as ours for estimating canopy cover and/or dry biomass is limited by these saturation or asymptotic effects. The reason for the difference in asymptotic properties between the IR/red radiance ratio and the VI is not understood at the present time. However, previous work by Colwell et al. (1977) suggested that the IR/red ratio was more linear in response and thus more useful as a predictive tool than the VI. This appeared to be true in our study (Fig. 1c, d, and 2c, d).

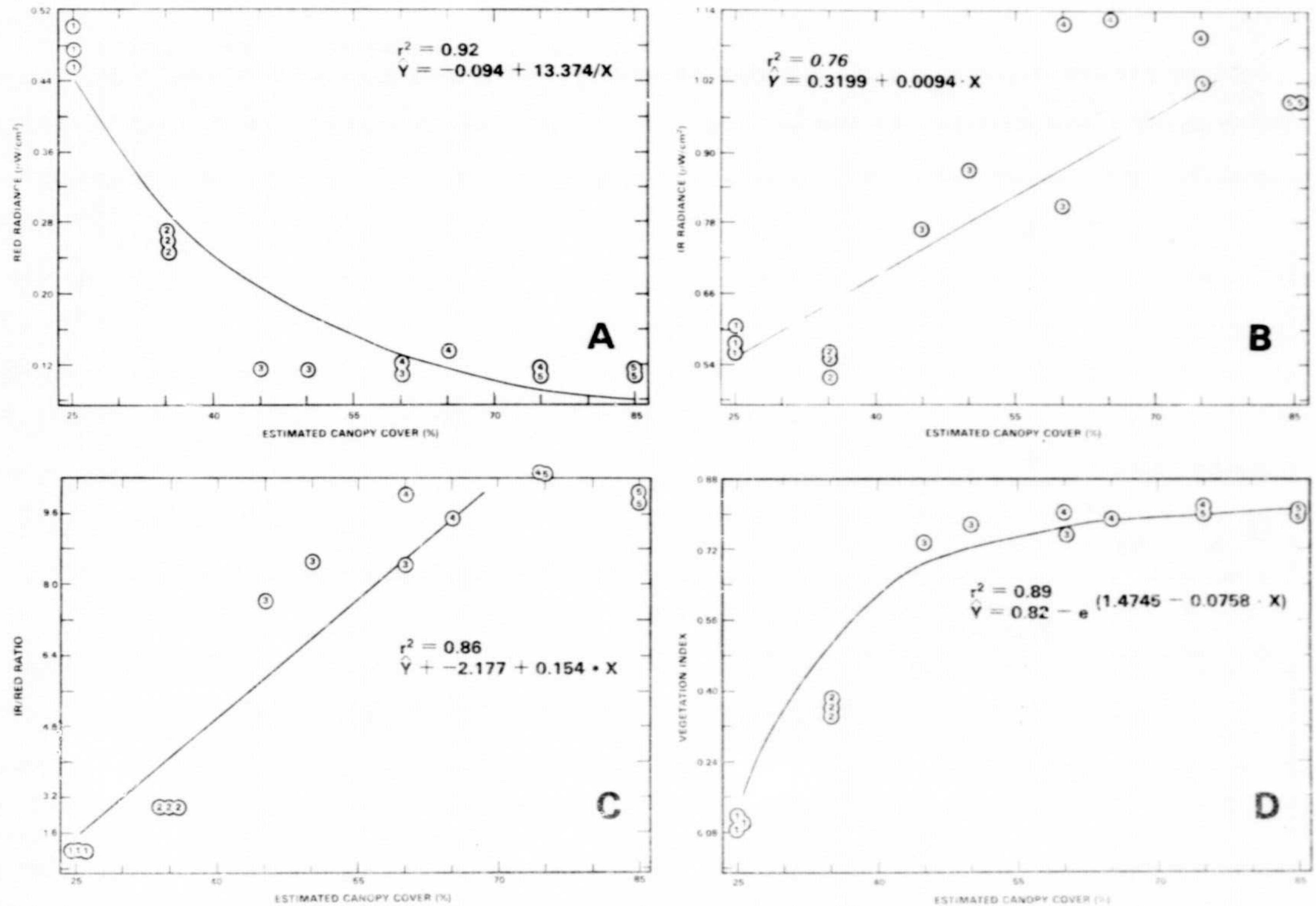


Figure 1 – (a) Red radiance, (b) photographic infrared (IR) radiance, (c) IR/red radiance ratio, and (d) vegetation index (VI) spectral measurements from a hand-held, two-band radiometer as related to estimated canopy cover over the 5-week growth of third-cutting alfalfa, June 30-July 28, 1977. Three plots were scored each week. The numbers inside each data point correspond to the week of sampling for the third cutting.

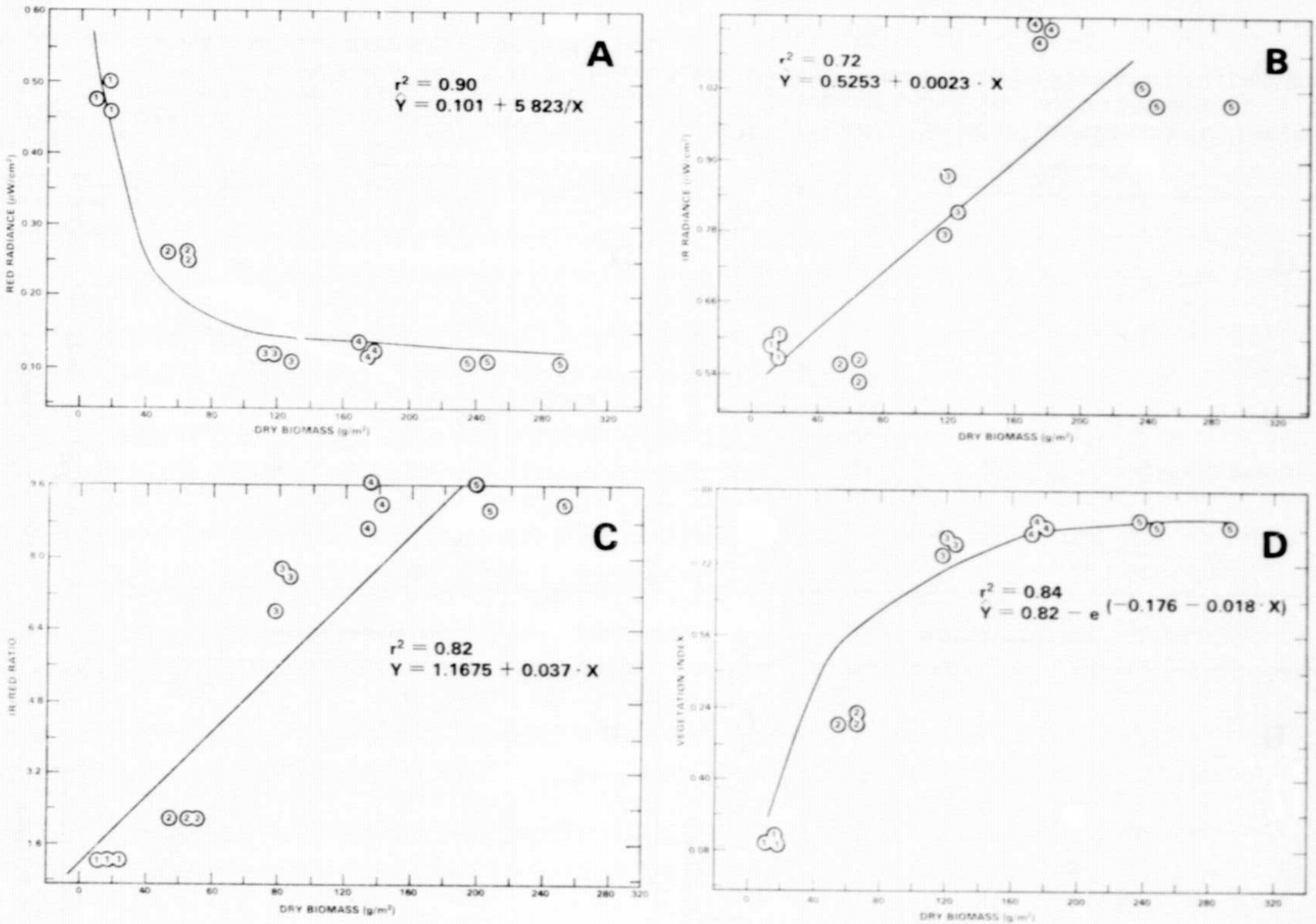


Figure 2 – (a) Red radiance, (b) photographic infrared (IR) radiance, (c) IR/Red radiance ratio, and (d) vegetation index (VI) spectral measurements from a hand-held, two-band radiometer as related to dry biomass over the 5-week growth of third-cutting alfalfa, June 30-July 28, 1977. Three plots were harvested and weighed each week. The numbers inside each data point correspond to the week of sampling for the third cutting.

## Fourth Alfalfa Cutting

The Fourth alfalfa cutting was quite different from the third cutting as a consequence of a period of severe drought. A small amount of growth was obtained. Maximum estimated canopy cover for the fourth cutting was only 50%; it had been 85% for the third cutting. Plant heights never exceeded 20 cm.

Estimated drought scores were taken along with the other agronomic measurements to assess vegetative condition. Highly significant correlations between the four spectral variables and estimated drought stress and forage water content were obtained from the fourth cutting. This indicated that the spectral measurements were sensitive to the severity of the drought stress (Table 2, Fig. 3).

In addition, a highly significant negative correlation ($r = -0.85$, $n = 9$) was obtained between the estimated drought scores and forage water content (Fig. 4), indicating a restriction of water uptake within the affected alfalfa canopy. Previous work has suggested a strong interrelationship between the photosynthetic leaf area, chlorophyll, and the forage water content. It was theorized that the chlorophyll concentration is reduced by photooxidation at a rate dependent upon the leaf water potential when the forage water content becomes limiting (Tucker et al., 1975). In any event, drought stress would be expected to reduce the *in vivo* chlorophyll concentration by limiting the water available for photosynthesis. This would be more apparent spectrally in the red (chlorophyll absorption region) than in the photographic infrared reflective region. Our data support this contention (Fig. 3).

Recent work by Thompson and Wehmanen (1979) has reported a general agreement between the Landsat derived green index number (GIN) (after Kauth and Thomas, 1976) and ground-based assessments of drought stress. The GIN is one of several "green vegetation indices" (others being the vegetation index, the ir/red ratio, etc.) which are sensitive to the photosynthetically active leaf area of plant canopies (Deering, 1978; Tucker, 1979). Thompson and Wehmanen (1979) were only able to qualitatively compare Landsat MSS imagery and ground-based areas suffering from drought

Table 2. Linear Correlation Coefficients Between Four Spectral Variables and Six Agronomic Variables for the Fourth Alfalfa Cutting at the Beltsville Agricultural Research Center, Maryland

| Spectral variable | (n=15) Plant height | (n=15) Estimated canopy cover | (n=15) Wet biomass | (n=15) Dry biomass | (n=15) Forage water content | (n=9) Estimated drought stress |
|---|---|---|---|---|---|---|
| | (cm) | (%) | ($g/m^2$) | ($g/m^2$) | ($g/m^2$) | (%) |
| Red | -0.38 ns | -0.42 ns | -0.64** | -0.24 ns | -0.83** | 0.89** |
| IR | -0.62* | -0.54* | -0.66** | -0.42 ns | -0.72** | 0.67* |
| IR/Red | 0.17 ns | 0.25 ns | 0.51 ns | 0.12 ns | 0.71** | -0.81** |
| VI | 0.19 ns | 0.28 ns | 0.52* | 0.11 ns | 0.74** | -0.84** |

*Indicates significance at the 0.05 level of probability.
**Indicates significance at the 0.01 level of probability.

stress. It is difficult to perform detailed plant canopy sampling which quantitatively represents Landsat pixel areas (~0.45 ha) in terms of drought stress, etc. However, when one combines the large area qualitative Landsat results of Thompson and Wehmanen (1979) with the small scale quantitative results reported herein, the case for remote sensing detection of drought stress is strengthened.

It must be emphasized that the results reported herein and those of Thompson and Wehmanen (1979) were not directly sensitive to drought stress *per se*. They were sensitive to the photosynthetically active leaf area which has been decreased as a result of drought stress. None of the bands used by Thompson and Wehmanen (1979) or by the work reported herein were directly sensitive to the leaf water content (Tucker, 1980). Landsat-D's thematic mapper (TM)*, by contrast, will have two bands which will be directly sensitive to the leaf water content. The bands in question, TM5 (1.55-1.75 μm) and TM6 (2.08-2.30 μm), offer the possibility of direct assessment of plant canopy drought stress (Tucker, 1980).

*Scheduled for launch in late 1981.

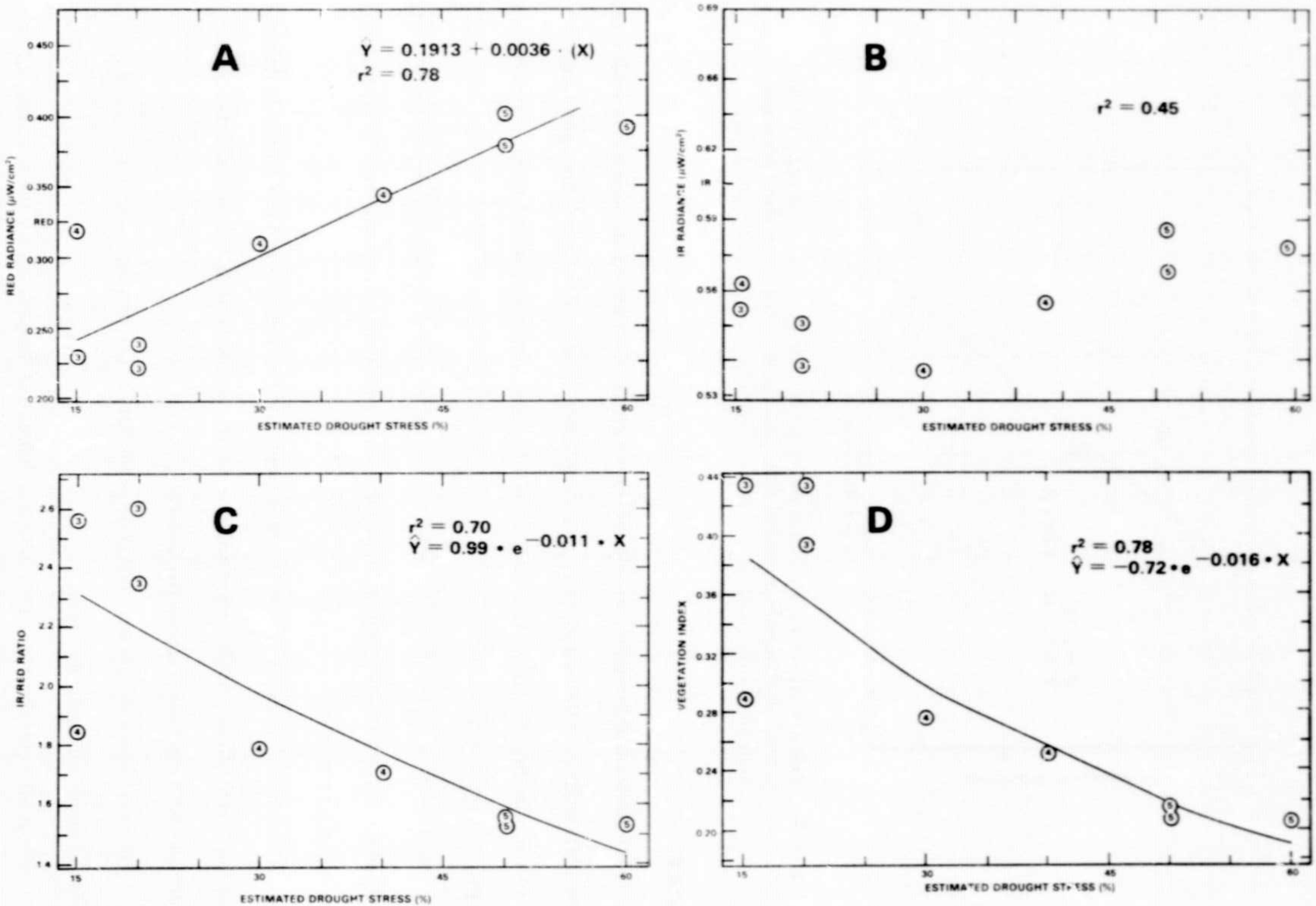


Figure 3 – (a) Red radiance, (b) photographic infrared (IR) radiance, (c) IR/red radiance ratio, and (d) vegetation index (VI) radiance measurements from a hand-held, two-band radiometer as related to percentage estimated drought stress over a 3-week period for the fourth-cutting alfalfa, August 19-September 19, 1977. Three plots were scored each week by estimating the percentage of the canopy wilted due to drought stress. The numbers inside each data point correspond to the week of sampling for the fourth cutting.

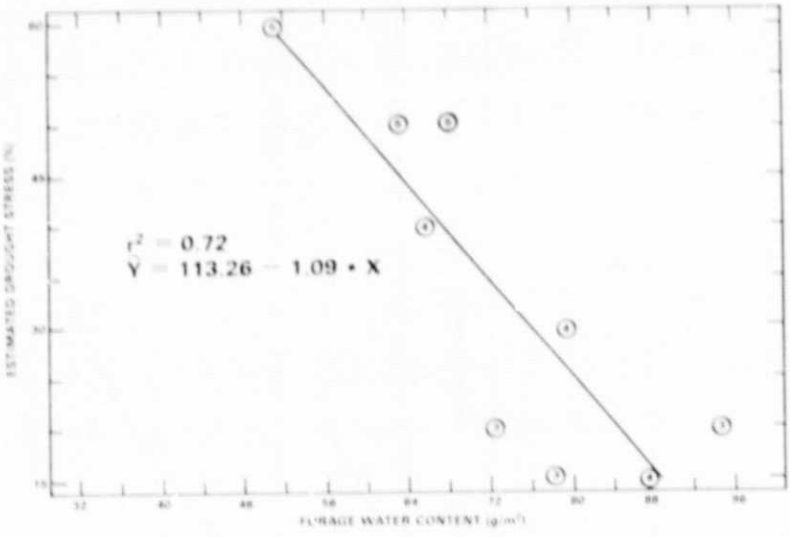


Figure 4 – Relationship between forage water content and estimated percent drought scored on drought-stressed alfalfa, September 1977. The numbers inside each plot correspond to the week of sampling for the fourth cutting.

## SUMMARY

1. For alfalfa, highly significant relationships were found between the spectral variables (red radiance, photographic infrared radiance, IR/red radiance ratio, and VI) and the agronomic variables (plant height, estimated canopy cover, wet biomass, dry biomass, and forage water content for the third alfalfa cutting.

2. Saturation or asymptotic effects limited the usefulness of the spectral data for estimating the agronomic variables at high amounts of canopy cover or biomass. This was more pronounced for the red radiance and VI.

3. A significant relationship was found between the spectral data and the estimated drought stress for the fourth alfalfa cutting. In addition, a significant relationship was found between estimated drought stress and the forage water content.

4. Spectral measurements were not good predictors of dry biomass, plant height, and canopy cover under drought conditions.

5. Our results corroborate the usefulness of hand-held radiometers for the collection of nondestructive argronomic data.

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