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LARS Technical Report 111484
NASA-Johnson Space Center
Contract No. NAS9-16528

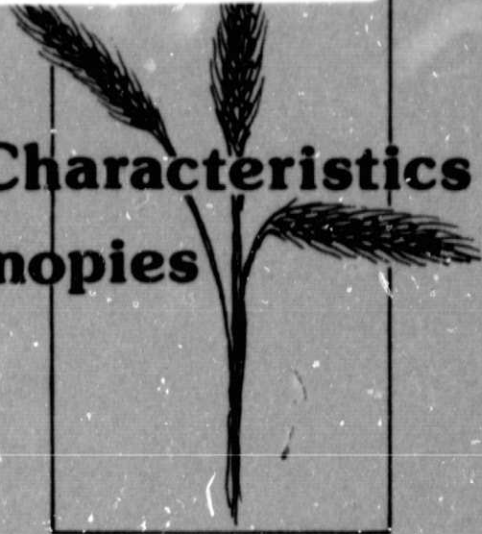
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(E85-10080 NASA-CE-171843) GROWTH AND REFLECTANCE CHARACTERISTICS OF WINTER WHEAT CANOPIES (Purdue Univ.) 21 p EC A02/MF A01 CSCL 02C N85-19494
Unclas
G3/43 00080

Growth and Reflectance Characteristics of Winter Wheat Canopies

by

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1. Report No	2. Government Accession No	3. Recipient's Catalog No	
4. Title and Subtitle Growth and Reflectance Characteristics of Winter Wheat Canopies		5. Report Date Nov. 14, 1984	
		6. Performing Organization Code	
7. Author(s) L.D. Hinzman, M.E. Bauer, and C.S.T. Daughtry		8. Performing Organization Report No 111484	
9. Performing Organization Name and Address Laboratory for Applications of Remote Sensing Purdue University 1291 Cumberland Ave. West Lafayette, IN 47906-1399		10. Work Unit No.	
		11. Contract or Grant No. NAS9-16528	
		13. Type of Report and Period Covered Technical	
12. Sponsoring Agency Name and Address NASA Johnson Space Center Houston, TX 77058		14. Sponsoring Agency Code	
15. Supplementary Notes			
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17. Key Words (Suggested by Author(s)) N fertilization, remote sensing, <u>Triticum aestivum</u> L., multispectral, leaf area index, phytomass		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

NAS9-16528
LARS 111484

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OF WINTER WHEAT CANOPIES

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November 1984

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ABSTRACT

A valuable input to crop growth and yield models would be estimates of current crop condition. If multispectral reflectance indicates crop condition, then remote sensing may provide an additional tool for crop assessment. Field experiments were conducted on a typical Argiaquoll at the Purdue Agronomy Farm, West Lafayette, IN to determine the effects of nitrogen fertilization on the spectral reflectance and agronomic characteristics of winter wheat (Triticum aestivum L.). The fertilization treatments consisted of 0, 60, and 120 kg N/ha, applied as urea in the spring. Spectral reflectance was measured 11 times during the 1979 growing season and 10 times during the 1980 growing season with a spectroradiometer (Exotech 20C) in the 400 to 2400 nm wavelength region. Agronomic data included total leaf N concentration, leaf chlorophyll concentration, stage of development, leaf area index, plant moisture, and fresh and dry phytomass. Relationships between spectral and agronomic variables were developed using data from 1979 and tested with data from 1980.

N deficiency caused increased visible, reduced near infrared, and increased middle infrared reflectance. These changes were related to lower levels of chlorophyll and reduced leaf area in the N deficient plots. Green LAI, an important descriptor of wheat canopies, could be reliably estimated with multispectral data. This study demonstrates the potential of remote sensing in distinguishing stressed from healthy crops and suggests that multispectral imagery may be useful for monitoring crop condition.

Additional Index Words: N fertilization, remote sensing, Triticum aestivum L., multispectral, leaf area index, phytomass

INTRODUCTION

Remote sensing is rapidly becoming a practical tool for obtaining information about the earth's resources. Agriculture is one area that can benefit greatly from the technology of remote sensing. Through an understanding of the interaction of solar radiation with vegetation, an accurate assessment of crop condition may be possible. This would be useful for more efficient and economic determination of the extent and severity of drought, diseases, insect infestations, and nutrient deficiencies. Remote sensing may provide the vehicle for these applications. A capability to remotely sense variables related to crop condition would enable yield models to be implemented in surveys of large areas.

Satellite measurements of spectral radiance have been successfully used for identification of crop species and area estimation (MacDonald and Hall, 1980); however, detecting and recognizing crop stress using remote sensing is a more difficult task (Bauer, 1975). Nitrogen deficiency, a problem common to field crops over much of the world, is a systemic stress characterized in wheat by leaf chlorosis, reduced net assimilation and relative growth rates, and lower leaf area index (LAI), phytomass, and grain yield (Osman et al., 1977). These characteristics, as well as ease of inducing N stress experimentally, make it an ideal stress to determine the potential of multispectral remote sensing for crop condition assessment.

Laboratory studies have shown the effects of nutrient deficiencies on the spectral reflectance and transmittance of single leaves (e.g., Al-Abbas et al., 1974), but there have been relatively few field measurements of crop canopies undergoing stress. By measuring the spectral reflectance in corn canopies, Walburg et al. (1982) were able to distinguish four levels of N deficiency. The reflectance differences were related to leaf chlorophyll and total N concentrations, LAI, and percent soil cover. Stanhill et al. (1972) found that the spectral response of N-deficient wheat canopies was primarily related to differences in total phytomass and only secondarily to leaf optical properties and canopy geometry. Spectral measurements related to canopy senescence rates and green leaf area duration were used by Pinter et al. (1981) to estimate grain yields of wheat and barley.

The objectives of this research were to (1) determine the seasonal changes in agronomic and spectral properties of winter wheat canopies with different levels of N fertilization and (2) identify the relationships of key agronomic and spectral characteristics of wheat canopies. Relationships between spectral and agronomic variables were developed with data from 1979 and tested with independent data from 1980.

METHODS AND MATERIALS

Experiments were conducted at the Purdue Agronomy Farm, West Lafayette, Indiana, on a Chalmers silty clay loam (typic Argiaquoll) soil with 0 to 1% slope during the 1978-79 and 1979-80 growing seasons. Plots of winter wheat (Triticum aestivum L., Caldwell and Monon) were planted on 5 October 1978 and 10 October 1979 in a randomized complete block design. Three blocks were planted in 1978 and two in 1979. The plots were 3.0 m wide and 19 m long with 18 cm wide north-south rows. Each block contained three replications of N treatments consisting of 0, 60, and 120 kg N/ha applied as urea on 3 April 1979 and 2 April 1980. Originally, the within-block replicates of N fertility were three leaf rust treatments; however, because significant amounts of disease did not develop, these treatments were subsequently considered as additional replications of the N treatments.

Spectral Measurements. Spectral reflectance measurements of the canopies over the wavelength range 400 to 2400 nm were made using an Exotech 20C spectroradiometer (Leamer et al., 1973) mounted on the boom of a mobile aerial tower. Measurements were made at two locations over each plot, looking straight down from a 6.0 m altitude. With a 15° field of view, the sensor viewed an area 1.6 m in diameter. All spectral measurements were made on cloudless or near-cloudless days prior to solar noon when the solar elevation was at least 45°. Data were acquired on 11 dates in 1979 and 10 in 1980 and all major stages of development from tillering to physiologic maturity were included.

The spectral measurements were expressed as reflectance factor which corrects for irradiance differences, facilitating comparisons within and among dates. Reflectance factor is the ratio of incident radiant flux reflected by a sample surface (e.g., soil or crop canopy) to that reflected into the same beam geometry by a perfectly diffuse (Lambertian) standard reference surface identically irradiated and viewed (Nicodemus et al., 1977). A 1.2 m square painted BaSO₄ panel with stable, known reflectance properties was used as the reference surface. Robinson and Biehl (1979) have described the spectral measurements and calibration procedures.

Agronomic Measurements. Plant samples were collected from the southern half of each plot, reserving the northern half for spectral measurement. From each plot, all of the plants in two 1.0 m sections of row were cut at ground level and combined. Fresh and dry phytomass and LAI were obtained from these samples. A subsample of 25 to 30 tillers was randomly selected from each sample, the leaf blades were removed, and the area of green leaf blades was measured with an area

meter (LI-COR LI-3000). The components of the subsample (leaf blades, stems including leaf sheaths, and heads) and the remainder of the large sample were put in separate bags, dried at 70° C to constant weight, and weighed. The LAI for each plot was calculated using the ratio of subsample green leaf area to subsample dry weight ratio, the total sample dry phytomass, and the soil area (0.365 m²). Plant water content was calculated as the difference between fresh and dry phytomass.

Stages of wheat development were assessed using a modification of the Feekes scale (Large, 1954). Total N of the green leaves was determined using micro Kjeldahl analysis at the IMC Labs in Terre Haute, IN. Chlorophyll concentration of the flag leaf was determined by methods described by Koller and Dilley (1974).

Data Analysis. Spectral response was represented in several forms for analysis. Treatment effects were analyzed qualitatively by examining reflectance spectra of each treatment. Seasonal trends of agronomic and spectral variable were plotted as means and standard deviations. Reflectance factor data were quantitatively analyzed as means of bands corresponding to the bands of the Landsat Thematic Mapper (TM). The six TM bands in the reflective portion of the spectrum are: 450 to 520, 520 to 600, 630 to 690, 760 to 900, 1550 to 1750, and 2080 to 2350 nm.

In addition to the reflectance factors of individual wavelength bands, several vegetation indices were considered. The greenness index, a constrained principal components transformation, was calculated by summing the products of a coefficient and the reflectance factor of each band; greenness index = $(-0.1004 \text{ RF1}) + (-0.1176 \text{ RF2}) + (-0.3250 \text{ RF3}) + (0.8577 \text{ RF4}) + (0.1748 \text{ RF5}) + (0.3228 \text{ RF6})$ where RF1 to RF6 are the reflectance factors in the six reflective bands of Landsat TM (Miller et al., 1984). The ratio of IR/red was calculated as RF4 divided by RF3. Normalized difference (ND) was computed as $(\text{RF4} - \text{RF3}) / (\text{RF4} + \text{RF3})$.

RESULTS AND DISCUSSION

Seasonal Changes

Although differences in these agronomic characteristics among the treatments were generally smaller in 1980 than in 1979, the three levels of N fertilization produced three generally distinct groups of wheat canopies in both years.

Maximum green LAI was reached prior to heading (Fig. 1C) and then declined as the lower leaves senesced. Wheat fertilized with 120 kg/ha of N had the highest LAI and maintained its green leaf area longer than the other treatments. Total fresh and dry phytomass continued to increase even as green LAI declined (Fig. 1). Maximum dry phytomass occurred at physiological maturity of the grain.

Plant growth was significantly affected by the level of N fertilization and these changes are manifested in their reflectances. Reflectance spectra, measured at four stages of development in 1979, are shown in Figure 2. The response to increasing levels of N fertilization is characterized by decreased reflectance in the visible and middle IR wavelengths and increased near IR reflectance. The greatest differences are in the near IR region and between the 0 and 120 kg/ha N treatments.

For example, on 1 May, the differences among treatments (Fig. 2) appear small in the visible (400 to 700 nm) and large in the near IR (700 to 1400 nm); however, the reflectance of N fertilized wheat is approximately half the reflectance of nonfertilized wheat in the visible and middle IR (1400 to 2400 nm). In the near IR, reflectance of fertilized wheat is up to 1.5 times higher than nonfertilized wheat. These changes in reflectance characteristics have previously been attributed to differences in LAI, percent ground cover, total phytomass, leaf pigmentation, leaf cell structure, and plant water content (Knippling, 1970; Al-Abbas et al., 1974; Thomas and Gausman, 1977; Walburg et al., 1982). Similar spectral responses of wheat to N were observed during both years. The spectral responses are qualitatively similar to the effects of N fertilization on reflectance of corn (Walburg et al., 1982) and spring wheat (Ahlrichs and Bauer, 1983; Daugherty et al., 1980).

Seasonal patterns of spectral response and agronomic characteristics of the canopies follow similar trends. The maximum near IR reflectance (Fig. 3B) occurred concurrently with the maximum LAI (Fig. 1C). Subsequently, as the amount of green leaf area decreased, reflec-

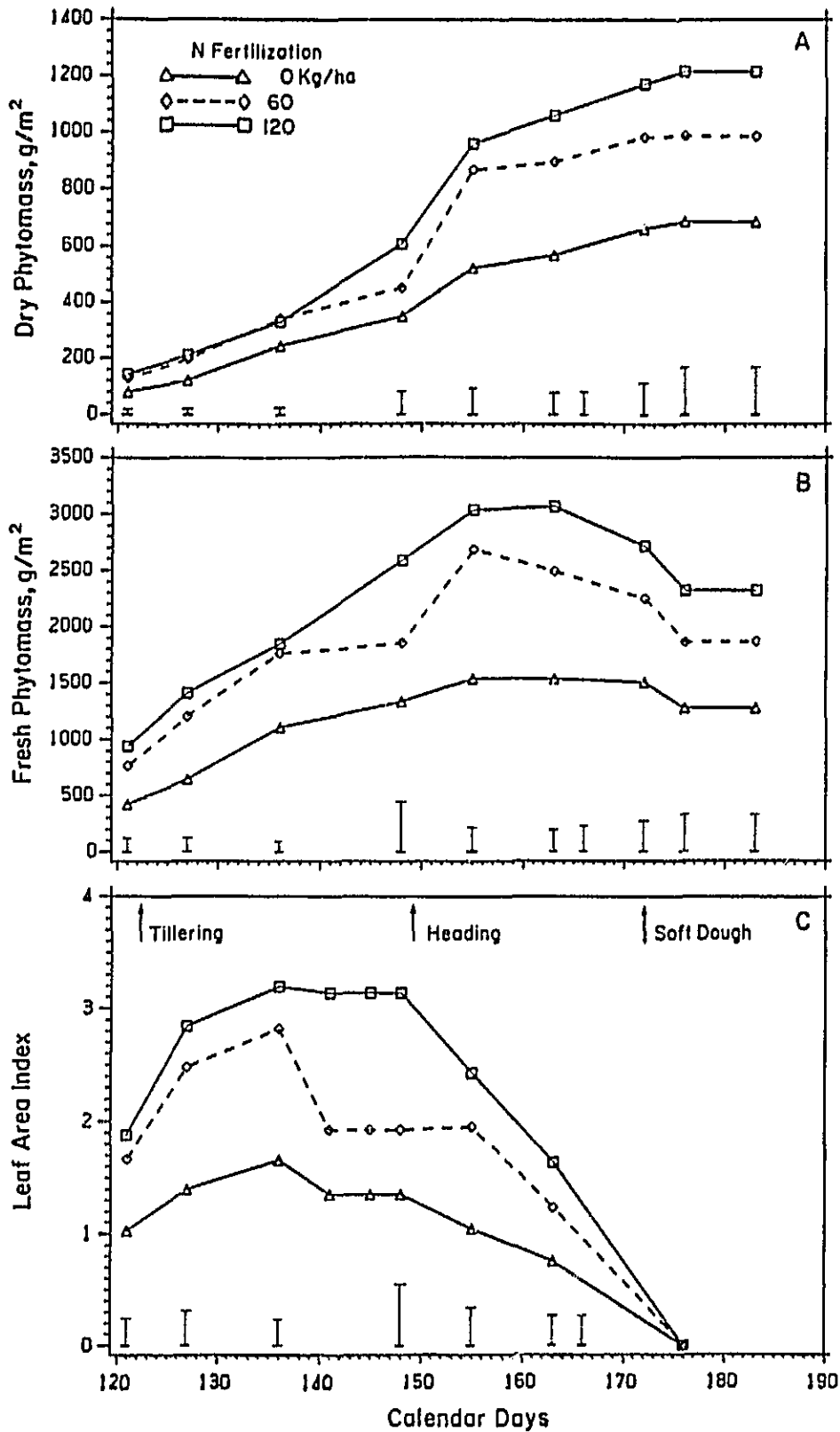


Figure 1. Seasonal changes in total dry phytomass (A), total fresh phytomass (B), and leaf area index (C) of winter wheat fertilized with three rates of N in 1979. Root mean square errors are indicated by the vertical bars for each sampling date. Data are means of nine observations per treatment.

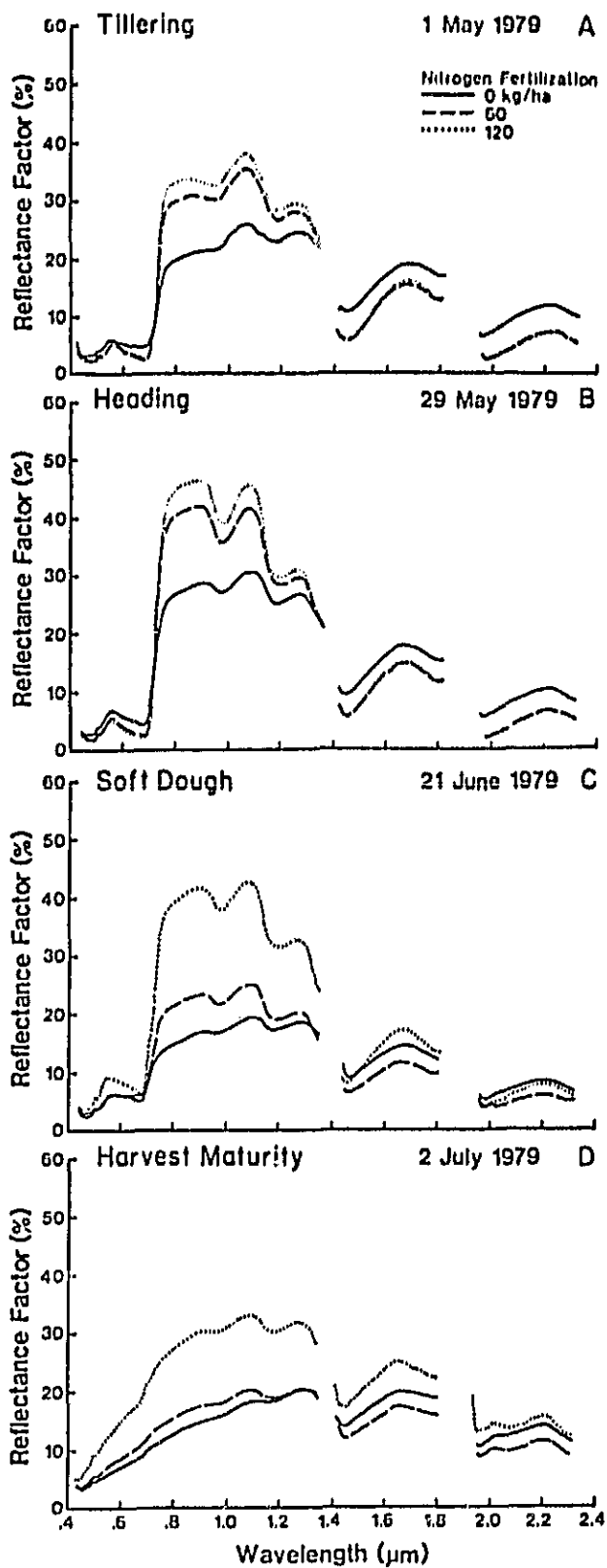


Figure 2. Spectral reflectance of winter wheat at four stages of development in 1979.

tance in the chlorophyll absorption bands (Fig. 1A) increased. Middle IR reflectance (Fig. 3C) also decreased as total phytomass increased and then increased as the moisture level of the canopy decreased. Results of the 1980 growing season were nearly identical to 1979.

Reflectances of wheat canopies are significantly lower than reflectance of bare soil in the visible (Fig. 3A) and middle IR (Fig. 3C) bands, but higher than bare soil in the near IR (Fig. 3B). As the wheat canopies mature and senesce, their reflectances approach those of bare soil. The anomalous increases in the reflectances of wheat fertilized with 120 kg/ha of N that occurred on day 164 resulted from moderate lodging after a storm (Fig. 3B). The normally erect wheat plants were blown down, forming a mat of leaves and stems which was more reflective in the visible and near IR than the erect plants. Stanhill et al. (1972) reported similar effects caused by abrupt changes in canopy geometry.

Leaf senescence is accompanied by loss of chlorophyll and disappearances of the chlorophyll absorption bands at approximately 450 and 670 nm (Fig. 2). The decrease in near IR reflectance presumably is associated with changes in cell structure (Knippling, 1970).

Precipitation one to two days before the spectral data were acquired decreased reflectances (Fig. 3). For example, precipitation which fell prior to acquisition of spectral data on day 172 darkened the soil and contributed to the abrupt decreases in reflectances on this date. These decreases were most evident for bare soil and for wheat with no applied N. Daughtry et al. (1980) noted similar decreases in reflectances following precipitation.

Some transformations of the reflectance data tend to minimize changes caused by precipitation (Kollenkark et al., 1982; Tucker, 1979). The changes in bare soil reflectance caused by precipitation were greatly reduced by certain spectral transformations (Fig. 4). Thus transformations may provide a more stable baseline to detect crop growth than reflectance factors in single bands.

The separability in agronomic and spectral characteristics of the N treatments may be assessed graphically using the root mean square errors (RMSE) shown in Figures 1, 3, and 4. In these figures, the RMSE approximates the least significant range of the Newman-Keuls tests at $\alpha = 0.05$ for observations per mean (Anderson and McLean, 1974). Thus, if two lines are separated by more than the distance of the RMSE for a given date, then the means are significantly different. These graphical analyses, which agree with the results of the analyses of variance and Newman-Keuls tests using the digital data, are used in this paper simply for brevity. The agronomic characteristics (Fig. 1) of the 0 and 120 kg/ha N plots were significantly different throughout the season; however, the 60 kg/ha N treatment was sometimes not separable from either of the other treatments.

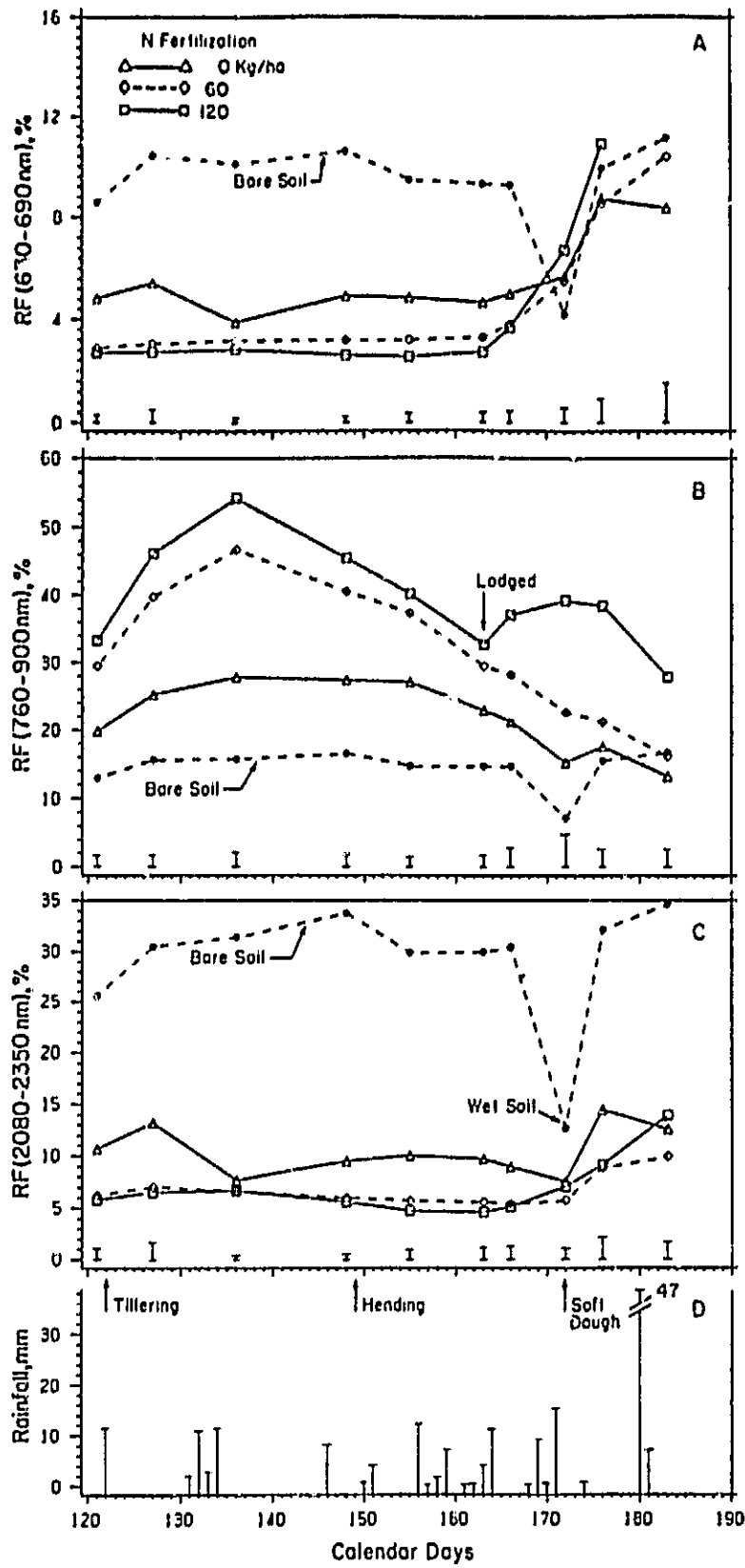


Figure 3. Seasonal changes in reflectance factors of winter wheat in 1979 for the red (A), near infrared (B), and middle infrared (C) bands. Root mean square errors are indicated by the vertical bars for each sampling date. Data are means of nine observations per treatment. The occurrence and amount of rainfall are indicated (D).

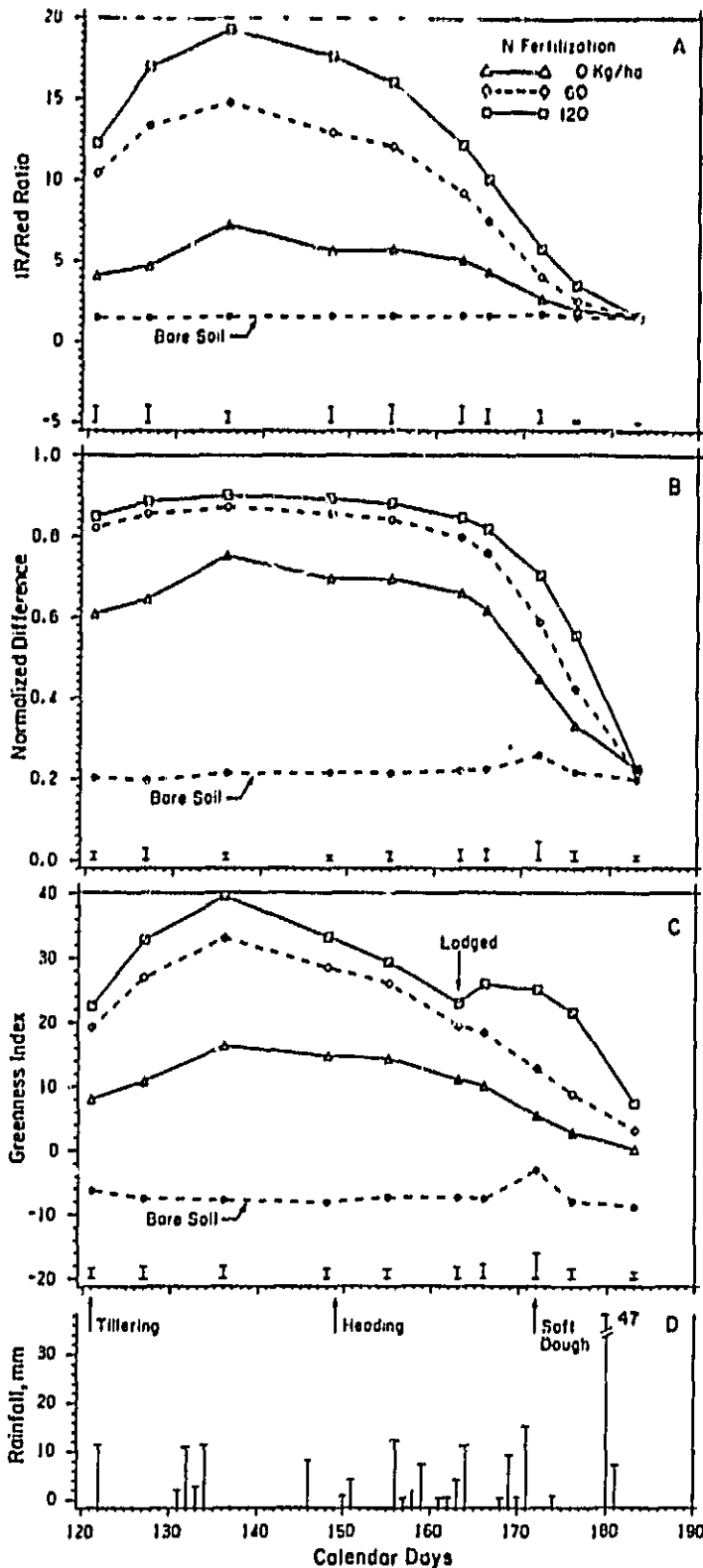


Figure 4. Seasonal changes in the near IR/red ratio (A), the normalized difference (B), and greenness index (C) of winter wheat in 1979. Root mean square errors are indicated by the vertical bars for each sampling date. Data are means of nine observations per treatment. The occurrence and amount of rainfall are indicated (D).

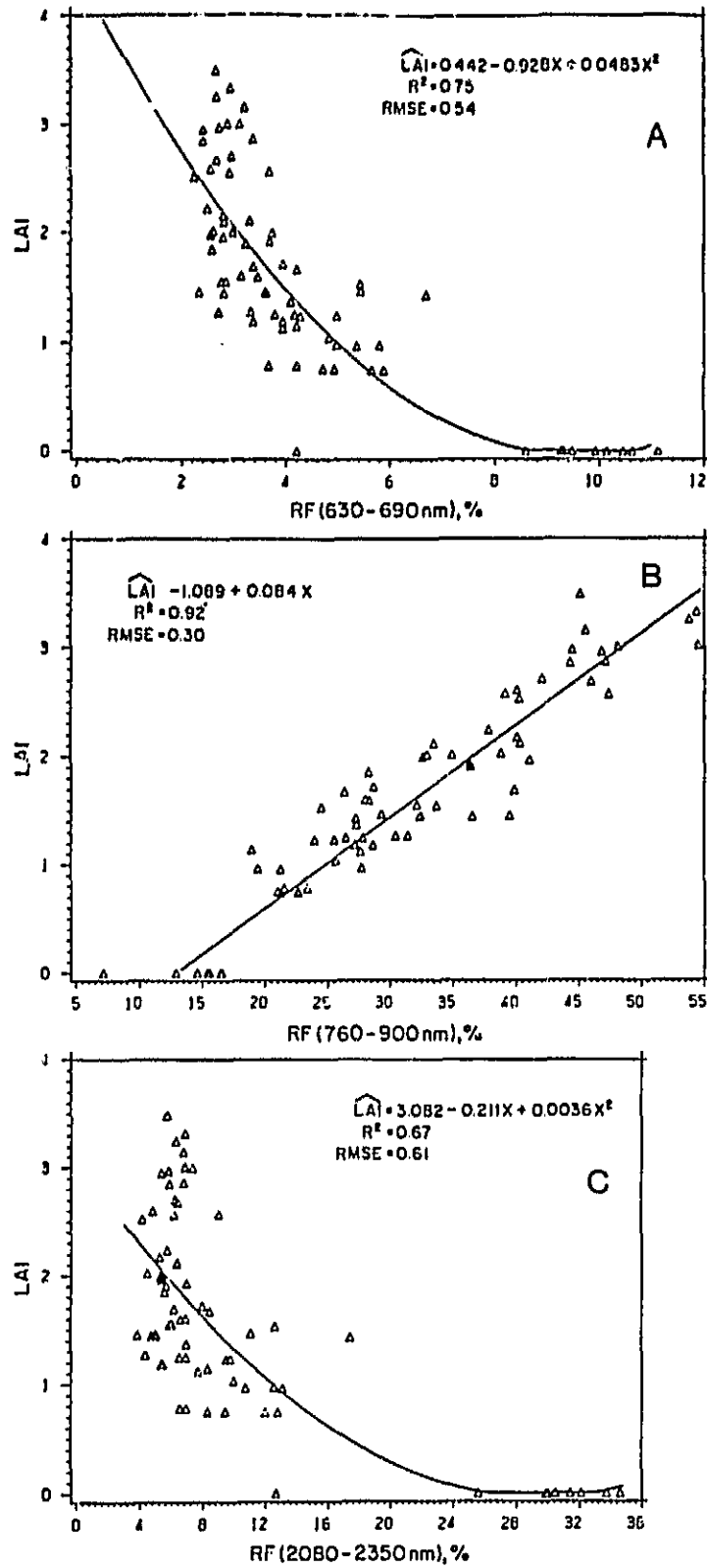


Figure 5. Green leaf area index of winter wheat in 1979 as function of reflectance factors in the red (A), near infrared (B), and middle infrared (C) bands. Data are means of three observations (n = 93).

The reflectances of the lowest and highest N fertilization plots were almost always significantly different for all spectral variables analyzed (Figs. 3 and 4). Like the agronomic characteristics, the spectral characteristics of the 60 kg N/ha plots were not always distinguishable from those of the 0 or 120 kg N/ha plots. When compared to the 120 kg N/ha plots, the 0 kg N/ha plots had greater red (630 to 690 nm) and lower near IR (760 to 900 nm) reflectance in both seasons. The near IR (760 to 900 nm) band and the greenness index consistently resulted in the greatest treatment separation in both years.

Relationship of Spectral and Agronomic Variables

The quality and condition of vegetation present in a scene are one of the primary factors affecting the spectral reflectance of crops. Figure 5 illustrates the relationship between an agronomically important canopy characteristic, green leaf area index, and several spectral variables. This figure contains data from all treatments in 1979 when green leaves were present (tillering through soft dough). Some of the scatter in the data is associated with the N treatments, as well as measurement errors in both the independent and dependent variables.

As LAI increased, red (630 to 690 nm) and middle infrared (2080 to 2350 nm) reflectances decreased and near infrared (760 to 900 nm) reflectance increased (Fig. 5). These relationships are nonlinear, particularly in the red band for LAI values greater than 3.0. Other studies have indicated similar asymptotic responses of reflectance (Tucker, 1979; Daughtry et al., 1980; Kollenkark et al., 1982).

The transformations of spectral data (Fig. 6) generally provided more information (i.e., higher R^2 and lower RMSE) related to LAI than reflectances in the single bands (Fig. 5). The IR/red ratio and ND which are functionally equivalent to each other (Perry and Lautenschlager, 1984) had comparable R^2 and RMSE values for their relations to LAI (Fig. 6). The three best relationships developed in 1979 (Figs. 5 and 6) between spectral data and LAI were used to predict LAI of wheat in 1980 (Fig. 7). Points that lie below or above the 1:1 line in Figure 7 were under- or over-predicted, respectively. The coefficients of determination and RMSE of the prediction indicate reasonably good predictive ability for the three models. Nevertheless the models developed in 1979 tended to underpredict LAI at values greater than 2.0 in 1980.

The concentration of chlorophyll in a leaf is sensitive to physiological stresses (Knippling, 1970; Thomas and Gausman, 1977). Chlorophyll concentration of upper leaves was significantly affected by N treatment and was separable into at least two classes throughout the season. Higher N fertilization rates produced plants with higher chlo-

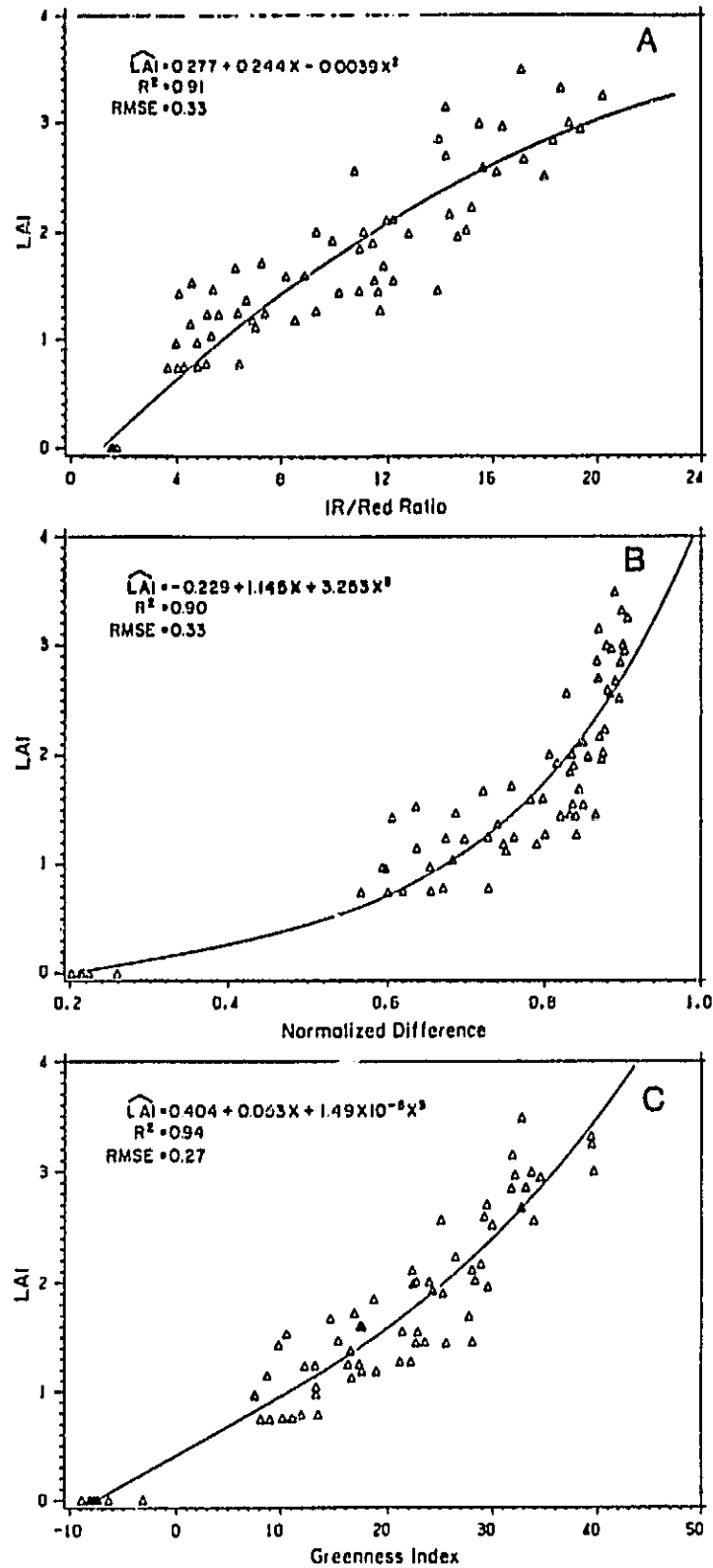


Figure 6. Green leaf area index of winter wheat 1979 as functions of the near IR/red ratio (A), normalized difference (B), and greenness index (C). Data are means of three observations ($n = 93$).

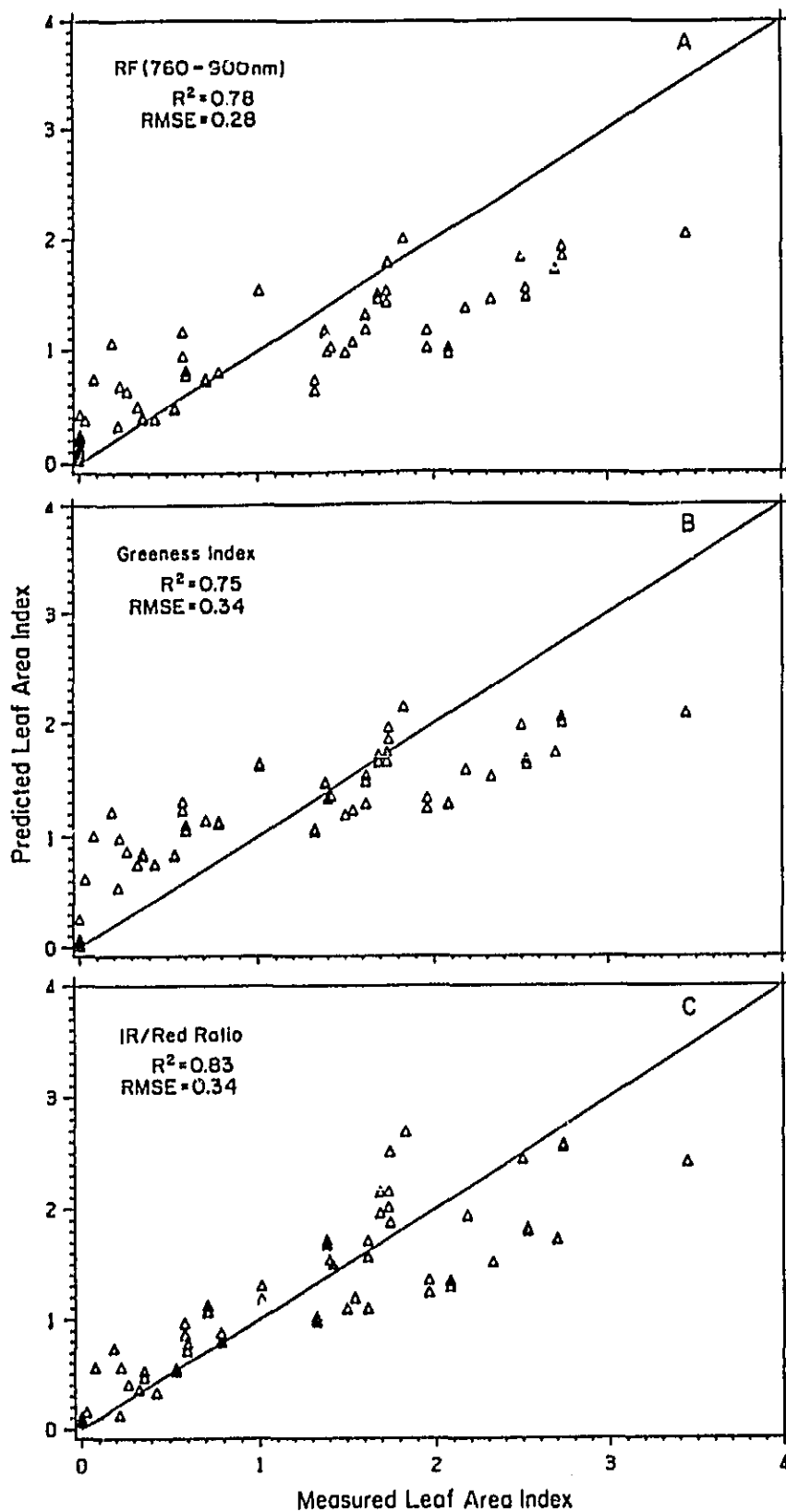


Figure 7. Predicted and actual leaf area index in 1980. Equations were developed using data from 1979. Data are means of three observations ($n = 72$).

rophyll concentrations, higher leaf total N concentrations and more leaves per unit area of soil (i.e., higher LAI). Thus one would expect that reflectance in a chlorophyll absorption band (i.e., 630 to 690 nm) may be a good indicator of crop physiological condition. However, reflectance in the red band was essentially constant throughout most of the season until senescence for each treatment (Fig. 3A). As the wheat senesced, chlorophyll deteriorated, absorption decreased, and red reflectance increased. Red reflectance of a leaf is highly correlated with the chlorophyll concentration of that leaf (Thomas and Gausman, 1977), but red reflectance of a canopy is more closely related to the chlorophyll density (the product of leaf chlorophyll concentration and LAI) (Fig. 8). Individually, LAI and leaf chlorophyll concentration were not always significantly different, but chlorophyll density was very sensitive to N fertilization rate and separated into three significantly different classes on each sampling date.

SUMMARY AND CONCLUSIONS

This study demonstrates the potential for using remote sensing to detect stressed crops. Although it was almost always possible to distinguish the agronomic characteristics of the 0 kg N/ha plots from the 120 kg N/ha plots, the 60 kg N/ha plots were not always separable from either the 0 or the 120 kg N/ha plots. The plots deficient in N showed greater reflectance in the visible and middle IR wavelengths and lower reflectance in the near IR wavelengths than those with adequate or high N fertility. These differences were caused by lower levels of chlorophyll, reduced leaf area, and less phytomass in the low N fertility plots. The reflectance of the lowest N fertilization plots was significantly different from the reflectance of the highest N fertilization plots for all spectral variables analyzed, suggesting that at least two condition classes can be identified from remote sensing data. However, the spectral reflectance characteristics of the 60 kg N/ha plots were frequently indistinguishable from the 0 or 120 kg N/ha plots. The near IR reflectance, IR/red ratio, and the greenness index performed best for discriminating treatment levels. Green LAI, an important descriptor of wheat canopies, can be reliably estimated with multispectral data.

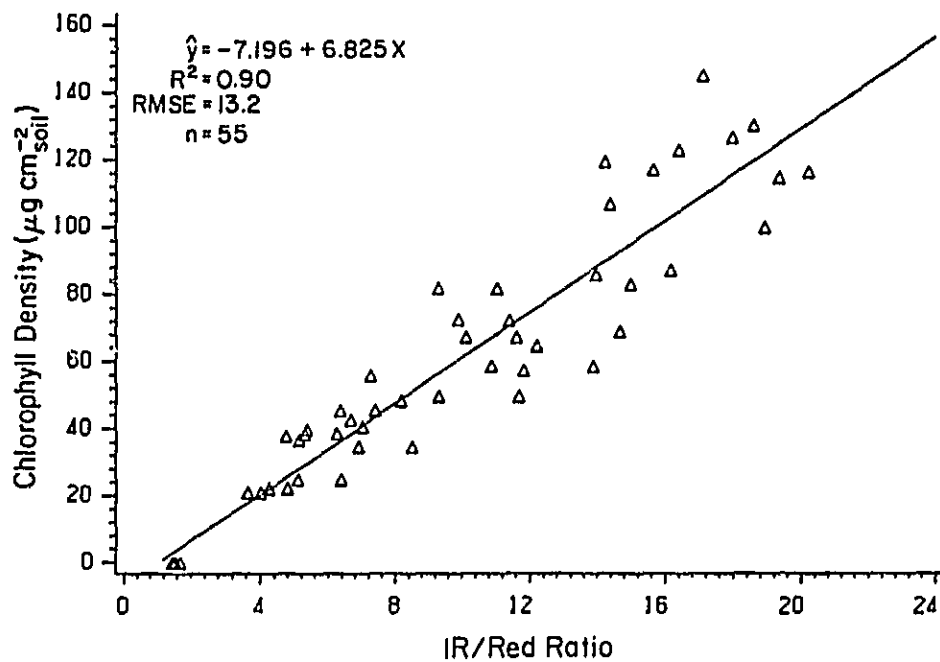


Figure 8. Chlorophyll density as a function of IR/red ratio in 1979. Data are means of three observations ($n = 45$).

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