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16. Abstract

An experiment was conducted in which spectral and agronomic measurements were collected from corn (Zea mays L.) canopies under four nitrogen treatment levels (0, 67, 134, and 202 kg/ha) at the Purdue Agronomy Farm, W. Lafayette, IN, on 11 dates during 1978 and 12 dates during 1979. Spectral measurements over the 0.4 to 2.4 μm wavelength region were acquired with a spectroradiometer and used to compute reflectance factor. Agronomic data collected included biomass, leaf area index, plant height, crop development stage, and percent soil cover. Data were analyzed to determine: (1) the relationship between the spectral responses of canopies and their agronomic characteristics and (2) the spectral separability of the four treatments.

Red reflectance was increased, while the near infrared reflectance was decreased for canopies under nitrogen deprivation. Spectral differences between treatments were seen throughout each growing season. The near infrared/red reflectance ratio increased spectral treatment differences over those shown by single band reflectance measures. The spectra of the four nitrogen treatments were significantly different on August dates; however, early and late in the season only two spectral classes were resolved. Of the spectral variables examined, the near infrared/red reflectance ratio most effectively separated the treatments. Differences in spectral response between treatments were attributed to varying soil cover, leaf area index, and leaf pigmentation values, all of which changed with N treatment. The results further confirm the potential of remote sensing for monitoring the growth and condition of crops.

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INTRODUCTION

Satellite measurements of radiation reflected from crop canopies have been used to identify crop type and estimate crop areas (MacDonald and Hall, 1980). Spectral measurements also have potential for use in monitoring crop condition and predicting yields (Bauer, 1975). Accurate assessments of growth and condition from spectral measurements will require further understanding of the relationship between canopy development and spectral response. Aspects of this relationship have been described for several crop species (Leamer et al., 1978; Daughtry et al., 1980; Tucker et al., 1979). Yet, greater knowledge of how canopy spectral response is affected by the many environmental and cultural factors which alter crop development is needed. In particular, relatively little research has been conducted on the effects of plant stresses on canopy reflectance.

Several laboratory studies of stress effects on single leaves have been performed. Al-Abbas et al. (1974) found that several mineral deficiencies increased the reflectance of radiation in the visible wavelength region of corn leaves, while effects on near and middle infrared reflectance varied with the specific mineral deficiency. Nitrogen deficiency increased visible (0.4 to 0.7 µm) and near infrared (0.7 to 1.4 µm) reflectance while decreasing middle infrared (1.4 to 2.5 µm) reflectance from sweet pepper leaves (Thomas and Oerther, 1972). The sensitivity of chlorophyll to metabolic disruption accounted for the response of leaf reflectance in the visible wavelengths to stress conditions (Knipling, 1970). Stress-induced leaf reflectance variations in the near and middle infrared wavelengths have been attributed to altered leaf mesophyll structure (Gausman et al., 1969) and water content (Carlson et al., 1971), respectively.

While changes in leaf reflectance are important stress indicators, differences in leaf area index (LAI) are frequently more useful for spectrally separating healthy from stressed plant canopies. (Knipling, 1970). A decrease in LAI causes canopy reflectance in the near infrared to decrease and in the red to increase without any change in the reflectance properties of individual leaves (Colwell, 1974). Stanhill et al. (1972) concluded that the major cause of altered spectral response of nitrogen deficient wheat canopies were differences in total biomass, while altered leaf optical properties or changed canopy configuration were only secondarily important.

The objectives of this research were: (1) to determine the seasonal spectral responses of corn canopies under varying levels of applied nitrogen, (2) to relate measurements of canopy spectral response to canopy agronomic characteristics, and (3) to determine the spectral separability of corn canopies under different treatments.

MATERIALS AND METHODS

Experimental Conditions. The experiment was conducted at the Purdue Agronomy Farm, West Lafayette, Indiana, during the 1978 and 1979 growing seasons. The soil was a Raub silt loam (Aquic Argiudoll). June through September rainfall was 34 cm in 1978 and 39 cm in 1979, both near the 27-year average of 39 cm.

A randomized, complete block design was used, with three replications of each treatment. Each plot consisted of six rows of corn planted 71 cm apart in an east-west orientiation. Corn (*Zea mays* L.) hybrid Beck 65X was planted on 31 May 1978 at a population of 54,000 plants/ha and Pioneer 3183 hybrid was planted on 10 May 1979 at 66,000 plants/ha. Nitrogen treatments were four levels of urea, 0, 67, 134, and 202 kg N/ha, applied in the spring. Identical rates have been applied to the same plots continously since 1965. In the fall, prior to planting, 49 kg/ha P and 93 kg/ha K were added to each plot. Atrazine was applied after planting for weed control.

Spectral Data Collection. Spectral reflectance between 0.4 and 2.4 µm in wavelength was measured with an Exotech 20 spectroradiometer (Leamer et al., 1973) mounted on the boom of a mobile aerial tower. Spectral data were acquired on 11 dates during 1978 and 12 dates during 1979. Measurements were made centered on the plot, looking straight down from an altitude of 9.1 m. With a 15-degree field of view the sensor viewed a 2.3-m diameter ground area from this altitude. All spectral measurements were made on cloudless or near cloudless days when the sun angle was greater than 45 degrees above the horizon and prior to solar noon. Each spectral data set was collected within a 1.5 hour time period. A 1.2-m square panel painted with barium sulfate was used as a reference surface for determining the reflectance factor (Robinson and Biehl, 1979). The response of the reference panel was measured approximately every 20 minutes throughout the data acquisition period.

Canopy Characterization. Agronomic variables were measured and observed throughout each season on the same dates as the spectral measurements. These data included: development stage, leaf area index, percent soil cover, fresh and dry biomass, leaf chlorophyll concentration, leaf nitrogen content, and grain yield.

Data Analysis. Spectral data were analyzed as band means corresponding to the Landsat multispectral scanner (MSS) bands and to the thematic mapper bands. The thematic mapper is an updated multispectral scanner scheduled for launching aboard the Landsat-D satellite (Blanchard and Weinstein, 1979). The thematic mapper bands are narrower and are more optimally placed for spectral characterization of vegetation than the Landsat MSS bands. The Landsat MSS spectral bands are: 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 µm. The reflective thematic mapper bands are: 0.45-0.52, 0.52-0.60, 0.63-0.69, 0.76-0.90, 1.55-1.75, and 2.08-2.35 µm. In addition to these single bands, the data were analyzed as ratios and transformations of the band means. Greenness, a transformation of the Landsat MSS bands (Kauth and Thomas, 1976), was computed using coefficients derived for spectrometer data (Rice et al., 1980). Greenness = $[(-0.48935)(R1)] + [(-0.61249)(R2)] + [(0.17289)(R3)] + [(0.59538)(R4)]$, where R1 to R4 are the reflectance factors of the four Landsat MSS spectral bands. The ratio of near infrared/red reflectance was computed using the 0.76-0.90 and 0.63-0.69 μm bands. Correlation and regression analyses of spectral response and the various agronomic measurements were performed and scatter plots made of their relationships. Duncan's multiple range test with $P = 0.05$ was used to perform mean separation tests on both the spectral and agronomic data.

RESULTS AND DISCUSSION

Reflectance spectra, measured on 4 August 1979, of corn canopies grown with varying rates of nitrogen (N) fertilization are shown in Fig. 1. Similar responses were observed on other dates in July and August during both years. The effects of varying nutrition were exhibited across the entire wavelength interval measured. Reflectance decreased in the visible and middle infrared wavelength regions with increasing N fertilizer application, while in the near infrared wavelength region reflectance was increased. Similar changes in visible and near infrared reflectance have previously been attributed to differences in LAI, percent soil cover, and plant biomass (Colwell, 1974; Knipling, 1970). It is likely that variation in spectral reflectance among N treatments also resulted from changes in leaf structure and composition, including pigment concentration, cell size, and cell wall composition and structure, all of which are altered by N treatment (Vesk et al., 1966).

Seasonal patterns of spectral response and canopy characteristics Figs. 2 and 3) were closely related and the effects of varying N fertilization on both crop growth and spectral response are seen throughout both seasons. As LAI, biomass and soil cover increased, the red (0.63 to 0.69 µm) reflectance decreased, while the near infrared (0.76 to 0.90 µm) reflectance increased. The middle infrared showed seasonal trends similar to the visible wavelengths. The middle infrared differs from the visible in that radiation is absorbed by plant water while absorption in the visible region is due to plant pigments (Gates et al, 1965). Near infrared reflectance increases with increasing vegetative cover due to increased light scattering and reflectance by multiple leaf layers (Gausman et al., 1976).

The large reflectance decrease measured on 30 June 1979, was due to 4.8 cm rainfall earlier that day, which caused a large decrease in the soil reflectance at a time when the canopy cover was relatively low.

The larger treatment effects observed in both red and near infrared reflectance in 1979 compared to 1978 were attributed to the greater differences in biomass and LAI between treatments in 1979. These were in turn attributed mainly to planting date. Date of planting is known to have major effects on crop development and yields (Genter and Jones, 1970). Wet soils delayed planting in 1978 until May 31, while in 1979 planting was nearer the mean for the 15-year history of these plots. The 1979 results are more typical of mean treatment differences in grain yield.

A frequently applied method of multispectral data analysis is based on ratios between different spectral bands. The near infrared/red reflectance ratio has been shown by Bunnik (1978) to be strongly related to variations in LAI of vegetative canopies, while being relatively insensitive to variations in soil background reflectance. The advantages of this ratio are evident in Fig. 4 which relates the near infrared/red reflectance ratio and red reflectance to LAI. A strong

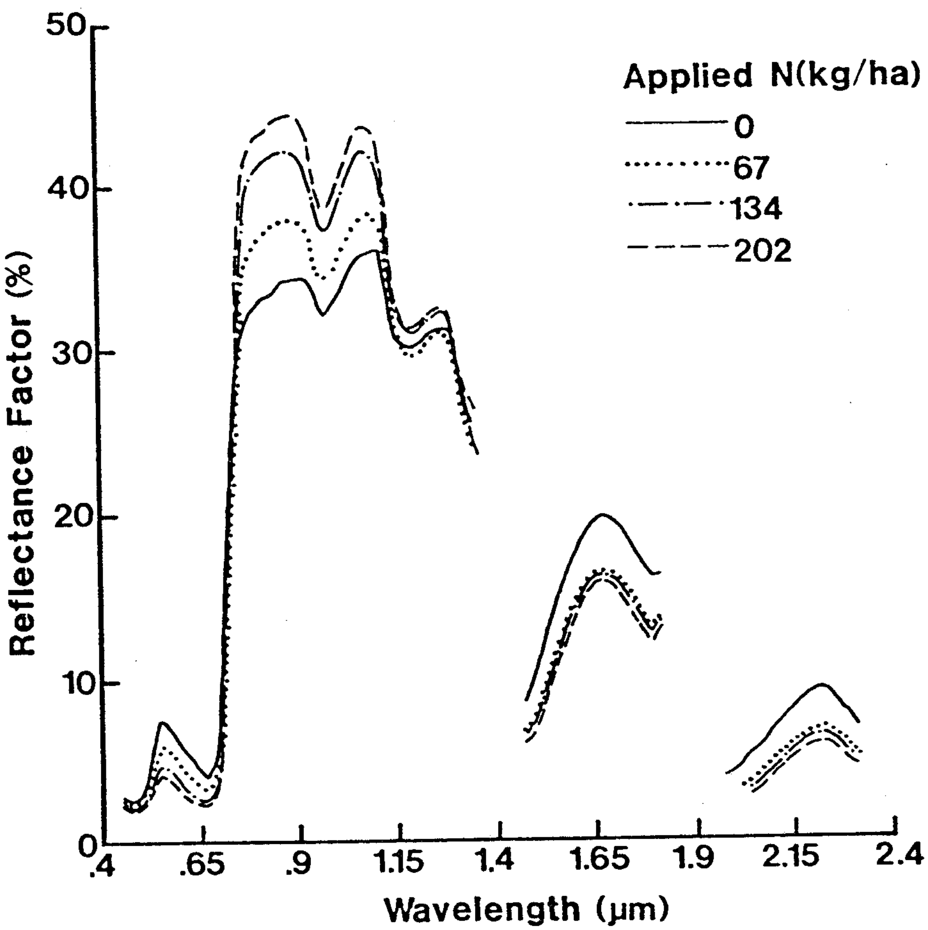

Figure 1. Reflectance factor as a function of wavelength for corn canopies under four N treatment levels on 4 August 1979. Each curve is the mean of three replications.

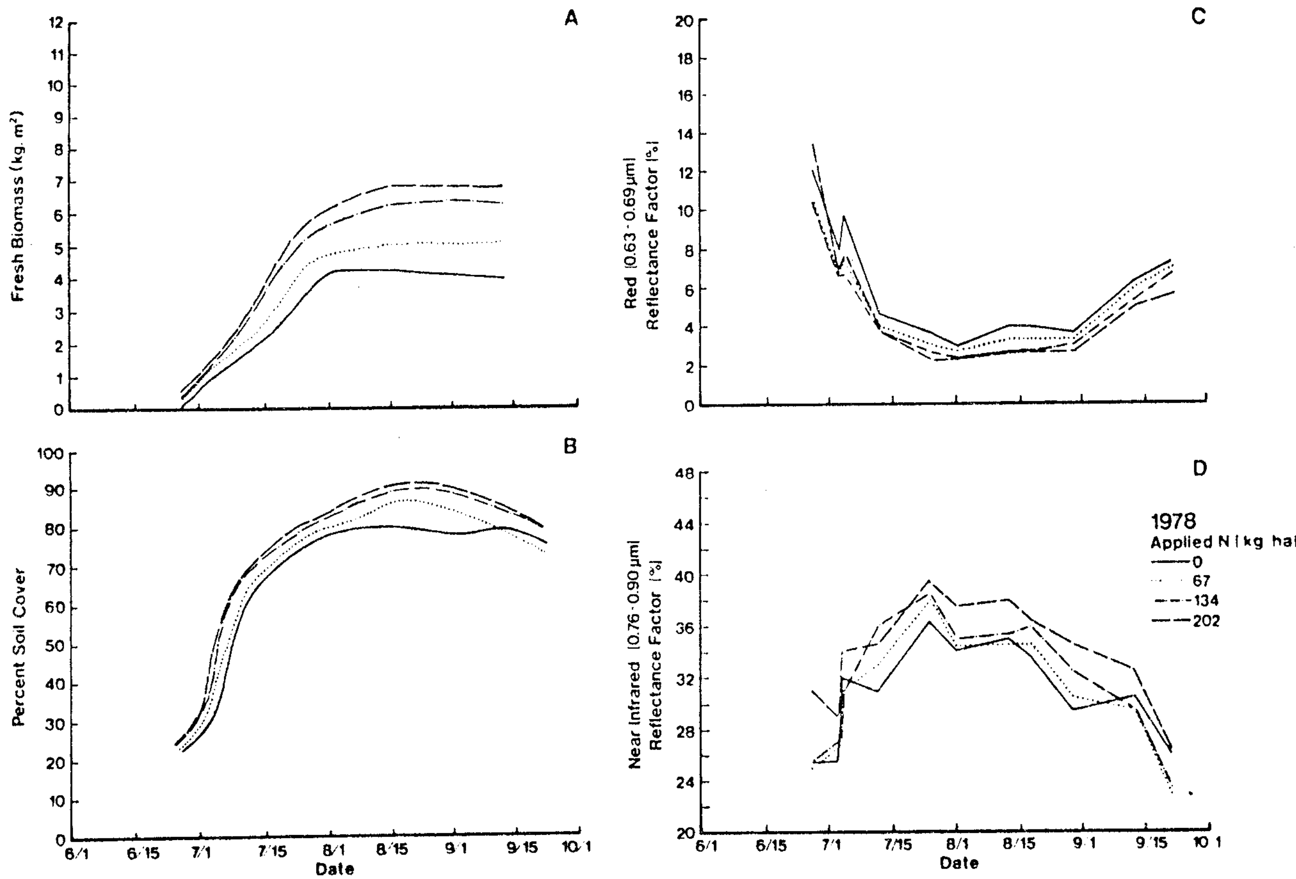

Figure 2. Temporal changes in (A) fresh biomass, (B) percent soil cover, (C) red (0.63-0.69 µm) and (D) near infrared (0.76-0.90 µm) reflectance factor for corn canopies under four N treatment levels in 1978.

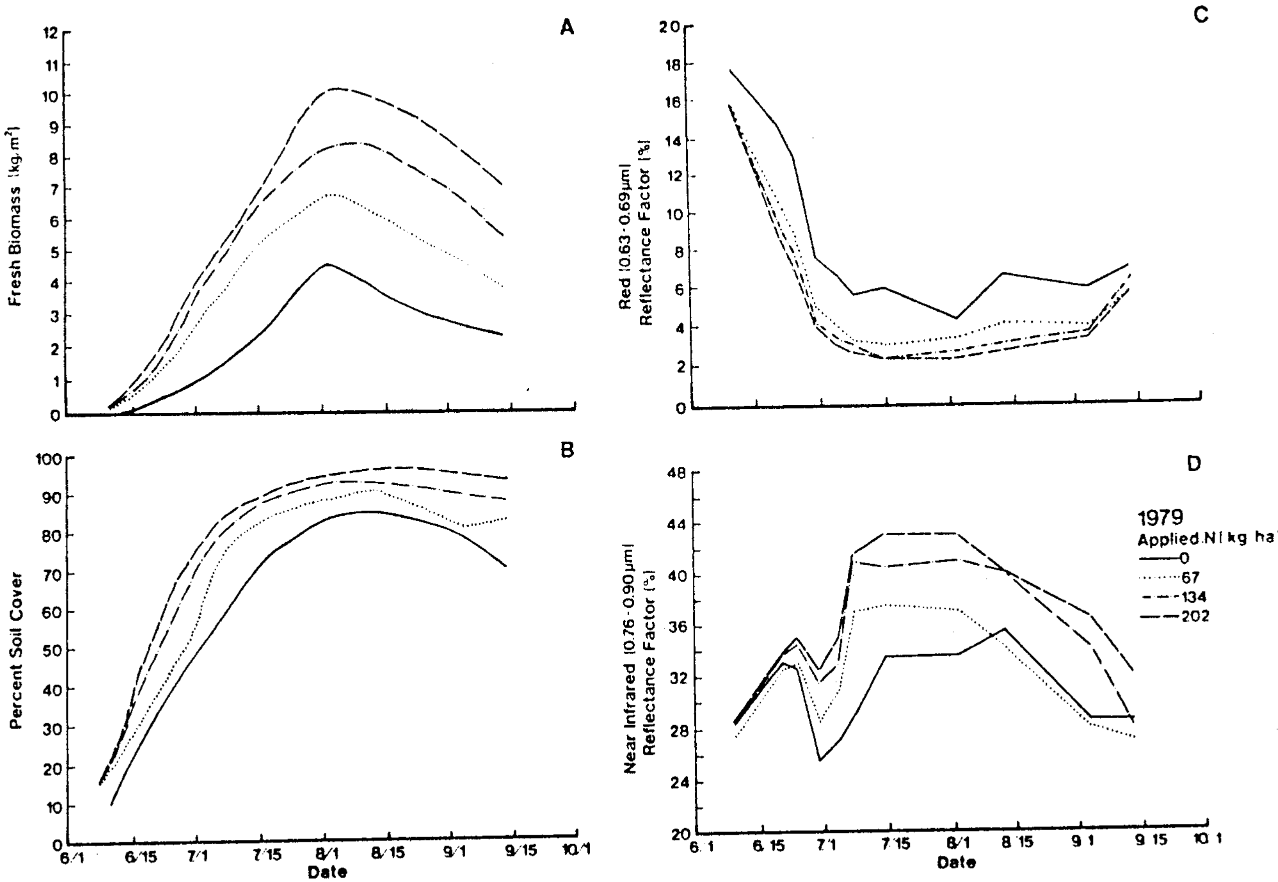

Figure 3. Temporal changes in (A) fresh biomass, (B) percent soil cover, (C) red (0.63-0.69 μm) reflectance factor for corn canopies under four N treatment levels in 1979.

positive relation of LAI to the near infrared/red ratio is found even when data from two growing seasons are included, while there is a considerable degree of scatter, particularly at low LAI values, in the relationship of red reflectance to LAI. The latter is attributed to variations in soil reflectance due primarily to changes in soil moisture and roughness. The near infrared/red ratio was a more sensitive indicator of LAI changes, within the range of values in this data, than either the near infrared band or the red band which approached an asymptote at LAI values above three. Fig. 5 shows the accentuation of treatment differences throughout the growing season in the near infrared/red ratio as compared to single bands (Fig. 2 and 3).

Six spectral variables, the near infrared/red ratio, greenness transformation, and the reflectances in four thematic mapper bands in different parts of the spectrum, were chosen for further analysis. Greenness has shown strong correlations with agronomic characteristics of crop canopies (Daughtry et al., 1980). The thematic mapper bands were selected for analysis since reflectances in these bands have shown higher correlations with crop canopy characteristics than the Landsat MSS bands (Ahlrichs and Bauer, 1978; Tucker and Maxwell, 1976).

Spectral discriminability of the N treatments varied over the season (Tables 1 and 2). For all spectral variables treatment separation was maximum on the August dates. This period corresponds to the stage of maximum vegetative development. At early dates, when the percent soil cover was low, treatment differences were less recognizable because the spectral response of the soil dominated the canopy response (Colwell, 1974). Late in the season, senescence caused treatment differences to decrease.

The discriminability of treatments also varied by the spectral variable used (Tables 1 and 2). The near infrared/red ratio separated the treatments into the most classes on the largest number of dates of all spectral variables; the near infrared band formed the fewest classes. On August dates the near infrared/red ratio separated all four treatments into discrete groups for two dates in 1978 and three in 1979. In contrast the near infrared band formed a maximum of three groups for one 1978 date and three 1979 dates. Early in the season greenness separated the treatments into more classes than the near infrared/red ratio; the green band (0.52 to 0.60 µm) formed more classes than the near infrared.

For most spectral variables, the 0 kg/ha N canopies were separable from the other three treatments during nearly all of the season for both years. Spectral separation of 67 kg/ha N canopies from 134 and 202 kg/ha N canopies was possible for most dates during both seasons, while the 134 and 202 kg/ha N canopies were separable on only a few dates.

Comparison of spectral treatment separation between years (Tables 1 and 2) shows that despite the larger treatment differences in 1979, the spectral separation was very similar for seven of the 11 or 12 dates

Table 1. Spectral responses of corn canopies under four N fertilization levels for selected dates in 1978. Data represent the mean of three replications.

Measurement Date	Applied Nitrogen	Spectral Variable: IR/red Ratio	Greenness	0.52-0.60μm	0.63-0.69μm	0.76-0.90μm	2.08-2.35μm
	kg/ha			Reflectance Factor (%)			
July 6	0	3.3a[†]	15.1a	8.8a	9.7a	32.0ab	22.4a
	67	4.4b	16.3b	7.1b	7.2b	31.0ab	15.6b
	134	4.6b	16.4b	6.7b	6.8b	30.6b	16.1b
	202	4.5b	18.0c	7.3b	7.6b	33.8a	18.1b
July 15	0	6.4a	17.4a	5.9a	4.8a	30.9a	10.0a
	67	8.2b	19.6b	5.2b	4.0b	33.0ab	8.7b
	134	9.8c	21.9c	4.8c	3.7c	36.0b	8.3c
	202	9.5d	21.2d	4.7d	3.7d	34.7b	9.0d
July 28	0	10.4a	22.1a	5.1a	3.6a	36.6a	8.1a
	67	12.5b	23.6ab	4.4b	3.1b	37.9a	7.4ab
	134	15.3c	24.5ab	3.6c	2.5c	38.4a	6.1c
	202	16.1c	25.1b	3.6c	2.5c	39.4a	6.3bc
August 3	0	11.5a	20.6a	4.6a	3.0a	34.2a	5.8a
	67	13.5ab	21.6a	3.8b	2.6b	34.7a	5.5a
	134	15.2bc	21.7a	3.3c	2.3b	34.9a	4.9b
	202	16.4c	23.4a	3.4c	2.3b	37.4a	4.7b
August 20	0	8.4a	19.9a	5.1a	4.0a	33.4a	8.2a
	67	10.2b	21.2ab	4.4b	3.4b	34.4ab	7.0b
	134	12.9c	22.6bc	3.7c	2.8c	35.8b	5.6c
	202	13.9d	23.3c	3.4c	2.6c	36.7b	5.8c
August 31	0	7.8a	17.1a	5.0a	3.8a	29.5a	7.7a
	67	9.1b	18.3ab	4.4b	3.4b	30.5ab	6.6b
	134	10.4c	19.9b	3.9bc	3.1bc	32.5bc	6.1b
	200	12.3d	21.7c	3.5c	2.8c	34.5c	5.9b
September 15	0	4.9a	16.5a	6.4a	6.2a	30.5ab	10.8a
	67	4.9a	16.3a	5.9ab	6.1a	29.6b	10.5a
	134	5.8ab	17.6a	5.2bc	5.3a	30.5ab	9.0a
	202	6.7b	19.4b	4.9c	4.9a	32.3a	9.3a

[†]Means followed by the same letter within each date are not significantly different at P=0.05 level by Duncan's Multiple Range test.

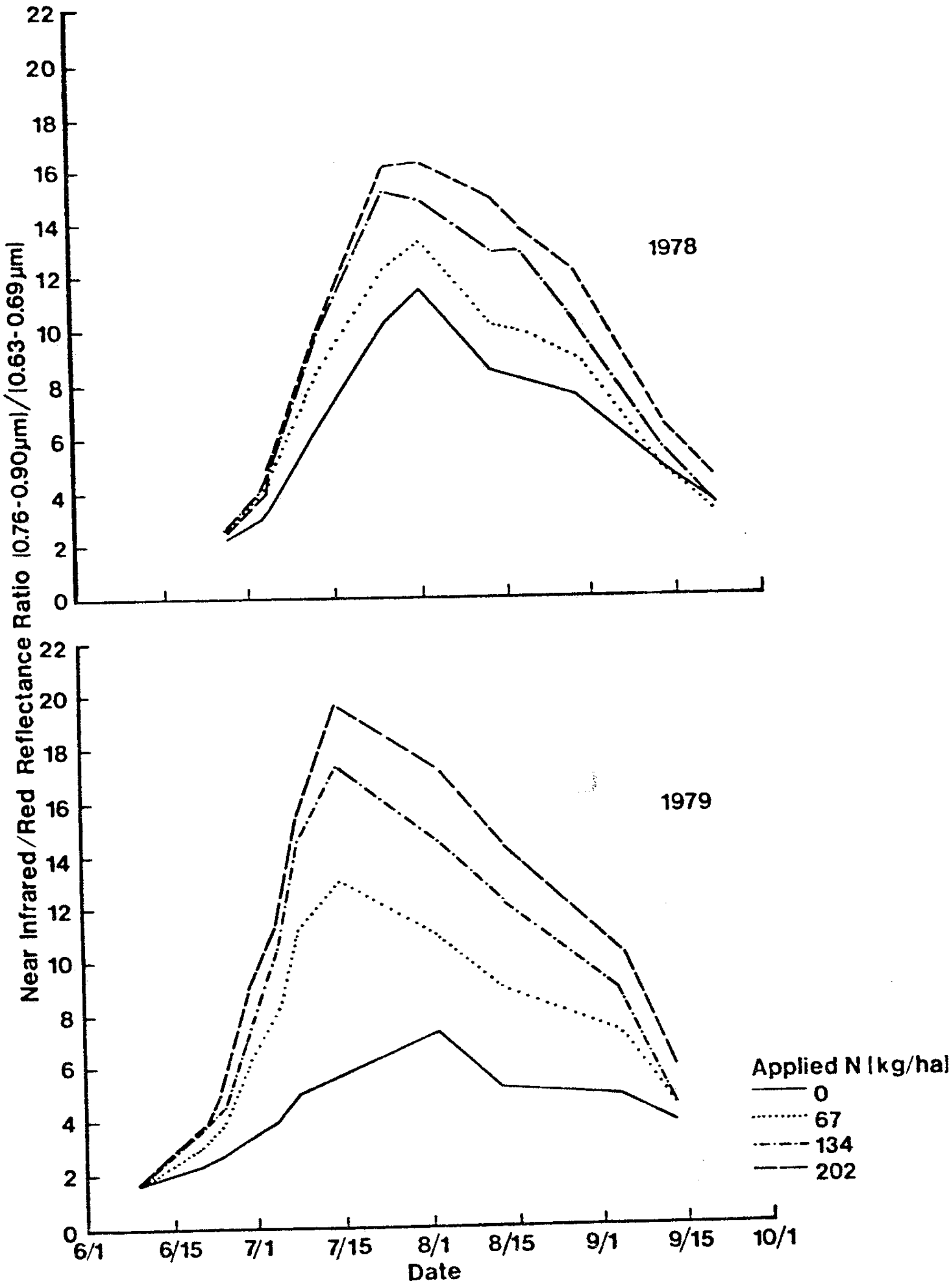

Figure 5. Temporal changes in the near infrared/red reflectance ratio, (0.76-0.90 um)/(0.63-0.69 µm), for corn canopies under four N treatment levels in 1978 (top) and 1979 (bottom).

considered each year. This result indicates the usefulness of the near infrared/red reflectance ratio as a discriminator. Further, the time after planting at which the treatments became separable was also similar between years.

Differences between the spectral responses of canopies under different N treatments are related to agronomic measurement of treatment differences (Tables 3 and 4). Leaf nitrogen concentrations document the effects of varying the level of applied N. The varying leaf chlorophyll concentrations contributed to visible reflectance variations between treatments. Decreased plant height, leaf area index, and biomass values, all associated with reduced levels of applied N, were evident.

Grain yield represents the integration of all the metabolic activities of crop plants over the growing season and is sensitive to N nutrition. Figure 6 shows a linear relationship between the grain yield and near infrared/red reflectance ratios integrated over the season, i.e., the area under the seasonal reflectance curves from Figure 4. A similar relationship is evident in both years, although the hybrid and plant population were different each year.

In summary, analyses of agronomic characterizations and spectral measurements of corn canopies varying in applied N fertilizer level showed that agronomic changes in canopies caused by N treatment resulted in detectable reflectance variations. Reduced leaf area, biomass, and soil cover, lowered chlorophyll content, and decreased plant height were among the effects seen in N-deprived canopies. These changes were in turn related to canopy reflectance changes. The near infrared/red reflectance ratio was shown to enhance treatment differences in canopy reflectance and reduce reflectance variability caused by extraneous factors. The spectral separability of the treatments throughout the growing season demonstrates the potential for detecting crop stress by use of multispectral remote sensing methods.

Table 3. Mean agronomic characteristics of corn canopies under four N fertilization levels for selected dates in 1978.

Measurement Date	Development Stage	Applied Nitrogen	Plant Height	Leaf Area Index	Soil Cover	Fresh Biomass	Dry Biomass	Leaf Nitrogen
		kg/ha	m		%	g/m^2	g/m^2	%
July 6	Eight leaf	0	1.0a	1.2a	30a	1031a	96a	2.7a
		67	1.1b	1.6a	36a	1301a	113a	2.6a
		134	1.2b	1.7a	38a	1430a	118a	3.2a
		202	1.3b	1.7a	37a	1449a	124a	3.3a
July 15	Ten leaf	0	1.2a	2.1a	64a	1827a	167a	2.4a
		67	1.5b	2.3ab	64a	2171ab	192ab	2.5a
		134	1.6c	2.6bc	75a	2783bc	234b	3.0b
		202	1.7d	2.8c	75a	3031c	250b	3.4c
August 3	Tasseling	0	2.8a	3.3a	79a	4260a	644a	1.5a
		67	2.9a	3.2a	80a	4518a	740ab	1.7a
		134	3.1b	3.7ab	79a	4973ab	905bc	2.2b
		202	3.1b	4.1b	83a	6200b	996c	2.6b
August 20	Blister	0	2.9a	2.6a	82a	4167a	781a	1.3a
		67	3.0ab	3.0ab	88b	5072ab	933a	1.6a
		134	3.1b	3.5ab	95bc	6141b	1037a	1.6a
		202	3.1b	3.8b	91bc	6787b	1168a	2.6b
September 15	Early dent	0	3.0a	2.0a	80ab	3985a	1075a	1.2a
		67	3.0a	2.3b	78a	5132ab	1529ab	1.0a
		134	3.2a	2.6c	85b	5401b	1562ab	1.6a
		202	3.2a	3.1d	84ab	6881c	1989b	1.7a

[†] Means followed by the same letter within each date are not significantly different at P=0.05 level by Duncan's Multiple Range test.

Table 4. Mean agronomic characteristics of corn canopies under four N fertilization levels for selected dates in 1979.

Measurement Date	Development Stage‡	Applied Nitrogen	Plant Height	Leaf Area Index	Soil Cover	Fresh Biomass	Dry Biomass	Leaf Nitrogen	Leaf Chlorophyll
		kg/ha	m		%	g/m^2	g/m^2	%	$\mu g/cm^2$
June 26	Eight leaf	0	-	1.0a†	45a	689a	83a	3.0a	25.1a
	Eight leaf	67	-	1.7b	61b	1188b	135b	3.0a	34.9b
	Eight leaf	134	-	2.0b	57ab	1669bc	183bc	3.2a	38.5bc
	Eight leaf	202	-	2.3b	66b	1905c	198c	3.2a	42.8c
July 10	Ten leaf	0	1.2a	2.1a	56a	1567a	199a	1.7a	14.2a
	Eleven leaf	67	1.7b	3.6b	76b	3757b	411b	2.4b	26.8b
	Eleven leaf	134	1.9c	3.9b	87c	4788c	476c	2.7b	36.8c
	Twelve leaf	202	2.0c	5.8c	85c	5182c	511c	2.7b	41.1c
July 18	Eleven leaf	0	1.4a	2.3a	71a	2283a	271a	1.2a	11.1a
	Thirteen leaf	67	2.0b	3.9b	85b	5101b	623b	2.1b	21.9b
	Thirteen leaf	134	2.3c	5.1b	88b	6415b	681b	2.3b	40.7c
	Fourteen leaf	202	2.3c	4.8b	84b	6565b	669b	2.4b	47.5c
August 4	Tasseling	0	2.3a	-	83a	4677a	-	1.5a	-
	Blister	67	2.7b	-	89ab	6894ab	-	1.8ab	-
	Blister	134	2.7b	-	93ab	8097bc	-	2.1ab	-
	Blister	202	2.8b	-	94b	10211c	-	2.3b	-
August 16	Silking	0	2.2a	-	85a	2884a	-	1.2a	25.1a
	Late blister	67	2.9b	-	91a	5707b	-	1.4a	34.9a
	Dough	134	3.0bc	-	93a	8134c	-	2.0b	51.0b
	Dough	202	3.2c	-	93a	8360c	-	1.9b	67.9c
September 4	Dough	0	2.1a	1.5a	78a	2581a	678a	1.2a	-
	Early dent	67	2.8b	2.2b	80a	4839b	1261b	1.1a	-
	Early dent	134	3.0bc	3.2c	88b	6504c	1822c	1.3a	-
	Middle dent	202	3.2c	4.2d	96c	8392d	2296d	1.2a	-

†Means followed by the same letter within each date are not significantly different at P=0.05 level by Duncan's Multiple Range test. ‡Hanway Scale

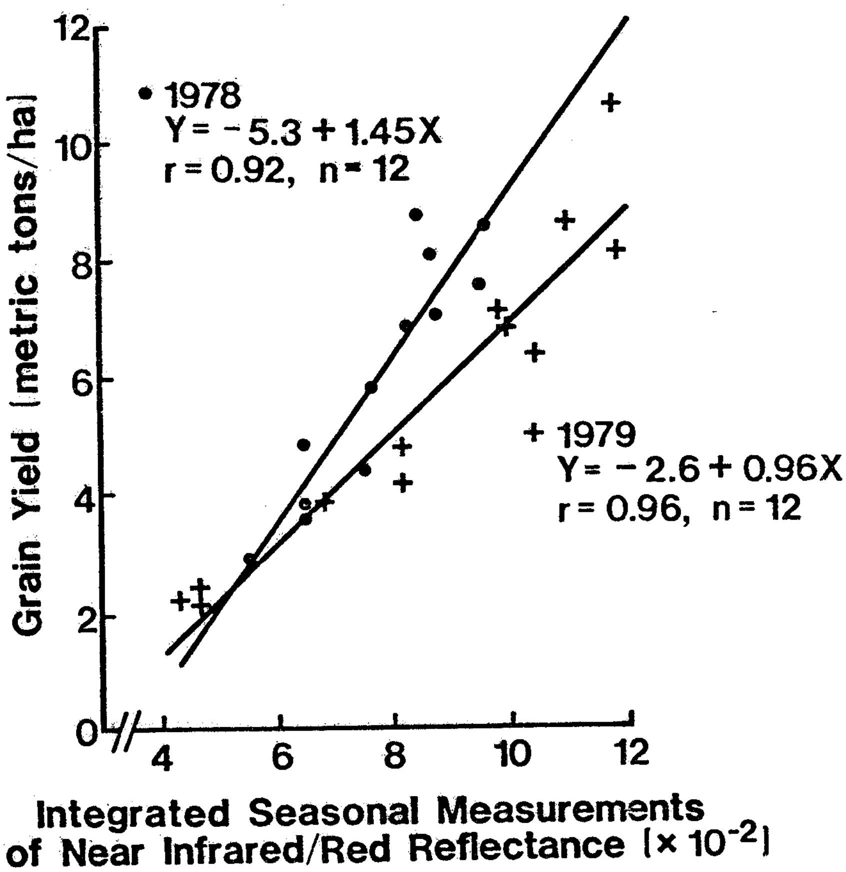

Figure 6. The relationship of grain yield to measurements integrated over the growing season of near infrared/red reflectance.

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