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Temporal Spectral Response of a Corn Canopy

Ground-based spectral measurements of corn plots taken over the growing season were used to determine the relationship of spectral response to grain yield and final dry matter accumulation.

Abstract: *Ground-based spectral measurements of corn plots taken over the growing season were used to evaluate the potential of remotely sensed data for providing corn yield information. Reflected radiances measured in the Landsat Thematic Mapper bands 3 (0.63 to 0.69 μm), 4 (0.76 to 0.90 μm), and 5 (1.55 to 1.75 μm) were correlated, in raw and ratio form, with both harvest grain yield and accumulation of dry matter. These analyses were performed using single date and temporally integrated radiances and ratios. Ratios involving the red (TM3) and near-IR (TM4) bands provided generally the highest correlations with grain yield and dry matter accumulation. These ratios accounted for 50 percent of the yield variation and 57 percent of the variation in dry matter accumulation on the best single date (mid-August) and 59 percent of the variation in yield and 66 percent of the variation in dry matter accumulation over the best integrated period. The added value of TM5 for providing yield information could not be tested adequately due to the lack of water stress conditions during the growing season. The results indicated that there is potential for providing corn yield information from visible and near-infrared remotely sensed data.*

Introduction

The ability to provide pre-harvest information on crop yields from space-based remote sensing platforms has been one of the driving forces behind NASA's Landsat program. This problem has been approached a number of different ways, primarily in the study of winter wheat. The different approaches have been reviewed by Tucker *et al.* (1980a) and reduce to basically two types. In the first type of approach meteorological conditions drive the yield prediction equations with the remotely sensed data providing only the crop acreage data, e.g., LACIE (MacDonald and Hall, 1980), or the meteorological conditions in the crop growing regions, e.g., Earthsat (1976). In the second type of approach the remotely sensed data provide direct information about crop status. The crop status, in turn, when monitored over the growing season can provide yield-related information. It is this second group of approaches that is the concern of this investigation.

Several different measures of crop status have been proposed. Idso *et al.* (1977) used stress, as defined by the temperature differential between

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the plant canopy and the air temperature, as a measure of crop status. The accumulated number of stress-degree-days over a critical growth period showed a relationship to yield in irrigated wheat in areas where the humidity is low. Colwell *et al.* (1977) used the green leaf area index (LAI), as estimated from Landsat spectral data, as the crop status indicator. Grain yield was usually correlated with the green LAI. Tucker *et al.* (1980a, b) used various ratios of the red and near-IR radiances, measures of the amount of photosynthetically active biomass, for assessing crop status. These ratios at particular times in the growing season, and when integrated over certain portions of the growing season, showed a relationship to winter wheat yield and accumulation of dry matter. Idso *et al.* (1978) used the minimum value of red reflectance achieved by wheat canopies prior to grain ripening, a measure of the maximum chlorophyll or biomass level achieved, as the crop status parameter. This parameter showed a good correlation to grain yield.

The principal objective of this research was to test certain of the winter wheat yield prediction techniques on corn. In particular, techniques similar to those of Tucker *et al.* (1980a) were chosen for evaluation, being typical of the approaches using reflected spectral radiances and being applicable to humid region crops. In addition, an extension of these techniques employing a shortwave-IR band (1.55 to 1.75 μm) theoretically sensitive to water stress (Tucker, 1980) was to be evaluated.

The ratios of red to near-IR radiances used by Tucker *et al.* (1980a) for indicators of crop status gain their value by combining the effects of a near-IR band (0.76 to 0.90 μm) positively correlated to green biomass, with a red band (0.63 to 0.69 μm) negatively correlated to chlorophyll content. The combination is, thus, sensitive to the photosynthetically active biomass, which is indicative of crop status. In addition, as the bands involved are spectrally adjacent, the ratios provide a degree of normalization for irradiational conditions (Tucker *et al.*, 1980a). With the shortwave-IR band being negatively correlated to leaf water content, its ratios with the near-IR band should also be sensitive crop status indicators, particularly under water stress conditions. However, the considerable spectral difference between the near-IR and shortwave-IR bands would lessen any irradiational normalization effects of the ratios.

Methods

The study site was a 0.4 hectare field of sandy loam with gravel components on the Beltsville Agricultural Research Center, Beltsville, Maryland. The field was plowed and disked according to normal practices and planted in 76 cm rows with Dekalb XL64A corn (*Zea mays* L.) on 12 May 1979. Prior to planting, fertilizer was applied at the rate of 90 kg N, 39 kg P, and 74 kg K per hectare. A total of 24 3- by 3-metre plots was designated within the field.

Data collection began on 14 June 1979 (day 165) and continued through 9 October 1979 (day 282). Spectral and agronomic measurements of the 24 plots were made at nominally one-week intervals. The radiometric measurements were obtained using a three-band hand-held-type radiometer as described by Tucker *et al.* (1981). This instrument simultaneously measures radiation in three spectral regions corresponding to Thematic Mapper bands 3 (0.63 to 0.69 μm), 4 (0.76 to 0.90 μm), and 5 (1.55 to 1.75 μm). Each channel has a circular instantaneous field-of-view of $\sim 24°$ and provides output proportional to target radiance.

The times for spectral data collection varied from 09:25 to 13:00 EST, which translated to a minimum solar zenith angle of 16° on 14 June to a maximum solar zenith angle of 43° on 27 September (Table 1). These data were collected under conditions of direct sunlight, with varying amounts of haze and clouds. Data collection was rapid, generally less than 30 minutes for the 24 plots, in an attempt to limit changes in atmospheric and illumination conditions. Particularly variable atmospheric conditions did occur during data collection on 17 July and 31 July, and these data were excluded from the analysis (Table 1). Prior to the availability of an extension boom (14-27 June), the instrument was used hand-held. Six radiometric samples were collected within each plot at a height at 1.7 metres (field-of-view = 0.41 m^2). After 27 June four radiometric samples were collected within each plot with the instrument boom-mounted 3.7 metres above the ground, resulting in a 1.9 m^2 field-of-view at ground level.

The agronomic data, periodically collected on the 24 plots, consisted of number visible nodes, crop growth stage (according to Hanway (1963)), plant height, percent canopy cover, and percent chlorosis. On 9 October 1979, after all the plots had reached physiological maturity, the total above ground plant matter in each plot was harvested by hand and weighed. The ears of corn were separated and shelled for each plot. The grain and cobs and stover samples were dried at 65°C for 6 days. Two quantities, the total dry matter accumulation and the dry grain yield, were determined and used for further analyses. Total dry matter accumulation was calculated by multiplying an average percent moisture for the stover by the wet stover weight and adding this result to the dry grain and cob weights.

The data were analyzed in the following manner. Four ratios were calculated from the three spectral radiances for each radiometric sample. The IR/red ratio and the (IR − red)/(IR + red) ratio (the normalized difference of Rouse *et al.* (1973)

TABLE 1. CONDITIONS FOR SPECTRAL DATA COLLECTION

Date	Time (EST)	Solar Zenith Angle (Degrees)	Atmospheric Conditions	Day of Year
6/14/79	12:25–12:55	16–19	Clear	165
6/22/79	10:50–11:28	23–18	Clear – Clouds Around Horizon	173
6/27/79	10:10–10:49	30–23	Slight Haze – Clouds Around Horizon	178
7/03/79	10:40–11:22	25–19	Clear – Scattered Clouds (20%)	184
7/06/79	11:17–11:44	20–17	Clear – Scattered Clouds (20%)	187
7/09/79	12:03–12:30	17–17	Hazy – 50% Cloud Cover	190
7/17/79	12:30–13:00	18–20	Heavy Haze – 70% Clouds	198*
7/27/79	09:25–09:45	41–38	Clear – Scattered Clouds (20%)	208
7/31/79	11:38–12:08	22–21	Heavy Haze – 70% Clouds	212*
8/02/79	11:17–11:48	25–22	Hazy – 50% Clouds	214
8/10/79	10:37–11:17	32–27	Heavy Haze – Scattered Clouds	222
8/20/79	10:10–10:33	38–34	Heavy Haze – Few Clouds	232
8/30/79	10:35–11:00	37–34	Hazy – 50% Clouds	242
9/07/79	10:14–10:43	42–38	Hazy – Scattered Clouds (20%)	250
9/13/79	10:28–11:06	41–38	Clear – 70% Cirrus Clouds	256
9/20/79	10:50–11:20	41–39	Clear – Cirrus Clouds	263
9/27/79	11:00–11:30	43–41	Clear – Scattered Clouds	270

* Not used in analysis.

and Deering et al. (1975)) were calculated using the Thematic Mapper bands 4 and 3. These, henceforth, will be referred to as RAT43 and ND43 respectively. Similar ratios were calculated substituting the shortwave IR band (TM5) for TM3 and are denoted as RAT45 and ND45. The mean of these ratios as well as of the raw radiances were calculated for each sampling date for each plot. Temporally integrated values were determined by taking the area under the curves (trapezoidal rule) of the ratios and raw radiances versus time for several portions of the growing season. The single date and temporally integrated values of the ratios and raw radiance values were individually correlated and linearly regressed with final dry yield and dry matter accumulation.

RESULTS

DATA DESCRIPTION

The agronomic data revealed a normal pattern of growth and development of the corn (Figure 1). Rainfall of approximately 31 cm between planting and harvesting was above average and generally well distributed throughout the growing season. No evidence of water stress was apparent. The addition of approximately 6 cm of water to half of the plots via sprinklers produced no apparent effect on the final yields. The final grain yields ranged from 495 to 818 grams/m² dry weight; the total accumulations of dry matter ranged from 959 to 1644 grams/m². The yield variations were probably related to subsurface soil characteristics including drainage, fertility, and particle size.

The patterns of the red (TM3) and shortwave-IR (TM5) band radiances over the growing season were similar: generally decreasing radiances during early plant development (through day 210), relatively constant radiances during the central portion of the growing season, and some-what increasing radiances during plant senescence (after day 250) (Figures 2a and 2c). The near-IR band (TM4) showed the reverse overall pattern: a slight increase in radiance during corn growth, a leveling off, and then a decrease in radiance during senescence (Figure 2b). All three bands showed local deviations from the overall patterns. To explain these deviations, a correction for sun angle was first applied to the data using the Turner and Spencer (1972) atmospheric model for hazy (10 km visibility) conditions (Figure 3). The remaining major deviations in the radiance patterns appeared to be related to soil moisture. In particular, on days

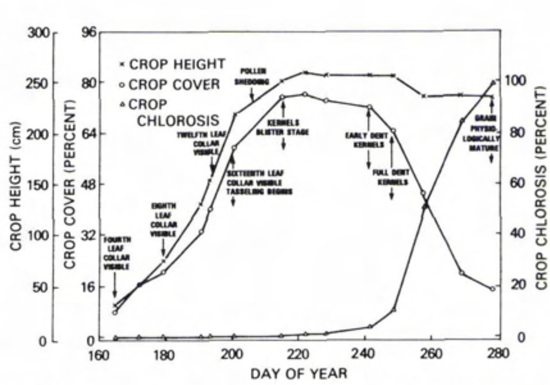

FIG. 1. Average crop conditions for the 24 corn plots on 14 days during 1979.

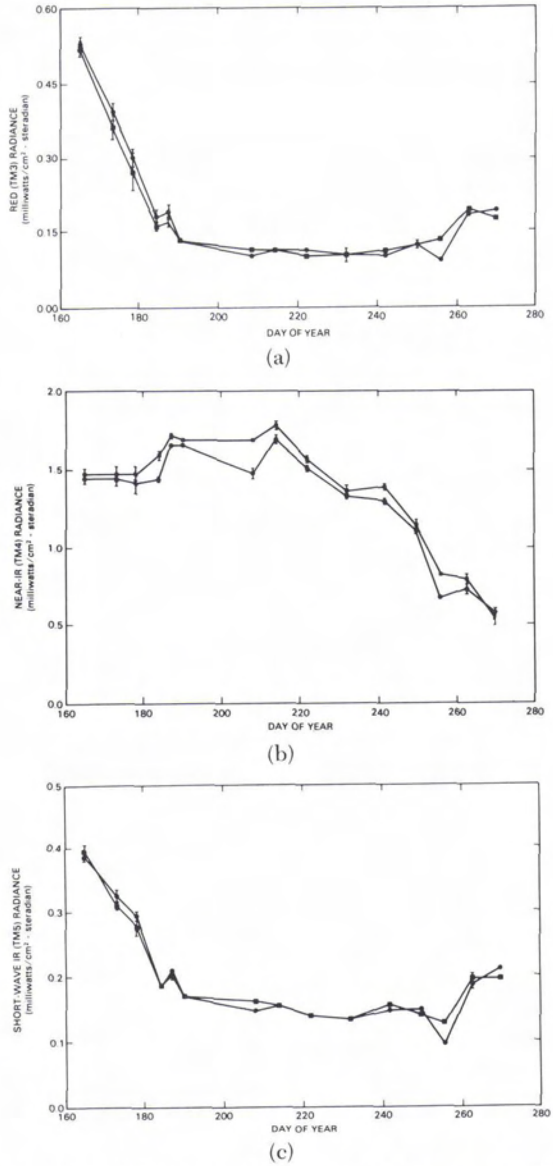

FIG. 2. Red (a), near-IR (b), and shortwave-IR (c) radiances for two of the 24 corn plots versus day of year. ●—low yielding plot (529 g/m²) ■—high yielding plot (809 g/m²) Error bars indicate ± the standard deviation of the four to six measurements per plot. Shown only if error exceeds size of plotting symbol.

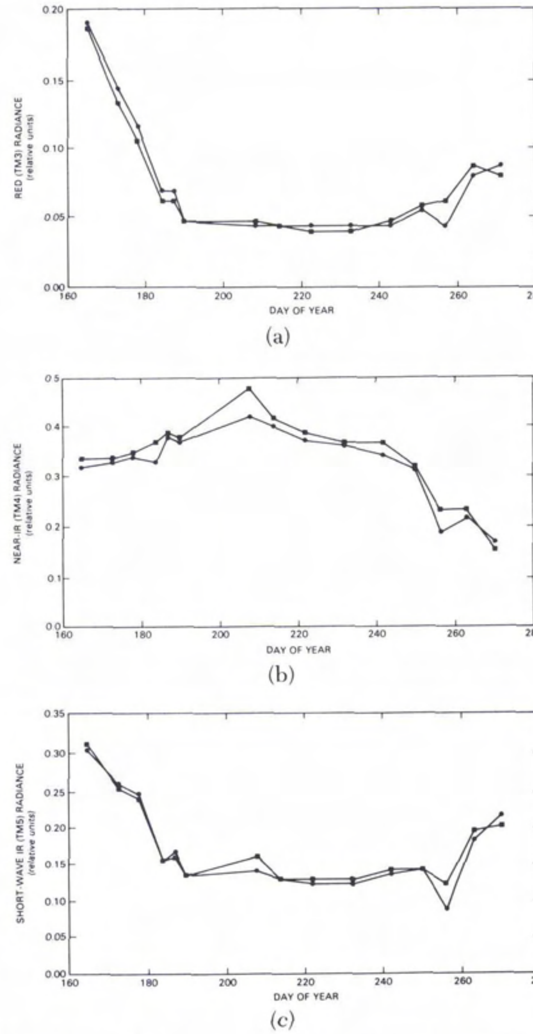

FIG. 3. Red (a), near-IR (b), and shortwave-IR (c) radiances for two of the 24 corn plots versus day of year with a sun angle correction applied. ●—low yielding plot (529 g/m²) ■—high yielding plot (809 g/m²) Moist surface soil conditions on days 184, 190, and 256 account for the depressed radiance values.

184, 190, and 256 the surface soil was damper than the surrounding sampling dates. On these days, the canopy closure was less than 50 percent, so the wetter, lower reflectance soil would have a lowering effect on the overall scene response.

Both the RAT43 and ND43 displayed concave downward patterns over the growth season: rapidly increasing with plant growth, peaking and then decreasing with plant senescence (Figures 4a and 4b). The RAT45 and ND45 behaved likewise (Figures 4c and 4d).

CORRELATION AND REGRESSION ANALYSIS

The strengths of the associations between the individual band radiances and yield were characterized by marked fluctuations over the growing season (Figure 5a). TM3 showed in general a small negative correlation with yield, TM4 a positive correlation, and TM5 no correlation over the season. The RAT43 and ND43 correlation patterns were much smoother and generally higher throughout the growing season than the individual radiances (Figures 5b and 5c). Each displayed an

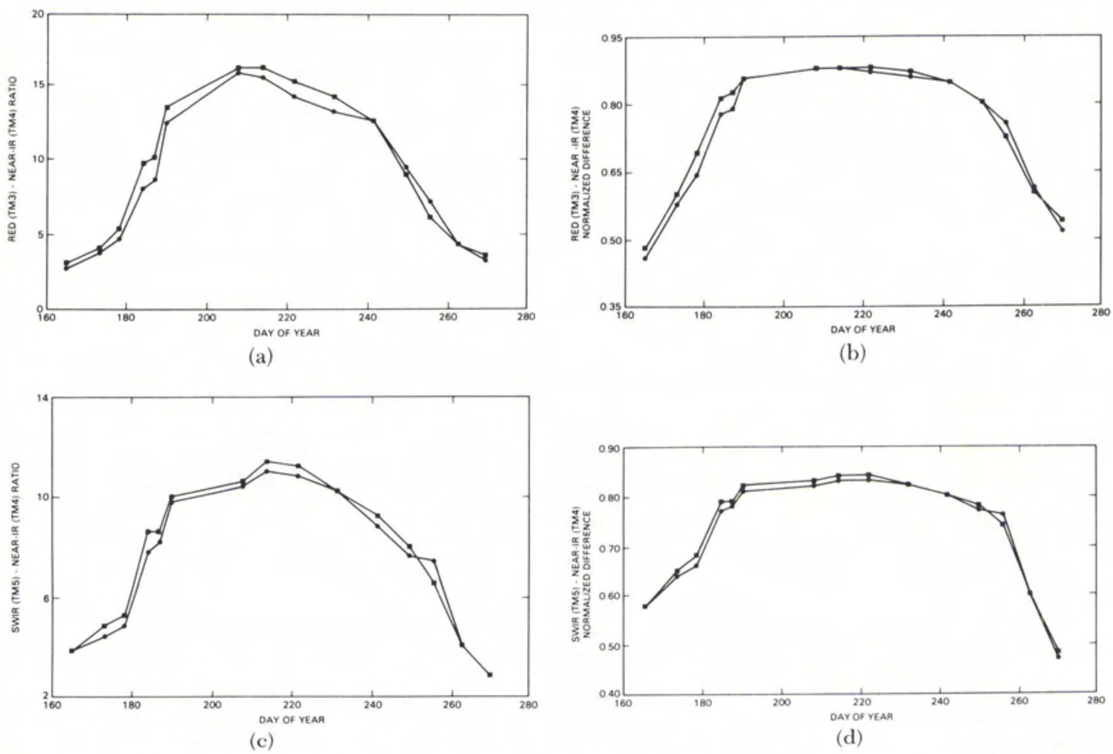

FIG. 4. RAT 43 (a), ND43 (b), RAT 45 (c), and ND45 (d) for two of the 24 corn plots versus day of year. ●—low yielding plot (529 g/m²) ■—high yielding plot (809 g/m²)

increase early in the season, two rounded peaks to a maximum r^2 of 0.45 to 0.50 at days 178-190 and 214-242 with a dip between, and a tapering off towards the end of the season. The RAT45 and ND45 showed more erratic and generally lower patterns of correlations. The correlation patterns of all the radiances and ratios to the final accumulation of dry matter followed closely those to yield, though averaging slightly higher. The peaks in the ND43 coefficients of determination reached 0.57, for example.

Integrating the spectral data across various combinations of periods corresponding to the peaks in the ND43 and RAT43 correlations improved the results. The best coefficient of determination for yield, 0.59, was achieved by integrating the ND43 from days 178-187 and 232-242 (Figure 6a). Across the same time period the coefficient of determination to final dry matter accumulation was increased to 0.66 (Figure 6b).

Discussion

Of the various spectral bands and ratios evaluated, only the ND43 and RAT43 appeared to give reasonable indicators of crop status. Only these ratios maintained a consistent pattern of correlation to yield over the season that was explainable in terms of the crop's phenology. This can be attributed to the high sensitivity of combinations of red and near-IR radiances to the photosynthetically active biomass. Also, these combinations have the ability to provide a degree of normalization for variations in illumination conditions that may have occurred over the nominally 30 minute data collection periods.

The fluctuating patterns of correlations and the overall poor results with the ND45 and RAT45 compared with the ND43 and RAT43 can be considered the result of several factors. First, water stress was not apparent at any time throughout the growing season. Thus, a band sensitive to leaf water content (TM5) would be potentially less indicative of crop status than under other conditions. Second, the bands used to form the ND45 and RAT45 are not as close spectrally in regard to atmospheric interactions as they are for the ND43 and RAT43. The illumination levels in the bands are less likely to respond similarly to changing atmospheric conditions during data collection, and calculating ratios would provide poorer normalization. Third, the vegetation/soil contrast in the TM5 spectral region for the field studied may not be typical, such that with other soils, TM5 might prove more useful.

The patterns of correlation of the ND43 and RAT43 to yield over the growing season are reasonable in terms of crop phenology. Prior to day 175 the low level of biomass present was likely a

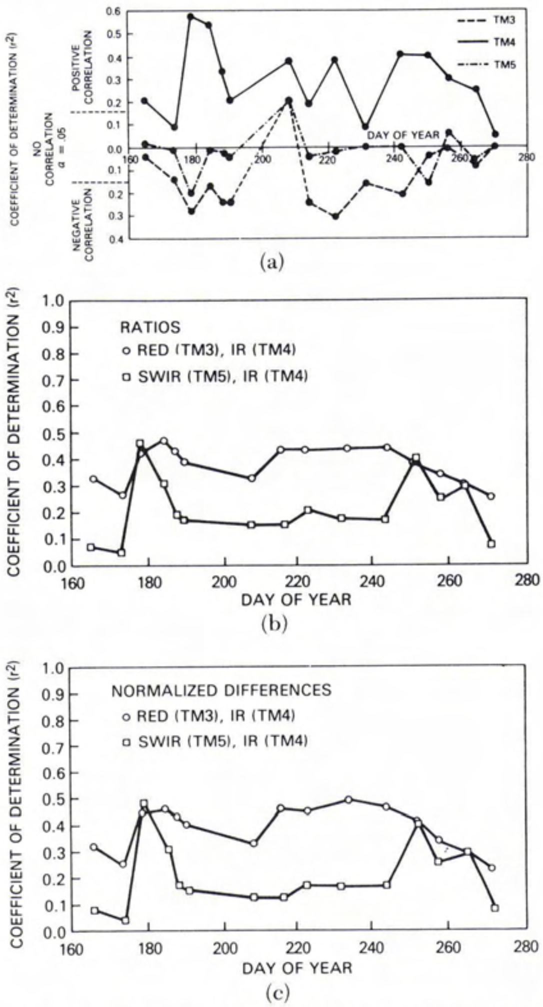

Fig. 5. Coefficients of determination (r^2) for correlation models of grain yield and individual data spectral data. (a) radiances, (b) simple ratios, and (c) normalized differences. Note in (a) that the r^2 value is plotted on the side of the x-axis corresponding to the sign of r.

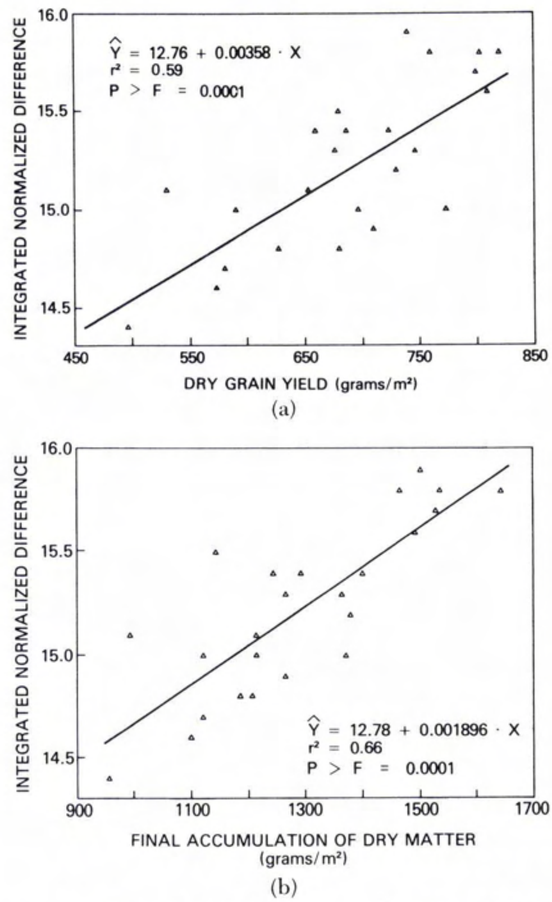

Fig. 6. The relationship between the TM4-TM3 normalized difference integrated from days 178 to 187 and 232 to 242 and (a) dry grain yield and (b) final accumulation of dry matter.

poor indicator of the seasonal productive capacity of the plants, hence the low correlations. As the crop developed, the level of photosynthetically active biomass would be expected to be more related to the final crop yield, as was generally observed by the higher correlations between day 175 and 250. The dip in correlation on day 208 can be explained by both the lowered sensitivity of the ratios to biomass differences under high biomass situations and any noise introduced by the between-plot differences in tasselling conditions on this date. This lowered sensitivity is a consequence of the asymptomatic nature of the relationship of NIR/red ratios, particularly the ND43, to photosynthetically active biomass (Tucker, 1979). With the beginning of senescence of all plots after day 250, lowered correlations were found because the level of photosynthetically active biomass this late in the season had little effect on the already developed grain.

The integration of the near-IR/red ratios across certain portions of the growing season can be seen as producing a better measure of seasonal crop status than that provided by any one date. This better measure of seasonal crop status is indicated by the improvement in the correlations to final dry yield and final dry matter accumulation. The particular value of the dates selected for the integration is in their inclusion of important mid-season growth periods, while avoiding periods of time where tasselling effects and near IR/red ratio insensitivity effects are potential problems.

The results of this study compared favorably with those of Tucker *et al.* (1980a) for wheat, though they reported somewhat higher coefficients of determination for the regressions, with 0.69 maximum. There are several possible reasons for the poorer performance with corn. First, for wheat, the IR/red radiance ratio peaked at 11 for the highest yielding plot and four for the lowest yielding. For corn, the corresponding figures were about 17 and 15. Although the instruments used had somewhat different bandwidths, so that the values of the ratios may not be comparable, it is apparent that a much larger range of ratios occurred for wheat. As the range of yields (percentagewise) was not much different between the studies, this implies that the photosynthetically active biomass in wheat, as measured by IR/red ratios, is considerably more sensitive to crop status than in corn. This could occur if there is a poorer relationship between the biomass and yield in corn than in wheat, or if smaller differences in photosynthetically active biomass in corn are indicative of larger changes in yield.

Second, atmospheric conditions in the humid region where these studies were conducted, tend to be considerably poorer and more variable during the corn growing season than the wheat. Thus, atmospheric noise may be concealing the relationships to a certain extent for corn.

As far as the implications of the results to the use of satellite data for corn yield prediction, several factors must be considered. First, the highest coefficients of determination between the spectral ratios and grain yield (r^2 = 0.59) and final dry matter accumulation (r^2 = 0.66), though statistically significant, are not indicative of particularly useful yield predicting techniques using solely spectral data. However, the range of yields observed in this study was rather restricted in that no very low yielding plots were present. These techniques would be expected to be more useful with the greater variation in crop conditions and yields that may occur in non-experimental fields. Second, to apply these techniques, particularly those involving integrating data across several portions of the growing season, to satellite data collected over an agricultural region, a corn crop calendar for that area and year must be available. Third, in a typical agricultural scene, more than one variety of corn may be planted. Additional research needs to be conducted on other varieties of corn to determine whether these techniques have any applicability beyond one genotype.

Summary/Conclusions

The ratios of the near-IR (TM4) and red (TM3) bands provided the highest and most consistent correlations to corn yield and dry matter accumulation. The replacement of the red band by the shortwave IR band (TM5) in these ratios generally reduced the correlations significantly. However, this test of the value of the TM5 band is not complete due to experimental conditions (i.e., lack of water stress) and the poor normalization provided by ratioing spectrally divergent bands. Integration of the spectral ratios over several dates improved the correlations to final yield/dry matter over that of any single date by achieving a seasonal, as opposed to an instantaneous, estimate of crop status. Additional work on corn under other growth conditions and on other varieties of corn is needed to determine whether satellite-derived spectral data will be useful for providing corn yield information.

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