Thematic Mapper Vegetation Indices for Determining Soybean and Corn Growth Parameters

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Abstract

The use of thematic mapper data to study crop growth parameters has primarily been conducted with hand-held and truck-mounted radiometers. In addition, most studies have not used mid-infrared bands to develop vegetation indices. This study used Landsat thematic mapper data and crop parameter data from corn and soybean fields in northern Ohio (1) to develop plant-water sensitive vegetation indices that included the mid-infrared, near-infrared, and red bands; and (2) to compare the ability of different vegetation indices to estimate crop yield, leaf area index, wet biomass, dry biomass, and plant height. Indices which included the mid-infrared thematic mapper bands 5 and 7 performed equal to or better than the widely used near-infrared band 4 and red band 3. The best relationships between vegetation indices and crop parameters had Spearman non-parametric correlation coefficients of 0.80 to 0.89 for all parameters except crop yield which was not highly correlated with the vegetation indices.

Introduction

Information on crop characteristics is often needed in order to develop site specific agricultural best management practices and for planning purposes. However, the cost of traditional field measurement techniques becomes prohibitive when applied to large areas and they are not practical at late crop growth stages. The use of data from satellite-born sensors is a practical alternative to field measurements, provided that suitable spectral vegetation indices (VIs) can be developed. The use of vegetation indices to study crop characteristics such as leaf area index, wet biomass, dry biomass, and plant height have primarily relied on near-infrared and red based indices (Baret and Guyot, 1991; Wiegand *et al.*, 1991). In recent years, research has shown increasing evidence of the usefulness of vegetation indices involving other wavebands such as mid-infrared (MIR) (Dusek *et al.*, 1985) and mid-infrared and thermal-infrared (Williamson, 1988). The thematic mapper mid-infrared bands are sensitive to moisture in plants (Tucker, 1980) and provide valuable additional information to red and near-infrared bands (Baret *et al.*, 1988). Kimes *et al.* (1981) suggested the conjunctive use of red and mid-infrared wavebands.

Landsat 5 Thematic Mapper (TM) data were used to evaluate soybean and corn crop growth characteristics and to compare the performance of red and near-infrared vegetation indices with vegetation indices involving mid-infrared wavebands. Specific objectives were to develop plant-water sensitive vegetation indices that included the mid-infrared, near-infrared and red bands; and to compare the ability of the different vegetation indices to estimate soybean and corn crop yield, leaf area index, wet biomass, dry biomass, and plant height.

Methods and Procedures

The study was based on Landsat 5 Thematic Mapper and ground-truth data for Seneca County, Ohio. The thematic mapper data were acquired for 25 August 1988 and 12 August 1989 overpasses corresponding to path 20 and row 31 of the Landsat world reference system (WRS). Characteristics of these data are described by Thenkabail (1992).

Crop growth data were obtained from commercially owned soybean and corn fields. The average size of the fields was about 100 hectares. Management groupings of the farms were either subsurface drainage or no-drainage, and conventional or conservation tillage on lakebed or till plain soils. Most of the crop growth information was collected, from a single location on each field, every 8 to 24 days to correspond with overlapping passes of Landsat 5. In 1988, data were obtained from 25 soybean fields and 26 corn fields. In 1989, 33 soybean fields and 14 corn fields were evaluated. The field measurements were taken throughout the growing season (1) in order to develop crop growth functions, (2) for use with process based simulation models, and (3) because of uncertainties associated with the availability and quality of the satellite sensor data.

Each monitoring location was located 5 m to 60 m from the field boundary and was selected so that it was representative of the dominant soil conditions in the field and had easy safe access. All field measurements were taken within 15 m of the monitoring station (a single pixel coverage). On each occasion during 1988, one or two plant samples were obtained from each field. On three occasions in 1989, five plant samples were obtained, while a single plant sample was obtained from each field on all other occasions. Crop pa-

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TABLE 1. CATEGORIES AND DEFINITION OF VEGETATION INDICES.

Category	Vegetation Index	Acronym	Definition
I	Simple	SVI	TM4/TM3
	Normalized Difference	NDVI	(TM4-TM3)/(TM4+TM3)
	Transformed	TVI	$(NDVI)^{0.5}$
II	Stress related 1	STVI1	(TM5*TM3)/(TM4)
	Stress related 2	STVI2	(TM4)/(TM3*TM7)
	Stress related 3	STVI3	(TM4)/(TM3+TM5)
III	Mid-infrared 1	MSVI1	TM4/TM5
	Mid-infrared 2	MSVI2	TM4/TM7
	Mid-infrared 3	MSVI3	(TM4)/(TM5+TM7)

rameters consisted of leaf area index (m^2/m^2), wet biomass (kg/m^2), dry biomass (kg/m^2), plant height (mm), and after-harvest yields (kg/ha). The plants were weighed to determine their above-ground wet biomass. They were then oven dried at 70 degrees centigrade until an equilibrium dry biomass was attained. Leaf area was measured in the laboratory using a LI-COR 3100 instrument. Leaf area index (LAI, m^2/m^2) and above-ground wet and dry biomass (kg/m^2) were then calculated based on plant and row spacings, and visual estimates of barren areas. Further details are presented by Thenkabail (1992) together with details on the soil, soil water content, water table elevation, and climatic data that were also collected.

Crop parameter values were calculated for each of the overpass dates by fitting polynomial curves to the temporal data sets for each field. A comparison between using polynomial equation estimates versus measured values on the day of the overpass is presented by Thenkabail *et al.* (1992). Crop parameters calculated from a polynomial equation were leaf area index (LAI), wet biomass, and dry biomass. Plant height was a direct above-ground measure. Crop yield was the after-harvest yield provided by the farmer.

Mean Thematic Mapper brightness values were extracted for each farm at a spatial scale of 10 pixels using the Earth Resources Digital Analysis System (ERDAS, 1990). To determine field locations and the ground-truth data collection sites, the distance from each monitoring station to the nearest road intersection was measured. This measurement was used to locate the coordinates of the monitoring station relative to the closest observed road intersection on a false color composite image. Aerial photographs of farm fields, soil maps, Unites States Geological Survey topographic maps, and knowledge of the farms aided in locating on the image the field boundaries and the monitoring locations. Ten pixels were selected in the immediate vicinity of the monitoring site based on the proximity of the site to field boundaries.

Vegetation indices which were developed and evaluated are presented in Table 1. Non-parametric statistics were adopted due to the non-Gaussian characteristic of the data, and to help handle small and unequal sample sizes. Lyon *et al.* (1988) and Helsel (1987) enumerate the advantages offered by non-parametric statistics over parametric statistics in handling data of this nature. Spearman rank correlation coefficient (r) values were obtained to evaluate the ability of the thematic mapper vegetation indices (VIs) to account for the between-field variability in the soybean and corn parameters. The significance of correlations is reported at a 0.05 level unless reported otherwise. The Statistical Analysis System (SAS, 1982) was used to perform the statistical analysis. Analyses were performed on (1) each crop for pooled data on the 1988 and 1989 overpass dates and (2) the individual data sets of each year. Pooled data sets for each crop were analyzed (1) with data outliers and (2) by removing data outliers.

Results and Discussions

General characteristics of soybean and corn crop data extracted from the two Thematic Mapper scenes and from field measurements of crop characteristics are presented in Table 2. Except for yield, the means of each of the crop parameters are significantly different (0.01 level) in the two years. This is due to the different crop growth stages on the two August overpass dates. In 1988, there was a severe drought with only 27 percent of the normal rainfall until the end of June. Soybeans on 25 August 1988 were in an advanced critical growth phases and with canopy cover of about 100 percent. The leaves were turning brown and the pods were filling. In contrast, soybeans of 12 August 1989 had green leaves, had a canopy cover of about 70 percent, and were flowering or just forming pods. These conditions resulted in the soybeans for the August 1989 image having greater reflectance than the soybeans for the August 1988 image.

The 1988 drought had a greater impact on corn than on soybeans. In many fields corn was in a senescing growth phase with 100 percent canopy cover. However, in a few fields the corn was still tasselling. In addition, many fields had a mixture of small and large plants as well as bare areas. Corn on 12 August 1989 had about an 80 percent canopy cover and was growing vigorously in the early tasselling phases of growth.

TABLE 2. INTER-YEAR COMPARISONS OF CROP PARAMETERS AND VEGETATION INDICES.[1]

Variable	Units	25 August 1988 Mean	25 August 1988 Std. Dev.	12 August 1989 Mean	12 August 1989 Std. Dev.
Soybeans (25 fields in 1988 and 33 in 1989)[2]					
NDVI	(no units)	0.62	0.05	0.51	0.06
STVI1	(μm)	21.33	3.09	32.30	7.91
STVI2	(μm^{-1})	6.83	1.41	10.70	4.08
MSVI1	(no units)	1.39	0.11	1.30	0.16
MSVI2	(no units)	4.44	0.60	4.13	0.90
Yield	(kg/ha)	1874	783	2040	433
LAI	(no units)	3.79	1.65	2.38	1.25
Wet Biomass	(kg/m^2)	2.20	1.04	1.13	0.64
Dry Biomass	(kg/m^2)	0.56	0.22	0.25	1.13
Height	(mm)	779	150	518	146
Corn (26 field in 1988 and 14 in 1989)[3]					
NDVI	(no units)	0.45	0.07	0.46	0.05
STVI1	(μm)	33.14	12.52	30.94	8.59
STVI2	(μm^{-1})	12.47	6.40	10.27	4.61
MSVI1	(no units)	1.11	0.17	1.39	0.19
MSVI2	(no units)	3.12	0.73	4.49	1.12
Yield	(kg/ha)	4927	1848	8068	1545
LAI	(no units)	2.24	0.66	2.91	0.81
Wet Biomass	(kg/m^2)	3.68	0.94	5.46	1.85
Dry Biomass	(kg/m^2)	1.00	0.36	1.35	0.52
Height	(mm)	1910	146	2220	403

[1] Vegetation indices are defined in Table 1.

[2] NDVI, STV1, STVI2, and all crop variables except yield are significantly different at 0.01 level between 2 years. MSVI1 is significantly different at the 0.05 level.

[3] MSVI1, MSVI2, and all crop variables except yield are significantly different at 0.01 level between the 2 years. Yield was significantly different at the 0.05 level.

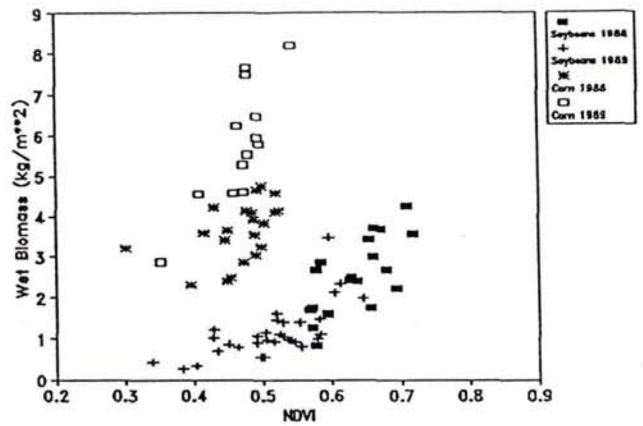

Figure 1. NDVI response to wet biomass (kg/m²) of soybean and corn crops in different growth stages demonstrating significant discrimination between crops [$n = 85$, insignificant correlation].

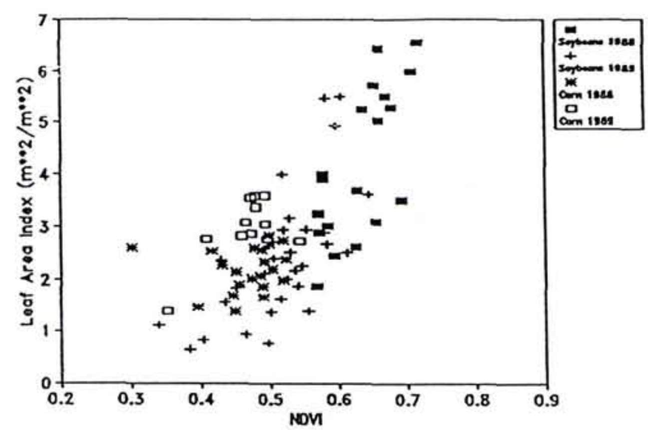

Figure 2. NDVI response to leaf area index (m²/m²) of soybean and corn crops in different growth stages [$n = 85$, correlation coefficient (r) = 0.70, significant at the 0.01 level].

The results in Table 2 demonstrate the usefulness of using several different vegetation indices. With the exception of the mid-infrared simple vegetation index one (MSVI1), mean values for each of the indices are only significantly different between years for one of the crops. For example, the mean values of the normalized difference vegetation index (NDVI) are significantly different for soybeans but not corn. This is attributed to NDVI reaching a plateau and then decreasing following a critical growth phase (Bausch and Neale, 1983; Tucker *et al.*, 1979a). In 1989, the soybeans had not yet reached a critical phase. Although on the two overpass dates corn was in different growth stages, it had reached a critical phase in both years.

The results also illustrate the need to use several crop parameters to characterize differences between crops. For example, soybeans were spectrally distinguishable from corn using wet biomass responses to thematic mapper data (Figure 1) but not by using LAI responses (Figure 2). Non-parametric Spearman rank correlations (r) between the three categories of thematic mapper indices and pooled data sets for each crop parameter are presented in Tables 3 and 5. Results for

TABLE 3. NON PARAMETRIC SPEARMAN RANK CORRELATION COEFFICIENTS (r) BETWEEN VEGETATION INDICES AND SOYBEAN CROP VARIABLES WITH DATA FOR THE TWO AUGUST DATES POOLED (SAMPLE SIZE 51).[1,2]

Category	Vegetation Index	Yield	LAI	Wet Biomass	Dry Biomass	Height
I	SVI	0.42	0.80	0.84	0.83	0.81
	NDVI	0.42	0.80	0.84	0.83	0.81
	TVI	0.42	0.80	0.84	0.83	0.81
II	STVI1	−0.37	−0.76	−0.81	−0.83	−0.85
	STVI2	0.44	0.77	0.81	0.81	0.81
	STVI3	0.51	0.70	0.76	0.69	0.71
III	MSVI1	0.53	0.56	0.63	0.51	0.55
	MSVI2	0.54	0.59	0.61	0.51	0.53
	MSVI3	0.54	0.59	0.64	0.52	0.55

[1] Vegetation indices are defined in Table 1.
[2] Significant correlations (at the 0.05 level) are reported. If outliers were not removed, r values were typically lower by about 0.06 with a maximum decrease of 0.12 for LAI. Similar r values found between different VIs with a particular crop variable is due to (1) ranking of the values in non-parametric statistics and (2) similar characteristics of the VIs.

TABLE 4. NON-PARAMETRIC SPEARMAN RANK CORRELATION COEFFICIENTS (r) BETWEEN VEGETATION INDICES VERSUS SOYBEAN CROP VARIABLES FOR THE INDIVIDUAL AUGUST DATASETS[1].

Category	Vegetation Index	Yield	LAI	Wet Biomass	Dry Biomass	Height
(a) 25 August 1988[2]						
I	SVI	0.57	0.69	0.70	0.52	0.44
	NDVI	0.57	0.69	0.70	0.52	0.44
	TVI	0.57	0.69	0.70	0.52	0.44
II	STVI1	−0.56	−0.62	−0.60	−0.52	−0.56
	STVI2	0.69	0.77	0.74	0.66	0.68
	STVI3	0.52	0.61	0.68	0.55	0.48
III	MSVI1	0.48	0.51	0.61	0.51	0.42
	MSVI2	0.65	0.72	0.74	0.65	0.59
	MSVI3	0.55	0.60	0.67	0.58	0.46
(b) 12 August 1989[3]						
I	SVI	0.55	0.66	0.66	0.61	0.66
	NDVI	0.55	0.66	0.66	0.61	0.66
	TVI	0.55	0.66	0.66	0.61	0.66
II	STVI1	−0.52	−0.59	−0.59	−0.53	−0.63
	STVI2	0.51	0.57	0.59	0.53	0.61
	STVI3	0.55	0.56	0.60	0.50	0.63
III	MSVI1	0.52	0.44	0.52	0.37	0.53
	MSVI2	0.48	0.50	0.54	0.49	0.58
	MSVI3	0.52	0.50	0.56	0.42	0.57

[1] Vegetation indices are defined in Table 1.
[2] Sample size was 19. All correlations are significant at the 0.05 level. If no outliers were removed from the 1988 dataset, r values were typically lower by about 0.06 with a maximum of 0.17 for LAI.
[3] Sample size was 32. All correlations are significant at the 0.05 level. If no outliers were removed from the 1989 dataset, r values were nearly the same with differences of about 0.01. This was expected as only one point was removed.

TABLE 5. SPEARMAN RANK CORRELATION COEFFICIENTS (r) BETWEEN VEGETATION INDICES AND CORN CROP VARIABLES WITH DATA FOR THE TWO AUGUST DATES POOLED (SAMPLE SIZE 34).[1,2]

Category	Vegetation Index	Yield	LAI	Wet Biomass	Dry Biomass	Height
I	SVI	NS	0.34	0.40	NS	0.40
	NDVI	NS	NS	0.34	0.40	0.40
	TVI	NS	NS	0.34	0.40	0.40
II	STVI1	−0.38	−0.52	−0.63	−0.65	−0.51
	STVI2	0.54	0.67	0.76	0.73	0.63
	STVI3	0.68	0.78	0.87	0.77	0.76
III	MSVI1	0.70	0.79	0.88	0.77	0.77
	MSVI2	0.69	0.80	0.87	0.76	0.75
	MSVI3	0.70	0.80	0.88	0.77	0.76

[1] Vegetation indices are defined in Table 1.
[2] Only significant correlations (at the 0.05 level) are reported. Non-significant correlations are represented by the symbol 'NS'. If no outliers were removed, r values were about the same for yield and height, lower by about 0.08 for wet biomass and dry biomass, and lower by about 0.14 for LAI.

the individual years are presented in Tables 4 and 6. For category I, results are reported for the three most commonly used spectral vegetation indices. In categories II and III, the three best indices are reported. Results for additional indices which were evaluated are presented by Thenkabail (1992). There were seven soybean fields and six corn fields that were removed from the pooled data sets of the respective crops. Fields that were removed had severe weed problems or contained large positive or negative residuals. Photographic slides helped identify the severity of weed in a given farm. An extensive presentation on the rationale and process of removing data outliers can be found in Thenkabail (1992).

TABLE 6. SPEARMAN RANK COEFFICIENTS (r) BETWEEN VEGETATION INDICES VERSUS CORN CROP VARIABLES FOR THE INDIVIDUAL AUGUST DATES.[1]

Category	Vegetation Index	Yield	LAI	Wet Biomass	Dry Biomass	Height
(a) 25 August 1988[2]						
I	SVI	NS	NS	0.47	0.45	NS
	NDVI	NS	NS	0.47	0.45	NS
	TVI	NS	NS	0.47	0.45	NS
II	STVI1	−0.44	−0.48	−0.69	−0.69	NS
	STVI2	0.46	0.49	0.65	0.68	NS
	STVI3	0.48	0.44	0.71	0.70	NS
III	MSVI1	0.48	0.44	0.73	0.71	NS
	MSVI2	0.45	0.51	0.68	0.68	NS
	MSVI3	0.47	0.48	0.72	0.70	NS
(b) 12 August 1989[3]						
I	SVI	NS	NS	0.64	NS	NS
	NDVI	NS	NS	0.64	NS	NS
	TVI	NS	NS	0.64	NS	NS
II	STVI1	NS	−0.62	−0.84	−0.66	−0.55
	STVI2	NS	0.63	0.84	0.65	0.52
	STVI3	NS	0.60	0.81	0.62	NS
III	MSVI1	NS	0.60	0.81	0.62	NS
	MSVI2	NS	0.58	0.83	0.63	0.48
	MSVI3	NS	0.58	0.83	0.63	NS

[1] Vegetation indices are defined in Table 1. Only Significant Correlations (at the 0.05 Level) Are Reported. Non-significant correlations are represented by the symbol 'NS'.
[2] Sample size was 21. If no outliers were removed from the 1988 dataset, r values were lower by about 0.08 for yield and lower by as high as about 0.25 for other variables.
[3] Sample size was 13. If no outliers were removed from the 1989 dataset, r values were lower by about 0.05.

The best results for the soybean yield, LAI, wet biomass, dry biomass, and plant height were 0.54, 0.80, 0.84, 0.83, and 0.85, respectively (Table 3). The category III indices were the least significant of the three categories. However, the results for the individual years (Table 4) do not indicate that one category is better than another. They highlight the ability of indices in explaining the dynamics of crop growth stage and growth condition. The senescing and drought stressed plants in 1988 had an increased sensitivity to the mid-infrared wavebands and decreased sensitivity to the near-infrared and red wavebands. In 1989, the photosynthetically active, vigorously growing soybeans had a higher sensitivity to the widely used category I vegetation indices. Clevers (1988), based on studies by Hatfield *et al.* (1984) and Holben (1980), states that the spectral vegetation indices (of category I type) were sensitive to changes in LAI until complete plant cover was achieved, but were only slightly sensitive for variations in LAI after complete plant cover has been reached.

Indices that provided the best soybean results and occurred most frequently were STVI1 and STVI2 and the commonly used indices SVI, NDVI, and TVI (Table 3 and Table 4). The relationship between STVI1 and plant height is shown in Figure 3. The best relationships using pooled data in category I and category II explained 71 and 72 percent of the variability in data, whereas the best relationship in category III only explains 41 percent (r = 0.64) of the variability in the data (Table 2).

The commonly used near-infrared and red based category I indices were found to be the least significant of the three categories of vegetation indices studied when correlated with the corn parameters (Table 4 and 5). These results were surprising considering the overwhelming use of category I indices in crop and vegetation studies.

The poor results of category I indices with corn parameters of 1988 (Table 5) were attributed to a combination of (1) 100 percent canopy cover, (2) senescing features, and (3) severe drought affects. Except for wet biomass, none of the corn variables show significant relationships with category I indices. This was rather unexpected as commonly used vegetation indices such as NDVI and SVI are expected to peak at the beginning of the tasselling phase of corn crop growth, and to plateau during the progression of the critical growth phases before starting to decrease (Bausch and Neale, 1983; Tucker *et al.*, 1979).

The single best relationships for each of the corn crop variables were found with a category III and/or category II index for both the pooled data (Table 4) and the individual year data (Table 5). The best relationship was between wet biomass and MSVI1 (Figure 4). This relationship demonstrates the capability to handle physiologically dissimilar growth phases and complex datasets consisting of drought affected and senescing corn, an important contrast compared to the ability of the commonly used near-infrared and red based indices.

Crop yield was insignificantly correlated with indices from all three categories for the 1989 data (Table 5). This contrasted with generally significant correlations of the other four crop variables with Thematic Mapper indices from all three categories. Thenkabail *et al.* (1992b) reported that there was little correlation between the crop parameters and yield. The best non-linear regression model included three crop pa-

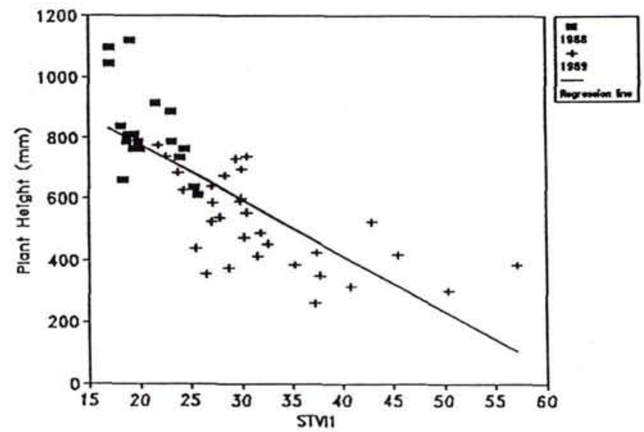

Figure 3. Soybean plant height (mm) versus STVI1 for the pooled sieved dataset [$n=51$, correlation coefficient (r) = -0.85, significant at the 0.01 level].

rameters and only accounted for 39 percent of the variation in corn yields.

General Discussions

The category 1 results compare well with previously reported studies on corn and soybeans. For example, Tucker (1979) and Tucker *et al.* (1979a) showed significant correlation coefficients of 0.73 and 0.70 between vegetation indices (based on data from a hand held spectrometer) and soybean wet biomass and crop height.

Overall, indices which included the mid-infrared bands performed equal to or better than near-infrared and red based indices. These results generally concur with other recent research findings. For example, Williamson (1988), in a study on grassland canopies using airborne multispectral scanner data, concludes that there was an increase in correlation between green LAI and vegetation indices which included mid-infrared and thermal-infrared waveband over the red and near-infrared vegetation indices. The study by Williamson (1988) showed grassland green LAI provided correlation coefficients (r) of 0.66, 0.75. and 0.80 with NDVI, the ratio of near-infrared to mid-infrared, and the ratio of near-infrared to thermal-infrared, respectively.

Dusek *et al.* (1985) used a Barnes MMR 12-1000 radiometer (which has spectral bands similar to the Thematic Mapper) to infer that the commonly used infrared/red ratio's produced considerably lower r^2 values than many other ratio indices when related to wheat crop variables such as LAI, wet biomass, and green ground cover. They demonstrated that mid-infrared bands appeared more frequently in the ratio indices than in the greenness indices. The ability of vegetation indices which incorporate mid-infrared wavebands to account for complex data is consistent with studies reported in the literature. Williamson (1988) and Dusek *et al.* (1985) both dealt with complex data bases. Dusek *et al.* (1985) incorporate several genotypes and diverse irrigation practices which include data from water stressed fields. Baret *et al.* (1988) found that mid-infrared bands in a similar range to Thematic Mapper band 5 and Thematic Mapper band 7 provided additional complementary information to red and near-infrared bands on the geometrical structure of the canopy and on the optical properties of the underlying soil.

The results in Table 2 through Table 5 show that (1) of the five crop variables studied, the vegetation indices were best related to wet biomass; (2) LAI, dry biomass, and plant height provided similar results which were only slightly poorer than for wet biomass; and (3) crop yield was not very highly correlated to the vegetation indices.

It can be seen from Figure 1 that the relationship between STVI1 and plant height is non-linear. Thenkabail *et al.* (1993) showed that the best correlation between vegetation indices and crop parameters was usually obtained with exponential models of NDVI, multi-linear models which included category 2 indices, or MSVI1 cubed. With the exception of crop yield, coefficients of determination (r^2) for the best models and corn and soybean crop parameters ranged from 0.61 to 0.80.

The performance of the indices which are presented is a function of the growth stages studied and the use of a single image for each year. The study and the development of the spectral vegetation indices was limited by the availability of cloud-free Thematic Mapper imagery. Based on a survey of Thematic Mapper data that was obtained prior to 1988, it was established that three or more images were usually available between April and September of each year. However, in both 1988 and 1989, partial cloud cover, fog, and/or sensor problems resulted in the August images being the only high quality images available during periods when the crop canopies were well established. It is anticipated, based on studies with hand-held and truck-mounted sensors (Dusek *et al.*, 1985; Baret *et al.*, 1988; Williamson, 1988), that the performance of the vegetation indices might well improve if they were developed based on temporal radiometric data. In addition, the ranking of the indices might well change. Although no imagery was available for early growth stages, the study does encompass different growth stages for both of the crops.

Conclusions

This study demonstrated the usefulness of the mid-infrared bands of Landsat 5 Thematic Mapper in studying soybean

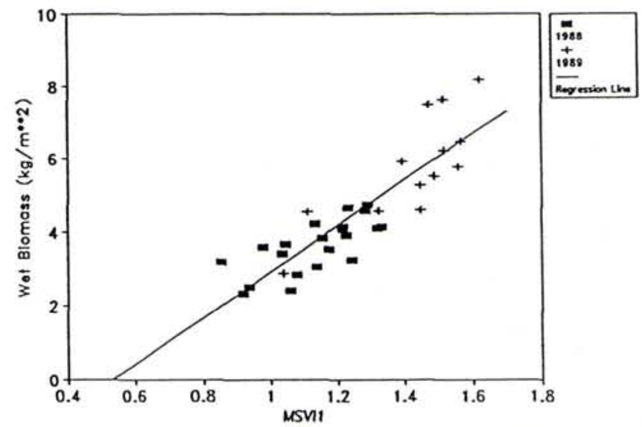

Figure 4. Corn wet biomass (kg/m^2) versus TM4/TM5 for the pooled sieved dataset [$n=34$, correlation coefficient (r) = 0.88, significant at the 0.01 level].

and corn crop growth and yield variables. Category II and category III indices which used the mid-infrared Thematic Mapper bands 5 and 7 performed equal to or better than indices based on the widely used near-infrared Thematic Mapper band 4 and the red Thematic Mapper band 3. Particularly high improvements in correlations were found with corn crop parameters. This was a surprising result considering the lack of use of indices involving mid-infrared wavebands.

Category II and category III indices demonstrated high levels of sensitivity in handling complex databases such as the pooled data sets of two physiologically dissimilar growth stages and conditions of drought. There were also some indications that, as crops attain advanced growth phases, there is an increased sensitivity of the mid-infrared based indices and an decreased sensitivity in the commonly used near-infrared and red based indices.

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