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COMPARISONS AMONG A NEW SOIL INDEX AND OTHER TWO-  
AND FOUR- DIMENSIONAL VEGETATION INDICES

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COMPARISONS AMONG A NEW SOIL INDEX AND OTHER  
TWO- AND FOUR-DIMENSIONAL VEGETATION INDICES\*

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BIOGRAPHICAL SKETCH

Craig Wiegand is a soil scientist in the Remote Sensing Research Unit, Agricultural Research Service, USDA, Weslaco, TX. He has 17 years experience in the agricultural applications of aerial photography, optical mechanical scanner, and satellite (LANDSAT, EREP, and HCMM) data. Jerry Richardson is a physicist with the same organization. His research experience includes crop and land use discrimination and pattern recognition, spectral vegetation and soil indices, atmospheric transfer modelling, and scene component analysis using ground, aerial, and space observations.

ABSTRACT

The 2-D difference vegetation index (DVI) and perpendicular vegetation index (PVI), and the 4-D green vegetation index (GVI) are compared in LANDSAT MSS data from grain sorghum (*Sorghum bicolor* (L.) Moench) fields for the years 1973 to 1977. PVI and DVI were more closely related to LAI than was GVI. A new 2-D soil line index (SLI), the vector distance from the soil line origin to the point of intersection of PVI with the soil line, is defined and compared with the 4-D soil brightness index, SBI. SLI (based on MSS5 and MSS7) and SLI6 (based on MSS5 and MSS6) were smaller in magnitude than SBI but contained similar information about the soil background. These findings indicate that vegetation and soil indices calculated from the single visible and reflective infrared band sensor systems, such as the AVHRR of the TIROS-N polar orbiting series of satellites, will be meaningful for synoptic monitoring of renewable vegetation resources.

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## INTRODUCTION

Vegetation indices (Rouse et al., 1974; Wiegand et al., 1974; Kauth and Thomas, 1976; Richardson and Wiegand, 1977; Tucker, 1979; Ashburn, 1979; and Jackson et al., 1980) are used for monitoring vegetation development, crop condition and stress, forage production, and grain yields (Deering et al., 1975; Richardson and Wiegand, 1977; Thompson and Wehmanen, 1979; Ashburn, 1979; Badhwar and Henderson, 1981; and Lautenschlager and Perry, 1981). The indices are ratios, differences, sums/differences, and linear combinations of visible (0.4 to 0.7  $\mu\text{m}$ ) and reflective infrared (0.75 to 1.35  $\mu\text{m}$ ) bands that reduce the information about the green vegetation cover and the soil background respectively, to a single numerical index.

Although the indices can be calculated from radiance, reflectance factor, or digital count as observed from any instrument, the most widely available and extensive data have come from the LANDSAT series of earth observation satellites through the impetus of the Large Area Crop Inventory Experiment (LACIE) (The LACIE Symposium, 1979). The LANDSAT MSS has two visible (0.5 to 0.6  $\mu\text{m}$  and 0.6 to 0.7  $\mu\text{m}$ ) and two reflective infrared bands (0.7 to 0.8  $\mu\text{m}$  and 0.8 to 1.1  $\mu\text{m}$ ) that are referred to as bands MSS4, MSS5, MSS6, and MSS7, respectively. As the three-year LACIE ended, uncertainty about continuation of the MSS and LANDSAT series, its rather infrequent coverage, and the desire to continue operational uses of such data for foreign crop production forecasting (MacDonald and Hall, 1980), prompted consideration of alternative satellite data sources. One such source is bands 1 (0.58 to 0.68  $\mu\text{m}$ ) and 2 (0.725 to 1.10  $\mu\text{m}$ ) of the Advanced Very High Resolution Radiometer (AVHRR) aboard the polar-orbiting TIROS-N series of National Oceanographic and Atmospheric Administration (NOAA) satellites. This series offers 5-day repeat nadir coverage and continuity through 1985 (Schwalb, 1978; Gray, McCrary and Armstrong, 1981). A preliminary test (Gray and McCrary, 1981) of band 2 minus band 1 of the AVHRR versus (2 MSS7-MSS5) of LANDSAT for common ground sites and overpass dates yielded a linear correlation coefficient,  $r=0.86$ .

Indices that utilize all four LANDSAT MSS bands, hence are four-dimensional (4-D) in terms of MSS data space are the "brightness" or soil brightness index (SBI), "greenness" or green vegetation index (GVI), "yellow stuff" (YEL) and "non-such" of Kauth and colleagues (Kauth and Thomas, 1976; Kauth, et al., 1979). The two-band or two

dimensional (2-D) indices that are also referenced to a soil line include the perpendicular vegetation index (PVI) and difference vegetation index (DVI) (Richardson and Wiegand, 1977). Should AVHRR data become widely used, then axiomatically only 2-D indices can be calculated from its single visible and single reflective infrared band. The purposes of this paper are to (a) derive a 2-D soil index, termed the soil line index (SLI) that is analogous to the 4-D SBI, and (b) compare the similarities and differences among the named 2-D and 4-D vegetation and soil background indices for a common data set.

#### EQUATIONS AND DEFINITIONS

Kauth and Thomas (1976) defined the plane of soil or soil brightness index (SBI) in LANDSAT-1 data transformed by axis rotation. The SBI equation for LANDSAT-2 equivalent\* digital count (DC) data adjusted to a constant solar zenith angle (SZA) of 39° (Kauth, et al., 1979) is

$$SBI = .332(MSS4) + .603(MSS5) + .676(MSS6) + .263(MSS7). \quad (1)$$

In a two-dimensional approach (Figure 1) that uses the red visible band (MSS5) and either MSS6 or MSS7, Richardson and Wiegand (1977), the vegetation indices are referenced to the line of soil. For satellite calibration and SZA 39° DC data the soil line is defined by

$$MSS5 = 0.26 + 2.73(MSS7) \quad (2a)$$

$$\text{and } MSS5 = -6.09 + 1.12(MSS6) \quad (2b)$$

Their difference vegetation index (DVI) is

$$DVI = 0.26 + 2.73(MSS7) - MSS5 \quad (3)$$

which by comparison with (2a) is the estimated value of MSS5 on the soil line,  $\hat{MSS5}$ , minus MSS5 or

$$DVI = \hat{MSS5} - MSS5. \quad (3a)$$

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\*Coefficients are available for converting LANDSAT-1 and LANDSAT-3 digital counts to equivalent LANDSAT-2 digital counts during the period 22 Jan 1975 through 15 Jul 1975. See the LANDSAT Data Users' Manual, p. AE16 for the basic data, or Richardson (1982).

By reference to Figure 1, DVI is the vertical distance from the soil line to the vegetation point, Rp 5, and the length of the hypotenuse, labeled c, of the right triangle formed by the soil line, the perpendicular vegetation index (PVI), and DVI.

Kauth et al. (1979) defined the "green stuff" or green vegetation index (GVI) component for SZA-corrected equivalent LANDSAT-2 data as

$$GVI = -0.283(MSS4) - 0.660(MSS5) + 0.577(MSS6) + 0.388(MSS7) \quad (4)$$

This component is orthogonal to the SBI component and is dominated by live, green vegetation. In a 2-D approach, Richardson and Wiegand (1977) defined the perpendicular distance from the soil line to the vegetation point Rp 7, Rp 5 by

$$PVI = [(Rgg5-Rp5)^2 + (Rgg7-Rp7)^2]^{1/2} \quad (5)$$

wherein Rgg7 and Rgg5 are the coordinates of the intersection of the PVI line with the soil line (Figure 1). For the soil line of (2a) Rgg7 and Rgg5 are defined by

$$Rgg7 = -0.084 + 0.323 Rp5 + 0.118 Rp7 \quad (5a)$$

$$Rgg5 = 0.031 + 0.882 Rp5 + 0.323 Rp7 \quad (5b)$$

and for the soil line of equation (2b)

$$Rgg6 = 3.03 + 0.497 Rp5 + 0.414 Rp6 \quad (5c)$$

$$Rgg5 = -2.70 + 0.556 Rp5 + 0.497 Rp6 \quad (5d)$$

PVI can also be derived from the formula for the distance from a point to a line (Jackson et. al., 1980; Lautenschlager and Perry, 1981). For Rp7 on the abscissa and Rp5 on the ordinate as in Figure 1

$$PVI_{7,5} = (a_1 Rp7 - Rp5 + a_0) / [(1)^2 + (a_1)^2]^{1/2} \quad (5e)*$$

\*When Rp5 is plotted on the abscissa and Rp7 on the ordinate, the equation equivalent to (5e) is

$$PVI_{5,7} = (Rp7 - a_1 Rp5 - a_0) / [(1)^2 + (-a_1)^2]^{1/2}$$

For this equation  $a_0 = -.095$  and  $a_1 = .366$ , so that the equation reduces to (5f).

Since  $a_0$  = the soil line intercept = 0.26 and  $a_1$  = the slope of the soil line = 2.73, the equation reduces to

$$PVI = \frac{.939Rp7 - .344Rp5 + 0.09}{0.09} = \frac{.939MSS7 - .344MSS5 + 0.09}{0.09} \quad (5f)$$

Similarly,  $PVI6 = .746Rp6 - 0.666Rp5 - 4.06$ . Both PVI and PVI6 equal 0 for bare soil and increase as green vegetation density increases.

In Figure 1 we have now defined sides a and c of a right triangle, so that the length of side b, the soil line leg (SLL) is

$$b = SLL = [(DVI)^2 - (PVI)^2]^{\frac{1}{2}}, \text{ or} \quad (6)$$

$$SLL = \cos 20.33^\circ(DVI) = 0.938(DVI). \quad (6a)$$

The length of the SLL for a given data set depends on the range in soil color, texture, and moisture content encountered in the observations; on the amount of shadow present; and, on soil tillage, cloddiness, and bleaching by the sun. Data for soil contaminated by cloud shadows or cloud tops will extend the lower and upper ends of the SLL, respectively, since both these features fall on the soil line. When such data are included, the line is properly called the shadow-soil-cloud line.

The length of the vector initiating from the origin of the soil line and terminating at the point (Rgg7, Rgg5) for each observation pair (Rp7, Rp5) is of greater interest than SLL. Using soil line definitions (2a) and (2b), this distance--termed the soil line index (SLI) for MSS bands 5 and 7, an' SLI6 for bands 5 and 6--is calculated by the respective equations

$$SLI = [(Rgg5 - .26)^2 + (Rgg7)^2]^{\frac{1}{2}}. \quad (7)$$

and

$$SLI6 = [(Rgg5 + 6.09)^2 + (Rgg6)^2]^{\frac{1}{2}}. \quad (7a)$$

SLI and SLI6 are the two dimensional analogs of SBI defined in eq. (1).

SLI and SLI6 reduce the information about the soil background to a single index for the respective bands used. Factors that can affect the value of SLI on a given observation date or for a particular site include soil type, solar zenith angle, water content of the surface soil,

soil crusting, proportion of shadows, bleaching of the soil surface, amount of standing, dry or littered plant residue, and cultural operations such as cultivation. Wet soil conditions, compared with dry soil background, and shadows lower SLI whereas soil bleaching and a more nadir solar zenith angle increase SLI. The soil background also influences plant canopy reflectance over most of the crop season. Reflectance modeling studies (Colwell, 1974; Chance and LeMaster, 1977; Kauth, et al., 1979) show that the soil background affects visible band responses up to an LAI of about 2 if leaves are uniformly distributed over the ground but up to an LAI of at least 6 in the reflective infrared bands. Consequently careful study of the seasonal trajectories of both the soil background index SLI and the vegetation indices in response to agronomic and natural variables should enhance scene understanding.

#### MATERIALS AND METHODS

We assembled a LANDSAT MSS data set for commercial grain sorghum (*Sorghum bicolor*, (L.) Moench) fields that included 9 scenes spanning the years 1973 through 1977 (Table 1). The computer compatible tapes (CCT) were obtained either from the Data Handling Facility at Goddard Space Flight Center, Greenbelt, MD or from the USDI EROS Data Center at Sioux Falls, SD. Line printer gray maps of areas in the vicinity of study fields were prepared, the study fields were identified and outlined, and the digital counts (DC) for each of the four MSS bands were extracted and averaged for the interior field pixels near the ground truth sites. The raw data were adjusted to a solar zenith angle of 39°, and the coefficients for adjusting the digital counts for other satellites and periods to those for LANDSAT-2 for the reference period January 22, 1975 to July 15, 1975, were applied.\*

The sample fields used were selected from two areas in Hidalgo County, TX (26.5 N Lat., 98° W. Long.). One was a dry farming (nonirrigated) area near McCook in the northwest part of the county. The predominant soils are McAllen (Aridic Ustochrepts) and Brennan (Arid Haplustalfs)

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\*Coefficients are available for converting LANDSAT-1 and LANDSAT-3 digital counts to equivalent LANDSAT-2 digital counts during the period 22 Jan 1975 through 15 Jul 1975. See the LANDSAT Data Users' Manual, p. AE16 for the basic data, or Richardson (1982).



fine sandy loams. Their Munsell colors are 10YR 6/2 and 10YR 4/3, respectively, in the dry state and they have a relatively high reflectance. The other group of fields came from the irrigated, eastern part of the county near Edcouch. These soils are finer textured and darker colored than soils at the nonirrigated site. They are typified by the Hidalgo (Typic Calciustolls) sandy clay loam and Raymondville (Vertic Calciustolls) clay loam series (Jacobs et al., 1981). Their Munsell colors in the dry state are 10YR 4/2 and 10YR 5/1, and they are less reflective than the dryland soils.

LANDSAT data were available for 108 fields, but ground observations of percent vegetative cover and leaf area index (LAI) were available for only 32 fields within a week of the satellite overpass. At our latitude, grain sorghum typically reaches the anthesis developmental stage by May 10. Grain filling follows for about 30 days. Near the end of grain filling leaves and leaf sheaths have chlorophyll degradation because of stresses such as foliar diseases and senescence. Consequently, data in Table 1 for July 10, 1975, represent standing stubble or tilled fields and that for October 17 were mainly of value to define the soil line.

The vegetation indices DVI, PVI, and GVI were calculated using equations (3), (5 to 5d), and (4), respectively. The soil indices SBI, SLI, and SLI6 were calculated using equations (1), (7), and (7a), respectively. Standard statistical procedures were used for linear regression and correlation analyses.

## RESULTS AND DISCUSSION

The relationships between the variable pairs MSS7 and MSS5, PVI and DVI, PVI and SLI, and GVI and SBI are displayed for the 108 fields in parts A through D of Figure 2. Although we used multirate and multisatellite data sources, the MSS7 vs MSS5 scatter diagram has the triangular shape usually observed in single date data (Kauth and Thomas, 1976; Kauth et al., 1979). The triangle is bounded on the left side, as in Figure 1, by the soil line leg (SLL) and across the bottom by the limiting value of PVI. The data points of the third side are best fit by a curved line that drops initially nearly vertically from the soil line, then curves outward as PVI increases. This suggests that the vertical displacement of a vegetation point from the soil line given by DVI (Figure 1) should describe vegetation conditions well at low vegetative cover. The constant relation between PVI and DVI shown in part B holds

for particular data pairs as well as for a whole data set so that DVI is not more sensitive to low vegetative cover than is PVI. A strength of PVI is that it is indifferent to position of Rg7, Rg5 along the soil line, and depends only on the perpendicular distance to the SLL wherever Rg7, Rg5 fall in the data triangle. On the other hand, because of the curvilinear nature of the side of the data triangle opposite the SLL, the intersection of the vertical or DVI line on the soil line can occur outside the range for soil--for example, in the range for cloud tops. Consequently, the DVI corresponding to large PVI may not be physically meaningful.

The relation between GVI and SBI is similar to that between PVI and SLI. However, GVI and SBI both appear to be dominated by the MSS6 response, because the DC and coefficient for the MSS6 band are large in both equations (1) and (4). This could happen in a procedure that optimizes plant and soil information because MSS6 is least affected by the atmosphere.

In Figure 2 the data displayed cluster by soil type. This is expected for the soil indices since the soil of the dryland and irrigated sites are known to differ in reflectance or brightness. The vegetation indices cluster by soil type partly because dense canopies were achieved only under irrigation. All indices are subject to scene-to-scene variability in the multitemporal and multisatellite data set.

The relation between SBI and SLI6 (Figure 3) is much closer ( $r^2 = .975$ ) than between SBI and SLI ( $r^2 = .719$ ). This is explained by the relative dominance of MSS6 in eq. (1) due to its large coefficient and the usual large DC for MSS6 relative to the other bands. SLI6 is about 0.9 the magnitude of SBI and SLI is about 0.7 the magnitude of SBI.

The ratio PVI/SLI and PVI6/SLI6 versus GVI/SBI (Figure 4) normalize the vegetation indices to the corresponding soil index. The scatter is less than in Figure 3 because, in this case, indices from the same bands are ratioed. The PVI/SLI versus GVI/SBI scatter diagram is slightly curvilinear over its whole range causing it to have a poorer linear correlation ( $r^2 = .942$ ) than PVI6/SLI6 ( $r^2 = .976$ ) versus GVI/SBI. Jackson et al. (1980) have noted a slight curvilinearity of the soil line from hand-held radiometer data, and the authors have observed that the bidirectional reflectance factor increases as reference panel reflectance increases (unpublished data). Consequently, it may express an artifact of MSS sensor calibration against a highly reflective barium sulfate-coated integrating sphere.

In any event, the reason PVI and GVI become more negative in Figure 2 the greater SLI and SBI of the bare soil needs to be explained.

The plots of SLI vs PVI, PVI6, and GVI in Figure 5 display an inverse relation between the vegetation indices and SLI. We expect this to be the normal behavior because the amount of soil in the sensor IFOV will decrease as vegetative cover increases. However, Heilman et al. (198\_) present data showing that SLI increased as soil cover by alfalfa increased. This could happen if the soil background bleached with time, or surface soil constituents separated during the sprinkler irrigations and a light-colored fraction was left at the soil surface.

Another way of comparing the vegetation indices is through a direct measure of vegetation density such as leaf area index (LAI), which was available for 14 irrigated and 18 nonirrigated fields during the grain filling stage of maturity. The relation between LAI and the vegetation and soil indices PVI, DVI, GVI and SLI (Figure 6) shows that for PVI, LAI was expressed by

$$\text{LAI} = 0.301 + 0.263 (\text{PVI})$$

for which the linear correlation coefficient ( $r$ ) was 0.782\*\*. The statistical fit for DVI was the same as for PVI. For GVI the corresponding equation was

$$\text{LAI} = 1.43 + 0.160 (\text{GVI})$$

for which  $r = 0.729$ \*\*. Thus the least squares fit is slightly better for PVI than for GVI.

The distribution of data points in A, B, and C of Figure 5 is such that the natural logarithm of LAI would express the relation about as well as the linear one presented. We believe, in agreement with Brakke and Barker (198\_) that the spectral data in Figure 6 is superior to the LAI data; over 40 spectral samples per band (interior field pixels) were used for some fields and no fewer than 8 whereas LAI is based on as few as 8 plants per field.

The scatter for the LAI vs SLI plot (Figure 6D) shows a clear separation between soil types on which the irrigated and dryland sorghum was grown. Again, the response of the soil indices to soil type or color is illustrated.

In Figure 6 there are few observations for LAI < 1.0 because these were fully-developed plants in commercial fields. The LAI intercept, when PVI and DVI was zero, was estimated to be 0.3. GVI values are negative at low LAI values; the predicted GVI at LAI = 0 is -9.0. The LAI of 8.1 predicted by the SLI equation (Figure 5D) was reasonable for the number of leaf layers that can affect near-infrared reflectance of crop canopies, but an SLI of 0 is unrealistic, except possibly for a rice crop canopy standing in water.

In summary, we have interrelated a number of soil and vegetation indices for a common data set, highlighted their similarities and differences, illustrated their relative magnitudes, and demonstrated their response to vegetative cover and to the soil background. Noteworthy are: (a) the explicit definition of the 2-D soil line indices SLI and SLI6, (b) the similarity in information content of 2-D and 4-D soil and vegetation indices, and (c) the dominance of MSS6 on both SBI and GVI. The similarity in 2-D and 4-D soil and vegetation indices follows from the long-recognized high correlation between the two visible and between the two near-infrared bands of the LANDSAT MSS, but merits reiteration with the interest developing in data from the AVHRR of the TIROS-N series of satellites. The AVHRR has one visible and one reflective infrared band so that only 2-D indices can be calculated that are analogous to LANDSAT MSS experience.

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Table 1. LANDSAT scenes and grain sorghum fields used in this study.

Date	JD	Scene ID	Landsat No.	Solar Zenith Angle (Degrees)	Culture	No. Fields	LAI Available
5/27/73	147	1308-16323	1	28	Irrig.	10	5
4/2/75	92	2070-16203	2	39	Irrig.	8	0
5/17/75	137	5028-16113	1	33	Irrig.	8	3
		"	"	"	Dry.	6	6
5/26/75	146	2124-16202	2	30	Irrig.	6	4
6/4/75	155	5046-16103	1	32	Irrig.	6	2
		"			Dry.	7	7
7/10/75	191	5082-16093	1	34	Irrig.	7	0
		"	"	"	Dry.	8	0
10/17/75	290	2268-16090	2	46	Irrig.	6	0
		"	"	"	Dry.	6	0
5/3/76	123	2467-16210	2	33	Dry.	6	5
6/2/77	153	2862-16003	2	35	Mixed	<u>24</u>	<u>0</u>
						108	32



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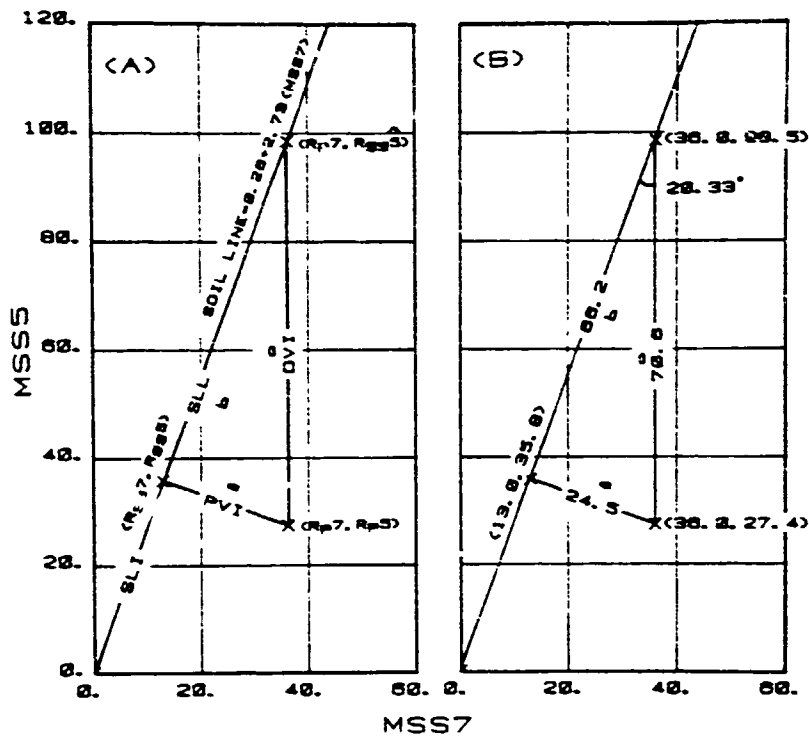


Figure 1 Graphical display of vegetation indices and defining vertices and sides of the triangle bounding vegetation in the visible red (MSS5) and reflective infrared (MSS7) wavelength intervals

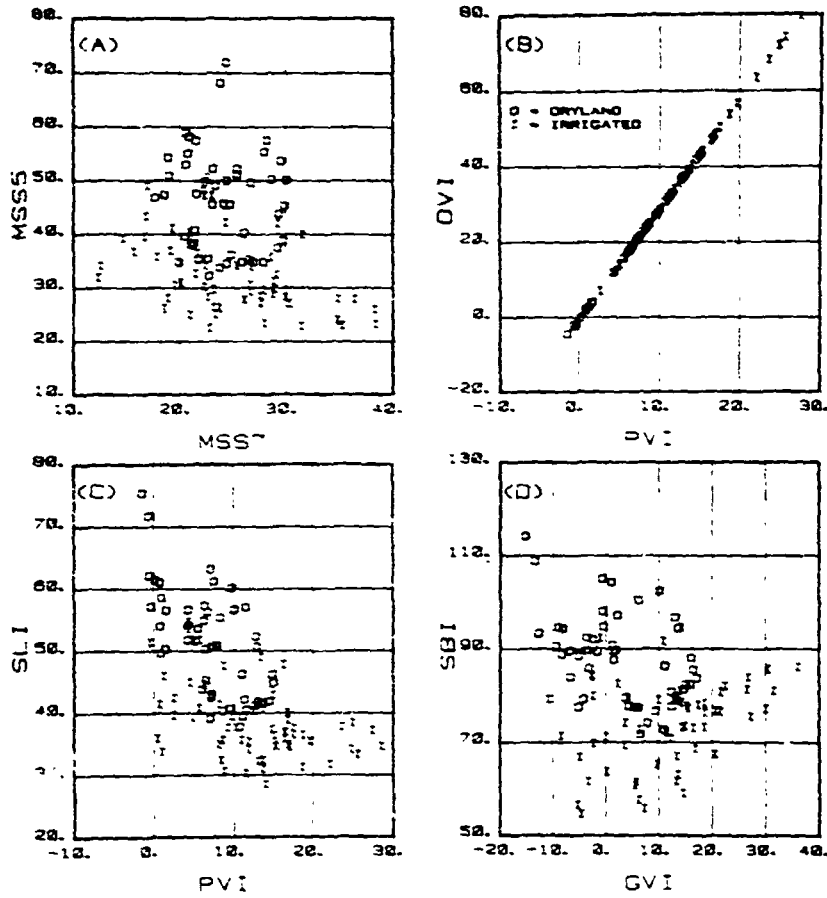


Figure 2. Relation between (A) MSS7 and MSS5, (B) DVI and PVI, (C) SLI and PVI, and (D) SBI and GVI

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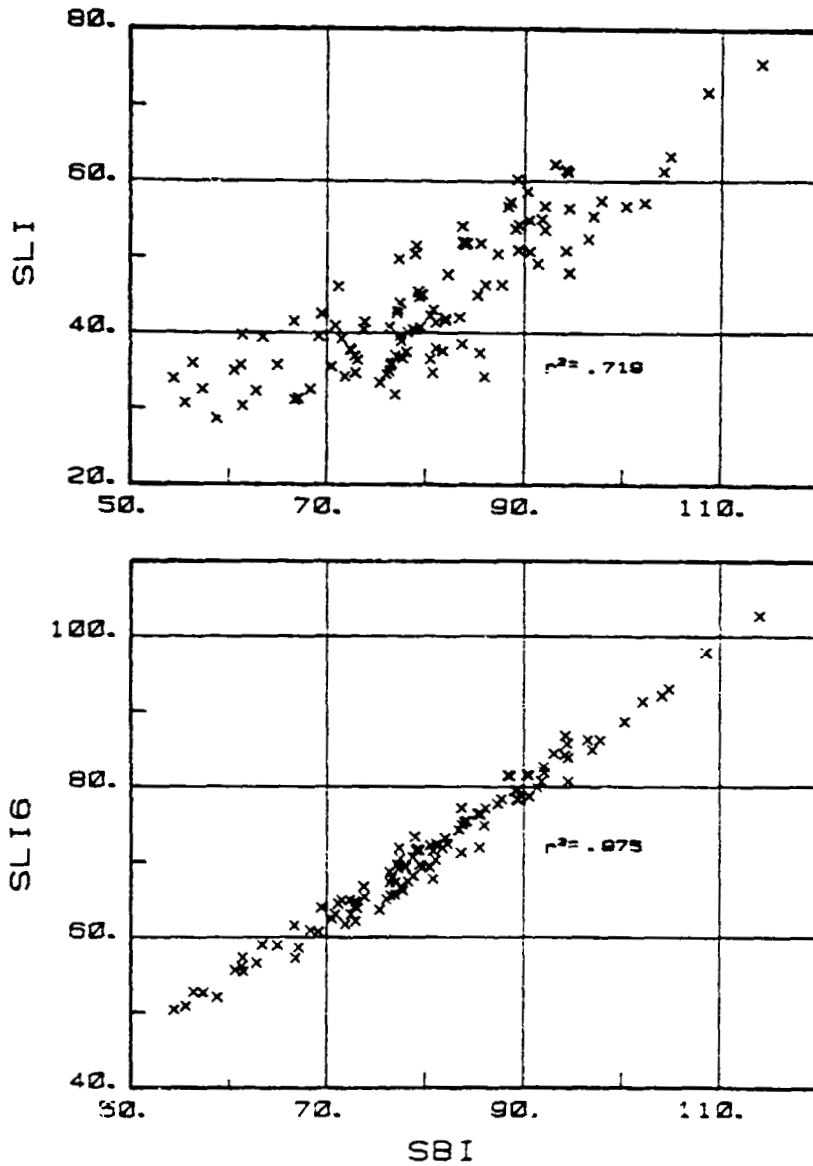


Figure 3. The soil brightness index (SBI) versus SLI and SLI6

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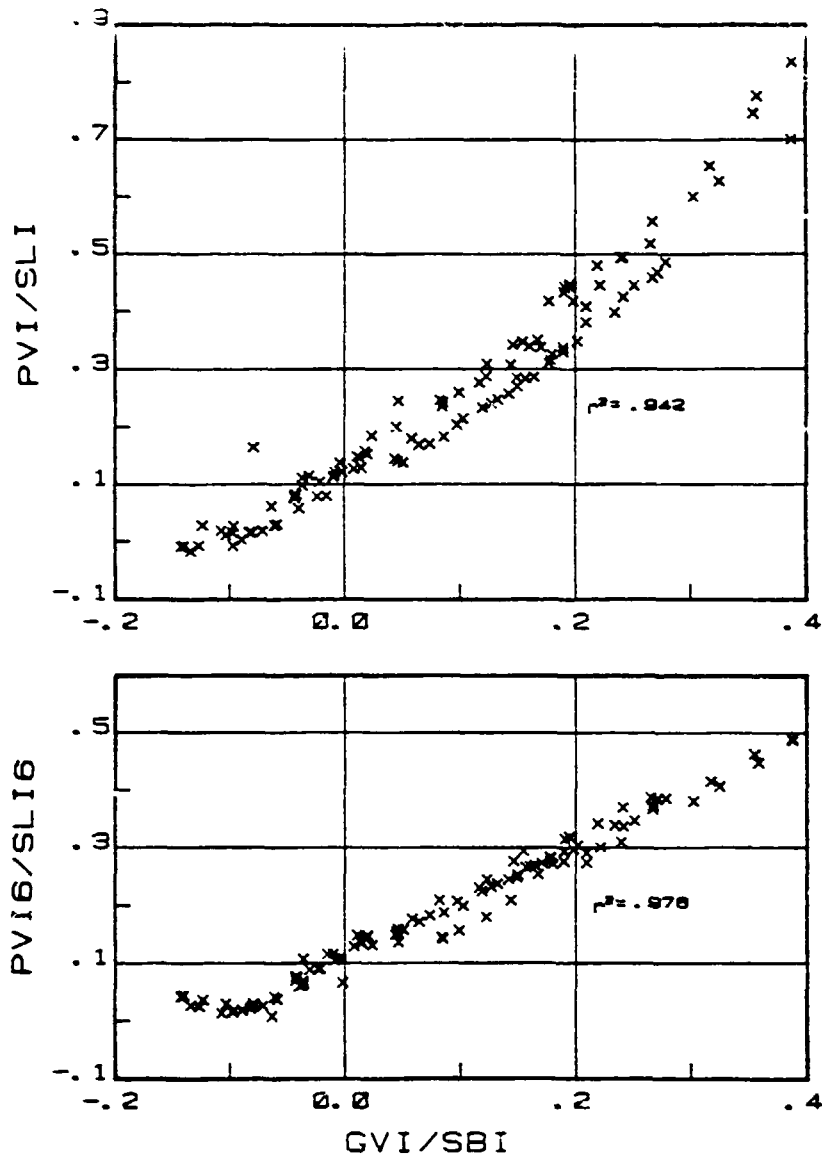


Figure 4. GVI/SBI versus PVI/SLI and PVI6/SLI6

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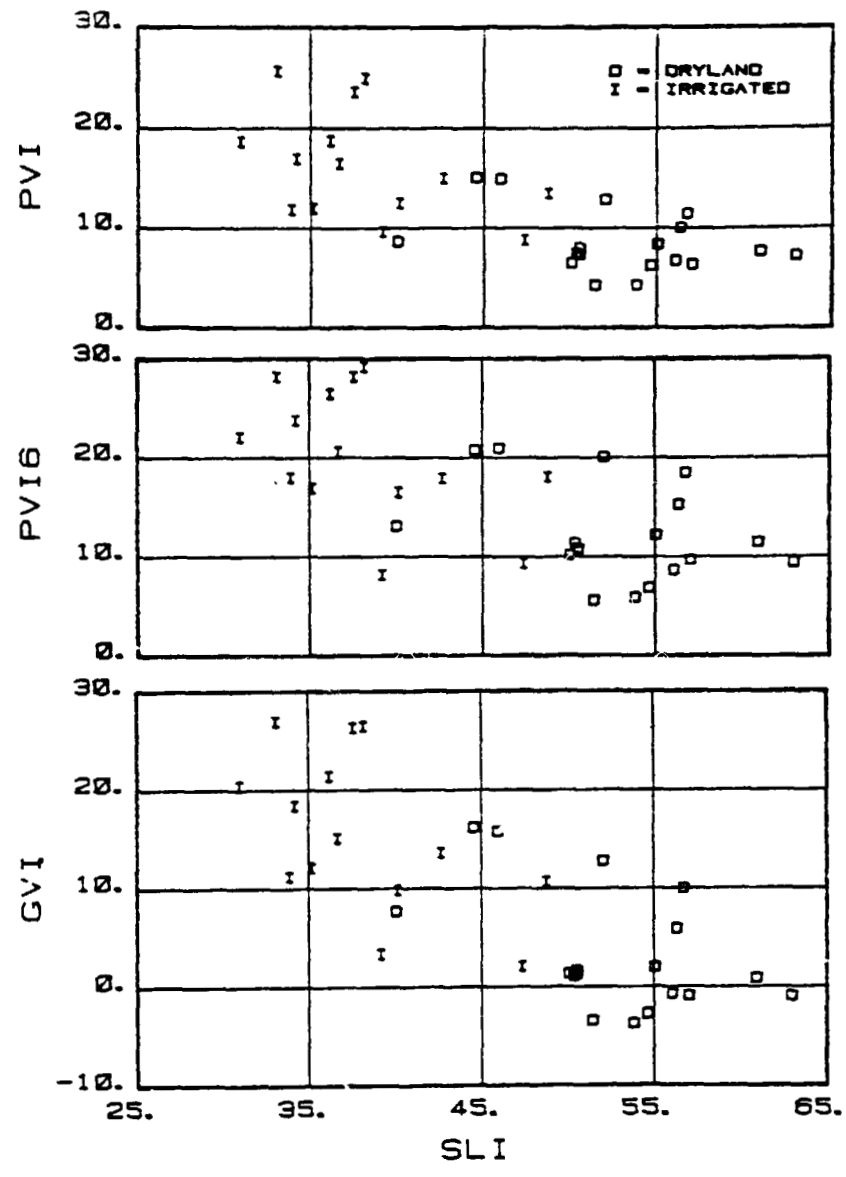


Figure 5. SLI versus PVI, PVI6, and GVI

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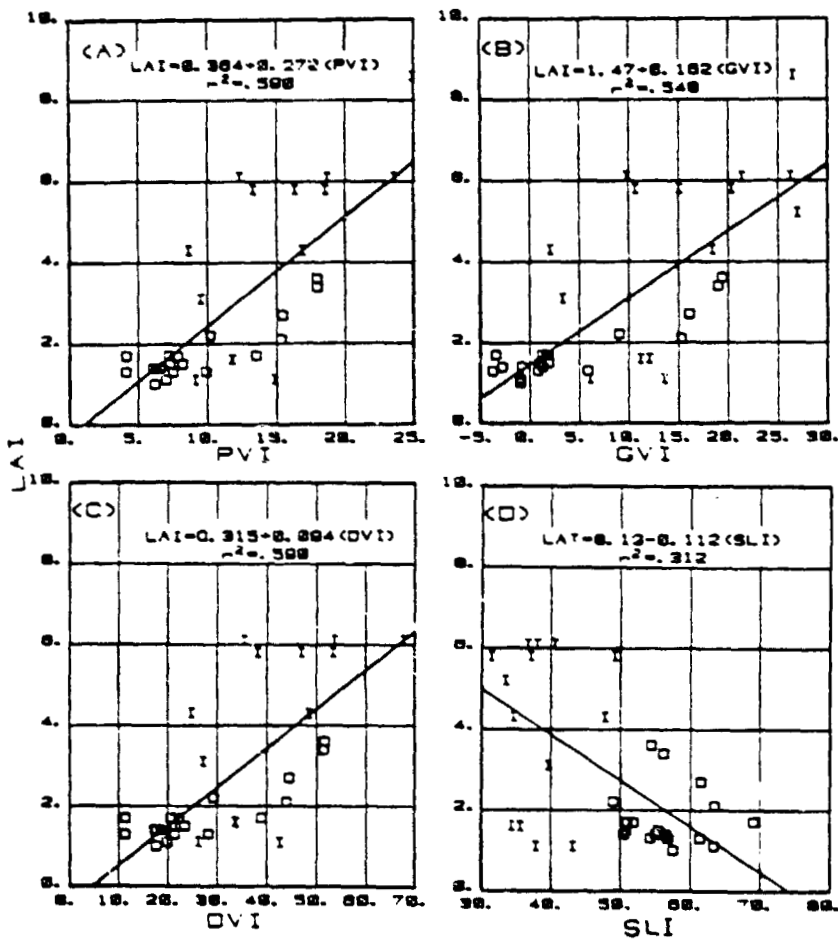


Figure 6. Leaf area index (LAI) versus (A) PVI, (B) GVI, (C) DVI, and (D) SLI