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THE TASSELED CAP: SIZE, SHAPE AND ORIENTATION CHANGES DUE TO SOIL BACKGROUND

ALFREDO R. HUETE

Department of Soils, Water & Engineering
University of Arizona
Tucson, Arizona

RAY D. JACKSON

U.S. Water Conservation Laboratory
Phoenix, Arizona

ABSTRACT

The empirical domain of the Tasseled Cap Graphic Model was examined in the soil brightness-plant greenness plane. Individual, soil-specific tasseled caps were derived for four different soil types with similar plant canopy conditions in order to analyze soil background influences on greenness results. The size, shape and orientation of these tasseled caps were strongly dependent on soil type, and greenness results for identical plant canopy conditions were not reproducible across tasseled caps. Greenness was comparable only when individual tasseled caps were scaled to similar sizes. In contrast to the global tasseled cap, soil-specific models significantly improved vegetation assessment, particularly at low green canopy covers.

I. INTRODUCTION

Multispectral data collected over vegetated regions include varying mixtures of plant, soil, and shadow components. The spectral properties of soils are rarely spatially or temporally uniform, varying in moisture content, surface roughness and color, while vegetation canopies vary in plant density, degree of development, plant species, and geometric configuration. As a result, distinct clusters of data points are rarely found and instead, a continuum of data points forms a large spectral cloud when spectral data are plotted in waveband-coordinate space.

The resulting spectral cloud will have a certain structure, size, shape and orientation, with the density of data points varying throughout. The dimensionality of the data cloud will be less than the number of coordinate band-axes. Finally, an important property of the distribution of the spectral data is that points in close proximity to each other represent target samples of similar spectral properties and characteristics.

Kauth and Thomas (1976) and Kauth et al. (1979), in a study of the distribution of soil spectra in 4-dimensional Landsat MSS signal space, found most of the variability of bare soil signals to be attributed to brightness as nearly all spectral data fell along a line extending from the origin. The emergence of green vegetation over a soil causes composite red radiance to decrease because of chlorophyll absorption and overall NIR response to increase as a result of leaf mesophyll structure (Knipling, 1970). Thus, deviations of spectral data from the bare soil line, in an appropriate direction, are attributed to the presence of green biomass.

Kauth and Thomas (1976) computed linear combinations of the four MSS bands (Tasseled Cap Transformation) to enable projection of 4-space spectral data onto a plane defined by soil brightness and plant greenness axes. In such a plane, soil and plant spectral behavior are least correlated to one another and plant greenness measures are relatively insensitive to soil background. The graphic tasseled cap has been shown to be most useful in modelling vegetation development from bare soil to full canopy (Fukuhara et al., 1979; Malila et al., 1980; Jackson, et al., 1983; Miller et al., 1984). Recently, Crist (1983) and Crist and Cicone (1984) developed a thematic mapper (TM) version of the tasseled cap model, employing six reflective spectral bands. Whereas, the vast majority of soils and vegetation spectral variance was confined to a two-dimensional plane in the MSS-tasseled cap, the inclusion of the longer, mid-infrared bands in the thematic mapper extended the feature space to three dimensions, partly due to plant and/or soil moisture spectral behavior.

Several studies have shown certain limitations in the ability of the Tasseled Cap Transformation to distinguish soil from vegetation spectral response. Jackson et al. (1980) reported a curvilinear soil line when a wide spectral range of soils were plotted. Malila and Gleason (1977) demonstrated soil brightness effects on the tasseled cap greenness of simulated wheat reflectances. Huete et al. (1984; 1985) found the tasseled cap greenness to be sensitive to both soil type and soil moisture condition. Both a soil brightness (amplitude of spectral signature) and a soil spectral effect (shape of spectral signature) were found to seriously hamper the assessment and characterization of vegetation canopies, not only at low green covers, but more seriously at green covers of 60 and 75%. They suggested that soil-specific greenness indices would greatly improve vegetation analysis.

In this paper, principal components analyses are used to decompose soil-vegetation spectral data sets into brightness and greenness components. First, the domain of the tasseled cap made from a developing cotton canopy over a single soil type was analyzed. The resulting greenness values were then compared with those obtained from separate, soil-specific tasseled caps with identical green cover amounts. Finally, all soil backgrounds were included in the derivation of a global tasseled cap. The purpose of this study was to explore the structure and empirical domain of the Tasseled Cap Model and critically examine its ability to discriminate soil background from vegetation density spectral changes over developing plant canopies.

a. EXPERIMENTAL PROCEDURE

Spectral reflectance measurements over a developing cotton canopy (Gossypium hirsutum L. var. DPL-70) were made using a Barnes[1/] modular multispectral radiometer (MMR), which measured radiant flux simultaneously in seven spectral bands (0.45-0.52, 0.52-0.60, 0.63-0.69, 0.76-0.90, 1.15-1.30, 1.55-1.75, and 2.08-2.30 μm), with a 15° field of view. These wavebands are numbered 1.7, respectively.

A support frame was constructed underneath the 0.5 m spaced cotton row canopy to allow soil-filled trays, of different soil types and moisture condition, to be readily inserted below the canopy. Spectra were measured over the developing cotton canopy from 0% to 100% green cover (Table 1). The four soil types used represent widely encountered agricultural, range, and forest soils (Table 2). Reflectances were calculated by ratioing observed spectral response of the soil-plant target with those obtained over a barium sulfate reference panel. Reflectances were corrected for solar zenith angles and adjusted to a constant time (1100h). Additional details were reported by Huete et al. (1985).

b. METHODOLOGY AND CALCULATIONS

The Tasseled Cap Transformation is obtained by decomposition of measured spectral response data, [D], into the weighted sum of unique (reflecting) ground features:

$$[D] = [R]\ [C] \qquad (1)$$

where [R] is a row matrix consisting of the spectral ground features; brightness, greenness, yellowness, wetness, etc., and [C] is a column or eigenvector matrix. Each spectral data point is thus represented as a linear sum of components with each feature weighted differently by the corresponding eigenvector elements.

Principal components analysis was initially used to decompose a spectral data matrix into abstract feature and eigenvector matrices: $[D] = [R]_A\ [C]_A$. Mathematically this was accomplished by solving the eigenvalue problem:

$$[Z]\ [C]_A = [\lambda]\ [C]_A \qquad (2)$$

where [Z] is a symmetric covariance matrix and [λ] is a diagonal matrix of eigenvalues. In principal components analysis, the eigenvectors are consecutively calculated so as to minimize the residual error in each step. Thus, each successive eigenvector accounts for a maximum of the remaining variance in the

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1/ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the University of Arizona or the U.S. Department of Agriculture.

Table 1. Mean canopy characteristics for cotton from bare soil to full cover.

Day of year (1983)	Green cover (%)	Canopy height (cm)	Leaf area index (m^2/m^2)	Dry biomass kg/m^2	Wet biomass kg/m^2
170	0	0	0	0	0
196	20	15	0.5	0.03	0.15
198	25	22	0.7	0.06	0.30
208	40	28	1.0	0.10	0.50
215	55	36	1.5	0.14	0.60
223	75	47	2.8	0.25	1.40
235	95	69	3.3	0.30	1.70
242	100	83	3.6	0.33	1.80

Table 2. Physical characteristics of the four soil background types.

Soil Series	Textural Class	Organic Matter (%)	Iron (Ex)* (%)	$CaCO_3$ (%)	Munsell color	
					Dry	Moist
Cloversprings	loam	5.7	1.8	0	10YR3/2 (grayish brown)	10YR2/1 (black)
Whitehouse	sandy clay loam	1.5	2.5	0	2.5YR4/6 (red)	2.5YR3/6 (dark red)
Avondale	loam	0.9	0.8	5	7.5YR5/4 (brown)	7.5YR4/4 (brown)
Superstition	sand	0.2	0.2	3	10YR7/4 (pale brown)	10YR5/4 (yellowish brown)

*Extractable

data. The resulting eigenvectors delineate the coordinate axes and orientation of the new feature space and the eigenvalues measure the relative importance of the associated eigenvectors.

The abstract feature matrix is then constructed according to:

$$[R]_A = [D][C]_A^T, \text{ where } [C]^{-1} = [C]^T \quad (3)$$

for orthonormal matrices. Each element of the feature matrix represents the projection of a spectral data point onto the respective eigenvector axes. Figure 1 illustrates the two primary features obtained when the Superstition sand--cotton data set was decomposed via principal components analysis. The plane on which these two features are plotted represents 99.5% of the original 7-band variance.

As can be seen in Figure 1, the unique orientation of the eigenvectors is based upon mathematical, not physical characteristics. The abstract eigenvectors may be linear combinations of physical properties rather than separate properties themselves. Consequently, to derive the proper tasseled cap model, a new set of axes was selected, within the same feature space, which transformed the abstract solution into a real, physically significant solution.

Rotation was accomplished through proper alignment of the base soil line with an eigenvector axis using a least-squares column matrix transformation technique (Malinowski and Howery, 1980). Figure 2 demonstrates the resulting rotational transformation. Since the eigenvector axis was rotated to lie parallel with the soil line, we call real feature 1 "brightness" and real feature 2, orthogonal to brightness and in the direction of green vegetation spectral response, is labelled "greenness."

Although the rotational process aligned the soil line parallel with the brightness feature axis so that bare soil spectra are uncorrelated with the greenness axis, the bare soil line is not at zero greenness. This problem may be solved by using the greenness value of bare soil to shift the entire tasseled cap to a zero baseline. Kauth and Thomas (1976) similarly translated their tasseled cap by attaching a constant term to their linear transform equation.

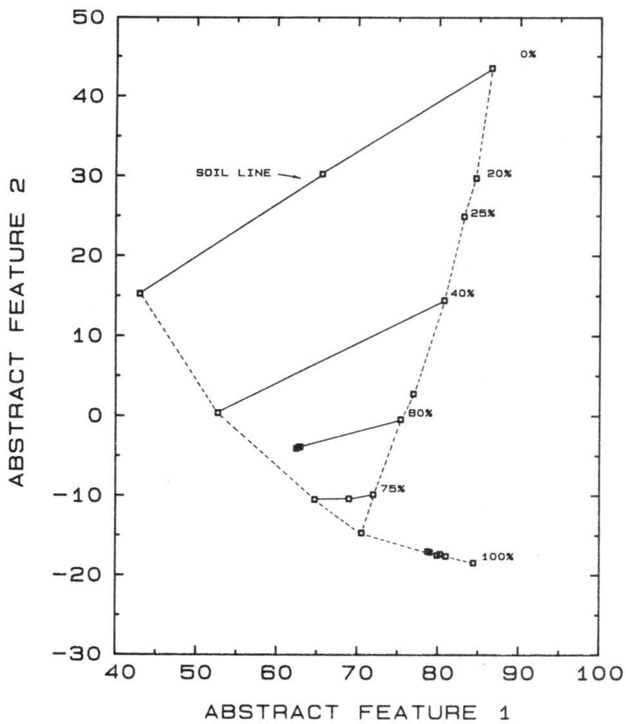

Figure 1. Superstition sand data set decomposed into the first two principal components and plotted in abstract feature space. Data points are labeled with the level of green plant cover.

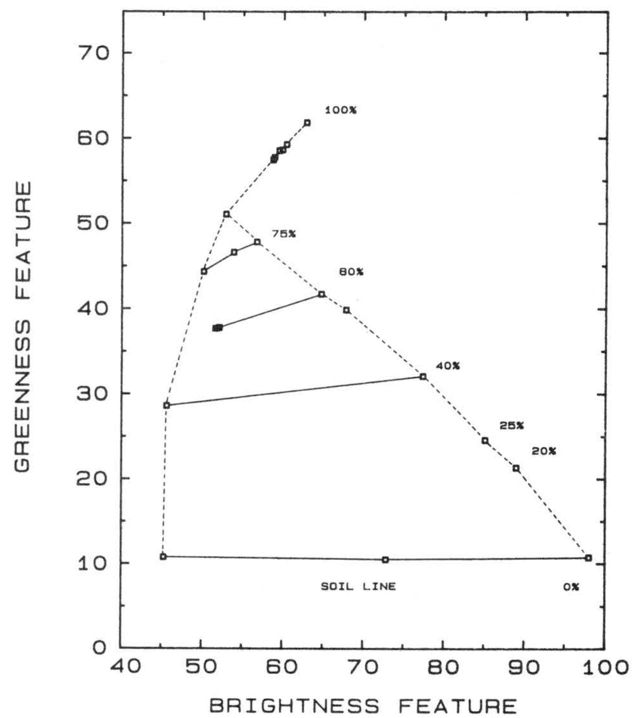

Figure 2. Superstition sand data set transformed and plotted in the brightness-greenness plane. Data points are labeled with the level of green plant cover.

II. RESULTS

Of primary concern in Figure 2 is the soil brightness effect seen at vegetation densities over 40% green cover. Wet soil backgrounds produced lower greenness values than dry soils under identical amounts of vegetation cover. With increasing vegetation cover, the brightness effect became stronger in magnitude as the 'greenness lines' of constant vegetation did not remain parallel with the base soil line, but instead increased in slope. For the single Superstition soil type, however, this soil influence was relatively minor, especially at low (<40%) vegetation covers where the greenness lines appeared almost parallel with the soil line.

The next question to consider is whether the greenness results obtained above are reproducible with identical vegetation conditions but different soil backgrounds. Table 3 summarizes the greenness values obtained by applying the equivalent principal component analysis and least-squares rotation to the same cotton canopy but different soil backgrounds. Such results could represent tasseled cap models developed over research plots at different locations and soil types. Several results were evident: (1) all soils produced a brightness effect as wet soils resulted in lower greenness values for equivalent amounts of vegetation; (2) the greenness values of bare soil lines varied greatly with soil type, thus requiring separate, soil-dependent adjustment terms to achieve 'zero' soil base lines and; (3) despite the large differences in greenness values for bare soil, the greenness values at full and nearly complete canopy covers were similar and less dependent on soil type.

Such a situation presents a dilemma because one cannot simply translate the base of a tasseled cap to zero greenness since the 'dynamic range' of greenness varies with soil type. Figure 3 illustrates the size differences of two soil-specific tasseled caps in their individual brightness-greenness planes.

Table 3. Greenness values obtained from the decomposition of individual-soil data sets.

Green Cover (%)	Surface Moisture	Superstition sand	Avondale loam	Whitehouse s.c.l.	Cloversprings loam
0	dry	10.73	5.50	13.03	1.48
0	d-w*	10.48	5.18	12.27	1.15
0	wet	10.73	5.50	13.03	1.48
20	dry	21.35	15.66	22.63	12.30
25	dry	24.60	18.18	25.24	15.46
40	dry	32.08	25.16	32.59	23.63
40	wet	28.59	22.25	30.42	22.45
55	dry	39.87	33.27	39.37	32.94
60	dry	41.71	34.28	40.29	33.72
60	wet	37.68	32.10	39.28	31.34
75	dry	47.79	41.86	47.52	43.13
75	d-w*	46.58	40.61	46.13	42.81
75	wet	44.34	39.56	45.97	42.75
90	dry	51.07	45.64	51.08	48.88
100	dry	61.85	-	-	63.90

*Partly wet soil.

These results suggest that greenness indices have to be scaled for each soil type in order to normalize the soil-dependent dynamic range of greenness. In Table 4, the soil-specific greenness measures are scaled from zero to one, forcing the bare soil and full canopy greenness readings to be the same for all soil types. This scaling procedure resulted in a linear correlation between percent green cover and scaled greenness (r = .988). At 20% green cover, the scaled greenness values ranged from 0.17 to 0.21. At 40% green cover, which included eight soil backgrounds (dry and wet), scaled greenness varied from 0.30 to 0.42. At 60% green cover (0.46 to 0.61) and at 75% green cover (0.59 to 0.72). The relationship between scaled greenness and green cover was weak at 90% cover (0.70 to 0.79). On the average, deviation in scaled greenness was around 0.10, which was approximately equivalent to a 10% green

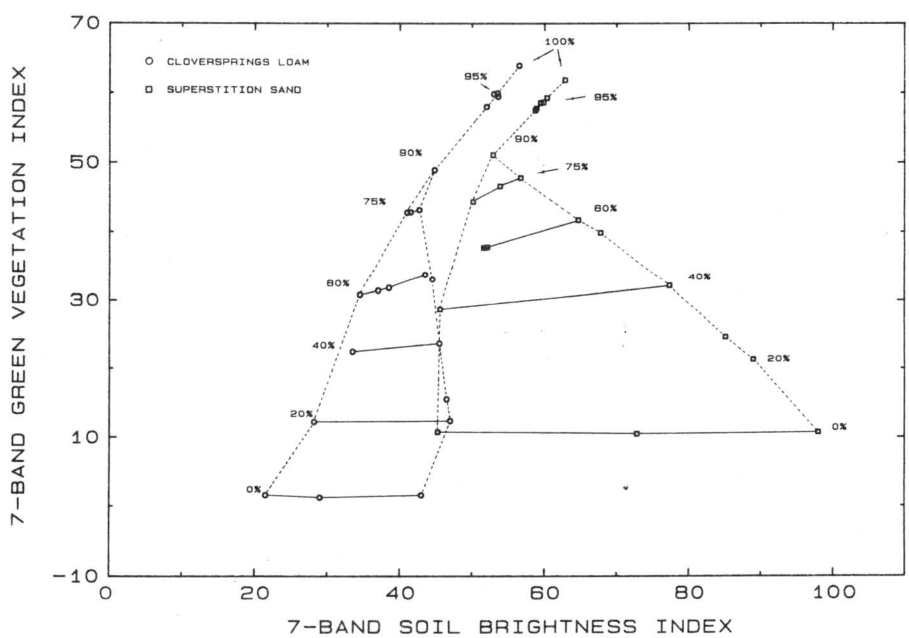

Figure 3. Individually derived tasseled caps for Cloversprings loam and Superstition sand backgrounds. Data points are labeled with the level of green plant cover.

Table 4. Scaled greenness to zero base line and unit full green cover, for individual-soil data sets.

Green Cover (%)	Surface Moisture	Superstition sand	Avondale loam	Whitehouse s.c.l.	Cloversprings loam
0	dry	0.000	0.000	0.000	0.000
0	d-w*	-.005	-.006	-.015	-.005
0	wet	0.000	0.000	0.000	0.000
20	dry	.208	.177	.193	.173
25	dry	.271	.221	.245	.224
40	dry	.418	.343	.392	.355
40	wet	.349	.297	.349	.366
55	dry	.570	.484	.528	.504
60	dry	.606	.502	.547	.517
60	wet	.527	.464	.527	.478
75	dry	.725	.634	.692	.667
75	d-w*	.701	.612	.664	.662
75	wet	.657	.594	.662	.661
90	dry	.789	.700	.763	.759
100	dry	1.000	-	-	1.000

*Partly wet soil.

Table 5. Greenness values obtained from the decomposition of all soils as a single, global data set.

Green Cover (%)	Surface Moisture	Superstition sand	Avondale loam	Whitehouse s.c.l.	Cloversprings loam
0	dry	-5.52	-.40	3.14	-1.40
0	d-w*	-1.67	1.22	4.20	-.44
0	wet	1.80	2.12	5.12	.20
20	dry	7.34	9.37	11.84	7.10
25	dry	11.31	12.98	14.44	9.83
40	dry	20.19	19.34	21.55	16.83
40	wet	20.74	18.64	21.06	16.79
55	dry	29.65	27.91	28.44	24.79
60	dry	31.99	29.01	29.58	25.90
60	wet	29.66	27.69	29.25	24.47
75	dry	39.25	36.79	36.88	34.04
75	d-w*	38.47	35.74	35.75	33.83
75	wet	36.73	34.88	35.72	33.91
90	dry	43.28	40.95	40.62	39.30
100	dry	52.42	-	-	51.16

*Partly wet soil.

cover. Maximum variation in greenness occurred at 60% green cover, resulting in a 15% green cover range. The scaling procedure did not remove the soil brightness influence which lowered greenness values over wet soil backgrounds.

c. GLOBAL TASSELED CAP MODEL

Table 5 shows the greenness values obtained when all soils (soil type and moisture condition) and vegetation densities were decomposed from one, overall data set. We ignored soil type differences and derived a global greenness index. The mean soil line was used to rotate the abstract eigenvector axis.

The greenness values of bare soils were no longer uniform and varied from -5.5 to 5.1, a greenness range of 10.6 units from an overall dynamic greenness range of 57.9 units for vegetation. Thus, 18% of the total greenness range was occupied by bare soil spectra alone without the presence of vegetation.

In Figure 4, the dry to wet reflectance behavior involving specific soil types is plotted in the global brightness-greenness plane at various levels of vegetation cover. Individual bare soil lines were not parallel with each other or with the overall, mean soil line, but instead, were oriented such that spectra from wet soil backgrounds produced higher greenness values than dry soil backgrounds. With increasing amounts of vegetation, the four lines representing different soil types but constant vegetation amounts gradually converged and became linear in overall behavior. However, the convergence to a single line, such as occurred at 75% green cover, did not produce a greenness line parallel with the mean soil line. Instead, greenness lines were significantly sloped and the range of greenness values for constant vegetation amounts were high. At 40% green cover, greenness varied from 16.8 to 20.7 and at 60% cover, the greenness range doubled in magnitude from 24.5 to 32.0. At 75% green cover, the range of values was still high (33.8 to 39.2), while the greenness variation at 90% cover (39.3 to 43.3) was equivalent to that from a 40% green cover.

The greenness variation or soil background influence at low (<40%) green covers were primarily a result of unique soil spectral effects caused by different soil spectral reflectance curves. With increasing vegetation densities, such effects gradually diminished as the separate, soil-dependent greenness lines converged to global greenness lines. However, the second soil influence, soil brightness, then became prominent as the greenness lines became sloped, causing higher greenness values over brighter, or drier, soils than over darker, or wetter, soils for identical amounts of vegetation.

III. DISCUSSION

The Tasseled Cap Visual Model was originally derived from empirical observations of the spectral-temporal development of agricultural crops (Kauth and Thomas, 1976). It is a useful graphic model that facilitates the study of spectral data structures and allows physical interpretation. The boundaries of a tasseled cap are easy to describe because they represent 'pure' targets. They include a base soil line made of zero vegetation and bounded by bright and dark soil spectra. The peak represents dense vegetation with no soil showing. Because the plant-greenness

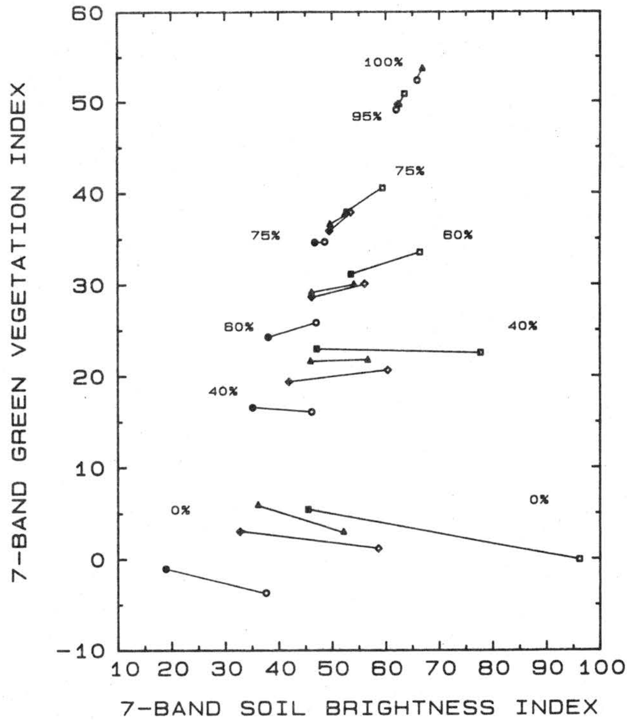

Figure 4. Dry to wet spectral behavior of specific soil types plotted in the global brightness-greenness plane. Square symbols represent Superstition sand; diamonds, Avondale loam; triangle, Whitehouse s.c.l.; and circles, Cloversprings loam. Dry and wet soils are represented by open and solid symbols, respectively. The percentages of green plant cover are shown near the data points.

and soil-brightness axes are made orthogonal to each other, soil spectral behavior is assumed to be uncorrelated with greenness measures.

The internal domain of a tasseled cap consists of spectral mixtures involving various vegetation and soil characteristics representing different vegetation and soil types, plant canopy geometric configurations, and background moisture and surface conditions. As seen in this paper, similar orthogonal distances from a soil line did not insure equal amounts of green vegetation due to soil influences on the greenness signal. Thus, the internal structure of the Tasseled Cap Model needs to be critically examined, subjected to quantitative tests and, if necessary, undergo model refinement until soil and plant spectral behavior are adequately explained.

In this study, the tasseled cap concept was tested for its ability to recognize soil background variations under constant green canopy covers. When the global tasseled cap, consisting of four soil types, was utilized to predict greenness, the problems reported in previous studies were evident (Huete et al., 1984; Ezra et al., 1984). Bare soil spectra, with no green vegetation present, produced significant greenness values, prohibiting reliable discrimination of vegetation below 20% green covers. At higher vegetation densities, greenness predictions for a constant green cover were sensitive to soil moisture and brightness such that wet or darker soils always resulted in lower greenness values. Thus, the orthogonal distance of a vegetated spectra, inside the tasseled cap, was a function of not only vegetation properties but also soil type and moisture condition.

Individually derived, soil-specific, tasseled caps significantly improved vegetation discrimination, especially at low (<40%) green covers. This was the green cover range that was least reliable in the global tasseled cap. Soil brightness influences were important above 40% green cover, but may be predicted in that wet or dark soils gave consistently lower greenness values. Thus, such influences may be modelled and incorporated into more refined tasseled cap models.

Soil-specific tasseled caps are beneficial in ground-based remote sensing research since greenness assessment is improved. Unfortunately, locally derived tasseled caps are not directly extendable to other research sites with different soil backgrounds. Greenness results obtained over one site are not comparable with those from other sites because of the wide range of tasseled cap orientations and sizes. In particular, the dynamic range of greenness is soil-dependent. Consequently, some form of scaling is required to standardize across-sites greenness data.

In this study, the scaling of greenness data was easily accomplished by using the same dense green canopy spectra with all soil backgrounds. This 'pure' green point is not easily encountered in all field studies or satellite images, and may vary depending on vegetation type and canopy configuration. It may be necessary to use standard pure green spectra from outside the site to scale greenness data. Thus, in reporting greenness data, one may simply include the pure green reference point from which all data was scaled. Other researchers will then be able to compare or verify greenness interpretations.

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Alfredo R. Huete obtained a B.S. in range science in 1977 from the University of Arizona. He started his graduate work at the University of California at Berkeley where he obtained an M.S. in soil and plant biology in 1981. His Ph.D. work was in soils and remote sensing which he completed in 1984 at the University of Arizona. He has since joined the Department of Soils, Water, and Engineering faculty where he is responsible for teaching two remote sensing in agriculture courses. His research interests include the spectral separation of soils and vegetation via factor analytic inversion techniques. He is a member of the American Society of Photogrammetry, American Society of Agronomy, and Soil Science Society of America.

Ray D. Jackson received the B.S. degree from Utah State University, Logan in 1956, the M.S. degree from Iowa State University, Ames in 1957, the Ph.D. degree from Colorado State University, Fort Collins in 1960, all in soil physics. He has been at the U.S. Water Conservation Laboratory, Phoenix, AZ, since 1960. His early research was concerned with the simultaneous flow of water and heat in soils and the evaporation of water from soils and plants. He is now involved with developing remote sensing techniques to quantify water and nutrient stress in crops. Dr. Jackson is a Fellow of the American Association for the Advancement of Science, the American Society of Agronomy, and the Soil Science Society of America. He is a member of the American Geophysical Union, the American Society of Photogrammetry and remote sensing, the Remote Sensing Society (England), and the Optical Society of America.