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The Relationships between Reflectance in the Landsat Wavebands and the Composition of an Australian Semi-Arid Shrub Rangeland

Field reflectance measurments and the exploration, through simulation modeling, of the wider implications of these measurements for the enhancement of Landsat data and for the derivation of useful vegetation indices are discussed.

ABSTRACT: *Measurements of the reflectance characteristics in the Landsat wavebands of the vegetation and soils from a semi-arid shrub rangeland are reported. In the Landsat data space these reflectance measurements form a structure analogous to the 'Tasselled Cap,' and the derivation of indices of 'cover' and 'greenness' are suggested. The influence of solar elevation on shadow formation and the dynamic range of the Landsat data were investigated by simulation modeling.*

INTRODUCTION

THE ARID LANDS of Australia occupy the central core of the continent, covering in all some 7.3 $\times$ 10^6 km^2, or 71 percent of the total land surface. Of this arid and semi-arid area, about 5.2 $\times$ 10^6 km^2 is used on a permanent basis as rangelands with sheep and cattle grazing year-long on the native pastures. These lands, though vast and sparsely vegetated, are an integral part of Australia's production of beef and wool, carrying some 20 percent of the nation's flocks and herds.

The management of these lands for their well-being in the long term is, thus, an important task. The advent of Landsat imagery with its multispectral, repetitive, and synoptic converage has generated a new appreciation and understanding of the past and present use of these lands by highlighting past and present rangeland management problems. In an initial survey standard Landsat image products were found to be of value in rangeland assessment generally, and to be particularly useful in the 'saltbush' country of southern Australia (Graetz *et al.*, 1976). This particular type of rangeland is comprised of low perennial shrubs, with the intervening soil surface being periodically covered with ephemeral forbs or annual grasses. As with all the Australian rangelands, the standing biomass of saltbush country is low, varying between 300 and 1500 kg/ha, with total foliage cover only rarely exceeding 30 percent.

The Australian Landsat Station became operational in late 1980. With a more assured acquisition of Landsat data and access to digital image processing facilities, an important research task is the development of appropriate enhancement procedures to maximize the extraction of ecologi-

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cal information from Landsat data. Our approach has been to seek a basic understanding of the relationships between the reflectance characteristics in the Landsat wavebands of these semi-arid landscapes and the ecologically important vegetation and soil attributes of that landscape. This paper reports on field reflectance measurements in 'saltbush' rangelands and the exploration, through simulation modeling, of the wider implications of these measurements for the enhancement of Landsat data and for the derivation of useful vegetation indices.

Experimental Details

All of the field measurements reported here were made in 'saltbush' (*Atriplex vesicaria*) rangelands within a 50 km radius of Broken Hill, Australia (Lat. 31°58′S, Long. 141°27′E, 304 m elevation above sea level). Measurements of irradiance and reflected radiance in the four Landsat MSS wavebands (0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 μm) were made with Exotech Model 100A radiometers, and reflectances for targets were calculted from the ratios of these measurements.

The irradiance measurements were usually made using the opaline diffusing optic elements in place to give an approximation to 2π steradian field of view. However, on some occasions, because of instrument problems, downwelling radiation values were determined indirectly from synchronous recordings of solar radiation, the linear relationships between the downwelling flux in any band and solar radiation having been determined on the previous day. The reflected radiance was measured by a vertically-aligned radiometer with a 15° field of view in such a way that the exact targets could readily be identified and photographed in stereo. Subsequently, by using a zoom-stereoscope and an incrementing stage, measurements of cover can be extracted from these stereo pairs (Wells, 1971) although these data are not reported here.

Absolute reflectance values were preferred to the more commonly measured bi-directional reflectance because they can be directly used in simulation modeling, and we believed it to be impossible to use and maintain a suitable reference standard (e.g., Fiberfax or $BaSO_4$ block) in a dusty field environment.

The reflectance (or, more correctly, apertured-reflectance (March, 1979)) values used in this paper were all determined with a 15° field of view to give a 25 cm diameter target.

Results and Discussion

REFLECTANCE MEASUREMENTS

The reflectance values in the four Landsat MSS wavebands (hereafter called #4, #5, #6, and #7) for the most common components of the landscape, are set out in Table 1. These values are the means of values collected on four separate occasions. The key landscape component in saltbush country is bare soil, here a reddish-yellow sandy loam (Munsell color notation of 7.5 YR, 6.6 dry), which is bright in all wavebands. Appreciable variations in reflectance values result from small changes in surface conditions, such as the presence of lichen crusts or a wind sorted surface. All other components are less reflective than bare soil in all wavebands with the exception of the perennial shrubs and annual herbage which, when lush and actively growing just post-rain, are more reflective in bands #6 and #7.

Ephemeral plants, both grasses and forbs, are the only vegetation class that are similar to agricultural crops. The high infrared (#6 and #7) reflectance of ephemerals is itself fleeting for water-stress or ageing results in a substantial reduction in reflectance in these bands. The relationships between 'vigor' and infrared reflectance has been well documented for agricultural crops and pastures (e.g., Tucker *et al.*, 1979a, 1979b). The perennial shrubs (predominantly 'saltbush') do not exhibit high infrared reflectance most of the time. This contrast of perennial shrubs to ephemeral and agricultural crops previously reported by Otterman (1974, 1975) and called by him the 'infrared paradox' is largely determined by the structure and state of the leaf mesophyll cells, but the low infrared reflectance may also be in part the result of leaf surface characteristics such as hairiness. Saltbush leaves, particularly when drought stressed, are covered with collapsed epidermal hairs that contain crystalline sodium chloride which substantially increases the reflectance in the visible wavelengths (Sinclair and Thomas, 1970).

The last two vegetation classes that are sufficiently common to warrant inclusion are dry grass (or standing-dead plant material) and litter (fallen-dead) plant material. Both have very similar four-band reflectance values, and the yellow-grey litter has much the same values regardless of its origin, that is, whether the plant material is derived from dead and desiccated ephemerals, from grasses, or from shrubs.

Shadows are almost uniformly dark and their characteristics are independent of the component species that cast them (i.e., shrubs or grasses) or by what they covered (bare soil, grass, litter, etc.). The contribution of shadows and shadowing in this rangeland type will be examined in more detail further in this report.

THE RELATIVE POSITION OF THE LANDSCAPE COMPONENTS WITH THE LANDSAT DATA SPACE

It has been reported many times previously that the four band Landsat reflectance values of natural and agricultural targets are correlated. In particular, the correlation is usually greatest between the

TABLE 1. MEAN REFLECTANCE VALUES IN THE LANDSAT WAVEBANDS FOR VARIOUS RANGELAND LANDSCAPE COMPONENTS STANDARD ERRORS ARE GIVEN IN PARENTHESIS

Component		Landsat MSS wavebands			
		#4	#5	#6	#7
Bare soil	Undisturbed (53)	0.12	0.24	0.36	0.42
		(0.009)	(0.009)	(0.012)	(0.012)
	Eroded (22)	0.15	0.35	0.54	0.54
		(0.005)	(0.008)	(0.011)	(0.013)
	Calcareous (17)	0.10	0.21	0.34	0.38
		(0.002)	(0.005)	(0.009)	(0.024)
	Lichen crusted (23)	0.06	0.12	0.22	0.25
		(0.004)	(0.006)	(0.011)	(0.012)
Litter (29)		0.04	0.07	0.12	0.14
		(0.001)	(0.003)	(0.004)	(0.005)
Perennial shrubs	Vigorous (28)	0.10	0.10	0.40	0.50
		(0.005)	(0.006)	(0.012)	(0.016)
	Non-vigorous (95)	0.07	0.07	0.19	0.20
		(0.002)	(0.002)	(0.004)	(0.004)
Grass	Vigorous (3)	0.09	0.11	0.43	0.50
		(0.01)	(0.014)	(0.035)	(0.029)
	Non-vigorous (24)	0.06	0.07	0.16	0.15
		(0.004)	(0.004)	(0.010)	(0.009)
Ephemerals	Vigorous (31)	0.04	0.04	0.42	0.53
		(0.005)	(0.010)	(0.010)	(0.010)
Shadow (10)		0.01	0.01	0.01	0.02
		(0.001)	(0.003)	(0.003)	(0.003)

The number of samples for each component are given in parenthesis following the target name.

two visible bands (#4 and #5) and between the two infrared bands (#6 and #7) such that, for agricultural targets, the data space is essentially of only two dimensions (Misra and Wheeler, 1978). That this is also true for targets from the saltbush rangelands is demonstrated in Table 2 where the correlation matrix for some 347 individual reflectance measurements of shrubs, grasses, and soils is set out. Overall, the correlation between all wavebands is high, with that between #5 and #7 being the lowest (0.53) and that between #6 and #7 being highest (0.93).

TABLE 2. LINEAR CORRELATIONS BETWEEN MEASURED REFLECTANCES OF FOUR LANDSAT WAVEBANDS FOR A SET OF 347 INDIVIDUAL SAMPLES OF TARGETS FROM SALTBUSH RANGELANDS

	Landsat MSS wavebands			
	#4	#5	#6	#7
#4	1.00			
#5	0.85	1.00		
#6	0.70	0.65	1.00	
#7	0.54	0.53	0.93	1.00

To examine the relative positions and movement within the Landsat data space of a few of the ecologically important components from Table 1, pair-wise plots of all the data used in Table 2 are presented as Figure 1 (a-f) in ascending order of inter-waveband correlation.

The plot of reflectance data in the #5/#7 space (Figure 1a) is of the greatest interest for it exhibits the lowest inter-waveband correlation. The points of eroded bare soil, 'green' ephemerals, and shrubs define the vertices of a triangle. The analogy of this triangle to the 'Tasselled Cap' of Kauth and Thomas (1976) becomes apparent when we consider the positions of other components within these triangular shaped bounds.

First, bare eroded soil is the brightest, most reflective component and determines the size of the triangle. This soil variant is one that has been wind-sorted; that is, the finer clay particles have been lost through wind erosion, leaving the larger (0.5 to 2.0 mm), coarser sand fraction behind to cap the soil surface. Though the particles are pure quartz, they still have the ferruginous red patina. Extensive areas of sheet erosion, or 'scalds,' are plainly visible on Landsat imagery of these rangelands and are the brightest features in all wavebands (see Graetz *et al.*, 1976). Conversely,

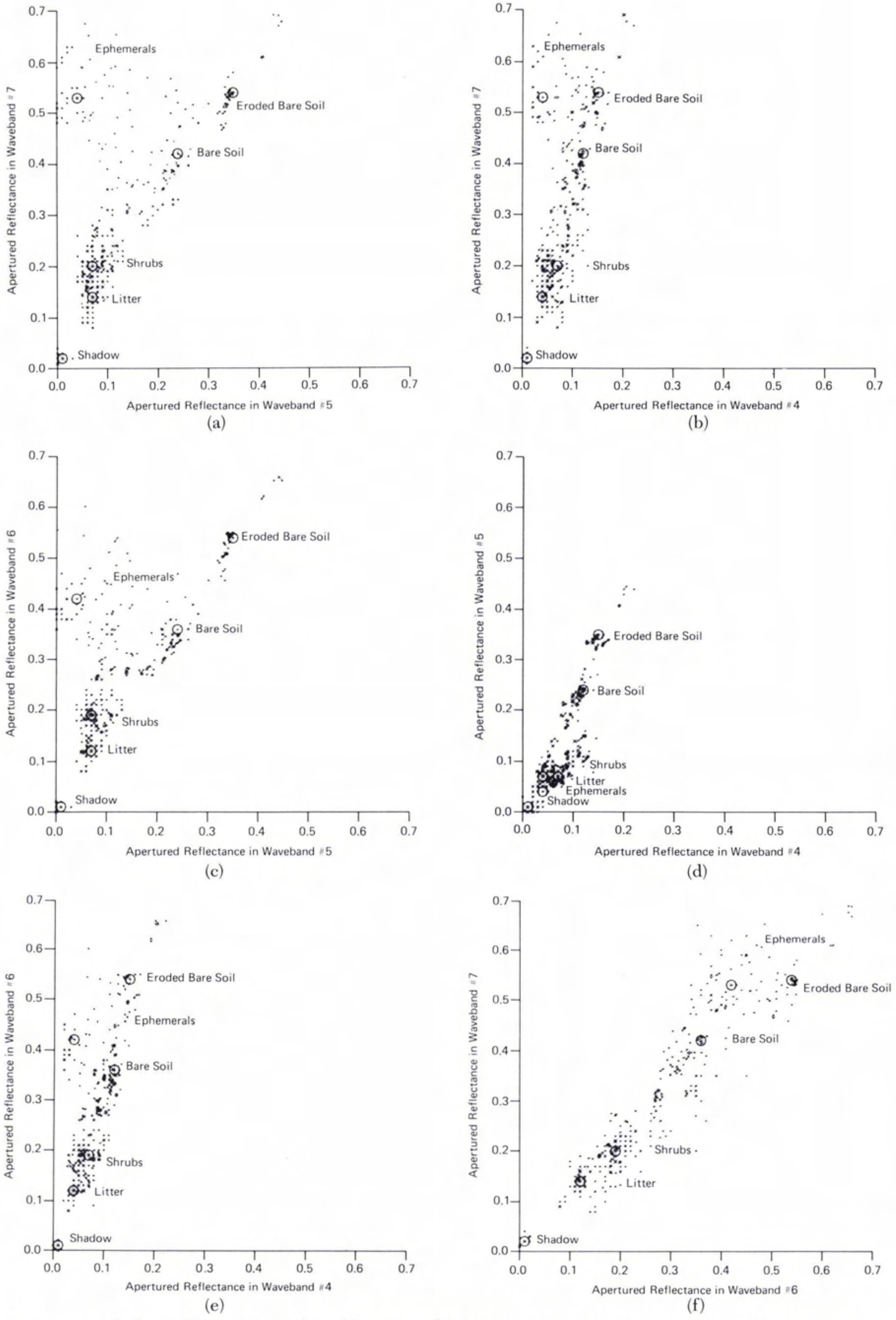

FIG. 1. A total of 347 reflectance samples of the various landscape components are plotted in pair-wise combinations of wavebands. The location of the mean values used for some components (Table 1) are marked.

both brown calcareous soils, bare soil, or those with a covering of lichen crust are darker (Table 1) and move away from the bare eroded-soil point towards the litter point. A 'cover line' can be thus defined which passes through the point of shadow, litter, and all of the soil points with a slope approximately 1.7 in this #5/#7 space.

The shrub point is a mean of several different species (*Atriplex vesicaria* ('saltbush'), *Kochia astrotricha* ('bluebush'), *Kochia pyramidata* ('black blue bush')) measured under normal conditions, i.e., when these species were not vigorous and actively growing. Shrubs, under these conditions, are only just 'greener' (i.e., more reflective in band #7) than litter. Measurements taken after rainfall, when the shrubs were actively growing and both the new and the old leaves were succulent, move along a convex line between litter and the ephemeral points. Similarly, green ephemerals and grasses, as they dry, move back down towards the litter point. The ephemeral point or 'green' point is the most variable of all of the points, with measured band #7 reflectances of $\leq$ 0.68. This is reflected by the scatter of points around the mean value.

The location of these 11 landscape components (see Table 1) within #4/#7 space (Figure 1b) is similar to that of #5/#7, but the separation of the groups is less distinct within the triangular envelope defined by the points of bare eroded-soil, litter, and green ephemerals. This envelope is more marked in the #5/#6 space (Figure 1c), but the soil variants have moved away from the 'cover' line defined by the litter and eroded soil points. In the #4/#5 space (Figure 1d) the triangular envelope has been inverted, with the vertices now being defined by the litter, bare eroded-soil, and vigorous shrub points, with the green ephemeral point coming to lie on the soil line. In the #4/#6 space (Figure 1e) the triangular slope of the data envelope is again present, but there is poor separation between the soil surface variants (lichen crusted and the brown calcareous types) and the green ephemerals and perennial shrubs. Lastly, in the highly correlated #6/#7 space (Figure 1f) all of the points lie within a narrow envelope.

The implications of the relative locations of the landscape components within the Landsat data space for enhancement and classification algorithm will be discussed later. It is interesting that we find the same structure within our rangeland data as did Kauth and Thomas (1976) and Kauth *et al.* (1979) for agricultural crops and Jayroe (1978) for a very heterogeneous urban/agricultural/forest area in Louisiana.

THE INTERACTION BETWEEN LANDSCAPE COMPONENTS

The sparse coverage of vegetation that is characteristic of this type of shrub rangeland exaggerates its vertical structure (Plate 1), and the principal interaction between landscape components is shadowing by shrubs of the intervening soil surface. To explore the interaction of vegetation structure and solar position, a simple stochastic model of the plant community was developed to calculate the area shadowed. The simulation model generated a distribution of shrub size and spacing, randomly located these within a simulated 10 by 10 m area, and computed the area of soil, vegetation, and self-shadowing. The parameters of shrub height, diameter, and distributions were determined from field measurements, and the solar geometry was calculated using the algorithms developed by Goodspeed (1975).

The potential contribution of shadows was significant. For example, taking the time of a Landsat overpass to be approximately 0950 hours Australian Eastern Standard Time at Broken Hill, the solar elevation varies from 21° in mid-winter to 53° in mid-summer. Theoretically, a shrub of 0.5 m height may cast shadows varying from 0.4 to 1.3 m in length. The area of shadows generated in hypothetical shrub communities by this range of solar elevations is illustrated in Figure 2. A dense stand of saltbush of 20 percent cover can obsure 8 percent of the intervening soil surface with shadow in mid-summer and some 35 percent in mid-winter. The relationship between the cover of vegetation and the amount of shadow on the intervening soil surface is weakly non-linear only over the range of values used here.

The theoretical shadowing graphed in Figure 2 will be reduced in the field because the ratio of direct to diffuse solar radiation also changes with solar elevation. This ratio is about 4:1 for a high sun and falling to about 2:1 for mid-winter solar elevation, and any increase in the diffuse radiation component weakens the intensity of the shadows. Nonetheless, the role of shadows as a scene component, and thus, as we shall show later, in the determination of the reflectance characteristics of a landscape, is appreciable.

SIMULATING THE COMPOSITE REFLECTANCE OF LANDSCAPES

The contributions of ecological parameters (e.g., species composition, total plant cover, etc.) and of solar elevation to the composite reflectance values of pixel-sized (e.g., 1 hectare) areas of land, was explored by modeling. Two assumptions were made. The first was that the reflectance characteristics of the composite are determined by the summation of the products of the reflectances of the individual landscape components and their proportional contribution to the total cover. That is, cover, not biomass, is the most important variable for these sparse communities. This assertion has also been made by Bentley *et al.* (1976), Richardson *et al.* (1975), Siegal and Goetz (1977), and Marsh (1979). We may write this as

PLATE I. An oblique view of the saltbush rangelands (solar elevation approx. 30°) showing the distribution and colors of the soils, vegetation, and shadows.

$$R_j = \sum_{i=1}^{n} p_i \cdot r_{i,j}$$

where R is the reflectance in waveband j ($j = 1,4$), p_i is the fraction in the scene of component i, and $r_{i,j}$ is the reflectance of component i in waveband j.

The second assumption was that the only interaction between components was shadowing. These assumptions are reasonable for this environment, and a more detailed statistical treatment and testing of this model is in preparation.

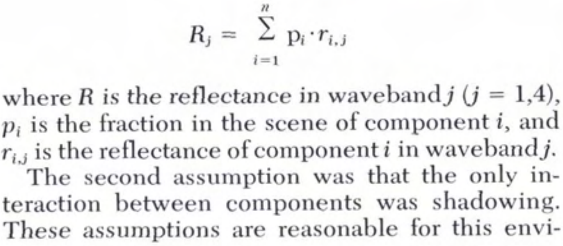

FIG. 2. The relationship between the cover of perennial shrubs and the area of the intervening soil surface that is shadowed at three solar elevations (20°, 35°, and 50°). These are simulated values.

To explore the influence of shadows in determining the composite reflectance characteristics, we modeled a simple but realistic community consisting of only saltbush and bare soil. The calculated reflectance values of such a plant community in #7 as a function of solar elevation (and hence the amount of shadow) and the cover of saltbush are plotted in Figure 3a. As the cover of nonvigorous saltbush increases over the range 0 to 30 percent, the #7 reflectance decreases approximately linearly from the starting point of bare soil; and the dramatic difference in rate of decrease between high solar altitudes (approximately midsummer, late spring) and the low mid-winter figure is due of course to shadows suppressing the bright soil. This pattern is similar in all wavebands, for soil is more reflective than nonvigorous vegetation in all wavebands, and the sensitivities of reflectance in all bands to changes in the plant cover for each solar elevation are equivalent.

Replotting the data for the above example in the #5/#7 space (Figure 3b) demonstrates that an increasing cover of (non-vigorous) perennial shrub shifts the response along a line away from the bare soil point along the 'cover' line of Figure 1a. Two important points emerge from this graph. First, for all points along this line, the ratio #7/#5, a commonly used biomass index for Landsat data (e.g., Richardson and Weigand, 1977), remains the same; that is, this index is independent of changes in the cover of perennial shrubs when they are in a non-vigorous growth stage. Second, solar elevation determines the range of movement of the re-

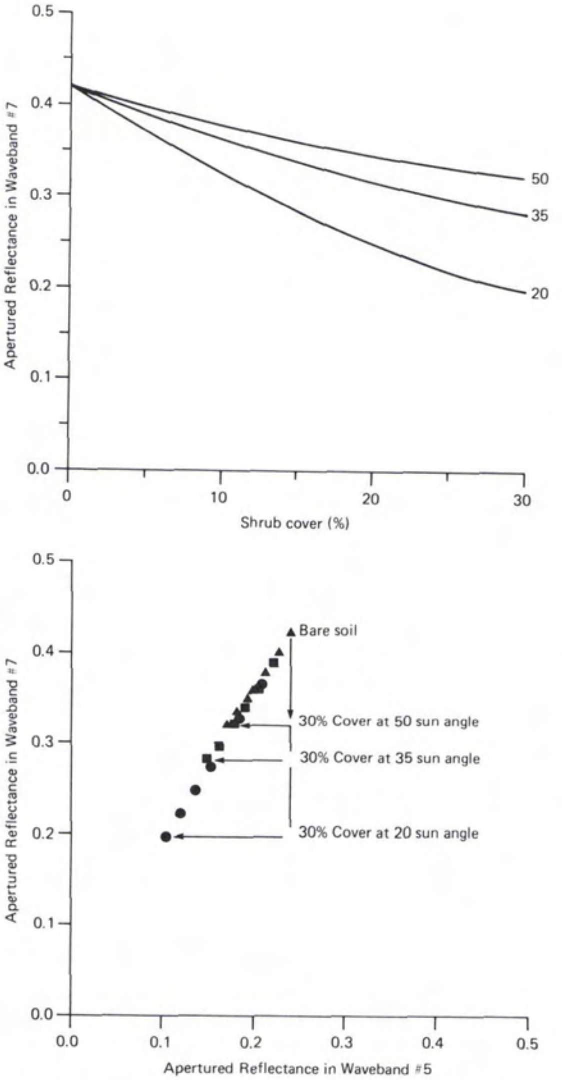

FIG. 3. (a) The relationship between #7 reflectance and non-vigorous saltbush cover (30 to 0 percent) for three solar elevations (20°, 35°, and 50°). These are simulated values. (b) The simulated values used in Figure 3 (a) replotted in the #5/#7 space.

sponse along the cover line with changing plant cover; with low sun angle (20°) the range is more than double that for a high sun angle (50°).

The recurrence of the 'cover' line suggests the development of a cover index whereby the position of a Landsat response value on this line relative to the bare soil and shadow points would indicate the cover of perennial shrubs present. The problems of formulating such an index will be discussed later.

SIMULATION OF TEMPORAL CHANGES IN REFLECTANCE

The temporal sequence of changes in the reflectance characteristics of agricultural crops throughout a growing season has often been found to be more useful in the identification and separation of crop types than the reflectance characteristics exhibited at any one time. We have modeled temporal changes to suggest data-processing methods that would enhance the amount of ecological information that might be extracted from Landsat data. It is essential to have some experience of the possible trajectories of landscapes within the Landsat data space before attempting the generation and interpretation of temporal-difference Landsat images on the time scale of years. The use of Landsat data for measuring long term changes obviously has potential in rangeland resource monitoring and management.

The temporal sequence of reflectance changes for simple but realistic rangeland plant communities were simulated and the results are plotted in #5/#7 space as Figure 4. The first of these curves is for a grassland changing from green conditions to senescence. It is initially composed of a cover of 50 percent green and vigorous ephemeral herbage and 50 percent litter, changing in 10 percent cover steps through to 0 percent cover of herbage and 50 percent litter. The reflectance of this community moves from the 'green' area of high #7 reflectance down to meet the 'cover' line where,

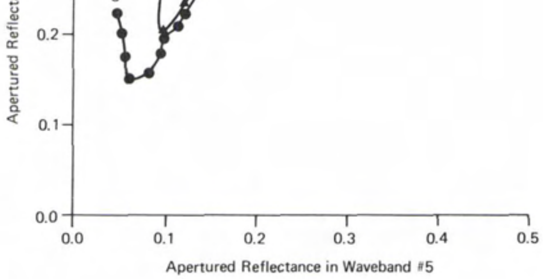

FIG. 4. The spectral trajectories in the #5/#7 space of three simulated communities. Curve 1 is that for a grassland going from a green and vigorous condition to dry litter and then the loss of this to bare soil. The other two curves are for a saltbush community in mid-summer (curve 2) and mid-winter (curve 3) wherein the herbage and shrub component is incrementally lost (see text).

with a decreasing cover of litter, the reflectance moves along this line to the bare soil point.

The next example consisted of a saltbush community just post-rain (25 percent cover vigorous shrub/40 percent of ephemerals/10 percent litter) moving through first the drying of the ephemerals to litter, and then the subsequent loss of this litter cover to an end point of 25 percent non-vigorous saltbush and only 10 percent litter. This sequence (curves 2 and 3), plotted for high and low sun, shows that the trajectories from the 'green' area down towards the soil line are essentially in parallel, meeting this line when composed of only non-vigorous shrubs and litter. As the cover of litter is reduced, the response then moves along this line towards the bare soil point.

The trajectories that have been plotted in Figure 4 from simulations using our reflectance data are directly comparable to the 'Tasselled Cap' structure derived from Landsat data by Kauth and Thomas (1976). Therefore, it should be possible to derive ecologically sound vegetation indices for the saltbush rangelands by utilizing and interpreting the structure present within the measured and simulated reflectance data. This will be attempted in the last section.

THE LIMITS TO RESOLUTION INHERENT IN THE LANDSAT QUANTIZATION PROCEDURE

The study of the location of landscape targets of interest within the four-dimensional Landsat data space is not complete without taking account of the procedure whereby surface reflectance values are recorded and subsequently made available by the Landsat spacecraft instrument payload. Unfortunately, we can be concerned here only with the quantization process and must, for lack of data, set aside the problems of atmosphere attenuation and scattering. By calculating the amount of solar radiation available at the Earth's surface within each Landsat waveband and equating this with the sensitivities of the detectors within the spacecraft scanner, the numbers of counts in each waveband that represent a 1 percent reflectance have been calculated for the latitude of Broken Hill using values from Quiel (1975) (Table 3). Using these values and the solar radiation available in mid-winter and mid-summer and the reflectance values from Table 1, the respective data triangles can be plotted (Figure 5). The dynamic range of the data is approximately 2.6 times greater in summer than in winter where, for example, the range of 0 to 100 percent in plant cover is represented by only 17 counts in the Landsat #5 digital data. Obviously, under winter irradiance conditions Landsat data would be much less capable of resolving changes in plant cover that are of ecological significance than will image data acquired in summer.

DISCUSSION

The reflectance data that we have measured and presented have provided considerable insight into how the saltbush rangelands are recorded and represented within Landsat data space and, thus, what enhancement procedures might be useful in extracting ecological information of interest. Our implicit assumption that the surface reflectance measurements will be highly correlated with Landsat data has only recently been demonstrated to be sound by the work of Marsh (1979) and Cipra *et al.* (1980). Obviously, the modifying role of intervening atmosphere cannot be ignored, but its influence is reasonably well understood (e.g., Kauth *et al.* (1979), and it does not alter the conclusions that we may draw from these field data.

The mean reflectance values of the various landscape components (soils, vegetation, etc.) that we have measured generally confirm the interpretations made on single band Landsat images (e.g., Graetz *et al.*, 1976). The bare red soils characteristic of these (and most of Australia's) rangelands occupy a pivotal position for it often is the

Table 3. Solar Radiation Intensities and the Landsat MSS Response Computed for Mid-summer and Mid-winter (in Parentheses) Conditions

Landsat MSS Waveband	#4	#5	#6	#7
Wavelength, μm	0.5–0.6	0.6–0.7	0.7–0.8	0.8–1.1
Solar flux incident above the atmosphere normal to path w/m^2	(22)	(57)	(52)	(65)
Solar intensity after reflection (reflectivity 1.0) = solar flux/w/m^2.sr	50 (22)	40 (18)	37 (17)	46 (21)
MSS maximum radiance/solar intensity = reflectivity with sun in zenith for saturation	0.50 (1.13)	0.50 (1.11)	0.48 (1.04)	1.0 (2.19)
Counts corresponding to percent of solar intensity (after diffuse reflection)	2.6 (1.1)	2.6) (1.1)	2.7 (1.2)	1.3 (0.6)

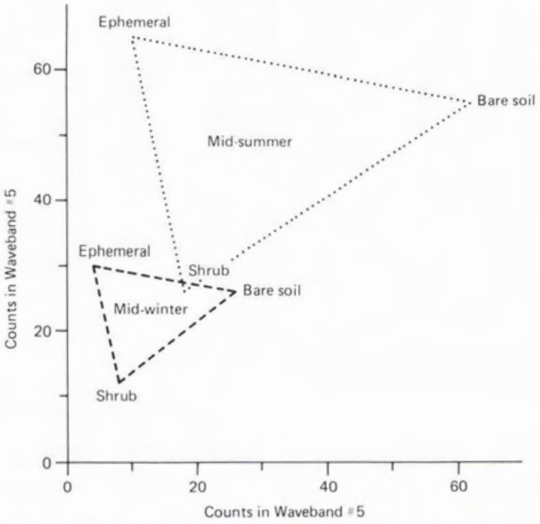

FIG. 5. A comparison of the size of the triangular data envelope for Landsat scenes acquired in mid-summer with that for mid-winter.

largest areal component of a pixel and it is highly reflective in all four Landsat wavebands. The bare soil measurements we obtained are in general agreement with those obtained by Cipra *et al.* (1980) and by Marsh (1979). Variations in surface conditions for any one soil type resulted in appreciable changes in reflectance.

The infrared "signature" of green vegetation was very distinctive whether it was measured for vigorous, actively-growing perennial shrubs or for ephemeral plants. Its origin is obviously analogous to that documented for agricultural crop plants (Gausman, 1974; Kauth *et al.*, 1979) and while most of the Landsat research that has gone on in agricultural lands has concentrated on this section of the Landsat data space, it is of only minor importance to rangeland management in Australia where yearlong rather than seasonal grazing usage is the norm (Graetz *et al.*, 1976). In contrast, the perennial shrubs are not usually highly reflective in the infrared bands and appear only slightly 'greener' than dead litter. This is unfortunate, for quantitative information on the cover of these perennials is basic to any range assessment procedures for these rangelands.

The four band reflectance values for all of the landscape components measured were highly correlated, though separation of each component could be achieved using only two wavebands. The efficiency of this separation varied with the wavebands used (Figure 1) and #5/#7 afforded the most useful separation of all components and display of the structure within the data. The structure is a rangeland analog of the 'Tasselled Cap,' and these measured and simulated data are the first direct test of the interpretation of this spectral-temporal structure. However, the interpretation that can be placed on the triangular shaped bounds of the data is slightly different. For the sparsely vegetated saltbush rangelands, the main diagonal line of the #5/#7 correlation is the 'cover line' rather than just a 'soil line' of Kauth and Thomas (1976). The two end points are defined by bare bright eroded soil and shadow and an increasing cover of vegetation (either dead litter or non-vigorous shrubs) moves away down it from the bare soil point. It is important to recognize that any cover, shrub, litter, or shadow, is essentially equivalent in darkening the bright bare soil. It is also obvious that the vegetation indices that are directly based on ratioing #5 and #7 will not in any way enhance or separate out cover but rather separate out cover from 'green.' The perpendicular vegetation indices of Richardson and Weigand (1977) are exceptions. For these rangelands, vegetation indices can be developed that utilize the triangular shape of the data in the #5/#7 space by first defining the vertices (bare, green, and shadow) and then mapping any pixel back onto the 'cover line' to give a 'cover' index value and, as well, onto the bare soil-green side of the triangle to give a 'green' index value. This is a simplified approach to the method advocated by McCloy (1977) and Smedes (1978). A more detailed derivation and testing of these indices is in preparation.

The simulation studies on the role of solar elevation (shadows) and intensity at time of acquisition and in the interpretation of Landsat imagery suggest that shadows represent a loss of information about the surface and that shadowing by perennial shrubs renders the cover/reflectance response non-linear. This coupled with the reduced dynamic range of Landsat digital data resulting from mid-winter solar intensities dictates that mid-summer acquisition is preferable. Because of the role of shadowing in sparsely vegetated communities such as these, Landsat digital data cannot be standardized to a reference solar elevation by using simple cosine-scaling as is routinely done for image data of agricultural scenes.

Finally, the observations reported here are from one rangeland type only—a low shrubland. Theoretically, we could expect that the above conclusions are generally applicable to all sparse plant communities, and two recent reports of Landsat applications to sparse woodlands (Tupper and Maxwell, 1981; Todd *et al.*, 1980) support this contention.

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