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Urban Residential Ground Cover Using Landsat Digital Data

Multiple regression analysis is used to examine the relationship between Landsat digital data and percentage cover data, sampled at the pixel level.

Abstract: *Residential areas in large cities are typically heterogeneous and as such are not amenable to classification by cluster or discriminant analysis. Multiple regression analysis is considered more appropriate and is used to examine the relationship between Landsat digital data and percentage cover data, sampled at the pixel level over the Sydney metropolitan area.*

Derived linear equations, with correlations ranging from 0.45 to 0.66, allow the approximate prediction of the 100 percent response values of each cover type. Cover types sampled were buildings, concrete, roads, trees, grass, water, and soil. Linear equations, relating response in each band to the change in a particular cover from an average background, are found to be more useful in suggesting desirable band combinations necessary to predict particular cover characteristics.

Suggested relationships are verified by relating individual cover percentages to various band combinations; here correlation ranged from a low of 0.33 for concrete percentage to a high of 0.72 for grass and tree percentage combined. Generally, the most significant response variables of those used were the normalizing ratios.

When the point spread function of the Landsat sensor is approximately accounted for, more reliable predictions of the reflectance of individual residential cover types are made.

Introduction

Background

The standard approach to classification of remotely sensed data, particularly Landsat data, is to assume that the area of study is comprised of a number of unique, internally homogeneous classes. Typically, cluster analysis or discriminant analysis is used to identify these unique classes by means of ground truth areas.

This approach is perfectly acceptable when crops or other agricultural lands are being examined or when urban areas are being classified into nominal classes at the broad general level, as for example using the proposed standard classification system of the U.S. Geological Survey (Anderson *et al.*, 1976).

Using Landsat data, some researchers have further broken the residential general class into sub-classes, but typically these are older and newer housing classes, residential and mixed residential classes, or some other dichotomous division. (Christenson and Lachowski, 1976; Welch *et al.*, 1973). Zobrist *et al.* (1976) report a more detailed breakdown having large buildings, strip cluster development, single family residential, and multiple family trailer courts as separate classes.

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A limitation to a more detailed classification is the heterogeneous nature of the urban surface cover. Todd *et al.* (1973) attempt to resolve this problem by distinguishing between homogeneous and heterogeneous urban classes. Todd and Baumgardner (1973) suggest that some land-use classes have been largely elusive to existing methods of classification because they do not exhibit spectrally separable characteristics.

In such areas the radiation received from a single ground element will be composed of radiation from a number of objects, or areas, which individually may have distinct spectral signatures. Their additive response may not be respresentative of any one class (Carter, 1977), and a single pixel classification may be incorrect (Nalepka *et al.,* 1972). Urban residential areas typically exhibit this problem.

Another but related problem in residential areas, which limits more detailed classification, is the continuous nature of the cover classes. In one area residential density may be low with few established large trees, another may have a similar density but mature vegetation, while a third may be of high density with little or no vegetation. Between each of these, intermediate examples occur.

If cover can be considered as a surrogate variable for density, age, quality, or other socio-economic characteristics, as has been suggested in part by Todd *et al.* (1973), then the data are not amenable to cluster or similar analysis which has as its final product a separation into distinct homogeneous classes.

PURPOSE AND SCOPE

This paper reports on a continuing research program to determine whether the proportional mix of cover classes in residential areas can be used as surrogate for more detailed classification of those areas and whether this mix can be adequately predicted from Landsat response data.

Some initial research into the mixed pixel problem in single family residential areas of Sydney, Australia is described. While the mixed pixel problem has been considered by others (Smedes *et al.,* 1975; Horwitz *et al.,* 1971; Jensen, 1978) none of these studies has been undertaken solely in an urban situation.

While Sydney has many unique characteristics, it is not atypical of western industrialized cities and in population, size, residential density, morphology, and climate is quite similar to the western seaboard American cities of Los Angeles and San Francisco. Some of the techniques and results discussed in this paper should therefore be transportable to other regions.

Four aspects of the problem are described:

- the relationship between sampled mixtures of cover data and Landsat response data;
- the effect of cover change on the Landsat response;
- the derivation of equations for the prediction of individual cover percentages; and
- the prediction of the reflectance of individual ground cover components (in each of the four Landsat bands) with a more critical examination of error effects, particularly those due to the point spread function of the sensor.

Landsat digital data for each of the four bands was obtained from the computer compatible tapes of Landsat scene No. 1141-23140, being the "Sydney Scene" of December 1972. Ground truth data of cover percentages for a number of sampling areas were derived from aerial photographs. These were black-and-white panchromatic photographs at a scale of 1:15,000, taken in late 1971 and enlarged to 1:2,000 to act as a sampling base. Large scale color or color infrared photographs taken at the time of satellite overflight would have been preferred; these, however, were not available.

ANALYSIS

DATA COLLECTION

Sample Design. One aim of the research is to determine whether variables derived from Landsat digital data can be used to predict the percentage of various cover classes over an extended area.

The relationships between the various data sets must first be determined from samples which can then be used as predictors for the whole population.

When two variables are studied, a simple measure of the relationship is the correlation coefficient. While it is hoped that correlation would be high, it is more important that the correlation is significant. A correlation coefficient, r, can be tested for signficance by the use of the Student's t distribution, using the following formula:

$$t = \frac{r.\sqrt{n-2}}{\sqrt{1-r^2}}$$

where n is the number of pairs of data studied and where the degrees of freedom are $(n - 2)$. The null hypothesis postulated is that there is no correlation between the variables.

For this study it was considered that a correlation of less than 0.3 was of very limited value and that its significance should be such as to be able to reject the null hypothesis at the 1 percent level.

A value of n of approximately 60 is required to achieve this significance. Any relationships having higher correlations than 0.3 or determined from more samples would necessarily be significant at the 1 percent level or better.

A systematic distribution of these samples was decided upon so as to obtain an adequate representation of the population. There is little chance with this method that a large contiguous part of the population would fail to be represented. A number of studies also report other advantages in addition to its convenience. Cochran (1963) reports a number of studies which indicate that systematic sampling shows a consistent gain in precision over stratified random sampling, particularly for data where variation would be nearest to continuous. Howard (1970) considers for photo-ecological studies, that systematic sampling can provide as good or sometimes a better estimate of the mean for a specified number of samples than does random sampling.

It was found that 70 sample areas at approximately 4 kilometre intervals adequately covered the Sydney metropolitan area. Samples were taken as being those residential areas at or nearest the 4 kilometre grid intersections. Although this was ten more samples than previously considered necessary on the basis of significance, the figure of 70 was adopted because of the administrative convenience of whole number grid intervals, and to provide a margin of safety, particularly when more than two variables were being related with a subsequent loss of degrees of freedom.

Because the relationship between cover percentages as sampled from aerial photographs and Landsat digital response was to be initially determined at the pixel level, sampled cover characteristics at this level had to be obtained. It was considered that a maximum standard error of the estimate of the percentage cover of approximately 10 percent would be adequate when an individual cover comprised 50 percent of the pixel. This figure can be approximately obtained when 20 sample points are used per pixel.

A stratified unaligned systematic sample with the pixel divided into 20 grid cells was considered appropriate because this method shows the best results when used on cyclic phenomena (Berry, 1962) and so should tend to reduce the systematic effects of a regular urban pattern. An overall cover of sample points is achieved with each point's position in its cell being essentially random.

A cluster of 40 such pixels at each sampling site was selected so that the effects of the point spread function of the sensor could be contained within the sampling area. Dye (1973) suggests a 7 by 5 array of pixels will adequately contain this effect, although for more approximate work a 3 by 3 array would seem sufficient (see Figure 1). The slightly larger array of eight pixels along scan and five across scan was selected to compensate for any positional error of the sampled array relative to the Landsat response array and also to increase the number of possible 3 by 3 arrays over each sample area if this was found to be sufficient.

A necessary procedure prior to the main study was the transformation of parts of the Landsat scene into the ground truth areas. As these ground truth areas were to be located at 4 km intervals, ground control sufficient to ensure a tight fit to each area and to allow examination of surrounding residuals was required. Control points also were located such that, if inadequate results were achieved from an overall polynomial transformation, individual affine transformations could be computed. With 70 ground truth sites, a total of 100 ground control points was needed to satisfy these aims.

Transformation procedures. Landsat digital data for each of the four bands were obtained from the computer compatible tapes of Landsat scene No. 1141-23140. Shade prints and ASCII character prints were generated for the Landsat scene and were used to determine, to the nearest half pixel, the line and pixel coordinates of each ground control point. Equivalent ground coordinates were obtained from 1:10,000 series planimetric maps.

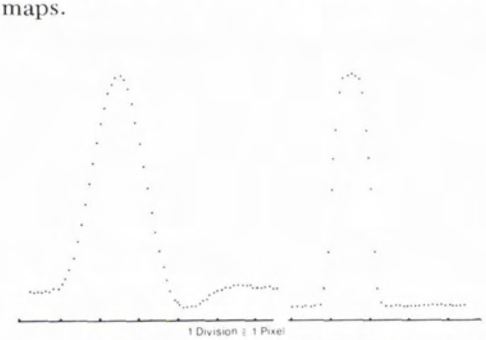

FIG. 1. Landsat point spread function (after Dye).

A complete 5th order polynomial transformation and also a correction for interswath discontinuity was applied to the data.

For the easting transformation a standard deviation of 32.3 m was obtained, and for northing a standard deviation of 24.8 m, giving an overall circular standard error of approximately 30 m.

The azimuth of the across-scan track was computed from the derived polynomial equations, and a calculated value of 11° 0.8′ was determined. As the scene in question extended east from the satellite nadir for approximately 30 Km, and given a circular standard error of ±30 m, the standard error of calculated azimuth was approximately ±0° 05′.

Data sampling. Seventy residential areas at approximately 4 km intervals were selected for study. An area of approximately 400 by 500 metres was to be sampled for cover percentages around each point. These areas are to contain 40 Landsat pixels, five across scan and eight along scan.

Data relating to cover characteristics were sampled from black-and-white panchromatic aerial photographs taken in 1971. These were at a scale of 1:15,000 and were enlarged to a scale of 1:2,000 over each sample area, to act as a sampling base. A sampling overlay at a scale of 1:2,000 was prepared. This consisted of an eight pixel along scan by five pixel across scan grid, with each row of the grid stepped 4 metres along scan to account approximately for sensor delay inherent in the Landsat system. In each pixel twenty sampling points were marked (Figure 2).

The centroid coordinates of each of the sample areas were transformed into their Landsat equivalents using the derived transformation parameters, and the small distances to the nearest pixel center (across scan) and midway between pixels (along scan) were determined, i.e., the center of a 5 by 8 block of pixels. These adjusted centroids and the direction of the across scan track were marked on 1:10,000 planimetric maps covering each sample area, and then transferred to each enlarged photograph by comparison of map and photo detail.

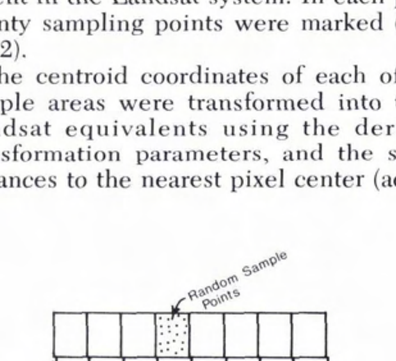

FIG. 2. Sampling grid used to estimate ground cover percentages, showing step for sensor delay. Each cell represents one Landsat pixel.

The sampling overlay was registered with each photo and the following data were sampled over each pixel:

- House percentage cover (H)
- Other building percentage cover (O)
- Road percentage cover (R)
- Concrete percentage cover (C)
- Tree percentage cover (T)
- Grass percentage cover (G)
- Water percentage cover (W)
- Soil percentage cover (S)

House roofs in Sydney are predominantly red/brown tile and should have similar reflectance characteristics. Other buildings consisted of small buildings separate from the main dwelling, which have predominantly weathered iron roofs. In addition, a small percentage of commercial, industrial, and multi-family units that encroached on the predominantly single family dwelling areas were included. Roads were of asphalt construction, and concrete included footpaths, drives, parking areas, etc. Tree and grass percentages are self explanatory; however, grass at the time of overflight (southern summer) is relatively dry and trees are predominantly native with relatively few deciduous trees. Water percentage included swimming pools, and in coastal area sea water where the sampling grid extended slightly over the sea.

Soil percentage was a catch-all class for any area that was not covered with vegetation or man-made structures. This included soil, exposed rock, and sand. These cover types have quite separable signatures normally, but in this study they amounted to only a small percent of the total cover and could be considered as "other."

The equivalent Landsat response in each band and for each individual pixel was obtained from the Landsat computer compatible tapes, by using the line and pixel coordinates of each to access the data. A computer card deck listing each pixel in blocks of 40 was prepared, with the appropriate cover percentages and response data related to it, forming a total data set of 2,800 pixels.

GENERAL AND METHODOLOGY

Landsat response vs. percentage data. The total radiance of a mixed surface area can be considered as the sum of the individual radiances from each component part. In addition, atmospheric scattering will introduce a constant additive effect, and the effect of atmospheric transmission will have a multiplicative effect.

An equation of the form

$$B_i = K_{i0} + K_{i1}H + K_{i2}O + K_{i3}R + K_{i4}C + K_{i5}T + K_{i6}G + K_{i7}W + K_{i8}S$$

is proposed, where B_i is the response count measured in Band i, K_{i0} is a constant effect, and K_{i1} to K_{i8} are coefficients to convert the cover percentages to response counts. Linear equations of this form are suitable for analysis by multiple linear regression techniques. Stepwise regression was used, so that the best sub-set of variables was output at each step. H, O, R, C, T, G, W, and S are the cover percentages for house, other, road, concrete, tree, grass, water, and soil as defined earlier.

Because the sum of the percentages of the cover types add to 100 percent, the variables form a closed set. A "closure problem" arises whenever a series of values are forced to a constant sum (Davis, 1973), which causes an induced negative correlation. In addition, the normal equations which form part of the regression solution become unsolvable if one of the independent variables is a perfect linear function of one or more of the others. For these reasons and because of its minimal effect, the variable soil percentage was excluded from this part of the analysis.

The results of using digital response values of Bands 4, 5, 6, and 7 as the dependent variables and cover percentages as the independent variables are shown in Table 1. Response from Band 7 was doubled to give a range equivalent to the other bands. Only significant coefficients were retained.

Cover change and its effect. Using the coefficients developed in Table 1, new coefficients were determined that represented the combined change from an average background response, that is, the total change due to an increase of one unit in a particular variable and the corresponding decrease of one unit of average response.

The average response for each band over all sampled areas and the average of each of the percentage cover variables over the same areas were as follows:

Band 4	38.77	H (House %)	22.81
Band 5	35.01	O (Other %)	5.09
Band 6	49.80	R (Road %)	13.79
2 × Band 7	48.82	C (Concrete %)	4.69
		T (Tree %)	16.17
		G (Grass %)	36.48
		W (Water %)	0.43
		S (Soil %)	0.54

For Band 4 the difference between the average response and the equation constant is 3.4. Thus, as the average background reduces by 1 percent, the response will increase by 0.034. However, if house percentage, for example, increases by 1 percent, the response will be reduced by 0.015. The combined effect for an increase of H of 1 percent above average will, therefore, be $0.034 - 0.015 = 0.019$. Similarly, coefficients for all bands and all cover variables can be derived. These are shown in Table 2. Coefficients of excluded or insignificant variables in the regression equation are assumed to be zero, giving a change from average coefficient in Table 2.

Prediction of Percentage Cover. Each of the cover variables and some derived cover variables were used as dependent variables and regressed against response in all of the four bands and with various derived response variables, as independent variables. These latter were

SUB 57	= B5 − B7
Ri	= Bi/(B4 + B5 + B6 + B7) for i = 4 to 7
Bi2	= (Bi)^2 for i = 4 to 7
TOT	= Σ (B4 + B5 + B6 + B7)
R75	= B7/75

Derived cover variables used were

ROOF	= $H + O$
GREEN	= $T + G$
CULT	= $H + O + R + C$,

representing total roof, vegetation, and cultural (i.e., man-made) percentages. The results are shown in Table 3. Only the two most significant response variables are shown for each dependent cover variable. The standard error of the coefficient estimate is shown in brackets below.

The equations developed for single pixel areas were applied to a number of sampling areas. Thirty such areas were selected at random and the percentage amounts of Green (G), Tree (T), Road (R), and Concrete (C) were predicted by substituting the average response variables for each area in the relevant equation. The correlation between predicted and observed percentage cover was calculated and the following values were obtained.

Green	%	R = 0.77
Tree	%	R = 0.85

TABLE 1. REGRESSION BETWEEN LANDSAT RESPONSE AND PERCENTAGE COVER

Band	Variable*	Coefficient	S.E.	R	R^2 (Adjusted)
	T	−0.139	0.005		
	O	+0.054	0.008		
4	*G*	−0.035	0.005	0.63	0.40
	W	−0.078	0.012		
	C	+0.049	0.013		
	H	−0.015	0.006		
Equation constant		42.19	0.42		
	T	−0.248	0.009		
	G	−0.120	0.009		
5	*W*	−0.227	0.018	0.66	0.44
	R	−0.074	0.011		
	C	+0.071	0.017		
	H	−0.038	0.009		
Equation Constant		45.05	0.771		
	G	+0.168	0.006		
	W	−0.211	0.018		
6	*C*	+0.199	0.018	0.54	0.290
	H	+0.090	0.008		
	T	+0.039	0.007		
Equation Constant		40.16	0.48		
	G	+0.257	0.009		
	T	+0.136	0.009		
7	*H*	+0.097	0.011	0.63	0.40
	C	+0.178	0.022		
	W	−0.219	0.022		
	O	−0.057	0.014		
Equation Constant		34.60	0.74		

* Variables listed in order of their entry into the equation.

Road % R = 0.84
Concrete % R = 0.52

RESULTS

Estimates of the 100 percent response for each variable in each band can be calculated by multiplying the individual coefficient in Table 1 by 100 and adding or subtracting from the constant term. Estimates of the response for various mixtures can also be calculated by inserting the appropriate cover percentages.

These initially determined equations are not particularly explanatory in their present form. An individual coefficient ostensibly represents the expected change in the dependent variable with a change of one unit in that variable when all other variables are held constant. Because of the interdependence of the variables, an increase of one unit in one variable must result in the loss of one unit from the combined sum of the other variables. The resultant measured response is thus due to the combined effect.

More explanatory equations result when the coefficients representing the combined change from an average background response (Table 2) are examined.

These new equations give insight into the desirable band combinations required to predict particular cover characteristics. For example, Band 4 should be a good predictor of the change in tree percentage from aver-

TABLE 2. COVER COEFFICIENTS FOR 1 PERCENT CHANGE FROM AVERAGE

Band	Average Response	*H*	*O*	*R*	*C*	*G*	*T*	*W*	*S*
4	38.8	+0.019	+0.088	+0.034	+0.083	−0.001	−0.105	−0.044	+0.034
5	35.0	+0.062	+0.100	+0.026	+0.171	−0.020	−0.148	−0.127	+0.100
6	49.8	−0.006	−0.096	−0.096	+0.103	+0.072	−0.057	−0.307	−0.096
7	48.8	−0.045	−0.199	−0.142	+0.036	+0.115	−0.006	−0.361	−0.142

Table 3. Coefficients for Predicting Residential Cover Percentages

	Roof*	Road	Concrete	Tree	Grass	Water	Green*	Cult*
B4				−14.55 (0.60)				
$B4^2$			−0.0029 (0.0007)	0.1548 (0.0077)				
B5								
$B5^2$			0.0063 (0.0005)					−0.0083 (0.0015)
B6								
$B6^2$					3.46 (0.15)			
B7								
$B7^2$								
SUB 57						−0.219 (0.016)		2.519 (0.085)
R4					173.2 (24.9)	137.4 (5.3)		
R5	399.2 (19.0)	70.4 (19.2)					−283.3 (25.3)	
R6	141.9 (22.0)						396.1 (31.5)	
R7		−173.4 (23.8)						
TOT								
R75								
Constant	−114.0 (11.6)	25.8 (8.3)	1.1 (0.5)	345.3 (11.7)	−93.4 (9.70)	−33.3 (1.3)	54.1 (10.9)	30.1 (1.2)
Correlation (R)	0.52	0.43	0.33	0.65	0.53	0.44	0.72	0.68
Explanation (R^2)	0.27	0.19	0.11	0.42	0.28	0.20	0.52	0.46

* NOTE ROOF = $H + O$, GREEN = $T + G$, CULT = $H + O + R + C$

age, because all other cover variables cause a relatively small change in the opposite direction. A similar suggestion could be made for the grass percentage in Band 7.

The Band 7, Band 5 difference should be a good predictor of green content (i.e., the sum of grass and tree percentages) because of the high reflectance of vegetation in Band 7 and the low reflectance in Band 5. The transformed vegetation indexes of Rouse *et al.* (1973) use a similar difference between visible and infrared response.

Less obvious effects can also be noted. The difference between Bands 4 and 5 should correlate with concrete percentage because it would then have the largest coefficient (assuming all other covers remain at approximately average levels). Normally, these two bands are considered so highly correlated that little information is contained in them. Care must be taken in using these equations, however, as the probability of seemingly insignificant coefficients having an effect will depend on the variance of their cover percentages.

These suggested band combinations for Tree percentage, Grass percentage, Concrete percentage, and Green percentage agree well with those calculated (see Table 3). Correlation is low in most cases, although the 0.72 value for Green percent is of the same order as that reported by Richardson and Wiegand (1977) for crop cover against a soil background. In this study correlation ranged from a low of 0.564 using Vegetation Index Models to a high of 0.809 using Band 5 (negatively correlated).

When the predictive equations were applied over extended areas rather than individual pixels, better results were obtained. The increase in correlation was substantial, with the correlation for Green percentage improving from 0.72 to 0.77, for Tree percentage from 0.65 to 0.85, for Road percentage from 0.43 to 0.84, and for Concrete percentage from 0.33 to 0.52. Interestingly, the cover variables with low average percentages have had the most dramatic increase. This effect is lessened when the average percentage is very low. The explanation for this is that cover variables with high percentages will be least effected by sampling and pixel position errors. Predicting the percentage cover for these variables over the extended area will only marginally improve correlation. Because very low percentage cover variables are substantially affected by sampling errors, the coefficients will be least significant and even application over an extended area can only cause a moderate improvement in correlation. Additionally, by averaging, variance is substantially reduced.

Discussion

General

The polynomial nature of the equation predicting Tree percentage has been observed before in vegetation studies. Colwell (1974) noted this type of relationship for the red part of the spectrum when he modeled the effect of increasing the total leaf area index of a grass canopy on a light-toned soil background. Milton (1978), using a portable "Landsat" radiometer with grass on a soil background, found a relatively sharp initial decline in Band 5 response, followed by a leveling off as the reflectance stabilized around that expected from a completely vegetated surface. He explained this effect as being partly due to the initial masking of a highly reflective background by a low reflecting green vegetation and partly to the effect of increasing amounts of low reflecting shadow falling on the exposed surface. In the urban situation a low percentage usually indicates a few isolated trees. The open nature of the eucalypt foliage means that most of the response is due to the higher ground reflectance. As the trees cluster, the canopy closes and any ground reflectance is from shadowed areas. The response initially declines rapidly, then approaches the true linear relationship.

Generally, the most significant response variables of those used were the ratios Band Response/Total Response. Difference on sum ratios, e.g., B5 − B7/B5 + B7, could be significant, but these were not tested in the present study.

Examination of Error Effects

The low correlations obtained for the response versus cover percentage equations (see Table 1) indicates that they are not particularly accurate in predicting the 100 percent response of individual cover variables. This low correlation can be attributed to errors from three main sources:

- Original sampling error of the percentage cover (will cause a maximum standard error of the estimate of the percentage cover of approximately 10 percent when an individual cover comprises 50 percent of the pixel);
- The positional error of each pixel with respect to the cover sampled data (will mean that the recorded response is not entirely due to the observed cover characteristics); and
- The point spread function of the sensor (will cause the recorded response to be derived predominantly from the observed pixel area but also partially from the surrounding pixels).

The first of these, sampling error, will be randomly distributed. This will increase the unexplained variance, and so lower the correlation; however, it should not bias the value of the computed coefficients. This will apply whether response is the dependent or independent variable.

The error effects due to pixel location and point spread function cannot be discounted so easily. The form of the point spread function for the Landsat sensors is shown in Figure 2. The measured response at the sensor is due to the sum of each elemental response weighted by the point spread function. For example, if an entire pixel is covered with water and surrounded by grass (which respectively have low and high responses in the near infrared), then the measured response will be partially due to water and partially due to grass, giving a combined medium level response from a pixel that is observed to be 100 percent water.

The average weight to be given to a central pixel and its surrounding pixels can be estimated from the point spread function. These values are shown in Figure 3.

The effect of this function can be shown by a numerical example. Assume the same situation of water surrounded by grass, and further that the true response of water is zero

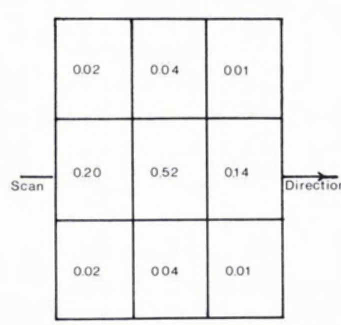

Fig. 3. Average convolution weights for a central pixel and its surrounding pixels due to the point spread function.

and that of grass, fifty. The observed response for the water covered pixel will then be

$$B_7 \text{ (water } 100\%) = 0.52(0) + 0.48(50) = 24 \text{ counts.}$$

If the central pixel was covered half by water and half by grass with the surround remaining the same, then

$$B_7 \text{ (water } 50\%) = 0.52\ (0 + 25) + 0.48\ (50) = 37 \text{ counts.}$$

For a full grass central pixel, equivalent to 0 percent water, then

$$B_7 \text{ (water } 0\%) = 50 \text{ counts.}$$

Therefore, while the relationship between water percentage and response would be linear and decreasing as percentage water increases, the predicted coefficient would be too small.

In general, the background of any pixel will tend to the average background of all pixels. The measured response of this background will be unaffected by the point spread function. Therefore, as the response of a cover type varies from the average, the predicted change will be increasingly too small.

The error due to incorrect pixel positioning will have a similar effect. As the positioning error increases, it is more likely that the measured response will be due to an average background. A similar reduction in the predicted change will occur.

However, the statistical character of the response from typical scenes has been studied, and this suggests that there is an overwhelming probability that two neighboring points will have the same response (Steiner *et al.*, 1975). This effect will tend to offset the logical assumption of an average background and it could, therefore, be inferred that the truth lies somewhere between. A mixed background cover of 50 percent average cover and 50 percent observed cover could be assumed.

This assumption was tested using water cover in Band 7. In this band water showed a response very close to zero. The average from a number of extended, inshore, ocean water sources was found to be 2.6 counts (on a doubled Band 7 scale). This includes the small effect of atmospheric scattering and possible reflectance from suspended sand and also wave caps. Average response over all sampled pixels was measured at 48.8 counts. Assuming a pixel entirely covered with water and a mixed background of 25.7 counts, then

$$100\% \text{ water response} = 0.52(2.6) + 0.48(25.7) = 13.7 \text{ counts.}$$

Predicted 100 percent water response from regression equation coefficient

$$= 34.6 - 100(0.219) = 12.7 \text{ counts.}$$

These values are sufficiently close to suggest that this approach is an acceptable one. Water response in Band 7 can be used as a datum for adjusting change from average coefficients of other cover types in all other bands. The correction factor required can be calculated as follows

$$K = \frac{\text{(Average Response} - \text{True Water Response)}}{\text{Predicted change from Average for } 100\% \text{ water}} = \frac{48.8 - 2.6}{36.1} = 1.28$$

All change from average coefficients (see Table 2) were multiplied by 1.28 to give the results shown in Table 4.

A better estimate of the 100 percent response of each cover type in each band can now be given. These are shown in Table 5.

These "count" values can be converted to radiance values by using the conversions

Band 4	$0.1953\ Wm^{-2}\ st^{-1}$ per count
Band 5	$0.1575\ Wm^{-2}\ st^{-1}$ per count
Band 6	$0.1386\ Wm^{-2}\ st^{-1}$ per count
Band 7	$0.3175\ Wm^{-2}\ st^{-1}$ per count

derived from the ERTS Data Users Handbook for Landsat 1.

It would be preferable for comparison if cover responses were measured in reflectance values. This requires the calculation of atmospheric scatter. Spectral solar irradiance at the top of the atmosphere and atmospheric reflectance can be interpolated from various published graphs (American Society of Photogrammetry, 1975) for an assumed dry turbid atmosphere and a known solar elevation of 60°.

Because the spectral response function of Band 7 drops off sharply to 1100 nm, the half bandwidth points actually approximate 800 to 1000 nm (Milton, 1978). This range and bandwidth were used for interpolation purposes, as well as the published 500 to 600 nm, 600 to 700 nm, and 700 to 800 nm, respectively, of Bands 4, 5, and 6.

Atmospheric scatter was approximately calculated using interpolated values for each

TABLE 4. CORRECTED COVER COEFFICIENTS FOR 1% CHANGE FROM AVERAGE

Band	Average Response	*H*	*O*	*R*	*C*	*G*	*T*	*W*	*S*
4	38.8	+0.024	+0.113	+0.043	+0.106	−0.001	−0.134	−0.056	+0.044
5	35.0	+0.079	+0.128	+0.033	+0.219	−0.026	−0.189	−0.163	+0.128
6	49.8	−0.008	−0.123	−0.123	+0.132	+0.092	−0.073	−0.393	−0.123
7	48.8	−0.058	−0.255	−0.182	+0.046	+0.147	−0.008	−0.462	−0.182

band. Values of 2.5, 1.2, 0.6, and 0.4 Wm^{-2} st^{-1} were determined for Bands 4, 5, 6, and 7, respectively.

Sensed radiances at the nadir for surfaces of 100 percent reflectance, for a dry turbid atmosphere, are graphed for various solar elevation angles in each Landsat band (American Society of Photogrammetry, 1975).

For a solar elevation angle of 60° radiances of 31.0, 27.0, 22.5, and 39.0 Wm^{-2} st^{-1} can be interpolated for a surface of 100 percent reflectance. As a good approximation, the total spectral radiant emittance is linearly proportional to the reflectance of the ground. Assuming Lambertian surfaces, radiance is, therefore, also linearly proportional to ground reflectance. Subtracting atmospheric scatter, conversion constants of 3.509, 3.876, 4.566, and 2.591 percent change in reflectance per Wm^{-2} st^{-1}, can be determined for Bands 4, 5, 6, and 7, respectively. Reflectance for all ground cover classes, for each band, were calculated. These values are graphed in Figure 4, showing all possible two-dimensional combinations of the four bands. The quite high correlation of the two visible bands and the two infrared bands is clearly evident. The benefit of ratioing is also evident in the visible/infrared band combinations.

CONCLUSIONS

Limitations to the more detailed classification of urban scenes using cluster or discriminant analysis are the heterogeneous nature of the urban surface cover, giving rise to mixed pixel effects, and, particularly in residential areas, the continuous nature of the cover classes.

TABLE 5. LANDSAT (CORRECTED) COUNT VALUES FOR VARIOUS URBAN COVER

Cover	Band 4	Band 5	Band 6	Band 7*
House	41	43	49	43
Other	50	48	38	23
Road	43	38	38	31
Concrete	49	57	63	53
Tree	25	16	43	48
Grass	39	33	59	64
Water	33	19	10	3

* Doubled Band 7 Scale.

To overcome this problem, the relationship between response and the percentage of various residential component covers was examined. It was found that equations relating response to changes in cover percentages were more explanatory than those using total cover percentages and gave insight into the combined response variables needed to predict individual cover percentages. Various response combinations were suggested.

These combined response variables were verified by computing the optimum combinations for predicting individual cover percentages. Correlations of 0.70 were achieved for some cover percentages, and it was shown that correlation was substantially increased when the computed relationships were applied over extended areas. Generally, the most significant response variables of those used were the ratios Band Response/Total Response.

The main errors affecting the response and cover relationships were considered to be the positional error of each pixel with respect to the cover sampled data and the effect of the sensor point spread function. By incorporating an average background effect, more reliable estimates of the reflectance of cover types was achieved.

Some approaches to the handling of the mixed pixel problem have been suggested. Further investigation of this problem is required, particularly the effects of point spread convolution.

RECOMMENDATIONS

It is suggested that in further studies the response at the sensor be related not to the sample cover within a pixel but to a weighted sample of the pixel and surrounding pixels, the weighting function being an approximation of the point spread function, i.e., the effective convolution of the ground data. This approach is being further investigated by the author.

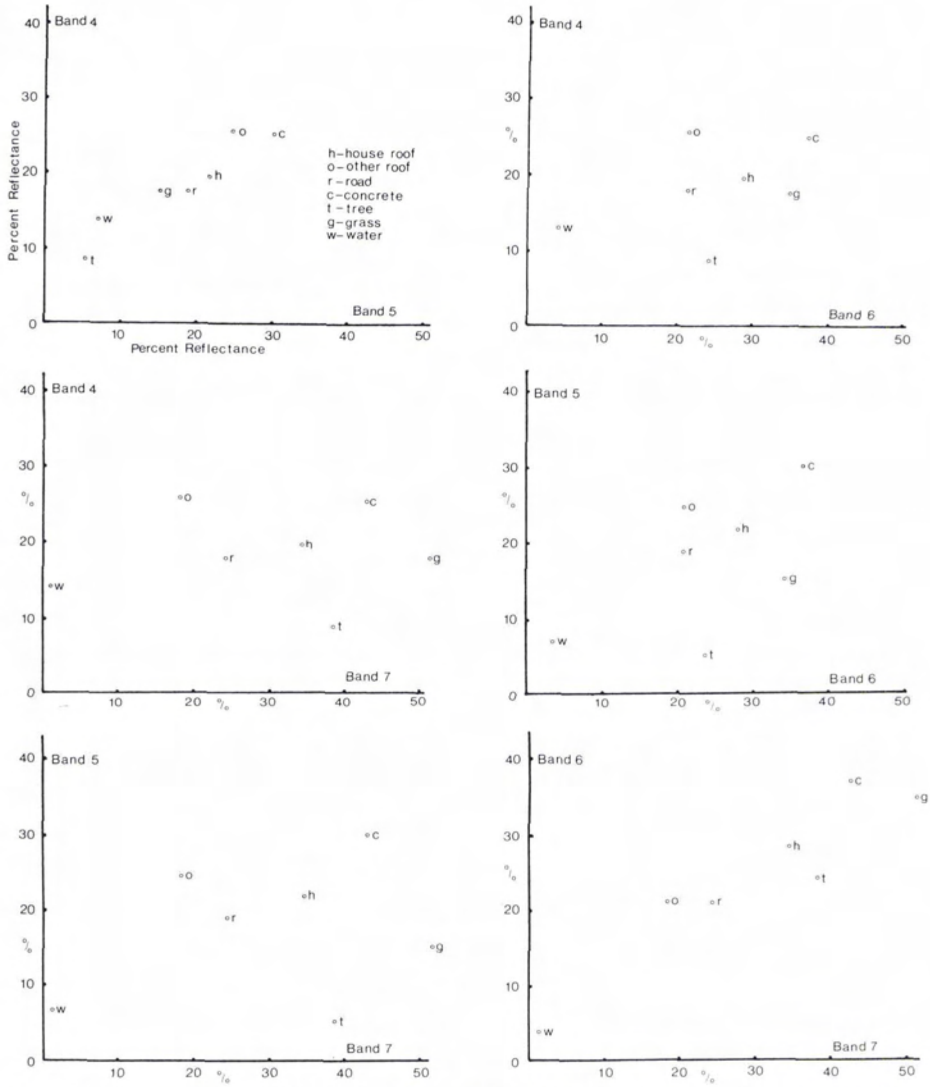

FIG. 4. Reflectance values for residential cover variables for all band combinations: (a) Band 4 and Band 5, (b) Band 4 and Band 6, (c) Band 4 and Band 7, (d) Band 5 and Band 6, (e) Band 5 and Band 7, (f) Band 6 and Band 7.

The relationship of physical cover data to the data normally required by planners and other urban professionals requires much further investigation, i.e., which of the cover variables explain or are surrogate variables of the urban residential character? Preliminary studies by the author indicate that property value, as a measure of residential quality, can be predicted from cover variables. The prediction of housing density also would appear feasible.

Two major orthogonal factors that are cited from factorial analysis of western, industrialized cities are family status and social status. These factors appear to be reflected in the physical environment of the Sydney urban area. Initial studies by the author show that percentage grass cover and percentage tree cover are uncorrelated and, thus, suggest themselves as surrogate variables for the orthogonal, family, and social status factors. Research into relationships of this type should be continued and extended.

The temporal variation of the reflectance of urban cover variables in the Australian environment requires further investigation, if actual land-use change is to be effectively monitored. Seasonal change in vegetation has caused problems in northern hemisphere urban studies because of the deciduous tree cover. This should not overly affect Australian studies because most vegetation is not deciduous; however, considerable seasonal variation in grass reflectance can occur.

The potential of satellite data for studies of urban areas would seem high, but as yet remains unproven. Further research and the introduction of higher resolution sensors should, however, lead to the realization of this potential.

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