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Remote Sensing of Salt Marsh Reclamation in the Wash, England[1]

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ABSTRACT

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Ground-based radiometry is used at a study site on the Wash estuary, England, to quantify the spectral reflectance properties of surfaces within the salt marsh environment. Measurements are made in four wave bands (465-515; 539-578; 622-664; and 778-975nm), which approximate bands 1-4 of the Landsat satellite Thematic Mapper. The aim of the study is to determine the spectral separability of the vegetation and sediment zones, and thereby evaluate the potential of remote sensing techniques for monitoring the effects of reclamation of salt marshes for agriculture. Results indicate that vegetated and non-vegetated zones may be separated into discrete units. Wavebands 622-664 and 778-975nm optimize separation of green vegetation groups, while 465-515 and 539-578nm enhance separation of non-vegetated surfaces.

ADDITIONAL INDEX WORDS: *Intertidal environments, reclamation, spectral reflectance, vegetation.*

INTRODUCTION

The salt marsh environment has been recognized as one of considerable physical, ecological, and recreational value. Salt marshes function as buffer zones between land and sea. They tend to ameliorate the adjacent land environment and act as sediment and nutrient traps. For such reasons they are attractive areas for shelter, feeding and breeding of diverse forms of wildlife.

Salt marshes support a wide variety of flora and fauna, but in an extremely dynamic and sensitive ecosystem. These areas are highly susceptible to disturbance brought about by conflicting land use activities, such as reclamation for agriculture and urban development, and as such require timely monitoring and careful management. Typically, salt marshes are difficult to access which makes ground monitoring and inventory a difficult and time-consuming process. Thus, the collection of data from airborne or satellite platforms is an attractive proposition.

Previous work has involved a qualitative interpretation of aerial photographs for delineation, classification, inventory, and monitoring of salt marsh vegetation communities. Black and white panchromatic and black and white infrared aerial photographs are frequently used by land resource management agencies. Color-infrared aerial photographs have also been used to yield qualitative information (*e.g.* HUBBARD and GRIMES, 1974). Satellite multispectral data have been used for plant community mapping, delineation of the wetland boundary, and monitoring the impact of man in the salt marsh environment (ANDERSON *et al.*, 1974; WIESBLATT, 1977). Often a multistage remote sensing approach is applied to the monitoring of tidal wetlands (DENNERT-MOLLER, 1977). More recently, effort has been directed towards the quantitative interpretation of remotely sensed data for the estimation of salt marsh biomass or primary productivity (BUDD and MILTON, 1982; BARTLETT and KLEMAS, 1979, 1980).

Exploratory studies directed at assessing the potential of the Landsat-4 Thematic Mapper for application to resource management indicate that the substantial increases, over the previous Landsat series, in spectral, spatial and radiometric resolution will especially benefit the monitoring of salt

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marsh because the ground resolution cell, or pixel, of 30 meters, is of the same order of magnitude as the vegetational zones of salt marshes within the Wash estuary, England.

STUDY OBJECTIVES

The overall objective is to determine the ability of remote sensing methods to distinguish between salt marsh and non-salt marsh vegetated and non-vegetated surfaces, and thereby monitor the effects of reclamation of salt marsh for agricultural extension. The aim of this preliminary study is, by ground-based radiometry, to determine quantitatively the spectral separability of vegetated and non-vegetated surfaces in, and bordering the salt marsh in four spectral regions (465-515, 539-578, 622-664, and 778-975nm) each at 1 m diameter spatial resolution. The measured ground reflectance values will then be used as a basis for determination of the optimum spectral bands for maximizing separation of salt marsh surfaces and reclaimed areas. These ground data will, in a subsequent study, assist in interpretation of Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) data.

STUDY AREA

The Wash is a large tidal embayment on the east coast of England (Figure 1) into which flow the rivers Great Ouse, Nene, Welland, and Witham. The Wash is characterized by shallow offshore topography and it provides a sheltered, low-energy environment in which large, destructive waves rarely occur. This environment favors sediment accretion.

Salt marsh development has been greatly influenced by land reclamation; 1245 km^2 of land has been reclaimed around the Wash margins since the 16th Century for agricultural purposes (COLLINS *et al.*, 1981). Enclosure of the upper areas of the salt marsh, through construction of a seabank, prevents inundation by sea water within the newly enclosed area and, by vegetation colonization to the seaward of the embankment, permits further seaward extension of the land.

Older sections of marsh are characterized by greater botanical and structural diversity, particularly in their upper reaches because they are subject to less frequent and shorter periods of tidal inundation. The salt marshes of the Wash are primarily important as wild fowl habitat. This area is the second most important in the United Kingdom and fourth most important in Europe for wading birds (NERC, 1976). Some species *e.g.* black-headed gulls (*Larus ridibundus*) nest regularly on the salt marsh, while others use the marshes for over-wintering, or as a resting site between north and south. Some of the birds feed directly on plants of the intertidal zone, the most important of which are *Enteromorpha*, *Salicornia* and seeds of *Aster*. Reclamation of land for agriculture has resulted in the systematic removal of vegetation and wildlife displacement. The reclaimed land is characterized by poor species diversity.

The selection of the study site at Butterwick Marsh (Figure 1) was based largely on accessibility. The development of Butterwick Marsh has been influenced by the construction of the 1971 seabank for reclamation by a local land-owner for agricultural use. The marsh consists of a series of vegetation zones which run approximately parallel to the shore, each containing distinct plant communities. Butterwick Marsh is relatively immature and as such has not developed a distinct upper marsh zone. Its upper margin is marked by the presence of a borrow pit which is dissected by a large creek. This represents the zone of excavation for bank material and is now a zone of accretion following stabilization. The borrow pit is characterized by rapid mud sedimentation and the presence of *Salicornia sp.* and *Puccinellia maritima*. Prominent vegetation species of the mid-salt marsh are *Halimione portulacoides*, *Puccinellia maritima*, *Aster tripolium*, and *Suaeda maritima*. *Halimione* dominates the creek sides and is significant in creek bank stabilization. *Puccinellia* and *Aster* are more common in the slightly lower-lying inter-creek areas. *Aster*, *Suaeda*, and *Puccinellia*, together with *Salicornia ssp.* are found in approximately equal proportions in the transition zone from mid-to lower-marsh. Small amounts of green algae are also present. The lower marsh, or pioneer zone, is dominated by the presence of *Salicornia*, which gives way to mud flat in its lower reaches. This zone consists of wet, fine-grained material which may have some brown algae cover, *Zostera*, and many pools of standing water. Stands of *Spartina townsendii* are infrequent at Butterwick. The sand flat was difficult to access and dangerous at Butterwick and additional sample points were established at Gibraltar Point (Figure 1) where reflectance data were collected from coarser sandy material of the sand flats and sand dunes.

FIELD METHODS

The spectral properties of specific vegetated and non-vegetated surfaces within and bordering the salt marsh were established through collection of surface

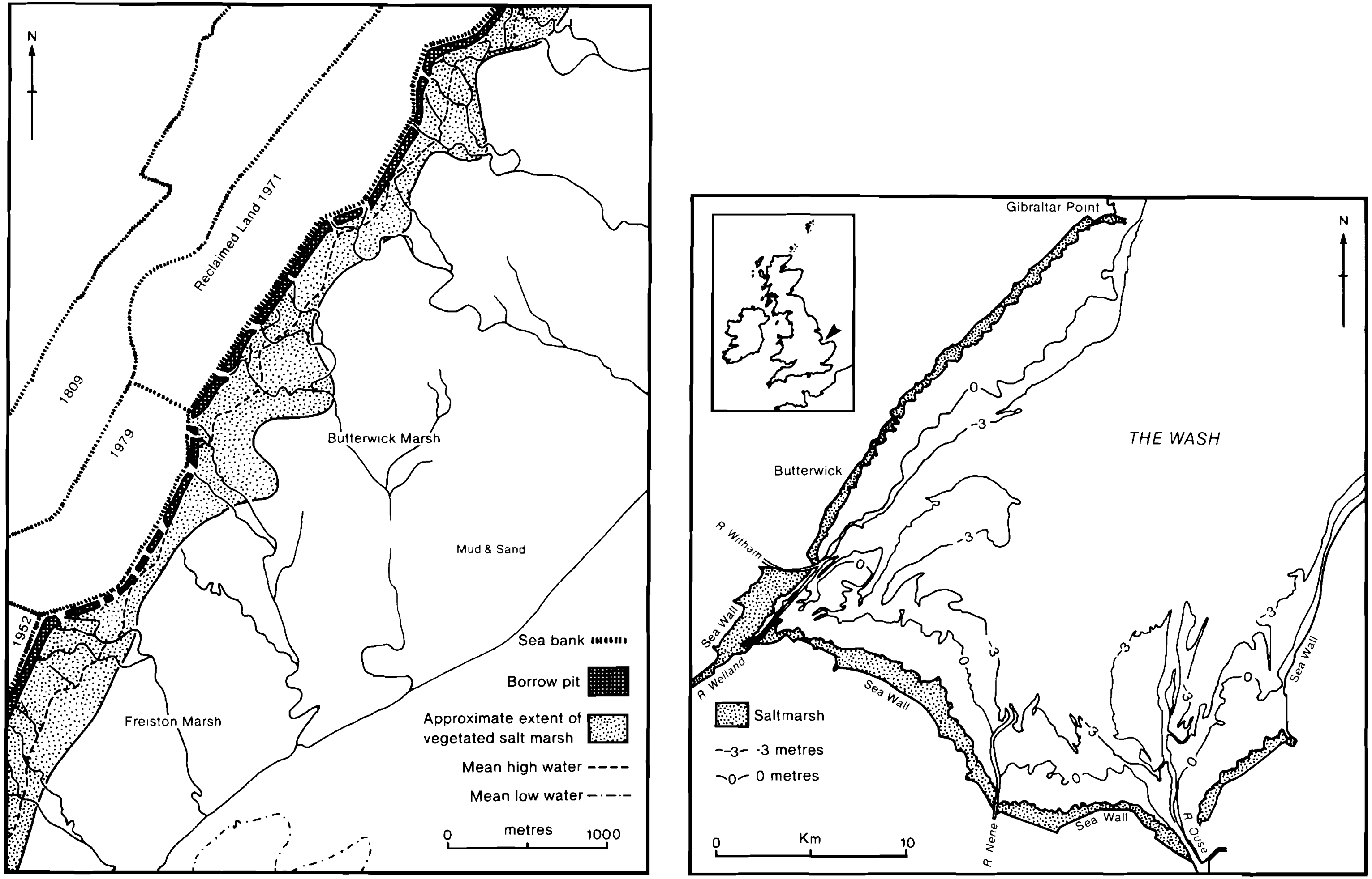

Figure 1. Location of the study area: Butterwick Marsh, Lincolnshire, UK (52° 59′; 0° 3′E).

type and radiance data at 1 m^2 scale using a 1 m^2 sampling grid and a portable Milton 4-band radiometer during July and September 1984. The Milton radiometer is comprehensively described in MILTON (1980). For the purpose of this study the sensor head was suspended from a vertical 2 m high aluminum mast in order to achieve an effective field of view of 1 m diameter. The four detector/filter combinations were configured to approximate the sensitivities of Landsat Thematic Mapper bands 1 to 4. (R1 = 465-515nm; R2 = 539-578nm; R3 = 622-664nm; R4 = 778-975nm; approximately equivalent to the blue, green, red, and near-infrared wavebands respectively). The system was standardized prior to each reading by sensing a Kodak grey reference card, which was removed from the field of view for sample measurement. However, variations are known to exist in the reflectivity of the grey card as a function of wavelength (MILTON, 1982). For this reason the grey card was standardized to a barium sulphate plate and the correction factor, $K\lambda$, was applied to the radiance data as follows:

Band (R)	$K\lambda$
R1	18.97
R2	19.15
R3	19.45
R4	22.06

The ratio of the flux reflected by the sample and that reflected by the grey card was calculated and the $K\lambda$ function applied, so as to reduce the effects of irradiance changes. This term is referred to as Bidirectional Reflectance Factor, BRF (ROBINSON and BIEHL, 1979):

$$Es/Ec \times K\lambda = BRF$$

Where: Es = radiance of sample
Ec = radiance of grey reflectance card
$K\lambda$ = correction factor

In addition, radiometer readings were repeated three times at each position to minimize the effects of fluctuations in incident radiation and recording error. Thus, a total of twelve readings were obtained at each sampling point.

Various ecologically distinct environments and salt marsh zones were identified and mapped. In each of the distinct salt marsh vegetational zones, a 30 m transect was established perpendicular to the shore. Radiometer measurements were taken at 2 m intervals along the 30 m transect and surface type descriptions were made at each of these points using a 1 m^2 grid which was subdivided into 25 equal units, thus allowing frequency estimations of vegetation cover, substrate, and standing water to be made. Where the environments or zones were less distinct and/or more homogeneous in terms of surface type the transect was not used but random points within that environment were sampled and described using the grid square and the radiometer as before. In total, 155 sample points were visited both within the salt marsh and in nearby agricultural land.

ANALYTICAL METHODS

Initially the 155 samples were classified into non-predetermined groups based on surface type, which was expressed as a percent of total cover within the 1 m sampling grid. Sixteen classes of surface type were identified and recorded as shown in Table 1. Other parameters were also recorded and were considered for the analysis of the reflectance data such as, the presence of silt on the leaves of some vegetation types, particularly *Salicornia* and *Puccinellia*, and coarseness, and, therefore, the water retention capacity of the sandflat.

Table 1. Sixteen Classes of Surface Type†.

Class	Surface Type
1.	*Salicornia*
2.	*Puccinellia*
3.	*Aster*
4.	*Halimione*
5.	*Suaeda*
6.	Mud
7.	Water
8.	Algae
9.	*Spartina*
10.	Sand
11.	*Spergularia*
12.	Seabank
13.	Field : Soil
14	Field : Barley
15.	Sand Dune
16.	*Zostera*

† Identified by field sampling.

A number of problems were caused by the distribution of the data because several types were recorded either as 0% or 100% cover (*e.g.* Seabank, Barley, Soil, Sand). The data relating to the sixteen surface types were positively skewed due to the number of 0% records. Neither the nature of the field sampling nor the distribution of the data justified the application of rigorous statistical classification techniques, therefore various statistical analyses already accepted in the ecological literature were employed. A decision was then made, essentially on subjective grounds, as to which method to accept. The main criterion was that greater weight should not be given to surface types which occur in low frequencies. Such indicators may be considered to be highly significant in the definition of ecological communities, but for the purpose of this study, the *a priori* decision was made that dominant surface types would dominate the radiance of a 1 m^2 surface.

Each of the vegetation data were transformed, following the recommendation of NOY-MEIR *et al.* (1975), using:

$$Y_{ik} = X_{ik}/q_i$$

where: Y_{ik} = transformed data score
X_{ik} = original data score for kth species in ith site.
q_i = sum of squares of x — scores for site

The site normalized analysis emphasizes the most widespread dominant surface types giving equal weight to each site, rather than allowing the most abundant types to dominate the results, as would occur with no transformation, or allowing species-rich sites to dominate the results, as would occur with transformation by species.

These transformed data were subjected to various clustering algorithms (minimum variance and nearest neighbor) using the euclidean measurement for the dissimilarity coefficient. These clustering processes were carried out using the MIDAS (FOX and GUIRE, 1976) statistical package (Minkowski(2) was used as the correct dissimilarity coefficient because the euclidean option in MIDAS does not provide the generally accepted definition of euclidean distance). The transformed data were also ordinated using Principal Components Analysis (PCA) based on the variance-covariance matrix and then clustered using the clustering algorithms described above.

These analyses revealed a relatively robust set of groupings from which the results of the minimum variance cluster analysis (Ward's method) were taken as the final groups. The decision behind this final grouping was ultimately subjective, although the following criteria were considered important: first, the use of the variance algorithm gave weight to the dominant surface types rather than the low frequency types. Second, there were relatively even-sized groups produced where required (*i.e.* where the grouping was not predetermined by a series of 100 percent surface type, 4 cases). Third, and perhaps most important, the groups were sensible. The similarities between the major vegetation groups as defined by the minimum variance (MINVAR) clustering method are summarized by the dendrogram in Figure 2. In the first instance the clustering procedure was performed using all the data (155 sites). The procedure was then repeated using data from 124 sites, which excluded those sites where the surface consisted of a single cover type (*i.e.* Seabank; Field: Soil; Field: Barley; and Sand Dune). Identical clusters were produced with both data sets but clearly the levels at which the single cover type groups join the dendrogram, in the first case, are of no significance. Thus, the dendrogram for the 124 sites was selected for illustration of the vegetation clusters produced by MINVAR. The main features of each of the final groupings are summarized in Table 2.

The PCA did not improve the interpretation of the groupings. The first few principle components showed high loadings for surface types which recorded either 0 or 100 percent. In order to include the majority of the surface types, 14 out of 16 principle components had to be considered and therefore classification of these effectively duplicated the minimum variance cluster analysis of the transformed data.

The third method of surface group determination employed was the Two-Way Indicator Species Analysis, TWINSPAN (HILL, 1979). This is a divisive method of classification based on the classification of the samples in the first instance and then on species classification according to their ecological preferences. The data were weighted using "pseudo-species," *i.e.* different quantitative values were used as "different" species and as indicators. Thus, to give weight to low frequency indicators which may be of ecological significance 0%, 5%, 26%, 51%, and 76% levels would be applied. For the purpose of classification according to reflectance properties levels 0%, 21%, 41%, 61%, and 81% were considered more appropriate. Due to the utilization by TWINSPAN of low frequency values, the groups Mud and *Salicornia*, and Water and Mud were divided into two separate groups.

Differences found between MINVAR and TWINSPAN are summarized in Table 3. The main discrepancies occur in the classification of sites with greatest richness, because the dichotomies in TWINSPAN were defined by the pseudospecies levels. The table indicates that many of the cases that classified differently are those having max-

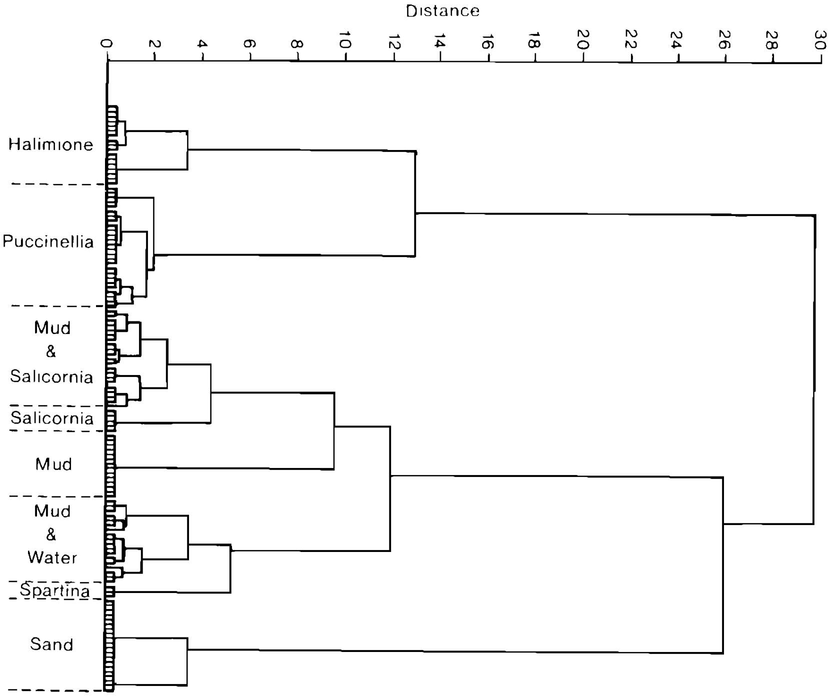

Figure 2. Dendrogram of the results of a minimum variance cluster analysis of vegetation types according to their surface cover (%) in the intertidal environment.

imum or minimum values for that class, and thus, are most likely to change class when an alternative classification procedure is applied.

RESULTS

Figures 3a and 3b show the generalized reflectance curves for vegetated and non-vegetated surface types. It may be seen that the groups are separable, to a greater or lesser extent, on the basis of their characteristic reflectance spectra. Typically the green vegetation exhibits reduced reflectance at 463-515 and 622-664nm, which represents absorption by chlorophyll a and b of blue and red light. The slight visual peak at 539-578nm represents reflectance of energy in the green portion of the spectrum, hence the green appearance of most plants. There is a considerably higher reflectance peak at 778-975nm, due to near-infrared reflectance by refractive-discontinuities at the cell wall-airspace interface of the mesophyll cells of leaves (GAUSMAN, 1977). Reflectance levels vary according to a complex of factors, of which species is one and it is this which enables us to discriminate between vegetation species. The reflectance curves of non-vegetated surfaces are typically flatter than those of vegetated surfaces. They differ as a function of particle size, moisture status and mineral/organic content. Figure 3b indicates that the dry sand flat readings were higher in each waveband than wet sandflat and mud flat readings. This is largely due to absorption by water of all visible wavelengths and particularly of infrared. Thus, for all subsequent analyses of the reflectance data the sandflat data were subdivided into the two groups.

The descriptive statistics (Table 4) and the scatterplots (Figure 4a and 4b) of the raw data indicate that the highest variance occurs in data collected in the infrared portion of the spectrum. The data collected in the visible wavelengths are highly correlated. However, inspection of Figures 3a, b and 4a, b reveals that some information relating to the discrimination of surface types may be gained by using combinations of all four bands rather than just the R3 and R4 which reveal the greatest separation for any combination of two bands.

Table 2. Summary of the Main Features of Each of the Final Surface Groups.

Group	Number†		MIN%	MAX%	MEAN%
1. Field: Soil	3	Soil	100	100	100
2. Field: Barley	3	Barley	100	100	100
3. Seabank	20	Seabank	100	100	100
4. *Halimione*	17	*Aster*	0	12	4.5
		Halimione	40	97	65.8
		Suaeda	0	10	2.6
		Mud	0	5	0.9
		Salicornia	0	1	0.1
		Puccinellia	2	53	26.1
5. *Puccinellia*	26	*Aster*	0	25	9.7
		Halimione	0	26	5.0
		Suaeda	0	25	7.1
		Mud	0	20	3.0
		Water	0	20	1.7
		Spergularia	0	4	0.2
		Salicornia	0	35	7.3
		Puccinellia	35	92	65.5
		Algae	0	8	0.5
6. Mud and *Salicornia*	21	*Aster*	0	4	1.0
		Suaeda	0	8	2.5
		Mud	24	75	44.0
		Water	0	25	3.5
		Salicornia	2	50	32.0
		Puccinellia	0	24	2.9
		Algae	0	30	14.9
7. Water and Mud	18	*Aster*	0	7	0.6
		Mud	0	64	26.6
		Water	30	100	53.6
		Salicornia	0	30	10.0
		Puccinellia	0	25	4.1
		Algae	0	34	5.1
8. Mud	14	Mud	85	100	97.5
		Water	0	15	2.5
9. *Spartina*	3	*Aster*	0	2	1.3
		Spartina	80	98	92.0
		Water	0	20	6.7
10. Sandflat	20	Water	0	50	8.5
		Sandflat	50	100	90.7
		Zostera	0	5	0.8
11. Sand Dune	5	Sand Dune	100	100	100
12. *Salicornia*	5	Mud	3	15	9.6
		Water	0	10	3.0
		Salicornia	80	95	87.0
		Puccinellia	0	2	0.4

†Number of cases in group.

Principal Components Analysis (PCA) has frequently been applied (*e.g.* BUDD and MILTON, 1982; SINGH and HARRISON, 1985) to assist interpretation of remote sensing data. PCA was performed using both the correlation matrix and the variance-covariance matrix. The results of which are presented in Table 5.

Scatterplots were inspected for each combination of bands in which ground reflectance data were collected and each combination of PC's 1-4 (Figures 5a and 5b). Because the first two principal components, using both the correlation and the variance-covariance matrix, contribute over 98% of the total variance and given the loadings shown in Table 5 and that bands 1, 2, and 3 are highly correlated, it is not surprising that the plots of PC1 vs PC2, for both methods of PCA, and the plots of the raw data are very similar. The PCA effectively condenses the information from four spectral bands into two new variables but apparently offers little to enhance the separation of groups beyond the combination of raw data collected in the R3 and R4.

Of the eleven sites which were classified differently by MINVAR and TWINSPAN (Table 3), nine

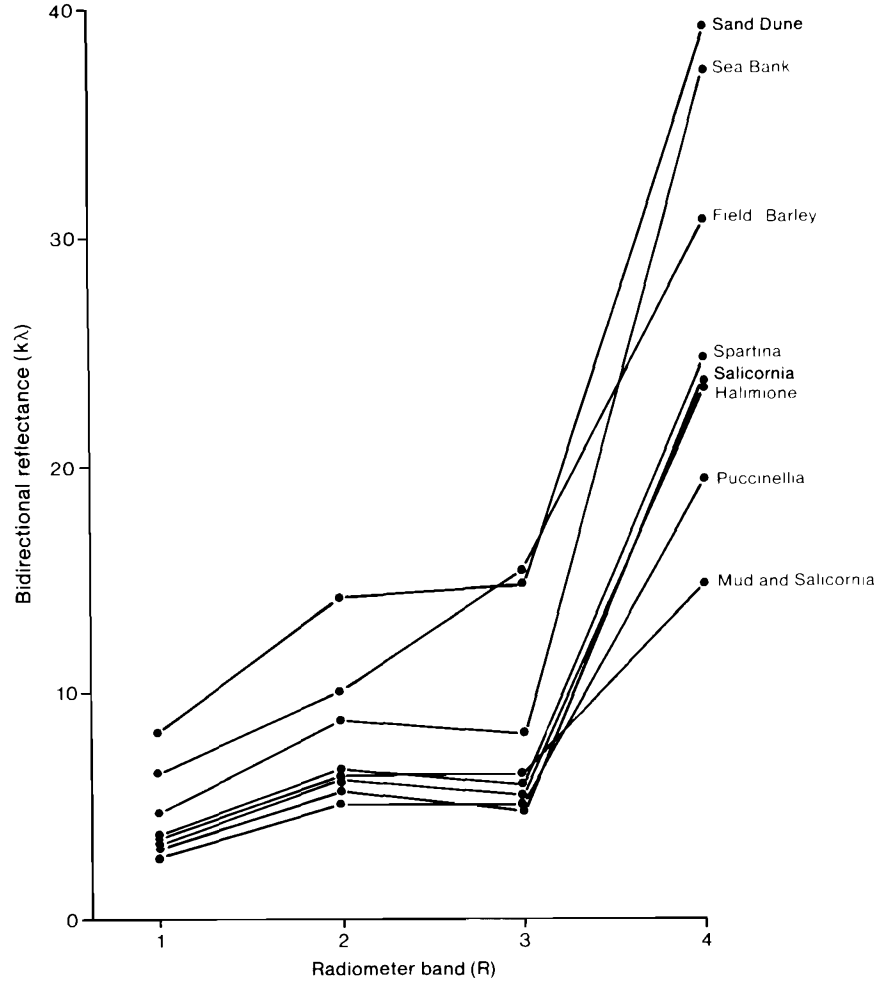

Figure 3a. Generalized reflectance curves of vegetated surface groups in and bordering the salt marsh. Refer to text for bandwidth of radiometer bands R1-4.

form either outliers, on figures 5a, b, from the main cluster or are at the edge of the cluster for their group as defined by MINVAR.

Thus, the difficulty, and also the subjectivity, of grouping a transitional change in vegetation assemblages is equally expressed in the ground reflectance data. From both the raw and ordinated reflectance data the following groups may be distinguished, although there is some overlap at the boundaries: Field:Soil; Field:Barley; Sand Dune; Dry Sand Flat; and Seabank. *Salicornia* and *Spartina* appear indistinguishable from *Halimione*. It should, however, be stated that only three sites of *Spartina* were measured, due to infrequent presence of this group. There is some overlap between *Halimione* and *Puccinellia*, but these groups are separable for the main part. Apart from the outliers identified, the Mud and *Salicornia* group apppears as a cluster. The main zone of overlap of the original groups is as follows: Wet Sand/Mud and Water/Mud.

Canonical variates analysis (CVA) is a method by which differences among the means of a number of groups, for which several variables have been measured, may be examined (BLACKITH and REYMENT, 1971; CHATFIELD and COLLINS, 1980). The computations for canonical variates are similar to those for principal components. Transformed axes are produced, where the first axis is aligned to

Table 3. Summary of Differences Between MINVAR and TWINSPAN

MINVAR	TWINSPAN	Site		% Surface Cover†					
Halimione			Group =	40-97 H	2-53 P	0-12 As	0-10 Su	0-5 M	
	P	22		40 H	53 P	4 As	1 Su	2 M	
	P	114		40 H	47 P	7 As	6 Su		
Puccinellia			Group =	0-35 Sa	35-92 P	0-20 M	0-20 W		
	M & Sa	40		15 Sa	72 P	12 M	1 W		
	M & Sa	44		35 Sa	35 P	20 M	10 W		
	M & Sa	45		8 Sa	60 P	12 M	20 W		
Mud & *Salicornia*			Group =	2-50 Sa	24-75 M	0-25 W			
	Sa	35		0-50 Sa	25 M	25 W			
Water & Mud			Group =	0-30 Sa	0-64 M	30-40 W	0-25 P	0-7 As	0-34 Al
	M & Sa	36		10 Sa	60 M	30 W			
	M & Sa	43		10 Sa	35 M	30 W			
	M & Sa	63		19 Sa	9 M	40 W	2 P	1 As	19 Al
	M & Sa	105		22 Sa	18 M	34 W	4 P	7 As	15 Al
	M & Sa	106		30 Sa	14 M	38 W	2 P	1 As	14 Al

† The first row indicates the range of surface cover (%) for each group (defined by MINVAR), while subsequent rows indicate the surface cover (%) of those sites classified differently by TWINSPAN.

Al = Algae; As = Aster; H = *Halimione*; M = Mud; P = *Puccinellia*; Sa = *Salicornia*; Su = *Suaeda*; W = Water.

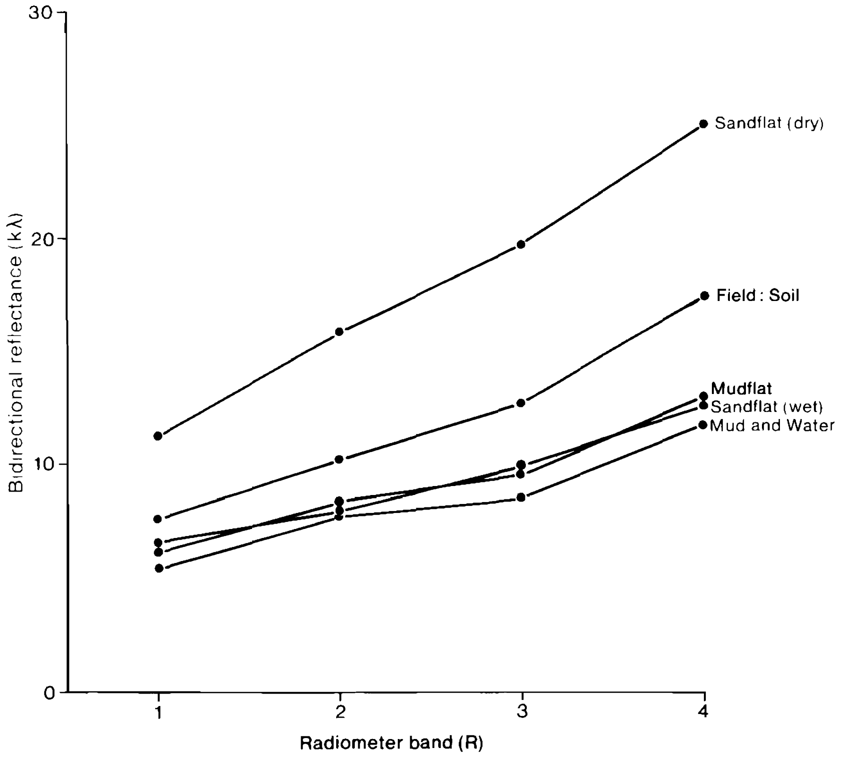

Figure 3b. Generalized reflectance curve of non-vegetated surface groups in and bordering the Salt Marsh. Refer to text for bandwidth of radiometer bands R1-4.

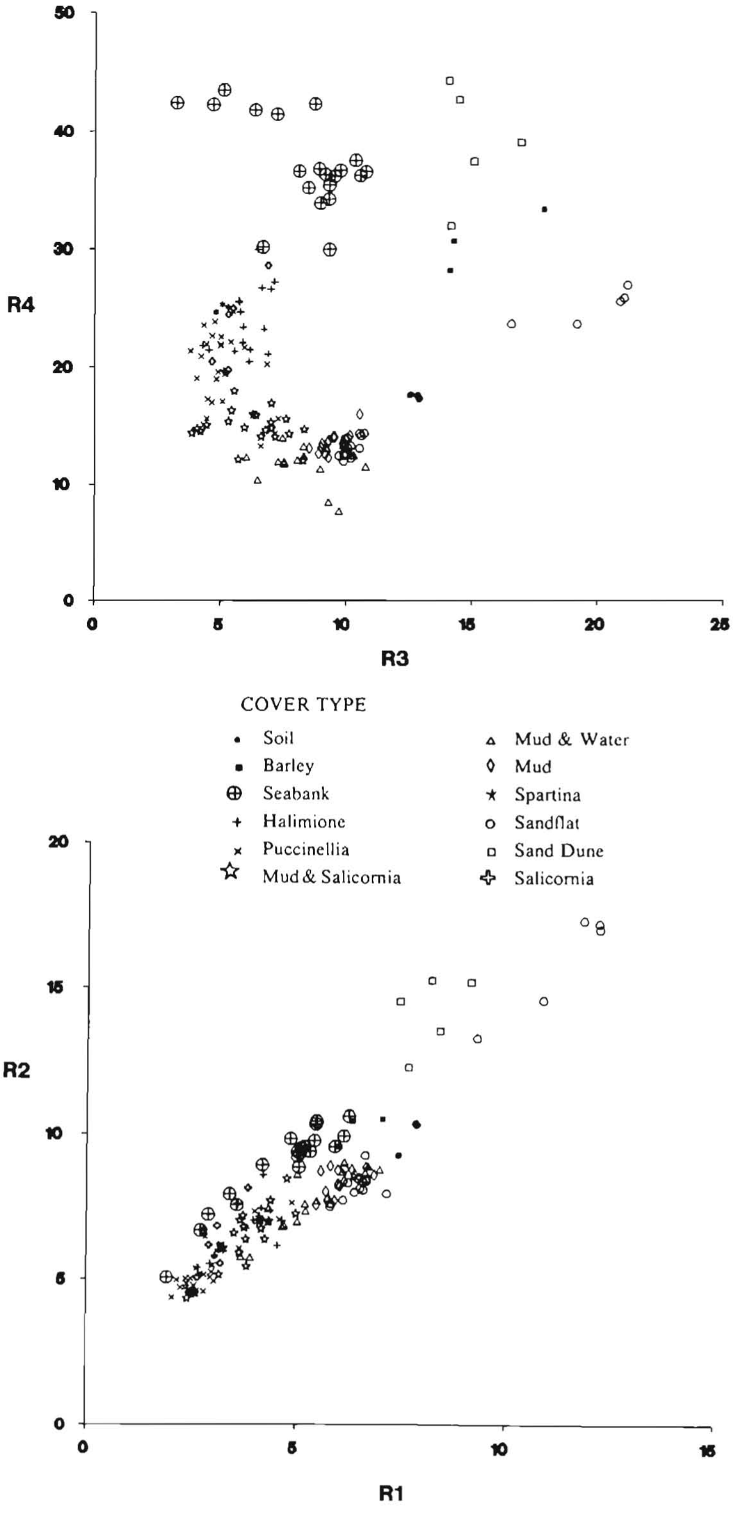
R4
50
40
30
20
10
0
0
5
10
15
20
25
R3
COVER TYPE
• Soil
▪ Barley
⊕ Seabank
+ Halimione
× Puccinellia
☆ Mud & Salicornia
△ Mud & Water
◊ Mud
★ Spartina
○ Sandflat
□ Sand Dune
✣ Salicornia
R2
20
15
10
5
0
0
5
10
15
R1

Figure 4. (Facing page) Scatterplot of the bidirectional reflectance values of saltmarsh surfaces (a) Band R3 (= red) data plotted against Band R4 (= infrared) data and (b) Band R1 (= blue) data plotted against Band R2 (= green) data. The 12 groups are those shown in Table 2.

Table 4. Descriptive Statistics for Ground Reflectance Data.

(nm)	Minimum (kλ)	Maximum (kλ)	Mean (kλ)	σ	Skewness
R1	1.92	12.19	4.86	2.00	1.11
R2	4.26	17.34	7.74	2.56	1.49
R3	3.24	21.12	8.20	3.48	1.48
R4	7.69	44.23	20.77	9.99	1.01

Correlation Matrix

	R1	R2	R3	R4
R1	–			
R2	0.91	–		
R3	0.96	0.94	–	
R4	0.03	0.34	0.15	–

Covariance Matrix

	R1	R2	R3	R4
R1	3.99			
R2	4.68	6.58		
R3	6.70	8.37	12.14	
R4	0.50	8.32	4.69	80.86

R1 = (465-515)
R2 = (539-578)
R3 = (622-664)
R4 = (778-975)

Table 5. PCA Results for the Ground Reflectance Data.†

(a) Correlation Matrix

	(nm)	PC1	PC2	PC3	PC4
R1	(465-515)	0.56	−0.25	0.11	0.78
R2	(539-578)	0.58	0.10	0.66	−0.47
R3	(622-664)	0.57	−0.13	0.73	−0.35
R4	(778-975)	0.16	−0.96	0.14	0.21
Total Variance %		73.13	25.28	0.98	0.61

(b) Variance-Covariance Matrix

	(nm)	PC1	PC2	PC3	PC4
R1	(465-515)	0.02	0.43	0.21	0.88
R2	(539-578)	0.12	0.50	0.74	−0.43
R3	(622-664)	0.08	0.74	−0.63	−0.21
R4	(778-975)	0.99	−0.13	−0.41	−0.05
Total Variance %		79.43	20.12	0.33	0.12

†Loadings of original variables for each Principle Component using (a) correlation matrix and (b) variance-covariance matrix.

indicate the greatest variability between means of the groups. The second axis is perpendicular to the first and is inclined in the direction of the next greatest variability (BLACKITH and REYMENT, 1971). The groups used are those defined by analysis of the vegetation and surface data. Canonical variates analysis may be employed as a discrimination technique to assess the numerical differentiation of the groups by use of the available reflectance data. In further analyses, unassigned cases could be allocated to the group with the nearest mean value. To test the significance of the separation between any pair of groups, it is assumed that the variables are normally distributed within each group and that the variance-covariance matrices of the groups are equal (BLACKITH and REYMENT, 1971; DAVIS, 1973). Furthermore, a logical prerequisite is that the groups are indeed separate (MATHER, 1976).

The data analysis was carried out by the CANVAR2 program of BLACKITH and REYMENT (1971) as modified by H.J.B. Birks (pers. comm., 1985). Not all the assumptions about the data may be tested. Tests for multivariate normality are not well-developed (MATHER, 1976) and because the group sizes vary between 3 and 26 cases, normality should not be accepted without reservation. Summary statistics for each variable in each group (*i.e.* reflectance measured in each spectral band) indicate that the worst measure of skewness is −1.38, although most values lie between +1.0 and −1.0.

The program was unable to perform the test of homogeneity of covariance matrices given the condition that the number of groups less one was greater than the number of variables. Some tests were carried out to investigate the situation where the number of groups equalled the number of variables (*i.e.* 4). The chi-squared test revealed that, in such cases, the assumption of homogeneity of dispersion matrices was valid. The equality of the means in each group is tested by the Wilks-Lambda criterion. In each analysis the null hypothesis could be rejected at the 0.01% level, *i.e.* it could be assumed that the group means were indeed different.

Although all the statistical requirements of the method could not be evaluated, most authors tend to agree that even moderate departures from the assumptions will not seriously affect the discrimininant functions (BLACKITH and REYMENT, 1971; DAVIS, 1973; MATHER, 1976). In the first case, CVA was carried out on the thirteen groups identified by the previous analyses, with the sand flat being treated as two groups, broadly described as wet sandflat and dry sandflat. Sixty-two percent of the total variance is explained by the first canonical variate and 29 percent is explained by the second (Table 6). Nevertheless, the third and fourth canonical variates should not be ignored because

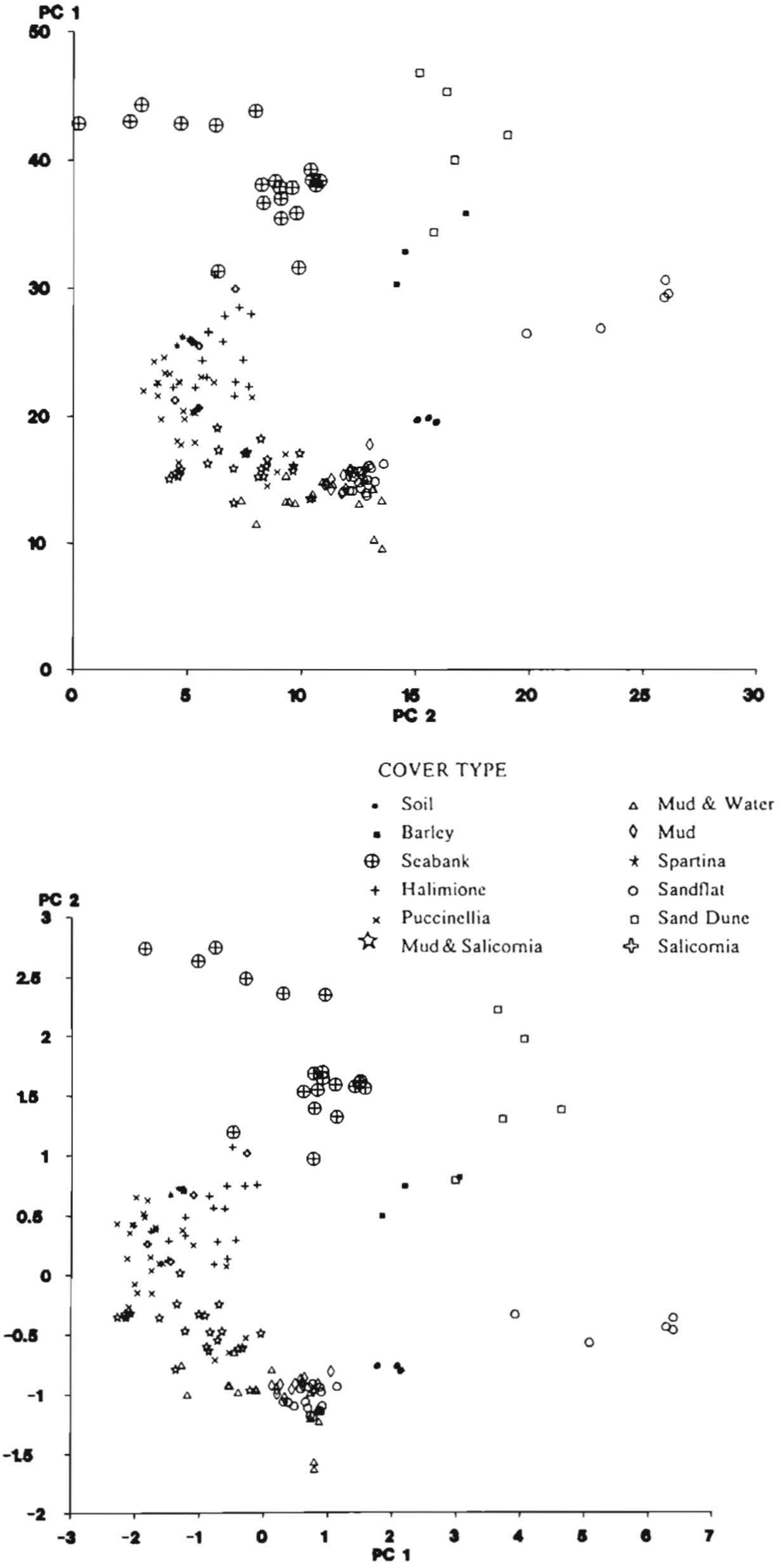
PC 1
50
40
30
20
10
0
0
5
10
15
20
25
30
PC 2
COVER TYPE
• Soil
▪ Barley
⊕ Seabank
+ Halimione
× Puccinellia
☆ Mud & Salicornia
△ Mud & Water
◊ Mud
★ Spartina
○ Sandflat
□ Sand Dune
✧ Salicornia
PC 2
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-3
-2
-1
0
1
2
3
4
5
6
7
PC 1

Figure 5. (Facing page) The reflectance data plotted on the first two principal components, using (a) the variance-covariance matrix and (b) the correlation matrix.

BLACKITH and REYMENT (1971) claim that canonical discriminators with small latent roots may be efficient identifiers. Data collected at 622-664nm and 778-975nm wavelengths contribute most to the first two canonical variates. On the first variate, both the wavebands combine to aid discrimination between the groups, on the second the 622-664nm data are most influential. The correlations between the original variables and the canonical variates help to explain the similarities between the plots of the transformed individual scores on the first two canonical variates (Figure 6) and the plots of the reflectance data (Figures 4a, b) and the first two principal components (Figures 5a, b). The orientation of these axes differ but the relative locations of the groups on the graphs are essentially similar.

The efficiency with which the discriminant function separates the thirteen groups using the transformed data may be assessed in numerous ways. First, by visual interpretation of the six plots of transformed scores using each of the pairs of canonical variates. It remains difficult to represent on a series of two-dimensional plots the separation of groups which lie on four separate axes. Figure 6 shows a number of mutually exclusive groups and also some (the main inter-tidal groups) which exhibit varying degrees of overlap when the range of each group is considered. The main feature of the third canonical variate is the separation of the mature barley crop from the rest of the sample points. The *Halimione* and Seabank groups are also shown to be mutually exclusive.

Table 6. Results of CVA for 13 Groups and 4 Reflectance Bands.

		CV1	CV2	CV3	CV4
A.		62.3	28.7	6.6	2.4
B.	R1	−0.01	0.03	0.61	0.67
	R2	0.23	−0.39	0.29	−0.71
	R3	−0.62	0.89	−0.74	−0.03
	R4	−0.75	−0.23	0.00	0.17
C.	R1	−0.42	0.84	0.34	−0.01
	R2	−0.69	0.61	0.31	−0.24
	R3	−0.55	0.82	0.11	−0.09
	R4	−0.91	−0.42	−0.01	0.01

A. % Total Variance Explained.
B. Standardized Canonical Coefficients.
C. Correlations Between Original Variables and Canonical Variates.

Table 7. Significance levels (>0.01) for the rejection of the null hypothesis of no difference between multivariate means based on canonical variates analysis for group pairs taken from the 13 original groups.

Groups	Significance Level
Halimione v *Spartina*	0.72
Halimione v *Salicornia*	0.14
Water & Mud v Mud	0.03
Mud v Wet Sand	0.10
Spartina v *Salicornia*	0.55

The second method involves use of the distance between the multivariate means of each pair of groups. The distance measure is referred to as the Mahalanobis distance. The significance of the separation of the two means may be assessed using an F-test.

Of the thirteen groups used in the analysis, those pairs for which the null hypothesis is rejected at a significance level of 0.01 (1%) or higher, are shown in Table 7. The significance levels shown in Table 7 give one indication of the efficiency of the analysis in discriminating between groups. These levels should be interpreted with caution due to the problems discussed earlier regarding the assumptions required of these data. Inspection of the plot of the data on CV1 and CV2 (Figure 6) and the significance levels shown in table 7 reveals that, while some of the groups have statistically separate multivariate means, based on the four canonical variables obtained from the surface reflectance data, there is some overlap associated with outliers from each group. The *Spartina* and *Salicornia* groups are clearly indistinguishable from the *Halimione* group.

The efficiency of the discrimination analysis can be further investigated using the Mahalanobis distance and F-test for each case to each group. Each of the 155 cases are then classified into groups according to these measures. The results are summarized in Table 8. These values were obtained using the stepwise discriminant analysis in the BMDP package (DIXON, 1983).

A significant difference between the multivariate means of groups does not indicate that there will be no overlap of the groups when plotted on the canonical variates. Generally, the lowest values for "Percent Correctly Classified" are for the same groups indicated in the table of significance levels (Table 7) — but any single case can only be assigned into one group. Therefore, where two or more groups have similar multivariate means the figures for the misclassification of cases (Table 8) will not show

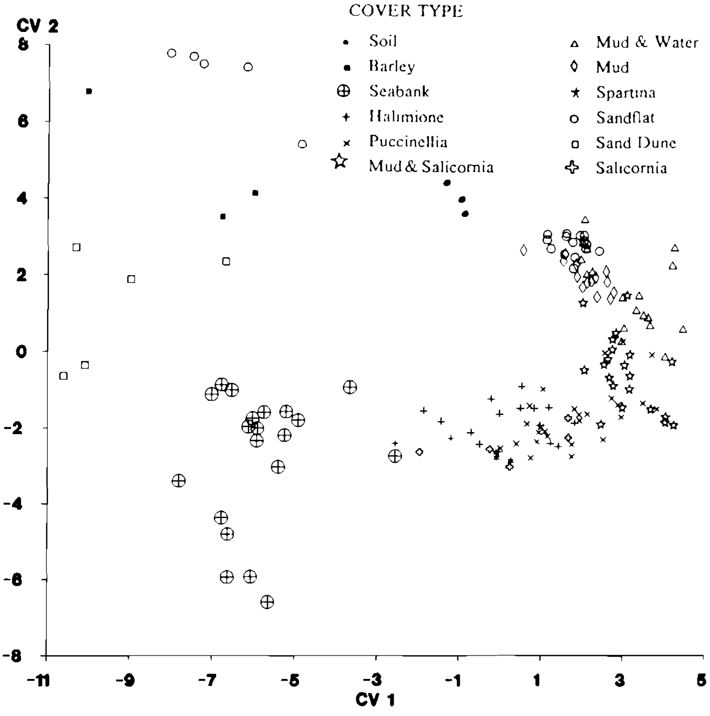

Figure 6. The reflectance data plotted on the first two canonical variates.

Table 8. Classification Matrix†.

Group	No.‡	%°	Number of Cases Classified into Groups F:S	F:B	S	H	P	M&Sa	W&M	M	Sp	WS	DS	SD	Sa
Field: Soil	3	100	3	0	0	0	0	0	0	0	0	0	0	0	0
Field: Barley	3	100	0	3	0	0	0	0	0	0	0	0	0	0	0
Seabank	20	95	0	0	19	0	0	0	0	0	0	0	0	0	1
Halimione	17	47	0	0	0	8	5	0	0	0	1	0	0	0	3
Puccinellia	26	65	0	0	0	1	17	2	2	0	0	0	0	0	4
Mud & *Salicornia*	21	95	0	0	0	0	0	20	1	0	0	0	0	0	0
Water & Mud	18	44	0	0	0	0	0	4	8	4	0	2	0	0	0
Mud	14	71	0	0	0	0	0	0	2	10	0	2	0	0	0
Spartina	3	100	0	0	0	0	0	0	0	0	3	0	0	0	0
Wet Sand	15	80	0	0	0	0	0	0	0	3	0	12	0	0	0
Dry Sand	5	100	0	0	0	0	0	0	0	0	0	0	5	0	0
Sand Dune	5	100	0	0	0	0	0	0	0	0	0	0	0	5	0
Salicornia	5	60	0	0	0	0	2	0	0	0	0	0	0	0	3
Total	155	75	3	3	19	9	24	26	13	17	4	16	5	5	11

† Based on discriminant analysis of the reflectance data from the 155 cases and the 13 predetermined surface groups.

‡ Number of cases in group.

°Percent correctly classified.

F:S = Field: Soil; F:B = Field: Barley; S = Seabank; H = *Halimione*; P = *Puccinellia*; M&Sa = Mud & *Salicornia*; W&M = Water & Mud; M = Mud; Sp = *Spartina*; WS = Wet Sand; DS = Dry Sand; SD = Sand Dune; Sa = *Salicornia*.

Table 9. Classification Matrix.†

			Number of Cases Classified into Groups										
Group	No.‡	%°	F:S	S:B	S	H	P	M&Sa	W&M	M	WS	DS	SD
Field: Soil	3	100	3	0	0	0	0	0	0	0	0	0	0
Field: Barley	3	100	0	3	0	0	0	0	0	0	0	0	0
Seabank	20	95	0	0	19	1	0	0	0	0	0	0	0
Halimione	25	72	0	0	0	18	7	0	0	0	0	0	0
Puccinellia	26	73	0	0	0	3	19	2	2	0	0	0	0
Mud & *Salcornia*	21	95	0	0	0	0	0	20	1	0	0	0	0
Water & Mud	18	44	0	0	0	0	0	4	8	4	2	0	0
Mud	14	71	0	0	0	0	0	0	2	10	2	0	0
Wet Sand	15	80	0	0	0	0	0	0	0	3	12	0	0
Dry Sand	5	100	0	0	0	0	0	0	0	0	0	5	0
Sand Dune	5	100	0	0	0	0	0	0	0	0	0	0	5
Total	155	79	3	3	19	22	26	26	13	17	16	5	5

† Based on discriminant analysis of the reflectance data from the 155 cases and 11 surface groups. *Halimione* includes the *Spartina* and *Salicornia* cases.

‡ Number of cases in group.

°Percent correctly classified.

F:S = Field: Soil; F:B = Field: Barley; S = Seabank; H = *Halimione*; P = *Puccinellia*; M&Sa = Mud & *Salicornia*; W&M = Water & Mud; M = Mud; WS = Wet Sand; DS = Dry Sand; SD = Sand Dune.

clearly how the efficiency of the analysis may be improved. This may be achieved by comparing the results from Figure 6 and Tables 7 and 8. The discriminant analyses were repeated using eleven surface groups, with *Spartina* and *Salicornia* cases included in the *Halimione* group. The matrix (Table 9) reveals an improvement in the classification of cases based on the discriminant functions. Those groups not from the inter-tidal zone, *i.e.* Field: Soil, Field: Barley, Seabank, and Sand Dune, are mutually exclusive (only one misclassification) and also distinguishable from all the inter-tidal groups. The three vegetated inter-tidal groups, *Halimione* (including *Spartina* and *Salicornia*), *Puccinellia* and Mud and *Salicornia*, can be discriminated with reasonable success (all>70% correctly classified). The most difficult groups to differentiate are those characterized by wet, unvegetated surfaces: Water and Mud, Mud, Wet Sand.

The clearly distinguishable non inter-tidal groups were removed from the analysis to determine if the discriminating power of the four canonical variates could be enhanced. The analyses were repeated for the nine inter-tidal groups (*Halimione, Puccinellia*, Mud and *Salicornia*, Mud and Water, Mud, *Spartina*, Wet Sand, Dry Sand, *Salicornia*) and then for seven inter-tidal groups (as above but with *Spartina* and *Salicornia* included in the *Halimione* group again). The results show marginal improvement in the ability to distinguish between the wet inter-tidal non-vegetated surfaces. These are illustrated in Table 10.

It has been noted throughout the analyses that the combination of the R3 and R4 data dominate the results. In order to examine this effect more closely the discrimination function was limited to a consideration of the data from only these two wavebands. The CVA and stepwise discriminant analyses were repeated for 13, 11, 9, and 7 groups. In every case the results show that the use of the reflectance data from four bands enhances the overall discrimination compared to just using two bands. Consistently there is an improvement of 15-19% correctly classified for the *Puccinellia* group, 10-14% for the Mud & *Salicornia* group and 14% for the Mud group. Only the Wet Sand group is less well classified, by 13%.

DISCUSSION

The vegetated marsh is clearly distinguishable from the non-vegetated, and there is little chance of mis-classification at the boundaries. Especially because the zones of overlap contain those individuals most likely to have been grouped differently if an alternative classification procedure is used. For example, the major outliers identified from the *Puccinellia* group, which overlap with the Mud and *Salicornia* group when CVA is applied to 13 groups/4 variables, are cases 40, 44, and 45 which are those classified differently by MINVAR and TWINSPAN analyses of the vegetational groups. Separation of vegetated from non-vegetated marsh will be most effective using imagery acquired in late

Table 10. Classification Matrix†.

Group	No.‡	%°	H	P	M&Sa	W&M	M	WS	DS
Halimione	25	72	18	7	0	0	0	0	0
Puccinellia	26	69	4	18	4	0	0	0	0
Mud & *Salicornia*	21	91	0	0	19	1	1	0	0
Water & Mud	18	56	0	0	2	10	4	2	0
Mud	14	71	0	0	0	2	10	2	0
Wet Sand	15	87	0	0	0	0	2	13	0
Dry Sand	5	100	0	0	0	0	0	0	5
Total	124	75	22	25	25	13	17	17	5

† Based on discriminant analysis of the reflectance data from 124 cases and 7 surface groups. *Halimione* includes the *Spartina* and *Salicornia* cases.

‡ Number of cases in group.

°Percent correctly classified.

H = *Halimione*; P = *Puccinellia*; M&Sa = Mud & *Salicornia*; W&M = Water & Mud; M = Mud; WS = Wet Sand; DS = Dry Sand

summer (September), when the transition zone contains mature *Salicornia*. By September the *Salicornia* zone is indistinguishable in spectral terms from the mid-marsh, or *Halimione* group; whereas in July the *Salicornia* zone is classified as Mud and *Salicornia*, according to the MINVAR and TWINSPAN analyses. The Mud and *Salicornia* group reveals some outliers overlapping with the non-vegetated sites (Figure 6) whereas the *Halimione* group is mutually exclusive from them.

Sites where 5-35% *Salicornia* was recorded in July showed 90-100% cover in September. Thus, comparison of July and September images are required to assess the extent of the *Salicornia* zone, or pioneer marsh, by subtraction.

The reflectance values of *Puccinellia* range from *Halimione* to Mud. A likely explanation for this phenomenon is that this group was marked by varying degrees of silt cover on the foliage. Thus, it may be expected to exhibit reflectance properties typical of vegetation where silt cover is absent or minimal but behave more like a non-vegetated surface, in spectral terms, where silt cover is greater. Little improvement in discriminating power is noted when inter-tidal groups alone are considered, *i.e.* if the seabank and landward groups are excluded. A case could be made for also excluding the Dry Sand group, in a stepwise approach, to further enhance the discriminating power for separation of the groups having more similar reflectance properties.

Based on reflectance properties, *Spartina* is indistinguishable from the *Halimione* group of the mid-marsh. This does not pose a problem for discrimination of the major salt marsh zones at Butterwick because *Spartina* cover is sparse. However, in cases where *Spartina* is well established throughout the marsh, discrimination of the various vegetated zones could be problematic.

The considerable overlap of the original groups of Wet Sand, Mud and Water, and Mud may be explained by the fact that the water present in these media strongly influences their spectral properties by absorbing most of the incoming wavelengths, especially the near-infrared, and as a result of this they all appear quite similar. As can be seen from the spectral data, sand, when dry, is clearly separable from other non-vegetated surfaces. The separation of sandflat from mudflat using reflectance data is difficult. However, is should be stated that visual separation of these two groups is difficult even in the field because the sandflat commonly has a veneer (approximately 1 cm) of silt/mud and, therefore, appears very similar to the mudflat when wet. Maximum discrimination between these two surfaces is likely to be achieved when the sandflat has been dry for a few hours as the sand will drain more rapidly than the mud and will therefore be more reflective. However, discrimination is improved when all four spectral bands are used as the 465-515nm and 539-578nm wavebands enhance separation of non-vegetated surfaces. Data should be acquired at a mid-to-low-tide level on a rising tide, thereby allowing for a maximum drying period for the sandflat.

In the statistical analysis of the reflectance data, it is difficult to determine whether principal components 3 and 4 add any more useful information to that gained from PCs 1+2, or if this additional information amounts to 'noise.' Visually, there appears to be little separation of the data into surface groups on PC3, except for the Field: Barley group (for both the correlation and variance-covariance matrix). This apparently results from the high separation of these points on the red band due to the ripeness of the barley. In the ripe state there is generally a shift in reflectance of vegetation from green to red wavelengths, which results from decline of the chlorophyll molecule and decrease in near-infrared reflectance, caused by a degeneration of the mesophyll structure of the foliage (Figure 3a).

Overall, PCA is a useful technique for exploring the structure of the data set. But when the data have been previously classified, discriminant analysis is the more logical method to apply and it would form the basis for classification of unallocated data points to known groupings.

CONCLUSIONS

Vegetated saltmarsh is separable from non-vegetated saltmarsh and landward surfaces are separable from inter-tidal surfaces, based on their spectral properties as determined by ground measurement.

Vegetated and non-vegetated inter-tidal zones may be further separated into discrete units. *Halimione, Puccinellia*, and Mud and *Salicornia* are distinguishable, although with some overlap. *Spartina* and *Salicornia* are not separable from the *Halimione* group. Dry Sand, Wet Sand, Mud, and Water and Mud are also distinguishable, with the latter group being the most difficult to identify based on spectral properties.

The use of all four spectral bands optimizes discrimination among surface types. R3 and R4 bands (622-664 and 778-975nm) are best for separation of green vegetation groups while R1 and R2 bands (465-515 and 539-578nm) enhance separation of non-vegetated surfaces, silt-coated vegetation surfaces, and ripe (senescent) vegetation.

The acquisition of ground reflectance data in July and September improves discrimination among salt marsh surfaces by exploitation of the seasonality exhibited by various vegetation groups. The optimum stage in the tidal cycle for discrimination of both vegetated and non-vegetated surfaces is mid- to low-water mark on a rising tide.

These analyses indicate the potential of using remotely sensed data for monitoring change in the saltmarsh and inter-tidal zone, prior and subsequent to reclamation, given the appropriate combination of sensor, spatial resolution, and timing of data acquisition.

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