Intertidal mapping of the Wash Estuary

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ABSTRACT

The paper compares two different techniques for mapping the intertidal zone of the Wash estuary on the east coast of the UK. Landsat 5 Thematic Mapper (TM) data and Daedalus 1268 Airborne Thematic Mapper (ATM) data are processed using both a conventional maximum likelihood classifier (MLC) and a fully constrained linear mixture algorithm. The data sets were atmospherically and radiometrically corrected in order to allow meaningful spectral analysis and comparison. The classified data sets were geometrically rectified and incorporated into a coastal monitoring Geographical Information System (GIS) along with information acquired from previous ground based and satellite based surveys. Cross tabulation with the ground based and satellite surveys determined the relative accuracy of the methods. The results show that both classification techniques adequately delimited and quantified the majority of Upper, Middle and Lower marsh vegetation. Both techniques had difficulty in mapping the vegetation of the Pioneer zone with the mixture algorithm performing better due to its ability of coping with mixed pixels. The integration of data sets from air and space borne platforms is problematical as a result of the radiometric and geometric corrections which must be carried out and this forms the basis of further research.

1. INTRODUCTION

The Wash Estuary and the surrounding Fenlands is one of the United Kingdom's major areas of saltmarsh **(Fig. 1)**, extending over 4,000 hectares (Doody, 1992). Analysis of remotely sensed imagery provides the potential for a rapid, consistent and economical way of mapping large areas, at regular intervals. Satellite data, such as Landsat 5 TM imagery, is appropriate for mapping most areas of the saltmarsh but it lacks the spectral and spatial resolution to map the limits of Pioneer zone vegetation accurately (Donoghue et al., 1994), especially early on in the growing season when the vegetation canopy of Pioneer zone species such as *Salicornia* has not yet developed (Hobbs and Shennan, 1986). This is a problem because the extent of Pioneer zone vegetation is a very sensitive and early indicator of saltmarsh expansion or contraction. This paper examines the potential of using Daedalus ATM data, with better spectral and spatial resolution than Landsat TM (Tab. 1), to increase the precision at which intertidal vegetation is mapped. Two different methods of classifying the imagery were evaluated, i) maximum likelihood classification (MLC) and ii) linear spectral unmixing **(Fig. 2)**. Two Landsat TM scenes (spatial resolution 30 m) acquired at low tide on 5/14/84 and 9/7/91 and a Daedalus ATM image (spatial resolution 5 m), also acquired at low tide on 19/9/86, were used in the study **(Tab. 1)**. All areas of the Wash estuary saltmarshes are exposed at low tide. The image timing therefore avoided issues of water clarity and turbidity being introduced into the classifications. The data were radiometrically and atmospherically corrected. The classifications were geometrically corrected and imported into a GIS **(Fig. 2)**. The integration of the data into the GIS allowed analysis and comparison of the classification techniques with previous ground based surveys.

Table 1 - Data Characteristics

Image Dates	ATM September 1986	Landsat 5 TM May 1984 September 1991
Ground Resolution	5 m	30 m
Near and Infrared Wavelength Bands (microns)	1 0.42-0.45 2 0.45-0.52 3 0.52-0.60 4 0.605-0.625 5 0.63-0.69 6 0.695-0.75 7 0.76-0.90 8 0.91-1.05 9 1.55-1.75 10 2.08-2.35	1 0.45-0.52 2 0.52-0.60 3 0.63-0.69 4 0.76-0.90 5 1.55-1.75 7 2.08-2.35

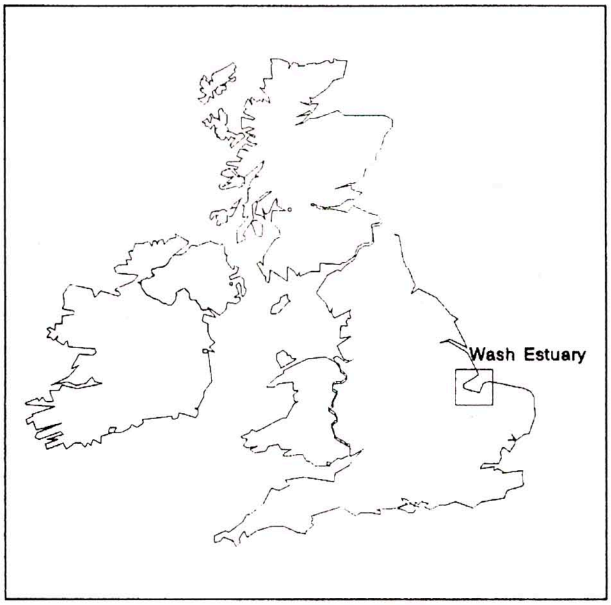

Figure 1 - Location Map of The Study Area

The importance of saltmarshes and the need to monitor them closely may be summarised under four headings.

Coastal And Flood Protection
Conservational Concerns
Reclamation Issues
Rising Sea Level

In response to these concerns two surveys of the Wash estuary saltmarshes were carried out, one in the 1970's and a second in the 1980's. These surveys were based on a combination of ground survey and aerial photography. In both cases 1 : 10,000 maps of saltmarsh vegetation communities were produced. The 1980's survey was carried out by the U.K. Nature Conservancy Council (N.C.C.) (Hill, 1988) during the period 1982-84 and formed a benchmark against which the present surveys were compared. The present survey focuses on the saltmarshes of Butterwick and Freiston **(Fig. 5)**. These areas are of particular interest as they have been subject to reclamation as recently as the end of the 1970's.

Saltmarsh vegetation develops at the interface of land and sea and forms a pattern of vegetation communities that reflect the level of inundation by saline water. These communities can form complex spatial structures, often in the form of broadly parallel zones made up of different species. The communities change their species mixtures with increased surface elevation. Saltmarshes present a difficult environment to map using satellite remote sensing because change is continuous not abrupt. Closest to the sea the saltmarsh is inundated with saltwater most frequently and only

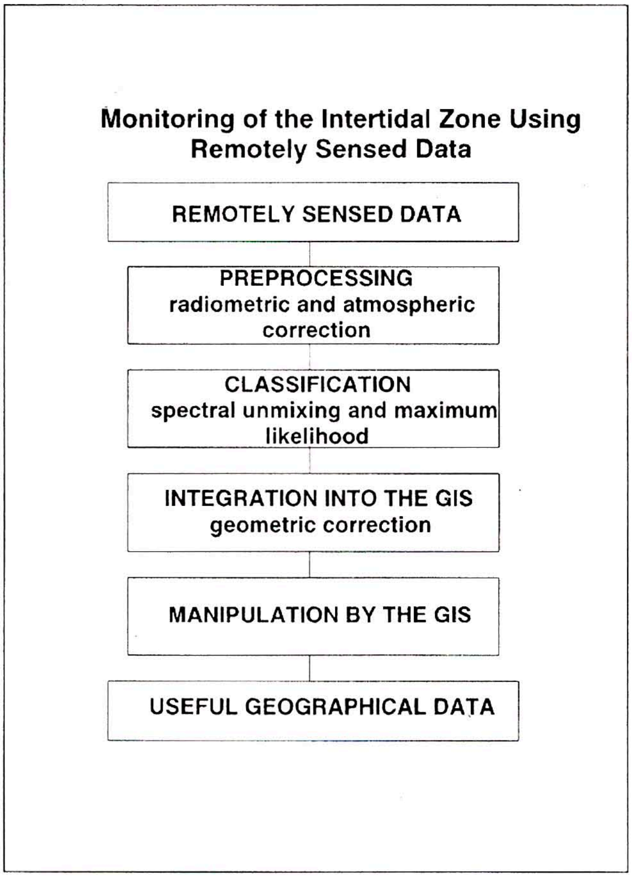

Figure 2 - Classification Flowchart

supports Pioneer communities. In the Wash estuary this zone is typically characterised by the presence of *Salicornia europaea*. As the frequency of tidal inundation decreases additional species appear. Lower and Middle marsh communities develop above the Pioneer zone. In the Wash estuary these are characterised by the presence of *Puccinellia maritima* and *Halimione portulacoides*. At the landward edge of the more mature Wash saltmarshes *Agropyron pungens* is found, this represents the Upper marsh zone. The notation of these zones is taken from the UK National Vegetation Classification (Gray, 1992). The principal period of vegetation growth occurs between May and September. There is considerable variation in the growth cycle of different species (Hobbs and Shennan, 1986).

2. CALIBRATION AND ATMOSPHERIC CORRECTION

The Daedalus 1268 ATM scanner has a fixed gain and offset value for each bandpass, these are determined when the instrument is calibrated in the laboratory. Gain and offset settings are multiples of these values and are set immediately prior to the data being acquired on board the aircraft. Calibration is essential for spectral analysis and interpretation of airborne scanner data. The conversion of digital number to radiance is determined using published calibration coefficients (Wilson, 1986).

The ATM data used in this study were acquired in 1986 in the absence of ground based spectral measurement or a detailed atmospheric profile. The data were severely affected by Mie and Raleigh scattering components. In order to minimise these effects and extract useful spectral signatures for the ground surface an empirical correction procedure was adopted. First, the additive scattering component was identified from the radiance of cloud shadow regions on the image. A histogram minimisation technique was used to correct for this effect. Secondly, a flat field correction was used to correct for multiplicative atmospheric effects. The method attempts to correct for wavelength dependent effects without allowing for topographic or other location dependent factors. The objective is to find spectrally flat locations within the image where no significant absorption features occur within the wavelength range of the data. A large area of dry sandflat was used as a spectral target and an average of 400 pixels was used to normalise the image for sun spectrum and atmosphere.

$$R_\lambda = kx\,\frac{S_\lambda}{F_\lambda}$$

R = Relative reflectance units
k = Scaling factor
S_λ = Radiance in band
F_λ = Flat field radiance in band

The two Landsat TM scenes were corrected using the radiometric rectification methods of Hall et al. (1991). The method corrects images for a common scene in a relative, rather than an absolute sense. The transformed data appear as if they were taken under the same atmospheric and irradiance conditions, by a sensor with the same radiometric sensitivity. Although this process is not necessary when classifying individual Landsat TM images it is essential for meaningful comparison of spectra obtained from different image dates and from different sensors. The intention of future studies is to integrate the airborne data into the radiometric rectification technique.

3. CLASSIFICATION

The present study assesses the ability of remote sensing techniques in delineating the extent of the entire saltmarsh. The results of the MLC and mixture algorithm classifications of the ATM imagery were compared with the 1982/4 N.C.C. survey and MLC and mixture algorithm classifications of the Landsat 5 TM imagery. Cross tabulation of the saltmarsh areas calculated by the different survey methods was carried out using a GIS. This calculated the level of agreement between the surveys produced from the different classification techniques. The study is, in part, limited by the availability of suitable imagery and the correspondence between ground survey and image acquisition. However, the NCC ground survey was completed in 1984, the closest Landsat TM scene is dated 1984, and the ATM scene was acquired in 1986. The extent and species composition of saltmarsh communities are not expected to have changed over this time period and so valid comparison can be made. A further Landsat TM scene dated from 1991 is included in the study to test for expansion or contraction of the marsh limits over a seven year period.

The first classification strategy examined was the Maximum Likelihood Classifier (MLC). For each pixel in the ATM imagery, the radiance is recorded for ten visible to short wave infrared wavelength bands. The thermal infrared band is commonly ignored in vegetation studies. A pixel may be characterised by its spectral signature, which is determined by the relative reflectance in the different wavelength bands. In practice the operator starts by extracting training areas from the image which represent different landcover classes. Multispectral classification is a process that analyses the spectral signatures of the training areas. The spectral characteristics of pixels from the whole dataset are subsequently calculated and assigned to categories based on similarity with the spectral characteristics of the training areas (Curran, 1985). The selection of accurate training data is essential to the accuracy of the overall classification. In the case of saltmarshes, it is desirable to locate areas which are dominated by different saltmarsh species. A set of training areas consisting of four classes: Upper marsh; Middle marsh; Lower marsh; and Pioneer zone were established from ground truth maps and further verified by fieldwork. Training areas were identified on the ATM imagery and spectral statistics were calculated for each of the ten ATM bands used. A similar methodology was carried out on the Landsat 5 TM images (Donoghue et al., 1994). The images were subsequently classified, rectified and imported into a GIS for comparison (**Tab. 2**).

The most disappointing aspect of the MLC classifications was their inability to classify the limits of the Pioneer zone with precision. This proved to be the case for both the airborne and satellite surveys. The MLC is based on the membership concept of classical set theory. This states that a set has a precisely defined boundary and an element is either inside the set or outside it. In the case of saltmarshes, it is almost inconceivable that only one kind of surface material will be contained in a single pixel. It is far more likely that an individual pixel will contain a mixture of surface classes including several vegetation species, detrital material, mud, water and shadow. All of these substances have a spectrally distinct signal but these individual signals will be integrated to give a single reflectance value for a Daedalus ATM or Landsat 5 TM pixel. When each pixel can be associated with only one cover class it cannot represent the mixture and intermediate conditions that occur in the saltmarsh. This was demonstrated in the present study where accurate classification of the Pioneer zone proved impossible using the MLC. Each pixel in the Pioneer zone contains a mixture of vegetation (predominantly *Salicornia*), mud and water. The MLC cannot cope with such mixtures and tries to force the pixel into a single class such as vegetation, mud or water. This is especially true early on in the growing season when *Salicornia* is present but has yet to develop a full vegetation canopy. Accurate classification can only be achieved if each ATM or Landsat 5 TM pixel is assigned several labels, along with the proportion assigned to each label present in each pixel. This can be achieved through the use of an appropriate spectral unmixing algorithm (Adams et al. 1986, Quarmby et al., 1992).

4. SPECTRAL UNMIXING

The aim of spectral unmixing is to decompose each pixel into its respective components or endmembers. Endmembers are defined in the present study as "the response that would be received in the absence of noise by a pixel containing nothing but the component of interest" (Settle and Drake, 1993) and correspond with different surface types. The algorithm produces Proportion maps, one for each spectral endmember. These are scaled from zero to one hundred percent and describe the proportional cover of each endmember within an individual pixel. The principal disadvantages of the technique are that the number of endmembers is restricted by the number of spectral bands in the data and that the identification of endmembers is often an empirical operation.

The mixing of spectra from different surface components may occur in a linear or non-linear fashion. A major concern about applying linear mixture algorithms to the intertidal zone has been the fact that mixing of some surfaces may be non-linear. It is important to investigate spectral feature space in multi-band imagery to identify possible mixing among endmembers. Experience has shown that a Principal Component Analysis (PCA) provides an effective method for identifying endmembers and mixing planes (Smith et al, 1985, Settle and Drake, 1993, Reid Thomas, 1994). **Figure 3** shows a summary diagram of a typical scatterplot generated from PC1 against PC2 within an intertidal zone containing vegetated and non-vegetated surfaces. The linearity of the unmixing algorithm was tested by identifying spectra systematically along the mixing planes from the PCA plot **(Fig.3, 1-5)**. These pixels were then located on both the TM and ATM images and their spectra plotted **(Fig. 4, 1-5)**. **Figure 4** shows how vegetation spectra change in ATM data along the transition from the Pioneer zone to the Upper marsh **(Fig. 3 and Fig. 4, 1-5)**. The graph shows that as the proportion of an endmember within a pixel changes so does the reflectance of the pixel in any given band. As one moves along the vegetation mixing plane between the Pioneer zone endmember and the mature marsh endmember **(Fig. 3, 1-5)** the pattern of changing reflectance appears very linear **(Fig. 4, 1-5)** and so it is appropriate to use a linear spectral unmixing algorithm (Reid Thomas, 1994). Similar results were obtained from the analysis of the Landsat 5 TM imagery (Donoghue et al., 1994). The spectral response of each pixel in any band is considered to be a linear combination of the responses of the endmembers which are assumed to be in the mixture. Each pixel contains information about the proportion and spectral response of each surface component within a pixel (Shimabukuro and Smith, 1991). As long as the number of endmembers is less than the number of ATM bands the system of linear equations is over determined and may be solved (Shimabukuro and Smith, 1991).

The selection and identification of the spectral endmembers in an image is the key to success of a linear mixture algorithm. In order to solve mixing equations the operator must establish the number of surface components or endmembers that are involved. Two different approaches have generally been used to define endmembers in a mixture algorithm: the use of a library of reflectance spectra (Adams et al., 1986); and the use of training spectra extracted from the image data itself. As no library spectra exist for vegetation the second approach was adopted in this study.

The number of endmembers and their location in the image must be identified if the mixing equations are to be solved. A common approach to this problem is to reduce the dataset to its intrinsic dimensionality by the application of a Principal Component Analysis (PCA) (Smith, 1985). The

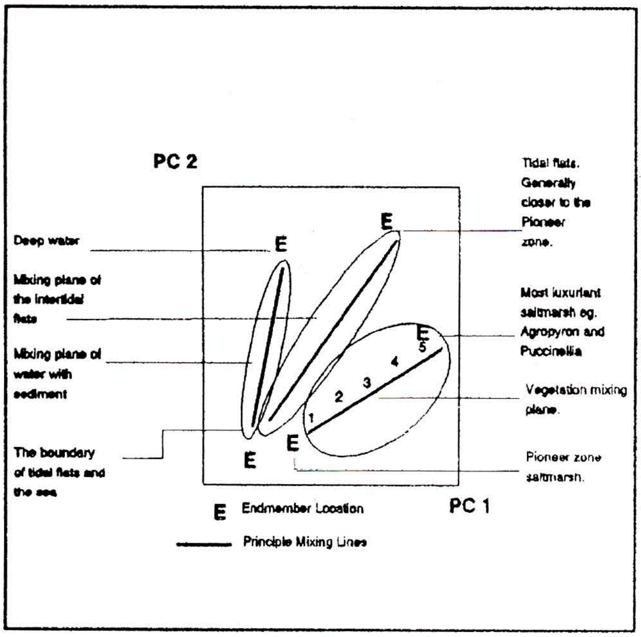

Figure 3 - Generalised linear mixing within the intertidal zone (PC1 against PC2)

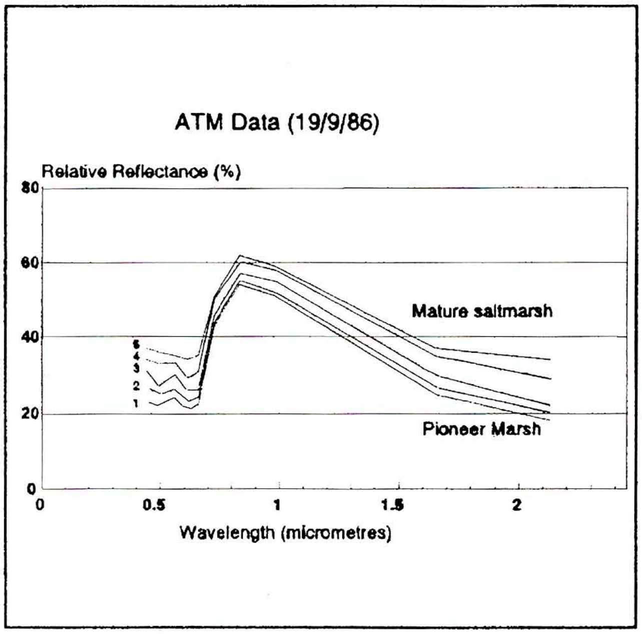

Figure 4 - Spectra taken from the vegetation mixing plane (Fig. 3)

number of endmembers is taken to be one more than the number of dimensions required to explain the variance of the data (Gillespie, 1990; Settle and Drake, 1993). A scatterplot was produced of PC1 against PC2 (**Fig. 3**). Examination of the scatterplot reveals distinct mixing planes. The location of the purest pixels in the image, representing endmembers, were identified from the extremes of the mixing planes. One water, two mature saltmarsh, a Pioneer zone and two non-vegetated endmembers were identified from the ATM imagery. One water, one mature saltmarsh, a Pioneer zone and two non-vegetated endmembers were identified from the Landsat 5 TM imagery. Interpretation of the scatterplots is subjective. If the mixture algorithm is to be used in an operational mode a method could be developed to extract endmember pixels from the extremes of the mixing planes objectively.

The constrained least-squares Mixtool program (Mazer, unpub.) was then applied to the data sets. The output was scaled between 0 and 100 so the proportions could be read as percentages. The scaled proportion maps were geometrically corrected and imported into the GIS. As this project was concerned with the mapping of intertidal vegetation, only the vegetation and Pioneer endmember proportion maps were examined in detail. It should be noted that much information concerning the nature of the whole intertidal area is contained in the other proportion maps.

5. GEOMETRIC CORRECTION

The images were geometrically corrected, with RMS errors less than one pixel for both Landsat TM and ATM images, using a nearest neighbour pixel resampling process before being incorporated into a GIS. Geometric correction cannot be done before classification as this would upset the spectral relationship between pixels. The geometric correction of airborne data is a considerably more difficult task than the correction of satellite data due to the instability and complex flight geometry of an airborne survey. This can be a severe limitation of airborne data.

6. RESULTS

In order to allow comparison with the other surveys and to ease interpretation, the saltmarsh vegetation proportion maps were aggregated to produce maps of vegetation extent for each mixture algorithm survey. With the GIS system, the saltmarsh was separated from the rest of the intertidal zone by excluding classified data with less than 20% vegetation cover. This division was made on the basis of transect surveys carried out during March 1993. The corresponding zones of the 1982/4 N.C.C. survey and the satellite classifications were aggregated in order to i) compare and evaluate the performance of the MLC and unmixing algorithms, ii) look at the effect of seasonality on marsh extent and iii) estimate possible saltmarsh contraction or expansion over a seven year period. Tabulation and comparisons were carried out using the GIS system (**Tab. 2**).

The comparison of the mixture algorithm survey of the ATM imagery with the ATM MLC classification revealed that the mixture algorithm was considerably more successful in locating the extent of Lower and Pioneer marsh. The mixture algorithm identified 60 hectares of saltmarsh more than the MLC. This area consisted of Lower and Pioneer marsh because the MLC cannot cope with mixed pixels. MLC forces a pixel into a single class and cannot represent the mixture of mud, vegetation and water that occurs in the Pioneer zone. As vegetation often covers a small, but important, fraction of the pixel area in the Pioneer zone the vegetation spectral signature is swamped by that of intertidal mud and is classed accordingly. The linear unmixing algorithm has the ability to distinguish the intermediate conditions that occur in the Pioneer zone and therefore provides a better representation of reality.

A comparison of the ATM mixture algorithm with the 1982/4 NCC survey (**Fig. 5**) produced a 62% level of agreement. The mixture algorithm mapped 50 hectares of saltmarsh that were not mapped by the NCC survey. This area mainly corresponded with Pioneer marsh in front of the most recent reclamation on the Freiston Shore and towards the southern end of Butterwick marsh. This is a seasonal effect. The aerial photographs that the 1982/4 NCC survey was based on were taken during March. At this stage of the growing season the *Salicornia* canopy may not have developed strongly enough to be seen on the aerial photographs (Hobbs and Shennan, 1986). The NCC survey mapped almost 25 hectares of saltmarsh that were not picked up by the mixture algorithm survey. These areas were accounted for by very thin vegetation cover surrounding fingers of marsh that follow creeks down into the intertidal zone. These areas correspond with vegetation cover of less than 20%. The mixture algorithm was able to map these areas but the problem of relaxing the 20% cut off limit is that much of the intertidal mud and sand flats become incorporated into the saltmarsh class. Ideally mixture algorithm data should not be aggregated but viewed in their raw form. This however leads to problems of interpretation and is one of the problems of using a mixture algorithm classification strategy.

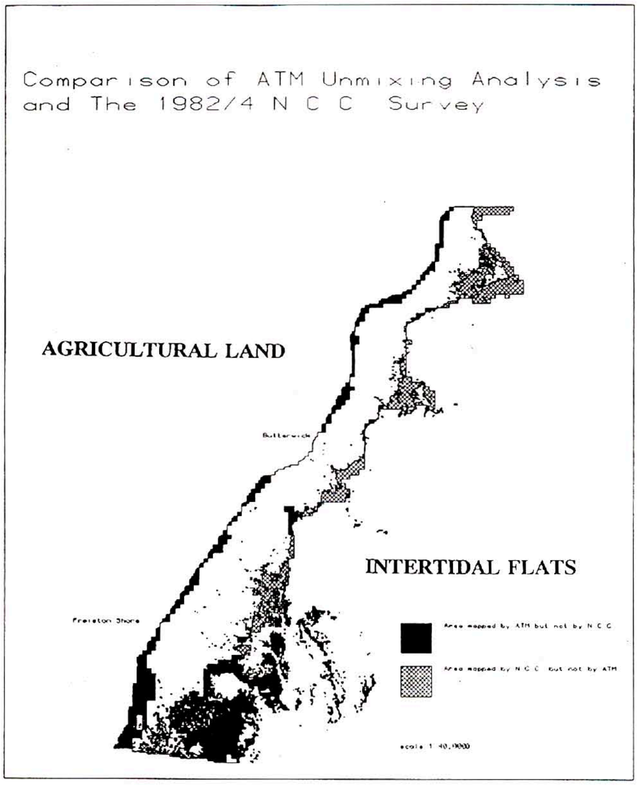

Figure 5 - Comparison of ATM Unmixing Analysis and the 1982/4 NCC Survey

Table 2 - Comparison Of the 1986 ATM Mixture Algorithm With the Other Survey Methods (Area in hectares)

	ATM Mixture Algorithm / ATM MLC	ATM Mixture Algorithm / NCC Survey	ATM Mixture Algorithm / 1984 Landsat Mixture Algorithm	ATM Mixture Algorithm / 1991 Landsat Mixture Algorithm	ATM Mixture Algorithm / 1984 Landsat MLC	ATM Mixture Algorithm / 1991 MLC
Area mapped only by ATM Mixture algorithm	62	50	73	66	97	48
Area not mapped by the ATM Mixture algorithm	1	25	3	5	1	22
Area mapped by both survey methods	111	120	96	105	74	123
% Agreement between the survey methods	64	62	56	60	43	64

A comparison of the ATM unmixing analysis with the 1984 satellite classification gave agreements of 56% for the mixture algorithm and only 43% for the MLC. This poor level of agreement may be explained by the fact that the satellite surveys were unable to map large areas of Lower and Pioneer marsh. In the case of the comparison with the satellite MLC classification, the ATM mixture algorithm mapped an area of nearly 100 hectares that was not picked up by the MLC. The poor performance of the satellite classifications in this case is explained by the effects of seasonality. The satellite image was taken in May. Early on in the growing season the spectral signature of the Pioneer zone vegetation is not strong enough to be separated from the spectral signature of the intertidal mud and sand flats. The ATM imagery was taken in September, after a full season of saltmarsh growth. At this time of year the Pioneer and Lower marsh zones can be more accurately mapped (Hobbs and Shennan, 1986).

The seasonal effect is again confirmed by the comparison of the ATM mixture algorithm survey with the 1991 satellite classifications. There are higher levels of agreement - 60% for the comparison of the ATM mixture survey with the Landsat mixture survey, and 64% for the comparison with the Landsat MLC survey. The areas of saltmarsh mapped by the ATM survey but not by the satellite surveys are smaller than in the comparisons of the 1984 satellite surveys. The areas mapped only by the ATM mixture survey again correspond with the area in front of the Freiston shore reclamations. This may be accounted for by the MLC's problem in dealing with mixed pixels. The 1991 MLC survey also mapped over 20 hectares of saltmarsh that were not mapped by the ATM imagery. This area corresponds with fringes of Pioneer marsh. It is possible that this is an area of saltmarsh expansion in front of the recent reclamations. The GIS pinpoints these areas and as the coverages are geometrically correct, the areas can be accurately located on the imagery and in the field for further evaluation.

7. CONCLUSION

Both of the classification strategies applied to the imagery adequately mapped the majority of Upper and Middle saltmarsh vegetation. The maximum likelihood classification was unable to delimit the extent of the Pioneer zone accurately due to the problem of mixed pixels. The mixture algorithm was able to cope with the mixed pixel problem and was therefore able to provide a more accurate representation of Lower and Pioneer marsh distribution. The comparison of the ATM surveys with the satellite surveys once more revealed the importance of seasonality in mapping saltmarsh. In order to remove the effects of seasonality it is important that images taken at similar times in the growing season are compared. The use of GIS provides a rapid, accurate and manageable method of incorporating the information gained from imagery into a coastal monitoring GIS. Maximum likelihood classification reveals considerable information about the distribution of plant species within the saltmarsh and the rate of maturity. The mixture algorithm gives quantitative information about the surface cover of the vegetation. Satellite imagery provides synoptic, reliable information arrived at cheaply, objectively and at regular intervals. Parts of the intertidal zone are difficult to classify accurately using the Landsat 5 TM sensor because of its limited spectral and spatial resolution. Airborne imagery provides a more precise mapping tool capable of identifying vegetation in the Pioneer zone and mapping sediment types. However, the use of an airborne platform introduces the need for accurate radiometric and geometric correction; processes that would be difficult to automate for operational surveys. Furthermore, the increased level of spectral complexity that is present in high resolution Daedalus ATM data makes the classification procedure more complex. For example, increasing the number of bands from six to ten in TM and ATM data respectively does not necessarily help to improve classification because spectrally adjacent bands may be highly correlated and different spectral features will appear in images with a high spatial resolution. A research strategy that combines satellite and airborne data in a GIS is ideal for coastal management. This is not easy to achieve in practice and a considerable amount of research is still needed to take advantage of the information provided from different sensors, including air and space borne platforms.

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