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The Assessment of Mangrove Areas using High Resolution Multispectral Airborne Imagery

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ABSTRACT

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Airborne multispectral sensors combine many of the advantages inherent in both satellite systems and aerial photography. However, they have not been used in remote sensing studies of mangrove areas which have traditionally utilised the latter two approaches. High resolution (1 m) multispectral imagery of mangroves in the Turks and Caicos Islands was collected using a Compact Airborne Spectrographic Imager (CASI). Hierarchical agglomerative clustering with group-average sorting identified six mangrove classes which were used to direct a supervised classification (overall accuracy 78.2%). Normalised difference vegetation index (NDVI) was calculated from CASI data: linear regression models were used to predict leaf area index and percent canopy closure from NDVI. LAI and canopy closure data, estimated from field measurements for a set of sites different to those used to derive the regression models, were used to test the accuracy of LAI and canopy closure prediction. Accuracy was defined as the proportion of accuracy sites at which the LAI or percent canopy closure value (as estimated from field measurements) lay within the 95% confidence interval for the predicted value. Accuracy was high: 94% for LAI and 80% for canopy closure. The superior spatial and spectral resolution of CASI allows mangrove areas to be assessed to a greater level of detail and accuracy than with satellite sensors. Some logistics for planning CASI campaigns are discussed.

ADDITIONAL INDEX WORDS: *Compact Airborne Multispectral Imager (CASI); remote sensing; Turks and Caicos Islands.*

INTRODUCTION

Satellite remote sensing of tropical coastal environments has undergone extensive development during the last twenty years (for a current review see GREEN *et al.,* 1996). In this period satellites have frequently been used to assess mangrove areas with a good rate of success (*e.g.* DUTRIEUX *et al.,* 1990; GANG and AGATSIVA, 1992; ASCHBACHER *et al.,* 1995). A major theme behind the development of this type of remote sensing has been the improvement of sensor specifications in the hope that Earth observation will become more detailed and perhaps more meaningful. While it is possible to obtain general information on mangroves relatively easily (*e.g.* BIÑA *et al.,* 1980, Landsat MSS; EONG *et al.,* 1992, Landsat TM; CHAUDHURY, 1990, SPOT XS) more specific information on density and height is a rarity (but see VIBULSRETH *et al.,* 1990 and GRAY *et al.,* 1990). Only two studies have used satellite data to analyse mangrove canopy structure (canopy cover, JENSEN *et al.,* 1991; leaf area index, GREEN *et al., manuscript*).

It is this apparent limitation on the level of detail (descriptive resolution) in satellite data which has contributed to the call for sensors with higher spatial and spectral resolution. Large scale aerial photography can attain a spatial resolution of less than 10 cm although at this resolution individual photographs may only cover an area of 400–900 m^2 (THAMRONGNAWASAWAT, *manuscript*). Mangroves frequently grow in discrete associations (TOMLINSON, 1985). This, and the difficulty of access to many mangrove areas, means that aerial surveys are well suited to the study of mangrove ecosystems, a fact which has been recognised since the early days of aviation (WATSON, 1929). Despite more than seventy years of effort it is difficult to obtain an overview of aerial photography for the assessment of mangroves because published accounts are scarce. This in itself is no reason to doubt the success of aerial photography, instead it undoubtedly reflects the low emphasis which governmental departments, aid agencies or consultancy firms naturally place on the publication of results in scientific literature.

The analysis of photographs using stereoplotters, tracing overlays and a digitising tablet or a digital rasterisation camera is often very time consuming. Thus, the relatively recent emergence of airborne multispectral sensors which collect digital data directly has stimulated considerable interest for

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Table 1. *Band settings for the CASI.*

Band	Portion of Electromagnetic Spectrum	Wavelength (nm)
1	Blue	402.5–421.8
2	Blue	453.4–469.2
3	Green	531.1–543.5
4	Green	571.9–584.3
5	Red	630.7–643.2
6	Red	666.5–673.7
7	Near Infrared	736.6–752.8
8	Near Infrared	776.3–785.4

a wide variety of applications and the subject already warrants dedicated international conferences. The major advantages of airborne multispectral remote sensing are:

(1) Greater number of spectral bands than are present on satellite-borne sensors.
(2) Great spectral versatility (the location and width of spectral bands can be chosen by the operator).
(3) Ability to characterise complete spectra of cover types using hyperspectral data.
(4) High spatial resolution (broadly comparable to aerial photography but the data are digital).

The Compact Airborne Spectrographic Imager (CASI) offers up to 18 spectral bands depending on the spatial resolution required. The user may specify bands anywhere within the blue to near infrared portion (400–1,000 nm) of the electromagnetic spectrum. Each band may have a minimum width of 2 nm and the instrument set-up can be modified during flight. Pixel size can lie between 10 m and 0.6 m. In addition, the instrument can be deployed in "spectral mode" whereby up to 288 bands may be used to determine the spectra (signature) of surface features. These hyperspectral data can be recorded for a maximum of 39 pixels but a single complete band (512 pixels wide) is also recorded to help relate the hyperspectral data to features of interest.

In short, airborne remote sensing appears to combine the desirable properties of both satellite imagery and aerial photography; namely, digital data in discrete spectral bands and high spatial resolution. In light of this it is perhaps surprising that airborne multispectral remote sensing has not been used for the mapping and assessment of mangroves until now.

METHODS

Image Acquisition Details

A spatial resolution of 1 m^2 was specified with 8 wavebands (Table 1). The CASI was mounted on a locally-owned Cessna 172N aircraft which was not specifically adapted for aerial survey work (*i.e.* the aircraft did not possess an observation hatch). The sensor was mounted by fitting a specially designed door with mounting brackets and streamlined cowling. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. The use of a standard aircraft and pilot, with the adaptations mentioned above, permitted the acquisition of image data at a fraction of the cost of conventional survey methods which utilise specialist aircraft, instrumentation and experienced survey pilots. Data were collected during flights over the Cockburn Harbour and Nigger Cay areas of South Caicos, Turks and Caicos Islands (21°30′N, 71°30′W) in July 1995. The CASI data presented here are only a small part of the whole airborne campaign. Further details are given in CLARK *et al.* (1997).

Table 2. *A summary of the field survey. Data were collected in two phases: one for the calibration of CASI imagery and two for accuracy assessment. The number of sites at which each type of data were collected is presented. Other refers to positional information for three non-mangrove categories (see text for further details).*

Purpose of Data	Calibration	Accuracy
Date	1995	1996
Species composition (%)	81	121
Tree height	81	121
Tree density	81	121
Canopy transmittance	30	18
Percent canopy closure	39	20
Other	37	67

Field Survey

Three species of mangrove, *Rhizophora mangle* (Linnaeus), *Laguncularia racemosa* (Gaertner) and *Avicennia germinans* (Stearn) grow with *Concarpus erectus* (Gaertner) in mixed stands along the inland margin of the islands fringing the Caicos Bank. The field survey was divided into two phases. Calibration data were collected in July 1995, accuracy data in March 1996 (Table 2). Species composition, maximum canopy height and tree density were recorded at all sites. Species composition was visually estimated from a 5 m^2 plot marked by a tape measure. Tree height was measured using a 5.3 m telescopic pole. Tree density was measured by counting the number of tree trunks at breast height. When a tree forked beneath breast height (~1.3 m) each branch was recorded as a separate stem (after ENGLISH *et al.*, 1994). The location of each field site was determined using DGPS with a probable circle error of 2–5 m (TRIMBLE NAVIGATION LTD., 1993).

Determination of Mangrove Habitat Categories

A habitat classification was developed for the mangrove areas of the Turks and Caicos using hierarchical agglomerative clustering with group-average sorting applied to the calibration data. The calibration data were 4th root transformed in order to weight the contribution of tree height and density more evenly with species composition (the range of data was an order of magnitude higher for density and height and would cluster accordingly). This identified seven classes which separated at a Bray Curtis Similarity of 85% level of similarity (Figure 1). Categories were described in terms of mean species composition (percent species), mean tree height and mean tree density (Table 3). One category, *Laguncularia* dominated mangrove, was discarded because white mangrove was rare in this area—in both the calibration and accuracy

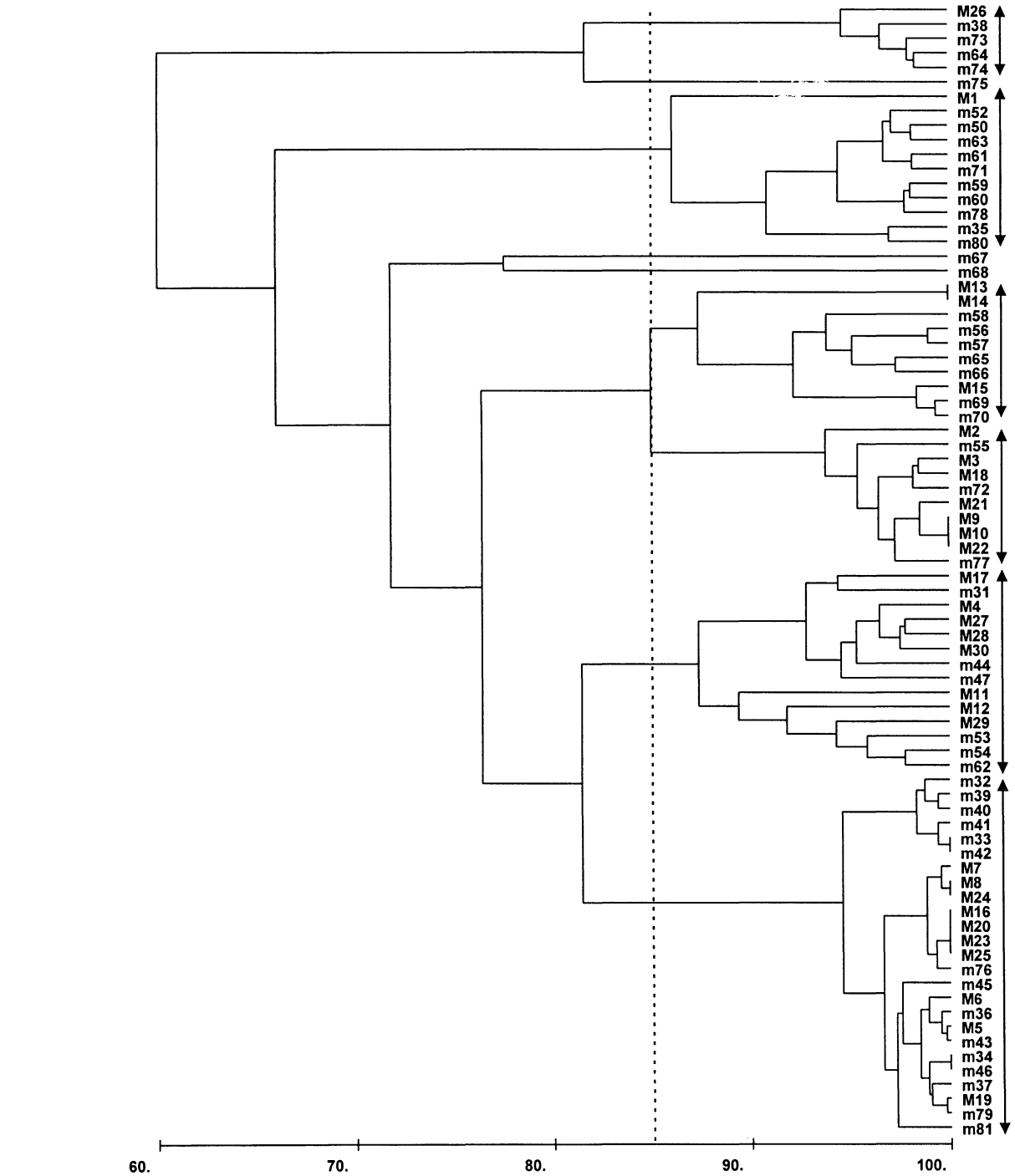


Figure 1. Dendrogram of 78 mangrove sites using group-average clustering from Bray-Curtis Similarities (bottom axis). Seven clusters which are <85% similar were identified. One consisting of sites 67 and 68 was discarded for reasons explained in the text: the other six, marked by double arrowheads were used to direct the supervised classification of the CASI data and an accuracy assessment. Horizontal axis is Bray-Curtis Similarity.

field phases it was observed at only two locations. Three other ground cover types were recorded, though no quantitative information was obtained beyond the location of 'typical' sites: (i) sand, (ii) saline mud crust, and (iii) mats of the halophytic succulents *Salicornia perennis* and *S. portulacastrum*. These nine habitat categories (six mangrove, three other) were used to direct the image classification of the CASI data, and the collection of accuracy data in 1996.

Table 3. *Descriptions for each of the mangrove habitat categories identified in Figure 1. N = number of calibration sites in each category.*

Habitat Category Description	N	Species Composition %				Tree Height (m)	Tree Density (m $^{-2}$)
		Rhz	Avn	Lag	Con	Mean (range)	Mean (range)
Conocarpus erectus	6	0	0	0	100	2.4 (1.8–4.5)	0.6 (0.5–1.0)
Avicennia germinans	11	0	100	0	0	2.6 (0.8–6.0)	0.6 (0.2–1.0)
Short, high density, *Rhizophora mangle*	10	100	0	0	0	1.1 (0.5–2.0)	8.0 (6.0–10.0)
Tall, low density, *Rhizophora mangle*	25	100	0	0	0	3.7 (2.0–7.0)	0.3 (0.2–0.5)
Short mixed mangrove, high density	10	62	38	0	0	1.7 (0.8–2.5)	8.1 (5.0–15.0)
Tall mixed mangrove, low density	14	56	43	0	1	3.5 (2.0–5.0)	0.6 (0.2–1.2)
Laguncularia dominated mangrove	2	35	5	45	0	3.8 (3.5–4.0)	2.2 (0.5–4.0)
Unclassified	3						

Estimation of Leaf Area Index (LAI)

In addition to species composition, maximum canopy height and tree density canopy transmittance was measured at all calibration and accuracy sites. Canopy transmittance was measured using a pair of MACAM™ SD101Q-Cos 2π Photosynthetic Active Radiation detectors connected to a MACAM™ Q102 radiometer and can be used to estimate the leaf area index of the canopy (CLOUGH *et al.*, 1995). LAI is the single-side leaf area per unit ground area, and is dimensionless.

There is a linear relationship between mangrove LAI and normalised difference vegetation index (NDVI) obtained from field measurements (RAMSEY and JENSEN, 1995) and linear regression models can be used to estimate LAI and NDVI derived from satellite data (GREEN *et al., manuscript*). NDVI is calculated using near infrared and red bands (Near Infrared – Red)/(Near Infrared + Red), see ROUSE *et al.*, 1973). As such there were four options for calculating NDVI from the CASI data with combinations of Bands 5 to 8 (Table 4). NDVI was calculated for all band combinations and regressed against values of LAI estimated from *in situ* measured canopy transmittance.

Estimation of Percent Canopy Closure

Wherever access underneath the mangrove canopy was possible percent canopy structure was measured using a hand held semi-hemispherical mirror (a spherical densiometer) which had a grid graticule engraved on its surface. Percent canopy closure was then estimated by computing the proportion of the mirror area covered by the reflection of leaves and stems.

Image Processing and Classification

CASI data were subjected to the following pre-processing steps:

(1) Compensation for aircraft roll (using data from the gyroscope mounted in aircraft during flight).
(2) Radiometric correction of data to reflectance values at the aircraft including ratio of upwelling radiance recorded by the sensor to downwelling irradiance incident upon the aircraft. This process compensates for variation in light intensity during imagery acquisition.
(3) Geometric correction (DGPS mounted in the aircraft plus ground control points) and georeferencing to map coordinates (Universal Transverse Mercator, zone 19).
(4) Submerged areas were masked out of the imagery using the infrared band 8 (Table 1). Previous work and ancillary field data had shown that the terrestrial vegetation had NDVI of 0.05 or less. Therefore, an image of NDVI was used to mask out the inland non-mangrove areas.

Signatures were collected from a 25 pixel area (*i.e.* 25 m^2) at each of the calibration sites. Using the habitat categories in Table 1 as a guide these signatures were edited (tested for separability) and merged into nine different classes, one for each habitat category. CASI imagery was then classified using a supervised processing routine (MATHER, 1987). The classified image was smoothed with a low pass 3 × 3 median filter and artificially coloured. NDVI was calculated from reflectance values in the masked (unfiltered) image.

RESULTS

Mangrove Habitat Map

Figure 2 is the filtered classified map of mangrove habitat categories. The high spatial resolution of CASI enables small

Table 4. *A summary of four models which regressed LAI estimated from* in situ *measurements of canopy transmittance.*

NDVI Equation	R^2	Intercept	Slope	p	SE
(Band 8 − Band 5)/(Band 8 + Band 5)	0.22	0.19	0.05	NS	1.93
(Band 8 − Band 6)/(Band 8 + Band 6)	0.12	3.68	2.29	NS	2.18
(Band 7 − Band 6)/(Band 7 + Band 6)*	0.77	0.32	9.76	<0.001	0.73
(Band 7 − Band 5)/(Band 7 + Band 5)*	0.43	1.81	5.71	<0.001	1.69

NDVI calculated from CASI data: NDVI was calculated from combinations of Bands 5 to 8 after Rouse *et al.* (1973). Bands 5 and 6 are in the visible portion of the electromagnetic spectrum, and Bands 7 and 8 in the near infrared (for exact wavelengths refer to Table 1). R^2 = coefficient of determination, p = probability of the F test for the model, NS = not significant at the p = 0.05 level of confidence, SE = standard error of the estimate. Degrees of freedom = 1,29 in all cases. For models marked *, the F-test and t-test for the slope estimate were both significant at the 0.001 level of confidence, which indicates that the relationship did not occur by chance and may be used to convert NDVI values to LAI

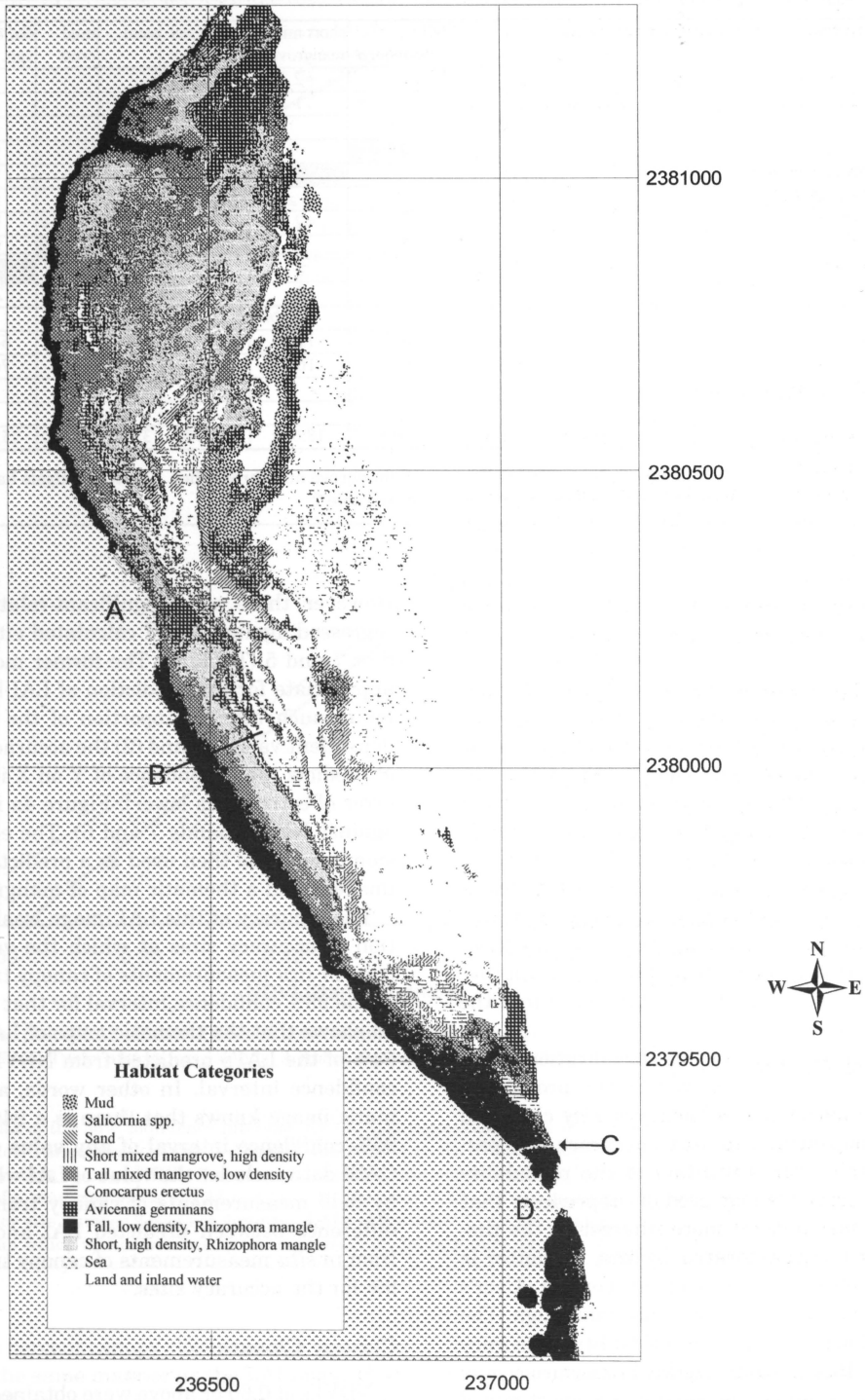


Figure 2. A mangrove habitat map for an area on South Caicos, Turks and Caicos Islands. The map has been produced from a classification of CASI data. Refer to Table 3 for a description of habitat categories. The letters A–D indicate features within the mangroves which are discussed in the text. The coordinate system is Universal Transverse Mercator; therefore, each grid square represents 500 × 500 m on the ground.

Habitat categories	*Conocarpus erectus*	*Avicennia germinans*	short *Rhizophora*	tall *Rhizophora*	short mixed mangrove	tall mixed mangrove	sand	mud crust	*Salicornia* spp.	row total
Conocarpus erectus	10	1			2	1				14
Avicennia germinans		24			1	2			3	30
short *Rhizophora*		4	15							19
tall *Rhizophora*				27		2				29
short mixed mangrove		1	3		1	1				6
tall mixed mangrove		1	1	5		16				23
sand		1			2		13		5	21
mud crust		1						28		29
Salicornia spp.	1				3				13	17
column total	14	33	16	32	9	22	13	28	21	188
producer's accuracy (%)	90.9	72.7	78.9	84.4	11.1	72.7	100.0	100.0	61.9	
user's accuracy (%)	71.4	80.0	78.9	93.1	16.7	69.6	61.9	96.6	76.5	
overall accuracy (%)	78.2									
category area (m^2)	21,800	102,500	104,000	76,400	18,000	119,700	3,900	23,400	25,800	

Figure 3. Accuracy matrix for the classified image containing nine classes, six mangrove and three other. Cluster analysis had identified that mangrove habitat categories were <85% similar. Descriptions of each category are given in Table 2.

clumps of short *Rhizophora mangle* (marked by the letter A in Figure 2) to be detected. This is a shallow area of many rooted seedlings and small (<50 cm) individual trees *i.e.* presumably an area where *Rhizophora mangle* is expanding. The mottled patches of this species in this area are markedly different from the rest of the tall *Rhizophora* coastline. Zonation in the mangrove stand can be seen clearly (along the line marked by the letter B). This zonation probably reflects a gradient in various environmental factors such as salinity, pH or shelter (but not freshwater input as there are no rivers or streams in the TCI). Areas of cleared mangrove are clearly visible. The letter C marks the end of a path about 3 m wide which has been cut through the mangroves to a boat jetty, and the area marked D is a large strip of cleared mangrove where burned domestic waste used to be bulldozed into the water.

Figure 3 is the accuracy matrix for this classification (CONGALTON, 1991). The producer's accuracy is the probability that any pixel in that category has been correctly classified and is a measure of omission. The user's accuracy of a particular habitat category is an indication of the probability that a pixel classified on the image actually represents that category *in situ*. The former is of more interest to the thematician carrying out the classification, whilst the latter is arguably the more useful in a management context. User's accuracies for mangrove categories are reasonably high. The exception is that for short mixed mangrove. Only six accuracy sites were surveyed in this category, so this low accuracy may be a function of a small sample size. In any case short mixed mangrove accounts for less than 4% of the total mangrove area mapped (44.1 ha).

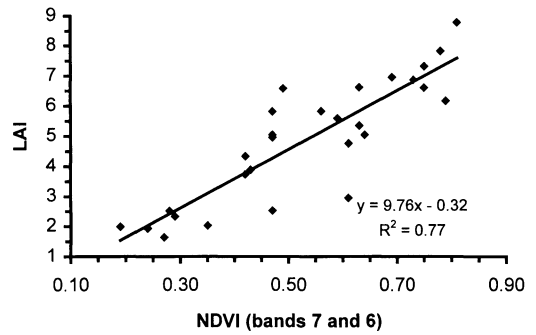
Leaf Area Index

The relationship between NDVI calculated from Bands 8 and 5, and values of LAI estimated from *in situ* measured canopy transmittance, was not significant (Table 4). Neither was a model using NDVI calculated from Bands 8 and 6. However, there was a significant relationship when LAI was regressed against NDVI calculated either from Bands 7 and 6 or 7 and 5 (Table 4). The former model was deemed more appropriate for the prediction of LAI because (1) it accounts for a much higher proportion of the total variation in the dependent variable, and (2) the accuracy with which the model predicts the dependence of Y on X is higher (the standard error of estimate is lower). Figure 4a is a scatter plot of LAI against NDVI (Bands 7 and 6). The equation of this regression model was then used as a predictor of LAI for the CASI imagery and a thematic map of mangrove LAI produced.

The accuracy of this LAI image was defined as the proportion of accuracy sites at which the value of LAI estimated from *in situ* measurements of canopy transmittance lay within the 95% confidence interval for that value of NDVI. Figure 4b shows that the thematic maps of LAI are highly accurate; 94% of the LAI's predicted from NDVI were within the 95% confidence interval. In other words, anyone using this thematic image knows that there is a 94% probability that the 95% confidence interval of any value of LAI predicted from CASI data includes the value of LAI which would be obtained by field measurements of canopy transmittance. The mean difference between predicted LAI and the value estimated from *in situ* measurements of canopy transmittance was only 9% for the accuracy sites.

Canopy Closure

NDVI's of 0.60 or above were obtained from sites with 100% canopy closure. Below 0.60 the relationship between NDVI and percent canopy closure was linear: NDVI calculated from Bands 7 and 6 was again a superior predictor of percent canopy closure ($R^2 = 0.92$, $p < 0.001$, $n = 19$) to NDVI calculated from other band combinations. Figure 5a is a scatter plot of LAI against NDVI (Bands 7 and 6). The equation of this regression model was then used as a predictor of LAI for the CASI imagery and a thematic map of mangrove canopy closure produced.



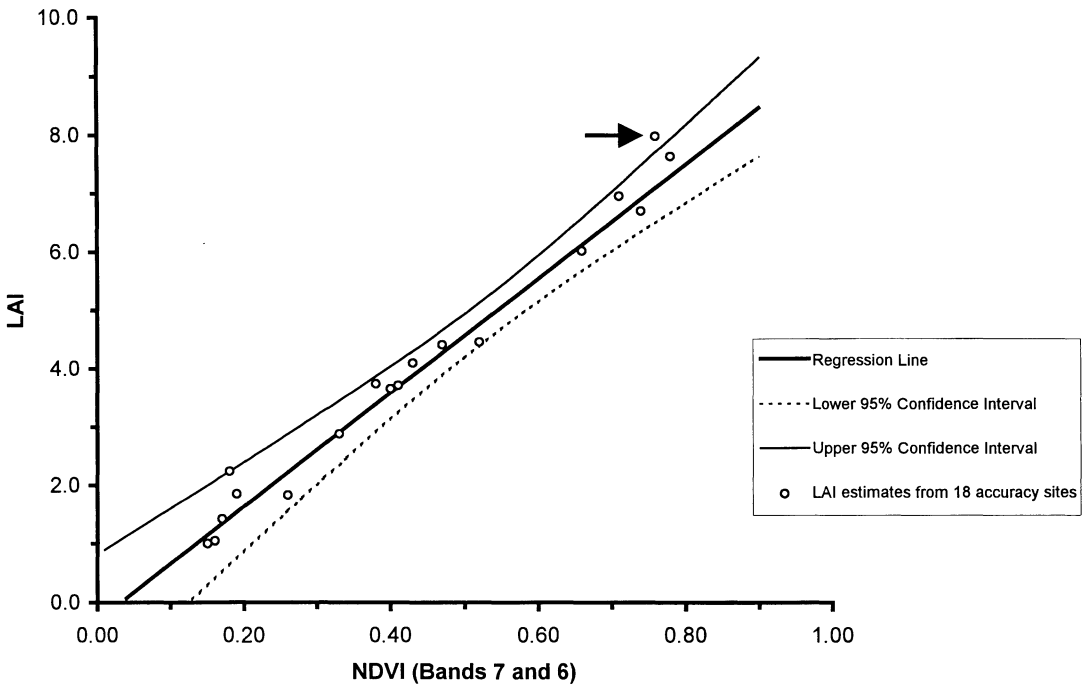


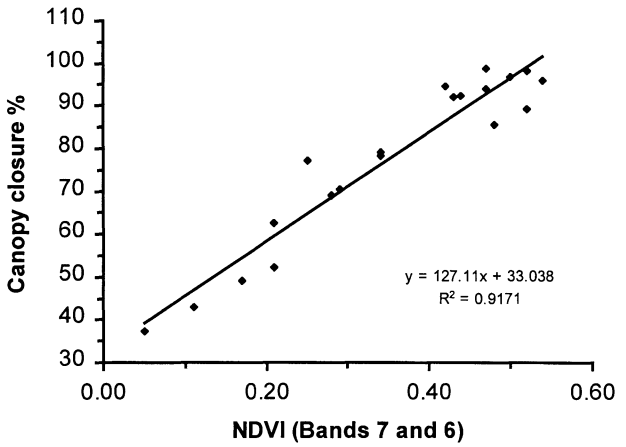
Figure 4a (Top). A scatter plot of LAI estimated from *in situ* measurements of mangrove canopy transmittance against NDVI derived from CASI data for 28 sites near South Caicos, Turks and Caicos Islands. A linear regression model has been fitted to the data and is significant at the 0.001 confidence level.

Figure 4b (Bottom). A plot of the 95% confidence intervals for the LAI regression model in Figure 4a. Values of LAI from 18 accuracy sites have been superimposed over this plot. The accuracy of the LAI image was defined as the proportion of 1996 accuracy sites at which the LAI value lay within the 95% confidence interval for that value of NDVI. For example, accuracy site number 9 (indicated by an arrowhead) has a NDVI of 0.76. At this NDVI the 95% confidence interval of a predicted value of LAI is 6.51–7.71. However, LAI at that site was estimated from measurements of canopy transmittance at 7.98. Therefore, accuracy site number 9 was not accurate. LAI's of the other 17 accuracy sites do lie between the appropriate confidence intervals. The accuracy of a thematic map which was created using the regression model in Figure 4a to convert NDVI to LAI would therefore be 94%.

The accuracy of the percent canopy closure image was 80%; this was assessed in the same manner as the LAI image (Figure 5b). The mean difference between predicted canopy closure and the *in situ* measured value was just 4% for the accuracy sites.

DISCUSSION

The technological advances which have produced new sensors such as CASI stimulate such great expectation that the user's accuracies presented in Figure 3 have to be interpreted in a proper context. A comparison of the descriptive resolution of CASI to satellite sensors is difficult because only three accuracy assessments for classifications of remotely sensed mangrove data are known to the authors. Despite this a quick comparison shows that with a similar approach higher accuracies are obtained from CASI data (Table 5). VITS and TACK (1995) achieved an average user's accuracy of 73% for four mangrove classes from SPOT XS. Water, which unsurprisingly classified 100% accurately, was included in this assessment. A more meaningful assessment would exclude water, and would certainly generate a lower accuracy as more than a quarter of their accuracy sites were over water. Here



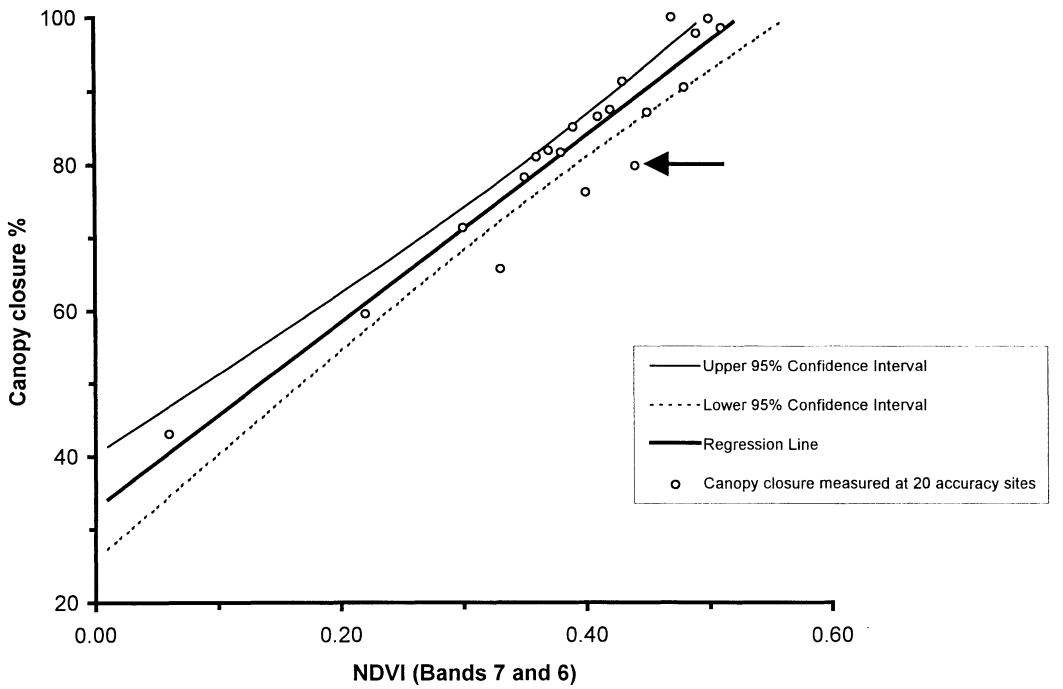


Figure 5a (Top). A scatter plot of percent canopy cover from *in situ* field measurements against NDVI derived from CASI data for 20 sites near South Caicos, Turks and Caicos Islands. A linear regression model has been fitted to the data and is significant at the 0.001 confidence level.

Figure 5b (Bottom). A plot of the 95% confidence intervals for the canopy closure regression model in Figure 5a. *In situ* measured values of percent canopy from 20 accuracy sites have been superimposed over this plot. The accuracy of the canopy closure image was defined as the proportion of 1996 accuracy sites at which the *in situ* measured value of canopy closure lay within the 95% confidence interval for that value of NDVI. For example, accuracy site number 4 (indicated by an arrowhead) has a NDVI of 0.40. At this NDVI the 95% confidence interval of a predicted value of canopy closure is 80.9–83.8%. However, canopy closure at that site was measured at 76.2%. Therefore, accuracy site number 4 was not accurate. Canopy closures of 16 accuracy sites do lie between the appropriate confidence intervals. The accuracy of a thematic map which was created using the regression model in Figure 5a to convert NDVI to canopy closure would therefore be 80%.

water was excluded and an average user's accuracy of 72% was obtained for a greater number of mangrove classes (six). It is reasonable to conclude then that the superior spatial and spectral resolution of CASI permits classification of the data to a higher level of accuracy and detail than can be obtained from satellite sensors.

At this point it is worth emphasising that all accuracy assessments must be interpreted in the light of the number and nature of the categories into which the data have been classified. An operator will select a level from a hierarchical scheme of habitat categories to which the data will be classified. The scheme used here to direct the classification of the CASI imagery was based on six mangrove categories which were <85% similar (Figure 1). At higher levels of similarity

Habitat Categories	*Conocarpus erectus*	*Avicennia germinans*	short mixed mangrove	tall mixed mangrove	non-mangrove	row total
Conocarpus erectus	10	1	2	1		14
Avicennia germinans		24	1	2	3	30
short mixed mangrove		5	19	1		25
tall mixed mangrove		1	1	50		52
non-mangrove	1	2	5		59	67
column total	11	33	28	54	62	188
producer's accuracy (%)	90.9	72.7	67.9	92.6	95.2	
user's accuracy (%)	71.4	80.0	76.0	96.2	88.1	
overall accuracy (%)	86.2					

Figure 6. Accuracy matrix for the CASI image which has been classified to four mangrove habitat categories <75% similar and one other, non-mangrove vegetation. *Conocarpus erectus* and *Avicennia germinans* categories are the same. Short, high density *Rhizophora mangle* and short mixed mangrove, high density, have been merged to create a short, mixed mangrove category. Likewise, tall, low density *Rhizophora mangle* and tall mixed mangrove, low density, have been merged to create a tall mixed mangrove category; sand, mud crust and *Salicornia* spp. to create non-mangrove. Average user's accuracy and overall accuracy are higher (82.3 and 86.2% respectively) as a result of classifying the data into fewer classes.

the field data do not define ecologically meaningful categories: in other words the maximum descriptive resolution of CASI was tested by selecting categories at the highest level of sensible similarity (for this area). These categories can be distinguished at an average user's accuracy of 72%. A scheme comprising fewer categories would be expected to improve accuracy, as is indeed the case: an average user's accuracy of 83% can be obtained from the data by selecting a scheme of four categories are <75% similar (Figure 6). Accuracy is higher because confusion between similar categories (such as short, high density *Rhizophora mangle* and short mixed mangrove, high density) is being avoided. As already noted in Table 5 very high accuracies of 89–94% can be achieved if the data are reduced further to just two categories.

Stands of single species are spectrally separable from stands of different species and stands of mixed species: monospecific groups of *R. mangle, A. germinans,* and *C. erectus* can be distinguished from each other. Species identification within a mixed species stand is not possible with CASI even at this resolution. Recent research in coniferous forests suggests that this would only be possible using high resolution (<50 cm) aerial infrared photography (MEYER *et al.,* 1996).

Table 5. *A comparison of overall accuracy achieved in mangrove classification from CASI and two types of satellite sensor.*

Categories	Tall	Short
Comparison with Palaganas (1992): accuracy 81%		
Tall mangrove	19	9
Short mangrove	4	89
Overall accuracy (%)	89.3	
	Mangrove	Non-mangrove
Comparison with Biña *et al.* (1980): accuracy 85%		
Mangrove	118	3
Non-mangrove	8	59
Overall accuracy (%)	94	

The accuracy data have been reworked into two categories: (i) tall and short mangrove for comparison with the results of Palaganas (1992), who classified SPOT XS into primary and secondary mangroves, (ii) mangrove and non-mangrove for comparison with the results of Biña *et al.* (1980) from Landsat MSS. Numbers are number of sites per category. In both cases, accuracies from classified CASI data are higher

LAI can also be estimated from CASI data at a greater level of accuracy than is possible from SPOT XS (94% as opposed to 88%, GREEN *et al., manuscript*). LAI can be used to model various ecological processes in mangrove forests. To continue the example discussed in GREEN *et al.* (*manuscript*) it would be a relatively straightforward task in a GIS to combine values for the average rate of photosynthesis of *R. mangle, L. racemosa, A. germinans* and *C. erectus,* the species composition of each mangrove category and LAI of the area to calculate the photosynthetic production of the whole mangrove canopy.

The results presented here must also be examined in the context of the area covered. The area in Figure 2 is slightly more than 0.5 km^2. Although classification and calibration of CASI imagery can be carried out at higher accuracies than satellite data, the latter cover an area which is approximately 10^4 or 10^5 times as large. There appears to be a tradeoff between accuracy and coverage to which careful consideration should be given when planning a remote sensing campaign. CASI is also relatively expensive in both financial cost and processing time. For example, in the Turks and Caicos study CASI costs (£ sterling km^{-2}) were approximately 400 times as much as SPOT XS whilst acquisition and correction of imagery took about twice as long (GREEN *et al.,* in press). A complete account of all the costs associated with the CASI campaign and a comparison of cost-effectiveness between different sensors will be the subject of a forthcoming paper. MUMBY *et al.* (in press) explain some important practical considerations to the use of CASI for the assessment of reefal habitats which apply in equal measure to mangrove areas. Although CASI offers extremely high spatial resolution, great care should be taken to decide whether high resolution is really necessary. Reducing pixel size from (say) 3 m to 1 m will have a direct effect on the width of the area surveyed along each flight line (approx. 1.5 km to 0.5 km). At a resolution of 1 m the error present in each position fix, even with a DGPS, means that site specific information has to be analyzed from a 5 × 5 block of pixels. Other considerations include (i) the

ratio of useful signal to noise which tends to be less for small pixel sizes, (ii) the frequent need to smooth images through filtering to facilitate visual interpretation of the final product, and (iii) reduced spectral resolution (8 rather than 18 bands for CASI). Weighed against these considerations is the ability to detect small, subtle features, for example the area of *Rhizophora* expansion.

High spectral resolution and the ability to select the location and width of the bands are considerable advantages to CASI, though ancillary data will frequently be necessary to exploit this feature fully. It is clear from the work of RAMSEY and JENSEN (1995; 1996), who have modelled mangrove canopy reflectance in Florida at species compositions very similar to the Turks and Caicos, that there is a sharp increase in reflectance at wavelengths of 710–720 nm (the mangrove red edge). In hindsight a better configuration for CASI might have been to place two red bands and two infrared bands either side of this red edge (*i.e.* at approximately 680–690, 700–710, 720–730 and 740–750 nm). Bands 7 and 6 were either side of the red edge and this probably explains why NDVI calculated from them was a better predictor of LAI and canopy closure than the more spectrally distant Bands 8 and 5. One practical consequence of high spectral (and spatial) resolution is that hardware must be capable of handling large amounts of data. CASI files, even of small areas, are relatively large: the file from which Figure 2 was produced was 47 MB. Another consequence of high spectral resolution is that image processing time can be complicated and considerably extended as a result of the various combinations of bands which can be used to generate signatures, calculate indices etc. Undoubtedly high spectral resolution can be immensely useful but again readers need to be aware of these realities.

Mangrove areas can be assessed using CASI imagery to a level of detail and accuracy which does appear possible with satellite multispectral sensors. Using an airborne sensor offers many advantages over systems carried on satellite, and if the end use of a particular project warrants the type of consideration discussed here, then CASI can be an effective and highly appropriate tool for the assessment of mangrove areas.

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