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The cost-effectiveness of remote sensing for tropical coastal resources assessment and management

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Although coastal habitat mapping is expensive, remote sensing is a more cost-effective technique than alternative field-survey methods (where effectiveness is defined as overall map accuracy). Satellite imagery is suitable for coarse detail habitat mapping where overall accuracies of c. *70% can be achieved but is inadequate for fine detail mapping, achieving* c. *40% accuracy. Four types of cost are encountered when undertaking remote sensing: (1) set-up costs, (2) field survey costs, (3) image acquisition costs and (4) the time spent on analysis of field data and processing imagery. The largest of these are set-up costs such as the acquisition of hardware and software which may comprise 48–78% of the total cost of the project depending on specific objectives. For coarse-detail habitat mapping with satellite imagery, the second highest cost is field survey which can account for* c. *20% of total costs and >80% of total costs if a remote sensing facility already exists. Field survey is a vital component of any habitat mapping programme and may constitute* c. *70% of project duration. For mapping small coastal areas (<60 km in any direction) in coarse detail, SPOT XS is the most cost-effective satellite sensor, but for larger areas Landsat TM is the most cost-effective and accurate sensor. Detailed habitat mapping should be undertaken using digital airborne scanners or interpretation of colour aerial photography (API). The cost of commissioning the acquisition of such imagery can be high [£15 000–£27 000 (US$24 000–$43 000) even for small areas of 150 km^2] and may constitute 27–40% of total costs (64–75% if set-up costs are excluded). Acquisition of digital airborne imagery is more expensive than the acquisition of colour aerial photography but is offset against the huge investment in time required to create maps from API. If habitat maps are needed urgently, API may be prohibitively time-consuming. For small areas of say 150 km^2, a map could be created within 25 days using CASI but might take six times longer to create using API. We estimate that API is only cheaper if the staff costs for API are considerably less than £80 day^{-1}. As the scope of the survey increases in size, the cost of API is likely to rise much faster than that arising from digital airborne scanners. If the costs of API and digital airborne scanners are similar, the latter instruments should be favoured because they are likely to yield more accurate results than API.*

Keywords: coastal management, coral reef, seagrass, mangrove, cost-effectiveness, remote sensing.

Introduction

Coastal habitat maps are widely regarded to be an essential data source for coastal management planning (Kenchington and Claasen, 1988; Cendrero, 1989; McNeill, 1994) yet there is little consensus of opinion on the cost-effectiveness of remote sensing methods used to create such maps. In a review of relevant literature (Green *et al.*, 1996), we found that more than a third of papers (31/86) considered remote sensing to be a cost-effective means of mapping tropical coastal habitats. However, when 60 coastal managers from tropical areas were questioned on their uptake of remote sensing methods, 70% considered cost to be the main hindrance to using remote sensing (Mumby, unpublished data).

Reconciling the issue of cost-effectiveness is complex. Few recent papers (if any) have presented an analysis of costs and any generic discussion of cost-effectiveness is limited by the large number of variables to take into

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account including mapping objectives, hardware availability, size of the study site, technical expertise of staff, cost of data acquisition (remote sensing method), intended accuracy of output maps and so on. These difficulties notwithstanding, an objective assessment of cost-effectiveness is urgently needed if coastal managers are to make appropriate choices when faced with the growing plethora of remote sensing technologies (reviewed in Stoney and Hughes, 1998), many of which have strikingly different capabilities (Mumby *et al.*, 1997b).

We draw on a case study from the Turks and Caicos Islands (TCI, British West Indies) to evaluate the relative cost-effectiveness of the most widely-used remote sensing methods for coastal habitat mapping. These include the satellite sensors, Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), SPOT multispectral (XS), SPOT Panchromatic (Pan) and two airborne methods: 1:10 000 colour aerial photography and digital multispectral scanning using the Compact Airborne Spectrographic Imager (CASI). The spatial resolutions of these sensors range from 1 to 80 m, and their spectral resolutions range from 1 to 16 bands. Costs are determined for various types of habitat mapping and degrees of field survey, and effectiveness is determined as the accuracy of output habitat maps (reviewed in Congalton, 1991). Two types of habitat mapping are considered: coarse habitat resolution (e.g. coral, seagrass, algae, sand, mangrove) and fine habitat discrimination (e.g. assemblages of coral reef organisms, seagrass standing crop, mangrove assemblages; for more details see Green *et al.*, 1998a, b; Mumby *et al.*, 1997a, b). Cost-effectiveness is evaluated first in the light of alternative methods of habitat mapping and second, between remote sensing methods. We argue that habitat mapping is expensive but that remote sensing is the most cost-effective method available.

Cost-effectiveness of remote sensing compared to alternative methods

The only alternative to remote sensing for mapping marine and shoreline habitats is use of boat-based or land-based surveys where the habitat type is recorded at each point in a grid and boundaries are fitted using interpolation methods (Figure 1). Unlike remote sensing methods, which sample the entire seascape, errors arise from sampling a grid of points because of the possibility of overlooking some habitats between adjacent survey sites. The probability of missing habitats decreases if a finer grid is surveyed, but a finer grid requires much greater survey effort. If say a 10% risk of missing boundaries is tolerated, the appropriate sampling density is approximately half the mean distance between habitat boundaries (Burgess and Webster, 1984a, b).

By calculating the spatial frequency (average patch size) of habitats on the Caicos Bank we were able to estimate the costs of using a boat survey to achieve maps of similar detail to those obtained using remote sensing. The analysis is conservative with respect to the boat survey because an additional reconnaissance survey of boundary spacings would be required to plan the sampling strategy for a purely boat-based survey. Using remotely sensed data as a surrogate reconnaissance survey makes the seemingly fair assumption that remotely sensed data reveal the boundaries between habitats, although this does not include the unrealistic notion that the habitats are identified correctly. At the scale of the Caicos Bank (15 000 km^2), coarse descriptive resolution (corals, seagrass, algae, sand) is more feasible than detailed habitat mapping (e.g. coral assemblages, seagrass standing crop) and data from the sensor Landsat TM were used to estimate mean boundary spacings from 2650 polygons on the image.

For a 10% risk of missing boundaries, the interval for a synoptic boat survey of the Caicos Bank mapping at a coarse descriptive resolution would be 152 m, which translates to *c.* 190 000 sites at an estimated cost of £380 000.[1] This would take a survey team of three more than 8·5 years to complete!

At the scale of marine protected areas (MPA median size = 16 km^2; Kelleher *et al.*, 1995),

[1]Costs assume 60 sites surveyed day^{-1} over the Caicos Bank but 150 sites day^{-1} in a small 16 km^2 area. Boat cost £125 day^{-1} including the captain's salary. Readers wishing to make an approximate conversion between UK pounds sterling and US dollars, should multiply costs given here by 1·6.

2. Point habitat data are entered into mapping software.

A	A	A	B	B	B	B	B	C	C
A	C	C	C	C	B	B	B	C	C
C	C	C	C	C	C	B	B	C	C
C	C	A	A	A	B	B	B	B	C
B	B	A	A	A	B	B	C	C	C
B	B	B	A	A	A	C	C	B	D
D	D	D	D	A	A	A	D	D	D
D	D	D	D	D	C	A	A	D	D
C	C	D	D	D	C	A	A	B	D
A	C	D	D	A	A	A	A	B	B

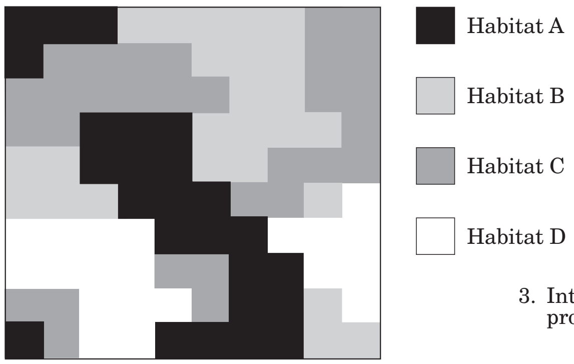

Figure 1. Overview of boat-based habitat mapping methods. A three-person team collect field data which are categorized by habitat type and interpolated to create a thematic habitat map.

where detailed habitat mapping is more feasible, CASI would be a more appropriate remote sensing method than Landsat TM (Mumby *et al.*, 1998a). Although the mean boundary spacing of habitats will vary according to the location of the MPA, a mean boundary spacing of 20 m was obtained from CASI data of a representative fringing reef and lagoon in the TCI (Cockburn Harbour). However, a corresponding grid spacing of 10 m would barely be possible, given the 5 m positional errors of differential global positioning systems (August *et al.*, 1994). A more realistic grid spacing of 25 m (half the mean boundary spacing of dense seagrass which had the largest patches) would still require 25 600 points, taking a team of three surveyors 170 days and would cost *c.* £21 250 in boat charges. To utilize CASI for such a small area would be approximately half this cost (£12 000) and field survey would be reduced to 1 day. Although image analysis may take about a month, boat-based survey would still be less accurate, more expensive, and involve an extra 16 person months of effort.

In summary, while almost 70% of ques-

Table 1. The cost of mapping submerged marine habitats based on a case study of 150 km^2 in the Turks and Caicos. The relative proportions of set-up (S), field survey (F) and image acquisition (I) costs are given for two scenarios—the costs required to start from scratch (i.e. including set-up costs) and the cost given existing remote sensing facilities (excluding set-up costs). API = aerial photograph interpretation. To convert costs and time estimates to those pertinent to mapping mangrove habitats, subtract £1030 from each total cost and subtract 57 days from each time estimate. The main assumptions of the table are given below.

	Landsat						SPOT						Airborne			API		
All costs (£)	MSS			TM			XS			Pan			MSS					
Total costs incl. set-up		41 030			42 820			42 270			42 670			66 870			56 370	
Cost component	S	F	I	S	F	I	S	F	I	S	F	I	S	F	I	S	F	I
% total cost	78	21	1	75	20	5	76	21	3	75	21	4	48	13	39	57	16	27
Total costs excl. set-up		8930			10 720			10 170			10 570			34 770			24 270	
Cost component	F		I	F		I	F		I	F		I	F		I	F		I
% total cost	98		2	82		18	86		14	83		17	25		75	36		64
Time taken (per day)		97			98			97			95			94			229	

Set-up costs assume that a full commercial image processing software licence is purchased and that the software is run on an UNIX workstation. Field survey costs assume that a differential GPS is included, that 170 ground-truthing sites and 450 accuracy sites are visited, and that boat costs are £125 day^{-1}. Estimates of time are based on a three person survey team and include the time required to derive habitat classes from field data and process imagery/photo-interpret and digitize photographs into a geographic information system.

tionnaire respondents considered the cost of remote sensing to be a main hindrance to using it for coastal habitat mapping, the issue is not that remote sensing is expensive but that habitat mapping is expensive. Remote sensing is just a tool which allows habitat mapping to be carried out at reasonable cost. Therefore, the main issue facing practitioners is, ‘Which is the least expensive remote sensing method to achieve a given habitat mapping task with acceptable accuracy?’.

The overall cost of remote sensing

Four main sources of expenditure are encountered during remote sensing: set-up costs (e.g. hardware and software), field survey, the time required for image processing (analysis) and derivation of habitat classes, and the cost of imagery. Specific costs will not be discussed here but a list is provided in Appendix 1. The overall costs of remote sensing have been simulated for an area of *c.* 150 km^2, based on the costs and time spent conducting a remote sensing project in the Turks and Caicos (Table 1).

Although set-up costs could be avoided by contracting consultants to undertake the work, this may prove to be a false economy given that much of the set-up equipment would be needed for an institution to make effective use of the output habitat maps in a geographic information system or image processing environment. Looking at the costs including set-up, it can be seen that imagery would represent a small proportion of the total cost (3–5%) if coarse-level habitat mapping using appropriate satellite sensors (Landsat TM and SPOT XS) was the objective. This rises to about 25–40% of project costs if accurate fine-level habitat mapping is required, in which case only digital airborne scanners (e.g. CASI) or aerial photograph interpretation (API) are adequate. If there are no set-up costs, the total costs fall dramatically and the acquisition of SPOT or Landsat TM satellite images account for between 10 and 20% of total costs. Field survey constitutes a significant proportion of remote sensing costs even if set-up costs are included.

How much field survey is required?

Field survey is an expensive but necessary aspect of remote sensing. Field data are needed to describe the habitats present in an

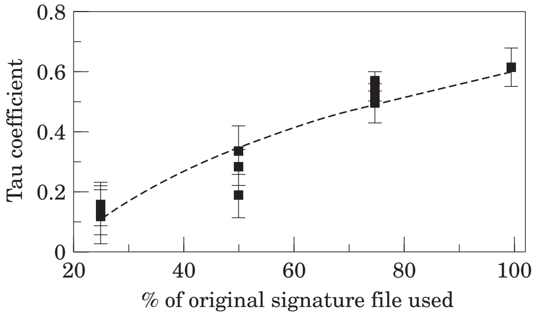

Figure 2. The effect of increasing amounts of fieldwork on classification accuracy expressed as the Tau coefficient (Ma and Redmond, 1995) for supervised multispectral classification of Landsat TM data at coarse habitat discrimination. Vertical bars are 95% confidence limits representing three random simulations.

area, identify the locations of habitats in the imagery (i.e. for interpretation of aerial photography or multispectral classification of digital data), and to provide an independent evaluation of the thematic accuracy of output maps (Congalton, 1991).

The derivation of habitat classes is discussed elsewhere (Mumby and Harborne, 1999) but the degree of survey effort will depend on the mapping objectives (descriptive resolution), size of the area and presence or absence of an existing habitat classification scheme (e.g. we surveyed 170 sites to create a classification of 13 habitats in the TCI).

It is difficult to give a generic estimate of the number of field sites required to classify remotely sensed data. However, in an empirical investigation, we used the TCI case study to examine the effect of various degrees of field work on the accuracy of marine habitat maps from Landsat TM. A total of 157 sites were used to ground-truth this image. To assess the effect of variable field data on accuracy, the supervised classification procedure (Mather, 1987) was repeated three times using a random sample of 25, 50, and 75% of these data (Figure 2). The accuracy of the resulting habitat maps was assessed using 450 independent data points.

The amount of field survey used to direct supervised classification profoundly influenced the accuracy of outputs although the increase in accuracy between 75 and 100% of field survey inputs was not significant (Figure 2). Seventy-five percent of the signature file in Figure 2 would give about 30 sites per class at coarse habitat discrimination (four habitat classes).

Although ground-truthing requirements may vary, it is imperative that an adequate number of sites are visited for accuracy assessment. Congalton (1991) recommends at least 50 independent sites per habitat.

How much image analysis is required?

A wide variety of image processing methods exist and the effects of conducting some of these are presented in Figure 3 (for more details on the methods refer to Green *et al.*, 1998a; Mumby *et al.*, 1998b). Two key points emerge from this figure: firstly, to achieve acceptable accuracy a considerable investment in staff time is required; approximately 1 month for Landsat TM (and other satellite imagery such as SPOT XS), and about 1·5 months for CASI or similar airborne imagery; secondly, increased image processing effort generally leads to increasing accuracy of outputs. A notable exception to this rule is the merging of Landsat TM data with SPOT Pan to increase spatial resolution. Although the merge produces visually pleasing outputs, the loss of spectral data during the intensity-hue-saturation merge (Mather, 1987) actually reduced accuracies (Green *et al.*, 1998a). Given the costs of inputs such as field survey data and set-up costs, extra effort devoted to image processing is worthwhile.

The relative cost-effectiveness of remote sensing methods

Whether a practitioner aims to map marine or terrestrial habitats, the choice of satellite vs. airborne sensors depends on the level of habitat detail required. If coarse descriptive resolution (e.g. corals/seagrasses; mangrove/non-mangrove) is all that is required, satellite sensors will be the most cost-effective option and reasonable accuracy (~60–80%) should be expected (Mumby *et al.*, 1997b; Green *et al.*, 1998a). For detailed habitat mapping, however, airborne remote sensing methods are far more likely to provide results of high

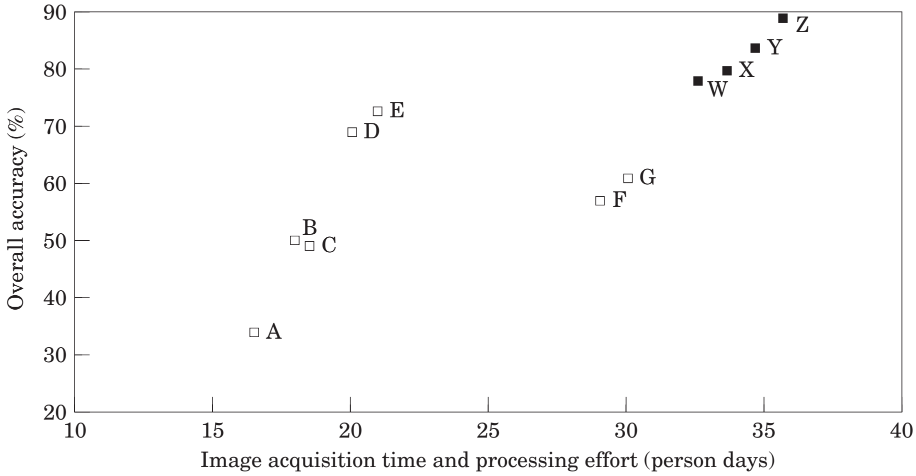

Figure 3. The relationship between the overall accuracy of marine habitat maps of the TCI and the time required in preparation from Landsat TM (and TM/SPOT Pan merge) and CASI data at coarse (□) and fine (■) levels of habitat discrimination, respectively. Time includes image acquisition, correction, image classification and the merging of SPOT Pan with Landsat TM data. Five levels of image processing effort were applied to Landsat TM alone: A = unsupervised classification of raw (DN) data; B = supervised classification of raw (DN) data; C = unsupervised classification of depth-invariant data; D = supervised classification of depth-invariant data, without contextual editing; E = supervised classification of depth-invariant data, with contextual editing. Depth-invariant Landsat TM data were combined with SPOT Pan to increase the spatial resolution, and the resultant merged image classified in two ways: F = supervised classification of merged image, without contextual editing; G = supervised classification of merged data, with contextual editing. Four levels of image processing effort were applied to CASI: W = supervised classification of raw (reflectance) data, without contextual editing; X = supervised classification of raw (reflectance) data, with contextual editing; Y = supervised classification of depth-invariant data, without contextual editing; Z = supervised classification of depth-invariant data, with contextual editing.

accuracy (Mumby *et al.*, 1998b). Therefore, the comparison between satellite and airborne methods is somewhat irrelevant because they are used to achieve different descriptive resolutions. Thus, the cost-effectiveness of satellite sensors and airborne sensors are compared separately. Data are presented for mapping marine habitats but a similar conclusion would be reached had we used data for mangrove mapping.

Satellite-borne sensors

The time required to process an individual satellite image does not vary substantially from sensor to sensor (Table 1) and therefore, the most cost-effective solution depends on the cost of each image and the accuracy achievable. Figure 4 compares the cost and expected map accuracy resulting from various satellite sensors for study sites of various magnitude. For areas less than 3600 km^2, SPOT XS is slightly more cost-effective than Landsat TM: the small (6%) rise in accuracy from SPOT XS to Landsat TM would cost *c.* £550 (i.e. just under £100 per 1% rise in accuracy). However, once the study site is too large to fall within a single SPOT scene (60 × 60 km), the cost-effectiveness of SPOT is drastically reduced. For example, an area of 15 000 km^2 would easily fit within a single Landsat TM scene (total cost *c.* £2700) while requiring five SPOT XS scenes (total cost c. £8300). In this case study, Landsat MSS could only be considered cost-effective if an overall accuracy of *c.* 50% was considered acceptable. However, given that half the pixels might be incorrectly assigned, this seems unlikely to be the case.

Digital airborne scanners vs. aerial photography

It is difficult to assess the relative cost-effectiveness of airborne remote sensing methods because the cost of data acquisition is so case-specific. The accuracies of tropical coastal habitat maps resulting from digital

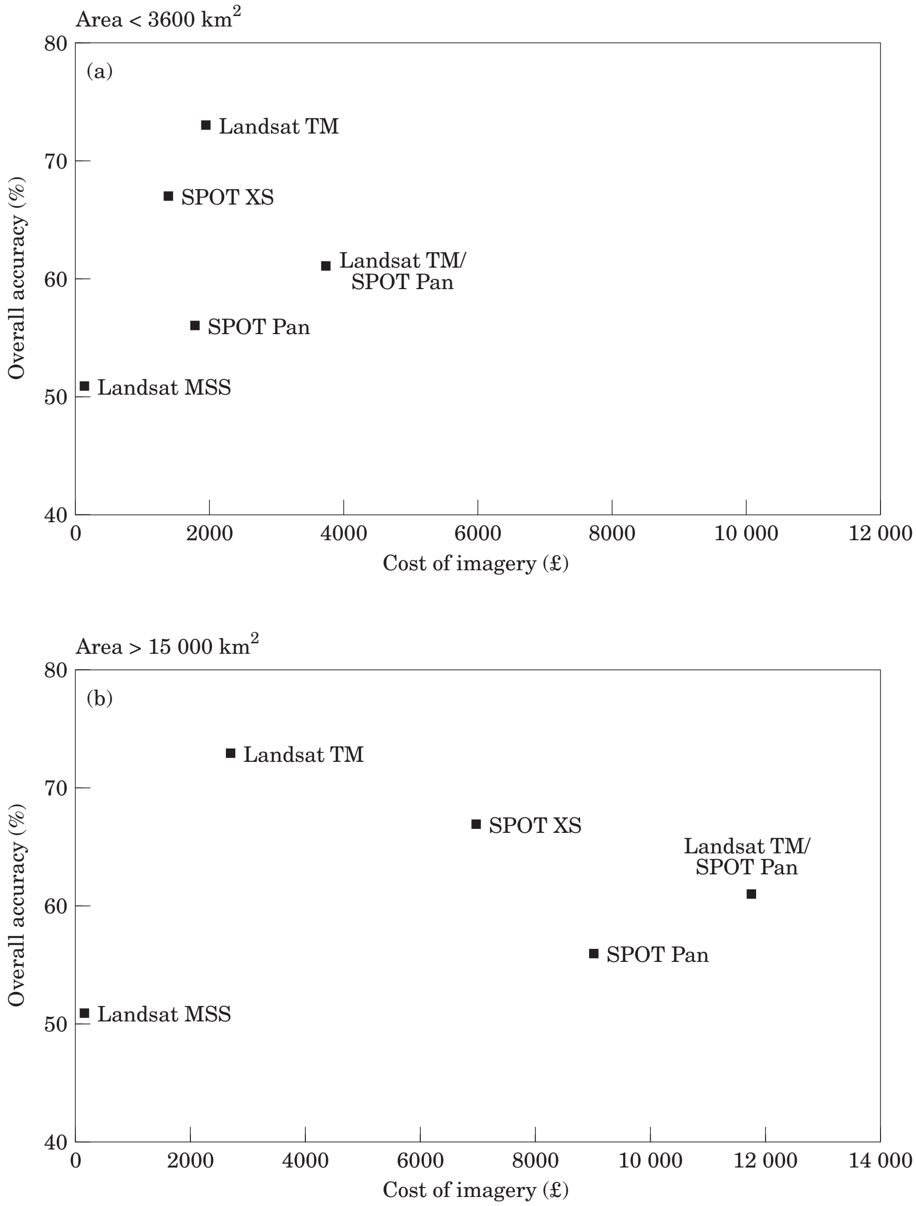

Figure 4. Cost-effectiveness of various satellite sensors for mapping coastal habitats of the Caicos Bank with coarse detail. (a) A small area within a single SPOT scene (3600 km^2), (b) represents a larger area comprising multiple (5) SPOT scenes.

scanners and aerial photographs have not been compared directly although Mumby *et al.* (1998b) made a tentative comparison of CASI data from the TCI and the results of Sheppard *et al.* (1995) in Anguilla using 1:10 000 colour aerial photography. We concluded that CASI is at least as accurate and possesses greater spectral sensitivity than colour aerial photography (i.e. overall accuracies for fine habitat discrimination, *c.* 80% and *c.* 60%, respectively). Therefore, if the costs of acquiring and processing digital airborne data and aerial photography are similar for a given study, CASI is likely to be the most cost-effective option.

The relative costs of commissioning new aerial photography and digital airborne scanners were compared using four independent quotes for mapping a coastal area of approximately 150 km^2. The prices are based on a remote coastal area so a survey aircraft would have to be specially mobilized (in this case, leased from the US). Specifically, quotes were sought for 1:10 000 colour aerial pho-

Table 2. Cost of mapping a coastal area of 150 km^2 using CASI and 1:10 000 colour aerial photography interpretation (API). CASI is more expensive to acquire but, being digital, requires much less processing time post-acquisition. Processing time (person days) for CASI assumes that mosaicing and geometric correction are carried out by contractor. Processing time for API assumes that polygons are digitized by hand using conventional cartographic methods and a geographic information system

Method	Cost of acquisition (£)			Staff time required post acquisition (pd)	
	Quotes	Mean	CASI–API		API–CASI
CASI—3 m pixels	27 000	26 000		25	
	25 000				
			10 500		135
1:10 000 colour API	16 000	15 500		160	
	15 000				

tography and CASI imagery with 3 m spatial resolution (Table 2). This is a fairly small area and the time required to photo-interpret and digitize aerial photographs would be disproportionately greater for larger study sites. Although scanning of aerial photographs should increase the speed of map production by allowing digital classification techniques to be used, the effect of scanning on accuracy and processing time has not yet been evaluated.

This comparison between CASI and aerial photography assumes that set-up costs and fieldwork costs do not differ between studies. This seems to be a realistic assumption, particularly if the map derived from aerial photography is to be used within a geographic information system which often have similar hardware requirements and software costs to image processing software. Assuming that the costs and mapping rates given in Table 2 are representative, CASI is more expensive to acquire but map production from API requires a six-fold greater investment in staff time. The overall cost of the two methods would be equal if the photo-interpreter was paid *c.* £80 day^{-1} (£10 500/135 day^{-1}). If staff costs exceed £80 day^{-1}, CASI would be cheaper, whereas if staff time costs less than this figure, API would be cheaper.

In practice, the relative costs of map-making with digital airborne scanners and aerial photography are likely to differ between developed and less-developed nations. A consultant might charge in excess of £300 day^{-1}, whereas the average staff cost for a non-consultant would probably be about £80 day^{-1} in some developed countries and less than £80 day^{-1} in some developed and most less-developed countries. Given that the accuracy of the final map is likely to be greater if a digital airborne scanner is used, it is probably only cost-effective to commission aerial photography when staff costs are appreciably less than £80 day^{-1}. As pointed out above, the disparity in time required to create habitat maps from airborne scanners and API will increase with size of the survey (i.e. as the scope of the survey increases, the cost of API is likely to rise much faster than that arising from digital airborne scanners).

A final consideration is the time required to deliver the final map, particularly if habitat mapping is being carried out to detect change in coastal resources (e.g. if investigating the effects of a pollution event or cyclone). If the extra time required to digitize aerial photographs is prohibitive, airborne scanners may be the only feasible solution.

Conclusions

Habitat mapping is an important activity for coastal management planning and although it is expensive, remote sensing is the most cost-effective method available. The Turks and Caicos Islands are an ideal site for remote sensing of coral reefs and seagrass beds because the banks are relatively shallow (average depth *c.* 10 m) and the water clarity is high (horizontal Secchi distance 30–50 m). Therefore, the accuracies quoted here for habitat maps are likely to represent the maximum accuracies possible for such habitats. With this caveat in mind, SPOT XS and Landsat TM are the most cost-effective means of mapping with coarse descriptive resolution. Airborne methods can provide significantly more detailed information on coastal habitats and the choice of commissioning digital vs. photographic (analog) sensors depends on staff costs and the urgency of data acquisition. As a rule of thumb, aerial photography should only be selected if photographs can be manually digitized at a cost considerably lower than £80 day^{-1}.

Given the dynamic, technology-led nature of remote sensing this study needs a temporal context. Our focus here is current remote sensing technology in which digital airborne multi-spectral imaging represents the state-of-the-art. It is too early to evaluate the effectiveness of new high resolution satellite instruments (Stoney and Hughes, 1998) and digital video cameras but it is hoped that the current study sets a precedent against which their capabilities for mapping tropical coastal habitats may be judged in future.

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Appendix

Overview of cost and time considerations when planning a remote sensing facility or campaign

Direct capital expenditure divided into four orders of magnitude (£): XXXX (>10 000), XXX (1000s), XX (100s), X (10s). Staff time expressed as XXX (>50 days), XX (10–50 days), X (<10 days).

Activity set-up costs		Direct capital	Staff time
	UNIX workstation	XXXX	
	Computer memory (2 GB minimum)	XXX	
	Colour printer, ink, paper	XXX	
	8 mm tape drive & tapes	XXX	
	Software	XXXX	
	Reference books	XX	
	Charts & maps of area	XX	
	Archived aerial photographs	X	
Field survey			
	Boat hire, operator time, fuel	XXX	
	Staff time (2–3 persons/day)		XXX
	DGPS	XXX	
	Lap-top computer	XXX	
	Laminated prints of imagery	XX	
	Depth sonar	XX	
	Diving equipment	XX	
	Quadrats	X	
	Hemi-spherical densiometer[a]	XX	
	2 PAR light sensors & data logger[a]	XXX	
	Telescopic measuring pole[a]	XX	
Image acquisition			
	Purchase of satellite data	XXX	
	Seeking quotes for airborne data		X
	Commissioning of airborne data	XXXX	
Image processing and derivation of habitat classes			
	Corrections to imagery		X or XX
	Derivation of habitat classes		XX
	Image classification		X
	Mosaicing of aerial photographs		XX
	Aerial photograph interpretation		XXX
	Digitising polygons from photographs		XX
	Contextual editing		X
	Accuracy assessment		X

[a]Equipment required specifically for mangrove surveys.