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Evaluating benthic survey techniques for validating maps of coral reefs derived from remotely sensed images

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Abstract Field validation of maps derived from airborne or satellite imagery is essential to enable their use for monitoring and managing coral reef habitats. Methods of benthic survey in coral reef ecosystems have been documented elsewhere, yet a comparative evaluation of methods for integrating field data with remote sensing has not been completed. In addition to meeting standard field survey requirements, data for validation of maps produced from remotely sensed images have several unique requirements in terms of spatial coverage, timing, information content and positional accuracy. This study compares ten different methods used to determine benthic cover for verifying image-based maps in coral reef environments. At three locations the field survey techniques were applied to the same section of reef, under similar environmental conditions, to measure benthic cover characteristics. The techniques tested were: line intercept transect, point intercept transect, 0.5 x 0.5m quadrat with ten points; 0.5 x 0.5m quadrat visual estimates, photographic transect, photographs of 25 or five cells in a 5.0 x 5.0m grid and visual estimates of a 5.0 x 5.0m grid. Digital photographic analysis used two different methodologies based on 12 and 1024 point processing. The final comparison covered both field survey and data processing techniques, in terms of: benthic cover, time and cost, degree of expertise, spatial intensity and the power of the final result. From this comparison it was concluded that the photographic transect using 1024 point analysis was the overall best choice given no limits on resources and available expertise..This implies that the method is also sufficient for any imagery with lower spectral or spatial resolution. Our findings should enable scientists or managers to make a more informed selection of field survey for mapping and validating maps derived from remotely sensed data.

Keywords: Remote sensing, field validation, benthic surveys, digital photography

Introduction

Airborne and satellite remote sensing technologies are increasingly being used for monitoring coral reef habitats. To create accurate and reliable maps, calibration of mapping algorithms and validation of output maps is necessary (Green et al. 2000). A common limitation of most image based mapping of coral reefs, which may be responsible for its limited uptake by managers, is an inadequate or absent validation program (Ahmad and Neil 1994, Green et al. 2000, Holden and LeDrew 1998). A variety of benthic survey methods have been used for validation, such as visual checks (Mazel et al. 2003), line intercept (Andréfouët et al. 2004), video (Louchard et al. 2003) and digital still surveys (Joyce et al. 2004). The most effective technique to implement is not always obvious and there are numerous benthic survey methods from which to chose (English et al. 1997; Hill and Wilkinson 2004).

Extensive work has been completed on sample design and statistical requirements for field survey of benthos and validation of maps of terrestrial environments derived from remotely sensed images (Curran and Williamson 1986, Long et al. 2004, Stehman 1999). In contrast, there are few reviews addressing field validation techniques for maps of coral reefs derived from remotely sensed image data (Green et al. 2000). Coral reef survey methods for estimating the composition of benthos, along with its condition and cover have been assessed in detail in terms of their cost, time required, accuracy, precision and statistical power in a number of reef systems worldwide (Brown et al. 1999; Hill and Wilkinson 2004).

Validating maps of coral reef composition, coral condition and coral cover requires field survey data to possess certain attributes: a spatial and temporal match to the image data used to produce the map; georeferencing precision and accuracy; and a match in information content between field data and image based variables (Congalton and Green 1999). The standard techniques used in remote sensing for collecting validation data and performing accuracy assessments have been developed for use in terrestrial environments (Atkinson 1991; Atkinson and Curran 1997; Congalton and Green 1999;

Foody 2002; Menges et al. 2002). With few exceptions e.g. (Green et al. 2000), these validation data collection techniques have not been developed for use in multi-scale heterogeneous environments, such as coral reefs, where it is difficult to determine where and how intensively to sample. Standard image based accuracy assessment, correlation analysis and root mean square analysis techniques can be applied to image maps of coral reef environments. To ensure effective use of current and future remotely sensed data sets in shallow coastal and marine environments, such as coral reefs, there is a need for a validation data collection technique that adequately represents the composition, condition or cover of reef environments.

Collection of field validation is challenging in marine environments due to additional constraints of safety, water clarity, water depth, currents, remoteness and logistics on the field survey process (Green et al. 2000). The most appropriate benthic survey validation method to use will depend on the answers to the key questions detailed below.

What benthic classes do you need to survey?

Remote sensing techniques are capable of mapping coral reef communities (Palandro et al. 2003), geomorphic zones (Andréfouët et al. in press), and impacts such as bleaching (Andréfouët et al. 2002), with the most current research differentiating blue and brown coral types (Hochberg et al. 2003). Benthic classes can vary from species level to description of geomorphic zones.

What resources are available to conduct the survey?

This concerns available funding for: logistics, equipment and people and may range from a viewing bucket (Roelfsema et al. 2002) to underwater photography and video (Joyce et al. 2004)

What scale of the validation is required?

Determined by the area to be covered, the type of information to be mapped, and the spatial resolution of the sensor used (Andréfouët and Claereboudt 2000).

What type of reef environment is to be mapped?

The effectiveness of a survey is influenced by a number of factors, some of which include: water clarity, water depth, currents, and leeward or windward position. Protected areas can be accessed any time, others require careful planning. Surface and underwater conditions influence safety.

Existing field survey programs, if suitable for the type of mapping application, may also be used in the validation activities, reducing survey costs and effort. The aim of this study was, to provide a preliminary comparison of benthic field sampling methods for validating image based maps of coral reefs environments. We have attempted here to provide a basis to enable the choice of an optimum field data collection method for validating image maps. This should be of value for producers and users of satellite or airborne image based maps.

Study Sites and Methodology

Study Sites

Surveys were conducted at sites where the authors were involved in ongoing image and field data collection programs. These sites included: Flinders Reef in Moreton Bay, Australia (27º S, 153º E) and Heron Reef, in the southern Great Barrier Reef , Australia (27º S, 153º E) and Eagle Reef (27º S, 153º E) in Palau..

Benthic Classes

For this study the benthic classes mapped were chosen through a combination of previous research (Joyce et al. 2004) and Reef Check classification scheme (Hodgson et al. 2004). The classes used were: branching corals; massive corals; plate corals; encrusting corals; turf algae; macro algae; sand; coralline Algae; and other. The class interpretation in this study (underwater and above water) was conducted by the same observer to reduce classification error.

Transect and Grid Surveys

The survey methods chosen for the comparison originated from a variety of projects with which the authors have been involved with (Ford et al. 2003; Joyce et al. 2004; Joyce 2003; McMahon et al. 2002; Mumby et al. 2004; Phinn and Neil 1998; Roelfsema et al. in press).

The comparisons were based on either a 20m transect line (conforming to the Reef Check protocol (Hodgson et al. 2004) or a 5.0 x 5.0m grid (Mumby et al. 2004) (Fig. 1). For the transect line, a 20 m section of a standard 50 m measuring tape was used. The grid consisted of 25 one meter grid cells in a five by five grid constructed from thin ropes (Fig. 1).The grid was positioned, so that its diagonal was parallel to the transect line and the grid centre point placed on the 10 m mark of the transect line.

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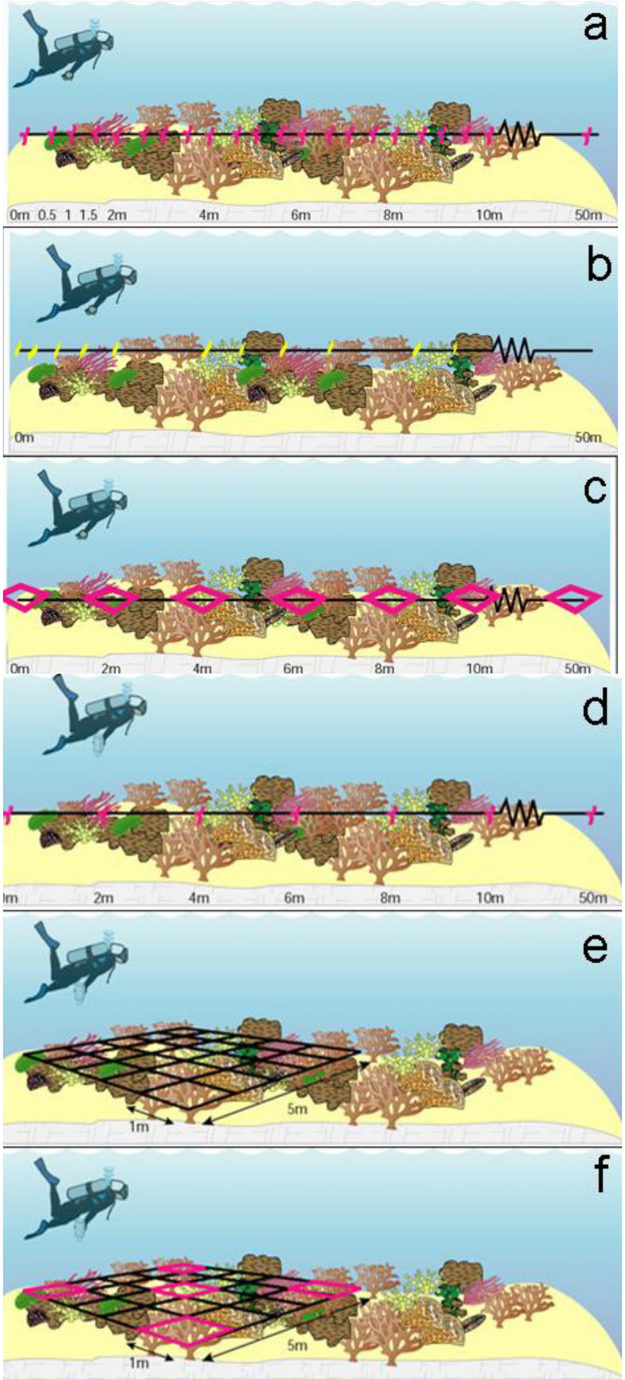

Fig. 1. Graphical depiction of the six benthic survey methods. a) Point intercept, b) Line intercept, c) Quadrat, d) photo transect, e) 5.0 x 5.0m grid with 25 cells and f) 5.0 x 5.0m with five grid cells (four corners and centre).

Percentage benthic cover was determined from in-situ assessment or from analysis of photographs from the transect and grid. Techniques for in-situ assessment were: point intercept, line intercept, quadrat (0.5 x 0.5m) estimate or ten points and visual estimates of a 5.0 x 5.0m grid. For photographic assessment, photos were captured of: the transect line, 25 cells or five cells (corner and centre cell) in a 5.0 x 5.0m grid.

Benthic Surveys – In-situ Assessment

Point Intercept

On the 20m transect at 0.5m intervals, benthic cover type observed directly under the measurement point and recorded on a dive slate. Percent cover of different benthic cover types for the transect was calculated by counting the occurrences of a benthic cover class on the transect line (Greig-Smith 1983; Hodgson et al. 2004) (Fig. 1a).

Line Intercept

Along each 20m transect the distance at which benthic cover changed from one cover type to another was recorded on a dive slate. Percent cover was calculated by determining the total distance on the transect covered by each class (English et al. 1997) (Fig. 1b).

Quadrat Estimate and 10 Point

On the 20m transect at 2.0m intervals a 0.5 x 0.5m quadrat was deployed. Percent benthic cover was determined for the quadrat using two techniques: a) visual estimate of percentage cover of the benthic cover classes for the complete quadrat, and b) determining benthic cover class for ten random points, marked within the quadrat, from which the percentage cover could be calculated (English et al. 1997) (Fig. 1c).

5.0 x 5.0m Grid Estimate

For the 5.0 x 5.0m grid, benthic cover was visually estimated for each of the 25 (1.0 x 1.0m) grid cells (Mumby et al. 2004) (Fig. 1e).

Benthic Surveys – Photographic Assessment

Field Component

For the digital photo surveys a SONY Cybershot PC9 4.3 megapixel in a Marine Pack underwater housing was used with a Sea and Sea 16 mm wide angle lens. The camera recorded images at medium resolution. For all surveys, photographs were captured of the benthos, from positioning the camera vertically at 1.5m above the bottom. The camera height above target was chosen to enable replication of a surface area of 1 x 1m within each image.

Photo Transects

A photograph was captured every 2.0m on the 20m transect line. The position of the photograph on the transect line could be determined by its number and/or reading the distance from the transect tape (Joyce et al. 2004) (Fig. 1d).

Photo of 25 or Five Cells (Four Corners and Centre) of 5.0 x 5.0m Grid

A photograph was captured of each of the 25 1.0m x 1.0m cells within the 5.0 x 5.0m grid. Each cell's photograph was followed by one of a magnetic slate with the cell number on it to determine the position of photo within grid (Fig. 1e) (Mumby et al. 2004). This method was repeated for only five cells (corners and centre cells) (Fig. 1f).

Photo Analysis

12 Point Photo

Benthic cover was determined for twelve points in a regular grid which was superimposed onto each photo. The regular grid was composed of three rows of four points at equal distance from each other. Twelve points were selected as the ‘optimum’ number for sampling after testing from 1- 40 points and observing the trade off between coral cover estimation accuracy and time spent in the analysis (Joyce et al. 2004). The benthic cover type was stored in a database using a customised graphical user interface in Microsoft Access. The database automatically calculates the percent cover as the proportional cover times 100, for each photo (Greig-Smith 1983; Joyce et al. 2004).

1024 Point Photo

Using the VidAna 1.0 (Hedley 2003) software package, polygons were drawn covering each benthic cover type present in the photo. Once the photo was covered, percent cover was automatically calculated by dropping a 1024 point regular grid onto the polygon and counting the number of points in each polygon (Hedley 2003).

Comparison of Field Survey Methods

The comparison of the field validation methods focussed on observed differences and similarities in percent benthic cover estimates, time and cost of survey, degree of expertise required for survey and analysis, sampling intensity, sampling power and non-quantifiable survey attributes.

Percent Benthic Cover

Percent cover for every class was calculated using the appropriate analysis technique for each survey method (English et al. 1997; Hedley et al. 2004; Hodgson et al. 2004; Joyce et al. 2004; Mumby et al. 2004).

Time and Cost

To determine the effectiveness of each survey method, time and air use of each dive were also noted for the different parts of the survey process in the field on a dive slate, e.g. deploying, surveying and retrieval. For the processing component, time was noted for downloading, interpretation and analysis of field notes and/or digital photos.

Cost was determined for the survey methods and their equipment needs. To place cost and time into perspective for the different field survey methods an example was established for a theoretical survey in a realistic mapping program. The case study focussed on validating the benthic cover for 25 sites at 5.0 m depth around Heron Reef. Prices were calculated based on personnel time, boat use and other necessary field equipment within compliance of local work place health and safety regulations.

Degree of Expertise

The degree of expertise required to complete the benthic survey method was determined by the authors. This was done by rating on a scale of one to five, the different components of the survey process, including planning and preparation; mobilisation to the field site; survey work; demobilising; and downloading and analysing the data). A rating of one represents minimum expertise, taking minimum time, effort and no special knowledge and skills.

Sampling Intensity for Satellite Image Data

In the context of this paper, sampling intensity was calculated as the surface area covered by the survey method, divided by the surface area of a pixel or the case study area. For example, the ratio between the surface area covered by each survey method and the surface area of a single 4.0 x 4.0 m Ikonos multispectral pixel or a single 30 x 30 m Landsat 7 (Enhanced Thematic Mapper plus) ETM+ pixel. For the case study area, Heron over the Heron Reef (28 km^2) image.

Power Analysis

Power analysis was conducted to measure the probability of several different benthic survey methods to correctly reject the null hypothesis (Ho), when Ho = no difference in coral cover % between two sample transects (Sheppard 1999). Previous power analyses of commonly used coral cover field measurement techniques were reported in Brown et al. (1999) for the Hawai’ian Coral Reef Assessment and Monitoring Program, indicating that fixed photo-quadrats had the highest statistical power, while the length of transect could be varied to maximise statistical power depending on the level of heterogeneity and coral cover in the area to be sampled. G-power software (Buchner et al. 1997) was applied to conduct a post-hoc power analysis on each of the ten survey methods using a two-tailed t-test ($\alpha = 0.05$) for comparing mean coral cover.

Results

Percentage Benthic Cover

Different study sites varied significantly in their benthic cover (Fig. 2). Each survey technique produced notably different results for Heron Reef which can be explained by the higher degree of spatial heterogeneity at this site in comparison to Eagle (Palau) and Flinders Reefs. For Palau and Flinders Reef, the methods gave comparable results. For Heron Reef, observed variations in percent-cover of coral was dependent on the method used. Estimation of percent benthic cover from photos using 1024 points showed similar cover distributions to the 12 sample point method on Heron Reef. The results for Eagle and Flinders Reef data (resulting from photo interpretation) were similar to the results of other methods.

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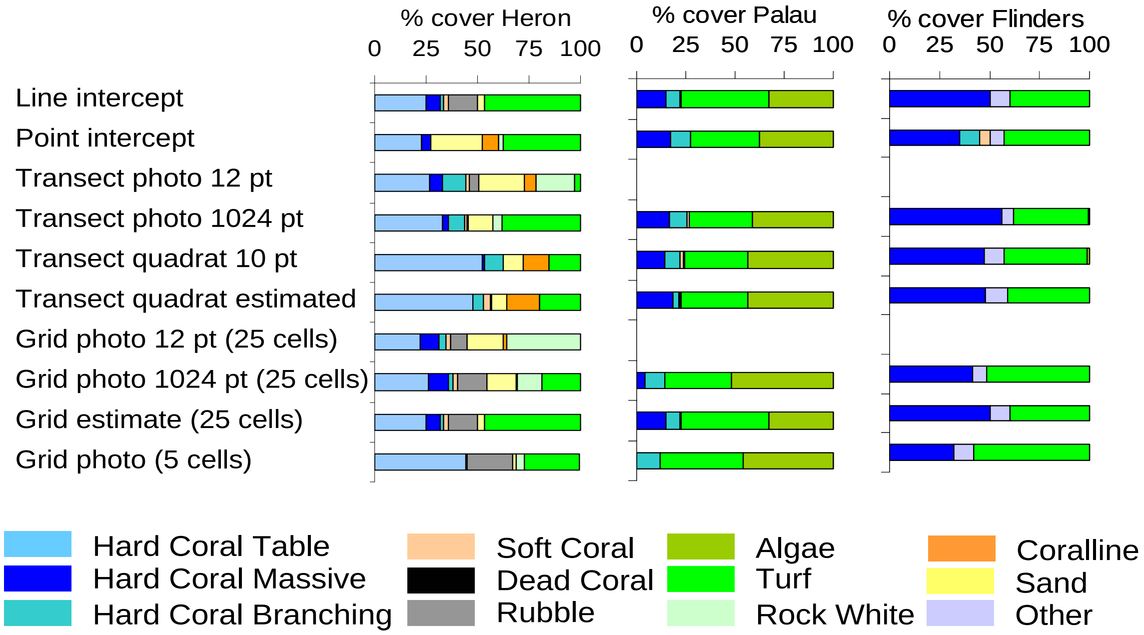

Fig. 2. Percent benthic cover recorded for eachof the three sites for each survey method.

Time and Cost

All survey methods took a similar amount of time for one site, with the obvious difference being the extra time needed for analysing photos (Fig. 3).

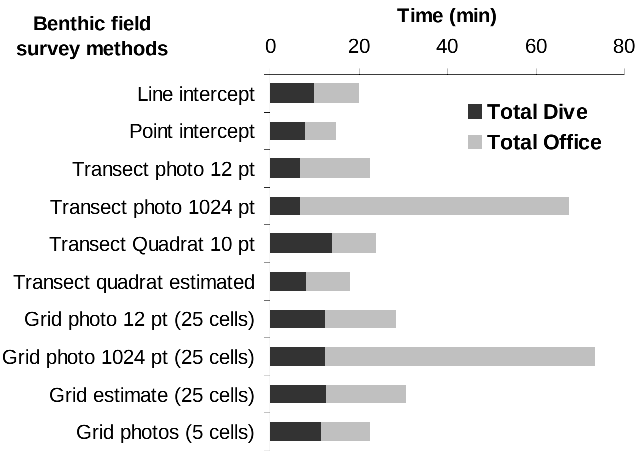

Fig. 3. Time needed to conduct survey and processing for one site per benthic survey method

From Fig. 4 it can be seen that, in the case of the theoretical study of 25 sites, the field cost is similar for almost all methods and is the highest in relation to analysis and equipment cost. This is due to the cost of diving and boating time and personnel. As a rough comparison, the cost of boat based video survey was added into Fig. 4 for reference. For this survey type a visual benthic assessment was made from a monitor in the boat so that nobody has to enter the water.

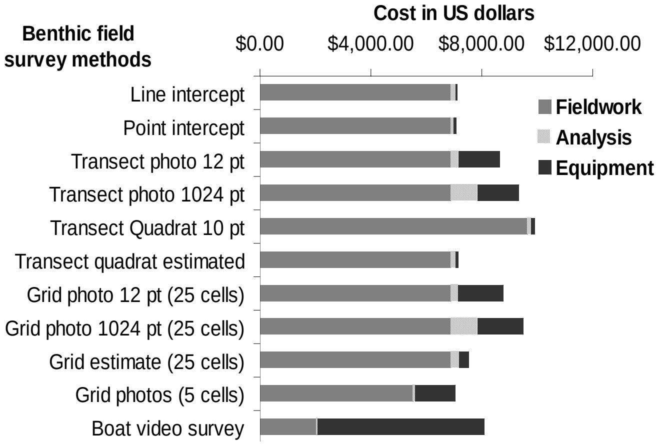

Fig. 4. Estimated cost for validating 25 sites at Heron Reef for each benthic survey method. Boat based video survey was added to the cost comparison since no diving and snorkelling is involved.

Degree of Expertise

Benthic survey methods using a grid were ranked the highest in terms of skill level required for data collection and analysis (Fig. 5). All photo-based survey methods also required a high degree of expertise. Line and point intercept methods were the easiest to conduct in relation to grid photo with 1024 point interpretation.

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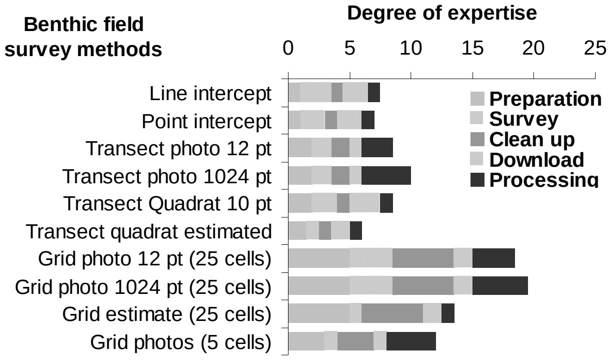

Fig. 5. Degree of expertise required to conduct survey and processing for each form of benthic survey method. Each stage of the survey and processing was scaled on score of one to five, where one was considered minimum expertise needed and five the maximum.

Sampling Intensity for Satellite Image Data

Fig. 6 shows two different groupings: one group contains line intercept, point intercept, transect photo 12 point, transect quadrat 10 point, and grid photo 12 point. A second group includes: transect photo 1024 point, transect quadrat estimated, grid photo 1024 point, grid 5 cell photo, grid 5 cell estimate. Only the transect photo 1024 point and the grid methods have a 100% sampling intensity for the Ikonos pixel.

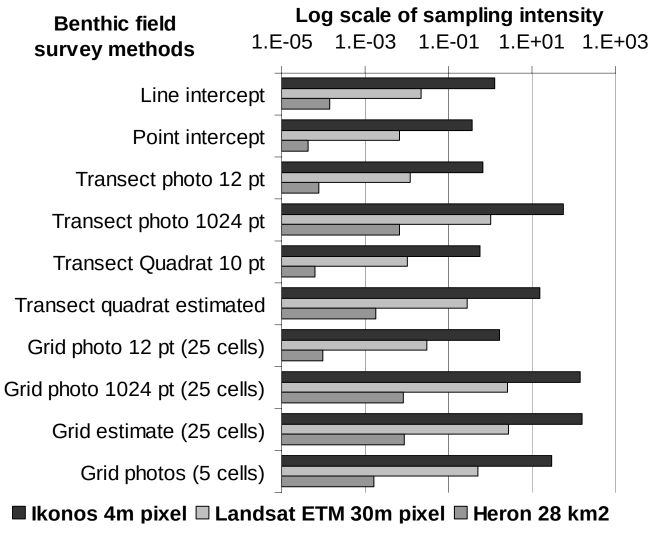

Fig. 6. Spatial intensity of different benthic cover survey methods in relation to a representative multispectral Ikonos or Landsat Enhanced Thematic Mapper pixel or a case study where 25 sites on Heron Reef need to be validated.

Power Analysis

Results of the post-hoc sample power analysis (Fig. 7) concurred with previous power analyses and comparisons of field survey techniques (Brown et al. 1999; Mumby 2002).

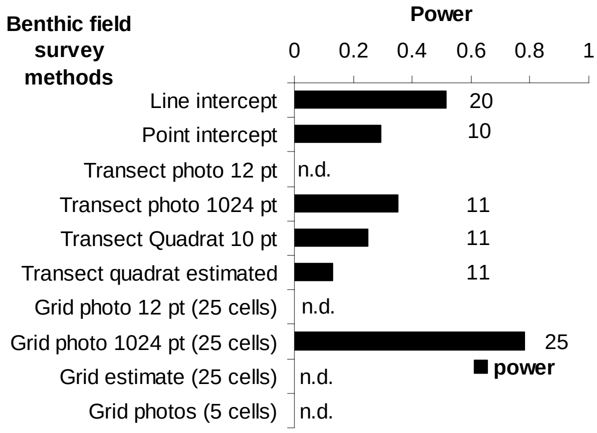

Fig. 7. Power analysis results of benthic field validation methods for mapping differences in live coral cover, conducted using a two-tailed post-hoc power analysis. With for each method the number of samples.

Coral cover estimates from fixed photographs over a relatively homogeneous area exhibited maximum statistical power (Carleton and Done 1995; Brown et al. 1999). Increasing the number of sample points per photograph and the number of sample photographs increased statistical power. The 10 point quadrat and more detailed analysis of the same transects using photo quadrats resulted in similar statistical power levels.

Discussion

Selection of an optimal field validation method for image based maps requires consideration of their strengths and weaknesses in relation to the intended application. This will often require trade-offs, for example, validation of maps derived from high spatial resolution image data requires positional accuracy as the critical factor. Since the trade-offs varying and are influenced by who and for what type of validation it will be used, it is not possible to specify an optimal technique. The results presented in this paper are an initial attempt at quantifying the strengths/weaknesses of field survey techniques for use in coral reef remote sensing.

To discuss which field validation methods may be optimal the results of this research are summarised in Table 1 and in Fig. 8.

Fig. 8 summarises key attributes for several representative survey techniques compared in this work using a multi-dimensional plot. Each axes of the graph represents one of the measured attributes of each field survey technique. The values along the axes are normalised to their maximum value with low values at the centre of the graph.

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Table 1. Comparison of benthic field survey methods for validating in remote sensing programs. The processing time is divided in L=Long, A=Average and S=Short.

Method		Transect						5 x 5 m Grid				
		Line intercept	Point intercept	Transect photo 12 pt	Transect photo 1024 pt	Transect Quadrat 10 pt	Transect quadrat estimated	Grid photo 12 pt (25 cells)	Grid photo 1024 pt (25 cells)	Grid estimate (25 cells)	Grid photos (5 cells)	Boat video survey
Processing time		S	S	A	L	S	S	A	L	S	A	S
Initial Equipment cost (US$)	General	75	75	225	225	120	120	375	375	375	375	2250
	Camera			1275	1275			1275	1275		1275	3750
Degree of expertise (scale 1 to 5)		1.5	1.4	1.7	2.0	1.7	1.2	3.7	3.9	2.7	2.4	1.2
Area	Length (m)	20	20	20	20	20	20	5	5	5	5	1
	Width (m)	0.05	0.05	1	1	0.5	0.5	5	5	5	5	1
Archival				✓	✓			✓	✓		✓	
Equipment needs	Transect line	✓	✓	✓	✓	✓	✓					
	Grid							✓	✓	✓	✓	
	Quadrat					✓	✓					
	Slate pencil	✓	✓			✓	✓			✓		✓
	Magnetic Wipe board			✓	✓			✓	✓		✓	
	Digital camera and software			✓	✓			✓	✓		✓	✓
	Field computer											✓
	Camera maintenance			✓	✓			✓	✓		✓	✓
General	Surface expert verification			✓	✓			✓	✓		✓	
	Underwater ID needed	✓	✓			✓	✓			✓		
	Spatial viewing dimensions	3d	3d	2d	2d	3d	3d	2d	2d	3d	2d	2d
Representative	of an image area	✓	✓	✓	✓	✓	✓					
	of a pixel area							✓	✓	✓	✓	✓
People needs	Advanced diver	✓	✓	✓	✓	✓	✓					
	Experienced advanced diver							✓	✓	✓	✓	
	ID expert above water			✓	✓			✓	✓		✓	✓
	ID expert under water	✓	✓			✓	✓			✓		

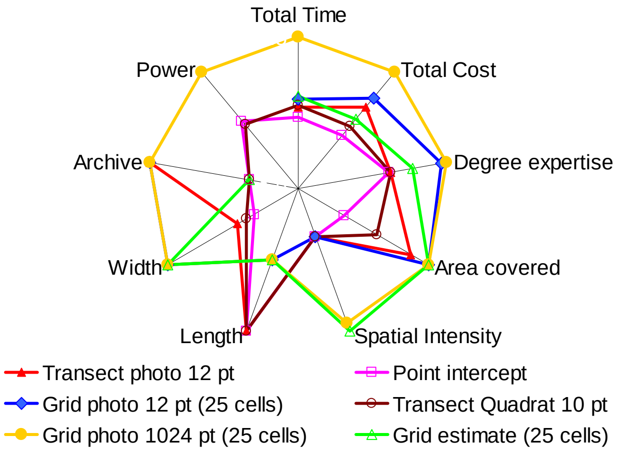

Fig. 8. Comparison of six benthic validation survey methods in terms of measured survey attributes. Attribute (axes) are normalised by to maximum levels. Attributes are: Total time (in field and office), Total cost (equipment+soft / hardware+labour), Degree expertise (average rating to conduct method), Area covered (surface area visually assessed), Spatial intensity (area covered / Ikonos pixel size), Length (length covered by survey), Width (widest with), Archive (photographs were captured resulting in an historical archive), Power = probability of methods to correctly discriminate percentage coral cover.

By analysing Fig. 8, it can be seen that none of the benthic validation methods compared were clearly "optimal". However, each method has its own characteristic attributes (Table 1 and Fig. 8) which make it suitable to a specific environment, image type and mapping problem.

Cost, Time, and Degree of Expertise

Transect-based methods were more suitable in this context, as their cost, time and degree of expertise are low in comparison to grid based methods. This was mostly due to simple survey methods which reduce the equipment cost and underwater time needed. Analysis of digital photos with 12 or 1024 points significantly increases the total time needed.

For validation of image based maps, significant attention needs to be paid to the number and distribution of sample site locations, a topic given extensive attention in terrestrial remote sensing applications (Atkinson 1991; Carleton and Done 1995; Green et al. 2000).Transect methods were faster and easier to implement than grid based methods. Combined with a reduction of in-water expertise by using digital photography, transects come close to the attributes required for an optimal method.

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Area Covered, Spatial Intensity, Length and Width

Ideally the surface area covered is large, covering the target scene and enabling sufficient sapling for high res pixels. Not all sensors have a high spatial resolution and the sampling intensity for other survey method in relation to a Landsat 7 ETM+ pixel was low. Manta tow survey (English et al. 1997) could cover a large spatial extent in a short time. However, this method has limited use due to: lack of detailed positional data, validation error and the fact that this technique is not supported by local workplace health and safety guidelines. Hence, the validation of image pixels with moderate to low spatial resolution (10m – 1km pixels) requires further consideration. In this case a survey method should cover several pixels. Transect based methods where the length of the survey area covered extends over several pixels should be suitable.

Which Method is Optimal?

With the information discussed it can be seen that an optimal field validation method is not obvious as it depends on a variety of factors. The choice can be narrowed down by knowing which type of image data will be used in combination with a set classification scheme, and by having access to a digital camera. With these variables in mind and the findings described in this manuscript, Table 2 was created. This table assists in selecting the type of field validation method to apply.

Table 2. Optimal benthic field validation methods for: a specific image types, benthic detail thought and camera availability. Spatial resolution = High < 10 m < Low 10 m. Spectral resolution = High > 8 bands > Low. Image extent = Small < 30 km2 < Large. Benthic classification detail = High > 20 classes > Medium > 8 classes > Low.

Sensor type		1	2	3	4
Spatial resolution		High	High	Low	Low
Spectral resolution		High	Low	High	Low
Image extent		small	small	Large	large
Example		CASI	Quickbird	EO-1 Hyperion	Landsat Thematic Mapper
Classification detail		High	Medium	Medium	Low
Camera	**Ideal method**	Photo grid (25 cells) with 1024 points photo analysis	Photo transect or grid (25 cells) with 12 points photo analysis	Photo transect with 12 points photo analysis	Photo transect with 12 points photo analysis
	Why	High level of detail, grid covers several pixel and many sites visits due to small image size.	Reasonable high level of detail and many sites visits due to small image size.	Enough detail and can cover many sites since analysis will go faster.	Enough detail and can cover many sites since analysis will go faster.
No camera	**Ideal method**	10 point Quadrat transect	10 point Quadrat transect	Point intercept	Point intercept
	Why	Relatively High level of detail and almost no analysis time could therefore visit more sites.	Relatively High level of detail and almost no analysis time could therefore visit more sites,	Enough detail and almost no analysis time could therefore visit more sites.	Enough detail and almost no analysis time could therefore visit more sites,

When analysing Table 2, in combination with the findings of this paper, one can conclude that the photographic transect field method with 1024 photo analysis was optimal. The method would give sufficient information to validate images from both the higher and lower spectral and spatial resolution sensors. The choice of this method does not consider available funding and accuracy needed in combination with spatial statistical analysis. The field component of this method is relatively fast, as it can easily cover several pixels (e.g. Landsat 7 ETM+ scale) and does not require highly trained personnel. The processing component on the other hand requires more time and higher degree of expertise due to image processing skills needed and benthic identification capabilities. Processing time can be reduced by using a 12 point photo analysis but this will result in less detailed analysis of photos. The photos are valuable since one would have a permanent archive and during classification process the photos could explain mis-classifications. Although not covered in the table above, benthic heterogeneity should also be considered when selecting a suitable technique. If the area to be surveyed is heterogeneous a photo survey will provide sufficient detail, while in homogenous areas point intercept or random spot checks (Andréfouët al. 2002) may be more suitable.

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