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Abstract: Our ability to map coral reef environments using remote sensing has increased through improved access to: satellite images and field survey data at suitable spatial scales, and software enabling the integration of data sources. These data sets can be used to provide validated maps to support science and management decisions. The objective of this paper was to compare two methods for calibrating and validating maps of coral reef benthic communities derived from satellite images captured over a variety of Coral Reefs The two methods for collecting georeferenced benthic field data were: 1), georeferenced photo transects and 2), spot checks. Quickbird imagery was acquired for three Fijian coral reef environments in: Suva, Navakavu and Solo. These environments had variable water clarity and spatial complexity of benthic cover composition. The two field data sets at each reef were each split, and half were used for training data sets for supervised classifications, and the other half for accuracy assessment. This resulted in two maps of benthic communities with associated mapping accuracies, production times and costs for each study-site. Analyses of the spatial patterns in benthic community maps and their Overall and Tau accuracies revealed that for spatially complex habitats, the maps produced from photo transect data were twice as accurate as spot check based maps. In the context of the reefs examined, our results showed that the photo- transect method was a robust procedure which could be used in a range of coral reef environments to map the benthic communities accurately. In contrast, the spot check method is a fast and low cost approach, suitable for mapping benthic communities which have lower spatial complexity. Our findings will enable scientists, technicians and managers to select appropriate methods for collecting field data to integrate with high spatial resolution multi-spectral imagery to create validated coral reef benthic community maps.

Keywords: coral reefs, photo transects, spot check, coral-seagrass community maps, calibration, validation, accuracy assessment, Quickbird, Fiji.

1 INTRODUCTION & ASSESSMENT OF CALIBRATION/VALIDATION TECHNIQUES FOR SATELLITE IMAGE MAPPING

Benthic community maps are essential for marine monitoring programs; they can function as a baseline for habitat inventory or may be used to determine changes. These maps are often based on remotely sensed image data [1, 2, 3, 4]. Benthic communities are defined as an assemblage of stony coral and/or other conspicuous benthic populations which can co-exist on reefal or non-reefal substrates [5].

For managers and researchers to use remote sensing effectively for mapping and monitoring programs concerned with benthic communities, adequate methods for calibrating the mapping process and validating the output maps are needed [1, 6, 7]. Prior to presenting the aims of this paper, the text below reviews calibration and validation of methods using remote sensing data for coral reef environments.

Several approaches are used to create maps of coral reef benthos and its substrate to various levels of detail. Examples are: manual delineation of polygons on aerial photographs using local knowledge [8]; pixel based classification of digital aerial

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photography [9]; pixel based classification of multi-spectral low and high spatial resolution satellite imagery [10, 11, 12]; sub-pixel based classification of airborne hyper-spectral imagery [13] and object-oriented mapping [14]. Over the past seven years these applications have used high spatial resolution imagery, with pixels < 5.0 m x 5.0 m in size, more frequently [2, 3, 4, 15, 16]. This is a result of a number of factors, including: the growing number of operational imaging sensors providing data at scales which allow delineation and identification of coral patches; increased accessibility to image data provided through web-based image viewing and search platforms such as Google Earth®, Microsoft Virtual Earth® and the Millennium Reef Mapping Image archive; and increased availability of software for satellite or airborne image mapping [16]. Mapping approaches to detect and quantify changes to reef properties at the scale of individual coral patches have not been established or validated for these data sets, and are required by reef science and management agencies as outlined below [17].

To date, a variety of approaches have been used in the collection of field survey data for mapping and validating coral reef and seagrass habitat, including: local knowledge [18]; expert knowledge [19]; spot checks [20, 21, 22]; manta tows [14]; various forms of line transects [23]; quadrat surveys [11, 24]; aerial photography [25], and photo or video transects [26, 27].

A review of 80 publications in peer reviewed journals, conference proceedings and reports on coral reef and seagrass habitat mapping, revealed that most field surveys were based on point data (e.g. spot check surveys), or line transect data (e.g. video or photo transects), (Table 1) .

Table 1. Summary review of 80 publications on coral reef and seagrass habitat mapping. The accuracy measures most commonly used in these papers were: Overall accuracy, Kappa and Tau accuracy. The numbers between [brackets] refer to example publications in the reference list, while the numbers in (brackets), refer to the number of papers in each category.

		References sorted based on the size of the area mapped			
Field method used (# papers),	**Accuracy Measure provided (# papers),**	**0-10 km^2 (18),**	**10-100 km^2 (37),**	**100-350 km^2 (15),**	**350- km^2 (10),**
Point(34), e.g. spot check	Yes (20),	[9, 28, 29, 30, 31, 32]	[11, 33, 34, 35, 36, 37, 38, 39, 40, 41]	[42, 43]	**[44, 45]**
	Other (11),	[46, 47, 48, 49]	[21, 50, 51, 52]	[53, 54]	[55]
	No (3),		[56]	[57]	[58]
Transect (31), e.g. photo or belt transect	Yes (17),	[59, 60, 61, 62]	[12, 63, 64, 65, 66, 67, 68, 69]	[14, 26, 70]	[71, 72]
	Other (3),	[73]	[74, 75]		
	No (13),	[13, 76]	[77, 78, 79, 80, 81, 82]	[83, 84, 85]	[86, 87]
Other (7), : e.g. local knowledge or aerial photo	Yes (1),		**[18]**		
	Other (3),		[6, 88]	[8]	
	No (4),	[89]		[90]	[19, 91]
Unknown (5),	Yes (2),		[92, 93]		
	No (3),			[94, 95, 96]	

Critical assessment of the level of the potential repeatability of the calibration/validation methods used in the 80 papers showed that only 13 provided sufficient detail to repeat the process, and only 39 of the papers reported a commonly used accuracy measure (Table 1).

Similar findings were derived from assessments of calibration and validation approaches applied in terrestrial vegetation mapping [97, 98]. The review of papers listed in Table 1 highlights the lack of consistently applied and documented methods for calibration and validation of the reef mapping process and output thematic maps. This was evident from the absence or limited description of sampling design specifics in the reviewed papers which defined the number and distribution of sample points and the level of detail collected at each sample point. Appropriate specifications for these components of field surveys are essential to produce an accurate and unbiased estimate of the level of agreement between field and image data values or categories [99].

Ideal sampling designs for remote sensing accuracy assessment have been thoroughly described in [100, 101]. These papers recommend randomly distributed sample units within the study area, where each mapping category contains at least 50 samples. Commonly used image based sample units include points (single pixel), or polygons (clusters of pixels). Previous studies also clearly recognise that the spatial complexity, or degree of heterogeneity, of the mapped landscape interacts with the image mapping process and accuracy assessment, to control the level of accuracy each class is able to be mapped at [24, 27].

Compared to land-cover mapping applications in terrestrial environments, limited research has been published on field sample design, calibration and validation data for mapping coral reef environments from satellite and airborne image data sets. Notable exceptions include: [1, 17, 62]. [62] focused on a comparison of the accuracy of transect survey and manta tows for validation of geomorphic zone maps derived from Landsat Multi-Spectral Scanner and SPOT multi-spectral imagery. [1] provided a general description of accuracy assessment and the potential cost for the field component for habitat mapping programs. [17] compared several field methods that could be used for accuracy assessment of benthic cover type maps produced from remote sensing imagery.

None of these papers explain in detail how the final coral reef map accuracy is influenced by the components of the field calibration and validation methods and/or complexity of the benthic cover of the study area. Although the conclusions drawn from these three papers and the 80 reviewed papers (Table 1), were supported by the results presented, the majority of the studies only mapped "one" site smaller than 100 km^2. This contrasts with the typically larger and/or more complex sites, which need to be mapped for management purposes within marine protected areas, or local, state and national jurisdictions throughout the world [102]. Hence, the techniques presented in Table 1, need to be proven over larger and/or more complex coral reef environments [99].

Our review of accuracy assessment approaches and spatial sampling designs of coral reef mapping approaches reveals an increased use of high spatial resolution imagery over the past five years (2004-2009). However, this has been accompanied by a lack of repeatable and appropriate field sampling design and data collection methods for calibration and validation of benthic community type maps derived from satellite and airborne images. Hence, the aim of this paper, was to conduct a cost-benefit comparison of two field survey methods for calibrating and validating maps of coral reef benthos derived from high-spatial resolution satellite images in three different coral reef environments. Costs were determined by time, labour and logistics associated with field sampling and data analysis, while benefits were quantified from the accuracy values of the maps.

The comparison focused on: field data type and field survey sample design, accuracy, reliability, and cost and time of the image based mapping products derived from georeferenced photo transects surveys and the spot check based field calibration or validation data. Spatial complexity of each reef mapped was also assessed. The results provide reef scientists and managers with an objective comparison of two appropriate field survey sample designs, and collection approaches for delivering calibration, and validation data for mapping coral reef environments from high spatial resolution imagery.

We first describe the georeferenced benthic photo transect and spot check field survey designs and sampling methods. Methods used to aggregate this data are then described, followed by a supervised image training and classification sequence. The resulting benthic community maps were validated and compared in relation to the two field methods and three different coral environments.

2 DATA AND METHODOLOGY

2.1 Study Areas and Assessment Overview

This study was conducted in three different coral reef environments in Fiji which varied in their water clarity, reef type, benthic community composition and spatial complexity of benthic cover features. The reef areas used were: Suva, situated on the south east coast of the city of Suva ; Navakavu, to the west of the city of Suva , and Solo, 70 km south of Suva (Fig. 1). All benthic field information was collected between August and October 2006. The images were captured on the 24th April 2006 for Suva and Solo, and the 17th October 2006 for Navakavu.

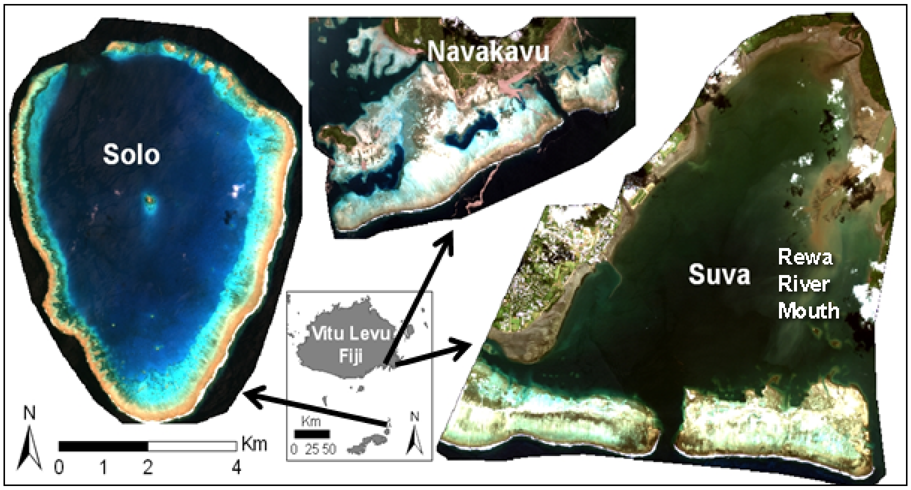

Fig. 1. Study areas: Suva, Navakavu and Solo reef areas, in the central part of the Fijian Island group. Quickbird images are shown in true colour and were collected on 24th April 2006 for Suva and Solo and the 17th October 2006 for Navakavu.

The Suva study area is frequently affected by turbid waters flowing out of the Rewa River, which has the largest catchment and highest rainfall in Viti Levu, the main island of Fiji [103]. Navakavu is influenced by smaller amounts of terrestrial run-off due to the smaller river catchment discharging near the reef. Solo reef is an oceanic atoll surrounded by deep water and is not directly influenced by run-off from major land masses (Table 2).

Table 2. Physical characteristics of the reefs making up the three study areas in Fiji.

Study Site	Water clarity	Site description	Benthic cover	Remarks	Total Study area (km^2)	Mapped area (km^2)
Suva	Turbid to clear	Estuarine shallow bank and barrier reef	Large Seagrass, sand and mud homogenous, areas also algae and coral reef	Large river and high rainfall	64	24
Navakavu	Turbid to clear	Fringing reef	Seagrass, algae, sand, rubble, algae and coral reef, hetrogenous	Smaller rivers and high rainfall	20	16
Solo	Clear	Atoll reef, (30 km from major islands)	Coral reef and cyano bacteria, homogenous cover	White sand, turf, cyano bacteria,	39	15

Fig. 2 outlines the process used for this study. Georeferenced benthic photo transect and spot check surveys were used for the comparison of calibration and validation methods in the Suva, Navakavu and Solo study areas.

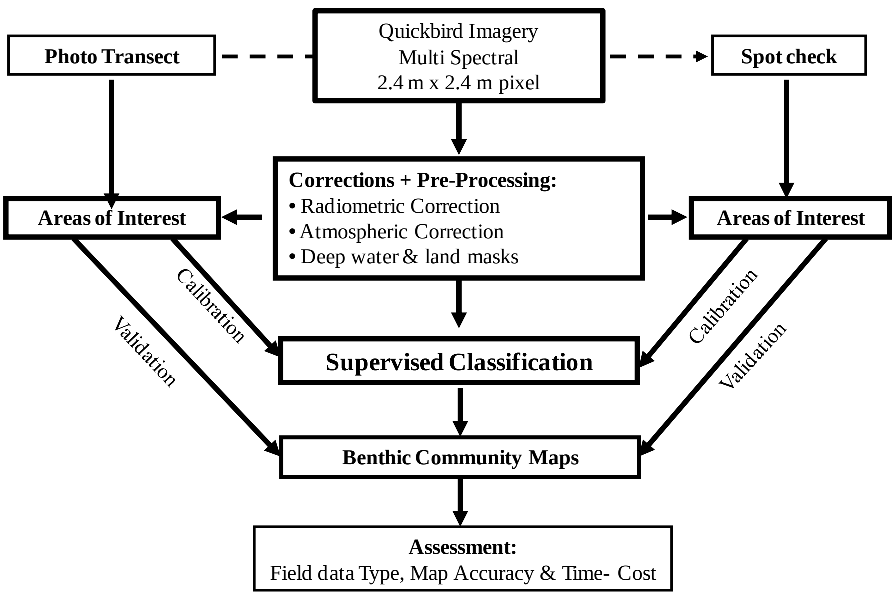

Fig. 2. Flowchart of the steps followed for Suva, Navakavu and the Solo study areas to conduct a cost-benefit comparison of two field methods for calibrating and validating maps of coral reef benthos derived from high-spatial resolution satellite images.

2.2 Field Data Collection

2.2.1 Georeferenced Benthic Photo Transect Data

For this survey a snorkeler or diver swam over the bottom while taking photos of the benthos at a set height using a standard digital camera and towing a surface float GPS which was logging its track every five seconds (Fig. 3a), .

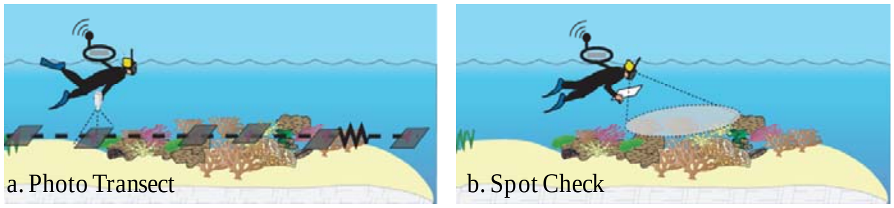

Fig. 3. Georeferenced photo transect (a), and spot check survey (b), by a snorkeler in coral reef environment.

A standard digital compact camera was placed in an underwater housing and fitted with a 16 mm lens which provided a 1.0 m x 1.0 m footprint, at 0.5 m height above the benthos. Horizontal distance between photos was estimated by three fin kicks of the survey diver/snorkeler, which corresponded to a surface distance of approximately 2.0 – 4.0 m. This distance was selected to approximate the length scale of the reef area represented in a Quickbird pixel. The GPS was placed in a dry-bag and logged its position as it floated at the surface while being towed by the photographer.

Selection of the photo transect location, direction and length, were made prior to surveys, by visual assessment of the spatial pattern of benthic structures evident in the Quickbird image for each study area. The different combinations of image pixel colours and texture of groups of pixels were assumed to represent the major benthic community types present in the study area. The true colour of the benthic features, and their depth, formed the colours of the image pixels, and the spatial distribution of these features determined the texture of groups of pixels. Photo transects were placed to sample over areas with a variety of major benthic community types present in the study area. Our approach was similar to previous methods that had been applied on larger coral reef study areas using Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM), imagery to map geomorphic features, including point checks and the "medium scale approach" [87].

Benthic cover composition for each photo was determined by overlaying it with 24 randomly distributed points, which were manually assigned a benthic cover type by an interpreter using Coral Point Count Excel® software [104]. The benthic cover types for the Fijian reef analyses were based on a hierarchical scheme containing nine major categories and 92 sub-categories, similar to those used in previous image based coral reef mapping [105].

The major categories mapped in each photo were: live coral, dead coral, soft coral, seagrass, macro algae, rubble, sand, rock and other life forms. Examples of the sub-categories included: massive live coral, seagrass species, algae species, turf on rubble, and crown of thorn. The detail of the sub-categories was required for two purposes. Firstly, the analysis of the composition would reveal that one benthic cover type covered large homogenous areas (e.g. 'turf on rubble' category at Solo reef), ; as a result it should be part the final mapping categories. Secondly, it enables the results to be used for a variety of future research or monitoring applications.

A mapping category (see legend Fig. 5), was assigned to each photo based on the classification scheme described above which was applied to quantify the benthic cover composition of each photo. This scheme was derived from the principles outlined in [106], and modified to suit user needs and composition of reefs in the study areas.

The benthic mapping categories, benthic cover composition of each photo, and the original photos were automatically linked to GPS coordinates through time synchronisation of the GPS and camera, using GPS-Photo Link® software. This allowed the photos and the corresponding benthic composition data to be viewed at their position in the study area through a GIS interface (Fig. 4).

2.2.1 Spot Check Survey Data

The spot check survey method was based on visual estimates of the area covered by major benthic categories recorded either from a boat or in-water over a variety of survey sites. Each site represented an area of 3.0 m radius at a maximum depth of 5.0 m. Additional sites were added on an ad-hoc basis in the field when benthic community compositions not previously sampled were observed. To ensure that the spot check data set represented a similar spatial distribution as the photo transect data set, additional spot check sites were simulated by deriving samples from each of the 20 points along a transect. Sampling every 20 points along the photo transect was chosen for the simulation as this would be an optimal spacing for fieldwork, in terms of snorkelling swimming/diving plans, and is within know limits of reef spatial variation for the sites used in this work

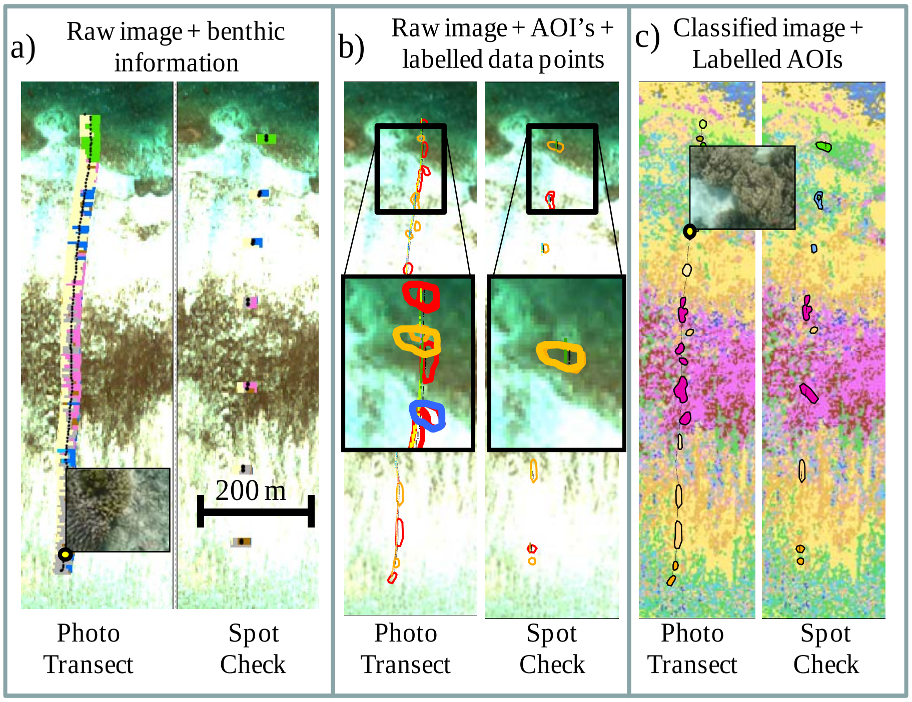

Fig. 4. Example image, field survey and mapping products derived from the georeferenced photo transect (700 m length), and spot check data points. (a), Raw image with benthic composition as a horizontal bar graph per data point, (b), Benthic mapping categories assigned to a data point with the outline of the manually digitised calibration and validation areas of interest (AOI's), and (c), Classified image with the labelled AOI's. The colours on each image map represent the different benthic categories, e.g. green seagrass, blue coral, yellow sand and pink algae. For the photo transect data points, georeferenced photos can be viewed using the GIS interface, as show in (a), – (c).

2.3 Image Acquisition and Pre-Processing

'Cloud free' multi-spectral high spatial resolution Quickbird 2 imagery were acquired for all sites, within one hour from low tide on the 24th April 2006 for Suva (17° off nadir), and Solo (16° off nadir), and 17th October 2006 for Navakavu (19° off nadir). Suva and Navakavu had less than 5% cloud cover along coastal fringe and Solo had none, with some sun glint. The Navakavu image had large areas of pumice-stone rafts covering significant portions of the reef, which were produced from recent volcanic eruptions in the South Pacific [107]. These images were geometrically corrected by the image provider to a standard map-product or "basic image" level, resulting in, i.e. maximum position error +/- 23 m[108]. As ground control points were hard to identify at sub-meter level in the coral reef environment, the positional error of the Quickbird image could not be improved.

Radiometric and atmospheric corrections were limited to removal of atmospheric effects to the Quickbird imagery to derive an at-surface radiance image data set capable of integration with field survey data. The images were corrected for additive path radiance by applying dark pixel subtraction [109]. An attempt was made to produce several depth-invariant bands using the approach of [110]. These bands were not used, as water clarity was not similar throughout the water-bodies covering the reefs in each image, especially in the Suva and Navakavu areas.

Each image was subset to exclude land and deep water areas, and to produce a working image area containing only shallow-submerged and exposed inter-tidal sections of reef. Land masks were manually delineated using expert knowledge of the coastal zone to differentiate between inter-tidal areas and land in the imagery. The near infra-red band could not be used as a mask as it did not allow all reef areas to be included. The deep water mask was digitised manually, and excluded areas where bottom features were not visible (approx. > 10 m depth). This approach was chosen because ancillary bathymetric data could not be accessed. The advantage of manually delineated deep water masks was that deeper areas in clear water would still be included. Finally, the subset areas of Suva and Navakavu reef images were manually segmented into two areas, off- and in-shore reef, to maximise the ability to discriminate benthic communities in each zone [34, 87].

2.4 Areas of Interest (AOI), for Calibration and Validation of Image Classification to Produce Benthic Cover Maps

For the image classification and accuracy assessment, pixel values for areas with known benthic community cover types were extracted for calibration of supervised classification from the atmospherically corrected satellite imagery, and for validation from the final classified image. The supervised classification would ensure that the minimum unit mapped was at pixel scale, since each image pixel would be assigned a thematic class. To determine which pixels would be extracted, areas of interest (AOI's), were manually digitised with ARCGIS 9.2 for each of the two field data sets, based on photo transect or spot check methods (Fig. 4b), .

For the photo transect based AOI's, the shape of the AOI and mapping category label attached to the AOI, were determined by the homogeneity of the image pixels and the benthic composition of several field data points in the vicinity of the AOIs. For each spot check based AOI, there was only one data point which determined the AOI mapping category and the AOI location, and the AOI shape was based on the homogeneity of the underlying image pixels (Fig. 4b).

The method followed to create the AOI's was developed to minimise spatial mis-registration problems that could be caused by the positional inaccuracies between image and field data [111]. Additional AOI's were created based on the author's image interpretation experience and knowledge of the study sites and were equally added to both photo transect and spot check based AOI's. The additional AOI's represented: pumice-stone rafts, clouds, cloud shade, exposed inter-tidal mud-banks, mangrove, breaking water, turbid water, river water and deep water.

The AOI's were then divided evenly and independently into 'calibration AOI's' and 'validation AOI's', by first sorting them on area size per mapping category, after which they were then labelled successively as either calibration or validation. This method ensured that the sample unit of the reference data, the thematic image pixel, had the same minimum mapping unit as the calibration data, as advised by [100].

2.5 Calibration and Validation of image Classification and Output Benthic Cover Maps

At-surface spectral radiance signatures were extracted from each of the corrected remotely sensed images for the training areas (calibration AOI's), enabling a characteristic "spectral radiance signature" to be defined for benthic cover types. Each image was subjected to a minimum-distance-to-means classification algorithm to group pixels with similar signatures to produce a map of benthic cover types. The minimum-distance-to-means algorithm is a commonly used, robust classifier which can be applied with minimal modification although it is insensitive to the degree of variance in the spectral response of the data [112]. This classifier was used to isolate the controls that the environmental features/patterns in each scene and the sampling design used for collection of calibration and validation data, had on the accuracy levels of each map. This was to avoid accuracy differences due to fine-tuning of classification methods. Using minimum distance means enabled all classification processes to be applied uniformly, without slight variations in parameters required for more advanced classification algorithms. The classification resulted in six maps, with two maps for each of the three study areas, one based on photo transect field data and the other one on the spot check data.

The quality of the maps was assessed through: a visual inspection; comparison of proportional area for each benthic community categories; and quantitative accuracy assessment [113]. For the quantitative assessments, overall and Tau accuracies, producer and user accuracies were calculated from a standard error matrix [40, 100, 114]. The error matrix resulted from the comparison of the pixel values of the validation AOI's (reference pixels), with the corresponding pixel values in the supervised classification results (map pixels), (Fig. 4c).

Overall and Tau accuracies defined the accuracy of the map product as a whole [100]. [112] defined the user accuracy as the probability that a pixel classified on the map actually represents that category on the ground. The producer accuracy was defined as the probability of a reference pixel being correctly classified. The validation procedure was repeated for maps based on photo transects and the spot check surveys of each of the sites, to produce six quantitative accuracy reports. It was assumed that the Tau accuracy approximated a normal distribution and Z-tests were performed to examine the difference between accuracies [40, 114].

2.6 Time & Cost Assessment

For each of the sites, field survey and office times and costs were calculated for the calibration and validation processes. Field survey time included the travel and collection time for the photo transects or spot check surveys. Office time included the time to plan, prepare, download data, analyse photos, make the maps and conduct a final accuracy assessment. The total cost included daily wages, transport (boat hire and fuel), and additional costs (e.g. extra logistics for remote areas). The wages incorporated those of the boat driver, research assistant and one additional research assistant in case of diving photo transects. For the Solo study area extra travel time and overnight accommodation were needed due to its remote location.

Equipment costs, such as: image processing, GPS Photo Link and GIS software, computing hardware, camera, GPS, and dry-bags, were not included, as they were considered a one-off cost to set up the work, not to actually conduct the work. An indication of some of these set-up costs are as follows: US $7-12000 for commercial GIS and image processing software licence, US $ 2500 for a suitable computer, US$ 600-1000 for a suitable digital camera with housing and wide angle lens, US$ 300-700 for a handheld GPS and for a dry-bag with line-reel US$ 100-200. The image costs were not included since these varied with regards to area size, licensing agreements and whether newly captured or archived images were used. 2009 Archived Quickbird 2 imagery cost US$ 26 / km^2 and for target capture costs are US$ 32 / km^2 (rates current as at February 2009 and can vary with type of licensing agreement, value of US$ and/or country where it was purchased).

3 RESULTS AND DISCUSSION

3.1 Assessment of Field Data Points and the Resulting AOI's for Calibration and Validation

In comparison to the spot check data, the field derived photo transects provide a more reliable basis for calibration of the mapping process applied to the high spatial resolution imagery and validation of the resultant benthic cover maps (Table 3 and Fig. 4). Table 3 shows that, in comparison to the spot check method, the photo transect method produced a larger and higher intensity sample size, with nine times more points than the sampled field points; eight times more samples per square kilometre; and almost double the amount of AOIs. On average, the photo transects AOI's were created using five times more field data points than were used for spot checks. Photo transects were considered more reliable than spot checks because of the increased detail available in the field data and the larger area represented by the field data (Fig. 4b). As a result, more AOI's were created with: higher detail in shape; better positioning in relation to field data; and a mapping category assigned based on more than one data point (Fig. 4). These findings were strengthened by previous research demonstrating that the statistical power of photo transect was high compared to other benthic field sampling methods [17, 115].

Table 3. Quantitative summary of the georeferenced photo transect and spot check field collection methods within each study area, showing: the number of field points collected; number of field points per km^2; number of AOI derived from field points; and the average number of field points used to create one AOI.

Study site	Suva		Navakavu		Solo	
Mapped Area (km^2)	24		15		14	
Method	Photo Transect	Spot Check	Photo Transect	Spot Check	Photo Transect	Spot Check
Field points (#)	1729	181	1904	224	1121	132
Field points desnity (#/km^2)	72	8	127	15	80	9
AOI's (#)	278	161	200	143	213	102
Field points / AOI's	6	1	5	1	5	1

The differences observed between Suva, Navakavu and Solo, in terms of number of field data samples and AOI's, were a result of variable study area size and the spatial complexity of the reef environments as represented in the image and in the field data sets. Larger areas (Suva), or areas with more benthic classes and complex patterns of benthic cover (Navakavu), required more field observations (Table 3). More detailed observation could be made by gathering continuous photos that overlap [27] or by using video instead [116, 117].

In comparison to the spot check method, the photo transect sampling took place at two spatial scales, a fine scale "the points on a photo transect" and coarse scale "the location of the photo transect in the study area." As a result, it provided information of the benthos at various levels of detail that were more suitable for use with high spatial resolution imagery. The disadvantage was that at a fine spatial scale the neighbouring samples could not be considered independent from each other, and would be auto-correlated. This was considered a trade-off for the sampling design as the number of data points and their distribution at fine and coarse spatial scales makes them more representative, and more statistically powerful, than those for the spot check based sampling design. To achieve the same fine and coarse spatial scales with spot check sampling, it would require many more data points which would not be feasible for completing the work.

3.2 Qualitative Accuracy Assessment of Coral Reef Maps

A comparison of the output benthic community maps, based on photo transects or spot check surveys, showed that the Navakavu photo transect based map had the highest degree of spatial variation in: complexity of benthic cover classes and composition of benthic mapping categories (Fig. 5).

Visual comparison of the maps between sites (Fig. 5), showed that they exhibited similar arrangements of benthic cover types (e.g. coral on reef slope, rock on reef crest and sand rubble on the reef flat). The sites varied in spatial extent of benthic cover type (e.g. Navakavu has large areas covered by Seagrass and Suva relatively small), and composition (e.g. Solo has no seagrass), as expected in coral reef environments [102]. Analysis of the mapping categories of each map showed that the Suva and Navakavu maps, compared with Solo, had no 'turf rubble' or 'deep reef', and that Solo had no 'algae', 'seagrass', 'mud' and 'mangrove' (Fig. 6). Navakavu was the only site which had 'pumice-stone rafts'. Navakavu also had large areas along the coastal fringe with a 'rock' substrate where the coastal fringe of Suva was mainly 'mud' being exposed inter-tidal mud-banks.

The differences observed in composition of the benthic categories present within each of the six maps (Fig. 6), could be explained by three factors. Firstly, if a mapping category was not present or observed in the field, it did not occur in the map (e.g. no occurrence of seagrass at Solo). Secondly, a category was not observed by the spot check field data, although it was present in the photo transect data. As a result, no calibration AOI's were created and therefore the category was missing in the spot check based map (e.g. live/dead coral in Navakavu). Thirdly, signatures for a mapping category, derived from the calibration AOI's, were sometimes confused with signatures of other mapping categories in the supervised classification and, as a result, the mapping category was falsely included and excluded pixels in the mapped area for each category.

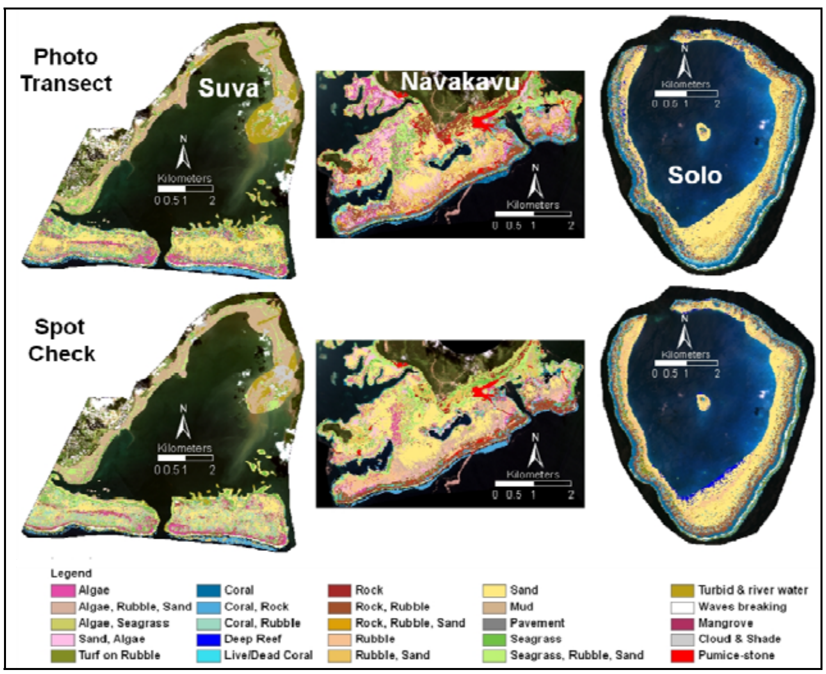

Fig. 5. Benthic community maps resulting from a supervised classification of Quickbird image using calibration data sourced from georeferenced photo transects or spot checks, for the three study areas: Suva, Navakavu and Solo reefs.

To provide context for interpreting the image mapping results, here we define the spatial complexity of each reef environment mapped. To assess the spatial complexity of reef community features on the accuracies of resultant benthic community maps, a quantitative measure of spatial complexity, patch richness density, was calculated from each classified image of each study area. Patch richness density was calculated from each Quickbird image based benthic community map using the Fragstats 3.3® spatial statistical software package. Patch richness density values quantify the relationship between the number of categories mapped in relation to the total extent of the area mapped [118, 119]. Typical values extend from: 0.4 (low richness or variety of benthic communities and spatial complexity), for 4 mapping categories in area of 10 km^2 to 2 (high richness or variety of benthic communities and spatial complexity), for 20 mapping categories in area with 10 km^2.

Some of the differences in relative extent of each benthic community class mapped and their spatial distribution resulted from differences in the level of detail distinguished by the photo transect based approach versus the spot check. This resulted in more categories being mapped and/or categories being better represented by their number of AOIs and the resulting signatures used to train the classification. Previous research shows that differences in spatial complexity of the terrestrial or benthic faunal communities interacts with the spatial scale of mapping to control resultant map composition and accuracies [120].

Some of the differences observed were a result of the level of discrimination among benthic community mapping categories and/or different water clarities [121]. This occurred where rock was erroneously classified as seagrass along the high wave-energy area of the fore-reef in Navakavu and Suva maps. This is not a preferred seagrass growth habitat, since seagrass requires low wave energy and unconsolidated substrate such as sand [122]. These types of errors could be reduced through contextual editing which could improve the quality of any of the maps [123].

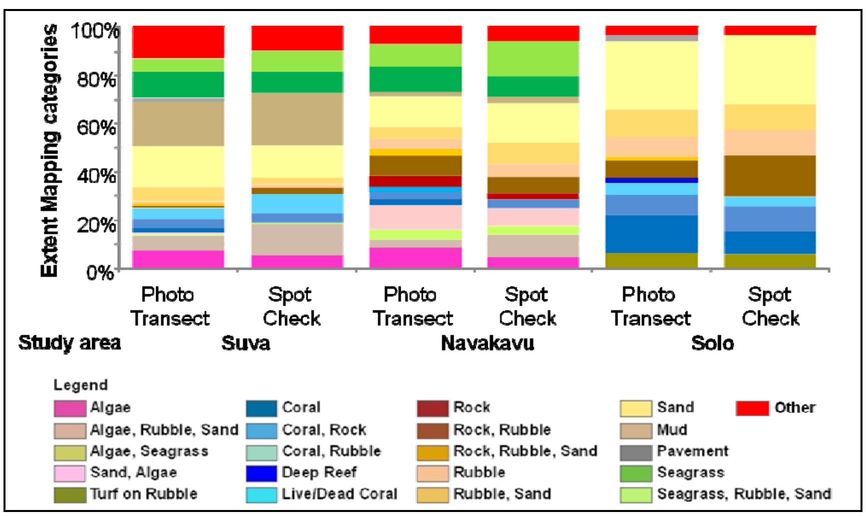

Fig. 6. Proportional composition of benthic community types present in each of the maps. Maps were created for each study area and resulted from supervised classification of Quickbird imagery, using georeferenced photo transect or spot check field survey data for calibration.

3.3 Quantitative Accuracy Assessment of Coral Reef Maps

3.3.1 Overall & Tau Accuracy

Assessment of the overall & Tau accuracy in relation to the variation in the spatial complexity of the benthic community cover showed that the photo transect method was more accurate than the spot check method for both simple and complex coral reef environments.

The overall accuracies for the photo transect and spot check methods were highest in the classified Suva image 69% and 65% respectively, followed by Solo 46% and 49% and Navakavu 43% and 24% (Fig. 7). Similar variations, but with lower values were observed in the Tau accuracies for Suva 68% and 64% respectively, Solo 45% and 46% and Navakavu 42% and 20%. The Tau accuracies had lower values, than the overall accuracies as it is reduced for likely agreement with a random classification [40, 114].

The differences in accuracies between photo transect and spot check based maps were similar for the Suva with a difference of 4% (Z= 6.6, P>95%), and Solo reefs, with a difference of 3%(Z= 0.1, P>95%). The Navakavu reef had a larger difference of 19% (Z= 19.7, P>95%). Differences in the spatial complexity of the reefs may explain why the spot and transect methods produced different results, as Navakavu was a more complex reef, in terms of its patch richness density (Fig. 7),

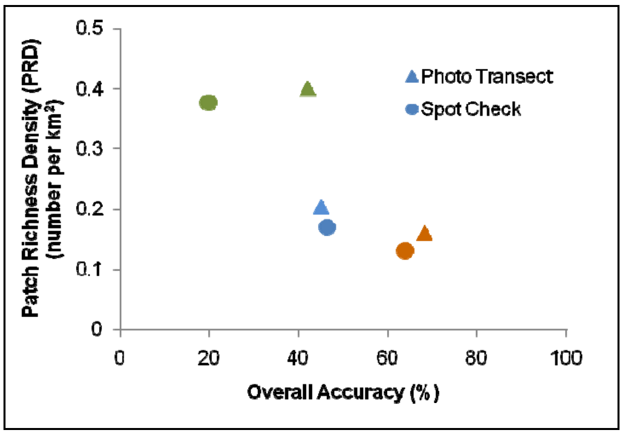

Fig. 7. Overall accuracy of the benthic community maps and patch richness density (PRD), for Suva (brown), Navakavu (green), and Solo reefs (blue). Calibration and validation data are based on georeferenced photo transects (triangles), or spot checks (dots), .

The spatial complexity of the benthic community cover in each mapped area was represented by the patch richness density index value. This value was twice as high for the Navakavu site compared to the Suva and Solo sites (Fig. 7). This confirmed two points. Firstly, the lower overall accuracy in the Navakavu map could partially be explained by its relatively higher spatial complexity, when compared to the two other study areas. Secondly, in combination with the higher overall accuracy for the Navakavu photo transect based map, our results showed that the photo transect method provided similar results for both simple and complex reef environments, with low to high numbers of benthic community types.

These findings were supported by previous studies in other reefs around the world, where overall mapping accuracy decreased with an increase in spatial complexity of, or richness of benthic communities found on the reef [124, 125]. In this study, the overall accuracies were generally lower and the associated number of mapping categories was higher, in comparison to previous related works examining reef mapping accuracy [26, 34, 126]. Although the overall accuracy could be increased by aggregating some of the mapping categories [34], this would reduce the level of benthic community detail able to be mapped. Contextual editing could also improve the accuracy [34], however this was not implemented for this study since this type of editing was assumed to be subjective and could therefore have compromised an objective comparison of the study results.

3.3.2 Producer and User Accuracies

The producer and user accuracies (Tables 4-5), show that the photo transect method was able to map more categories with higher accuracy than the spot check method. These results also show that, in environments with higher spatial complexity, the spot check method was less suitable. Our findings also indicate that sample design (e.g. sample size and location), in relation to the size and spatial complexity of the area mapped, influences producer and user accuracies of benthic community maps.

The category 'other' was considered an outlier since the values were larger than 60% and were similar between maps, except for the Navakavu spot check based map. There could be two explanations for this. Firstly, their calibration and validation AOI's were based exclusively on expert knowledge and were therefore identical in both photo transect and spot check based maps. Secondly, the 'other' category was a combination of sub-categories (e.g. clouds, breaking water, mangrove and pumice-stone), which were highly distinctive in the map due to their spectral characteristics (e.g. high reflectance by clouds). The category 'mud' (inter-tidal mud banks), had similar accuracy levels to the categories 'other' since it was generated in the same way to the categories that make up 'other'.

Table 4. Producer accuracy (%), for the mapping categories for the thematic maps resulting from georeferenced photo transects or spot checks for Suva, Navakavu and Solo reefs. Categories, "other" consisted of: pumice-stone rafts, clouds, cloud shade, mud, mangrove, breaking water, turbid water, river water, and deep water.

	Suva		**Navakavu**		**Solo**	
Number of pixels used for validation	**13329**	**8282**	**6543**	**3583**	**4087**	**1501**
Approach	**Photo Transect**	**Spot Check**	**Photo Transect**	**Spot Check**	**Photo Transect**	**Spot Check**
Seagrass	48	51	50	8		
Coral	21	2	44		69	17
Algae	46	49	48	44		
Sand	47	22	65	33	55	90
Rubble		67	14	34	32	23
Rock			43	6		
Live/Dead Coral			14			
Pavement					52	
Rubble, Sand	11	8	19	11	31	16
Seagrass, Rubble, Sand	14	15	25	34		
Algae, Seagrass	77		1	4		
Sand, Algae	8		27	16		
Turf on Rubble					49	24
Algae, Rubble, Sand	16	19		13		
Coral, Rubble	24	10			27	11
Coral, Rock	56	64	27	40	15	24
Rock, Rubble	24	56	40	33	25	43
Rock, Rubble, Sand	95		55			
Deep Reef					20	
Mud	83	96				
Other	91	78	66	36	100	98
Average (no mud and other)	37	33	34	23	37	31

Table 5. User accuracy (%), for the mapping categories for the thematic maps resulting from georeferenced photo transects or spot checks for Suva, Navakavu and Solo reefs. Categories, "other" consisted of: pumice-stone rafts, clouds, cloud shade, mud, mangrove, breaking water, turbid water, river water, and deep water.

Site	Suva		Navakavu		Solo	
Number of pixels used for validation	13329	8282	6543	3583	4087	1501
Approach	Photo Transect	Spot Check	Photo Transect	Spot Check	Photo Transect	Spot Check
Seagrass	46	31	49	12		
Coral	12	50	36		60	50
Algae	38	54	38	25		
Sand	59	14	56	41	74	81
Rubble		33	30	20	25	30
Rock			33	9		
Live/Dead Coral			4			
Pavement					26	
Rubble, Sand	24	14	15	3	26	17
Seagrass, Rubble, Sand	15	12	25	13		
Algae, Seagrass	35		5	17		
Sand, Algae	29		10	8		
Turf on Rubble					56	14
Algae, Rubble, Sand	31	15		27		
Coral, Rubble	11	9			22	9
Coral, Rock	22	20	18	37	23	21
Rock, Rubble	21	34	45	74	27	42
Rock, Rubble, Sand	43		34			
Deep Reef					9	
Mud	71	84				
Other	95	99	75	83	84	94
Average (no mud and other)	30	26	28	24	35	33

Analysis of the producer's and user's accuracies for the individual mapping categories produced from the photo transect and spot check methods did not provide consistent findings. This could be due to three types of problems caused by the sampling design. Firstly, within and among study areas, a variation in benthic cover type and composition would affect the accuracy assessment when random stratified sampling was implemented [127]. Random sampling, in combination with increased number of samples, would make sampling independent of these variations, however, this would make sampling more time consuming, and hence more costly [128]. Secondly, the sampling methods were intended to gather benthic cover and composition information within a study area using the different methods at roughly the same location, so the same mapping categories would be represented evenly.

Due to the differences in field methods used, different levels of detail were available for the AOI's creation. This influenced the level of detail digitised by the operator. This process could be improved through automatic creation of the AOI's using image segmentation, where segments created could be labelled based on the overlapping field data. Thirdly, the AOI's within each mapping category were divided evenly into two equal sized groups for calibration and validation, based on the AOI's area size. Since the spot check and photo transect AOI's vary in size, they represent spatially different areas for the validation This difference may result in variation in accuracy levels, as the choice of sample location influences the observed accuracy [100].

All three problems outlined above represent challenges that affect estimated map accuracy levels, making the comparisons conducted in this paper less thorough. These challenges are part of normal conditions that scientists, technicians and managers involved in mapping reef environments have to deal with. Our findings indicate that comparing accuracies between different studies is difficult due to variations in the methods used in the collection and analysis of the reference data. Further study to determine suitable accuracy measures is needed for comparing the quality of maps within or between locations.

3.3.3 Positional Errors Between Field and High Spatial Resolution Image Data

The accuracy levels observed for the classification results could also be influenced by spatial mis-registration between high spatial resolution satellite imagery and the field data [129]. These types of errors were not tested in this study; however, ways to reduce these errors will be discussed as they are a common and often under-estimated challenge of linking field and image data sets for reef mapping. The magnitude of spatial mis-registration between field and image data could be several Quickbird multi-spectral pixels (2.4 m), in length scale as a result of the positional error of the: (1), Quickbird image standard product, reportedly +/- 23 m [108]; and (2), the low cost handheld GPS, with a positional accuracy of +/- of 10 m for the positioning the field data [130].

Previous research [131] and the experience of the authors in comparing single field data points with the georeferenced high spatial resolution satellite image pixels (e.g. Quickbird), indicated that sub-pixel scale matches between field and image data were not possible. This study applied an approach that minimised mis-registration errors between image and field data by drawing areas of interest based on interpretation of image texture, pixel colours and the field data around image objects that were within the mis-registration bounds of the image and field data(Fig. 4b), [111].

To draw the AOI's, the benthic community types at each of the field sample points was determined from the colour and texture of the image pixels within 2-5 pixels of these points (Fig. 4b). Other options for reducing mis-registration errors between high spatial resolution imagery and field data include the:

- Positioning field data with a differential GPS, accompanied with image georeferencing using natural control points. This would be challenged by the ability to differentiate sufficient natural control points in the marine environment and in the high spatial resolution image.
- Moving each single field data point manually to match its expected location in the image, based on local knowledge [11, 30]. This would be constrained by the ability to recognise natural features in the image and may introduce biases.
- Assuming that all field data positions can be moved manually based on matching only a few key data and ground control points (e.g. start and end points of transect lines), to its same feature in the image. This was based on the assumption that a positional error at ground control point would be the same for a field position measured hours later or kilometres further.

The method developed in this work may result in lower overall map accuracy values based on spot check data due to image to field data mis-registration problems. Increasing georeferencing accuracy of the satellite images and field data may therefore affect the spot check based maps and accuracy assessments, more than the transect based methods.

For this study, the positional errors of the field data due to the offset between camera and GPS were kept at a minimum during the snorkel based photo transects and were around 1.0 m – 1.5 m. For the dive photo transect, the error was larger due to the drag of the GPS at the surface and was estimated to vary between 1.0 m and 5.0 m. These errors were reduced by keeping the line tight at all times and planning photo transects in the direction of the current, since the drag would be reduced. Alternatively, the use of underwater acoustic positioning systems could increase the positional accuracy, but would also increase equipment and deployment cost [132].

3.4 Time & Cost assessment of Calibration and Validation Methods

The analysis of time and cost needed to create benthic community maps and to then determine the associated accuracy, showed that photo transect field methods take more time and have a higher cost than the spot check method. However, the photo transect surveys produced more observations and more reliable data (Fig. 8). Figure 8 shows that in comparison to spot checks, photo transects took twice as long at double the cost, but did collect nine times more data points.

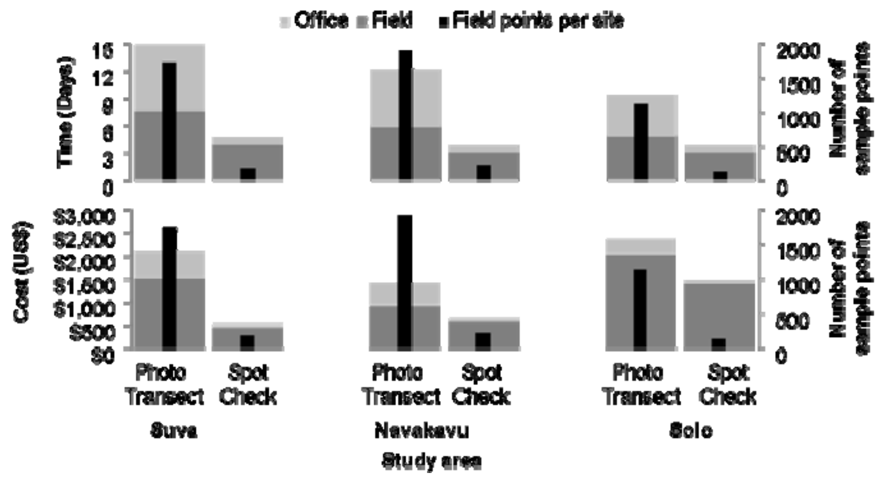

Fig. 8. Field and office times and costs (in US dollars), to create habitat map versus number of data points collected on photo transects or spot checks, for Suva, Navakavu and Solo reefs. Cost included wages, transport, and consumables, but did not include field equipment, satellite imagery and soft/hard ware.

The difference in time and cost between the two mapping methods was the result of two main factors. Firstly, the photo transect method took 30% longer than the spot check, as more field effort was needed to complete each photo transect. This increase in field time produced higher boating costs (e.g. hire and fuel), and wages for the field crew. Secondly, it was found that analysis of the field data for the photo transect method took five times longer than the spot check method, producing a further increase in wages. The photo transect method required each photo to be manually analysed in the office, whereas the spot check data were interpreted in the field.

In comparison to the Suva and Navakavu areas, Solo had the highest cost for photo transect and spot check method (Fig. 8). The higher cost for Solo was due to its remote location, which required greater and more complex logistical arrangements, producing an increase in transport and accommodation costs. These findings suggest that for remote locations, the photo transect method could be more appropriate than spot checks, as it allowed more data to be collected for the same approach.

A reduction in office time could be achieved for the photo transect method by reducing the number of sample points and photo interpretation categories or by automating the photo analysis [133].The spot check method may provide a wider and more representative data set if more field sites were visited. However, this would also take more time and increase the cost.

Although the set-up costs were excluded from the analysis, the necessary set-up costs varied between the photos transect and spot check methods, where the first method was US $500 - $2000 higher depending on the type of acquired: photo linking or analysis software, compact camera and underwater housing, dry-bag and real. There was no difference in set up cost due to GIS and remote sensing software package as both methods used same software. As the purchased hard- and soft-ware could be used for various projects it was considered one-off and excluded from the cost analysis.

3.5 Overall Effectiveness – of Photo Transects versus Spot Check for Benthic Community Mapping from Classified Satellite Image Data

The findings of this study are summarised in Table 6 and can be used by scientists or managers to assess which of the two field methods for calibration and validation would be more suitable for a particular benthic habitat mapping project. Several additional considerations for selecting suitable field data collection were also added to the summary.

The additional factors were safety and environmental conditions. Safety was considered an important aspect; since extensive field work require longer exposure to marine elements, which could lead to increased risk with regard to exhaustion, hyperthermia, and injury by coral cuts, currents and dangerous animals. Time to complete photo transect or spot surveys, will also be lengthened by adverse environmental conditions encountered during the fieldwork.

Although each of the two field survey methods had their advantages and disadvantages, they both could be adjusted to suit calibration and validation needs. For the spot check method this could mean more sample points and a higher level of detail in the properties of benthos assessed in the field. The field interpretation was considered subjective and depended on the knowledge/experience of the field person. The observations made would be readily available when returning from the field but could not be reviewed quantitatively at a later stage.

Table 6. Summary of advantages (+), and disadvantages (-), of two types of field methods for collecting data for calibration and validation of coral reef benthic community maps: georeferenced photo transect (T), or spot check (S), .

	Item	T	S	Remark
Quality	**Number of data points**	+	-	Transect had nine time more data points
	Georeferenced photos	+	-	Photos assessed in GIS environement to confirm findings
	Number of validation and calibration pixels	+	-	More available which can increase accuracy and reliability
	Subjectivety	+	-	Benthic information was assessed using standarderdised analysis
	Repeatibility	+	-	Transect method is systematic and can therefore be repeated
	Representativeness	+	-	More points with higher spatial density
	Reliability	+	-	Reliable AOI's through sufficient points for location, shape & label
	Spatial complexity	+	-	Transect field data quantitive data at image pixel scale
	Accuracy for spatial complex habitats	+	-	Transect preferable above spotcheck
	Accuracy for spatial not complex habitats	+/-	+/-	Accuracy are similar
Cost & Time	**Field time**	-	+	Transect take more due to effort in the field
	Office time	-	+	Photo analysis takes time depending on detail required.
	Field cost	-	+	Transect need more people and boat time resulting in higher cost
	Office cost	-	+	Spot check does not involve tedious photo analysis
	Cost per point	++	-	Transect cost was lower due efficient field data collection
Additional	**General**	+/-	+/-	Spot checks fast, transect flexible at high detail
	Photos	+	-	Snap shot, archival, revisited when needed
	Equipment	-	+	Compact digital camera, dryback,real are higher cost but once
	Software	+/-	+/-	transect: GPS download, excel, Linking Photos to GPS, CPCe Spot Check: GPS download, excel
	Safety	-	+	Spot check prevent long exposure to elements
	Environmental	-	+	Spot check no currents, or entangeling of lines
	In field data analysis	+/-	+/-	Infield analysis, not much office analysis but expertise needed
	Field expertise	+	-	Spot check needs expert in field transect not
	Office expertise	+	+	For planning, data analysis and mapping

The photos of the photo transect method, on the other hand, could be reassessed retrospectively at various levels if more or other benthic information were needed from each photo. A "low level" analysis of the photos could assign an individual mapping category to one photo based on a qualitative assessment of the photo and its location in the field. Whereas a "higher level" but slower analysis, could quantitatively assign benthic cover types assigned to x number of randomly distributed points in each photo, the composition of each photo could then be used to determine its mapping category.

More detail on the benthic composition in the study area from the photo transect method could be achieved by adjusting the length, photo sampling interval, and size of photo foot print. The ease of implementation and the availability of digital cameras and handheld GPS units will also make the photo transect method an ideal tool for adoption in operational practices by a field team in possession of a variety of knowledge, skills and experience. These types of field teams often provide the basis for global monitoring programs (e.g. Reef Check), . Use of georeferenced photo transect method in these applications could increase the spatial cover of data collection for validation of imagery [10].

Several papers have discussed the cost-effectiveness of remote sensing, but these focussed mainly on the image and the processing cost, and not on the integration of field and image data in relation to calibration or validation [1, 75, 134]. Two publications described how the cost and accuracy of a coral reef map were influenced by varying either the number of data points [123], or the image type or size of the mapped area [11]. [17, 62] focussed on comparing the cost and accuracy of field methods for calibration and validation to create and assess benthic habitat maps, but did not produce a habitat map. Several papers describe the cost effectiveness of benthic cover field methods, but not in relation to remote sensing applications to which they could be combined [115, 135, 136].

4 CONCLUSIONS AND FUTURE WORK

Our findings show that georeferenced photo transect surveys were more robust than spot check surveys when applied in spatially complex and diverse coral reef and seagrass environments of Fijian Coral Reefs. The photo transect method was considered to be more robust as it:

- is relatively insensitive to variations in spatial complexity reef benthos;
- is more representative of benthic composition;
- has an accuracy that is not influenced as strongly by the spatial complexity of the mapped environment as spot check based methods are;
- provides a spatially explicit verification through use of standardised photo analysis and an ability to view the photos at its original location in the satellite image at any time; and
- gathers significantly more data for calibration and validation, although it takes more time and has a higher cost.

Considering the scope of our study sites and methods, our findings do not show that spot check surveys are un-suitable for calibration and validation surveys. On the contrary, past studies have shown that spot check can be a useful approach for mapping projects [137] but has mostly been used in combination with moderate resolution imagery (e.g. Landsat ETM, ORS-LISS, ALOS), and depends on having access to experts capable of interpreting the benthos in the field. The spot check approach may provide robust results, if it is applied in a standardised manner, providing a description of selected homogenous areas with georeferenced benthic cover photos [22, 138].

The explicit integration of the field and image data sets made this study different from previous remote sensing studies which focussed mainly on field data [17, 23] or the image data [1, 123, 131, 134, 139].

Our findings also provide suggestions on ways to improve cost effective coral reef mapping:

- reducing photo analysis time through further simplification [104] or through automated [133] photo analysis.
- automatic creation of areas of interest for image training/calibration and validation sites to reduce subjectivity with manual digitising., this could be achieved through segmentation of the image and assigning labels to the segments based overlapping field data.
- identifying what appropriate mapping accuracy measures should be determined to compare the quality of benthic community maps within and between coral reef environments.

Our results demonstrate that standard field methods, using digital camera and GPS, combined with high spatial resolution image data, can be used to accurately map the benthic community in a range of coral reef environments. The results will assist scientists and managers to design and implement calibration and validation methods suited to apply and validate supervised classification of high spatial resolution multi-spectral imagery to map benthic communities in coral reef environments.

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