Current application and future needs of the NOAA Pacific Islands Fisheries Science Center's Coral Reef Ecosystem Division seabed mapping program

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1 The need for marine seabed mapping and focus of this report

The need for marine seabed mapping within US waters is ever more important, as different sea users increasingly compete for access to marine resources. The importance of seabed mapping has been highlighted in the US government's recently published 'Final Recommendations of the Interagency Ocean Policy Task Force (2010).' A key focus of the new Ocean Policy is the use of Coastal and Marine Spatial Planning (CMSP) as the main mechanism by which ocean activities should be managed, and which being by its very nature spatial and temporal relies heavily on seabed mapping. Other policy drivers for seabed mapping include Executive Order 13158 – Marine Protected Areas, which calls for a national system of MPAs to be established by strengthening and expanding the nation's current MPAs, and The Magnuson-Stevens 1996 Act which requires mapping of essential fish habitat to support fisheries management. Specific to mapping of coral reefs, the Coral Reef Conservation Act of 2000 includes a remit for "mapping, monitoring, assessment, restoration, and scientific research that benefit the understanding, sustainable use, and long-term conservation of coral reefs and coral reef ecosystems" and is a key driver behind the mapping activities undertaken by the NOAA Pacific Islands Fisheries Science Center's Coral Reef Ecosystem Division (CRED).

Seabed mapping therefore provides essential information to underpin effective management of the marine environment, to shape and inform monitoring programs and measure change, to document extent and distribution of particular habitats of concern, to inform conservation measures and selection of Marine Protected Areas (MPAs), and to support fisheries management decisions. These and other examples of the uses of mapping data are reviewed in more detail in Section 3.

This report presents a review of what seabed mapping is, how mapping data can be used, how CRED currently collects mapping data, and the applications to which this data can be applied, as well as recommending future applications and analyses that can make the data collected by CRED of even greater application.

2 What is seabed and habitat mapping?

Seabed mapping and marine habitat mapping are both loosely defined terms and can have varying meanings depending on the application. Often the term marine habitat mapping is applied to a range of seabed mapping activities that do not specifically map habitats, and in these cases it may be more appropriate to use the terms 'seabed mapping' or 'marine mapping.' For example, seabed mapping may be as simple as bathymetry (depth) information or points representing observations of a single species or habitat across a defined area. In this report, the term seabed mapping will be used as a more general term to describe any activities involving mapping of the seabed, whereas habitat mapping will only be used to specifically refer to mapping of habitats. Habitat mapping involves describing or characterizing the benthic habitat across a given area of seafloor, although some studies may also include characterization of the water column above (Connor et al. 2006). Benthic habitat usually refers to the combination of the physical environment of the seabed and the biological communities that it supports. Some habitat mapping products take this one step further by conducting habitat classification, whereby habitat characteristics are grouped into distinct habitat types. This process is greatly aided by the use of pre-defined habitat classification schemes, which may be defined for a local, regional, national or even international scale (see Section 2.1 below).

2.1 Habitat Classification Schemes

Habitat classification schemes are a way to categorize habitats (encompassing both physical characteristics and associated biological communities) into discrete units. These can then provide a defined unit for mapping, which integrates multiple layers of information, rather than a user having to separately view maps of bathymetry, substrate, dominant fauna etc. In some cases a habitat classification scheme will have been developed for an isolated study, and the resulting habitat types may not be applicable beyond the study area. In other cases however, classification schemes have been developed by committee, using data from multiple surveys. Such classification schemes have multiple benefits, including ensuring consistency when describing habitats in different mapped products, and across wide areas. This allows like-for-like comparisons to be made, which can be very important when trying to manage a particular habitat or species, as well as enabling multiple people to use a shared terminology when communicating about habitats. Hierarchical schemes have a further advantage of allowing habitats to be aggregated to a coarser level, thus allowing comparisons to be made between different studies using the same scheme, even when different levels of detailed information are available. Examples of existing classification schemes, described below, reveal the range of approaches that have been used to develop and apply habitat classification.

One example of a classification scheme that has been created at an international level is the European Nature Information System (EUNIS) habitat classification scheme, which was developed by the European Environment Agency and is used widely across Europe (Davies et al. 2004). It is largely based on The Marine Habitat Classification for Britain and Ireland (Connor et al. 2004) and the Northeast Atlantic Classification developed by Oslo-Paris Commission (OSPAR), with further development to include the full range of marine habitats present in Europe, both coastal and offshore. By having a European-wide classification scheme it has been possible for numerous individual mapping studies conducted throughout north-west Europe to be brought together and integrated into one northwest European habitat map (Mapping European Seabed Habitats 2010).

A similarly extensive regional benthic classification scheme was developed by Geoscience Australia for the entire Australian EEZ (Commonwealth of Australia 2006). The classification scheme was developed with a hierarchical structure, with provinces, biomes (e.g., continental shelf) and geomorphological units (e.g., submarine canyons) at the upper levels of the hierarchy defined by physical characteristics and which could be assigned based on existing data. Lower levels in the classification scheme (biotopes, biological facies and micro-communities) utilized biological data, and could be applied at a more local scale where data were available. This scheme was initially applied to the southeast marine bioregion (Butler et al. 2001) but was further developed to allow standardization across the extensive area of Australian waters and has since been applied more widely (Commonwealth of Australia 2006; Heap et al. 2005). However few examples exist so far that take the classification scheme down to the biological levels of the hierarchy. Despite this, the application of the current scheme is an effective tool for management, including providing a framework by which to design a representative suite of marine protected areas.

At a regional scale, Mumby and Harborne (1999) developed a scheme for Turks and Caicos and Belize, which could be used to derive habitat classes from multispectral satellite imagery. Their scheme describes habitats both in terms of geomorphological characteristics and the biological assemblage, although not within an integrated hierarchy; each map unit is separately assigned a geomorphological and biological category. Geomorphological categories were based on those in Holthus and Maragos (1995), and arranged in a two-tier hierarchy, whereas the biological habitat classes were derived from hierarchical cluster analysis of biological data obtained in the Turks and Caicos, and Belize.

Due to the absence of sufficient biological data, some habitat classification schemes are based purely on physical and environmental features of the seafloor environment, which are used as a proxy for habitats, on the assumption that there is a strong correlation between non-biological features and biological communities. Roff and Taylor (2000) developed such a scheme for Canadian waters. The hierarchical classification is based on enduring physiographic (latitude, depth, sediment particle size) and oceanographic (e.g., ice cover, temperature, mixing regime) features, that are assumed to correlate with the overlying biological component.

Another classification scheme relying primarily on physical characteristics of the seafloor, is Greene et al.'s classification scheme that was developed for coastal Californian deep (>30 m) seafloor habitat (Greene et al. 1999). This is a hierarchical scheme, with the different levels of the hierarchy aligned to mapping at different spatial scales (megahabitat, mesohabitat, macrohabitat, microhabitat). The scheme primarily utilizes physical characteristics of the seafloor, such as physiography, depth, substrate characteristics, and geomorphology. Biology plays a more minor role in this classification scheme, in terms of comprising some biogenic habitats, and as a modifier of meso- and macrohabitats. The scheme has been widely used, has been applied beyond the Californian waters for which it was originally developed, and has subsequently been refined (Greene et al. 2007).

Within the US, NOAA has been developing a national classification scheme to be applied to all US coastal and marine environments at many spatial scales. The scheme, as initially described in Madden et al. (2008), aimed to encompass the full character of the coastal and marine environment by classifying three components; benthic cover, water column and geoform components. These can be used independently as three separate schemes, or together to provide a more complete classification. The benthic cover component is classified according to a 7-level hierarchy. The highest level splits the marine and coastal environment into 'systems' (e.g., nearshore, oceanic) while the lowest level of the hierarchy is at the biotope level (e.g., *Macrocystic pyrifera* kelp bed). Although the structure is in place for this most detailed level of the classification, specific biotopes are yet to be defined. The water column component is also a 7-level hierarchy, but using different types of classification to the benthic component. The geoform component is intended to represent geomorphological features of the marine and coastal environment, and expands upon the scheme described by Greene et al. (2007). It is again hierarchical, with the four levels of the hierarchy referring to features at different spatial scales. The hierarchical levels are megageoforms (e.g., lagoon), mesogeoform (e.g., canyon), macrogeoform (e.g., rock outcrop), and microgeoforms (e.g., individual coral head). The geoform component still requires further development to describe all of the types of geoforms encountered at each level of the hierarchy. The classification of the components is further refined by the additional incorporation of fine-level attributes (called classifiers or modifiers). The scheme outlined above, is currently being updated with the addition of two further components;

the surface geology component and the sub-benthic component (Standards Working Group 2010). Both of these describe aspects of the geological composition of the substrate, providing a smaller-scale geological component than described by the geoform component. The surface geology component characterizes the substrate to a depth of 15 cm, using particle size analysis, in a hierarchical scheme that can be applied to a range of spatial scales, depending on the sampling tool used. The sub-benthic component also classifies the surface substrate, but also includes characterization of the substrate profile below 15 cm, using data from cores.

While habitat classification schemes all go some way to realizing the benefits outlined above, there can also be limitations.

One disadvantage of many habitat classification schemes is that they are inherently biased depending on the data used to originally identify the habitats. For example the British-Irish scheme was originally developed using largely near-shore data, primarily from grab sampling and, to a lesser extent, diver surveys (Connor et al. 2004). This means the scheme is less well-developed for offshore habitats, particularly those occurring on hard-substrates. A further limitation is that many of the habitats on soft or unconsolidated sediment are defined by the infaunal component, and do not fully take account of the epibiotic component, which may change across a different spatial scale. Similarly, other schemes which have been developed for interpretation of satellite imagery (e.g., Mumby and Harborne 1999) may not be applicable to data obtained from other sources, as it may not be possible to distinguish the same habitats from different methods.

Many of the schemes outlined above have limited integration of biological data. While this allows habitats to be defined using classification of geomorphological data alone, which tends to be more easily available over a wider area and tends to have more distinct boundaries, this could result in a loss of comparability of schemes if individual users end up deriving their own habitat classes. Other schemes do include biology but this is not integrated so that when producing a habitat map one must separately apply geomorphological and biological habitat classes.

3 Uses of seabed mapping data

Seabed mapping data have a variety of uses, ranging from scientific investigation and increasing understanding of ecosystems, monitoring of marine resources and habitats, to more applied management purposes. Often a map product can meet multiple management and scientific needs, and in some cases seabed mapping is carried out at a regional or national scale with the purpose of meeting a range of different needs.

Reasons for producing maps may include; spatial management, selection of marine protected areas (MPAs), management of marine resources, evaluation of management effectiveness, survey planning, mapping or predicting species and habitat distribution, biodiversity assessments. Some of these applications are discussed in more detail below:

3.1 Marine spatial planning

One use of mapping data that has had an increased profile in recent years is marine spatial planning. Marine spatial planning involves analyzing the spatial and temporal distribution of human activities in the marine environment, and managing these in such a way as to balance environmental, economic and social needs and minimize inter-sector conflict. A key step in marine spatial planning is to collect and analyze data on the current status of ecological, oceanographic and socio-economic conditions in order to make appropriate planning decisions. Mapping data are essential to carry out such a task. Frequently required data are maps of bathymetry, seabed geology and sediment type, distribution of marine habitats and species, locations of ecologically sensitive or important conservation habitats, fisheries data, oceanographic conditions, as well as human activities. Marine spatial planning has been applied to varying extents both nationally and internationally, but the recent US National Ocean Policy requires Coastal and Marine Spatial Planning (CMSP) to be implemented nationally, which is likely to increase the demand for the data necessary to support this (Interagency Ocean Policy Task Force 2010). CMSP will bring together many different management processes that are already undertaken, such as selection and designation of MPAs, fisheries management, and permitting for marine industries, some of which are discussed in more detail below.

3.2 MPA selection

A variety of approaches have been taken to incorporate mapping data into MPA selection.

As part of the Australian Oceans Policy, a network of representative MPAs is being established on a region-by-region basis. In the southeast region of Australia the development of an MPA network was underpinned by a regional mapping exercise (Harris 2007). This primarily relied on the mapping of geomorphological features, derived from 250-m gridded bathymetry. On the continental shelf, the geomorphological features were integrated with additional mapped variables (including water depth, sediment characteristics and currents), and analyzed to produce a more detailed seascape map. These two maps, with input from stakeholders, were used to identify 'Broad Areas Of Interest' within which the establishment of an MPA was considered likely to make the greatest contribution to biodiversity conservation objectives. Areas were chosen that had the greatest diversity of geomorphological or seascape features on the assumption that diversity of geomorphological features was positively correlated with the diversity of habitats.

On a more local scale, the Tasmanian Government used habitat mapping methods to delineate the boundaries of a new MPA. In this case, single beam bathymetry data was classified into broad habitat types, using variations in the echo that relate to changes in roughness and hardness of the seafloor. Ground-truth data from underwater towed-video camera were then used to characterize these habitat types. The resulting habitat map was one of a number of data layers used to delineate potential MPA boundaries (Jordan et al. 2005).

In a similar example, the UK Government commissioned a habitat mapping survey of the Dogger Bank sandbank in the North Sea in order to define the boundary for a proposed marine protected area (Diesing et al. 2009). Multibeam bathymetry, sidescan sonar, beam trawls, grab samples and video imagery were collected over the sandbank, the boundaries of which had been previously derived from historic seabed sediment maps. The data were processed to produce both individual mapped layers (e.g., seabed sediments, geologic bedforms, infauna, epifauna) and then integrated to produce a habitat map for the survey area. The resulting habitat map was used to re-define the boundary of the sandbank and hence the MPA.

The above examples primarily involve the selection of MPAs to either protect specific habitats, or to protect a representative range of habitats across a given sea area. For MPAs selected to provide fisheries benefits, additional mapping products would be required, such as mapping important nursery areas, spawning aggregation sites, or other areas integral to the life-history of important fish species.

3.3 Management of fisheries resources

Seafloor mapping has now become a critical tool in fisheries management, in terms of defining and mapping Essential Fish Habitat (EFH). The Sustainable Fisheries Act (1996) (Magnuson-Stevens Act) requires that all EFH be identified and described in order to be sustainably managed, and for the effect of habitat loss or degradation on fishery stocks to be evaluated and mitigated. To do this, it is necessary to map the seafloor, identify areas with different environmental conditions such as substrate type, and relate these to the distribution, abundance or other metrics of commercially important fish species. For example, Rooper and Zimmermann (2007) mapped essential fish habitat in the Aleutian Islands, using sidescan and multibeam sonar integrated with visual observations from underwater video. Seabed substrate, as observed in the video, was classified into distinct substrate classes. Acoustic characteristics (derived from multibeam bathymetry and sidescan) were then put into a classification tree to predict substrate, as observed in the video, with the aim of producing substrate maps that could subsequently be used to examine fish distribution with relation to the different habitat types.

Stock assessment has also been enhanced by marine habitat mapping. As an alternative to traditional fishery-dependent single-species stock assessment techniques, Nasby-Lucas et al. (2002) proposed a habitat-based community assessment, relying on benthic habitat mapping. Multibeam sonar and underwater video from submersibles was used to characterize the seafloor habitat. The video imagery was used to derive groundfish species and abundance, and habitat characteristics (primarily substrate). The habitat information from the video was then used to classify the video track into sections of discrete habitat, and fish density was calculated per habitat type. Acoustically homogenous areas were delineated from the multibeam bathymetry and backscatter data. The fish density data was then extrapolated from the video transects to the wider areas of similar habitat that had been derived from the acoustic data. This allowed fish abundance per habitat type to be calculated. By doing this, it was then possible to estimate total fish abundance for each species for the total area of each habitat. While this particular study did highlight various limitations with the data, the principles of the method are still valid, and the use of habitat mapping data to conduct groundfish stock assessment in this way is likely to become ever more important as scientists strive to find fishery-independent methods of stock assessment.

A similar method was used by Gilbert et al. (2006) whereby Quickbird imagery was used to inform stock assessment of the Giant Clam (*Tridacna maxima*) fishery at three island atolls in French Polynesia. One was mapped using aerial photography, but two other islands were surveyed and mapped using Quickbird images (2.5 m resolution). The Quickbird images were used to stratify in situ surveys. Sites were selected to sample different geomorphological units identified from imagery, as well as a range of exposure, current strength, dominant substrate, distance to coast, and distance to villages. Within these sites, snorkel and dive surveys were conducted to measure benthic cover and clam density. Hierarchical cluster analysis of the benthic data from the in-situ surveys was performed to cluster the data into benthic habitats. These habitats were then mapped to the Quickbird image using a combination of supervised classification and contextual editing. To arrive at an estimate of the total clam population, the mean clam density per habitat type was multiplied by the total area of each habitat, as derived from the classified Quickbird image.

3.4 Evaluation of management effectiveness

Habitat mapping, when conducted repeatedly to generate a time series of maps, can be an effective tool for measuring temporal change in habitats, which can allow effectiveness of management practices to be measured. Dobson and Dunstan (2000) conducted textural analyses of Landsat Thematic Mapper images covering a time series of 1975 to 1996 to measure change in coral reef extent. Subsets of the images were selected that covered two reef areas, known to have undergone extensive change during the time period, an urban area known to have undergone rapid expansion, as well as sandy, mangrove and deep water areas that had remained relatively stable. Textural analysis of these images showed that change over time could be measured from the satellite images.

3.5 Predictive species and habitat mapping

Habitat mapping techniques can be used not only to map the distribution of species and habitats using in situ data, but also to predict the distribution of the same habitats and species beyond the extent of occurrence data. Habitat suitability modeling allows the relationship between a particular species or habitat to remotely sensed or geophysical data (e.g., bathymetry derivatives, substrate type) to be quantified. This relationship can then be used to predict the occurrence of the species or habitat wherever the remotely sensed or geophysical data are present. This is very advantageous in being able to provide cost-effective information for effective management, without having to exhaustively sample the distribution of the habitat/species, by giving some indication of distribution in areas that have not been surveyed. They can also be used to inform survey strategies, by allowing survey effort to be prioritized in areas where the target species or habitat is predicted as more likely to occur (Section 3.6).

Iampietro et al. (2008) undertook habitat suitability modeling for three species of rockfish, as a means to support habitat-based stock assessment. Multibeam bathymetry data was used to derive various seascape metrics such as slope, aspect, rugosity and Topographic Position Index (TPI). The distribution, abundance and relative size of three species of rockfish was recorded from video imagery obtained by a Remotely Operated Vehicle (ROV). These data were then used to produce general linear models (GLM) of habitat suitability, with the resulting product being a map showing the probability of occurrence for each species across the survey area.

A similar study by Moore et al. (2009) involved applying two modeling techniques to data collected from baited video systems. The study was conducted in Australia’s Cape Howe marine national park and utilized multibeam bathymetry and predicted habitat maps that had been previously generated for the area (Holmes et al. 2008). The bathymetry and habitat map were used to select sites at which to deploy the baited video cameras, aiming to represent the range of predicted habitat types within the park. Classification trees and generalized additive models (GAMs) were developed for four different demersal fish species that were prevalent throughout the park. The models utilized data derived from both the bathymetry (depth, aspect, measures of curvature, relief, rugosity and relative elevation) and the habitat map (broad habitat type). The presence of all four species was successfully modeled by different combinations of the bathymetry-derived and habitat variables.

Similar approaches have been used to predict species assemblages rather than just individual species. Pittman et al. (2009) derived metrics (e.g., depth, rugosity, slope, slope of slope) from lidar bathymetry at different spatial scales and used boosted regression trees to model the relationship between these and 19 metrics for fish and coral. Fish metrics included abundance and biomass of family and trophic groups, as well as overall species richness, biomass and abundance. Coral metrics were scleractinian coral species richness and coral cover. The models showed good predictive ability for many of the variables investigated. The production of predictive maps of coral reef ecosystem variables would have high value in supporting effective management of un- or under-surveyed regions.

Predictive mapping of this nature has also been applied to single species, as in the case of predicting the distribution of the cold-water corals *Lophelia pertusa* and *Madrepora oculata*. Dolan (2008) carried out habitat suitability model of these two species using data collected by ROV on a carbonate mound in the Porcupine Seabight, SW Ireland. An ROV, mounted with a high-resolution multibeam system, was towed ~100 m above the seabed to obtain multibeam and backscatter data over the mound. The ROV was also mounted with two video cameras; one downward-facing and one mounted at an oblique angle. Geo-referenced stills were extracted from the video data and from these the occurrences of two species of cold water corals were recorded. Multibeam data were processed and gridded at 0.5-m and then analyzed to derive maps of slope, aspect, BPI, three measures of curvature, and three measures of surface roughness. Ecological Niche Factor Analysis was carried out. This relates predictor variables (in this case terrain variables from the multibeam-derived maps) to species observations and uses the resulting model to map habitat suitability. The results showed that the presence of the two species of coral could be predicted using a model that included BPI, fractal dimension (a measure of roughness) and aspect.

3.6 Planning of surveys and monitoring programs

Marine mapping may be used to inform survey planning and monitoring. For example, if monitoring is to be focused on a particular species or habitat of interest, then mapping data can be used to identify areas likely to support these species or habitats. This allows for more targeted survey work to be planned, thus ensuring efficient use of resources and time. In the North West Hawaiian Islands, surveillance monitoring of non-native species was planned by using a habitat suitability model, developed from mapped bathymetry data that had been collected by CRED (Menza et al. 2010). Gridded bathymetry data was used to derive a map of bathymetric complexity, which in turn was used to identify areas of complex topography within a given depth range. Such areas were considered most likely to provide areas suitable for the invasive octocoral *Carijoa riisei* which preferentially inhabits shaded areas on hard substrates. The resulting habitat suitability map provided a tool by which survey effort could be targeted more effectively, thus making the best use of available resources.

3.7 Other

Recognizing the multiple uses of good quality mapping data, the Irish government has supported broadscale mapping of the Irish EEZ with the intention of producing baseline maps to support numerous applications, including research, policy, conservation and industrial initiatives. All data collected as part of the Irish national seabed survey program is freely and publicly available to support these uses. The Geological Survey of Ireland and Irish Marine Institute have, since 2000, conducted extensive survey of the Irish territorial seas which cover 525,000 sq. km. Initially the focus was on offshore areas, collecting primarily multibeam sonar data, and producing bathymetric and geological seabed classification maps (Geological Survey of Ireland and The Marine Institute 2010b). Ancillary data (singlebeam sonar, sub-bottom profiling, CTD, ground-truth data and sidescan sonar) were collected opportunistically but not fully processed. From 2006, the work moved to more inshore areas, aiming to cover a large number of bays and a smaller number of priority areas (Geological Survey of Ireland and The Marine Institute 2010a). Inshore mapping had a wider remit, aiming to collect a wider range of data (multibeam echosounder, single beam echosounder, sub-bottom profiler, seismic sparker, side scan sonar, LIDAR, sediment samples) as standard. Once collected, the data are processed and routine products are bathymetry and seabed sediment classification charts.

4 CRED mapping of coral reef habitats

CRED has been carrying out seabed mapping since 2002. The drivers behind CRED's mapping program, a history of CRED's mapping efforts, and a discussion of the mapping products are discussed extensively in Miller et al. (in prep.) and so will only be briefly described here.

4.1 Methods used for coral reef mapping

For many coral reef researchers, mapping of shallow coral reef habitats is achieved by using satellite imagery, ground-truthed by diver or video surveys. For example NOAA's Center for Coastal Monitoring and Assessment (CCMA) Biogeography Branch has undertaken habitat mapping using satellite imagery for a number of US coral reefs including the main Hawaiian Islands. Here, ground-truth validation data were used to classify satellite (IKONOS) images into 32 distinct habitat types, which were then digitally mapped in GIS (Battista et al. 2007). Similar work has been undertaken in Moloka'i by US Geological Survey, using SHOALS lidar bathymetric data and aerial photography, which has allowed the creation of more detailed habitat maps, albeit using the same NOAA classification scheme (Cochran-Marquez 2005).

In general habitat maps are created by identifying the spectral signatures representative of different habitat types and then using these to classify the entire useable image. Classification may be done through automated or manual techniques. Limitations can include distinguishing between habitats of similar spectral signatures, although in some cases this can be mitigated by including contextual editing e.g., adding rules that constrain habitat types by specific environmental variables such as applying depth limits. Furthermore, while there is confidence in using these techniques to discriminate broad habitat types, there may be issues in trying to distinguish between fine-scale habitat types, or levels of cover of different benthos. For example, Benfield (2007) compared accuracy of using 7 different methods to apply a Landsat ETM+ and Quickbird satellite image of a reef in Pacific Panama. The images were classified to three levels; coarse (e.g., sand versus coral), intermediate (e.g., live branching coral reef versus dead reef framework) and fine (e.g., < 20% coral cover versus 20–40% coral cover). The highest accuracy was achieved using the Quickbird image and using eCognition software. Accuracy for fine-scale classes using the 7 different methods ranged from 59.1–83.5% accuracy, indicating that the type of image and the classification method used can have a great difference in the level of accuracy achievable. Use of hyperspectral rather than multispectral satellite imagery provides a greater number of bands that can be used to classify images (>100 bands versus 3–7 in a multispectral image), which could allow for finer discrimination between spectral signatures. Preliminary research using images obtained from one of the first commercially available hyperspectral satellites over the Great Barrier Reef showed that it was still not possible to distinguish between many habitat types that were spectrally similar (Kutser et al. 2006). For example, three classes (reef framework, rubble and dead coral) were all found to be optically similar as all tended to be covered with a mixed algal community. The use of hyperspectral satellite imagery for marine habitat mapping is still in its infancy, and additional research would help to identify the possible benefits of this method. One potential concern is that there may be a trade-off between the high spectral resolution versus low spatial resolution with hyperspectral sensors compared to existing multispectral sensors (Velez-Reyes, 2011).

Use of satellite imagery has also been used to monitor temporal change, by generating habitat maps from a series of satellite images over time. Scopelitis et al. (2009) used this method to measure change on Saint-Leu Reef, La Réunion, using a time series of aerial photographs and satellite images taken between 1973 and 2007. Images were interpreted using color and texture, and ground-truthed using field survey data, to identify coral reef communities. All the images were compared to the 1973 baseline to produce coral community change maps, from which it was possible to quantify change in coral reef extent that had occurred in the intervening years.

Satellite imagery has proved to be suitable for use in shallow waters, albeit bearing in mind the limitations outlined above, and is relatively cost effective, as a single image can cover a large area, and existing images for many areas are readily available. However, this method is only suitable for mapping a relatively shallow depth range and can be limited by low resolution, data gaps resulting from cloud cover, surface reflectivity, etc. Higher resolution imagery can be obtained from airborne platforms, i.e., airborne hyperspectral imagery or aerial photography, but this still requires good water clarity and can also be affected by cloud cover, sun glint etc., and may be more expensive and less readily available than satellite imagery. Lidar can achieve a slightly better depth limit in clear waters (up to 50 m) but is limited to providing bathymetry data rather than imagery that can be interpreted for habitat characterization. In deeper (> 20–30 m) waters, satellite imagery cannot penetrate, and therefore other methods must be used. CRED’s application of multibeam sonar, combined with the use of towed-video systems enables mapping of these deeper areas.

In these deeper waters it is necessary to use alternative techniques such as ship-based acoustic technologies. Prada et al. (2008) conducted habitat mapping of coral reefs in Puerto Rico using side scan sonar. Intensive surveying was done, to obtain a continuous mosaic over the survey area, which was then ground-truthed with video surveys and quadrats surveyed by divers along transects. Polygons of benthic habitats were digitized in the mosaic, using sidescan brightness and texture, integrated with the ground-truth information. The benthic habitats identified through the study were arranged into a hierarchical classification scheme that could be applied in subsequent studies. While this study demonstrates the use of techniques other than satellite imagery in coral reef mapping studies, obtaining complete coverage of a study area using side scan sonar can be more expensive than interpretation of satellite imagery. However, although this study focused on depths of < 20 m, such a technique could be applied to deeper waters beyond the limitation of mapping using satellite imagery.

Multibeam technology has been widely used in habitat mapping of temperate waters, but less commonly used in tropical reef environments. Harper et al. (2010) conducted multibeam and sidescan survey over a reef area in Pacific Panama with the aim of mapping habitats important to fisheries resources. A 2-m gridded bathymetry surface was generated, and sidescan backscatter data were used to select ground-truthing sites, to sample areas of seabed with different acoustic signatures. Habitat types and sediment information were derived from sediment samples and interpretation of video imagery. A combination of backscatter signature, BPI and rugosity were used to manually digitize polygons corresponding to broad habitats, such as rocky reefs, and rhodolith beds, with the intention of using the resulting habitat map to identify valuable fish aggregation sites.

4.2 CRED seabed mapping program

Acoustic mapping carried out by CRED is primarily focused on collecting data in deeper coral reef ecosystems (below 30 m depth) that can be surveyed by ships and small boats. Multibeam bathymetry data has been collected extensively around CRED's area of operation, which covers five regions of the Pacific; the Main Hawaiian Islands, Northwest Hawaiian Islands, Commonwealth of the Northern Marianas and Guam, American Samoa, and the Pacific Remote Island Area. To effectively map the location of coral reef ecosystems, and to provide context, CRED aims to provide complete coverage around these islands in depth of 30 m to > 300 m. Multibeam provides both bathymetry (depth) information as well as corresponding backscatter (signal strength) data which can be interpreted to give an indication of the nature of the seafloor (texture and substrate). As mentioned above, multibeam bathymetry data are generally not available in waters less than 20–30 m depth, due to safety constraints that preclude working close to shore. This can lead to situations were shallow areas around islands cannot be easily mapped, leaving a gap encircling the island. However, where good quality satellite imagery is available, it is possible to derive estimated depths from these images, and thus fill the data gap (Hochberg *et al.* 2007). For example, IKONOS images have been used to derive depths for shallow islands around a number of islands within CRED's area of operation. Where such derived depths are available, they can be integrated with the multibeam bathymetry data to produce a seamless bathymetry map from the coast to the seaward extent of the collected data (see http://www.soest.hawaii.edu/pibhmc/), a product that is currently not widely available.

Optical data that can be used for ground-truthing is collected by scuba divers (diver observations and still images) conducting reef surveys in < 30 m water, and by towed video and unmanned submersibles — Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) — in > 20 m water. To date, CRED have collected approximately 660 km (estimated tow distance) of optical data using the towed-video camera, 26 km using AUV and 113 km using ROV within CRED's area of operation. In addition, CRED have surveyed ~ 1546 km of seafloor with towed-divers.

Limitations of the data collection include the mismatch between the spatial extent of the multibeam data and the optical data. This is partly due to logistical constraints; topography and sea conditions often mean that getting close inshore to map shallower depths with multibeam is not safe or feasible. Conversely, scuba divers are limited to safe diving depths, and in general dive surveys are conducted in 3–30 m of water. Video and photographic imagery can help bridge this gap by obtaining data in depths that correspond to those mapped with multibeam, however, logistical and time/resource constraints have resulted in insufficient data being collected by these methods in most places within CRED's area of operations.

Routinely, multibeam bathymetry acquired by CRED is processed (cleaned of 'noise') and used to generate gridded bathymetry maps, with 5-m grids for shallower (< 300 m) waters, and 60-m grids for deeper (> 300 m) waters. Multibeam backscatter data are also processed and individual swaths are joined together to produce a seamless backscatter map, however, nothing similar to backscatter can be derived from satellite images. Bathymetry data are further analyzed to produce 4 derivative maps; slope, rugosity (surface roughness/complexity), Bathymetric Position Index (BPI) zones and BPI structures. The BPI analysis compares the height of the seafloor in a particular grid cell to the height of cells within a defined surrounding radius (Lundblad et al. 2006). The resulting BPI values indicate whether a cell represents a hill, valley or flat area. The BPI values along with slope measurements are used to classify the seabed into zones, which represent large-scale topography (crests, depressions, flats and slopes) and structures, which represent smaller-scale topography, equivalent to geomorphic features (e.g., broad crest, narrow depression, mid-slope depression). Where good quality backscatter data have been obtained, these can be used, along with rugosity, and bathymetric variance, to produce an unsupervised substrate classification, that maps the predicted distribution of hard and soft substrate across the survey area. In addition, if sufficient optical data are available, these can be used to ground-truth the predictive substrate map, thus resulting in a validated substrate map.

4.3 Potential uses of CRED mapping data

Mapping data collected by CRED can be used to fulfill many of the uses outlined above (Section 3) and with further processing could be used to achieve even more. Below, the uses to which CRED mapping data can be applied are outlined, as well as limitations with the current data, and recommendations for further analysis or data collection that could enhance the applicability of CRED mapping data.

4.3.1 Marine spatial planning

As described in section 3.1, maps including bathymetry, seabed geology, sediment type and distribution of marine habitats and species are often required to implement marine spatial planning. Issues of important for MSP include having data of sufficient quality across a large enough area to assist with regional planning, while at a resolution small enough to inform more local decision making.

Maps of CRED bathymetry and bathymetry derivatives (e.g., slope, rugosity, BPI) are therefore essential sources of data. Where hard-soft substrate maps are available, these are also of great value, however, there is currently limited data that map particular habitats or species. While cover of functional benthic groups (coral, macroalgae etc.) can be extracted from diver surveys, these tend to encompass a very narrow depth range around each island. Similarly, although the same information can be extracted from deeper video imagery (from towed camera, ROV or AUV) this is very limited in spatial extent. Both streams of optical data therefore are useful in providing some indications of where particular habitats or species may be present, but fall short of fully documenting distribution. CRED is currently working to develop a standardized scheme that can be used to classify benthic communities using imagery data from both divers and towed-video, ROV and AUV. This will allow standardized maps that cover shallow to deeper reef ecosystems to be produced, for example, showing percent cover of coral or other functional groups. In general though, to make management decisions regarding the conservation of habitats, or managing activities to minimize impacts on particular habitats, more complete habitat and species distribution data are required. To provide comprehensive data to support spatial management, a goal would be to have complete habitat maps for areas of interest, covering the full range of habitats present. These may not be required for all areas, for example for locations that are particularly remote and somewhat isolated from human activities. To fill this gap additional optical data are required, especially in deeper reef areas where optical data are very limited, and is insufficient even to accurately document the extent of coral reef habitat.

4.3.2 MPA selection

To support selection of MPAs, CRED mapping data again provides useful baseline information. In many of the places that CRED conducts seabed mapping, there is insufficient data on biodiversity to make educated choices about where MPAs for biodiversity conservation should be selected. As a proxy to detailed habitat maps, researchers in other parts of the world have mapped geomorphological features and sediment types. CRED BPI structure maps represent the distribution of a number of geomorphological features, but lack sufficient ground-truth data to validate whether they provide a good proxy for the distribution of biological communities. This is particularly true for ground-truthing of non-hard substrate areas, as necessarily effort has historically been focused on mapping of hard reef areas. Adequate substrate maps would be one more step towards the goal, and these have been produced by CRED in some areas, but in others, insufficient quality backscatter data mean that it is not possible to produce such maps, or lack of ground-truthing means that the maps rely on unsupervised-classification and are not validated. For MPAs selected for the conservation of specific habitats, using a proxy habitat map may not be suitable as it would lack accuracy in documenting the exact distribution and extent of the habitat of interest. In such a situation, there is no alternative but to obtain additional biological data, although maps such as substrate, bathymetry, and geomorphology would help to focus survey effort in targeting the habitat of interest.

To support selection of MPAs for fisheries protection, additional data are required, such as locations of important nursery areas, spawning aggregation sites, areas of high abundance of target species. In addition to data on shallow-water fish abundance and distribution that is collected by CRED scuba divers, in recent years CRED has increasingly collected data on fish in deeper waters using the towed-camera sled and AUV. Data collected with the towed-camera since the additional of a forward-facing video camera in 2008 is suitable for surveying reef-associated fish populations. Downward-facing imagery from both the towed-camera and the AUV still provide valuable information on habitat, but the orientation of the camera makes this a sub-optimal tool for analyzing fish abundance. Simultaneous collection of both habitat and fish data are advantageous as this allows the two types of information to be accurately related. The planned addition of a forward-facing video camera on the AUV in early 2011 will also make this a valuable method to collect data on reef-associated fish communities. There are currently only a small number of areas where sufficient data exist to be able to provide help with selection of MPAs for fisheries protection, due to overall lack of optical data, limitations of the equipment setup, and also because data has historically not been collected with fish in mind, and have been collected at different times of day and night thus sampling different fish communities. Where data on fish are available, further work can be done to relate the fish abundance to habitat characteristics, and this information would be valuable in helping to select MPAs for fisheries protection (see also Section 4.3.3). This will certainly be an area that CRED will hope to do more work in future.

4.3.3 Management of fisheries resources

Mapping of Essential Fish Habitat often relies on substrate maps. CRED has aimed to produce hard-soft substrate maps where sufficiently high quality backscatter data are available, but there has not always been sufficient optical data to ground-truth the classified map. If additional optical data were obtained to ground-truth hard-soft substrate maps, this would enable more accurate substrate maps to be available to support fisheries use.

Fisheries stock assessment is now increasingly looking to relate fish abundance and distribution to habitat characteristics, to improve stock assessment estimates and to reduce the reliance on fishery-dependent data. This is a key focus of the 2010 National Marine Fisheries Service (NMFS) Habitat Assessment Improvement Plan, which outlines the role of NMFS in pursing habitat science and developing habitat assessments in order to sustain marine fisheries and associated habitats (NMFS 2010). CRED substrate maps provide a layer of information that could support this. With existing data in some areas, it may also be possible to do further work delineating areas with distinct acoustic characteristics. It may be possible to relate these to fish abundance and diversity information. So far, limited information on fish species abundance is available through analysis of the towed-camera underwater video. However, additional video data are available that can still be analyzed to support this work. Furthermore, as mentioned above, a new forward-facing camera to be added to the CRED AUV is currently under development. This camera is intended to be able to obtain data on abundance and diversity of fish living within 3 m of the seafloor. Additional fisheries data obtained by this method would be able to further support the goal of relating fish abundance to habitat characteristics. Subject to funding, there are also plans to mount a forward-facing sonar on the AUV, designed to obtain acoustic data that can be used to obtain data on size and quantity of fish within the field of view. These additional data would allow relationships between habitat characteristics and fish community characteristics to also be investigated. Therefore, while further analytical work can be done with data currently held by CRED, it is intended that this will be a developing area of work where new data can allow methods and processes to be further developed.

4.3.4 Evaluation of management effectiveness

In order to demonstrate effectiveness of management practices using seabed mapping data, a temporal component is required. Repeated mapping of coral reefs for example can show change in reef extent over time, or even, with sufficient resolution and quality of data, change in extent of different reef habitats. So far, this has only been demonstrated with using satellite imagery to demonstrate change in shallow reef areas (Dobson and Dustan 2000). Assuming that multibeam data could be demonstrated to measure the extent of specific habitats then repeated multibeam mapping of a given area would be able to also measure change and therefore evaluate management effectiveness. The CRED mapping program has historically focused on conducting acoustic mapping of specific areas just once, as the exceptionally large area of operation has and will require many years to completely map even once, without contemplating conducting repeat mapping. Furthermore, as effort has focused on providing a broad characterization of the seabed, resolution of existing data may not be sufficient to discern distribution of habitats on a fine scale, or to measure change. However, in principle, if there were a high priority management need, it could be feasible to conduct repeat mapping on a small area for this purpose.

4.3.5 Predictive species and habitat mapping

Modeling the predictive distribution of habitats, or of other metrics (e.g., coral cover, fish abundance and biomass) has been demonstrated using bathymetry and bathymetric derivatives from both lidar and multibeam. The basic requirement is to have good quality bathymetry data at an appropriate resolution for the analysis and sufficient biological data (e.g., video imagery) to relate to the acoustically different areas.

Although no research has been conducted thus far, there is good potential for CRED to use multibeam collected in a few areas where sufficient optical validation data exist, to model relationships between acoustically-derived seascape metrics (e.g., slope, rugosity, BPI) and benthic community metrics (e.g., coral cover) or fish metrics (e.g., abundance, species presence), using similar methods to those outlined in section 3.5 above (Iampietro et al. 2008; Pittman et al. 2009).

For example, Donham (2010) used CRED multibeam data and towed-camera video imagery from French Frigate Shoals to investigate relationships between fish assemblages and habitat characteristics that had been derived from the multibeam bathymetry and backscatter. Significant relationships were found between fish assemblage and substrate type, depth and slope of slope, indicating that the data would be suitable for further investigation and could be used to model distribution of key fish assemblages. This approach could be expanded to investigate the relationship between the same acoustically-derived habitat characteristics and coral cover. The current limitation to carrying out this analysis more widely within the CRED area of operation is that, while suitable multibeam data are available for many locations, insufficient optical validation data exist across the range of acoustic signatures.

4.3.6 Planning of surveys and monitoring programs

Basic mapping data such as seabed bathymetry is an essential tool in survey planning, particularly where specific habitats or depth ranges are being targeted. Many of the areas where CRED has collected multibeam have previously had very little bathymetry data, often only navigation charts constructed from few historic depth soundings. Relying on such historic data for survey planning can mean that something as simple as depth stratification of survey sites can be hit or miss. Additional habitat characterization data such as substrate type (as presented in the CRED hard-soft substrate maps) allows further stratification of survey sites by habitat type, or allows areas of low interest (e.g., soft-sediment non-reef areas) to be excluded. Therefore where good quality bathymetry and backscatter data have been collected by CRED these are highly useful in planning survey strategies, although in some areas, lack of ground-truthing means that the substrate maps can only provide an estimated distribution of sediment type, and may not be accurate. Additional optical validation over areas where high-quality multibeam data has already been obtained will allow further habitat characterization (such as mapping habitat extent, or validating hard-soft maps) to be conducted, which would provide additional benefit in survey planning or development of monitoring strategies. As described in section 3.6 CRED seabed mapping data has already been used to inform survey planning (Menza *et al.* 2010) and CRED frequently receives requests for seabed mapping data which will be used for such purposes. CRED also regularly use optical data collected to support survey planning around the Main Hawaiian Islands. CRED, in collaboration with the Bishop Museum, Department of Aquatic Resources and University of Hawaii, are currently involved in researching mesophotic coral reef ecosystems in the Hawaiian archipelago. Optical data from TOAD and ROV surveys have been analyzed to describe the benthic cover, including coral cover, and these data are used to plan dive sites, tracks of future tows and locate suitable areas to deploy instrumentation.

5 Conclusion and recommendations

The current and potential application and benefits of CRED mapping data have been outlined in section 4.3 above, in relation to the range of uses to which mapping data can be applied. The limitations which are also described above generally relate to three issues. Firstly the lack of bathymetry data, in shallow (< 20–30 m depth) waters around some locations, although as mentioned in section 4.2 this gap is being addressed where possible. Secondly, the majority of optical data collected by CRED is limited to the depth range of scuba divers (~ 30 m). Thirdly, and most significantly, video imagery in waters beyond 30 m depth is very limited in spatial extent, leading to a significant lack of geographical overlap between acoustically collected data (i.e., multibeam) and optical data.

Despite these limitations there are a number of areas in which CRED could develop methods and processes to further the use of existing data. The main areas in which further development could occur, are:

- Relating fish abundance and other fish community measures to habitat characteristics, using existing habitat data from analyzed towed-video and that derived from multibeam bathymetry and backscatter.
- Use existing multibeam bathymetry and backscatter data to delineate areas with distinct acoustic characteristics, and investigate whether these can be related to fish or benthic community characteristics.
- Investigating different methods for delineating specific habitats using existing multibeam and optical data.
- Modeling relationships between acoustically derived seascape metrics and benthic or fish community metrics, with the aim of developing the model into predictive distribution maps.
- Using the newly agreed CRED benthic classification scheme (see section 4.3.1) to develop seamless maps of benthic community characteristics (e.g., coral cover) from shallow to deep waters.
- Investigating the application of the NOAA Coastal and Marine Ecological Classification Standard (version 3.1) to CRED mapping data, to provide a uniform way of classifying and describing habitats in any mapped products.

To address the limitations outlined above and in section 4.3, the following data gaps need to be addressed:

- Obtaining additional optical data, especially in depths below 30 m, would allow the generation of complete habitat maps for areas of interest (e.g., for marine spatial planning); production of maps showing distribution of key habitats and species; ground-truthing of BPI maps to determine whether these provide a good proxy for distribution of biological communities; validation of hard-soft maps; investigation and possible modeling of the relationships between acoustic and benthic, or fish data in more locations.
- Obtaining additional optical data with video imagery (e.g., using towed-camera, ROV or AUV) in shallow water areas that overlap with towed-diver data would allow the two methods to be cross-referenced, which would provide additional confidence in interpretation of results and help to identify potential limitations with the two methods.
- Obtaining additional backscatter data, where current data are missing or lacks quality would allow production of hard-soft substrate maps where these are currently lacking, which in turn can help to support CMSP, MPA identification, management of fisheries resources, and survey planning.

- Obtaining additional video data from forward-facing cameras would provide data for selection of MPAs for fisheries protection by identifying areas important for fish lifestages.
- Repeated multibeam mapping of specific areas may allow measurement of change in habitat distribution, providing the habitat in question could be accurately delineated with the types of multibeam and optical data CRED can collect.

Addressing these issues both in terms of conducting further research, and obtaining additional data, would go a long way to adding value to the data which has already been collected by CRED, through funding provided by NOAA's Coral Reef Conservation Program (CRCP) and others, and allow CRED to more fully support some of the important goals of CRCP and NOAA.

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