Palmyra Atoll Coral Reef Habitat Mapping Completion Report

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THE NATURE CONSERVANCY IN HAWAII

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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION
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NATIONAL CENTERS FOR COASTAL OCEAN SCIENCE
CENTER FOR COASTAL MONITORING & ASSESSMENT
BIOGEOGRAPHY BRANCH

And

Analytical Laboratories of Hawaii, LLC

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1.   Introduction

The United States Coral Reef Task Force (USCRTF) was established in 1998 by Presidential Executive Order 13089 to lead U.S. efforts to preserve and protect coral reef ecosystems. Current, accurate, and consistent maps greatly enhance efforts to preserve and manage coral reef ecosystems. With comprehensive maps and habitat assessments, coral reef managers can be more effective in designing and implementing a variety of conservation measures, including:

- Long-term monitoring programs with accurate baselines from which to track changes;
- Place-based conservation measures such as marine protected areas (MPAs); and
- Targeted research to better understand the oceanographic and ecological processes affecting coral reef ecosystem health.

The National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) is tasked with leading the coral ecosystem mapping element of the U.S. Coral Reef Task Force (CRTF) under the authority of the Presidential Executive Order 13089 to map and manage the coral reefs of the United States.

1.1   Background

The U.S. Coral Reef Task Force (USCRTF) has committed to produce comprehensive digital maps of all U.S. shallow-water (less than 30 meters) coral reef habitats, and to characterize priority moderate-depth (30-200 meters) reef systems. Coral reef mapping efforts are coordinated through the USCRTF Mapping and Information Synthesis Working Group, composed of representatives from the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), National Aeronautics and Space Administration (NASA), other Federal and State agencies, and academic and nongovernmental organizations (NGOs).

Figure 1. The robust wildlife population of Palmyra is reflected in the large numbers of coconut crabs which on many other islands have been depleted due to harvesting for consumption by humans.

The working group defines mapping as the process of identifying and delineating sea-floor features in georeferenced, remotely sensed imagery and assessing the thematic accuracy of the resulting map. An accurate georeferenced map is critical when characterizing the health of benthic (e.g., coral) communities, and monitoring to detect and measure changes over time. It is important to recognize that "mapping" may include many activities, including delineating shoreline, surveying to obtain high-resolution bathymetry, defining habitat classification systems, and producing digital habitat maps.

The objective of this task, supported in concert with NOAA, The Nature Conservancy (TNC) and the U.S. Fish and Wildlife Service (USFWS), was to generate a benthic habitat map the entire atoll of Palmyra to support baseline ecosystem characterization, evaluating the efficacy of management efforts, and assisting in designing monitoring strategies of tropical flora and fauna (Figure 1). Standard benthic habitat mapping techniques (e.g., visual interpretation of suitable imagery, (see section 2.5) was used to generate a benthic habitat map of approximately 50.26 sq km of its lagoon and surrounding reef. High-resolution multispectral satellite imagery was used to perform all boundary delineation associated with the generation of the benthic habitat map and subsequently all necessary fieldwork intrinsic with the mapping.

1.2   Geology and Benthic Habitats

Palmyra Atoll has the largest land mass of the six islands of the central U.S. Pacific Remote Island Area. It is located at 5°52′N 162°6′W, 61 km and lies in the center of the Line Island chain (Figure 2). Palmyra's administrative status is unique in that it is owned by a private organization, The Nature Conservancy but administered by the Office of Insular Affairs, DOI. In 2001 the USFWS established a National Wild Life Refuge (NWR) at Palmyra.
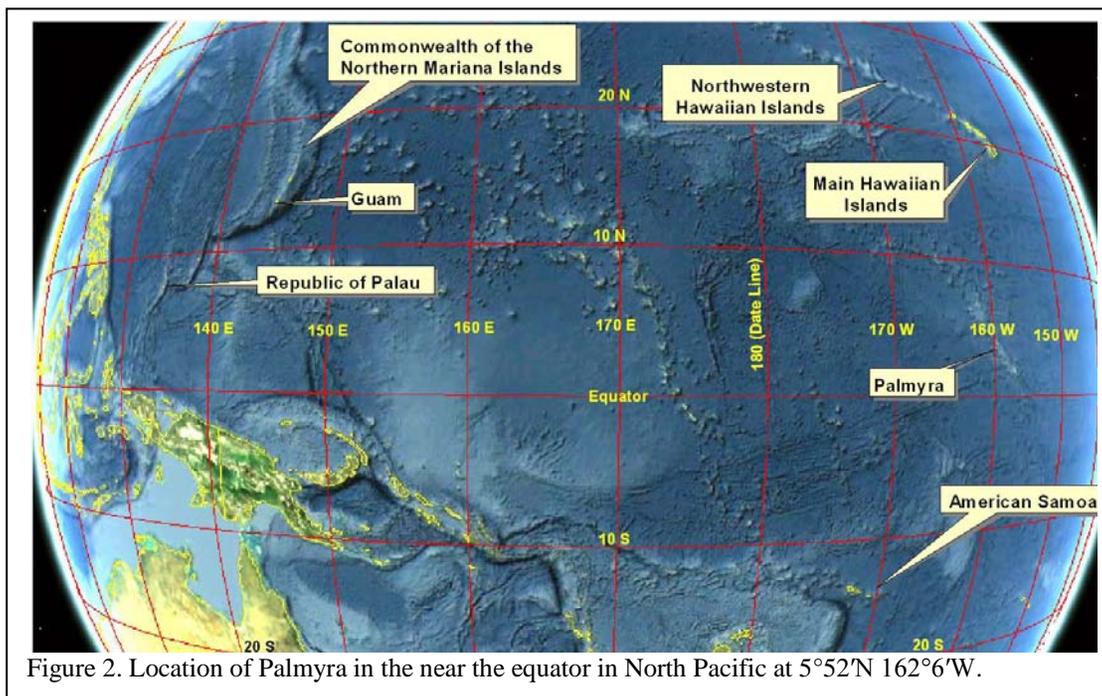
Figure 2. Location of Palmyra in the near the equator in North Pacific at 5°52′N 162°6′W.

The atoll lies just 652 miles (352 n.m.) north of the Equator and has light, variable winds and a humid tropical climate with an average of 175 inches of rain/yr. The lush vegetation includes coconut trees, native ferns and shrubs. Palmyra also has unusually rich biodiversity with 29 avian and 125 coral species documented. Palmyra is a relatively large atoll with extensive reef and 54 islets and bars. The atoll has four shallow interior lagoons and a steep escarpment flanks on all sides outside of the lagoon (http://www.soest.hawaii.edu/pibhmc/pibhmc_pria.htm#palmyra) The area within the atoll encompasses about 12 sq km and the entire atoll including the bank/shelf includes 50.26 sq km. It was used as a naval base by the US during WWI and considerable modifications were made to the water flow regime through the atoll by dredging and building causeways. Though the ecosystem remains robust with abundant wild life, several

invasive organisms have significantly modified the biological communities of both terrestrial and marine ecosystems (http://pubs.usgs.gov/of/2010/1097/).

## 2.	Methods used in Map Production

Early in the planning process of developing the strategy and methods to complete this task, it was recognized that a broad set of technical expertise was needed to accommodate the high level of diversity and challenges that would be encountered meeting this goal. It was also recognized that a mapping program in Geographic Information System (GIS) format would facilitate the most powerful analytical tool for management of the resource. Thus, a very important component in the planning stage of this work was initiated in the year 2000 when NOAA conducted studies to determine what type of techniques and equipment were most suitable for habitat mapping in and around coral reefs. It became apparent that general depth intervals should be addressed for particular sets of instrumentation.   Several types of sensors capable of surveying specific depth intervals were identified. Common technologies such as hull-mounted multibeam sonar that produces both bathymetric and acoustic backscatter data were chosen as the most appropriate technology for benthic habitat mapping in areas as shallow as 20 meters which was determined by the limitation of the vessel size needed to support this equipment. Shallow water surveys from shoreline to 30 meter depth were addressed using both fixed wing platforms and satellite imagery acquiring spectral content allow for a true color visible image to be generated of the seafloor. Each method has specific advantages and limitations and as a result a suite of methods were adopted that allow for comprehensive spatial data acquisition which can be modeled into useful resource management tools.

Simultaneously and in concert with all habitat mapping programs, a clear set of habitat nomenclature, a habitat classification scheme, was developed that allows marine resource managers functional access to spatial models that identify such critical ecological aspects as marine community sensitivity analysis and habitat utilization patterns. Capabilities such as these provide the marine resource manager the tools needed to facilitate conservation of both broad and specific management objectives.

### 2.1	Development of the Benthic Habitat Classification Scheme

A specific set of criteria must be met when designing a habitat classification scheme. Included but not limited to the criteria of a habitat classification scheme are:

- Ability to extract all habitat classes from the source data at a predetermined and agreed upon thematic accuracy.
- Habitat classes must be mutually exclusive
- Consultation with State, academic and private sector partners
- Requests of the management community
- NOS's coral reef mapping experiences
- Quantifiable data exists
- They must be within the budget constraints of the funding agency
- They must be contained in a boundary no smaller than the minimum mapping unit

One of the standards incorporated into the final map products is the minimum mapping unit (MMU). The MMU is the smallest polygon or feature that will be delineated. Establishing the MMU required several considerations including but not limited to:

- The needs of the coral reef management communities interests in having finer resolution maps to make resource management decisions
- Ability to accurately interpret features in the imagery
- Level of effort needed to complete map production

Figure 3. Coral reef community illustrating a geomorphologic classification of hard bottom, aggregate reef and biological cover classified as continuous live coral.

Several efforts were undertaken that examined the feasibility and effectiveness of mapping at various MMUs. In general the management community was interested in as small an MMU as was feasible. Results showed that the smallest MMU was driven primarily by the funds that are available for the designated area and the quality and resolution of the available remotely sensed imagery used in map production. Furthermore, it was observed that a threshold MMU exists where additional resolution is not needed for purposes of monitoring and modeling specific applications. Habitat utilization modeling showed that little additional information is gained by reducing the MMU below one acre. Never-the-less, managers have expressed interest that NOAA's initial MMU of one acre be reduced. As a result attempts to generate maps at less than the one acre MMU continue. NOAA has recently completed a technical memorandum that describes a new mapping effort that has been completed for St. John in the US Virgin Islands. This memorandum combines most recent classification scheme interests with a MMU of 0.25 acres or about 1000 sq. meters. It was decided that the optimum MMU Palmyra should be 0.25 acres.

The sequence used to development of habitat classification scheme typically follows these steps:

- A first draft scheme is generated by professionals with expertise in processing remotely sensed data from the sensor that has been selected to collect the data that will be used to generate the GSI map product.
- This classification scheme developed during the initial (and any historical classification schemes) is presented in a series of workshops, professional meetings and presentations within key marine management hubs for the overall geographic area that is to be mapped.
- A second draft scheme is generated based on the expert's comments and modified according to technical feasibility and as many habitat classes are incorporated into a third draft scheme as possible. This plan is distributed to the managers and other users and the logistical phase of the mapping effort is initiated.

It is recognized that not all habitats are represented in all reef systems. Small variations occur in areas where unique habitats may occur (e.g., vertical walls occur in many Pacific islands but are rare or non-existent in Florida reef systems). The final benthic habitat classification schemes that have been developed in this program have been divided into four sections (Figure 3):

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- Zone: Zone refers only to each benthic community's location and does not address substrate or cover types that are found within it.

- Geomorphologic Structure: Structure refers only to predominate physical structural composition of the feature and does not address location (e.g., on the shelf or in the lagoon) or be biological community colonizing its surface (e.g., live coral).

- Biological Cover: Biological Cover and Cover Modifier categories area identified that dominate the benthic substrate.

- A separate field in the GIS data base has been included in this scheme which quantifies coral cover into four intervals even if it is not dominant.

2.2   Imagery used for coral reef mapping

Two different sources of commercial satellite imagery were used for visual interpretation of benthic habitats. They include the IKONOS satellite, owned and operated by GeoEye, and the Quickbird II (QB2) satellite, owned and operated by Digital Globe. Both satellites have been used extensively for habitat mapping projects however, given the differences in the spatial resolution of the data, there are differences in their utility. Both satellites simultaneously collect a four-channel 11 bit multispectral image (Blue, Green, Red, and NIR) and panchromatic image. However the spatial resolution of IKONOS is 1m Pan and 4m MSI, while Quickbird II is 0.61m Pan and 2.44m MSI. For both sensors, NOAA produced pansharpened individual scenes to produce a higher resolution fused product for mapping. The horizontal resolution for the IKONOS and QB2 pansharpened scenes are 1m and 2.44m, respectively. The availability of the IKONOS and QB2 imagery provided a useful time serious of the region given the IKONOS scenes were acquired in 12/2001 and QB2 from 2/2006 to 9/2009. The initial preliminary habitat map for Palmyra was produced using IKONOS data. However during that effort, it was determined that additional imagery would be helpful given the poor IKONOS optical penetration of the east and west Banks. Several additional archive QB2 images were purchased to compliment the IKONOS scenes. The QB2 imagery was exceedingly helpful in discriminating habitats in all areas given its higher spatial resolution. Virtually the entire initial map created using the IKONOS imagery was updated using the QB2 imagery.

All imagery data used was post-processed by NOAA to improve its positional accuracy and correct for atmospheric and surface effects. Photo-identification points were occupied in June 2005 and during subsequent field missions to provide absolute positions of features visible in the imagery themselves (Figure 5). Using the positional information recorded at occupied location in addition to ephemeris satellite information data provided by the vendors, individual scenes were positionally rectified to +/- 1m of their true position on the earth using softcopy software. More details of these steps are included in the GPS Project Report (Palmyra_GCP_projectreport.pdf) and in the Imagery metadata reports.

2.3   Records and Metadata

All data and data products, such as reports and benthic habitat map products were documented according to Federal Executive Order 12906. Metadata records were delivered which detailed field sampling dates, horizontal and vertical datums, projections, resampling algorithms, processing steps, field records, and any other pertinent information for all data and data products.

The metadata records conform to the Content Standards for Digital Geospatial Metadata (CSDGM) (FGDC-STD-001-1998), as published May 1, 2000 by the Federal Geographic Data Committee (FGDC). Profiles and extensions to the standard that have been endorsed by the FGDC were used if they are applicable to the data or data products. The metadata records contain any and all elements, including those that are considered optional, wherever applicable to the data or data product according to FGDC CSDGM standards.
http://www.fgdc.gov/standards/standards.html

The metadata records were delivered free of errors in both content and format, as determined by the metadata parser (mp) program developed by Peter Schweitzer of the USGS or equivalent (http://geology.usgs.gov/tools/metadata/).

2.4   QA/QC standards, Geodetic Control, Accuracy and Verification

Quality control was established by implementation of four steps. These assured a final product meeting the specification of spatial accuracy of GPS data not exceeding 5 meters at a 95% sigma RMS error from their true geographic location. This plan ensured the reliability and accuracy of the field data collected for benthic habitat accuracy assessment and the final GIS map output.

1) GIS Quality Control

All GIS map products generated during this work were closely examined (Table 1). Errors such as multipart, overlapping, sliver and void polygons were identified and corrected using an ArcView GIS Quality Control extension downloaded from the ESRI web site. The extension was also used to topologically clean the GIS data. Polygons that are adjacent and have the same zone and habitat attributes are identified using an ArcGIS script and all errors are corrected. Attribution of GIS polygons was conducted seamlessly using the NOAA habitat digitizing extension software thus errors are not expected. As an additional step in quality control, a tool within this extension searches the GIS database and identifies all polygons where mismatches occur between the polygon attributes and the habitat classification scheme and all errors have been corrected. GIS data from this work were delivered to NOAA free of errors and a final review by the contractor and a subsequent review by NOAA confirmed this.

Table 1. Quality control of GIS data delivered in this work.

Topology – All GIS data is topologically cleaned
Void polygons – Data are free of void polygons
Adjacent polygons with the same zone or habitat do not exist in the data
Multipart polygons do not exist in the data
Overlapping polygons do not exist in the data
Sliver polygons do not exist in the data
All polygons attributed consistent with the classification scheme
All fields in the GIS data base are populated
All "unknown" zones have unknown habitats

2) Data Security

All digital and hard copy records were kept in secure locations and daily backups were made of field data. The field data acquired each day were archived on CD ROM and handwritten records were collected. Chain of custody records were not needed as all data were maintained in secure custody of ALH at all times.

3) Tabular Data Quality Control

A paramount effort was made to include seamless software processing of all tabular data. Manual entry of data was minimized to limit the possible introduction of human error. However, in some cases, manual entry of information was unavoidable. These steps were identified and particular attention was given to control these processes. An original handwritten record was made for all data where manual entry was required. This record was securely archived and two independent reviews were conducted of the data subsequent to the transfer of the data to the GIS database.

4) GPS Quality Control

Collection of new GPS data was needed to complete this work. Methods that accommodate levels of accuracy needed to meet the objectives of each task were used.

GPS data was acquired for accuracy assessment of the habitat maps. It was also collected for ground validation information that was used to investigate uncertainties on the photo interpreter's behalf during the decision making process of the manual delineation of zone, structure and biological cover. The accuracy assessment data was generated on a random stratified point basis. Ground validation data
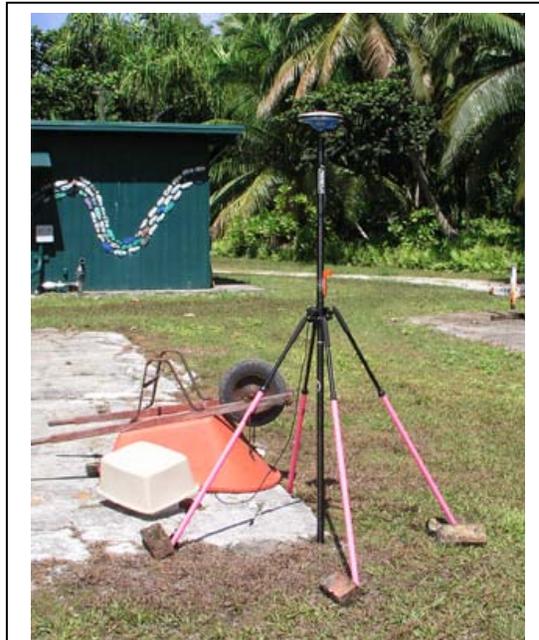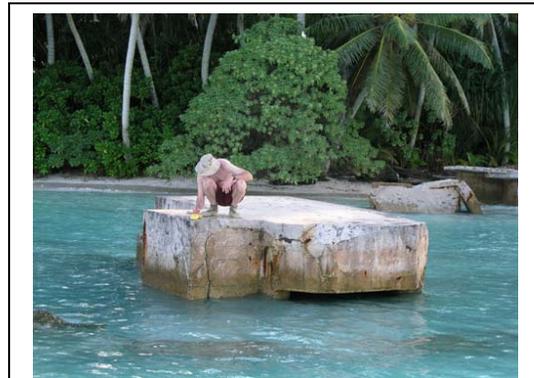
Figure 5. Ground truth data collection for imagery positioning and subsequent imagery position validation.

was generated by selecting specific targets in areas where habitat type was not certain during photo interpretation and needed to be examined in the field or where gradients through habitat type resulted in uncertain habitat boundaries.

Quality control was established by implementation steps that assured a final product meeting the specification of spatial accuracy of GPS data not exceeding 5 meters at a 95% sigma RMS error from their true geographic location. This plan ensured the reliability and accuracy of the field data collected for benthic habitat accuracy assessment and the final GIS map output.

Figure 4. Base station used for acquisition of differential correction data.

2.5   Habitat Map Preparation from Photo Interpretation

Traditional methods of stereo plotter digitizing of photo interpreted habitat classes have been nearly completely replaced by computerized on screen digitizing methods. The latter method has distinct advantages.

- It eliminates the intermediate digitizing step reducing positional error of the habitat boundaries.

- Productivity is higher.

- It develops an active link between the mapped image and the associated database.

Thus a Geographic Information System (GIS) is superior and desired. The application of GIS provides a powerful analytical tool that yields critical information and contributes to the ability of making sensible long-term natural resource management plans.   The maps and mapping methods described in this report were developed using Environmental Systems Research Institute (ESRI) ArcGIS software version 9.3.

All benthic habitats were mapped from the shoreline to a depth of 30 meters. This task was accomplished using on screen digitizing in ArcView GIS format facilitated by the Coral Reef Digitizer Extension developed by NOS and published on the NOAA web site (http://biogeo.nos.noaa.gov/products/apps/digitizer/).

2.5.1   Five Step Map Production Process

The coral reef benthic habitat maps were prepared in a five step process.

1) A first draft coral reef habitat map was produced by delineating all features that could be identified by visual inspection of the satellite imagery. This first draft map includes all zones, geomorphologic structure and biological cover types as well as shoreline and unknown areas. It was generated by heads up "on screen" manual photo interpretation and delineation in ArcGIS format. NOAA staff has published an editable ArcGIS extension that allows for a custom habitat classification scheme to be developed based on the user's needs. The software also allows for zone classifications to be included and toggles between the legends of the habitats and zones within the GIS system. It provides the option of setting the area of minimum mapping unit (MMU) and   informs the photo interpreter when a polygon is being closed that has an area below the selected MMU. It provides the option of including or eliminating that polygon.

All manual delineation was conducted based on the color and texture of the features in the imagery as well as the contractor's extensive knowledge of the coral reef systems and field observations.

2) Areas that were difficult to interpret or where the photo interpreter needed additional field information were identified and labeled as ground validation positions. These locations were explored in the field to enhance map accuracy. These surveys were completed and the maps were edited based on the ground validation information to generate a second draft map product.

3) A second set of field survey positions were created and used for accuracy assessment of the map products. This second set of points was generated by stratifying each habitat and structure type and generating a minimum of 25 randomly distributed field positions per class. During the edit of the maps in step 2, the accuracy assessment data was withheld from the photo interpreter. This process step is completely described in Section 2.5.4. If the accuracy met NOAA standards,

the process proceeded to step 4. If it did not, it was returned to the photo interpreter to be further refined. If additional ground validation observations were needed to improve accuracy, they were collected at this time.

4) After demonstrating that the map products meet the NOAA accuracy standards, these map products were reviewed by local marine biologists, coral reef scientists and marine recourse managers. Comments were integrated into the map products to generate a third draft map.

5) Content Standard for Digital Geospatial Metadata (CSDGM) compliant metadata summaries were prepared for all point and polygon GIS data generated. These GIS data and metadata summaries were provided to be reviewed by NOAA and prepared for publication.

2.5.2   Geographic Reference System

All geospatial products generated in this work were referenced to a specific Datum and projection. In all cases the data were projected to the appropriate Universal Transverse Mercator (UTM) Zone and NAD 83 Datum. Projection information of each geospatial product was documented in the CSDGM/FGDC compliant metadata summary.

2.5.3   Acquisition of Habitat Characterization Data

A Trimble GEO XH hand held GPS units and Trimble Pathfinder Office Software was used for all post processing and differential correction of the raw GPS data (Figure 6). All GPS data was post-processed to base station positioned on the Atoll for the duration of field activities. A NOAA dual-frequency Ashtech Z-Extreme was used to compute static positions (Figure 4). Habitat attribute information was collected on site using the GPS data logger with a custom data dictionary designed to reflect the NOAA (Table 2). Biogeography classification scheme for benthic habitats (Section 2.6). Furthermore, manual records were kept that include the same information as a hard copy filed record as a backup to the digital data collected on the GPS data logger.

Figure 6. Field data collection on a Trimble GPS data logger.

Figure 7. In suitable conditions in shallow water quality, observers characterize the benthos using a glass bottom look-box.

These data were used as ground truth to determine the accuracy of the maps produced in this work and to refine areas where habitat determination was uncertain. Waypoints were generated using a stratified random sampling regime for assessment of thematic accuracy or were selected to explore specific features in the imagery for ground validation. Each waypoint that could be safely occupied was navigated to using a suitable sized boat to accommodate the sea conditions. After arrival at the way point, 100 GPS positions were collected at one-second intervals and were averaged to generate a single position. After GIS data collection was complete the habitat characterization was conducted in a circular area of 7.5 meter radius centered on the way point. Each feature was populated with site-specific data using the Trimble GPS data logger.

The geomorphologic structure was determined and estimates of each of the biological cover types in the classification scheme were made. The depth of the site was recorded using a hand held depth sounder or a depth sounder on the survey vessel. The benthic habitat assessments were made using a glass bottom look box, free diving, video drop camera or observing from the surface (Figures 7 & 8). All diving was conducted by breath holding or snorkeling on the surface. In areas where waves and sea conditions were prohibitive to safely access the waypoint by boat, the GPS was placed in a watertight box and swam to the survey point.

At the end of each field day, the data was downloaded from the GPS data logger and later post-processed to the base station. The Trimble GPS file was then converted to an ArcGIS shape file and the data was compared with the handwritten field notes. All data were processed at the end of each field day.

Figure 8. Video Drop Camera used to observe and record benthic characterization data.

Table 2. Data collected using Trimble Geo XH logger at each benthic habitat characterization site during field habitat surveys.

Site Data	Habitat Data
Study Area	Major Structure and Detailed Structure
UTM Zone	Hierarchical Biological Cover and Modifier
Site ID	Estimated Coral Cover
GP Date	Estimated Seagrass Cover
GPS Time	Estimated Macroalgae Cover
GPS Position	Estimated Coralline Algae Cover
GPS Statistics	Estimated Turf Cover
Depth	Estimated Emergent Vegetation Cover
Photo Information	Estimated Uncolonized Bottom
Initials of observer	Comments

2.5.4. Assessment of Thematic Accuracy

A statistically robust data set composed of random field habitat observations were made to assess the thematic accuracy of the mapped product. For most of the areas NOAA has mapped, the area was so extensive that discrete test areas were selected and were chosen based on input from the local marine biologists and coral reef managers. These groups provided advice on the location of the most diverse benthic communities and also areas of particular importance based on management strategies and marine protected areas. However the entire area of coral reef habitat was small for Palmyra Atoll so the entire extent of the map was used for thematic accuracy testing (Figure 9). To determine the overall accuracy of the mapped product, conventional
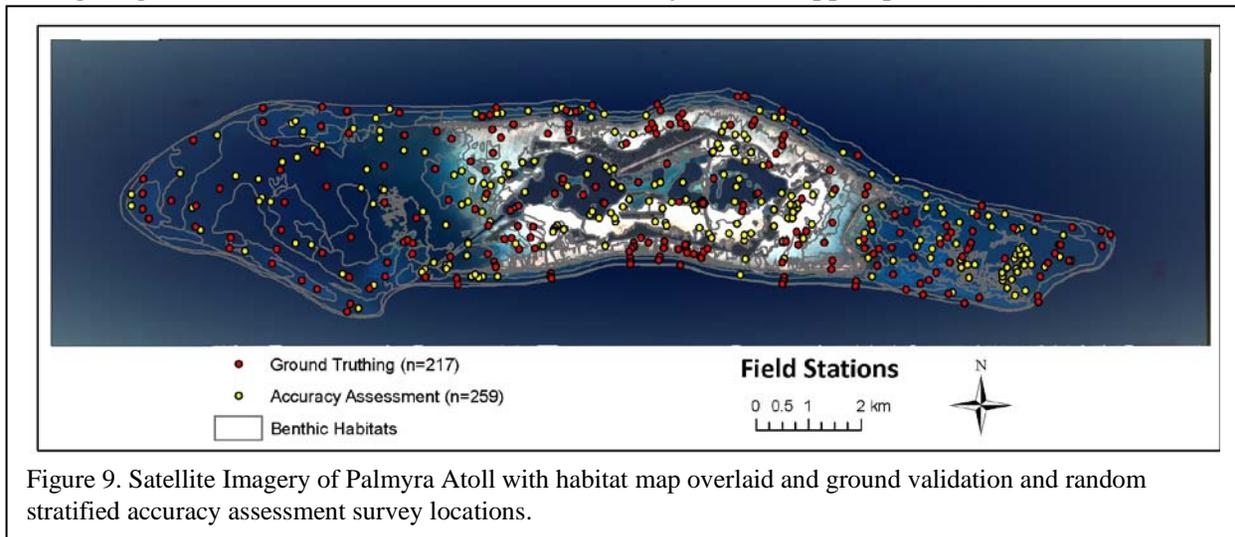
Figure 9. Satellite Imagery of Palmyra Atoll with habitat map overlaid and ground validation and random stratified accuracy assessment survey locations.

assessment of the accuracy of resource maps prepared from remotely sensed data was completed. The accuracy assessment system was designed and executed to quantify the thematic accuracy of the maps generated at all levels of the classification scheme. Statistical analysis methods have been applied that have been developed by other researchers (Hudson and Ramm 1987, Congalton 1991, Rosenfield et al. 1982). The accuracy assessment is prepared from a matrix that compares

the attribute assigned to a polygon that was generated from the interpretation of the image with that of the determination from field observation. Traditionally, the data is organized into columns that represent the field habitat validation data and the rows are organized into the interpretation of the images. The overall accuracy is typically measured by dividing the total correct determinations by the total number of assessments. This overall statistic represents the simplest estimate of accuracy. This result only incorporates the major diagonal of the table and excludes the omission and commission errors where as the Kappa analysis (Cohen, 1960) indirectly incorporates the off-diagonal elements as a product of the row and column marginals. Furthermore, the Tau analysis generates a similar statistic as Kappa but compensates for unequal probabilities of groups or for differences in numbers of groups (Ma and Redmond, 1995). In addition, accuracies of individual categories can be computed in a similar manner. However, this case is a little more complex in that one has a choice of dividing the total number of correct observations with either the total number of observation in the corresponding row or column. When one uses the column total as the result indicates the probability of the field observations are correct and is referred to as the "producer's accuracy. When one divides by the row total the result represents the probability that one will encounter the correct map attribute when visiting random sites in the field. This estimate is commonly referred to the users accuracy as it is typically in the map users interest to know the reliability of the map when one plans activities such as developing models for monitoring.

2.6.   Coral Reef Habitat Classification Scheme

Geographic Zone	Geomorphological Structure	Biological Cover
Land	Coral Reef and Hard Bottom	**Major Cover**
Salt Pond	Rock Outcrop	Algae
Shoreline Intertidal	Boulder	Live Coral
Lagoon	Aggregate Reef	Coralline Algae
Reef Flat	Individual Patch Reef	Mangrove
Back Reef	Aggregated Patch Reefs	Seagrass
Reef Crest	Spur and Groove	No Cover
Fore Reef	Pavement	Unknown
Bank/Shelf	Pavement with Sand Channels	**Percent Major Cover**
Bank/Shelf	Reef Rubble	10% - <50%
Escarpment	Rhodoliths	50% - <90%
Channel	Unknown	90% - 100%
Dredged	Unconsolidated Sediment	Unknown
Unknown	Sand	
	Mud	**Coral Cover**
	Sand with Scattered	**Percent Coral Cover**
	Coral & Rock	0% - <10%
	Unknown	10% - <50%
	Other Delineations	50% - <90%
	Land	90% - 100%
	Artificial	Unknown
	Unknown	

Table 3. Summary of habitat classes from the most recent classification scheme developed by NOAA.

Many important factors were considered in the development of the habitat classification scheme used to map Palmyra including: requests of the management community, existing classification schemes for coastal ecosystems, quantitative *in situ* habitat data, minimum mapping unit (MMU) and spectral limitations of remotely sensed imagery. The habitat classification scheme was tested in St. John, USVI, and was based on the evolution of schemes developed by NOAA in efforts to map the U.S. Caribbean and Pacific Islands (Kendall et al. 2001, Battista et al. 2007a, and Battista et al. 2007b).

The fundamental difference in the St. John scheme, as compared to other NOAA coral reef classification schemes, was the deviation from coral-centric classification rules to a biological dominance scheme in which benthic habitats were classified based on the dominant biological cover type present on each feature.

In previous NOAA coral reef classification schemes, the biological cover component was assigned to a step-wise progression to first capture the presence of live coral and then attempt to classify any other biological cover if coral was not present. In other words, during map creation the interpreter would assign a polygon to the *Live Coral* biological cover class if there was 10% or greater live coral cover even if the polygon was predominantly covered by another biological cover type. For example, a patch reef covered by 15% live coral and 85% turf algae would be described in the previous classification schemes as *Live Coral* 10% - <50%. This approach often mislead map users in overstating the degree of live coral cover at the expense of the more prevalent biological cover type.

In NOAA's new habitat classification scheme, there were no formal hierarchal classification rules; instead biological cover was described as the dominant cover type on each feature of the map. The importance of always describing the percent cover of live coral was maintained in the by the introduction of a new map attribute *Percent Coral Cover*. This attribute describes the percent live coral cover for every feature at the scale of diver observation in the water, with no regard to dominant biological cover. It is important to note that *Percent Coral Cover* refers only to the hardbottom component of any mapped polygon. For instance, an area of sand with some small scattered coral heads in it could be classified as *10% - <50%* live coral cover even though 90% of the polygon is bare sand.

Thus, the Palmyra Atoll habitat classification scheme defines benthic communities on the basis of four primary coral reef ecosystem attributes: 1) broad geographic zone, 2) geomorphologic structure type, 3) dominant biological cover, and 4) degree of live coral cover.

2.6.1. Geographic Zone

Thirteen mutually exclusive zones can be identified from shore to shelf edge corresponding to typical insular shelf and coral reef geomorphology.
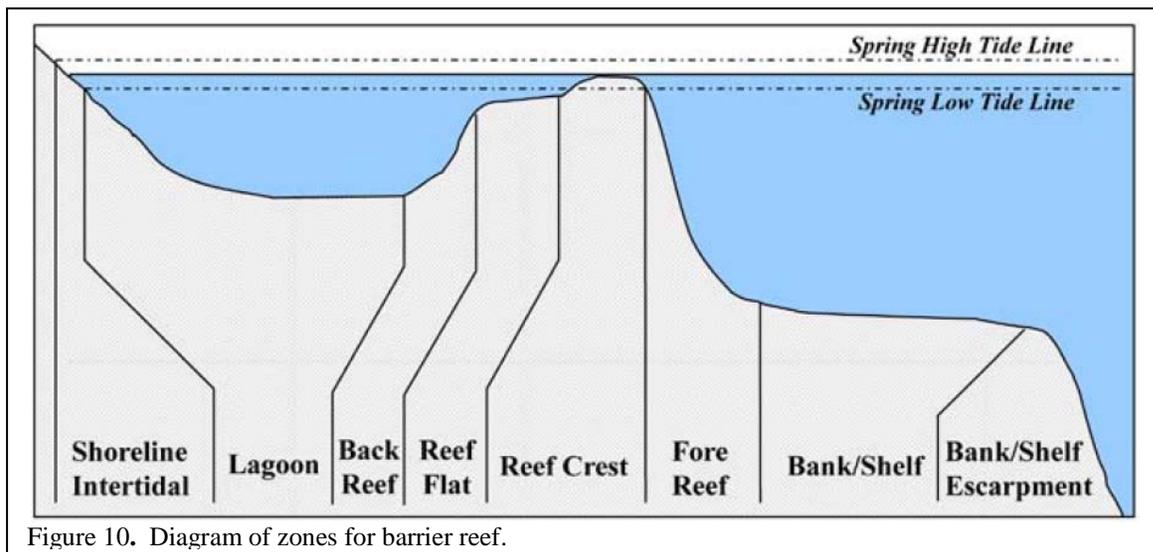
Figure 10. Diagram of zones for barrier reef.
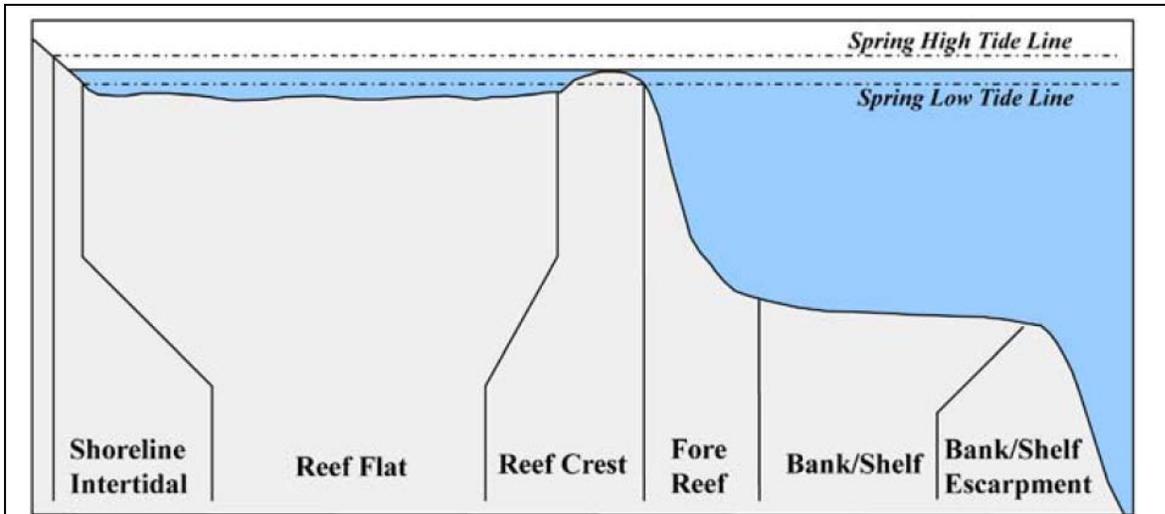
Figure 11. Diagram of zones for fringing reef.
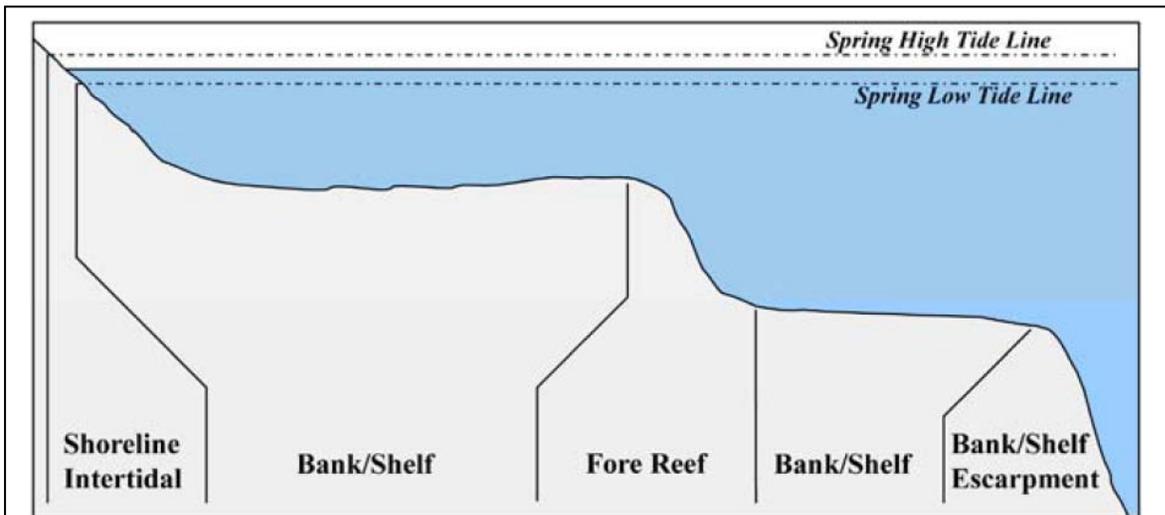
Figure 12. Diagram of zones for an area where neither a barrier or fringing reef are present.

These zones include: *Land, Salt Pond, Shoreline Intertidal, Reef Flat, Lagoon, Back Reef, Reef Crest, Fore Reef, Bank/Shelf, Bank/Shelf Escarpment, Channel, Dredged,* and *Unknown*. Figures illustrate zone types across typical cross-sections when the reef feature is either separated from shore by a lagoon (Figure 10), fringing the shore (Figure 11), or not emergent (Figure 12). Zone refers only to each benthic community's location and does not address substrate or biological cover types that are found within. (Kendall et al. 2001).

2.6.2. Geomorphologic Structure

The major geomorphologic coral reef and hard bottom classes includes areas of both shallow and deep-water seafloor with solid substrates including *Rock Outcrop, Boulder, Spur and Groove, Individual Patch Reef, Aggregated Patch Reefs, Aggregate Reef, Reef Rubble, Pavement, Pavement with Sand Channels,* and *Rhodoliths* (Figure 13). Most of the detailed geomorphic structure classes are derived from deposition of calcium carbonate by reef building organisms. Substrates typically have no sediment cover, but a thin veneer of sediment may be present at times especially on low relief hardbottoms. Detailed major unconsolidated structure classes include: *Mud, Sand,* and *Sand with scattered coral and rock*.

Figure 13. Geomorphologic structure formation supporting a continuous biological cover of coral.

2.6.3. Biological Cover Classes

Eighteen biological cover classes were identified that could be mapped through visual interpretation of remotely sensed imagery. Cover classes refer only to the dominant biological component colonizing the surface of the feature and do not address location (e.g., on the shelf or in the lagoon) or structure type. (Figure 14). Habitats or features that cover areas smaller than the MMU were not considered. The cover types are defined in a collapsible hierarchy ranging from eight major classes (*Algae, Seagrass, Live Coral, Mangrove, Coralline Algae, No Cover, Unclassified* and *Unknown*), combined with a modifier describing the distribution of the dominant cover type throughout the polygon (*10%<50%, 50%-<90%,* and *90%-100%*). It is important to reinforce that the modifier represents a measure of the level of patchiness of the biological cover at the scale of delineation and not the density observed by divers in the water. This classification scheme represents a significant change in classification philosophy. The classes of Biological Cover are attributed based on dominance as whereas previous schemes were

Figure 14. Biological cover type of continuous algae on a reef crest in Guam.

hierarchical. The percent of Live Coral Cover for each polygon is assigned to a new field in the GIS.

2.6.4. Live Coral Cover

The estimated live coral cover is made in the final process of attributing a polygon independent of other live cover types. It is important to remember that both soft and hard coral contribute to this class (Figure 15).

Figure 15. Soft corals in a groove of a spur and groove reef in the Florida Keys.

3.   Results

3.1.   Ground validation

During the initial delineation of habitat polygons the photo interpreter identified the areas where uncertainty existed in the visual interpretation of the any attributes in the classification scheme. These positions were converted to way points, uploaded to a Trimble GPS with a customized data dictionary designed to reflect the habitat classification scheme. Camera, GPS base station and other survey equipment was prepared for travel and the team deployed to Palmyra Atoll and began field surveys on November 12, 2009. 193 positions that had been identified and determined essential to the preparation of the coral reef habitat map were occupied and surveyed during the November 2009 mission.

The team returned to Hawaii and prepared and interim map product using the data collected during the November field survey. During the processing of the field data and the preparation of the habitat map a new and far superior set of imagery was obtained that made benthic features visible that were not delineated from the first set of imagery. As a result, twenty four additional ground validation positions were collected and provided to the photo interpreter during a second field survey mission (Accuracy Assessment Mission June 2010). During the second field deployment all accuracy assessment data was successfully collected and withheld from the map producer. The habitat visible in the video clips of the twenty four additional ground validation points were provided to the visual interpreter, characterized, incorporated in the ground

validation data set and the coral reef habitat map was revised based on these additional data. The map that was produced based on the new imagery included significant detail that the map generated from the first imagery did not include. A total of 217 positions were surveyed for ground validation including both field efforts (Figure 9).

3.2.   Coral Reef Habitat Area Summary of Palmyra

Illustrations are provided here of the GIS habitat map products displaying the zone, detailed geomorphologic structure, detailed biological cover and percent coral cover for the entire atoll (Figures 16 – 19). A total of 50.26 sq. km. of coral reef area were mapped excluding land, artificial and the area that was too deep to map outside the bank/shelf escarpment.

At the simplest level of the classification scheme, the classes can be broken down to hard bottom and unconsolidated sediment. Of the total 50.26 sq.km. coral reef habitat mapped, 85.75% are coral reef and hard bottom, and 14.25% are unconsolidated sediment (Table 4) not including 25.88 sq.km of 'other Delineations' (Artificial and Land) mapped.

Table 4. Area of hard and soft bottom around Palmyra Atoll.

Major Structure	Number of Polygons	Area (sq. km.)	Area (%)
Coral Reef and Hardbottom	420	43.10	85.75%
Unconsolidated Sediment	57	7.16	14.25%
Total	477	50.26	100.00%
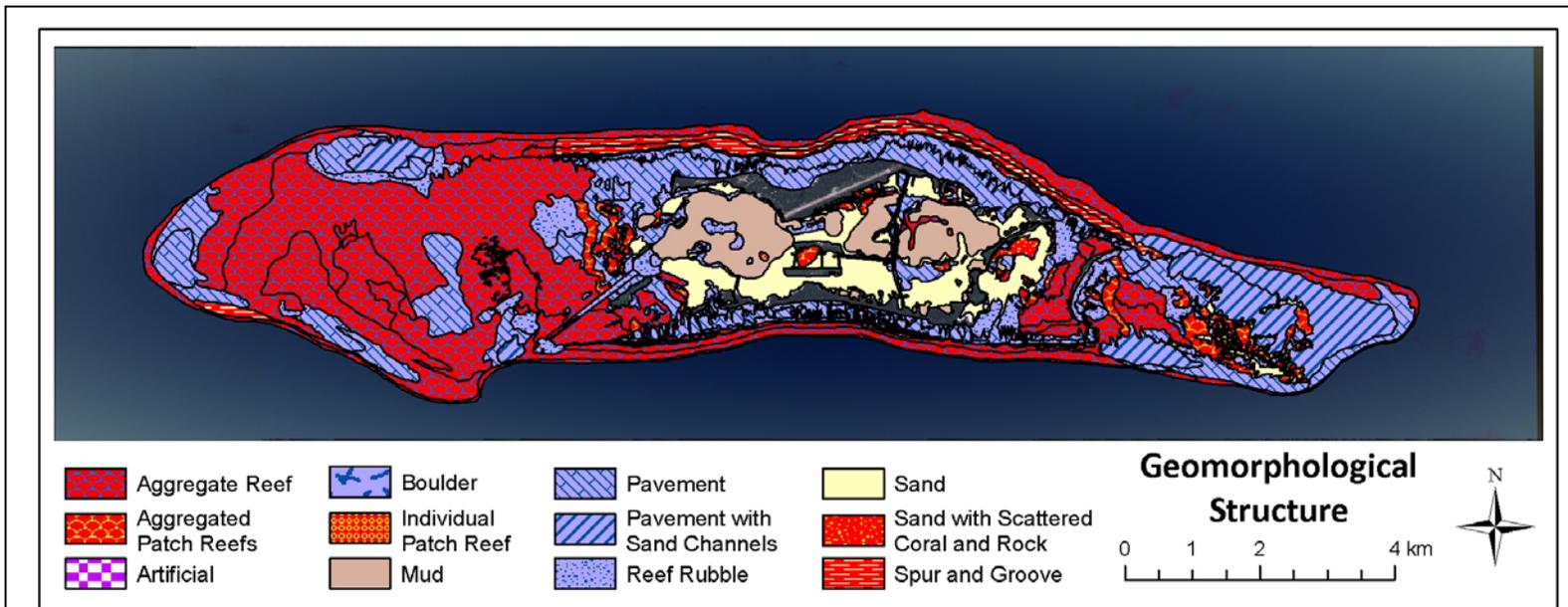
Figure 16. Map of Geomorphologic classes on Palmyra Atoll.
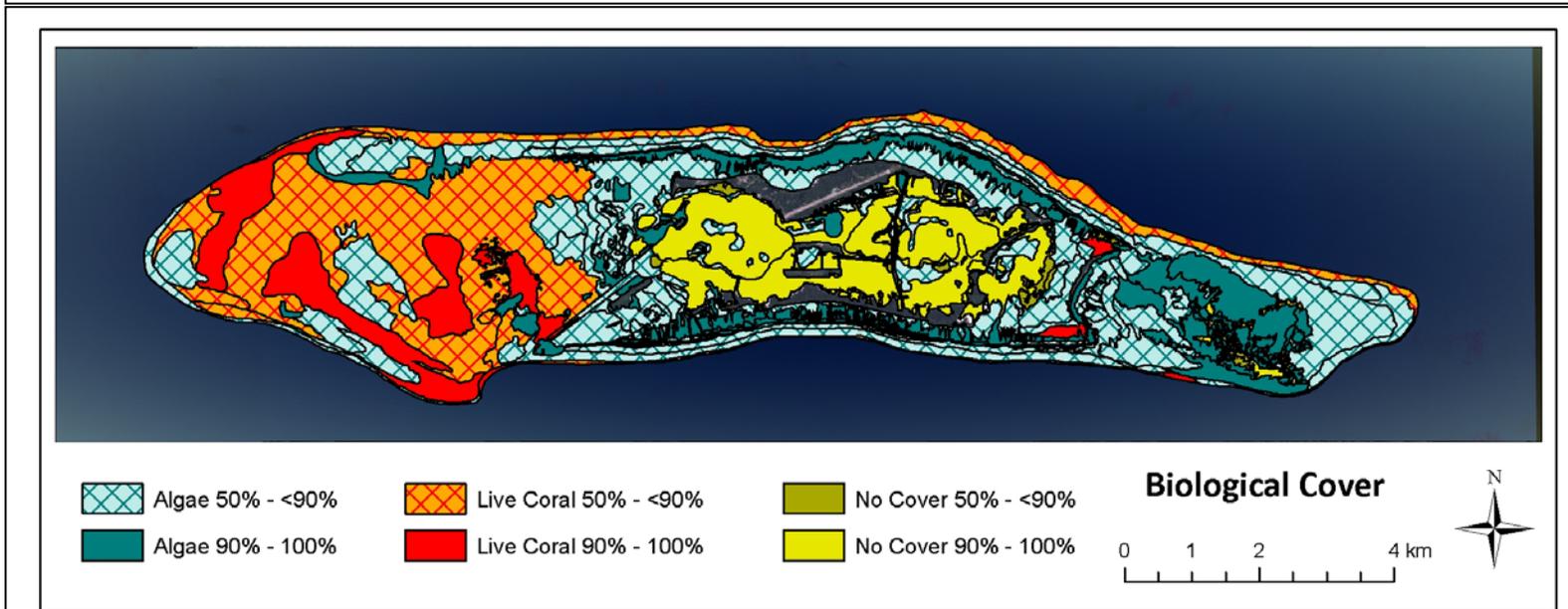
Figure 17. Map of dominant biological classes on Palmyra Atoll.
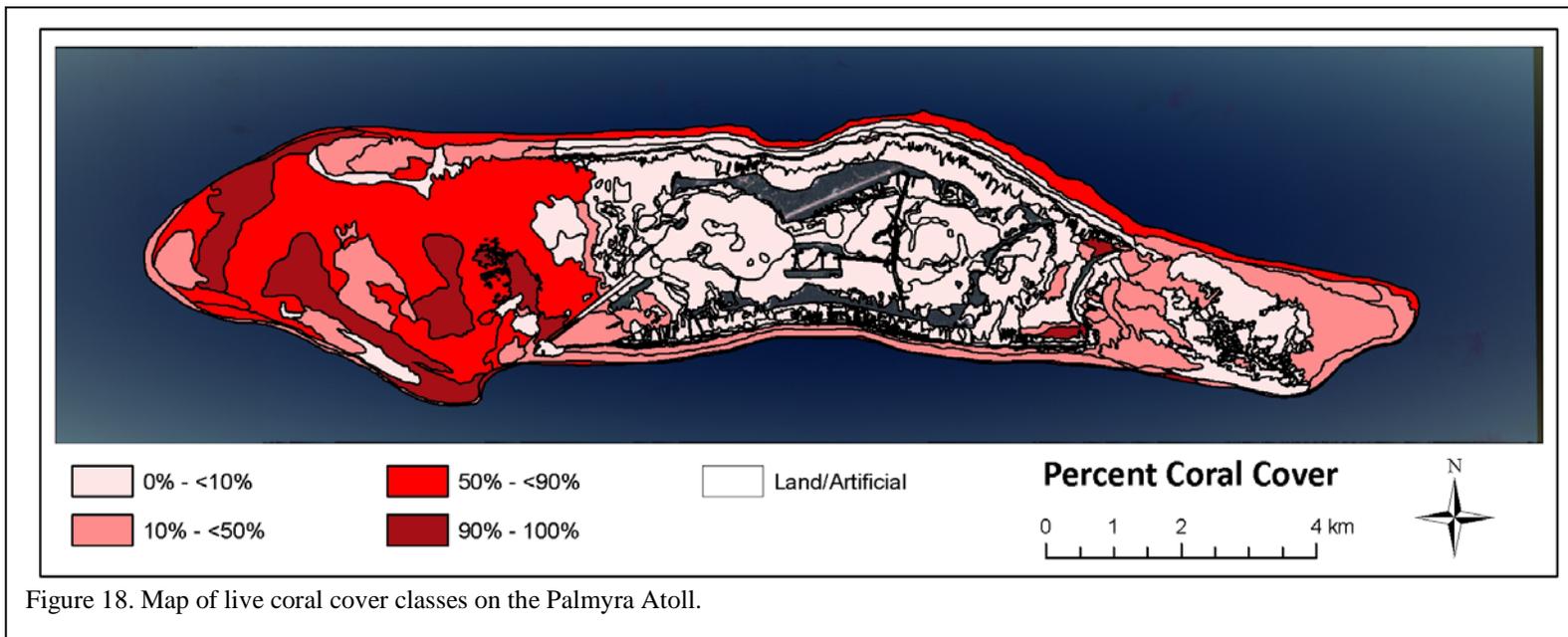
Figure 18. Map of live coral cover classes on the Palmyra Atoll.
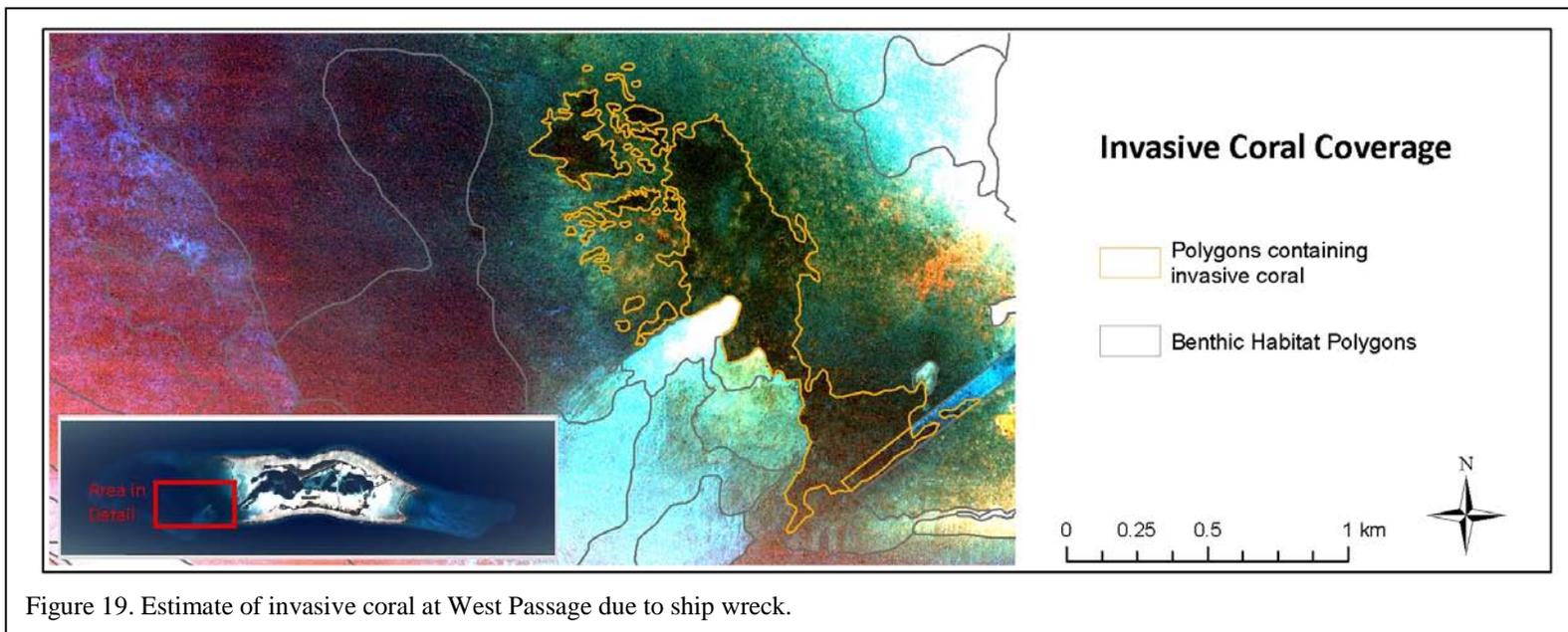
Figure 19. Estimate of invasive coral at West Passage due to ship wreck.

Similarly, a GIS area summary was tabulated for Detailed Geomorphologic Structure, Major Biological Cover, Detailed Biological Cover and Coral Cover (Tables 5 – 8).

Table 5. Area of detailed geomorphologic structure types at Palmyra Atoll.

Detailed Structure	Number of Polygons	Area (sq. km.)	Area (%)
Aggregate Reef	98	21.06	41.90%
Aggregated Patch Reefs	32	1.68	3.35%
Boulder	1	0.0057	0.011%
Individual Patch Reef	39	0.15	0.29%
Mud	27	3.21	6.39%
Pavement	118	10.96	21.80%
Pavement with Sand Channels	8	3.78	7.52%
Reef Rubble	112	33.29	6.56%
Sand	29	3.81	7.57%
Sand with Scattered Coral and Rock	1	0.15	0.29%
Spur and Groove	13	2.16	4.30%
Total	477	50.26	100.00%

Table 6. Area of dominant major biological cover types at Palmyra Atoll.

Major Biological Cover	Number of Polygons	Area (sq. km.)	Area (%)
Algae	354	27.94	52.56%
Live Coral	53	19.18	33.02%
No Cover	70	7.58	14.42%
Total	477	50.26	100.00%

Table 7. Area of dominant detailed biological cover types at Palmyra Atoll.

Dominant Cover Type	Number of Polygons	Area (sq. km.)	Area (%)
Algae 10% - <50%	1	0.013	.025%
Algae 50% - <90%	197	19.00	37.81%
Algae 90% - 100%	156	7.41	14.73%
Live Coral 50% - <90%	14	12.15	24.17%
Live Coral 90% - 100%	39	4.45	8.85%
No Cover 50% - <90%	20	0.39	0.78%
No Cover 90% - 100%	50	6.85	13.63%
Total	477	50.26	100.00%

Table 8.   Area of live coral cover in percentage intervals at Palmyra Atoll.

Coral Cover (% Range)	Number of Polygons	Area (sq. km.)	Area (%)
0% - <10%	379	23.16	46.07%
10% - <50%	46	10.52	20.92%
50% - <90%	13	12.14	24.15%
90% - 100%	39	4.45	8.86%
Total	477	50.26	100.00%

3.3 Assessment of Classification Accuracy

A comprehensive assessment was conducted to evaluate the thematic accuracy of the Palmyra Atoll benthic habitat map. Thematic accuracy was characterized for major and detailed geomorphological structure, major and detailed biological cover, and percent coral cover classifications.

3.3.1   Field Data Collection

Target locations for the accuracy assessment (AA) procedure were determined by an iterative, GIS-based, stratified random sampling technique to ensure that all bottom classifications would be assessed. Points were randomly placed within each geomorphological structure class of the draft habitat map using Hawth's Analysis Tools (Beyer, 2004). No buffer from polygon edges was used. Approximately 25 points were randomly distributed within each detailed structure class. Classes occupying larger areas were often allocated more than 25 points. A total of 265 sample locations were targeted, of which 259 were sufficiently surveyed to be included in the accuracy assessment.

Data were collected during a field mission from 6/2/10 to 6/8/10. Sample locations were navigated to using a hand-held Garmin 76 CS WAAS-enabled GPS unit. Underwater video from a SeaViewer Sea-Drop 950 camera and underwater camera were taken at each site. A weight was tied to the bottom of the camera to help lower the camera to the bottom, and the camera operator adjusted the camera position to get a downward and side view of the habitat at each location. Video length depended on the habitat type and vessel drift, ranging from approximately 30 seconds to two minutes. Videos of large, homogeneous sand habitats were generally short while heterogeneous coral reef habitats (especially edges) were typically longer. While the video was being recorded, GPS waypoints were recorded on board the vessel using a Trimble GeoXT GPS receivers. This resulted in a string of epics that tracked boat position at each site. An observer categorized each site according to the video for each level of the map classification scheme: major/detailed geomorphological structure, major/detailed biological cover, and percent coral. Data was entered into a custom data dictionary on the Trimble data logger and recorded on waterproof data sheets. Videos were recorded to tape using a Sony Walkman video recorder, and converted to digital video clips using Final Cut Pro software.

3.3.2   Evaluation of Assessment Data

The GPS data were processed using Trimble Pathfinder software. GPS data, which were

originally recorded as carrier/code phase signals, were differentially post-processed to the survey grade dual frequency Ashtech Z-Extreme base station. For each survey site, individual epics were averaged to generate an "average" GPS point. The GPS data were then exported and plotted in ArcGIS along with the corresponding field notes. In most cases, the average point was a sufficient representation of the survey site; however in cases where the survey was conducted along or crossed a polygon edge, the average GPS point did not always fall into the polygon that was assessed. In these cases, the survey point was shifted to the portion of the transect and polygon that was classified.

Prior to analysis, each video clip was re-analyzed and viewed in concert with the benthic habitat map overlaid on the acoustic imagery. It should be noted that all analysis at this stage was made by a scientist independent of the cartographer who created the map. Density of the biological cover was assessed at the video level and patchiness of the biological cover polygon level. As a result, it was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and map scales. Similar adjustments were sometimes necessary to correctly characterize detailed structure. For example, heterogeneous hardbottom classes, such as pavement with sand channels, could not always be correctly classified from the video alone. In other cases, additional information on the position, size and shape of hardbottom features was needed to determine whether the structure should be classified as aggregate reef or a patch reef (either individual or part of an aggregated patch reef feature, if below the MMU).

Following these adjustments, data were then spatially joined to the benthic habitat layer to extract the map classification for each point. Sites that differed between field notes and map classification were evaluated both in GIS and from video to determine possible source of disagreement. These disagreements were discussed and evaluated with the cartographer before being scored incorrect. The benthic habitat map was then corrected to its Final version using information collected from the accuracy assessment and released for publication.

3.3.3   Analysis of Thematic Accuracy

The thematic accuracy of the St. John benthic habitat map was characterized in several ways from these data. Error matrices were computed for the attributes major and detailed geomorphological structure, major and detailed biological cover, and percent coral cover. Overall accuracy, producer's accuracy, and user's accuracy were computed directly from the error matrices (Story and Congalton, 1986). The error matrices were constructed as a square array of numbers arranged in rows (map classification) and columns (accuracy assessment, or groundtruthed classification). The overall accuracy (P_o) was calculated as the sum of the major diagonal (i.e. correct classifications, divided by the total number of accuracy assessment samples).

The producer's and user's accuracies were calculated to characterize the classification accuracy of individual map categories. The producer's accuracy (omission/exclusion error) is a measure of how well the cartographer classified a particular habitat (e.g., the percentage of times that substrate ground-truthed as sand was correctly mapped as sand). The user's accuracy

(commission/inclusion error) is a measure of how often map polygons of a certain habitat type were classified correctly (e.g., the percentage of times that a polygon classified as sand was actually ground-truthed as sand). Each diagonal element was divided by the column total to yield a producer's accuracy and by the row total to yield a user's accuracy.

In addition, the Tau coefficient (T_e), a measure of the improvement of classification accuracy over a random assignment of map units to map categories (Ma and Redmond, 1995), was calculated. As the number of categories increases, the probability of random agreement (P) diminishes, and T approaches P. Values of T were calculated as follows:

Tau coefficient $= T_e = (P_o - P_r) / (1 - P_r)$,

where $P_r = 1/r$. The variance of Tau (Ma and Redmond 1995) was calculated as:

Variance of Tau coefficient $= \sigma_r^2 = P_o(1 - P_o) / n(1 - P_r)^2$

Confidence intervals were then calculated for each Tau coefficient at the 95% confidence level (1-α), using the following generalized form:

95% CI $= T_e \pm Z_{\alpha/2}(\sigma_r^2)^{0.5}$

While stratification ensures adequate evaluation of all map categories, it has the undesired effect of introducing bias into the error matrix (Hay 1979; Card 1982). A minimum number of sites were targeted within each mapping category, which caused rare map categories to be sampled at a greater rate than common map categories. For example, although *Aggregate Reef* habitat comprised 42% of the map area, only 20% of the target points were allocated for this habitat. The bias introduced by differential sampling rates was removed using the method of Card (1982), which utilizes the known map marginal proportions (i.e. the proportional areas of map categories relative to the total map area). The map marginal proportions were calculated as the area of each map category divided by the total mapped area of the Palmyra Atoll benthic habitat map. The map marginal proportions were also utilized in the computation of confidence intervals for the overall, producer's, and user's accuracies (Card 1982; Congalton and Green, 1999). This method was also used in the recent accuracy assessment of the NOAA Florida Keys benthic habitat map (Walker and Foster, 2009) and the NOAA shallow-water St. John habitat map (Zitello et al., 2009).

The known map marginal proportions (π_j) were computed from the GIS layer of the draft benthic habitat map for each of the four error matrices (major and detailed geomorphological structure, major and detailed biological cover), by dividing the area of each category by the total map area. Marginal proportions were not computed for the percent coral cover matrix, as this would have required an estimate of the percent hardbottom within each polygon to truly estimate the area of live coral. The map areas were exclusive to categories present in the error matrix. For the example of detailed structure category *Aggregate Reef*, π_j was 0.36 (18.10 km^2/50.31 km^2). The individual cell probabilities, i.e. the product of the original error matrix cell values and π_j, divided by the row marginal (total map classifications per category), were computed for the off-diagonal elements using the following equation:

Individual cell probabilities = $\hat{P}_{ij} = \pi_j n_{ij} / n_{-j}$

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row marginals were forced to the known map marginal proportions (i.e. the row total of a particular habitat now equaled the fraction of map area occupied by that habitat, instead of the total number of accuracy assessment points). The estimated true marginal proportions (p_i) were computed as the sum of individual cell probabilities down each column of the error matrix.

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row marginals were forced to the known map marginal proportions (i.e. the row total of a particular habitat now equaled the fraction of map area occupied by that habitat, instead of the total number of accuracy assessment points). The estimated true marginal proportions (p_i) were computed as the sum of individual cell probabilities down each column of the error matrix.

The π_j-adjusted overall, producer's, and user's accuracies were then computed from the new error matrix, now populated by individual cell probabilities. The values of the π_j-adjusted overall and producer's accuracies differ by design from those of the original error matrix, as they have been corrected for the areal bias introduced by the stratified random sampling protocol. The user's accuracy, in contrast, is not affected. The variances and confidence intervals of the overall, producer's, and user's accuracies were then computed from the following set of equations (Card 1982; Walker and Foster, 2009):

Overall Variance $= V(\hat{P}_c) = \sum_{i=1}^{r} p_{ii}(\pi_i - p_{ii})/n_i)$

Overall Confidence Interval $= \text{CI} = \hat{P}_c \pm 2[V(\hat{P}_c)]^{1/2}$

Producer's Variance $= V(\hat{\theta}_{ii}) = p_{ii} p_i^{-4}[p_{ii}\sum_{j\neq i}^{r} p_{ij}(\pi_j - p_{ij})/n_{-j} + (\pi_i - p_{ii})(p_i - p_{ii})^2/n_{i-j}]$

Producer's Confidence Interval $= \text{CI} = \hat{\theta}_{ii} \pm 2[V(\hat{\theta}_{ii})]^{1/2}$

User's Variance $= V(\hat{\lambda}_{ii}) = p_{ii}(\pi_i - p_{ii})/\pi_i^2 n_i$

User's Confidence Interval $= \text{CI} = \hat{\lambda}_{ii} \pm 2[V(\hat{\lambda}_{ii})]^{1/2}$

3.3.4 Accuracy Assessment Results and Discussion

Major Geomorphologic Structure

Error matrices for major geomorphological structure are displayed in Tables 9 and 10. The overall accuracy (P_o) at the major geomorphological structure level was 97.3% (Table 9). The Tau coefficient for equal probability of group membership is 0.959 ± 0.036 ($\alpha=0.05$). The error matrix in Table 10 is populated by the individual cell probabilities (p_{ij}), which in review are the product of the original error matrix cell values (Table 9) and the map marginal proportions, divided by the row marginal of the original matrix (i.e.,

Table 9: Error matrix for major geomorphological structure.

		Accuracy Assessment (i)				
		Coral Reef and Hardbottom	Unconsolidated Sediment	Other Delineations	$n_{\cdot j}$	User's Accuracy (%)
Map Data (j)	Coral Reef and Hardbottom	192	3		195	98.5%
	Unconsolidated Sediment	4	52		56	92.9%
	Other Delineations			8	8	100.0%
	$n_{i\cdot}$	196	55	8	n=259	
	Producer's Accuracy (%)	98.0%	94.5%	100.0%	$P_o =$	97.3%
					$T_e =$	0.959 ± 0.036

total map classifications per category). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was 97.7 (± 1.8)% ($\alpha=0.05$). The user's and producer's accuracies were similarly high for both hard and soft-bottom habitats (Table 10). The *Other Delineations* class indicates areas of "Artificial" structure category.

Table 10: Error matrix for major geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

		Accuracy Assessment (i)					
		Coral Reef and Hardbottom	Unconsolidated Sediment	Other Delineations	$\pi_{\cdot j}$	User's Accuracy	User's CI (±%)
Map Data (j)	Coral Reef and Hardbottom	0.8463	0.0132		0.860	98.5%	1.6%
	Unconsolidated Sediment	0.0100	0.1295		0.139	92.9%	1.6%
	Other Delineations			0.0010	0.001	100.0%	0.0%
	$p_{i\cdot}$	0.856	0.143	0.001	$\pi=1$		
	Producer's Accuracy (%)	98.8%	90.7%	100.0%	$P_o =$	97.7%	
	Producer's CI (±%)	1.1%	9.7%	0.0%	CI(±) =	1.8%	

Detailed Geomorphologic Structure

Error matrices for detailed geomorphological structure are displayed in Tables 11 and 12. The overall accuracy (Po) at the detailed geomorphological structure level was 84.2%, with a Tau coefficient (Te) of 0.827 ± 0.050 ($\alpha=0.05$) (Table 11). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, improved slightly to 85.0 (± 4.9)% ($\alpha=0.05$), because the classes that covered the most area were also the most correctly interpreted. Adjusted user's accuracy was above 70% for all categories with the exception of Sand category, which had a calculated user's accuracy of 65.6% (Table 12). *Sand* was primarily confused with *Mud* habitat in the inner lagoon where it was difficult to distinguish the two since the substrate composition was often a mixture of fine and coarse sediment rather than clearly separate and distinct classes. For example, sand was sometimes covered with a thin layer of silt.

Table 11: Error matrix for detailed geomorphological structure.

Map Data (j) \ Accuracy Assessment (i)	Aggregate Reef	Aggregated Patch Reefs	Artificial	Boulder	Individual Patch Reef	Mud	Pavement	Pav w/ Sand Channels	Reef Rubble	Sand	Sand w/ SCR	Spur and Groove	$n_{\cdot j}$	User's Accuracy (%)
Aggregate Reef	39						2						41	95.1%
Aggregated Patch Reefs	3	20											23	87.0%
Artificial			8										8	100.0%
Boulder				9									9	100.0%
Individual Patch Reef					4								4	100.0%
Mud						23			1				24	95.8%
Pavement	4						27	1	2	1			35	77.1%
Pav w/ Sand Channels							3	28	1				32	87.5%
Reef Rubble	1	1					6		21				29	72.4%
Sand						6	1		2	21	2		32	65.6%
Sand w/ SCR											2		2	100.0%
Spur and Groove	4											16	20	80.0%
$n_{i\cdot}$	51	21	8	9	4	29	38	30	27	22	4	16	n=259	
Producer's Accuracy (%)	76.5%	95.2%	100.0%	100.0%	100.0%	79.3%	71.1%	93.3%	77.8%	95.5%	50.0%	100.0%	$P_0 =$	84.2%

$T_e = 0.827 \pm 0.050$

Categories with the lowest adjusted producer's accuracy were *Sand with Scattered Coral and Rock* and *Reef Rubble* (Table 12). In these cases, there was a comparatively high degree of variance, and *Sand with Scattered Coral and Rock* was relatively undersampled compared to the other map categories. There were several reasons why the resulting number of samples in these this category was fewer than planned, including: inaccessibility, different classifications in the final map compared to the draft map, and inadvertent sampling of an adjacent polygon. Patch reef and spur and groove features were often small and/or narrow, so the probability of drifting into an adjacent habitat tended to be more frequent than with larger features. Several points ground-truthed as *Sand with Scattered Coral and Rock* (Figure 16) were mapped as habitats that were similar in structure (i.e. *Sand, Reef Rubble* and *Aggregated Patch Reefs*).

Table 12: Error matrix for detailed geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Map data (j)	Accuracy Assessment (i)														
	Aggregate Reef	Aggregated Patch Reefs	Artificial	Boulder	Individual Patch Reef	Mud	Pavement	Pav w/Sand Channels	Reef Rubble	Sand	Sand w/SCR	Spur and Groove	$\pi_{.j}$	User's Accuracy (%)	User's CI (±%)
Aggregate Reef	**0.3424**						0.0176						0.360	95.1%	3.1%
Aggregated Patch Reefs	0.0053	**0.0352**											0.041	87.0%	1.3%
Artificial			**0.0010**										0.001	100.0%	0.0%
Boulder				**0.0001**									0.000	100.0%	0.0%
Individual Patch Reef					**0.0029**								0.003	100.0%	0.0%
Mud						**0.0603**			0.0026				0.063	95.8%	1.0%
Pavement	0.0284						**0.1917**	0.0071	0.0142	0.0071			0.249	77.1%	5.0%
Pav w/ Sand Channels							0.0070	**0.0655**	0.0023				0.075	87.5%	1.7%
Reef Rubble	0.0026	0.0026					0.0154		**0.0541**				0.075	72.4%	2.4%
Sand						0.0144		0.0024	0.0048	**0.0502**	0.0048		0.077	65.6%	2.4%
Sand w/ SCR											**0.0029**		0.003	100.0%	0.0%
Spur and Groove	0.0110											**0.0441**	0.055	80.0%	2.0%
$p_{i.}$	0.390	0.038	0.001	0.000	0.003	0.075	0.232	0.075	0.078	0.057	0.008	0.044	π=1		
Producer's Accuracy (%)	87.9%	93.2%	100.0%	100.0%	100.0%	80.8%	82.7%	87.3%	69.3%	87.6%	38.0%	100.0%	P_o = 85.0%		
Producer's CI (±%)	6.7%	12.5%	0.0%	0.0%	0.0%	11.5%	10.3%	17.3%	19.9%	21.6%	32.3%	0.0%	CI(±) = 4.9%		

Major Biological Cover

Error matrices for major biological cover are displayed in Tables 13 and 14. The overall accuracy (Po) at the major biological cover level was 91.9%, with a Tau coefficient (Te) of 0.892 ± 0.050 (α=0.05). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was similar at 93.0 ($\pm$2.4)% (α=0.05).

Accuracy was high for all major cover levels. The category with the lowest producer's and user's accuracy was *No Cover* (uncolonized). *Unclassified* Artificial habitat features had the lowest number of accuracy assessment points in this category was too few to robustly assess this category due to the rarity of polygons mapped.

Table 13: Error matrix for major biological cover.

Map Data (j)	Accuracy Assessment (i)					
	Algae	Live Coral	No Cover	Unclassified	$n_{.j}$	User's Accuracy (%)
Algae	**145**	5	2		152	95.4%
Live Coral	4	**31**			35	88.6%
No Cover	10		**54**		64	84.4%
Unclassified				**8**	8	100.0%
$n_{i.}$	159	36	56	8	n=259	
Producer's Accuracy	91.2%	86.1%	96.4%	100.0%	P_0 = 91.9%	
					T_e = 0.892 ± 0.050	

Table 14: Error matrix for major biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

		Accuracy Assessment (i)					
Map data (j)		Algae	Live Coral	No Cover	Unclassified	$\pi_{.j}$	User's Accuracy (%)	User's CI (±%)
	Algae	**0.4942**	0.0170	0.0068		0.518	**95.4%**	0.0%
	Live Coral	0.0379	**0.2935**			0.331	88.6%	4.7%
	No Cover	0.0234		**0.1262**		0.150	84.4%	2.2%
	Unclassified				**0.0010**	0.001	100.0%	0.0%
	$p_{i\cdot}$	0.555	0.311	0.133	0.001	$\pi=1$		
	Producer's Accuracy (%)	89.0%	94.5%	94.9%	100.0%	$P_o =$	91.5%	
	Producer's CI (±%)	6.7%	11.8%	11.9%	0.0%	$CI(\pm) =$	4.2%	

Detailed Biological Cover

Error matrices for detailed biological cover are displayed in Tables 15 and 16. The overall accuracy (P_o) at the detailed biological cover level was 86.1%, with a Tau coefficient (T_e) of 0.841 ± 0.048 ($\alpha=0.05$). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, was similar at 83.0 (±5.8)% ($\alpha=0.05$).

Table 15: Error matrix for detailed biological cover.

		Accuracy Assessment (i)									
Map Data (j)		Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Live Coral 50% - <90%	Live Coral 90% - 100%	No Cover 50% - <90%	No Cover 90% - 100%	Unclassified N/A	$n_{\cdot j}$	User's Accuracy
	Algae 10% - <50%									0	n/a
	Algae 50% - <90%		105	3	5			2		115	91.3%
	Algae 90% - 100%		5	32						37	86.5%
	Live Coral 50% - <90%		4		25	1				30	83.3%
	Live Coral 90% - 100%				3	2				5	40.0%
	No Cover 50% - <90%		6				1	3		10	10.0%
	No Cover 90% - 100%	2	1	1				50		54	92.6%
	Unclassified N/A								8	8	100.0%
	$n_{i\cdot}$	2	121	36	33	3	1	55	8	n=259	
	Producer's Accuracy (%)	0.0%	86.8%	88.9%	75.8%	66.7%	100.0%	90.9%	100.0%	$P_o =$ 86.1%	
										$T_e = 0.841 \pm 0.048$	

The greatest source of confusion at the detailed biological cover level was degrees of density within *Live Coral* and *No Cover* (uncolonized) categories. For example, the adjusted user's and producer's accuracy of the *Live Coral 90%-100%* were 40% and 66.7%, respectively (Table 15).

Of the 5 sites mapped as *Live Coral 90%-100%*, 3 were interpreted to have 50%-<90% density in the accuracy assessment. Given the low percentage of *Live Coral 90%-100%* (8.85%) respective to the total area mapped, it was challenging to conduct sufficient number of accuracy assessment point to fully verify this class.

Table 16: Error matrix for detailed biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

		Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Live Coral 50% - <90%	Live Coral 90% - 100%	No Cover 50% - <90%	No Cover 90% - 100%	Unclassified N/A	π.j	User's Accuracy (%)	User's CI (±%)
Map Data (j)	Algae 10% - <50%									0.000	n/a	n/a
	Algae 50% - <90%		**0.3239**	0.0093	0.0154			0.0062		0.355	91.3%	2.4%
	Algae 90% - 100%		0.0219	**0.1402**						0.162	86.5%	2.9%
	Live Coral 50% - <90%		0.0325		**0.2034**	0.0081				0.244	83.3%	4.7%
	Live Coral 90% - 100%				0.0524	**0.0349**				0.087	40.0%	7.0%
	No Cover 50% - <90%		0.0092				**0.0015**	0.0046		0.015	10.0%	0.8%
	No Cover 90% - 100%	0.0050	0.0025	0.0025				**0.1254**		0.135	92.6%	1.6%
	Unclassified N/A								**0.0010**	0.001	100.0%	0.0%
	p_i-	0.005	0.390	0.152	0.271	0.043	0.002	0.136	0.001	π=1		
	Producer's Accuracy (%)	0.0%	83.0%	92.3%	75.0%	81.1%	100.0%	92.1%	100.0%	P_o =	83.0%	
	Producer's CI (±%)	0.0%	7.7%	7.1%	3329.4%	34.5%	0.0%	6.6%	0.0%	Ci(±) =	5.8%	

Accuracy Assessment (i)

Percent Coral Cover

The error matrix for percent coral cover is displayed in Table 17. The overall accuracy (P_o) at the detailed biological cover level was 86.5%, with a Tau coefficient (T_e) of 0.831 ± 0.052 (α=0.05). A second matrix using the true map marginal proportions was not computed for percent coral cover.

Table 17: Error matrix for percent coral cover.

		Accuracy Assessment (i)						
		0% - <10%	10% - <50%	50% - <90%	90% - 100%	N/A	n.j	User's Accuracy (%)
Map data (j)	0% - <10%	154	19	1	0	0	174	89%
	10% - <50%	4	34	4	0	0	42	81%
	50% - <90%	1	2	25	2	0	30	83%
	90% - 100%	0	0	2	3	0	5	60%
	N/A	0	0	0	0	8	8	100%
	n_i-	159	55	32	5	8	n=259	
	Producer's Accuracy (%)	97%	62%	78%	60%	100%	P_o =	86.5%
							T_e =	0.831 ± 0.052

Hard and soft corals were not discriminated as the optical signature is impossible to distinguish from the satellite imagery. It is worth noting the reduction in User's accuracy between 50-<90% and 90%-100% coral. Given the low area of highest coral densities and the difficulty of distinguishing coral density at the 90% threshold, contributed to difference. Since percent coral cover was recorded at all sites regardless of whether it was the dominant cover type, this is a better measure of coral accuracy than is found under *Major Biological Cover*.

4.   Deviations from Original Production Plan

The plan for map production, thematic accuracy assessment and QA/QC was completed as planned. One modification to the plan and value added modification was added as opportunities presented themselves during execution of the project.

4.1.   Rework of Map Product upon Receipt of Second Set of Satellite Imagery

NOAA provided the contractor with an original set of imagery parts of which at best, was marginal for visual interpretation of habitat features. At the time of the acquisition of that set of imagery, a large north swell was breaking on the entire north shore of Palmyra, completely obscuring the benthic habitat features. Furthermore, the West end of the bank/shelf was plagued by poor water quality which also made the benthic features difficult to discern. A third problem was small spatial incongruity between the positioning of the IKONOS imagery and the QB2. Although the same methodologies were used to rectify the scenes, some offsets were detected to subtle variations in the satellite collection geometries.

Subsequent to the completion of the first map based on the original imagery, a second set of far superior imagery was received. It made it apparent the significant modifications to the first map were needed. Thus, the contractor prepared a new draft map and designed a new set of ground validation positions that were needed in areas that could be mapped using the new imagery but were not mappable in the original imagery. During the collection of thematic accuracy field data by NOAA in May, 2010, NOAA conducted surveys on 23 additional ground validation positions that had been identified by the contractor. These were provided to the contractor and the information integrated into the knowledge base used to prepare the map on the new imagery. This second map product was used to assess the thematic accuracy.

4.2.   Value Added Modification of GIS Data Base

In the year 1991, a 100 foot ship ran aground a short distance north of the Palmyra West Passage. It is believed that seepage of fuel and/or iron from the corrosion of the vessel and its hardware has resulted in the competitive advantage of the invasive solitary coral *Rhodactis howesii*. The coral has grown to a confluent mat that has displace all other organisms over a significant area and is establishing patchy communities a significant distance from the grounded vessel which lies on its port side with the starboard side emergent and awash.

During visual interpretation of the benthic communities in the IKONOS satellite imagery, a digital stretch was performed that enhanced the visibility of this invader. An additional field was added to the GIS database with the heading "Invasive". All of the *R. howesii* that could be identified in the imagery was delineated independent of MMU and attributed as "Invasive Coral". This same field can be used to edit the GIS content of the map for other invasive species including terrestrial community if it is in

the user chooses. The classification scheme was not modified. The "Invasive Coral" attribute was entered into the attribute table manually.

Figure 19 illustrates the extent of the invasive coral Genus sp. around the ship wreck near West Passage. Using the GIS area calculations, it was determined that 0.532 sq. km. is colonized by this invader or approximately 1% of the total reef area of Palmyra Atoll. It must be recognized that this calculation is made by visualization from IKONOS satellite imagery. The extent of this invasive coral is likely greater than has been delineated here, particularly at low densities that may not be visible in the imagery.

5. Acronyms

CCMA – Center for Coastal Monitoring and Assessment

FGDC – Federal Geographic Data Committee

CSDGM – Content Standard for Digital Geospatial Metadata

GIS – Geographic Information System

MMU – Minimum Mapping Unit

NCCOS – National Centers for Coastal Ocean Science

NOAA – National Oceanic and Atmospheric Administration

NOS – National Ocean Service

QA – Quality Assurance

QC – Quality Control

USCRTF – U. S. Coral Reef Task Force

USGS – U.S. Geological Survey

NASA – National Aeronautics and Space Administration

NGOs – Nongovernmental Organizations

TNC – The Nature Conservancy

USFWS – U.S. Fish and Wild Life Service

GPS – Global Positioning System

ESRI – Environmental Science Research Inc.

CORS – Continually Operating Reference System

UTM – Universe Transverse Mercator

USVI – U. S. Virgin Islands

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