Title
Two-Dimensional, Near-Shore, Large-Scale Marine Benthic Imagery: Creating a Valuable Tool for Coral Reef Conservationists and Managers

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TWO-DIMENSIONAL, NEAR-SHORE, LARGE-SCALE MARINE BENTHIC IMAGERY: CREATING A VALUABLE TOOL FOR CORAL REEF CONSERVATIONISTS AND MANAGERS

2015 Masters of Advanced Studies in Marine Biodiversity and Conservation Capstone Project

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Submitted to:
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Dr. Stuart Sandin, Scripps Institution of Oceanography

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The objective of this report is to identify the monitoring needs of coral reef managers and conservationists; propose two-dimensional, near-shore, large-scale, marine benthic imagery (coral reef photomosaics) as a valuable monitoring tool; and outline the work that has been done as part of my capstone project to make the creation of coral reef photomosaics less expensive and more accessible to the coral reef management community.

THE IMPORTANCE OF MONITORING

Coral reefs are an essential part of most coastal, tropical communities. Globally coral reefs contribute $30 billion a year to economies in the form of good and services (Cesar et al., 2003). Coral reefs support fisheries and provide food, economic opportunities, and ecosystem services; they have great social and economic importance to these coastal communities (UNEP-WCMC, 2006). However, many studies have shown the very reefs that support these communities are declining globally, and have been for decades (Fosberg, 1951; Rogers et al., 1994; D’eath et al., 2012; Jackson et al., 2014). Governments and non-governmental organizations alike have rallied behind the need to properly manage and conserve coral reefs all across the globe.

Monitoring is a critical part of any management plan (Mumby et al., 2014). Monitoring of coral reefs informs scientists and managers on the status of the reef and documents how the reef has changed overtime (Rogers et al., 1994). A good monitoring plan is necessary to determine if the conservation steps taken are effective; and the data and results produced by the plan are used to inform management decisions to sustain coral reefs (Heenan and Williams, 2014). In the United States one of the earliest publicized calls for global standardized monitoring techniques on coral reefs can be traced back to the early 1950s in the first edition of the *Atoll Research Bulletin*:

“If, over a period of several years, such a series of detailed, integrated investigations [of coral reefs] might be made, a fairly broad base of modern reliable comparative information could be established.” (Fosberg, 1951)

Furthermore, the call for effectively disseminating coral reef monitoring and research results can be seen in publication as early as the 1950’s as one of the goals of the *Atoll Research Bulletin* (McCutcheon, 1991). In the early 1970’s, the United Nations Educational, Scientific
and Cultural Organization (UNESCO) established a working group “to make recommendations for standardized procedures in reef studies” (Stoddart and Johannes, 1978). However, there is still little consensus on effective management and monitoring techniques and the dissemination of the resulting information. A recent study looked at over 40 years of coral reef monitoring data from the Caribbean and found the data and monitoring plans are "scattered, disorganized, and largely ineffective" (Jackson et al., 2014). These findings catalyzed a group of managers and scientists to develop a regional coral reef monitoring plan for the Caribbean. This working group determined the most important shortcomings of the regional monitoring plan fell in to the following three categories: data collection and archiving, internal network communication and dissemination of information, and support for regional and sub-regional cooperation (GCRMN, 2014).

**RESOURCE MANAGEMENT**

A good management plan consists of six main phases: planning; data collection; data entry, storage, and processing; data analysis; dissemination of information and adapting the management plan based on the results of the data analysis. Management plans should collect ecological and socio-economic data. This report will focus on ecological data collection, specifically methods of collecting coral and benthic data.

![Resource management cycle](image)

*Figure 1. Resource management cycle. Note the steps highlighted in red will be the focus of this report*
Coral reef monitoring can help managers in the following ways (Hill and Wilkinson, 2004):

- Resource assessment and mapping
- Resource status and long-term trends
- Impacts of large-scale disturbances
- Impacts of human activities
- Performance evaluation and adaptive management
- Education and public awareness
- Building resilience in to marine protected areas (MPA’s)
- Contributing and adding capacity to regional and global networks

THE NEEDS OF CORAL REEF CONSERVATIONISTS AND MANAGERS

Once a monitoring plan has been established, the managers need to decide which monitoring methods will fulfill their needs. The needs of coral reef conservationists and managers are relatively simple. They need monitoring plans and tools that are (Dahl, 1981; Mumby et al., 2014; Jackson et al., 2014; Rogers et al., 1994; Stoddart and Johannes, 1978):

- simple, inexpensive, robust, and standardized;
- able to rapidly produce meaningful results that can inform management decisions;
- and can easily be used to communicate the status of the reef to inform policy makers and the general public.

While the needs may be simple and straightforward, designing, implementing, and effectively executing a monitoring plan can be far more complicated. Effective monitoring plans are contextually specific depending on several factors including: management objectives, funding, and personnel level of expertise. Furthermore, there are several different coral and benthic monitoring methods that can be used to meet the objectives of the monitoring plan. Table 1 presents the most popular coral and benthic monitoring technique’s scale, level of detail, and potential information obtained.
PHOTOMOSAICS

While traditional methods have been used to serve the needs of the monitoring community, new advances have provided a novel tool to managers and conservationists in the form of photomosaics. Photomosaics are large, detailed pictures that are made from many photographs. Photomosaics are a recently developed, and developing, tool used to monitor and study near-shore benthic communities, coral reefs specifically. Over the past decade, significant advances have been made in recording and processing marine benthic community digital imagery using two-dimensional photomosaicing computer algorithms (Gracias et al., 2008). The current, standardized method for creating and analyzing two-dimensional, near-shore, large-scale photomosaics has been developed by the Reid Lab at the University of Miami Rosenstiel School of Marine and Atmospheric Science (RSMAS) and the Sandin Lab at Scripps Institution of Oceanography (SIO). The current method of creating large-scale reef images can be broken down into three main steps:

1. Image collection – high-resolution imagery is collected at a location (most of the time an island or coral atoll) with 8 sites selected to adequately represent each location. Each site usually covers 100 – 200 m² of the reef and approximately 2,000 – 5,000 images are collected at each site. The images are collected using two high-resolution digital single lens reflex (dSLR) cameras in underwater housings and a custom fabricated frame, see Figure 1.

2. Photomosaic processing – a custom computer algorithm developed in the Reid Lab at RSMAS joins, or “stitches”, together the thousands of images into one big photomosaic. The algorithm is similar to the technology used by many smartphones to create panoramic photographs. The processing step requires specialized software, computer programming expertise, and can only be performed at the Reid Lab at RSMAS.

3. Photomosaic analysis – once the photomosaics are “stitched”, trained personnel from the Sandin Lab trace and identify individual stony coral colonies and their dominant competitors. Once the corals and dominant competitors have been traced and identified any number of coral health metrics can be derived from the photomosaic, see Table 1.
Figure 2. Photomosaic image collection equipment - custom fabricated frame holding two dSLR cameras and underwater housings (Photos courtesy of the Sandin Lab)
Table 1. Popular coral and benthic monitoring techniques scale, level of detail, and potential information obtained (adapted from Mumby, 2014 and Hill and Wilkonson, 2004)

<table>
<thead>
<tr>
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<th>Tagging colonies</th>
<th>Transects</th>
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<td>Fine</td>
<td>Fine</td>
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<tr>
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<td>Quantitative</td>
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<td><strong>Information obtained</strong></td>
<td>Percent cover</td>
<td>Percent dead coral</td>
<td>Percent dead coral</td>
<td>Percent bleaching</td>
<td>Percent bleaching</td>
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<td></td>
<td>Percent bleaching</td>
<td>Percent bleaching</td>
<td>Percent bleaching</td>
<td>Medium to detailed growth</td>
<td>Biological condition</td>
<td>Biological condition</td>
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<tr>
<td></td>
<td>Biological condition</td>
<td>Disease prevalence and progression</td>
<td>Disease prevalence and progression</td>
<td>Family, genus or species level ID</td>
<td>Growth</td>
<td>Growth</td>
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<td>Species diversity</td>
<td>Physiological aspects of bleaching or disease</td>
<td>Physiological aspects of bleaching or disease</td>
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<td>Growth &amp; shrinkage rates of large &amp; small colonies</td>
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<td>Relative abundance</td>
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<tr>
<td></td>
<td>Medium to detailed growth form info</td>
<td>Growth &amp; shrinkage rates of</td>
<td>Growth &amp; shrinkage rates of large and small colonies</td>
<td>Invertebrates</td>
<td>Density</td>
<td>Density</td>
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<tr>
<td></td>
<td>Family/genus/species level ID</td>
<td>large &amp; small colonies</td>
<td>Growth &amp; shrinkage rates of large &amp; small colonies</td>
<td>Rugosity (chain)</td>
<td>Size</td>
<td>Size</td>
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<td></td>
<td>Rugosity (chain)</td>
<td>Reef topographic changes</td>
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<td>Invertebrates</td>
<td>Invertebrates</td>
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<tr>
<td></td>
<td>Landscape scale competitive interaction</td>
<td>Reef topographic changes</td>
<td>Reef topographic changes</td>
<td>Recruitment</td>
<td>Recruitment to species or genus level</td>
<td>Recruitment to species or genus level</td>
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Unfortunately, the methods for creating photomosaics are largely inaccessible to most coral reef conservationists and managers but this need not be the case. Photomosaics provide a unique and valuable monitoring tool with the following benefits:

- Robustness
- Repeatability
- Communication and Outreach
- Archival Data

Photomosaics are a robust tool because they provide flexibility in monitoring. They can provide conservationists/managers with a metric as simple as number of colonies or a more complex analysis such as digitally tagging individuals and tracking their growth over time, or tracking disease on tagged individuals over time. This tool also eliminates some diver error in measurements and/or counts; the analysis of the plot is much easier to do in the lab than under water. Furthermore, photomosaics capture landscape scale processes and patterns. The scale of the mosaics allows managers to monitor changes in spatial patterns and processes at a landscape scale - provides a map-like approach to tracking changes through time. Photomosaics afford managers the ability to collect the mosaic imagery on one dive and then select the level of analysis that is sufficient for their management plan; potentially saving the time and money of having to make subsequent dives to collect more information, see Table 1.

Photomosaics are an effective tool for communicating the health of coral reefs, and trajectory of health with a time series of mosaics, to policy makers and the general public. Humans have an intuitive "feel" for what a healthy reef looks like and when shown a holistic, landscape view of the reef it resonates with them. Most people in coastal communities don’t get to see the reef in their backyards, and photomosaics provide a way to show people tangible images of the reef.

In addition, the photomosaics provide a great platform for interacting with the reef. The simplest form of interaction is simply printing and publically displaying large posters of the reef images. On a recent trip to Kiribati, members of the Sandin Lab met with conservationists and managers in the central Pacific. They felt the photomosaics would be an excellent tool to display in schools, community centers, and other public locations to raise
awareness of the reef’s condition (Maddalene, 2015). Software, like Zoomify, allows people all across the world to virtually interact with these landscape-scale images online. Using Zoomify, photomosaics can be posted online and browsers can pan and zoom through the images, given them a greater knowledge of what reefs are like from all over the globe.

Using photomosaics as a coral reef monitoring tool ensures a greater probability of capturing imagery of the same area with repeated surveys. For example, a large-scale photomosaic is more likely to have overlap in survey area from one year to the next than if the photoquadrat method is used. One can return to the same site with photoquadrats but capturing the same area in individual photos from year to year is difficult. High repeatability in surveys allows for digitally tagging both large and small colonies and tracking their growth/shrinkage and survivorship through time. Digital tagging is advantageous because it is easier, less expensive, and less time consuming than physically tagging colonies.

Photomosaics provide archival data in the form of the raw images, or video, collected and in the mosaics themselves. As technology improves and post-processing becomes more automated, the archival images will provide a unique dataset to both scientists and conservationists. Archived images from around the world will lead to a better understanding of the spatial configuration of reefs under different environmental conditions, and human influences, and will ultimately contribute to better management plans.

LIMITATIONS OF CURRENT PHOTOMOSAICING METHODOLOGY

There are two major roadblocks for managers keeping them from using photomosaics:

1. expense, and
2. access to the stitching software.

The current photomosaicing methodology does not fully meet the needs of the coral reef monitoring community. The equipment is expensive. The currently method uses two dSLR cameras with underwater housing and a custom fabricated frame, which total about $10,000. Furthermore, the collection methods are relatively complicated; the processing of the images is time-consuming, computationally intensive, and expensive (the raw images must be sent to
RSMAS be processed on high-performance computers). Fortunately, these roadblocks can be overcome.

**MAKING THE TOOL LESS EXPENSIVE AND MORE ACCESSIBLE**

The two biggest expenses are equipment and processing costs (both time and money). One of the goals of my capstone project is to make the photomosaicing monitoring tool more accessible to coral reef managers and conservationists. To reduce equipment costs I proposed using smaller, less expensive underwater video cameras to collect the imagery. Inexpensive underwater video cameras have been used in the past to create photomosaics but having access to the stitching software kept the technology out of the hands of most coral reef managers. The new process uses three underwater video cameras (GoPros) to collect video footage. *Figure 3* below shows the less expensive GoPro photomosaic image collection array with three cameras mounted on it and the array collecting video footage on reef off the coast of Montserrat. For a detailed description of the equipment and methods see Appendix I.
To reduce the processing cost, and make the photomosaic processing more accessible to managers, I worked with the Reid Lab to create a stand-alone software package that does not require an expensive software license or computer programming knowledge. The software will be combined with an in-depth user manual that provides the end-user the ability to create photomosaics on a personal computer (see Appendix II). The stand-alone software will allow managers to produce mosaics with no processing fees and be able to generate results in a timely fashion. These developments will bring the value of large-scale coral reef photomosaics within the reach of managers all across the globe.

Figure 3. GoPro photomosaic image collection array (top) and array collecting video footage on Montserrat (bottom) (Photo credit: Stephanie Roach)
PROTOTYPE STAND-ALONE STITCHING SOFTWARE

The prototype stand-alone stitching software comprises three modules:

1. Video frame extraction and calibration module – this module prompts the user for the file locations of the raw video footage and the calibration file. The software then reads the video footage, from a single file or multiple files if using multiple cameras, extracts and calibrates the extracted still image and saves it to a directory. The calibration corrects any optical distortion in the image due to the camera lens.

2. Global matching module – the global matching module identifies features in each extracted image. Then the software looks at each pair of consecutive images and matches the features; as this step is being completed it tracks and records the motion of camera over the plot. This is used for proper placement of images in the final mosaic creation. Once the consecutive pairs are matched, the program looks for features to match between combinations of all of the images, not just consecutive pairs; this fills in any gaps in the mosaic by creating more matched images. The user has the option to select a low, medium or high distance acceptance threshold for matching images. A low distance acceptance threshold may cause some images to not be match while a high threshold may falsely match images to one another. This step also creates input files for the mosaic renderer module.

3. Mosaic renderer module – this module has a fully functional graphical user interface (GUI), see Figure 4, that prompts the user to select the correct input file from the global matching module and also allows the user to select the range of images to stitch together. The stitching process places the matched images in their correct location and orientation, cuts them to match, and then blends the images together to get rid of any visible seams. This module produces the final mosaic.
The figure below (Figure 5) shows the process of the new, less expensive and more accessible coral reef mosaicing process. It is important to note the extracted image quality control step. In the step the end-user must review the extracted images and take out any “bad” ones, see Appendix II for detailed instructions on how to use the stand-alone software and examples of “bad” images.

Figure 4. The graphical user interface for the mosaic renderer module

Figure 5. GoPro and stand-alone photomosaic creation process
LIMITATIONS OF THE PROTOTYPE SOFTWARE

There are some limitations to the prototype software. The mosaics produced using the combination of the GoPro collection method and the stand-alone stitching software will not be as high-resolution as the standard photomosaics. This means that the mosaics created by the new process will not provide the end-user with as many analysis options. For example, managers will most likely not be able to identify corals to the species level or be able to identify small recruits. However, the mosaics will be able to provide managers with the general coral health metrics they are most interested in. Due to some of the stitching limitations of the software, it is essential that extra care and fastidiousness is taken when collecting the video footage, see Appendix I for instructions on how to properly collect the video footage.

Another important limitation to note is the issue of analyzing the mosaics. There will need to be training modules created to teach the managers how to work with the mosaics to interpret them and extract their desired metrics.

THE BLUE HALO INITIATIVE

To test the prototype photomosaicing tool, and compare it with the current method, I partnered with the Waitt Institute. The Waitt Institute recently launched the Blue Halo Initiative. The Blue Halo Initiative’s mission is to “empower communities to restore their oceans, and use ocean resources sustainably, profitably, and enjoyably for this and future generations” (Waitt Institute, 2015). To accomplish this mission the Blue Halo Initiative has partnered with communities on three Caribbean islands; Barbuda, Montserrat, and Curacao with the plan to partner with one new government each year.

The goals of partnering with the Waitt Institute were to identify an immediate user group that worked with resource managers; assist the Blue Halo Initiative with coral reef monitoring; and test the prototype software. To assist the Blue Halo Initiative with coral reef monitoring I traveled to both Barbuda and Montserrat to collect images of the coral reefs. With the assistance of the Blue Halo team, we identified 8 sites to mosaic on each island, see Figure 6 and Figure 7.
At all 16 sites on Montserrat and Barbuda we collected imagery using the dSLR cameras and GoPro video footage. On Barbuda, 5 of the 8 sites were replicated using the three GoPro array; and on Montserrat, all 8 sites were replicated with the three GoPro array, see Figure 8 showing the two different collection methods. The three sites on Barbuda that were not replicated with the three GoPro array had GoPro video footage collected because there is a GoPro camera mounted on the dSLR rig. Therefore, mosaics created with the GoPro method and the standard, dSLR method can be compared at 16 sites.
Figure 7. Montserrat Blue Halo Initiative coral reef photomosaic sites
NEXT STEPS AND FUTURE APPLICATIONS

The new proposed mosaicing methodology is just a first step in making the photomosaicing tool more accessible to managers. In the future, subsequent versions of the software will add functionality (such as color correction), flexibility, and higher resolution to the final product. The next versions of the software will be expanded to work on several operating systems (the software currently operates on Windows 64-bit operating systems) and contain calibration files for several models of underwater video cameras. Eventually the software will have a fully functional graphical user interface that allows the end user to create higher resolution mosaics and will allow for more flexibility when troubleshooting the stitching process.

As mentioned previously, this project addresses the data collection and processing accessibility issues associated with photomosaics. Once the photomosaicing tool is more available managers will begin using it and this will produce a plethora of new data that needs
to be stored, analyzed and shared. To build capacity across regions and the globe a central online repository that can store, analyze and share the photomosaics needs to be developed. Without a central online repository we will not be able to achieve a widespread, comparable coral reef monitoring dataset.

There are other exciting possible uses for the new photomosaicing process. One is citizen science; being able to collect video footage using inexpensive cameras and making the stitching software readily available will allow almost anyone to create photomosaics. This is exciting because citizen science enhances education, awareness and local stewardship of resources through the participation of community members. These are essential parts of effective coral reef management plans.

The photomosaicing technology is constantly being refined and developed. On the research side, the goal is to fully automate most steps of the monitoring process. From using automated underwater vehicles to collect the imagery to using computer vision image recognition technology to analyze the photomosaics.

**CONCLUSION**

Coral reefs are an important and beautiful resource that is threatened globally. To help protect these vital resources governments and non-governmental organizations alike have proposed and implemented management plans to conserve and protect coral reefs. Having the best possible monitoring tools is essential to having an effective management plan. This report has identified the need of coral reef managers; illuminated the value of using large-scale coral reef photomosaics as a monitoring tool and described the steps taken to make large-scale photomosaicing more accessible to coral reef managers and conservationists.

Making these two-dimensional, near-shore, large-scale photomosaics more accessible to managers and conservationists is analogous to the paradigm shift that occurred in forest ecology when satellite imagery became readily available. This advancement forever changed how scientists and managers viewed, and practiced, terrestrial spatial ecology and resource management. Large-scale photomosaics have the potential to similarly impact how scientists and managers view, and practice, marine spatial ecology and resource management.
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