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Creating Three-Dimensional Models of Coral Reefs at Papahānaumokuākea Marine National Monument Using Structure-from-Motion Software

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ABSTRACT: Coral reefs are essential ecosystems that provide important structurally complex habitat and food resources to the organisms that reside within them. They are colonial organisms, made up of the coral animal and a photosynthetic algae, known as *Symbiodinium*, residing in its tissues. The delicate balance of coral reefs are often threatened by environmental stressors that could eventually lead to the degradation of the structurally complex habitat that marine invertebrates and fishes rely on. Currently, the most common way to research coral reefs in on SCUBA, but this is very limited by air supply and decompression limits. A more recent method to assess coral health, and finally quantify driving factors of complexity, is using Structure-from-Motion software to recreate the benthic environments three-dimensionally. This allows for post-processing of the survey areas, and opens up opportunities to learn about 3D habitat metrics. Through my EPSCoR-funded research opportunity in data science, I have been an intern helping with studies of coral reefs in the Northwestern Hawaiian islands. During the internship, I have used Agisoft and GIS ArcMap softwares to build and analyze 3D models for 19 sites in French Frigate Shoals. These sites were all analyzed for the years 2015-2017 to contribute to the long-term monitoring project for the Papahānaumokuākea Marine National Monument. Now that scientists are able to recreate benthic environments, structural complexity can now be quantified; this will be important to see what corals and morphologies create the best habitats for different marines species, and determine what will happen to abundance and diversity as climate continues to change.

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1. Introduction

Coral reefs are essential ecosystems that provide important structurally complex habitat and food resources to the organisms that reside within them (Graham & Nash 2012). Their resilience is crucial to the survival of many reef fishes, as well as the continuation of food sources to many coastal and island communities (Hoegh-Guldberg *et al.* 2007). Unfortunately, coral reefs are under threats of decline due to ocean acidification (Hoegh-Guldberg *et al.* 2007), rising ocean temperatures (Cantin *et al.* 2010), and slow coral growth rates (Rinkevich 2005). The severity of these external stressors combined with the fragility of coral reefs (Mora *et al.* 2016) hastens the rate in which these balanced ecosystems decline in health.

Corals are symbiotic, colonial animals that form the complex structures of coral reefs. A living coral is made up of two organisms: the coral animal and single-celled photosynthetic algae known as *Symbiodinium* or zooxanthellae (Lough & van Oppen 2018). The relationship between the coral animal and its *Symbiodinium* is very delicate and is greatly affected by stressors resulting from human activity and climate change. When corals are over-stressed by natural environmental stressors, like increasing carbon dioxide concentration (Hoegh-Guldberg *et al.* 2007), low salinity, pollution, and unusual water temperatures (Lough & van Oppen 2018), or by human pressures, like fisheries, human density, urban development, and waste runoff (Mellin *et al.* 2016), they eject their *Symbiodinium* as an autoimmune response. This ejection results in what is known as coral bleaching, where the loss of the symbiotic algae also brings a loss in pigmentation. On a small scale, coral bleaching is a natural response to stressors; however, on a larger scale, global bleaching events can drastically affect coral reef ecosystems and result in a significant decline of reef-dwelling organisms (Lough & van Oppen 2018). Large-scale bleaching events such as the one that occurred in the main Hawaiian Islands in 2015 are concerning for the current health of coral reefs around the world (Rodgers *et al.* 2017). During this massive bleaching event, the main Hawaiian Islands showed over 90% bleaching and more than 50% subsequent mortality and the Northwestern Hawaiian Islands experienced up to 91% coral bleaching, and a 68% average loss of coral cover on Lisianski Island (Couch *et al.* 2017). If large bleaching events like this one continue to occur, coral reef ecosystems, that are often unable to recover naturally from anthropogenic stressors (Rinkevich 2005), could potentially be so threatened that they might not be able to recoup.

Threats of recurring global bleaching events (Couch *et al.* 2017) highlight the need to understand causes and possible preventions of bleaching more than ever. Unfortunately, there is still little known about the immune responses of corals, what causes coral disease and growth anomalies, and how to prevent bleaching. Currently, the most common way to research coral reefs is to go out into the ocean with a slate, transect, and quadrat to observe and record coral species. Using this method, scientists, commonly on SCUBA, can see coral colonies up close and from many angles, and then record coral species, approximate cover, presence and percentage of cover of diseases, and any other abnormalities (Burns *et al.* 2015). While this method has been effective enough to gain a general understanding of coral health and the physiological characteristics and anthropogenic stressors that correlate with coral health, SCUBA surveys lack high resolution because they are limited by air supply, and rely on the judgement of the scientist to record what is seen.

With the knowledge of different coral diseases, warning signs of bleaching, and external stressors that cause bleaching, scientists have begun to use computer software to more easily identify patterns within coral colonies, and compare environmental, species, and disease data to other coral colonies in different sites around the world. Structure-from-motion (SfM) photogrammetry with geospatial software can be used to create "textured mesh models of a reef" in order to quantify three-dimensional complexity. SfM requires scientists to go out into the field, and take hundreds of photos of the reef they wish to analyze, and then those photos can be uploaded and aligned through the software. The aligned photos are then used to generate a point cloud, followed by connecting all of the points to create the textured mesh and a 3D model. This high-resolution data can then be used to develop reliable ecosystem models and greatly improve scientists' ability to monitor the changes in health of coral reefs. After a 3D model is created, it can be uploaded into a data analysis program called ArcMap to quantify many parameters of the model. The values that ArcMap computes are then stored on a data sheet to be used in several statistical tests comparing different plots on a reef to each other, or different reefs altogether. Each individual coral species on a model is then outlined and labeled, so the data can later be inputted into the computer to teach it to recognize the coral species and contour (Burns *et al.* 2015). This will allow much faster computing time, as the software will use algorithms based on what it was taught to identify the coral species present and their relationship to diseases present, reef complexity, percent bleaching, and many other factors.

During my internship with Dr. John Burns, we used SfM to recreate coral reefs from several photographic surveys taken at French Frigate Shoals in the Papahānaumokuākea Marine National Monument over the years 2015-2017, and assess coral cover, health, complexity, and bleaching. This widened our understanding of the changes corals in French Frigate Shoals underwent, and identified which coral species have been most effective in reef building and had the most resilience to bleaching events there. We were then able to use this massive data set to teach our computer software to recognize coral species, different disease patterns and other coral abnormalities to more easily and quickly compare reef sites from year to year, and to greater understand the resilience of corals to environmental and human stressors, as well as their ability to recover from severe, semi-fatal bleaching events.

2. Objectives

1. Become proficient in identification of Hawaiian corals
2. Learn to create 3D models of coral reefs using Agisoft software
3. Learn to run analyses on 3D models using GIS ArcMap software
4. Digitize corals from each model to go towards demographics calculations and machine learning
5. Use CoralNet to annotate photos and create graphs

3. Materials and Methods

3.1 Learning Hawaiian Coral Species and Morphologies

In order to be accurate in identifying corals from the northwestern Hawaiian islands that are not prevalent in the main Hawaiian islands, it was imperative to spend time learning the coral species and their morphologies. Using slideshows prepared by NOAA's Coral Reef Conservation Program for the Rapid Assessment Monitoring Program (RAMP), I studied all of the coral species found in the northwestern Hawaiian islands as well as the various morphologies that they can grow in. This took a few weeks to become proficient, and then while I was working through the digitizing and CoralNet processes for my first few times, I would ask for verification from graduate student, Kailey Pascoe, to make sure I was accurately representing the species in the reef plot I was assessing.

3.2 Creating 3D Reconstructions of Coral Reefs in Agisoft

Each of the lab computers is equipped with Agisoft and GIS ArcMap software. In Agisoft, photos collected on survey dives from various sites in French Frigate Shoals from 2015-2017 were uploaded and aligned to make the photos follow the spatial pattern and contour of the reef that was surveyed. A point cloud, where the photos begin to create a three-dimensional environment, was generated, and each point was connected to create a mesh, which forms 2D faces between each point. The triangular faces connecting the point cloud begin to create the elevation and three-dimensionality of the coral reef. Then, the texture was added over the mesh, which makes the photos conform to the shape of the mesh and adds the realism and scale of the reef. Lastly, the orthomosaic (an accurate representation of the reef area surveyed) and the digital elevation model (DEM, a 3D representation of the benthic terrain surface), scaled to 1 cm, were exported to be used in GIS ArcMap. The model was orthorectified using x-, y-, z-coordinates from ground control points that were placed during the survey swim. Both the orthomosaic and DEM were layered using the same coordinate system so they can be used for measuring the coral colonies (Burns *et al.* 2015).

3.3 Collecting 3D Habitat Metrics in ArcMap

The orthomosaic and DEM were layered in GIS ArcMap, the 10-meter by 5-meter survey plot was outlined, and I tested several statistical factors including: statistical aspect (surface direction), slope, curvature (first-derivative of slope), surface area to planar area (evaluates rugosity), and terrain ruggedness (surface roughness) (Walbridge *et al.* 2018). The data from those tests were recorded in a spreadsheet to be used in comparative statistical analyses for Dr.

John Burns' study assessing how coral assemblage structure drives 3D habitat complexity of coral reef environments.

3.4 Digitizing

After the sites were modeled, tested, and recorded on the spreadsheet, each model was uploaded into ArcMap one more time for digitization. This process requires meticulous tracing of the individual coral colonies using a polygon tool, and then identifying the species to mark it with a shapefile. Although time consuming, the data from identifying and tracing each individual coral colony in the digitization process is used to collect important demographic data, and will be used for machine learning, in order to be able to identify corals automatically in future models.

3.5 CoralNet Annotation

CoralNet is a program created by University of California, San Diego to annotate coral models. However, the original model photos are too large to upload into CoralNet, so using Adobe Photoshop, I cropped a 10-meter by 5-meter plot to make the photo size smaller and uploadable into CoralNet. The program randomly overlays 1000 points over uploaded photo plots, and I looked at each point one at a time to identify corals to genus and morphology, or annotate other abiotic and biotic features, that lie beneath the point. After all of the sites are annotated, the data from CoralNet was then used to calculate the Shannon-Weiner Diversity Index for the various sites over the years 2015, 2016, and 2017.

4. Discussion

For this internship, I assisted Dr. John Burns on his study assessing drivers of coral reef complexity in French Frigate Shoals. French Frigate Shoals is the largest atoll in the Papahānaumokuākea Marine National Monument, with over 938 km^2 of coral reef area. This atoll has the largest variety of coral species, with over 41 different stony corals (French Frigate Shoals). It is the only island in the Hawaiian archipelago that is dominated by *Acropora cytherea*, which is entirely absent in the main Hawaiian islands. *Acropora cytherea,* known as the table coral, grows out like a table from a central point. In the 10m x 5m plots that I was analyzing, some of the *Acropora cytherea* colonies took up over half of the plot area. In addition to the dominant *Acropora* in French Frigate Shoals, there is also *Pocillopora meandrina, Porites lichen, Porites lobata,* and some *Montipora* corals as well. It's important to assess how the coral assemblage structures of different reefs affect the ecological processes that occur in these extremely diverse and productive environments.

Using Structure-from-Motion photogrammetry techniques to create high resolution 3D reconstructions of benthic environments allows ecologists to quantify 3D features of coral reefs that were not quantifiable before. Conventional 2D approaches of coral reef assessments cannot capture the link between 3D reef complexity and live coral assemblage structure (Burns *et al.* 2019). Using the new methods described in this paper, accurate measurements of 3D habitat structural complexity can be collected, and used to determine how changes in coral assemblage structure can impact the reef structure. The calculations in ArcMap performed on the orthomosaic from the models are ultimately to quantify these different drivers of habitat complexity.

The ability to assess coral reefs for specific drivers of complexity is now paving a road towards being able to predict how changes in coral assemblage structure could affect the functions of these important ecosystems. This allows for more efficient long-term monitoring efforts of sites all around the world, as well as rapid assessments after a major disturbance like hurricanes or massive swells. It's now possible to predict which coral species will be affected most by these events and bleaching events, and which corals will be the most resilient and able to recuperate after a disturbance.

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