

INVESTIGATING VARIATIONS IN CORAL REEF MORPHOLOGY WITH
PHOTOMOSAICS AND ANALYSIS OF PERCENT COVER

by

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PHOTOMOSAICS AND ANALYSIS OF PERCENT COVERAGE

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Coral reefs serve as an important component of tropical marine ecosystems' functionality and composition. However, coral cover in the Caribbean reefs continues to decline due to climate changes. Corals are adapted to thrive in a limited range of environmental conditions, where small changes in the oceans structure, such as temperature, light intensity, and physical disturbances, can lead to wide-scale loss of organisms. In the present study, I investigated five categories of coral reef morphology--massive, brain, flowering, plating, and branching--to assess how variations in depth change coral coverage and abundance. A section of the coral reef was surveyed off the coast of Bonaire, Netherland Antilles, in the Southern Caribbean. The study collected large-scale imagery, called photomosaics, were used to create a robust, archived dataset with detailed representation of the benthic organisms. The study site contained two 50m² subplots, one shallow and one deep, to represent two separate conditions based on environmental variables such as light intensity and nutrient availability. Each subplot was traced in Photoshop based on each morphological type. The GPS coordinates of each subplot boundary allowed for

the images to be placed into a geographic information system to calculate precise percent coverage data from each type of morphology. Plating, flowering, and massive corals had a higher percent area cover in deeper depths compared to shallower depths. Brain and branching corals had a higher percent area cover in shallower depths. With variations in morphology and rising sea levels, certain species of coral may dwindle in numbers, leading to declines of biodiversity and coverage.

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Introduction:

Coral Reefs:

Coral reefs serve as an important component of tropical marine ecosystems' functionality and composition, containing many organisms, including fish, invertebrates, stony corals, soft corals, sponges, gorgonians, plankton, and other species. These organisms share the reefs, where relationships between species include: competitive relationships where organisms compete for space and food, symbiotic relationships, and mutualistic relationships (Sheppard 2014). Specifically, corals structural variations and abundance are important in the dynamics of the whole community, where interstitial species depend on the continuation of a mutualistic relationship (Connell 1997). Coral reefs are known as an ecosystem with one of the highest biodiversity levels in the world, containing an abundant variety of organisms. The complexity of coral reefs matches its importance, socially and economically providing food to the growing demand by people (Sheppard, 2014). As humans recognize the importance of corals for economic and social benefits to the coastal communities, the cost of damage of coral reefs is substantial (Birkeland 1997). Coral reefs are in decline around the world, with an estimated 30% of coral reefs categorized as severely damaged (Hughes et al. 2003). Thus, it is an important time to understand the current state of coral reefs, how to protect and stop the

destruction of a fragile ecosystem, and to implement proper conservation and mitigation plans.

The benefits of a coral reef ecosystem relate to biological processes that are beneficial for marine waters composition and stability. Specifically, hermatypic corals, also called stony corals, create the foundation of coral reefs through the deposition of calcium carbonate, creating the structural framework of a stony coral (Baker and Weber 1975). Within the stony corals are symbiotic algae, known as zooxanthellae, that are along the surface of corals and can photosynthesize, releasing oxygen into the atmosphere (Porter 1976). Coral reefs balance the carbon dioxide chemistry in waters through photosynthesis by zooxanthellae, however with global CO₂ rise in oceans, the skeletal structure of corals may be weakened (Hughes et al. 2003). The zooxanthellae photosynthesis process correlates with the morphology of corals, where maximizing the surface area allows for zooxanthellae to be exposed to sunlight, thus helping to coral to continue to grow based on their symbiotic relationship (Porter 1976). Sunlight drives photosynthesis within zooxanthellae and the more surface area provided by the coral skeletal structure allows for more growth of the coral, creating a mutualistic relationship. Thus, coral cover is impacted not only by growth and competition for space along the benthos by each coral species, but is dictated by external factors including depth, sunlight, and zooxanthellae abundance.

Specifically, this research was conducted within the Caribbean Sea, where changes in coral reef composition and structure are occurring on a large scale. The coral cover has decreased in recent decades in Caribbean reefs (Aronson 2001). As

climate change continues, the key factors expected to change coral reefs' composition are sea-level rise, increasing seawater temperatures, altered carbonate mineral saturation, and natural disasters (Birkeland 1997). The altering state of coral reefs will impact multiple ecosystems, where the conservation and preservation of coral reef ecosystems is vital to continue the diversity and value gained from coral reefs. This research was conducted on Bonaire Netherland Antilles, an island 50 kilometers north of Venezuela, where the coral reefs are an ideal location for research on changing coral reefs.

The coral reefs along Bonaire are located along a fringing reef slope, where a sand flat runs along the shallows and transitions into a reef slope with the formation of a reef crest (Figure 1). The majority of the corals are found along the reef slope, which ranges from 10 – 30 meters in depth. However there are some species of corals that prefer the shallower depths along the sand flat. We conducted surveys along the reef slope, where coral abundance and diversity were highest. Additionally the entire coastline of Bonaire is protected, creating a sanctuary for educating local divers and community members on conservative practices, as well as allowing for researchers to study and mitigate Bonaire's coral reef health.

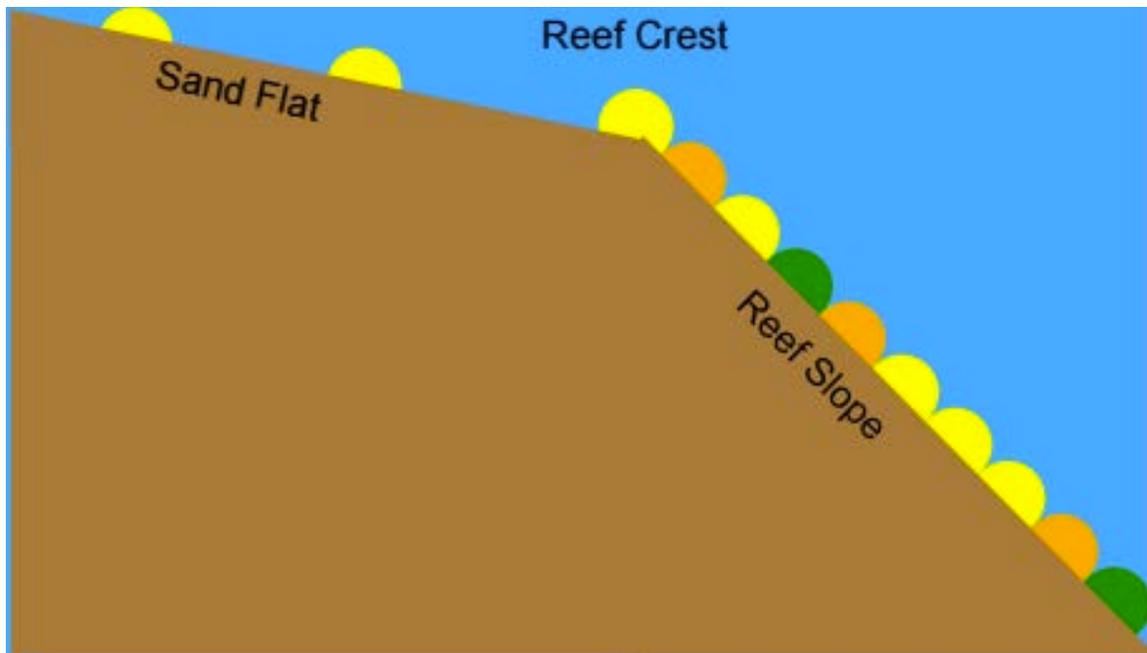


Figure 1: Graphic depiction of the fringing reef slope along Bonaire coastline.

Graphic provided by Nathaniel Holloway.

Marine Protected National Park:

Bonaire is one of several islands in the Caribbean Sea that established its coastal waters as a Marine Protected National Park. The Bonaire Marine Park (BMP) was created in 1979, following laws of coral reef protection in 1975 and restriction of spear fishing in 1971 (STINAPA). The marine park encompasses all waters surrounding both Bonaire and Klein Bonaire to high-tide depths of 60 meters, totaling 6672 acres (STINAPA) (Figure 2). However in the mid 1980s, the BMP was temporarily halted due to lack of funding (Pendleton 1995). In 1990, the Island Government of Bonaire applied for re-establishment of the park by increasing admissions fee's for using the park, continuing scientific research, and implementing new staff and managers (Dixon et al. 1993). The scuba diving tourism industry

continued to increase, allowing for economic growth on the island to continue and funding towards the new BMP program to excel.

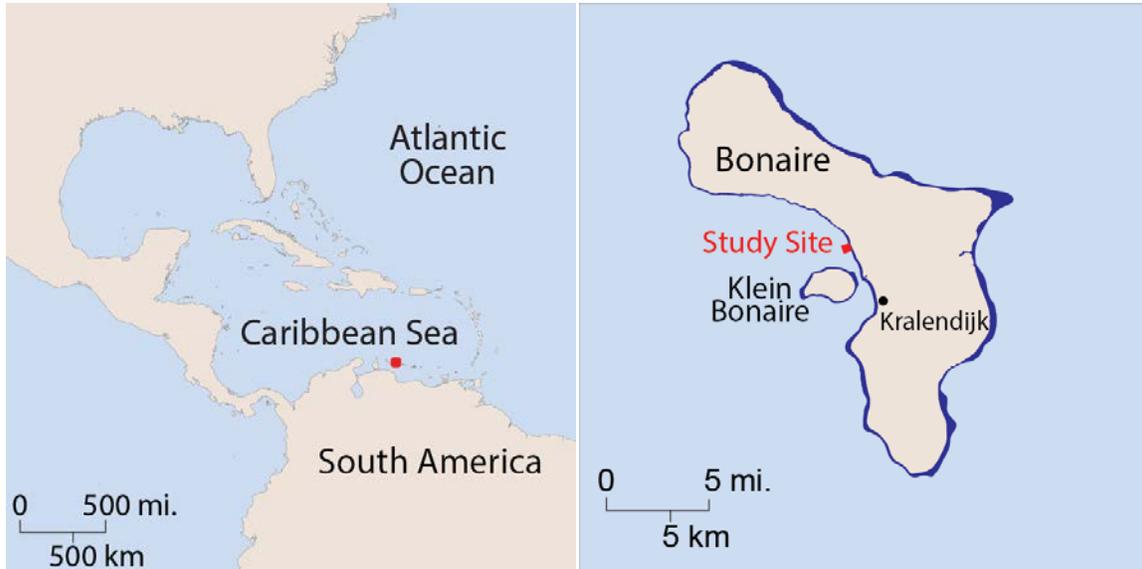


Figure 2: Location of Bonaire, Netherland Antilles in the Caribbean Sea. Dark blue area shows Marine Protected National Park boundary around Bonaire and Klein Bonaire. Data provided by Natural World and Dutch Caribbean Biodiversity Database

The Marine Protected National Park on Bonaire is the oldest protected area within the Caribbean, making it an ideal place for data collection and long term ecological monitoring of the coral reefs. The decline in coral reef cover is well established through large number of studies (Parsons and Thur 2007), however longitudinal data is minimal, especially with coral reefs deeper than 20 meters (Bak et al. 2005). Since Bonaire’s waters have been protected for nearly 30 years, it is an ideal location for ecological monitoring conducted on reefs with minimal human disturbance, other than the potential impact of recreational divers. The marine park

creates an ideal habitat for observing percent coverage of corals in relation to natural disturbances and environmental changes endured over the past 30 years.

The Caribbean Sea contains 62 species of corals that vary based on geographic location and depth (AGRRA). In Bonaire, not all 62 species are found, and 19 corals were researched in the present study due to their abundance along Bonaire's benthos (Figure 3). The 19 corals fall within varying ranges along the benthos and each type of coral grows at individual rates. Additionally, each coral's range of coverage varies by several factors, including depth, amount of sunlight reaching the coral's zooxanthellae, water temperature, competition for space with other corals and organisms, and coral diseases.

Types of Caribbean Coral Morphologies:

| Name of Coral Species | Category of Morphology | General Location on Bonaire Benthos |
|----------------------------------|------------------------|-------------------------------------|
| <i>Acropora palmata</i> | Branching | Sand flat |
| <i>Acropora cervicornis</i> | Branching | Sand flat |
| <i>Colpophyllia natans</i> | Brain | Reef slope |
| <i>Dendrogyra sp.</i> | Branching | Reef slope |
| <i>Diploria labyrinthiformis</i> | Brain | Sand flat |
| <i>Diploria strigosa</i> | Brain | Sand flat |
| <i>Eusmillia fastigata</i> | Flowering | Reef slope |
| <i>Madracis aurentenra</i> | Branching | Reef slope |
| <i>Meandrina meandrities</i> | Meandroid | Reef slope |
| <i>Millepora alcicornis</i> | Branching | Reef crest |
| <i>Millepora complanata</i> | Plating | Sand flat |
| <i>Montastrea cavernosa</i> | Massive | Reef slope |
| <i>Mycetophyllia</i> | Plating | Reef slope |
| <i>Orbicella annularis</i> | Massive | Reef crest |
| <i>Orbicella faveolata</i> | Massive | Reef slope |
| <i>Porites astreoides</i> | Massive | Sand flat and reef crest |
| <i>Porites porites</i> | Branching | Reef slope |
| <i>Siderastrea siderea</i> | Massive | Sand flat |
| <i>Undaria agaricities</i> | Plating | Reef crest |

Figure 3: Nineteen species of coral researched within the study, their type of structural morphology, and the relative location of the species along the reef slope.

Massive Corals:

The massive corals researched through the study include *Montastrea cavernosa*, *Orbicella annularis*, *Orbicella favelota*, *Porites astreoides*, and *Siderastrea siderea*. Massive corals are the largest coral morphology on Bonaire, growing to sizes larger than 2 meters in height. These corals vary in shape and color, but are

distinguished for their size and rigid structure. Large mounds along the corals surface help to identify massive corals, such as with *Orbicella sp.* Massive corals are one of the lowest growing morphologies, reaching a max of 1.4 cm per year despite their overall large size (Hubbard and Scaturro 1985).

Many massive corals are facing loss of cover due to multiple types of diseases. Common coral diseases found on massive corals include black band disease, yellow band disease, and dark spot disease (Halloway 2016). Black band disease and yellow band disease, in particular, are widespread throughout Bonaire waters, affecting the majority of *Orbicella sp.* (Halloway 2016). Through observations during dives, the majority of massive corals appeared to at least have one type of disease affecting their growth.

Brain Corals:

The brain corals researched through the study were *Colpophyllia natans*, *Diploria labyrinthiformis*, and *Diploria strigosa*. Brain corals are round with unique grooves similar to that of a human brain. Additionally, brain corals are one of the more colorful corals, ranging from bright yellow to brain corals such as *Copophyllia natans* that have a bright green coloration between the skeletal grooves. Caribbean brain corals grow at a very slow rate compared to other Caribbean corals, where one study found over 40 years that a brain coral grows on average 3mm per year (Cohen et al. 2004).

Brain corals are facing decreased area cover due to white plague disease, which is a bacterial pathogen that creates large white spots of dead coral (Halloway

2016). *Colpophyllia natans* is affected by type one, two and three of white plague, while *Diploria strigosa* and *Diploria labyrinthiformis* are affected by types one and two (Sutherland et al. 2004). The other common coral disease affecting brain corals is yellow band disease (Sutherland et al. 2004). Due to the very slow growth rate of brain corals, these diseases can kill brain corals at a faster rate than they can grow, severely decreasing the living brain coral cover.

Flowering Corals:

The only flowering coral researched was *Eusmilia fastigata*, which is distinguished by a specific polyp structure, which is one of the largest polyps of the stony corals researched. The coral contains large, round polyps in the shape similar to a bouquet of flowers, where each polyp is lined with ridges, which increases surface area of the polyp. *Eusmilia fastigata* has a growth rate of 1cm per year, similar to the rate of massive corals (Langmead and Sheppard 2004). *Eusmilia fastigata* is one of the coral species that is highly resistant to disturbances due to its unique structure (Langmead and Sheppard 2004). Additionally, this coral species is resilient to coral diseases, where only type-two white plague disease affects the health of the coral (Sutherland et al. 2004).

Plating Corals:

The plating corals researched include *Millepora complanata*, *Mycetophyllia*, and *Undaria agaricites*. These corals are categorized based on their thin, flat structure, both horizontally and vertically along the benthos. *Undaria agaricities* is

the most abundant coral found on Bonaire, as it is adapted to thrive in both shallow and deep coral reef ecosystems (Halloway 2016). Due to the high growth rate of such plating corals, reaching 5 cm per year of growth, the cover has increased continuously over the last thirty years (Bak et al. 2005). *Millipora complanta* is found vertically within the sand flats, and did not appear within the plots of this study, but is the most abundant coral found along the sand flats of Bonaire.

Plating corals are becoming particularly susceptible to coral bleaching and other diseases due to their high abundance and surface area along the coral reefs. As the plating corals flatten out in shape to be in contact with sun, the zooxanthellae leave the corals, resulting in bleaching (Bak et al 2005). Additionally, the white plague disease is impacting plating corals such as *Undaria agaricites* along Bonaire's coastline, resulting in its mortality (Sutherland et al. 2004).

Branching Corals:

The branching corals researched through the study included *Acropora palmata*, *Acropora cervicornis*, *Dendrogyra sp.*, *Madracis aurentenra*, *Millipora alcicornis*, and *Porites porites*. This morphology of coral contains an adaptation of the skeletal pores that allows for rapid distal growth along the branches (Hughes 1987). The *Acropora* species of coral is found within the shallow waters, at roughly 0-5m of water depth, but has declined in numbers since the 1980s (Brukner 2002). However, these species grow at fast rates compared to other corals, averaging a growth rate of approximately 10cm per year (Bak 2009). In contrast to the general range of growth for branching corals, *Dendrogyra sp.* produce thicker vertical

branches, causing a slower growth rate of approximately 0.8 cm per year (Hughes 1987). Each species varies in growth rates, but overall branching corals are adapted to have a faster growth rate compared to other morphological species (Hughes 1987).

One factor causing a decrease in the cover and abundance of branching corals is the harmful diseases that are killing the branching species. In particular, the white plague disease and white band disease are the most common disease found on Caribbean branching corals (Sutherland et al. 2004). White plague disease starts at the base of a branching coral and moves up the branch in rings until it completely kills the entire branch (Sutherland et al. 2004). White plague disease grows at a rate of 0.3 – 2cm a day (Halloway 2016), which can greatly affect the health and cover of branching corals. White band disease only affects *Acropora* species, but grows at a rate of 2cm per day (Halloway 2016), leading to the mass decline of *Acropora* species on Bonaire.

Key Factors Affecting Coral Growth Rate:

Shallow and deep water vary in the amount of sunlight received, the nutrient levels, temperature, and interaction with algae and grazers, which effect the distribution and abundance of corals. The key component of this study is researching the effects of depth on coral cover, where changes in depth also create variations in the light spectrum and intensity that the coral receive. Light is a key arguably the most important environmental factor that drives the vertical distribution of corals and colony structure by species (Baker and Weber 1975).

Light intensity decreases at an exponential rate with an increase in depth, changing the color spectrum to blue wavelengths (Birkeland 1997). This light change can affect the morphological characteristics of corals, where in the shallows the corals may be mounded and in deeper water become more plating in form (Birkeland 1997). Light intensity is most significant within the shallower depths since deeper parts of the ocean floor do not receive an abundant amount of sunlight (Bak et al. 2004). However, with clear waters and the range of depth for corals on Bonaire, light intensity plays a role in the coral cover, growth, and rate of bleaching.

Temperature of oceans impacts the health of corals, where increased temperatures can lead to coral bleaching. When ocean waters are too warm, it causes the coral-algae symbiotic zooxanthellae to be expelled from the coral, ultimately leading to coral death (Eakin et al. 2005). In contrast, too low of temperature reduces the energy rate and activation of growth within hermatypic corals, leading to the probable idea of why these corals are isolated in geographical distribution (Stehli and Wells, 1971). In relation to changes in temperature increase, coral bleaching was observed among all types of corals in the Antilles up to 40 meters in water depth (Eakin et al. 2005). With global warming, bleaching will begin to increase in scale among corals. Coral bleaching, similar to coral diseases, decreases the living coral cover and play a potential role in the coral cover observed within this study.

Another factor impacting coral cover is the symbiotic zooxanthellae algae density within corals in relation to marine grazers. There is a strong link to the growth rate of carbonate skeletal structures of hermatypic corals and the symbiotic

relationship with zooxanthellae (Baker and Weber 1975). With a buildup of algae, corals are susceptible to diseases that can lead to death of a coral. (Mumby et al. 2007). However, the symbiotic relationship of grazers, such as sea urchins, parrotfish, and damselfish with corals allows for the algae to be consumed and thus not harming corals. However, the decline in grazers, particularly the sea urchin that began their decline in 1983, resulted in parrotfish becoming the primary grazers, which diminished the resilience of corals (Mumby et al. 2007). Grazers play an important role in the recovery of corals, particularly after a disturbance, allowing for coral recruits to grow along the benthos (Adam et al. 2015). Corals are particularly susceptible to changes in health with varying algae levels. The relationship with grazers plays an important role in the resilience of corals. With proper levels of algae on the corals surface, new coral recruits increase coral cover and allow for corals to expand in area covered.

Underwater Photography and Videography for Ecological Monitoring:

Conventional monitoring protocols, such as transect and quadrat methods, allow SCUBA divers to properly assess the health of the coral reefs (Gintert et al. 2008). These methods can involve extensive surveys, long dive times, and collection of non-permanent data (Gintert et al. 2008). For example, one monitoring survey of *Undaria agaricites* in Curacao, an adjacent island to Bonaire, used underwater photographs to monitor the corals surrounding substratum (Van Moorsel 1985). To compensate for such weaknesses in current practices of underwater monitoring, one practice is to create photomosaics, which rely on a combination of pictures to

create a singular large-scale depictions of the coral reef. These landscape photomosaics are useful to create permanent data to assess the damage and health on the benthic community of coral reefs on a large-scale (Lirman et al. 2010).

The use of photomosaics improves survey collection through its large-scale imagery and surveying complete organisms along the benthos, such as types of stony corals (Lirman et al. 2007). Estimating percent cover of various organism groups through photomosaics can help determine the state and health of a coral reef. Even though research has identified variations in morphology of corals based on various factors (depth, sunlight, nutrients, etc.), documenting the changes with large-scale photographs and accurate percent coverage estimations is a new area of research. This method may provide new insights into more accurate representations of the true coverage of coral reefs and their distribution based on changes in depth.

Research Question and Hypotheses:

In this study I investigated the dependence of coral coverage on changes in depth. The central research question was: how does coverage of stony corals with different physical morphologies change with variation in depth at Bonaire, Netherland Antilles? Based on observations from diving, the initial hypotheses were that massive corals would be the dominant morphology found within the study site due to the sheer size of these corals and the abundance observed at the site. Another hypothesis based on the conditions of the reefs in Bonaire is that branching corals would show minimal coverage, as they tend to grow vertically and in small groups

within the shallows and sand flat, limiting their area coverage from a 2-dimensional vertical view in the study site.

Methodology

The study site was located on the leeward side of Bonaire one mile north of Kralendijk off the shore line by roughly 100 meters. The starting position of the plots was the reef crest, at a depth around 10 meters. Six pins were hammered into the sandy bottom to create the plots and GPS coordinates were taken of the first pin. The study site's first pin was located at N 12.17654 latitude and W 68.29253 longitude, with a bearing of 230 degrees taken from the first pin down the reef slope to the third pin, where these two pins were perpendicular to the reef crest (Figure 4). With the GPS coordinates and bearing, the other pin placements were calculated based on the lengths measured between each of the pins. The plot gradually declined in depth at an approximate 30-degree slope from the reef crest from depths of roughly 10 meters to roughly 30 meters (Figure 4).

Study Site:

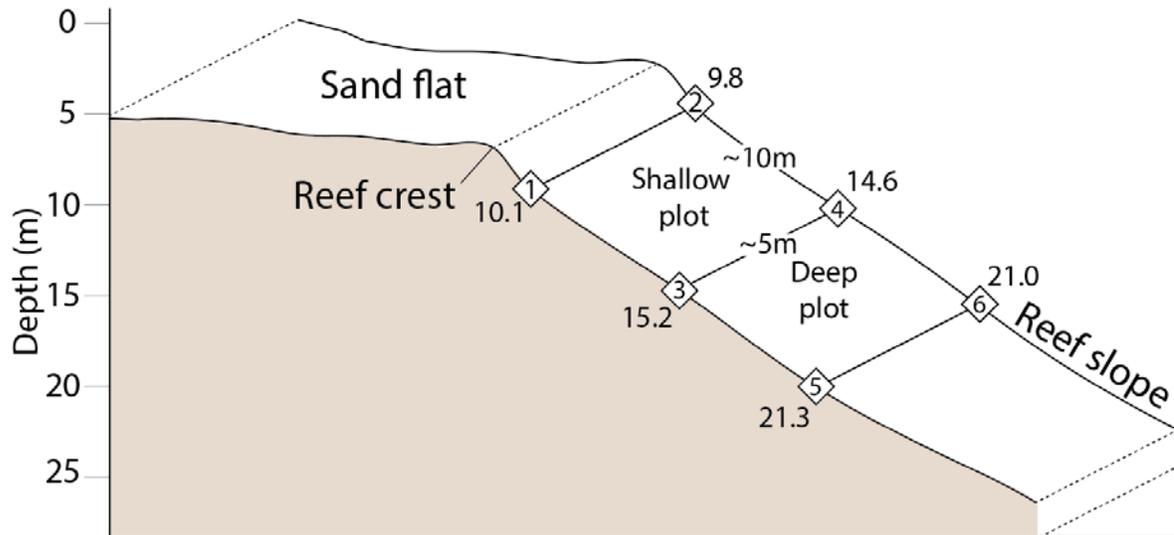


Figure 4: Site map showing deep and shallow plots and locations with depth of each pin relative to the reef crest, sand flats, and reef slope.

Creating the Study Plot:

A photomosaic plot was established to investigate varying coral reef types and morphologies with depth. The plot had a shallow (~10 – 15 m) and deep (~15 – 20 m) plot. Rebar pins were placed 5 m apart, at depths indicated in Figure 4. The distance between the pins perpendicular to the shoreline was ~10 m (Figure 4). A total of six pins made up a plot. The total surface areas of the shallow and deep plots were 43.8m² and 36.3m². To ensure correct depths and locations of pins, cross sections of the plot were measured. Additionally, a cardinal bearing was taken from pin one to pin three to be used later for analysis with GPS locational points.

Photomosaic Image Collection and Stitching:

A photomosaic was created in August 2016 from the imagery collected within each plot. Two photomosaics were created: one for the shallow plot and another for the deep plot (Figure 1). The photomosaics were collected by attaching two Sony RX 100 M3 digital cameras to a PVC frame, which were each two meters in length. The cameras were placed into two Nauti-cam underwater housing units and mounted one meter apart on the PVC frame. The cameras were installed in a down-looking position with four lights on either side of the cameras. To ensure image overlapping, 18 megapixels still images were captured at one-second intervals using a time-lapse application. In order to correct image distortion during the imaging processing, still images were taken of a checkerboard underwater for calibration of the cameras. The checkerboard was placed in several positions to show multiple angles of the board. This step is completed to ensure that the coloration of the cameras is set accordingly for the light exposure underwater. The photomosaic image collection was done by a single diver who stayed roughly 2 meters above the coral reef, while swimming in a lawn mower pattern over each individual plot as seen in figure 5 (Lirman et al. 2007). The overlapping imagery for each of the plots over two dives.

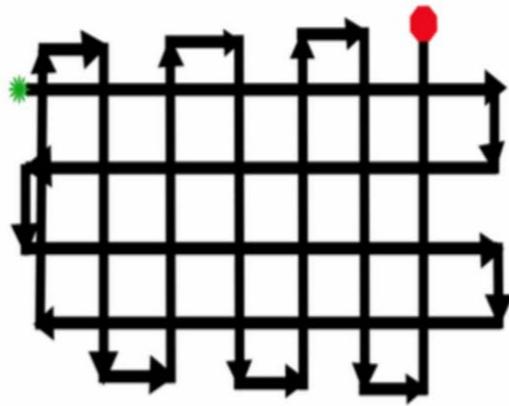


Figure 5: Pattern completed by the diver taking one-second overlapping imagery of a plot. Green sign indicates starting position and red symbol indicates ending position (Cook and Marx 2015).

A photomosaic processing software, developed by the Reid Lab at the Rosenstiel School of Marine and Atmospheric Science, was used to create the photomosaics from the collected photos. The software utilizes the first generation mosaic-processing algorithm presented in Lirman et al. (2007). A global matching module was used for sequential image feature matching and non-adjacent image feature matching (Gracias and Santos-Victor 2000). Once matching was completed, the photomosaic renderer module was used to stitch together portions of the individual raw images by selecting the portions of the image that were closest to the center of the image frame (Lirman et al. 2007). In total, the image selection method blended about 1500 to 2000 images for each plot photomosaic. The photomosaic encompassed the entirety of each plot as well as surrounding coral reef area in all directions to ensure the entire plot was captured (Figure 6 and 7).

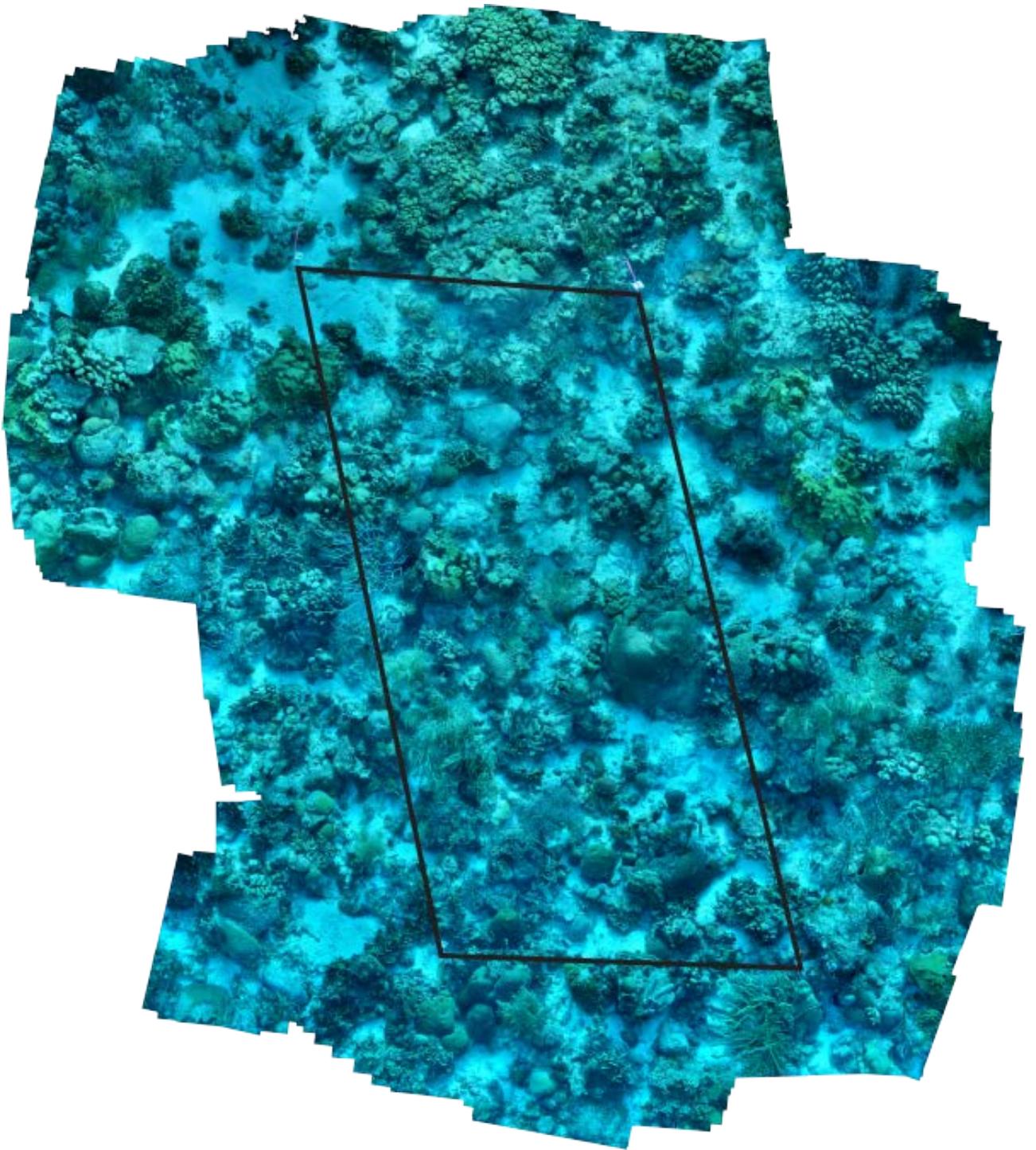


Figure 6: Photomosaic of shallow plot with boundaries totaling 43.77m²

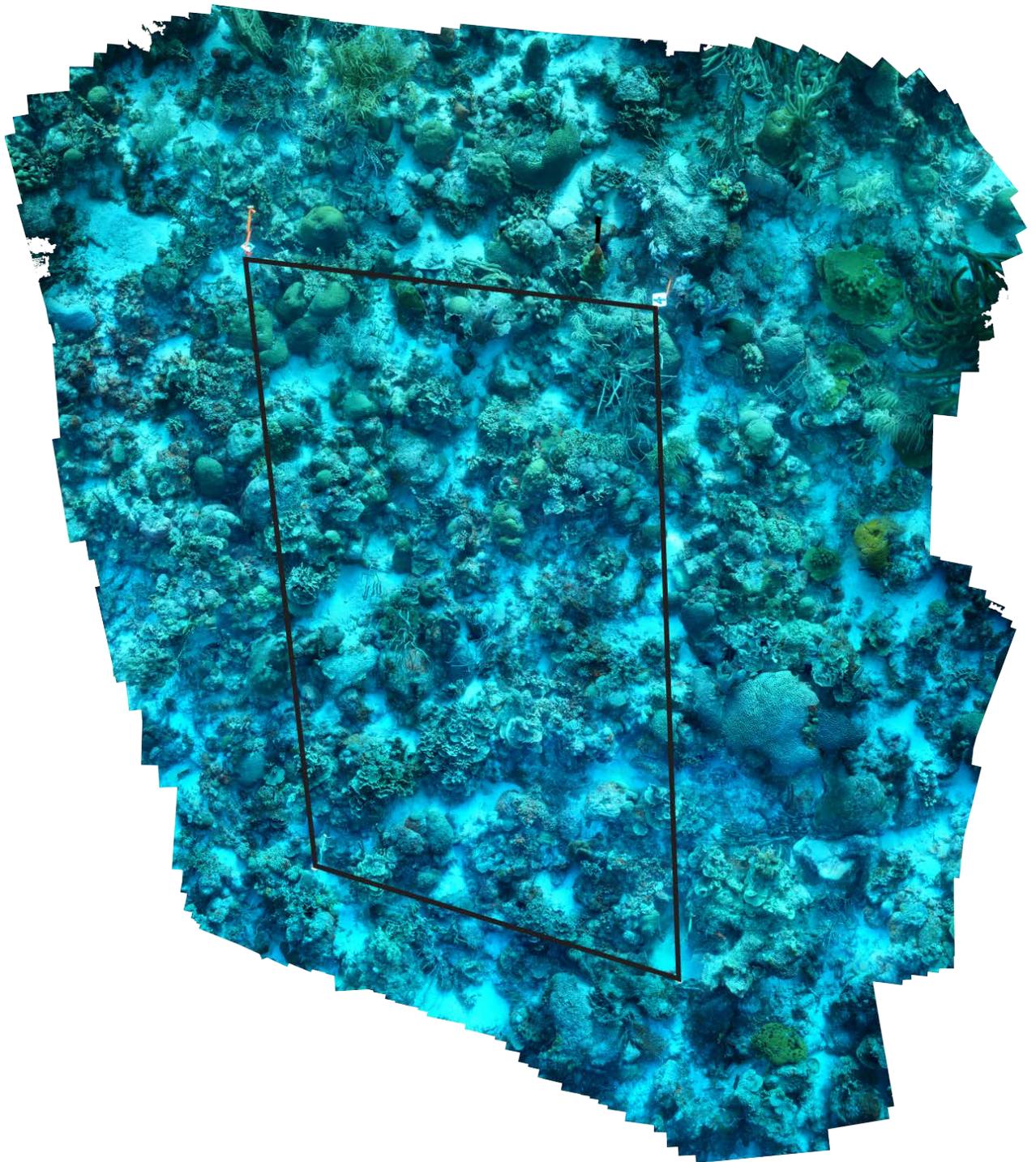


Figure 7: Photomosaic of deep plot with boundaries totaling 36.25 m²

Photomosaic Analysis:

The first step of analyzing the photomosaic included tracing the boundaries and pins of the plot. The next step involved tracing the raw image path based on the diver's path to be able to check identification of corals with the raw images collected (Figure 8). Tracing the boundaries of the stony corals in Photoshop digitized the photomosaic images. Researchers digitized the entire photomosaics with a pen-tablet in Adobe Photoshop. Then the stony corals were distinguished based on five morphological categories: massive, brain, flowering, branching, and plating. Light purple represents massive corals, orange for brain corals, green for flowering corals, red for plating corals, and yellow for branching corals. (Figures 9 and 10). Dark purple around the plot shows corals that were not included in the analysis. Only corals that were completely or partially within the plot boundaries were included in the analysis, but surrounding corals were identified as a buffer.

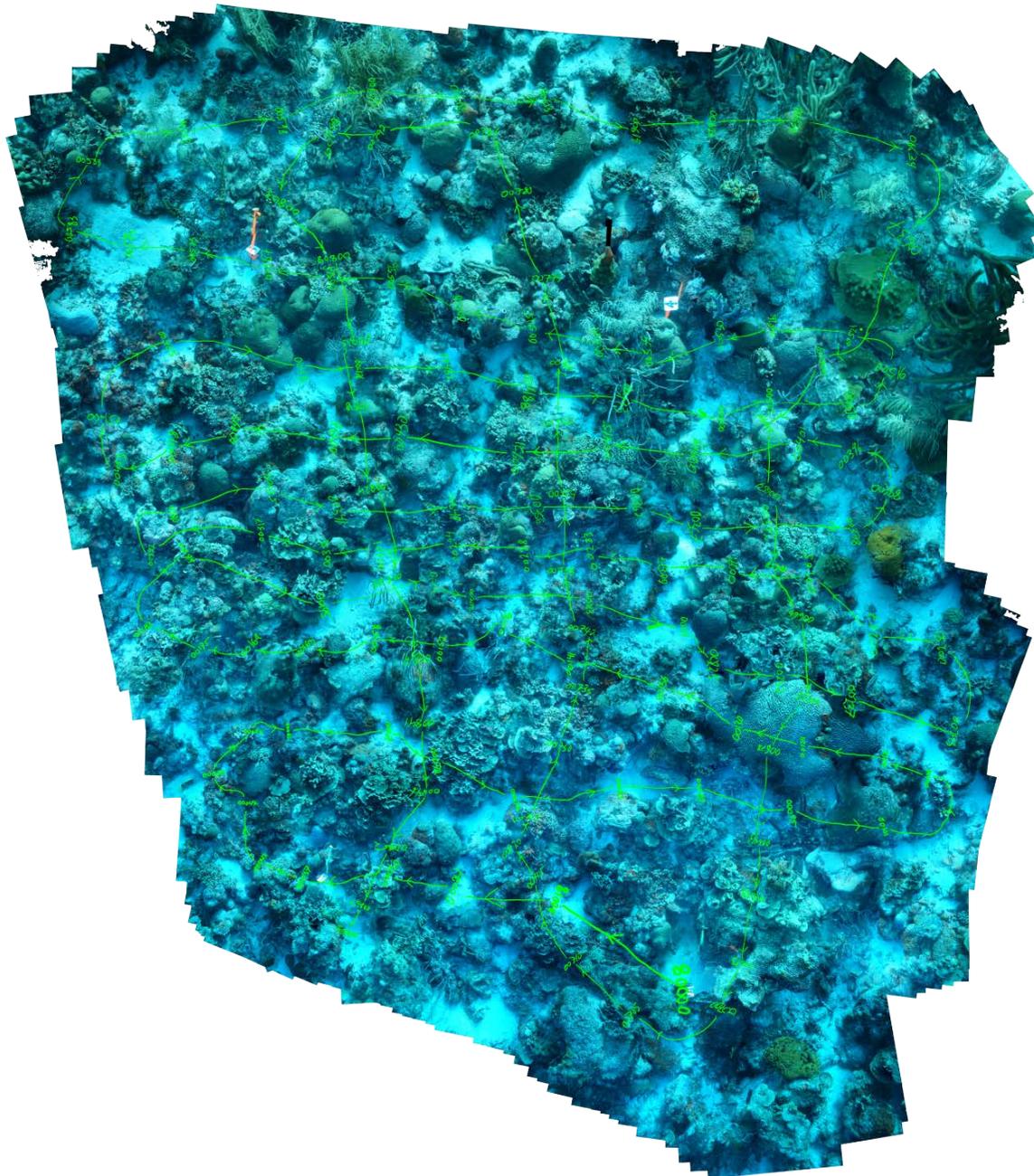


Figure 8: Tracing of pathway the diver took to collect the imagery. Allows for raw images to be analyzed with the photomosaic if identification of a species is unclear.

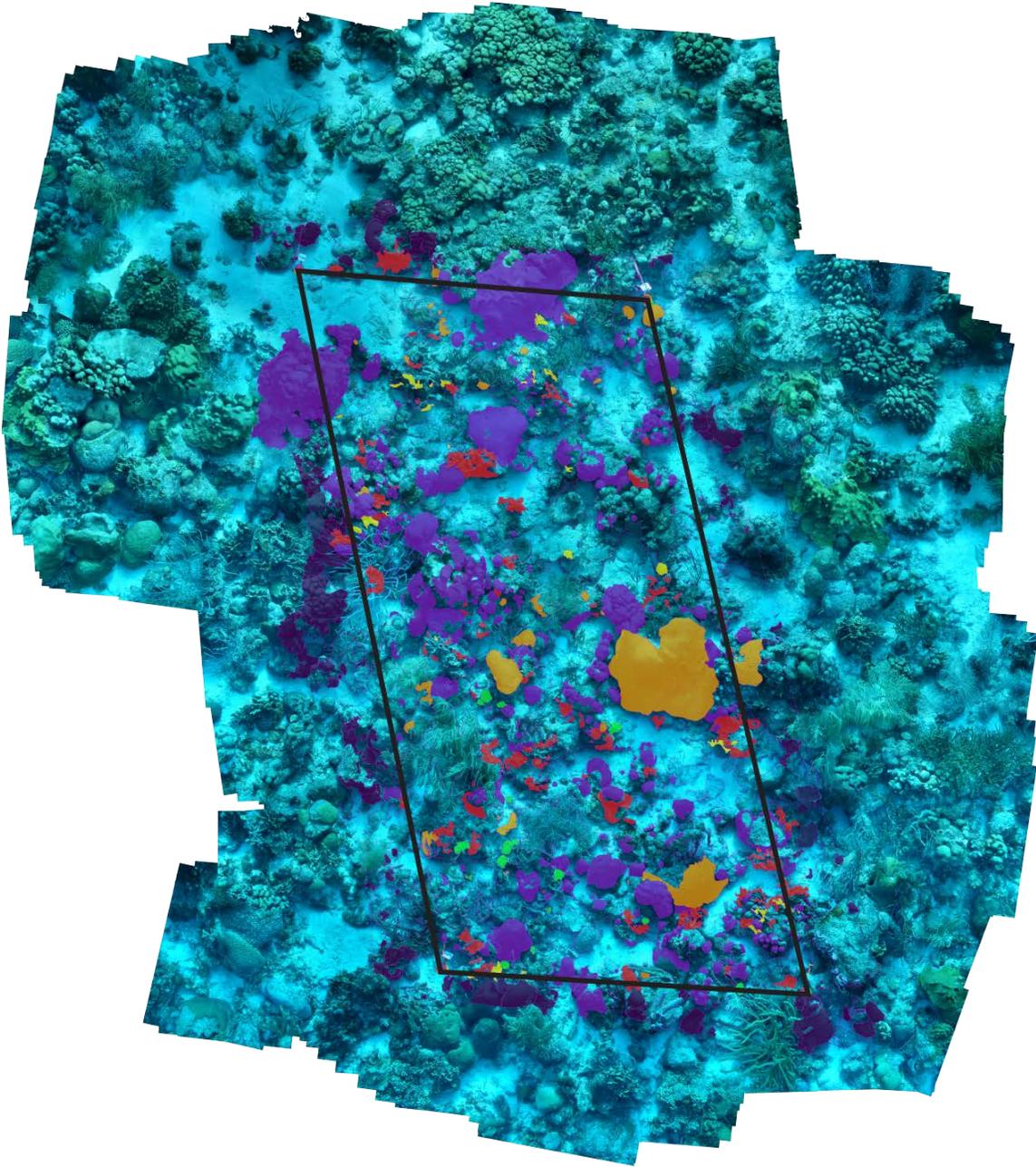


Figure 9: Traced and filled areas of coral based on type of morphology for the shallow plot.

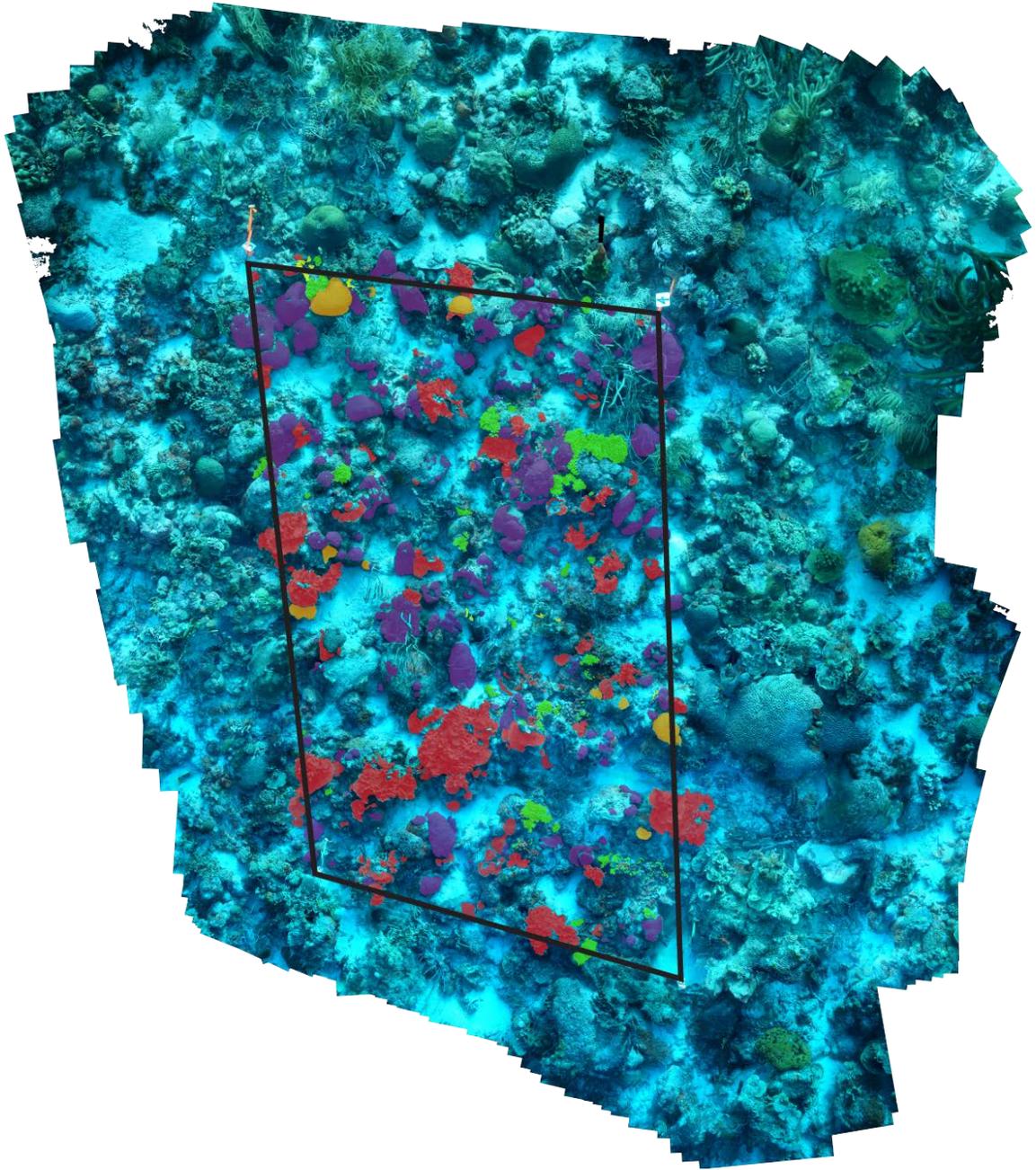


Figure 10: Traced and filled areas of coral based on type of morphology for the deep plot.

The aforementioned morphological groups were exported from Photoshop as separate raster images. The raster images were imported in to Quantum GIS (QGIS v2.14 Essen), an open source geographic information system software, and the individual benthic group raster images were geo-referenced using detailed plot measurements and GPS coordinates taken in the field. To create a more spatially accurate image, the rasters were transformed using the thin plate spline transformation method and the nearest neighbor resampling method. The spatially accurate raster images were then converted into vector data (polygons) to calculate a spatially explicit estimate of benthic organism and substrate percent cover. The raster images were clipped to only account for areas that fell within the boundaries of the plot.

Statistical Analysis:

Each polygon represented a single coral that contained spatially accurate data on the area in meters squared and perimeter in meters. Average areas for each coral morphology were compared using a one tailed t-test. The null hypothesis for the t-test was that depth did not have a significant effect on the average area coverage of a particular coral morphology. Percent cover was then graphically depicted to compare the cover between the two plots. An analysis of variance (ANOVA) was performed to compare coral coverage of each morphology within each plot (shallow and deep). All tests used a significance p value of 0.05. A Post Hoc Tukey test was conducted if the ANOVA results were significant. Lastly a visual graphic was used to depict the range limits of each coral morphology based on absence or presence of that morphology within the photomosaics.

Results

Descriptive Statistics, T-test, and ANOVA

In the shallow plot (Figure 11 and 12), massive corals (n=261) were the most abundant coral species averaging an area of 245.59cm². Brain corals (n=28) were the largest area coverage that averaged 790.69cm². Flowering corals (n=17) averaged an area of 97.58cm². Plating corals (n=105) average an area of 142.80cm². Branching corals (n=10) were the smallest area coverage that averaged 66.66cm².

In the deep plot (Figure 11 and 13), Massive corals (n=253) were the most abundant coral species and average an area of 182.73cm². Brain corals (n=9) were the largest area coverage that averaged 404.79cm². Flowering corals (n=76) average an area of 109.56cm². Plating corals (n=137) average an area of 271.05cm². Branching corals (n=9) were the smallest area coverage that averaged 38.57cm².

Average area covered for each morphology was compared between the shallow and deep plot (Figures 12 and 13). There was no significant difference in area covered between massive corals (T=1.32, p=0.09), brain corals (T=0.45, p=0.32), branching corals (T=1.43, p=0.07), or flowering corals (T=-0.19, p=.042). Plating corals were the only coral morphology to show significance of area cover with variation in depth (T=-1.77, p=0.04).

For percent area cover within both of the plots, massive corals had the highest percent cover with 61% in the shallow plot (Figure 14) and 47% in the deep plot (Figure 15). Through the t-test analysis, plating corals were the only morphology to show percent cover significance between the shallow plot and the deep plot (Figure 11).

| | Type of Coral Morphology | Massive | Brain | Flowering | Plating | Branching | ANOVA Within Plots | |
|----------------------|---------------------------------|---------|--------|-----------|---------|-----------|--------------------|--------|
| Shallow Plot | Total Number of Colonies (n) | 261 | 28 | 17 | 105 | 32 | F-value | 3.74 |
| | Total Area (m ²) | 6.42 | 2.21 | 0.17 | 1.50 | 0.21 | | |
| | Average Area (cm ²) | 245.9 | 790.7 | 97.6 | 142.8 | 66.7 | P-value | 0.04* |
| | Percent Cover (%) | 61.1 | 21.1 | 1.6 | 14.3 | 2.0 | | |
| Deep plot | Total Number of Colonies (n) | 253 | 9 | 76 | 137 | 9 | F-value | 2.42 |
| | Total Area (m ²) | 4.31 | 0.40 | 0.84 | 3.74 | 0.04 | | |
| | Average Area (cm ²) | 182.7 | 404.79 | 109.6 | 271.1 | 38.6 | P-value | 0.005* |
| | Percent Cover (%) | 46.6 | 4.4 | 9.1 | 40.4 | 0.4 | | |
| T-Test Between Plots | T-value | 1.32 | 0.45 | -0.19 | -1.77 | 1.43 | - | - |
| | P-value | 0.09 | 0.33 | 0.42 | 0.04* | 0.08 | - | - |

Figure 11: Summary of spatial data from photomosaics. ANOVA F-values based on comparisons of area cover within each plot and T-values are based on comparisons of area cover for each morphology between plots. * indicates $p < 0.05$.

Area Coverage:

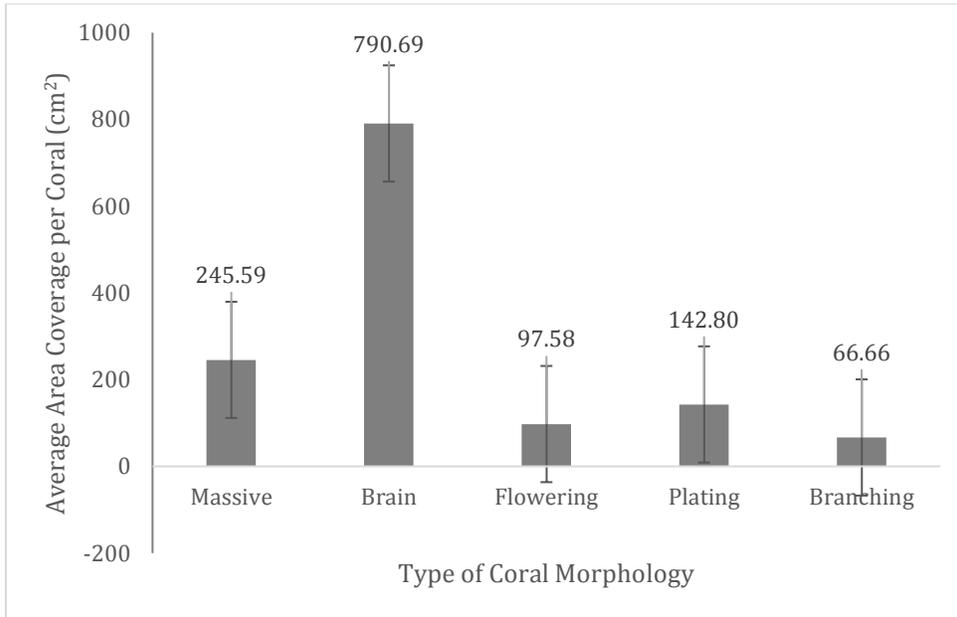


Figure 12: Average area coverage of a single coral (mean \pm 1SE) for each morphology in the shallow plot.

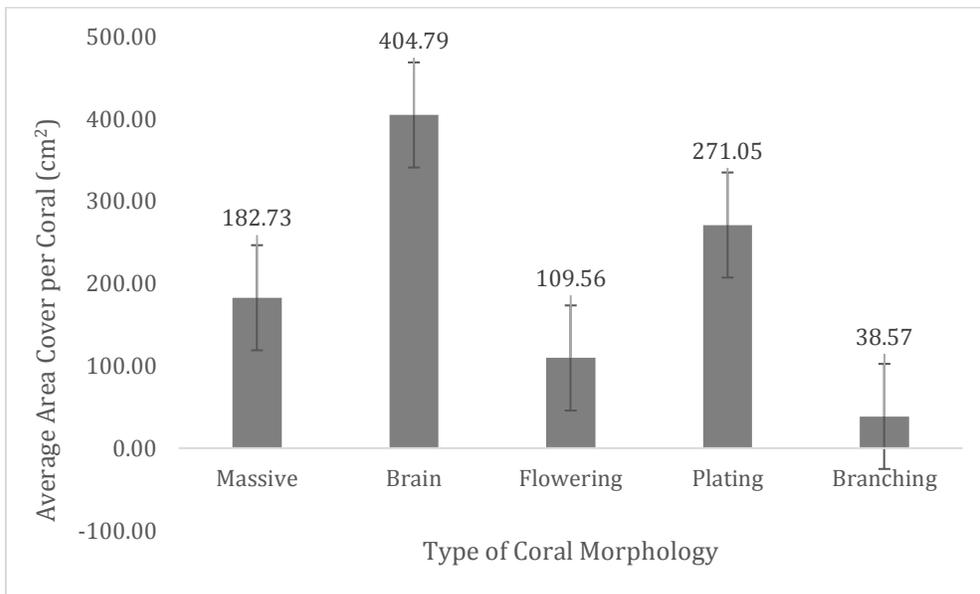


Figure 13: Average area covered of a single coral (mean \pm 1SE) for each morphology in the deep plot.

Percent Cover:

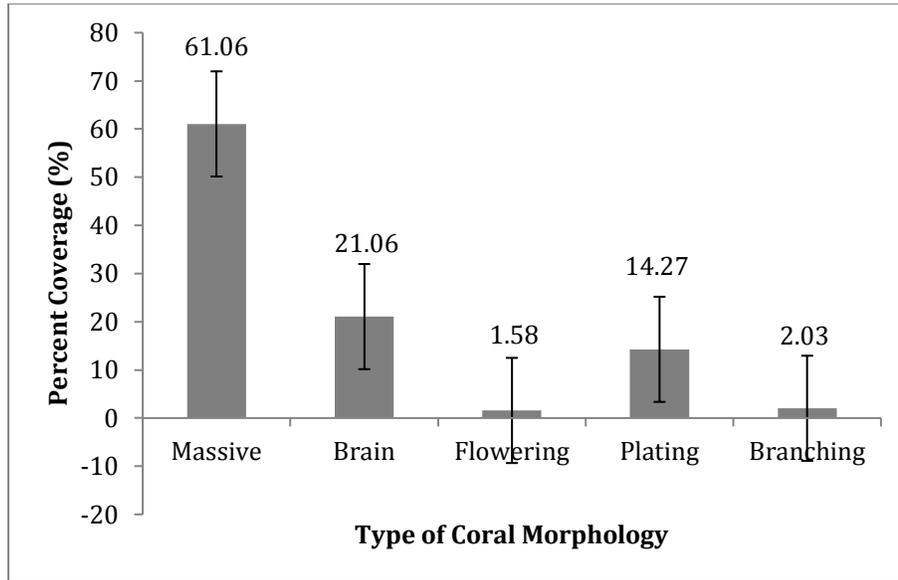


Figure 14: Percent coverage of stony corals in the shallow plot (mean \pm 1SE) based on type of coral morphology. Total stony coral percent cover in the shallow plot was 24%.

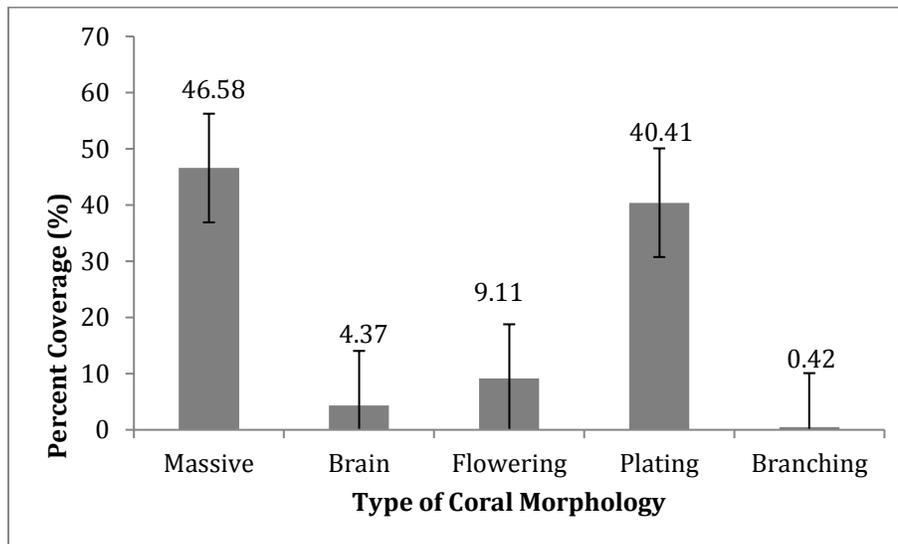


Figure 15: Percent coverage of stony coral in the deep plot (mean \pm 1SE) based on the type of coral morphology. Total stony coral percent cover in the deep plot was 25%.

Post Hoc Tukey Analysis:

Shallow Plot

| Descriptive Statistics | | | Total |
|------------------------|------------------------|----------------|-------|
| Morphology Type | Mean (M ²) | Std. Deviation | (N) |
| Massive | 0.0246 | 0.0675 | 261 |
| Brain | 0.0791 | 0.02673 | 28 |
| Flowering | 0.0098 | 0.0065 | 17 |
| Plating | 0.0143 | 0.0206 | 105 |
| Branching | 0.0067 | 0.0060 | 32 |

| Tukey HSD Q Statistic | | | | | |
|-----------------------|---------|--------|-----------|---------|-----------|
| | Massive | Brain | Flowering | Plating | Branching |
| Massive | 1 | | | | |
| Brain | 4.562* | 1 | | | |
| Flowering | 0.9867 | 3.754 | 1 | | |
| Plating | 1.4860 | 5.072* | 0.2880 | 1 | |
| Branching | 1.5940 | 4.660* | 0.1716 | 0.6279 | 1 |

Deep Plot

| Descriptive Statistics | | | Total |
|------------------------|------------------------|----------------|-------|
| Morphology Type | Mean (M ²) | Std. Deviation | (N) |
| Massive | 0.0183 | 0.0308 | 236 |
| Brain | 0.0405 | 0.0441 | 10 |
| Flowering | 0.0110 | 0.0251 | 77 |
| Plating | 0.0271 | 0.0719 | 138 |
| Branching | 0.0039 | 0.0020 | 10 |

| Tukey HSD Q Statistic | | | | | |
|-----------------------|---------|-------|-----------|---------|-----------|
| | Massive | Brain | Flowering | Plating | Branching |
| Massive | 1 | | | | |
| Brain | 2.10 | 1 | | | |
| Flowering | 1.70 | 2.68 | 1 | | |
| Plating | 2.52 | 1.25 | 3.47 | 1 | |
| Branching | 1.36 | 2.50 | 0.65 | 2.17 | 1 |

Figure 16: Results of a Post Hoc Turkey Q-statistical analysis from a significant results of the ANOVA analysis. * Indicates Q-statistics that are significant between the comparisons of coral morphologies

Depth Range Analysis:

Based on the photomosaic imagery, the range of corals depth outside of the plots could be calculated based on the presence or absence of that morphology in the surrounding photomosaic (Figure 17). Flowering coral was not identified in shallower depths above the plots, only appearing in the photomosaic at 13 meters and deeper. Branching coral was found only in depths above 16 meters. Brain coral were not identified beyond 18 meters in depth. Both massive and plating coral were

identified beyond the plot boundaries both in shallow and deep waters. However, this does not mean that brain, flowering, or branching corals aren't found beyond the aforementioned depths in the surrounding area.

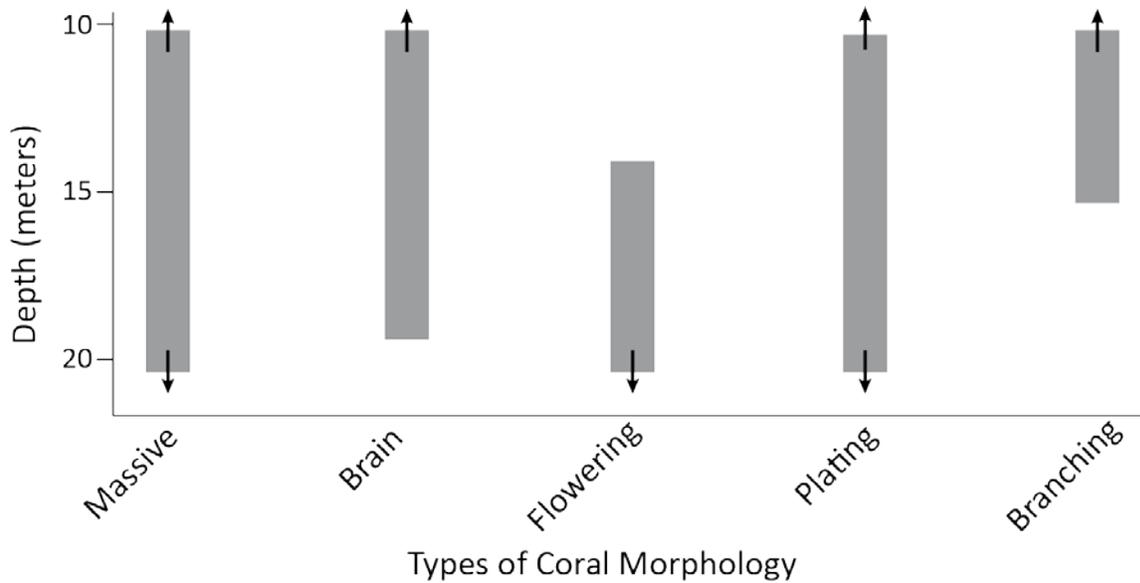


Figure 17: Estimation of depth ranges of each coral morphology based on analysis with the photomosaics study area.

Discussion

Photomosaics were used to calculate the percent coverage of the stony coral within a shallow and deep plot. Photomosaics can assess the benthic community because of the high spatial accuracy and precision that the large scale 2-Dimensional maps provide (Cooke and Marx 2015). Through the processing, massive corals were found to have the highest percent coverage within both the shallow and deep plot (61% and 47% respectively, Figure 14 and 15), possibly due to the physical characteristics, structure, and growth rate of massive corals. From the comparison of coral morphologies between the shallow and deep plot, the plating corals had higher spatial percent coverage in the deep plot (Figures 11, 14 and 15). *Undaria agaricites* is the main plating species on Bonaire that can cover large areas based on its morphology and ability to grow above and over other corals (Halloway 2016). The way that plating corals grow with thin, flat physical features allows for the coral to maximize its surface area that is in contact with light from above. The higher coverage at depth found for this species is potentially due to the flat growing physical characteristic of these corals, where in deeper depths the coral will spread out horizontally to increase surface area towards the surface for light absorption, while in shallower depths this is not as necessary. However a current drawback to this characteristic is since the majority of the coral surface is directly facing upwards, high levels of coral bleaching can potentially develop (Kolbuk and Lysenko 1994).

There were differences in the area cover between the different coral morphologies within a single plot, i.e. same depth range (Figure 11). These results

conclude that the percent cover between the various coral species is significantly different from each other. However the results were further analyzed with a Post Hoc Tukey statistical test, which compares one type of coral morphology to another, and analyzes all the different combinations of comparison. Through this test, the deep plot showed no statistical significance of area cover between plots. However in the shallow plot, the comparison of area cover between brain corals to massive ($q=4.56$), plating ($q=5.07$), and branching ($q=4.66$) morphologies showed significances (Figure 16).

The brain coral morphology had the highest average area cover within both the shallow and deep plot (791 cm^2 and 405 cm^2 respectively, Figure XX). Even though brain corals were not very abundant in the shallow plot ($n=28$) and deep plot ($n=10$), a few large brain corals identified in both plots skewed the average area cover to be larger than is typically found. Particularly in the shallow plot, one brain coral of *Copophyllia natans* measured an area of 1.404 m^2 , nearly double the size of the next largest coral found within the shallow plot (Figure XX). The size of brain coral and the low abundance correlates with the significance found with this morphology compared to other morphologies. Thus, it is a weakness for the study as it skews the results and may not be representative of the true coral cover in Bonaire.

The ability to use photomosaics to analyze coral cover is useful as the data are robust with information that is achievable, in opposition to transect or quadrat analysis. Photomosaics are also beneficial for repeatable methods, where plots can be analyzed and re photographed over long time spans to measure changes in the plot cover. Photomosaics allow for a unique interaction, where a multitude of data

can be gathered and developed to conduct numerous research projects. However, photomosaics do not give an accurate representation of a coral's entire morphology. The photomosaics provide a 2-Dimensional map of the benthic community, but cannot show the vertical and underside of stony corals, incomplete data to be collected on the entire surface area of each coral colony. However photomosaics are recommended when analyzing coral reef percent cover in terms of what surface area is in contact with light and what intensity that light is based on depth. Additionally, to have statistically significant data for the percent coverage of stony corals, it is recommended to perform Coral Point Count (CPC) analysis on photomosaics, where random points are pulled from individual photographs to determine the community composition (Kohler and Gill 2005). This methodology would be able to further the weakness addressed with the brain coral as being an outlier within the plots, where it could analyze the coral communities with further accuracy.

When analyzing the results for both photomosaics, each photomosaic was traced by two individual researchers, where this could present problems in observer bias in identification of presence or absence of corals within the two plots. With two researchers tracing the corals, error lies within the accuracy of the area traced and the attention to detail of where the boundary of coral cover is present. However identification of each stony coral based on morphology was completed by one research, decreasing the researcher bias in the identification step.

Conclusion

The importance of this research lies in the potential of future ecological monitoring projects and the significance it has for Bonaire's future in the preservation and conservation of the coral reefs. Current governmental practices through STINAPA run monitoring surveys to develop a database for the health of the islands coral reefs. Their mission involves several aspects, including economic growth of the island, environmental education, equipment management, and research analysis on the quality of the reefs. The increase in funding allows for proper site maintenance, law enforcement protocols, equipment purchasing for research and monitoring programs, and finding means to publicly educate the diverse residents and travelers on the island. Based on the results of this study, STINAPA could further their ecological database and use the photomosaics for long term ecological monitoring practices. The significance of the results could allow for STINAPA to implement different protocols or monitoring programs to further research and preserve the health of the coral reefs on Bonaire.

Scuba divers greatly value the visibility, species diversity, and percent of coral cover and state these as reasons for choosing Bonaire as a diving destination (Parsons and Thur 2007).

Through my own personal observations in the waters of Bonaire, I realized how fragile the ecosystem truly is. Through dives, particularly those with recreational divers, I observed how easy it is to accidentally hit and break a part of coral. Individuals want to observe the organisms along the reefs in close detail, where divers become unaware of their surroundings. It may appear insignificant,

but after this research project I realized that breaking a coral is substantial, because it took decades for that piece of coral to grow. It is for that reason I feel this research and data collect is so important. Corals take decades and centuries to get to be the size they are, and if other variables such as natural disasters, diseases, or coral bleaching are killing these corals, the reefs continue to decline with recreational divers adding to their loss in abundance and size.

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