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How Large Area Imagery Can Be Used to Quantify Growth of a Complex Branching Coral
Species

A thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Marine Biology

by

Laura A. Gibson

Committee in charge:

Professor Stuart Sandin, Chair
Professor Octavio Aburto Oropeza
Professor Jennifer Smith

2021

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The thesis of Laura A. Gibson is approved, and it is acceptable in quality and form for publication and on microfilm and electronically.

University of California San Diego

2021

DEDICATION

This thesis is dedicated to my mother and grandparents. Without their love and support I may never have found my way into science and the blood, sweat and tears that I put into this research would not have been worth it. For my mother - none of my successes and experiences would have been possible without you. You have been my rock and cheerleader from the beginning and I am forever grateful. For my grandparents – who both gave me the tools necessary from a young age to understand what kind of person I wanted to become, and whose time spent with me shaped me into who I am today. I love all of you eternally, this is for you.

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ABSTRACT OF THE THESIS

How Large Area Imagery Can Be Used to Quantify Growth of a Complex Branching Coral Species

by

Laura A. Gibson

Master of Science in Marine Biology

University of California San Diego, 2021

Professor Stuart A. Sandin, Chair

Species of branching *Acropora*, once dominant, complex coral species, have experienced major decline over the last several decades due to physical and anthropogenic disturbances. Following this decline, species of *Acropora* have been a direct focus of coral monitoring and restoration efforts across the Caribbean, in hopes of recovering populations of these threatened species. Measuring growth in the field presents countless challenges, including inaccuracy and imprecision of measurements due to intricate branching morphologies, the amount of time a diver

can spend underwater measuring aspects of coral health, and unpredictable diving conditions. Here we used large-scale 3D imagery derived using Structure from Motion photogrammetric techniques to quantify branching *Acropora* species across multiple reef terrace sites on Palmyra Atoll. We estimated branch density (number of branches per thicket) and various metrics of linear and areal size of colonies within imagery which facilitates a direct comparison of commonly used metrics to track growth. We were able to monitor growth based on initial size through larger thicket form for six *Acropora* thickets through multiple time points from 2012-2019. The use of large area imaging technology provides a permanent record and a powerful tool to quantify growth using a variety of metrics, not constrained by *in situ* logistics. Gaining access to and perfecting methods that account for accurate size and growth measurements for reef accretion can hold the key to long-term successful ecological monitoring and restoration efforts.

Introduction

Restoration methodology has received praise and has been commonly utilized over the last two decades in many forms. Although many organizations utilize a variety of restoration methodologies, the structure and standardization of growth metrics for these restoration projects is not yet comprehensive (Boström-Einarsson et al. 2020). Further scientific input could greatly aid in the future success of the restoration field (Foo & Asner 2020). Recently in the Caribbean and tropical Pacific, a significant portion of restoration methods have utilized the branching coral genus *Acropora* and focused on *in situ* efforts, or a combination of these efforts and large area imaging and photogrammetry for monitoring. Some common projects *in situ* have included: coral nurseries, gardening/pruning of reefs, artificial reefs, larval enhancement, microfragmenting, and many more (Boström-Einarsson et al. 2020). Although the design of restoration projects as a whole have been enhanced over the years, the tracking of metrics of previously restored coral has not. A common fault of previously utilized metrics is that projects utilize too short of a time frame that make it difficult to measure coral resilience and fail to paint a complete picture of current methodologies (Boström-Einarsson et al. 2020; Bruckner and Bruckner 2001; Griffin et al. 2015). To refine future restoration methods, we must find a way to maximize data collected and maintain long-term monitoring efforts, which can ensure that restoration practices shift and maintain priorities on design elements.

Previously utilized *in situ* restoration monitoring have many limitations: the amount of time a diver can spend underwater measuring aspects of coral health, unpredictable diving conditions, difficulty getting both accurate and precise measurements (utilizing visual scans of percent cover or coral growth can be inaccurate or difficult to do with measuring tape and photoquadrats for more complex species), etc. Although some growth metrics taken underwater

can be more rapidly estimated, these estimations may not account for potential visual factors divers may miss such as other biological influences surrounding coral outplants and colonies that may be affecting their growth and general health. Overall, strictly *in situ* methodologies have proven to be cumbersome and outdated and have paved the way for an evolution highlighting modern day technology utilizing 3D photogrammetric imagery. This imagery allows for monitoring while not only diving, but for years to come after divers have left the reef and gone back to the lab, even if the restoration efforts have ceased. A plethora of information can be extracted from imagery: percent cover, approximating change utilizing ellipses, and a variety of other metrics (Johnson et al. 2011; Kiel et al. 2012; Linares et al. 2011; Schopmeyer et al. 2017).

The *Acropora* genus is the most commonly used coral in restoration efforts in both the Caribbean and tropical Pacific (Boström-Einarsson et al. 2020). This is due in large part to its complex branching morphology and being considered extremely fast growing, as well as a key species for reef health and fish abundance (Lirman et al. 2014). Survivorship of *Acropora* is also high with increased levels of fragmentation, making it resilient during the restoration process (Gladfelter et al. 1978; Highsmith 1982; Lirman et al. 2010; Tunnicliffe 1981; Young et al. 2012). *Acropora* colonies have been shown to lose up to approximately 95% of their overall tissue and skeleton via fragmentation and still continue to maintain superior growth and recovery (Lirman et al. 2014). These life history components make *Acropora* very successful overall within coral nurseries and restoration projects, and give hope for the future of their continued success with active restoration (Lirman et al. 2014). From initial outplant size up until much larger thicket form, *Acropora* is extremely productive, with high rates of new coral being produced (Lirman et al. 2014). Once *Acropora* reach a more complex thicket form, albeit years later, populations generally see a reduction in growth and productivity (Lirman et al. 2014; Soong and Chen 2003; Yap et al.

1998). This can be due to crowding within the thicket or lessened space in the surrounding area depending on location population. Restoration projects have focused on active nursery habitats in locations where negative factors are at a minimum to ensure survival and rapid growth until *Acropora* outplants can be transferred to their long-term substrate (Boström-Einarsson et al. 2020). If the location is somewhat protected from external forces, *Acropora* can continue thriving.

The goal of this study was to highlight the use of a large area imaging approach using a variety of growth metrics that were then compared to previously utilized *in situ* methodologies. We were able to do this by tracking six *Acropora* thickets of various sizes on Palmyra Atoll through multiple time points from 2012-2019 utilizing large area imagery. With this technology, we measured growth using a variety of metrics including maximum diameter, ellipse area, uniquely fitted polygon area and 2D orthoprojected surface area, and finally branch density in each thicket. The Structure from motion software created a detailed baseline that is necessary to monitor change over time in both reef structure and coral community. This study focuses on extensive methodology regarding the calculation of growth metrics utilizing large area imagery in the hope that it paves the way for future restoration practitioners to follow similar protocol.

Methods

2.1 Study Site

The entirety of this study was conducted utilizing four reef terrace sites on Palmyra Atoll, located within the Northern Line Islands in the Central Pacific (5° 52' N, 162° 06' W). Palmyra Atoll was chosen as the study site due to its high density of branching *Acropora* within reef terrace sites, which are located within the island inlet (Fig. 1). Palmyra is considered to be a geographically

remote location, with little human impact (Sandin et al. 2008); this coupled with limited hydrological effects on *Acropora* made it a prime location for this study.

The reef terrace sites (Fig. 1) are sheltered by the island on their eastern side. Coral colonies at this location don't have to withstand significant wave action as other forereef sites would on Palmyra. The long western and eastern terraces are shallower and more shielded from physical damage overall. Nearly all of the hydrological action within reef terrace sites is internal with very little outside oceanographic influence (Geister 1977; Pandolfi 2022). Although shallower than forereef sites on the southside of Palmyra, none of the reef terrace sites are shallow enough for air exposure at low tide. Branching *Acropora* that have some sort of hydrodynamic force barrier have been shown to have a more widely dispersed branching density per colony volume, so a broad range of data across all six thickets was expected (Huntington and Miller 2013).

2.2 Study Design

Overall growth of *Acropora* colonies were estimated by tracking six individual thickets through time. Colonies were chosen from all four reef terrace sites on Palmyra Atoll based on varying sizes, shapes, and species. The time series for each thicket varied based upon image reconstruction capability (thicket visibility from year to year), with thickets ranging from a four to seven-year time frame.

2.2.1 Field Image Acquisition

Four 200-m² (20 m x 10 m) sites across the reef terrace of Palmyra were surveyed annually from 2012-2019. Each of the four sites is very shallow, centered at an approximate depth of 5 m. All 20 m x 10 m plots include: two geo-referenced steel pins that are denoted by GPS, six boundary

markers for reference located along the four corners and adjacent to the steel pins, and four 0.5 m scale bars to help account for scale within images. At each boundary marker, specific depths were collected to give a z-dimension georeference point. Divers used two Nikon D7000 16.2-megapixel DSLR still cameras that were mounted to custom frames (Sandin et. al 2020) for field imagery collection. Both cameras had a wide-angle 18-mm focal length lens and a 55-mm lens to capture images once per second as divers swam a gridded pattern maintaining a height of approximately 1.0-1.5 m from the bottom (Sandin et. al 2020; Koderer et. al 2020). This process was repeated at each of the four sites in years 2012-2019, yielding approximately 5000 images per camera per site. A more detailed summary of imagery collection specifics has been previously documented (Edwards et al. 2017).

2.3 Image Processing

To build the 3D models, commercially available Structure from Motion (SfM) software Agisoft *Metashape* 1.6.0 (Agisoft LLC., St. Petersburg, Russia) was utilized. *Metashape* has the ability to estimate the location and depth of recurring pixels across images and stitch them together into a 3D point cloud model with help from the various 18-mm images taken in the field. The aforementioned 0.5 m calibration bars were used to scale the model, leaving an accurate depiction of the reef in 3D. The models were then converted into 2D orthorectified (ie. geometrically corrected) images using the custom visualization software *Viscore* (Petrovic et al. 2014). These 2D orthorectified images allow for unbiased estimates of planar area and branch density estimates in this study. 2D planar area metrics have been shown to provide precise estimates of coral colony dynamics and are vital to include when looking at various growth metrics within large area imagery (Kohler and Gill 2006; Lirman et al. 2007).

2.4 Large Area Imaging Metrics

We have chosen to set a baseline for measuring growth using large area imaging by digitally recreating common *in situ* approaches to measure coral growth: maximum diameter, various forms of 2D planar area and branch density (Fig. 2). Each of the six thickets varied in size and shape, from scattered branching to densely packed branching colonies, and were chosen to highlight the ability of *Viscore* to measure complex morphologies. After assigning all thickets a unique color scheme, each thicket was annotated within the 3D model. We were able to monitor thickets from their initial form and document their changing shape and annual size changes during monitoring years.

2.4.1 Linear distance & two-dimensional planar area

Linear distance and two-dimensional area provide a top-down view of a coral colony and can be calculated a number of ways *in situ* or utilizing large area imagery with variants of length and width. Here, we measure maximum diameter and ellipse area, which are popular methodologies *in situ* (Kiel et al. 2012), and two growth metrics that can be completed utilizing solely photogrammetry.

Maximum Diameter

Maximum diameter was selected as a growth metric due to its popularity as a restoration metric for outplants (Kiel et al. 2012; Johnson et al. 2011; Schopmeyer et al. 2017). This method is generally completed with a meter rod, flexible measuring tape and/or calipers *in situ* and measures the longest length of a coral colony (Kiel et al. 2012). The same process can be completed

throughout the duration of restoration projects and as outplants grow into more complex morphologies.

Within *Viscore* orthoprojection mode, the model was placed into a two-dimensional space in which the viewer sees a top-down view of the model. With the thicket clearly in view, the longest extending branch tip at either end of the length of the thicket was zoomed in on and markers were placed on each end. Then, the same process was completed for the width of the thicket, placing markers on either end of the longest extending branch tips. Whichever measurement was larger was used as the maximum diameter. *Viscore* provides a measurement of the space between all four markers while accurately taking into account the depths and scale bars incorporated in the initial image processing of the model.

Ellipse Area

Ellipse areas are another popular method of calculating growth of coral colonies in the field (García-Urueña and Garzón-Machado 2020; Kiel et al. 2012; Linares et al. 2011; Yap et al. 1998). This is done *in situ* by using a meter rod and/or flexible measuring tape and taking measurements of length and width, then determining areas with the ellipse mathematical formula $A = \pi a b$, where ‘a’ and ‘b’ refer to the radii (Garzo 2020; Linares et al. 2011). Ellipse areas can also be estimated by staging the tools above and collecting imagery of the colonies and deriving metrics back in the lab (Kiel et al. 2012).

In *Viscore*, the same two-dimensional top down orthoprojection was utilized along with the initial grid. Once the thicket was fully within the grid, the overall number of squares was tallied and utilized to lay down markers on the top, bottom, left, and right portions of the thicket. The

markers ensured equidistance between all four points. The ellipse formula was then utilized to calculate area based on horizontal and vertical markers.

Polygon Planar Area

A method was developed to take the two-dimensional area of thickets which encompassed as much of the colony and excluded as much empty space as possible. To accomplish this, a base shape was created in the orthoprojection mode with the grid to envelop the entirety of each thicket. For most *Acropora*, this shape was a rectangle; 2015 and 2016 time points for Thicket 4 were significantly smaller than other thickets, so a triangle was initially used instead of a rectangle for area calculations. Markers were placed at each corner, then lengths and widths were measured to ensure uniformity. Each corner of the rectangle was aligned to be a 90-degree angle, made possible by utilization of the grid. Each area within the rectangle not occupied by branching coral was altered by dropping markers in the shapes of right triangles. The number and size of right triangles varied annually and was colony specific, with a minimum of two and a maximum of five right triangles per time point utilized. The total area was calculated by subtracting all triangles of empty space from the initial rectangle.

Total Planar Area

Within *Viscore*, an image of the annotated thickets was captured both with and without the scaled grid and transferred to Photoshop. Once there, the scale of the grid was converted to pixels using the measurement tool. The number of pixels in each annotated colony was calculated and, using the scale from the grid, we converted these pixel counts to area measurements. The polygon planar area method and total planar area methods were compared, and it was determined that the

total planar area calculations would be the final values utilized for this project, although results from all area growth metrics will be shown.

2.4.2 Branch Density (Number of branches per unit area)

Common forms of branch density measured *in situ* either follow specific branches and note new termini in individual time points (Soong and Chen 2003; Yap and Gomez 1984) or count the total number of branches within a thicket (Johnson et al. 2011; O'Neil 2015). Branch density can be useful for a variety of reasons, whether measuring number of new branch tips (termini) or number of branches total per standardized area.

With increased complexity in all six thickets of branching *Acropora*, it was not possible to accurately and precisely count the number of new termini of randomly chosen branches in each time point, due to difficulty identifying the same specific branches on an annual basis, and not being able to see directly into thickets within 3D models to follow some branches that may have been hidden within.

For thickets small enough to count every number of branches on, a screenshot of the thicket was taken using the photo overlay in *Viscore* and transferred into a Microsoft Word document. Then, using the Touch to Draw tool, a marker was used to count each branch within the thicket. The total number of branches was then divided by the total Photoshop pixel area of the colony and set equal to 'x' number of branches per m² the standardized number of branches per m² was calculated by solving for 'x'.

Due to difficulty counting every branch in larger thickets 1, 5, and 6, a randomized subset was utilized from initial density calculations. Grid cells needed to contain at least 75% area of thicket to be included within a randomized subset, keeping underestimation of branches to a

minimum. Thickets used a range of 67 – 173 total grid squares. After grid placement, four squares were randomly chosen with a random number generator without replacement and number of branches were counted within each square. An average number of branches were taken from the subset and divided by the total area of each square from the 20 cm x 20 cm grid ($400 \text{ cm}^2/0.04 \text{ m}^2$), and set equal to 'x' number of branches.

Results

A total of 32 yearly transitions were included in this study across six branching *Acropora* thickets at four sites, varying in intervals between 2012-2019. Total planar area was utilized as the final area measurement to account for two-dimensional annual change within thickets. This was due it being the highest standard, showing the most comprehensive and detailed results, whereas maximum diameter and ellipse areas represented values that were estimates. Thickets generally saw a stabilized but linear growth in area over individual monitoring periods, with some variation on an annual basis.

Maximum Diameter

RT 4 – Thicket 1

Thicket 1 had a maximum diameter of 2.53 m in 2016 during the first year of monitoring. By 2017, the diameter had increased to 2.66 m. In 2018 the thicket measured 2.85 m and saw a small decrease in 2019 to 2.82 m (Table 1). Overall, this colony remained stable and continued to extend its branches further outward, increasing in size until 2018 when it stabilized. From 2016-2019, this thicket increased by 0.30 m in total (Fig. 9).

RT 13 – Thicket 2

Thicket 2 fluctuated greatly during monitoring in 2016-2019, beginning in 2016 at 2.22 m and decreasing to 1.81 m the following year. In 2018, Thicket 2 continued decreasing in size to 1.40 m, but by the final year in 2019 measured 1.67 m (Table 1). This colony demonstrated variability in maximum diameter, growing across some transitions and shrinking in others, resulting in a net loss of 0.56 m over the four-year period (Fig. 9).

RT 13 – Thicket 3

Thicket 3 showed a consistent annual increase in maximum diameter across the time series. In 2014, maximum diameter was 1.65 m and increased to 1.78 m the following year in 2015. In 2016 and 2017 thicket 3 had a maximum diameter of 1.82 m and 1.89 m respectively. Thicket 3 continued to extend its longest branches outward in 2018 to 2.25 m and measured 2.59 m 2019, for an overall total increase over six years of 0.94 m (Table 1; Fig. 9).

RT 13 – Thicket 4

Thicket 4 showed consistent increases in maximum diameter annually from 2015-2019, beginning with 0.54 m in 2015. In 2016, the colony increased to 0.72 m, followed by an increase to 0.80 m the following year. In 2018 the thicket had a maximum diameter of 1.04 m and measured 1.20 m in 2019, for a total increase of 0.66 m over the five-year period (Table 1; Fig. 9).

RT 1 – Thicket 5

Thicket 5 had inconsistent fluctuations in maximum diameter annually from 2013-2019. Initial measurements in 2013 yielded 3.21 m and decreased in 2014 to 2.36 m. In 2016, maximum

diameter of thicket 5 increased to 3.21 m before decreasing in 2017 to 3.00 m. Thicket 5 decreased again in both 2018 and 2019, reaching 3.00 m and 2.75 m respectively (Table 1). In total, maximum diameter results had a total loss of 0.456 m (Fig. 9).

RT 10 – Thicket 6

Generally, maximum diameter measurements for this thicket remained unchanging from 2012-2019. In 2012, maximum diameter was 3.40 m, decreasing slightly to 3.06 m in 2013 and again to 2.88 m in 2014. Thicket 6 reached 3.23 m in 2015 and had a small decrease after a gap year of monitoring in 2017. By 2018, the colony had grown to 3.31 m before reaching 3.42 m in 2019 (Table 1). Overall, thicket 6 saw only an increase in maximum diameter of 0.16 m during the seven-year period (Fig. 9).

Ellipse Area

RT 4 – Thicket 1

Ellipse area in 2016 for thicket 1 measured 4.07 m² in size. This thicket then increased to an area of 4.20 m² and 4.48 m² in 2017 and 2018 respectively. In the final year of monitoring the ellipse area was 5.31 m² (Table 1), presenting an overall growth of 1.25 m² over the four years (Fig. 10; Fig. 14).

RT 13 – Thicket 2

In 2016, ellipse area was 2.47 m², decreasing to 1.86 m² the following year. Thicket 2 decreased to 1.40 m² in 2018 and was followed by another decrease to 1.33 m² in 2019 (Table 1), making the total loss in ellipse area to 1.14 m² during from 2016-2019 (Fig. 10; Fig. 15).

RT 13 – Thicket 3

Ellipse area showed a constant increase throughout monitoring. At the start of the time series thicket 3 had an area of 1.81 m² in 2014 and increased to 2.28 m² in 2015. By 2016 it had increased slightly to 2.38 m², followed by growth to 2.72 m² in 2017; this “L” shaped thicket measured 3.17 m² in 2018 and 3.26 m² in 2019 (Table 1; Fig. 10; Fig. 16).

RT 13 – Thicket 4

In 2015, this colony measured 0.21 m² and increased to 0.33 m² in 2016. Thicket 4 grew in 2017 to 0.39 m², followed by a larger increase in 2018 to 0.66 m², and had an ellipse area of 0.95 m² in 2019. Overall, this thicket grew 0.74 m² during monitoring (Table 1; Fig. 10; Fig. 17).

RT 1 – Thicket 5

Ellipse area values for this thicket varied annually. In 2013 thicket 5 was 7.55 m² and decreased the following year to 4.09 m². Thicket 5 grew in 2016, 2017, and 2018 to 6.11 m², 6.22, and 6.77 m² respectively. The final year of measurements showed a decrease in size to 5.74 m² (Table 1). Net loss of area totaled 1.81 m² over the six-year period (Fig. 10; Fig. 18).

RT 10 – Thicket 6

Ellipse areas for thicket 6 began in 2012 at 8.69 m². The thicket decreased to 7.23m² in 2013 and to 6.36 m² in 2014. In 2015, this colony had a larger increase to 7.82 m, and in 2017 to 7.78 m². Thicket 6 grew in size to 8.33 m² in 2018 and reached 9.18 m² in 2019 (Table 1), for a total ellipse area growth of 0.49 m² (Fig. 10; Fig. 19).

Polygon Planar Area

RT 4 – Thicket 1

In 2016 the area was 3.23 m², almost a 1 m² difference from the ellipse results. The thicket continued to increase in size in 2017-2019, exhibiting areas of 3.61, 4.2 and 4.44 m² respectively (Table 1). This method indicated a total growth of 1.12 m² during monitoring (Fig. 11; Fig. 14).

RT 13 – Thicket 2

Polygon planar area results were much lower than those of ellipse area. Thicket 2 measured 1.28 m² in 2016 and decreased in area similar to the prior metric to 0.95 m² in 2017. Thicket 2 increased to 1.01 m² in 2018 and 1.12 m² in 2019 (Table 1). This method exhibited a loss of 0.16 m² overall during monitoring (Fig. 11; Fig. 15).

RT 13 – Thicket 3

Polygon Planar Area results for thicket 3 exhibited lower values than those of ellipse. Thicket 3 had an area of 0.52 m² in 2014, increasing to 1.22 m² in 2015 and 1.47 m². In 2017, the thicket increased in area to 1.58 m² and decreased to 1.54 m² in 2018 and measured 0.81 m² in 2019. Overall, this thicket had a net gain of 0.30 m² with this method (Table 1; Fig. 11; Fig. 16).

RT 13 – Thicket 4

This metric had results that were lower than those of ellipse. Initial results from 2015 measured thicket 4 area at 0.19 m², increasing to 0.29 m² the next year. Thicket 4 continued increasing in years 2017 and 2018 with values of 0.37 m² and 0.74 m² respectively. The colony

had a polygon area of 0.88 m² in 2019, for a total growth of 0.69 m² overall. This area also showed an increase in every year of monitoring (Table 1; Fig. 6; Fig. 11; Fig. 17).

RT 1 – Thicket 5

Generally, polygon areas for thicket 5 displayed values less than ellipse areas. In 2013, thicket 5 measured 1.44 m² and increased to 1.73 m² in 2014. This thicket exhibited substantial growth to 3.27 m² in 2016 and in 2017 to 4.69 m². The last two years of monitoring yielded planar areas of 5.08 m² and 5.09 m² (Table 1). In total, thicket 5 grew 3.65 m² during this study period (Fig. 11; Fig. 18).

RT 10 – Thicket 6

Polygon planar areas fell below values of ellipse area, but increased steadily in all years. In 2012, thicket 6 exhibited an area of 4.18 m², which grew to 4.54 m² the next year. Thicket 6 increased to 4.87 m² in 2014 and again the following year to 5.36 m². This colony grew almost two meters squared in size in 2017 to 6.79 m² and measured 7.08 m² in 2018. By the final year of this study, thicket 6 had reached 7.36 m² (Table 1). Total growth for this colony was 3.18 m² over seven years (Fig. 11; Fig. 19), and was the largest thicket overall in this study.

Total Planar Area

RT 4 – Thicket 1

This metric presented results very similar to those of the polygon planar area. Thicket 1 had an area of 3.56 m² initially in 2016 and grew in size to 3.62 m² by the following year. In 2018

and 2019, thicket 1 had total planar areas of 4.20 m² and 4.31 m² respectively (Table 1), resulting in growth of 0.752 m², for a total of 21.1% overall (Fig. 3; Fig. 12; Fig. 14).

RT 13 – Thicket 2

Total planar area measurements for thicket 2 were lower than those of polygon planar area, but showed total increase in area overall where the aforementioned metrics represented net loss over the monitoring period. Thicket 2 had a total planar area of 0.96 m² in 2016, which decreased to 0.85 m² in 2017. This was followed by another decrease to 0.74 m² in 2018 and a sizeable increase in 2019 to 1.09 m² (Table 1). Total planar area growth for thicket 2 was 0.124 m² and 12.9% (Fig. 4; Fig. 12; Fig. 15).

RT 13 – Thicket 3

Total planar areas for thicket 3 also showed fluctuation from year to year, similar to results of polygon planar area. Initial area was 1.15 m² in 2014, increasing to 1.18 m² by the following year in 2015. Area values decreased in 2016 to 1.15 m² and in 2017 to 1.35 m². Thicket 3 showed an increase during the final two years of monitoring in 2018 and 2019 at 1.38 m² and 1.87 m². Total growth during monitoring was 0.72 m² and 62.5% (Table 1; Fig. 12; Fig. 16), which differed from net growth calculated within polygon planar area.

RT 13 – Thicket 4

Total planar areas exhibited very similar results to those of polygon planar area with consistent increases in all years. In 2015, total planar area was 0.17 m² and increased to 0.24 m² in 2016. Area measurements increased to 0.34 m² the next year and again in 2018 to 0.73 m². Thicket

4 had an area of 0.92 m² in 2019, for a total increase of 0.72 m² and 450.0% (Table 1: Fig. 12; Fig. 17).

RT 1 – Thicket 5

Total planar areas showed slight differences from polygon planar area results. Thicket 5 began in 2013 at 2.56 m² and had grown to 2.91 m² in 2014. By 2016, this colony was 3.508 m² and increased in size every year following: 2017 had a planar area of 4.09 m², 2018 results were 4.54 m², and 2019 had an area of 5.21 (Table 1), for a total gain of 2.65 m² and 103.6% (Fig. 7; Fig. 12; Fig. 18).

RT 10 – Thicket 6

Total planar areas for thicket 6 revealed very similar results to those of polygon planar area. Thicket 6 initially measured 3.98 m² in 2012 and increased to 4.74 m² the next year. In 2014 values were up slightly to 4.77 m² and grew to 5.50 m² in the year following. After a gap year in monitoring, thicket 6 was 7.22 m² in 2017, over a 1.5x increase from 2015. 2018 and 2019 had planar area totals of 7.10 m² and 7.51 m² respectively (Table 1). Within this area metric, the colony grew in size a total of 3.53 m² and 88.5% (Fig. 8; Fig. 12; Fig. 19).

Branch Density

RT 4 – Thicket 1

Branch density for thicket 1 remained stable over the course of monitoring with little fluctuation. Due to larger thicket size, the subset randomization of squares was utilized to estimate average branch density. In 2016, the thicket averaged 612 branches/m² and decreased to 537

branches/m² in 2017. In 2018, average count was 581 branches/m² and decreased slightly in 2019 to 556 branches/m² for a total approximate loss of 56 branches/m² (Table 1; Fig. 13).

RT 13 – Thicket 2

Since colony size was not exceptionally large compared to other thickets in this study, the total number of branches were counted annually. Branch density in thicket 2 fluctuated across the time series. In 2016, thicket 2 had 187 branches/m², increasing to 194 branches/m² the following year in 2017 and had a 1.5x increase to 326 branches/m² in 2018, but decreased to 193 branches/m² in 2019 (Table 1; Fig. 13).

RT 13 – Thicket 3

Thicket 3 maintained stable branch density throughout the six-year period before dropping in 2019. Total number of branches were counted due to smaller colony size. In 2014 the thicket had 281 branches/m² and decreased in 2015 and 2016 with 272 and 260 branches/m² respectively. Densities decreased once again in 2017 to 216 branches/m² and increased slightly in 2018 to 225 branches/m², before final branch counts of 149 branches/m² in 2019 (Table 1; Fig. 5; Fig. 13).

RT 13 – Thicket 4

Branch density values for thicket 4 were variable annually. Due to smaller colony size, the entirety of branches was counted and standardized. In 2015, 619 branches/m² were calculated, followed by a decrease in 2016 to 485 branches/m². Thicket 4 decreased to 388 branches/m² in 2017 and increased in 2018 to 527 branches/m². During the final year of monitoring branch density was 411 branches/m². Thicket 4 had a total loss of 208 branches/m² (Table 1; Fig. 13).

RT 1 – Thicket 5

Thicket 5 maintained relative stability with regard to branch density throughout monitoring. Due to larger thicket size, a randomized subset was used to estimate density. In 2013, thicket 5 had an average of 406 branches/m² and increased to 493 branches/m² in 2014. The following year decreased to 343 branches/m² and increased slightly to 368 branches/m² in 2017. This colony expanded in 2018 to 375 branches/m², and averaged 350 branches/m² in 2019 (Table 1), for a total loss of approximately 56 branches/m² (Fig. 13).

RT 10 – Thicket 6

Thicket 6 remained comparable in branch density during monitoring. Larger thicket size called for a subset randomization to calculate density values. In 2012, thicket 6 had 375 branches/m², which decreased to 368 branches/m² in 2013. In 2015, this colony averaged 468 branches/m² and decreased for the following two time points to 356 branches/m² and 350 branches/m² in 2015 and 2017, respectively. Values increased in 2018 to 443 branches/m² and had an average of 325 branches/m² in 2019 (Table 1). Branch density for thicket 6 had a net loss of approximately 50 branches/m² (Fig. 13).

Summary of Results

Overall, results for maximum diameters showed both over and underestimations across colonies. In larger thickets, these values were underestimated, and in smaller and more sparsely branched thickets, diameters were overestimated. Ellipse values were generally overestimated for all thickets in this study, and these values covaried to those of maximum diameter in almost all

cases. Both polygon planar and total planar areas for thickets were comparable to one another, with percent variations in the same general vicinity ranging from -36.7% 9.3%, but did include some thicket specific outliers. Thicket 3 had 56.6% and 55.1% polygon and total planar area variations in two time points, which can be attributed to improper alignment within these models, allowing polygon planar area measurements to be underestimated. In thicket 5, variation in two time points showed 40.6% and 43.9%, with polygon planar area being underestimated in comparison to total planar area. This difference in area also had to do with an improper alignment methodology between models, which put edges of the thicket at different water depths and made the thicket uneven. Total planar areas demonstrated the most accuracy and colonies presented growth as a whole for all thickets within this metric. Branch density measurements were also stable for most thickets, with limited outliers and differences within thickets annually, although all branching *Acropora* except one colony showed decrease overall.

Discussion

In this study, we utilized large area imagery to quantify growth metrics for six *Acropora* thickets of varying sizes across Palmyra Atoll at multiple time points from 2012-2019. An acute attention to detail was made possible by completing large portions of analysis within *Viscore* and not being completed entirely *in situ*. Each metric was chosen due to comparability with current field restoration methodologies used for outplants and measuring growth with complex branching *Acropora*. Using total planar areas as the standardized area, we observed systematic growth of all colonies, with increases in planar area ranging from 12.90% to 450% over the span of four to eight years. Maximum diameter values for this study were variable, while ellipse areas were generally overestimated. We found that some *in situ* metrics were comparable as representations of various

2D growth assessments and are a permanent and robust tool for successful long-term monitoring, even for colonies with complex branching morphologies.

Maximum Diameter

Maximum diameter is a fairly straightforward metric that can be taken *in situ* with the tools described above. However, utilizing standalone photogrammetry or alongside the tools we utilized in this study can be a more reliable and comprehensive method of tracking growth, since many physical, biological, and human interferences can occur in time between *in situ* visits and having a visual record to look back on would be a vital tool. If practitioners find it necessary to complete some of the growth metrics *in situ*, an approach can be taken with meter rods or flexible rulers for reference and then the creation of 3D models back in the lab can allow for maximum diameters to be measured, or practitioners can use imagery alone to do so in cases that do not require any *in situ* methodology. This produces a permanent record of restoration processes utilized outside of the water, and in the case the project is deemed unsuccessful, will be utilized to pinpoint flaws in the procedure or how to better structure efforts for the future.

Utilizing maximum diameter to estimate areas for larger and more complex thickets did not provide a realistic depiction of thicket growth on an annual basis, or any particular procedure that could be exactly followed from year to year when compared with values of total planar area. Precision capability was also limited by the maximum extended branches of thickets being unevenly spaced out annually. This form of area measurement exhibited scattered values with no established baseline for calculation other than to follow branches that were most extensive. Since branches from year to year moved and changed shape with thickets, this methodology could not be relied upon for accurate or precise measurements once thickets reached a more mature and

complex morphology. When measuring outplant sizes during restoration projects, utilizing maximum diameter to calculate growth is feasible until outplants have reached a larger size, albeit years down the line, and most likely long after the restoration efforts have ceased.

Here, maximum diameters for thicket 1, a larger thicket in the study, fluctuated in growth and loss each year, while ellipse, polygon, and total planar areas showed increase in area every year. Thicket 2, a smaller and more sparsely branching colony, showed a decrease in diameter in three out of four years, where other metrics showed a fluctuation in growth and loss in all years. Thicket 5, another larger colony, also showed a decrease in size in all years except one, whereas other metrics showed growth in all years of monitoring. Thicket 6, which was the largest colony, showed fluctuations in growth and loss of diameter across time points, where polygon and total planar area only showed growth. This was most likely due to intricate layouts of thickets: larger and more dense colonies did not necessarily have branches extending far outwards, while smaller and more sparse colonies had scattered branches extending further out in measurements.

Ellipse Area

Ellipse area is not always conclusive due to all thickets not fitting an ellipse as their best fit shape, making areas for all thickets and time points generally overestimated based on overall colony shape. Ellipse values for thickets 1 and 4 were comparable to those of total planar area, which could be attributed to the shapes of thickets as being closer to those of an ellipse. The limitation of using a single result in some area estimates being accurate will vary on a thicket-by-thicket basis depending on the complexity of the corals shape.

In this study, ellipse area measurements covaried from those of maximum diameter, which was expected. This method allowed for additional space to be included that was not directly part

of thickets, so measurements were often overestimated. This highlighted the central theme that one shape does not fit all thickets and each study must take into account individual colony measurements and not rely on blanket calculations. Final area measurements under this metric were not precise, but scattered, with no set patterns of annual growth.

Polygon Planar Area

To ensure a more accurate and precise form of area measurement, a unique workflow was created. The polygon planar area method created a robust metric that solely utilized *Viscore* and does not have a similar process that it completed *in situ*, unlike metrics of maximum diameter and ellipse that are comparable by collection *in situ* or through a combination of *in situ* and photogrammetry. This allowed for a unique perspective that counted every thicket and time point individually by fitting right triangles independently to each model, giving a clear indication of fluctuations in growth. This methodology utilized a specific technique to ensure that empty space for complex shapes was minimized within area counts and found a distinctive way to take a more accurate approach to planar area than both maximum diameter and ellipse area measurements. More often than not, an ellipse shape is utilized to describe branching coral thickets, which allows for little variation and leaves much room for inaccurate and over/underestimations of calculations. Results in this study generally showed polygon planar area measurements were much lower than those of maximum diameter and ellipse areas, except in thickets 1 and 6, in which areas fell between values of maximum diameter and ellipse areas. This may demonstrate that these thickets more closely resembled the shape of an ellipse, whereas colonies that had lower values (thickets 2, 3, 4 and 5) had shapes that were not (Fig. 3-8).

Total Planar Area

A major advantage of the total planar area measurement is that it only took into account the portions of thicket that had been annotated within *Viscore*. This allowed for the greatest amount of precision in only including area that should be counted, as opposed to being a fitted area estimate like the previous metrics. Similarities in polygon planar area, total planar and ellipse area occurred when colonies were largely elliptical in area, resulting in comparability within these metrics.

The utilization of total planar area featured growth in every thicket, ranging from 12.90% to 450% over the span of four to seven years. As a whole, the polygon planar area method generally performed similarly to total planar area, with some outliers, while maximum diameter and ellipse area generally showed higher values, with only Thickets 1 and 6 showing values in between those of maximum diameter and ellipse.

Branch Density

Branch densities in this study that calculate the total number of branches, as opposed to solely counting new termini, does take into account growth on an annual scale of all thickets. This metric also provides evidence that although thickets may change shape and look physically different, branch density does not necessarily significantly change annually, but is thicket dependent. Branch density can be beneficial to painting a more complete picture of reef level health overall, and can help assess productivity within colonies, and present potential consistency and documentation of patterns unique to thickets of varying complexity. Density results showed fluctuation due to a potential variety of reasons. In some cases, thickets that demonstrated area growth on an annual basis but lost branch abundance might have added branches to their intricate morphologies that are not seen with top down 2D areas in *Viscore*. Additionally, larger thickets

(1, 5, and 6) utilizing the subset estimation could have been underestimated by randomly selected grid squares on an annual basis, leading to inconsistencies within time points.

Other Growth Metrics

Another valuable growth metric often used *in situ* is Total Linear Extension (TLE), or the summed length of each individual branch in an outplant or within a colony (O’Neil 2015; Schopmeyer et al. 2017; Yap and Gomez 1984). This metric is fairly simple to measure when outplants are still of a fairly small size, before they have intertwined together to become a more complex thicket later in life. In this study, several tactics were employed within large area imagery to complete subsampling and obtain these measurements. Due to intricate morphologies, it proved difficult to track the same branches on an annual basis and measure lengths of main stalks. The capability to overlay the 18 mm and 55 mm high resolution images onto the model made the process of locating certain branches more attainable, but proved unsuccessful for every subset to be viewed in its entirety in order to set down virtual markers and combine measurements for TLE. Early on in restoration projects, this metric might prove to be obtainable *in situ* and by utilization of large area imagery during span of projects and for some years afterward, but outplants or thickets might be too difficult to measure after reaching a certain size.

***In situ* vs. *in silico* fieldwork**

The benefit of tracing such complex thickets, though time consuming, allowed for more flexibility in descriptions, coral morphology overall and the capability to see changes within models by toggling through multiple time points side by side. This comprehensive view of the reef also provided a unique perspective on other biological surroundings, including key changes to

colonies and the surrounding reef, which would not have been possible conducting research solely *in situ*, since a permanent record would be unavailable to reflect upon if significant changes occurred between visits to restoration locations. Thicket 4, although the smallest colony in this study, had one of the most interesting growth stories. By utilizing large area imagery and temporally replicated data, we were able to see a neighboring sparsely branched thicket migrate closer to main thicket and eventually join together to all become one colony, doubling its area as a result between 2017 and 2018 time points (Fig. 6). Similarly, thicket 6 had a separate branching cluster underneath it when monitoring began in 2012 that was not yet intertwined with the majority of the thicket, which eventually grew upwards to combine with the initial colony from the 2015-2017 time points (Fig. 8).

Conclusion/Recommendations

Assessing complex branching morphologies utilizing large area imagery allows for attention to detail that is not always possible with *in situ* methods and can maximize efficiency, which is of critical importance in covering more area in less time for monitoring outplant growth up until more complex thicket form. Metrics can be more time consuming to complete at larger thicket sizes, but still allow for accuracy and precision, with no time restrictions once photographs are collected, no affliction of having to complete extensive measurements while *in situ*, and other logistical restraints are limited. A current necessity in restoration is formalized documentation for assessing specific growth metrics and how they are obtained. There is an absence of overall baseline standardization for how restoration practitioners calculate and choose metrics, and presently no straightforward set standard for factoring in growth within studies (Boström-Einarsson et al. 2020). The availability of *in situ* metrics as well as those possible with use of large

area imagery is broad, but current literature does not provide a comprehensive guide for how corals should be measured to provide the best information for restoration goals. A standardized variety of 3D photogrammetry and large area imagery growth metrics, along with long-term monitoring, can ensure that future restoration practices shift and keep priorities on design elements that encompass the unique qualities of each colony and its' story. This process also highlights overall reef health, painting a more complete picture of resiliency and whether certain methodologies are working, or finds shortcomings in contemporary methods and uses that information to create a new restoration path for future endeavors.



Figure 1 Map of the four reef terrace sampling locations on Palmyra Atoll, chosen to maximize areas with abundant branching coral and minimal physical hydrological effects and human impact. As seen here, these reef terrace sites are protected on their eastern side by the Atoll, subject only to physical oceanographic effects from the western side.

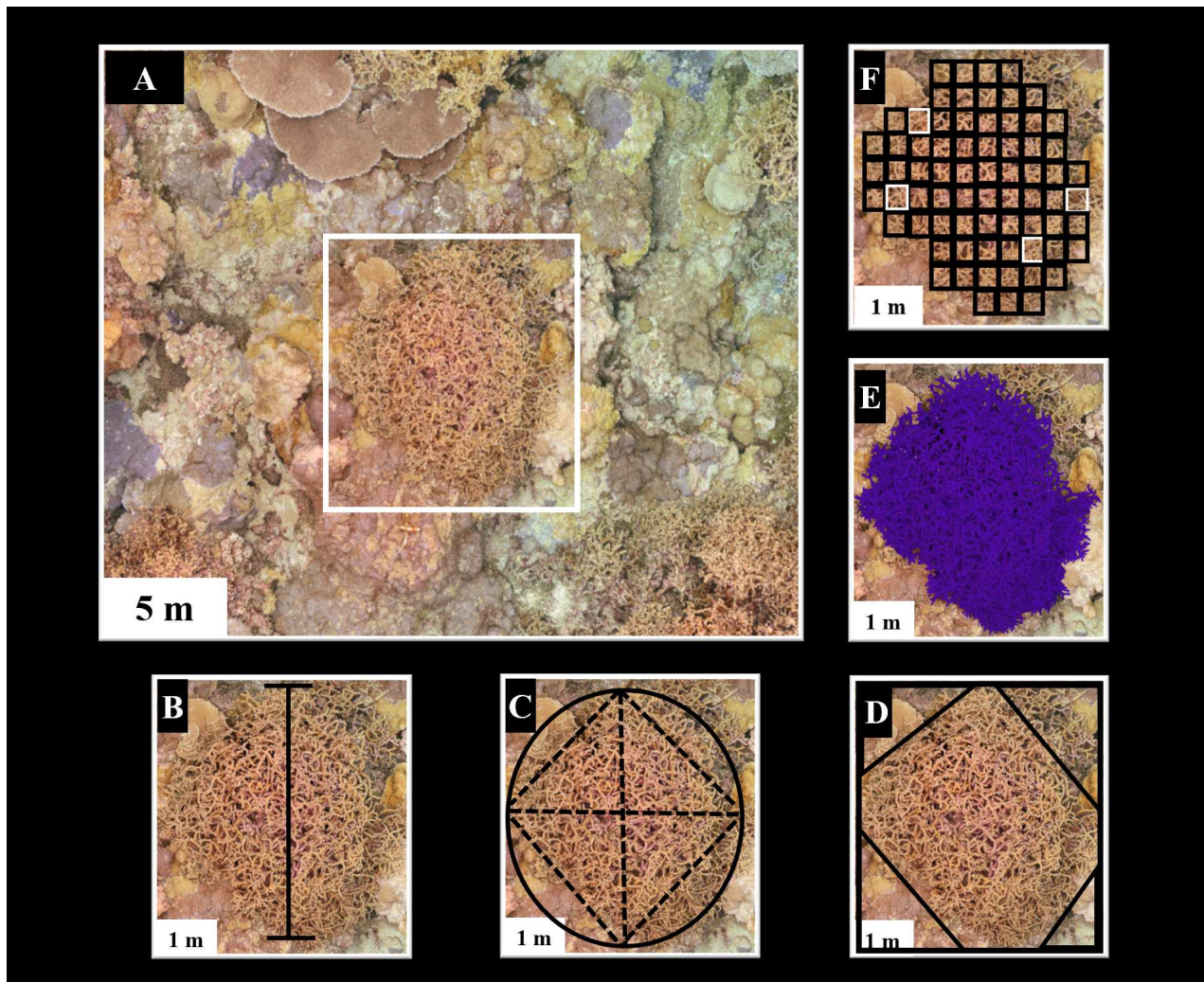


Figure 2 (A) subsection of imagery from RT10 2012 branching *Acropora* thicket #6 used for various growth metrics (B) maximum diameter (C) ellipse area (D) polygon planar area (E) total planar area and (F) branch density (number of branches per unit area)

Table 1 Summary of sampling statistics from RT sites for *Acropora* Thickets 1-6

Site	Year	Thicket #	Maximum Diameter (m)	Ellipse Area (m ²)	Polygon Planar Area (m ²)	Total Planar Area (m ²)	Branch Density (#/m ²)
RT 4	2019	1	2.82	5.31	4.35	4.31	556
RT 4	2018	1	2.85	4.48	4.20	4.20	581
RT 4	2017	1	2.66	4.20	3.61	3.62	537
RT 4	2016	1	2.53	4.07	3.23	3.56	612
RT 13	2019	2	1.67	1.33	1.12	1.09	193
RT 13	2018	2	1.4	1.4	1.01	0.74	326
RT 13	2017	2	1.81	1.86	0.95	0.85	194
RT 13	2016	2	2.22	2.47	1.28	0.96	187
RT 13	2019	3	2.59	3.26	0.81	1.87	149
RT 13	2018	3	2.25	3.17	1.54	1.38	225
RT 13	2017	3	1.89	2.72	1.58	1.35	216
RT 13	2016	3	1.82	2.38	1.47	1.15	260
RT 13	2015	3	1.78	2.28	1.22	1.18	272
RT 13	2014	3	1.65	1.81	0.52	1.15	281
RT 13	2019	4	1.20	0.95	0.88	0.92	411
RT 13	2018	4	1.04	0.66	0.74	0.73	527
RT 13	2017	4	0.80	0.39	0.37	0.34	388
RT 13	2016	4	0.72	0.33	0.29	0.24	485
RT 13	2015	4	0.54	0.21	0.19	0.17	619
RT 1	2019	5	2.75	5.74	5.09	5.21	350
RT 1	2018	5	2.99	6.77	5.08	4.54	375
RT 1	2017	5	3.00	6.22	4.69	4.09	368
RT 1	2016	5	3.21	6.11	3.27	3.51	343
RT 1	2014	5	2.36	4.09	1.73	2.91	493
RT 1	2013	5	3.21	7.55	1.44	2.56	406
RT 10	2019	6	3.42	9.18	7.36	7.51	325
RT 10	2018	6	3.31	8.33	7.08	7.10	443
RT 10	2017	6	3.21	7.78	6.79	7.22	350
RT 10	2015	6	3.23	7.82	5.36	5.50	356
RT 10	2014	6	2.88	6.36	4.87	4.77	468
RT 10	2013	6	3.06	7.23	4.54	4.74	368
RT 10	2012	6	3.40	8.69	4.18	3.98	375

Acropora organized by thicket number and associated annotated color scheme in *Viscore*.

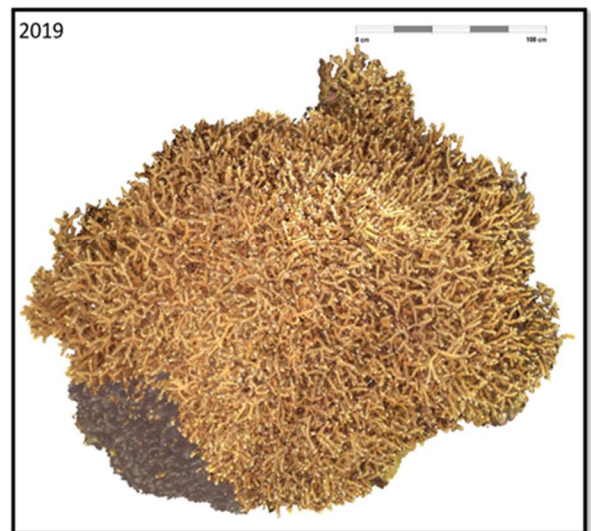
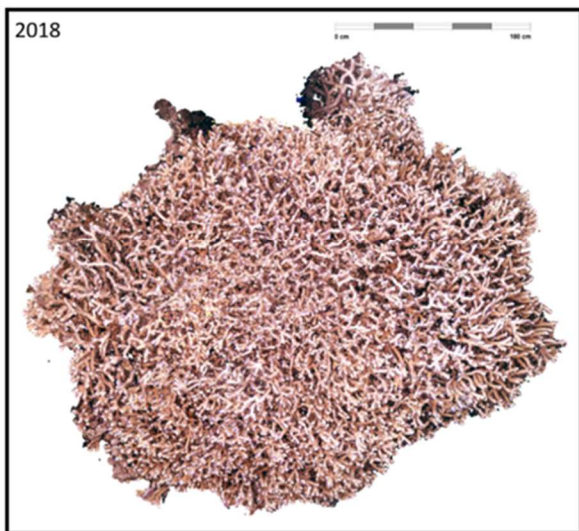
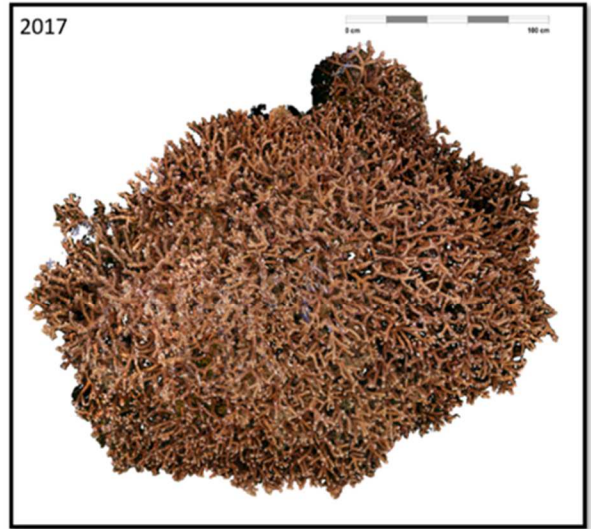
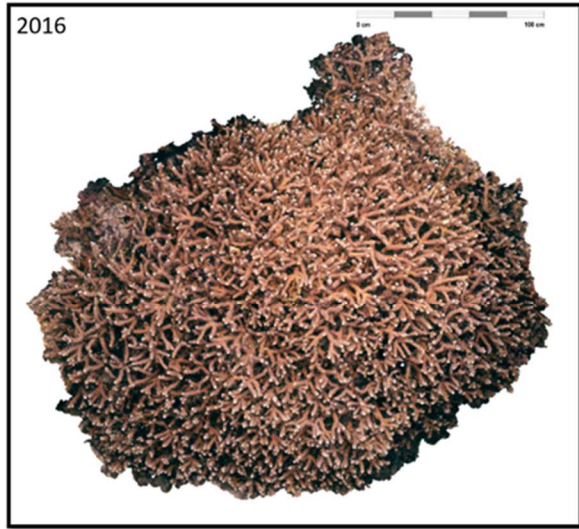


Figure 3 Thicket 1 growth progression from monitoring 2016-2019, taken from annotated images in *Viscore*. Annotations demonstrated a consistent shape within the colony which most closely resembled that of an ellipse.

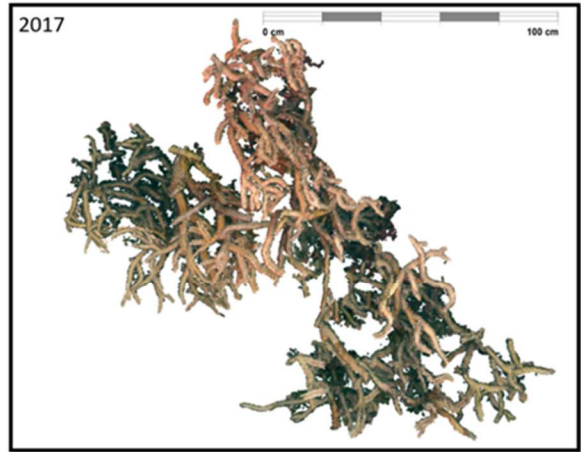
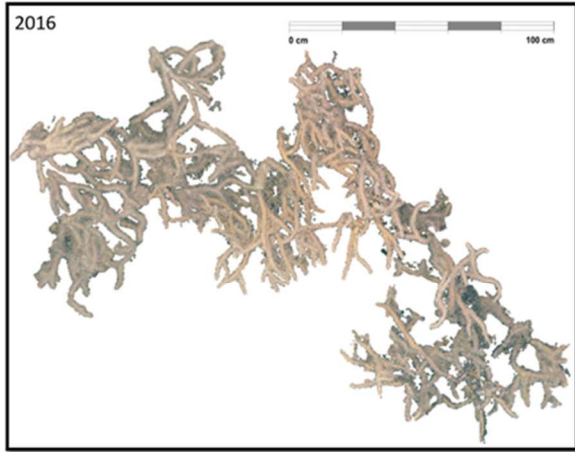


Figure 4 Thicket 2 growth progression from monitoring 2016-2019, taken from annotated images in *Viscore*. This colony had the most apparent change in appearance on an annual basis, not maintaining one specific shape and had a very sparse branching pattern during annual monitoring.

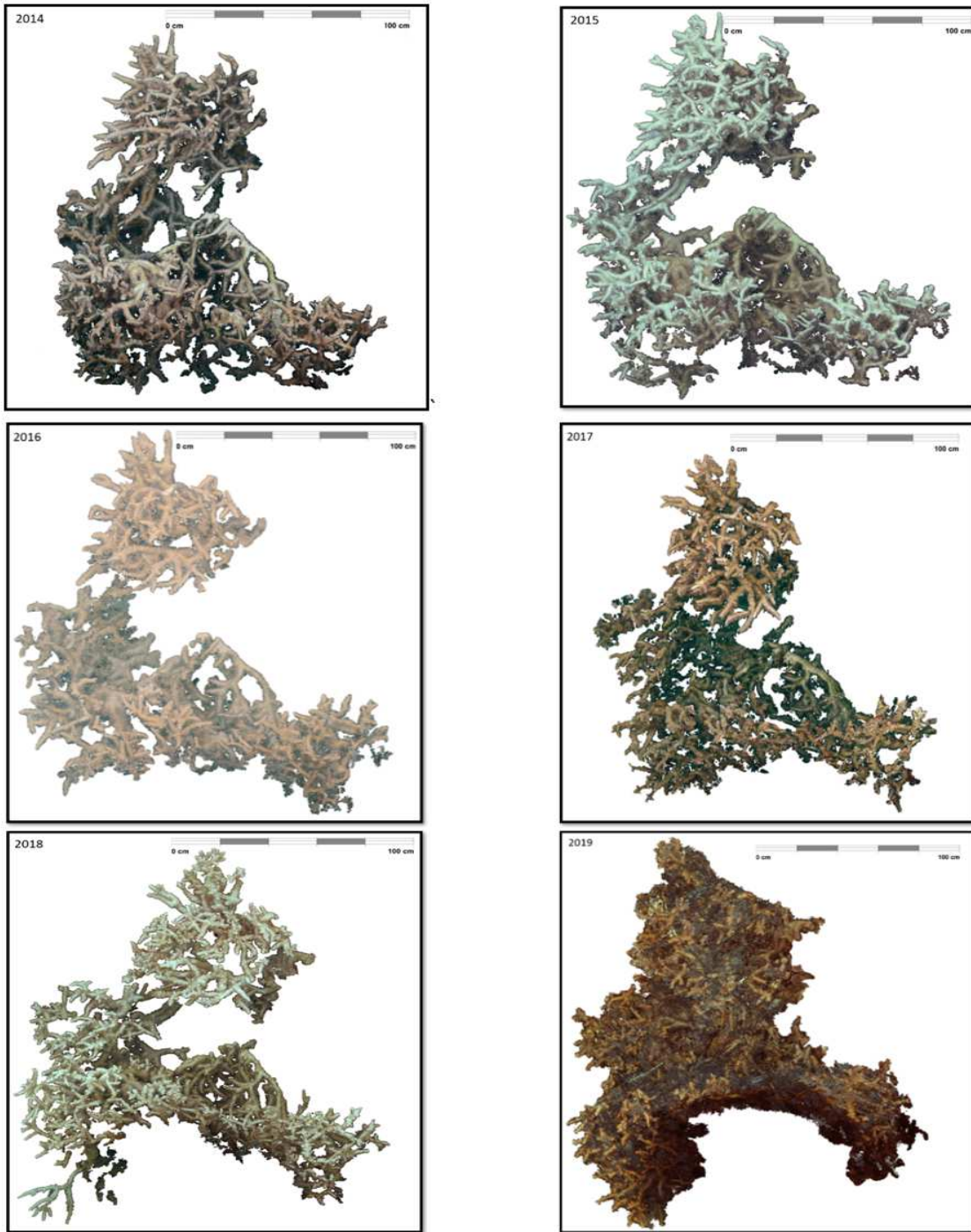


Figure 5 Thicket 3 growth progression from monitoring 2014-2019, taken from annotated images in *Viscore*. Overall thicket shape remained stable although colony began to fill in by 2019.

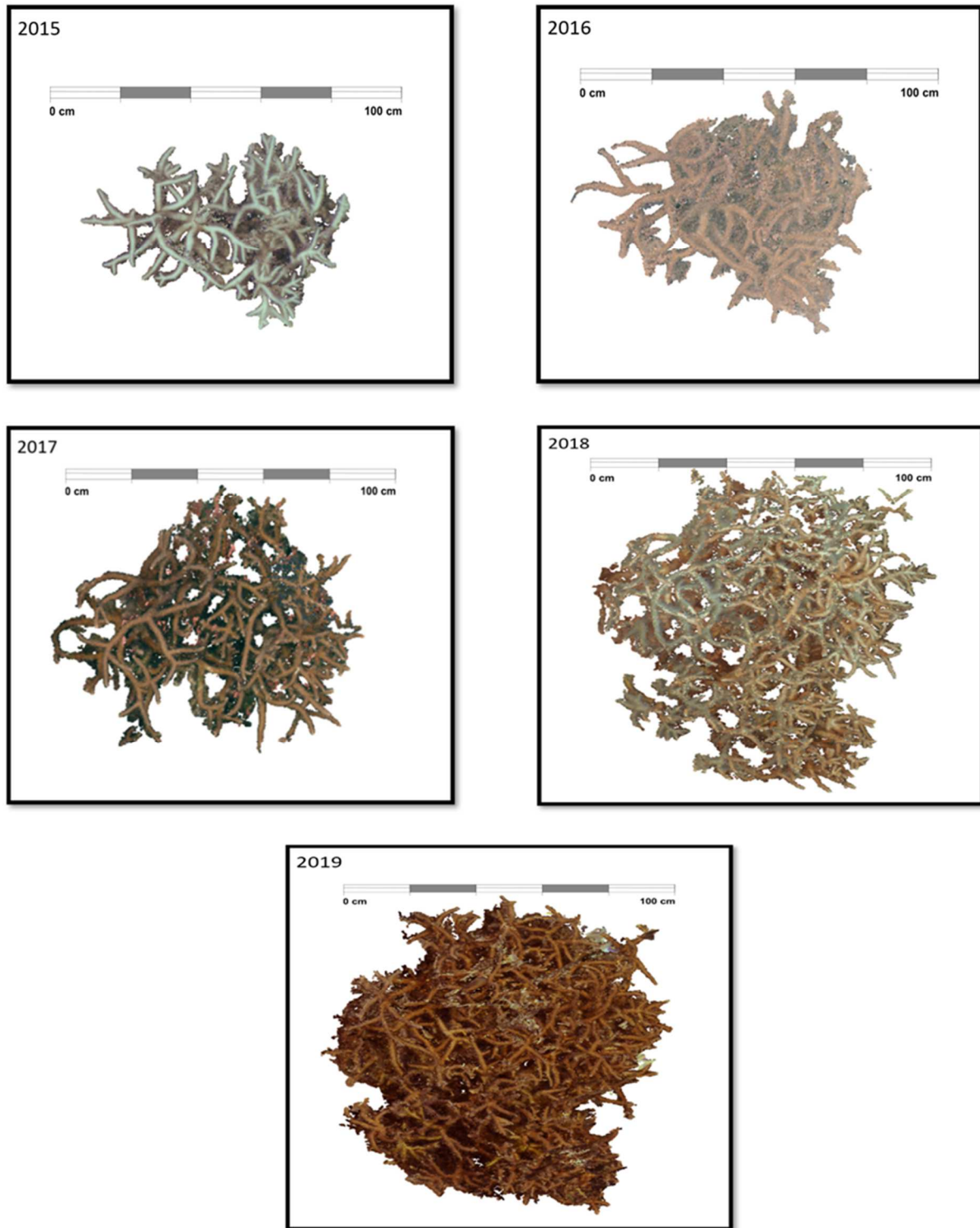


Figure 6 Thicket 4 growth progression from monitoring 2015-2019, taken from annotated images in *Viscore*. The shape of the thicket was variable due to perpetual growth from 2015-17 until the addition of a neighboring thicket in 2018, when shape elongated before stabilizing.

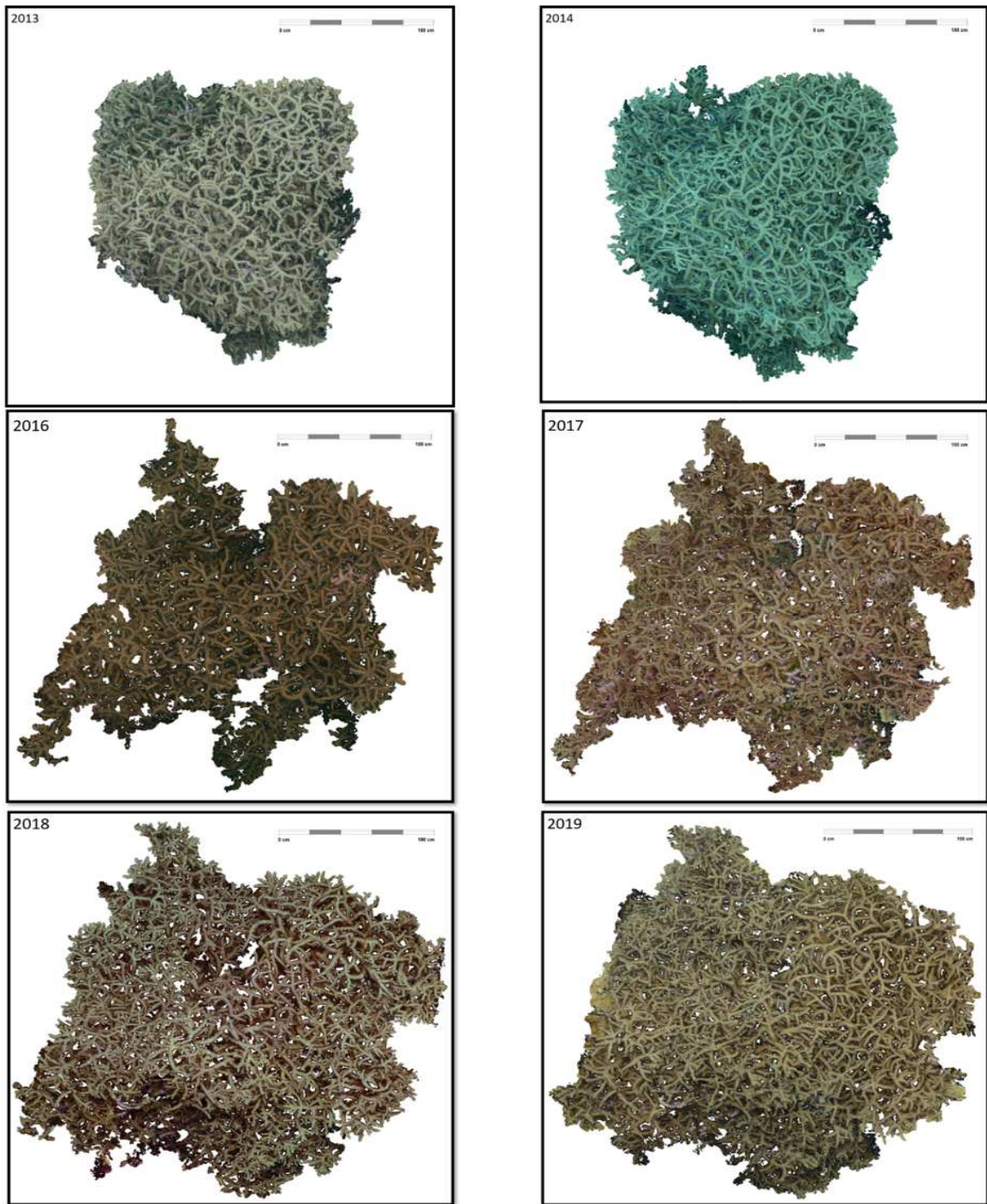
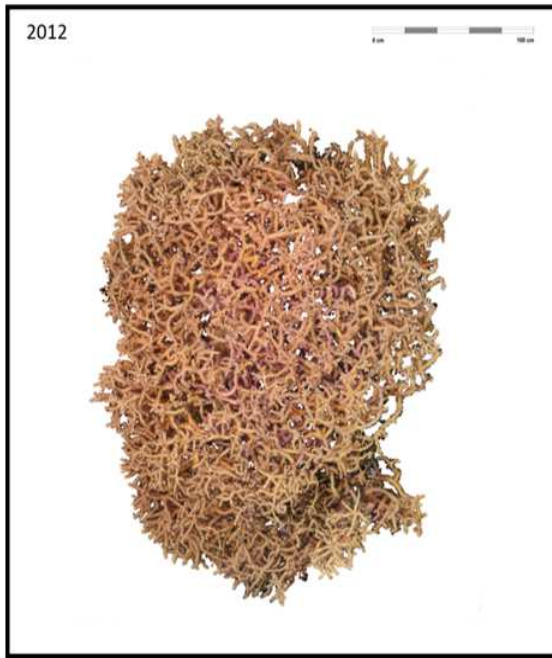


Figure 7 Thicket 5 growth progression from monitoring 2013-2019, taken from annotated images in *Viscore*. In addition to growing yearly, this colony also presented variables shapes on an annual basis.

Figure 8 Thicket 6 growth progression from monitoring 2012-2019, taken from annotated images in *Viscore*. This *Acropora* colony had the highest total growth over the seven-year period, partially due to a neighboring thicket joining the majority of the colony in 2017 and beyond.



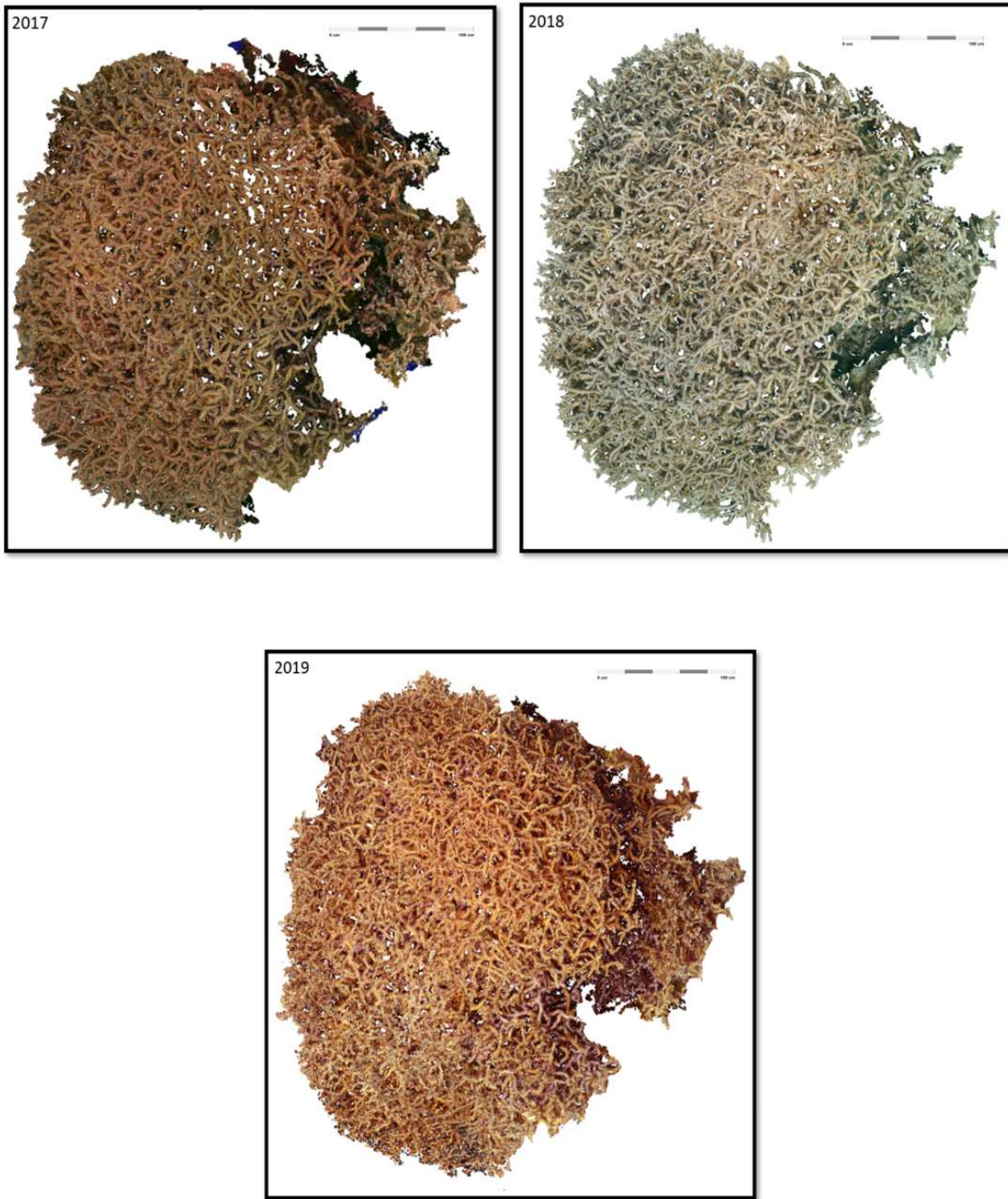


Figure 8 Thicket 6 growth progression from monitoring 2012-2019, taken from annotated images in *Viscore*. This *Acropora* colony had the highest total growth over the seven-year period, partially due to a neighboring thicket joining the majority of the colony in 2017 and beyond, continued.

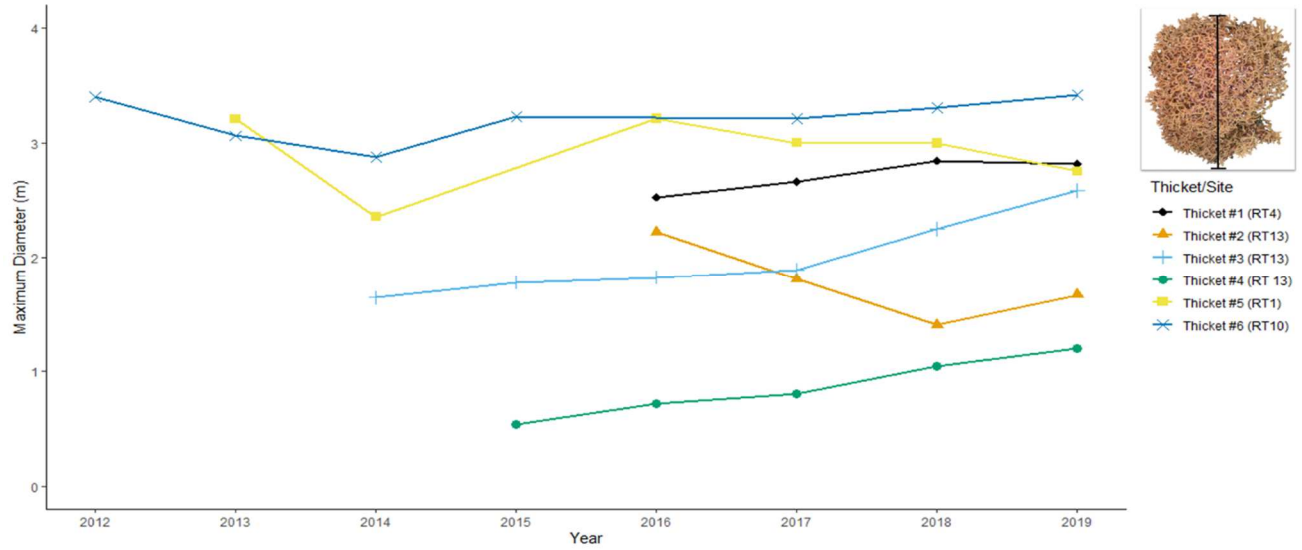


Figure 9 Maximum diameter measurements for Thickets 1-6 on RT sites on Palmyra Atoll. Thickets generally demonstrated a linear pattern, with some colonies and years showing non-patterned variability. This variability could be due to different branches extending furthestmost outward annually, causing inconsistency within diameter measurements.

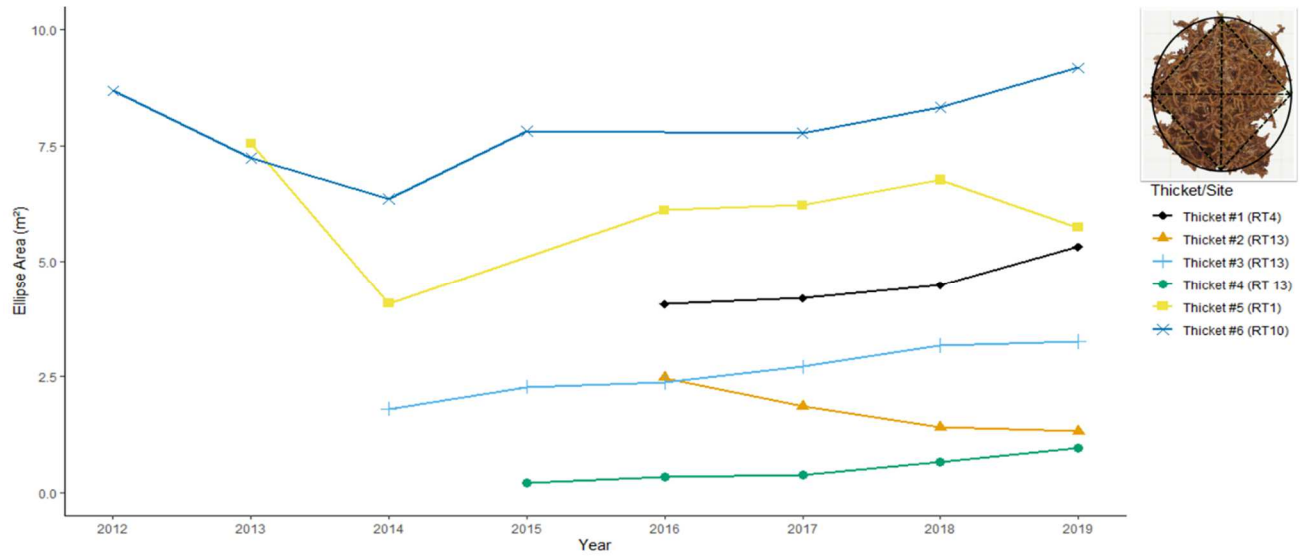


Figure 10 Ellipse area measurements for Thickets 1-6 on RT sites on Palmyra Atoll. Thickets showed a very similar pattern to that of the maximum diameter results, with annual variability dependent on colony. In this case, inconsistencies could be attributed to thickets not exhibiting the appropriate ellipse shape.

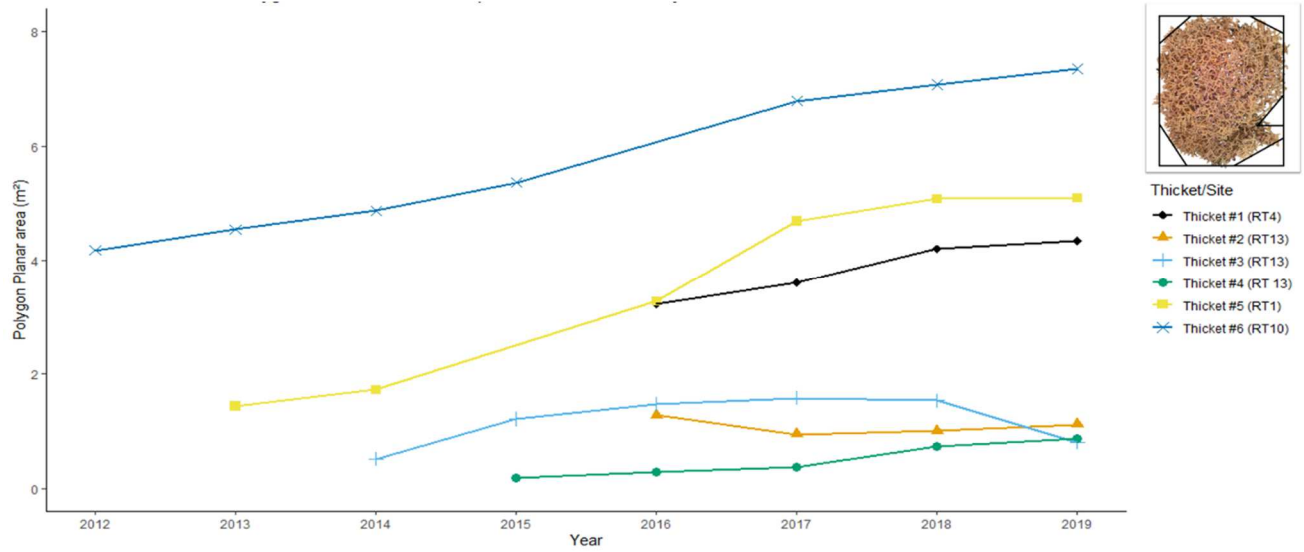


Figure 11 Polygon planar area measurements for Thickets 1-6 on RT sites on Palmyra Atoll. These results show a much smoother annual linear relationship with little variation within thickets. This is likely due to the fact that the polygon metric did not categorize thickets into one specific shape, and removed most areas of empty space so they would not be included in final results.

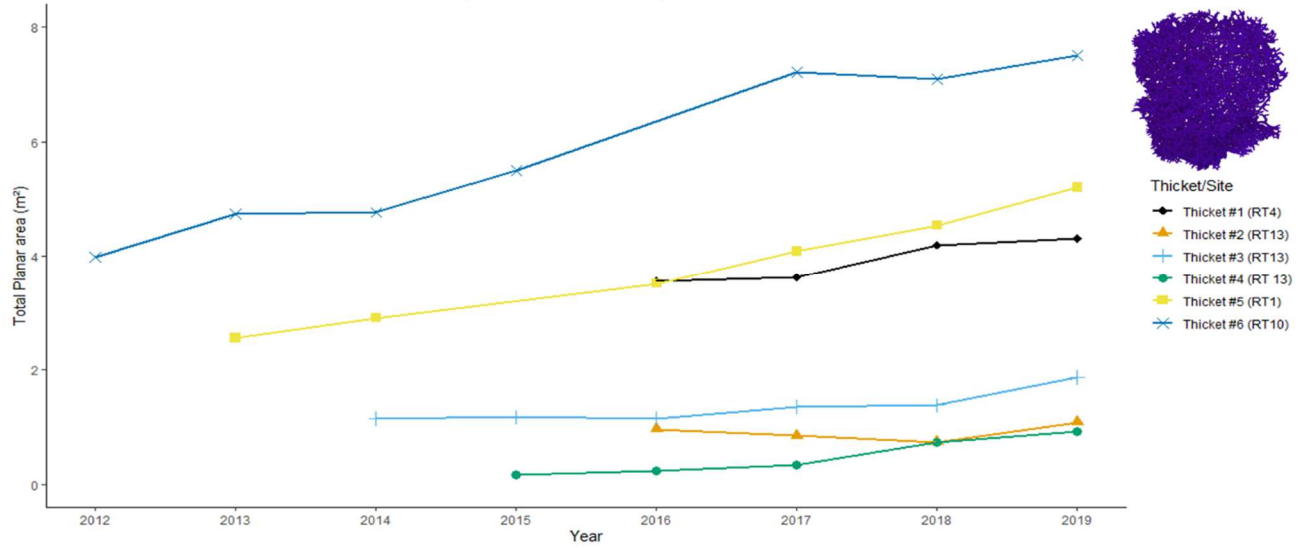


Figure 12 Total planar area measurements for Thickets 1-6 on RT sites on Palmyra Atoll. Thickets displayed results similar to polygon planar area, which is expected due to total planar incorporating only annotated thicket and polygon planar area counting space thickets actually represented. Final total planar areas follow expected growth paths for thickets of more advanced sizes.

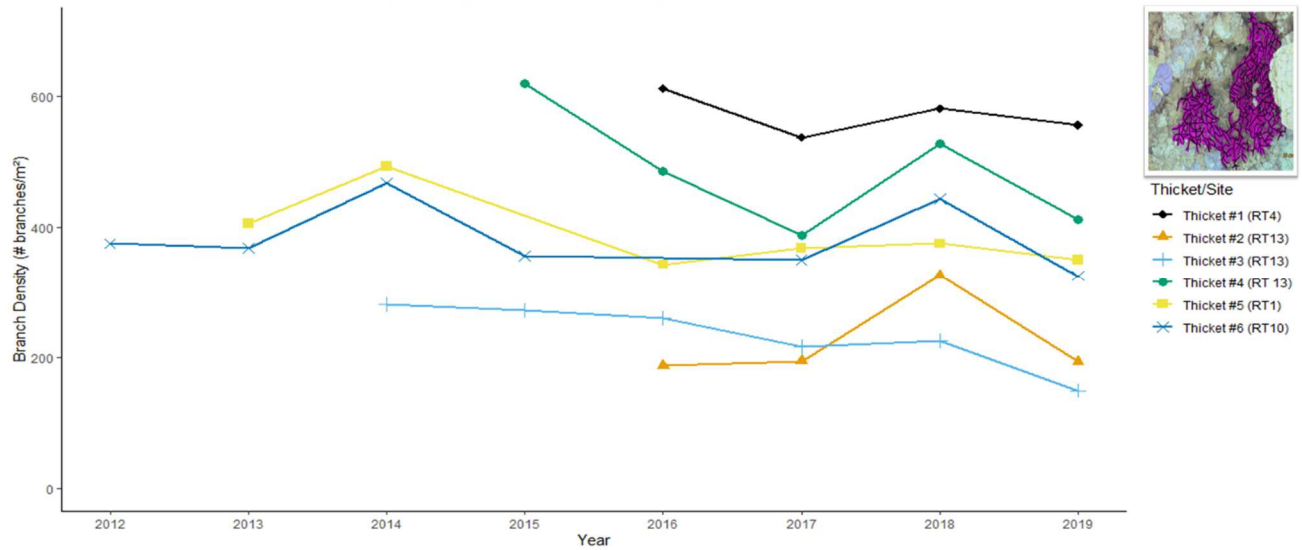


Figure 13 Branch density measurements for Thickets 1-6 on RT sites on Palmyra Atoll. Thickets 2, 3, and 4 all had densities calculated utilizing the entirety of colonies. Thickets 1, 5, and 6 were calculated with generalized densities due to larger size and increased complexity. Both methods demonstrated similar results, with some variability within years and thickets.

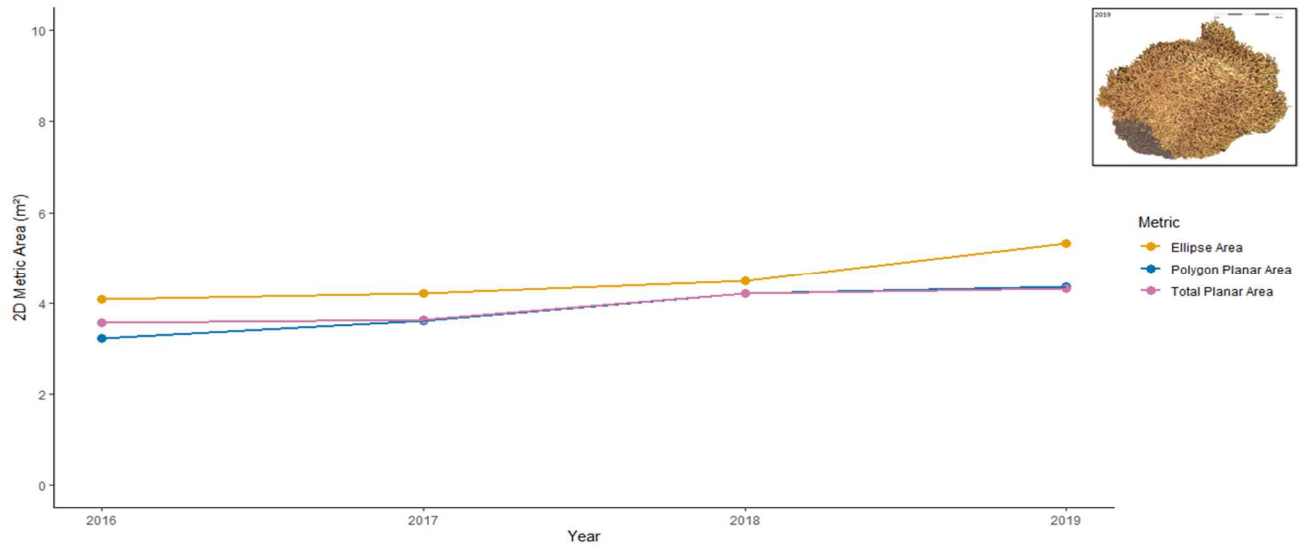


Figure 14 Thicket 1 2-dimensional comparison between ellipse area, polygon planar area, and total planar area metrics from 2016-2019.

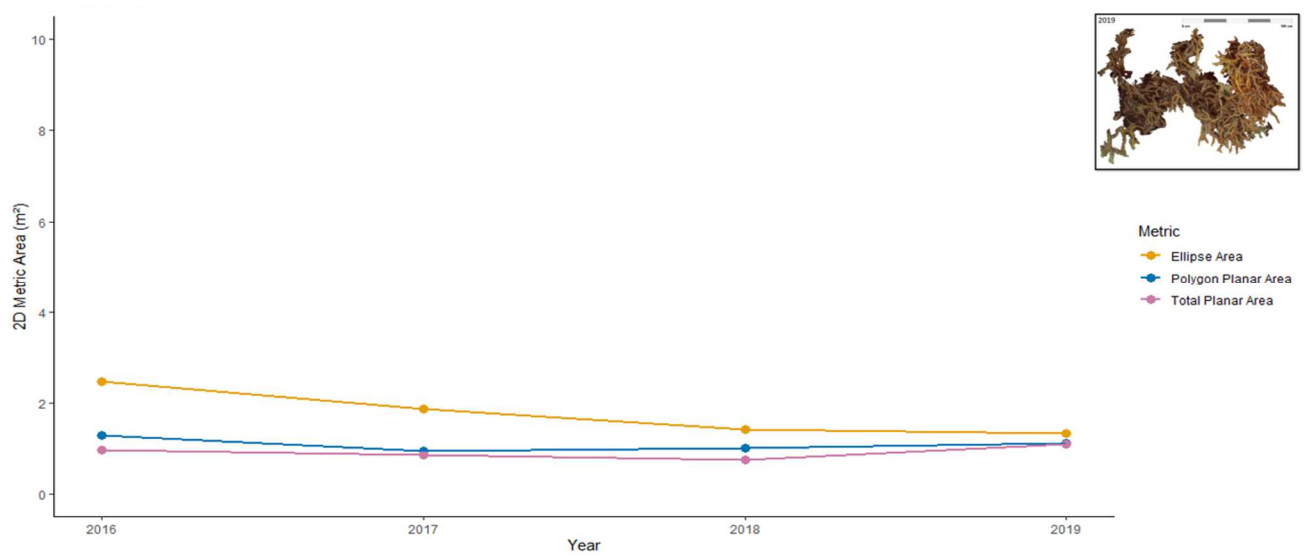


Figure 15 Thicket 2 2-dimensional comparison between ellipse area, polygon planar area, and total planar area metrics from 2016-2019.

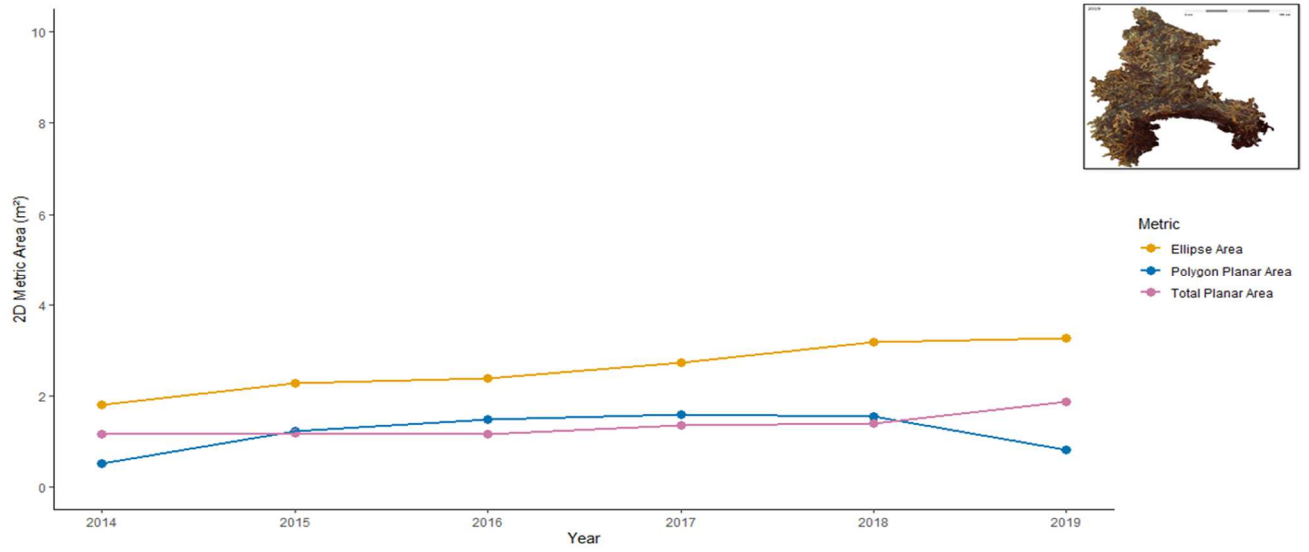


Figure 16 Thicket 3 2-dimensional comparison between ellipse area, polygon planar area, and total planar area metrics from 2014-2019.

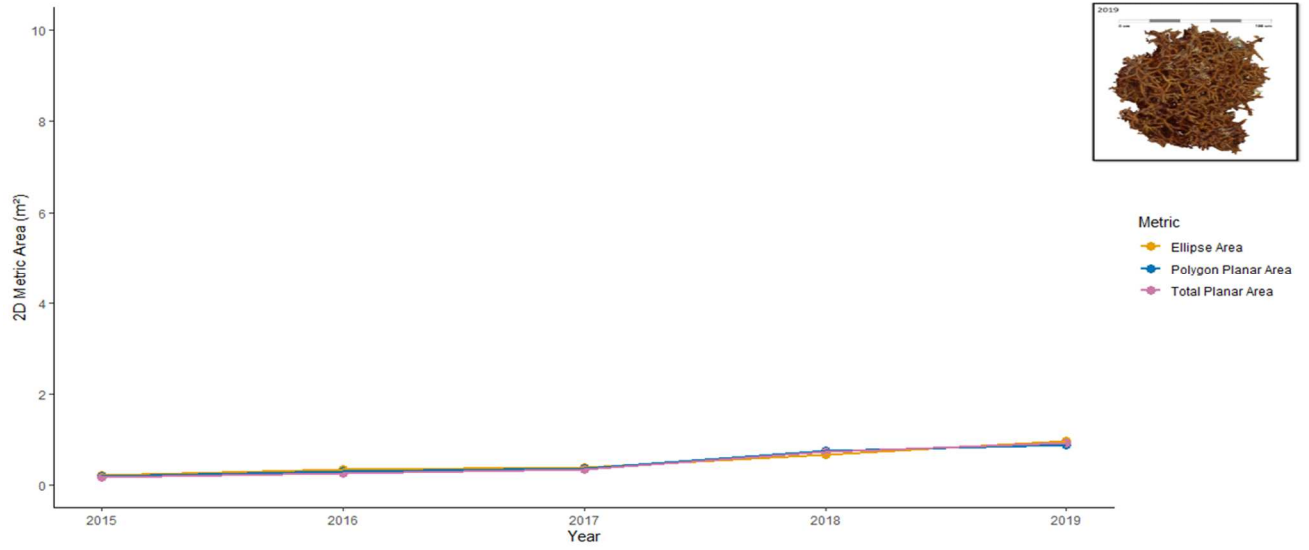


Figure 17 Thicket 4 2-dimensional comparison between ellipse area, polygon planar area, and total planar area metrics from 2015-2019.

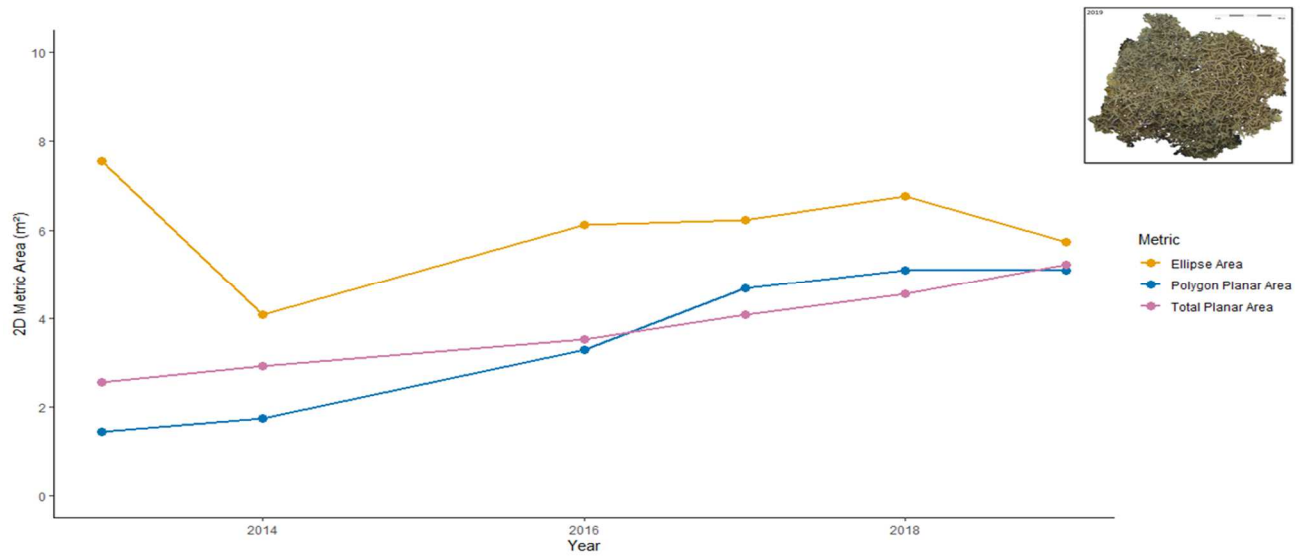


Figure 18 Thicket 5 2-dimensional comparison between ellipse area, polygon planar area, and total planar area metrics from 2013-2019.

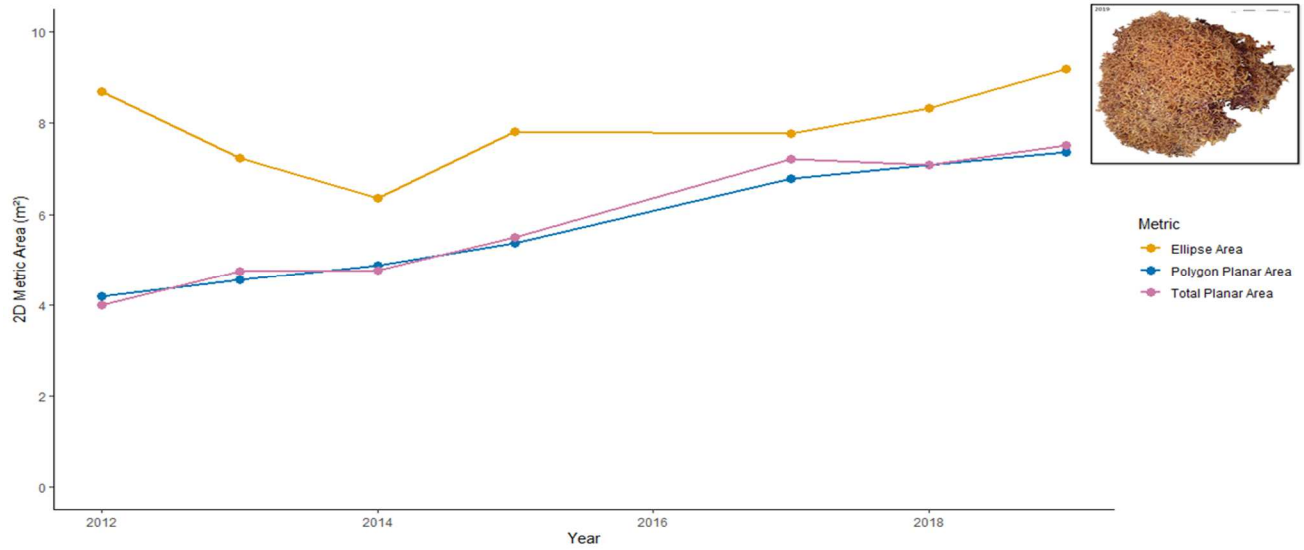


Figure 19 Thicket 6 2-dimensional comparison between ellipse area, polygon planar area, and total planar area metrics from 2012-2019.

Material from this thesis is currently being prepared for submission for publication. Gibson, Laura A.; Edwards, Clinton B.; Pedersen, Nicole E.; Petrovic, Vid; Sandin, Stuart A. The thesis author was the primary author of this material.

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