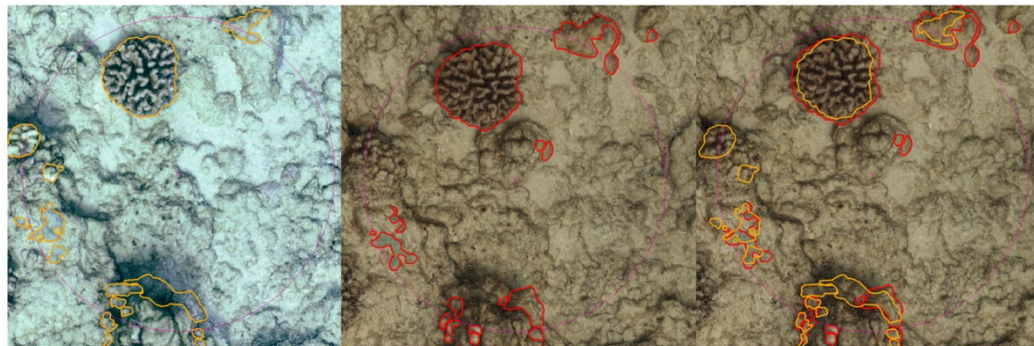# Measuring Coral Vital Rates Using Structure-from-Motion Photogrammetry at Fixed Sites: Standard Operating Procedures and Error Estimates

Caroline Rodriguez, Corinne Amir, Andrew Gray, Mollie Asbury, Rhonda Suka, Mia Lamirand, Courtney Couch, Thomas Oliver

Measuring Coral Vital Rates Using Structure-from-Motion Photogrammetry at Fixed Sites: Standard Operating Procedures and Error Estimates

Caroline Rodriguez[1], Corinne Amir[2,3], Andrew Gray[2,3], Mollie Asbury[2,3], Rhonda Suka[2,3], Mia Lamirand[2,3], Courtney S. Couch[2,3], Thomas Oliver[3]

[1] California State University Monterey Bay
   100 Campus Center
   Seaside, CA 93955

[2] Joint Institute for Marine and Atmospheric Research
   University of Hawaii
   1000 Pope Road
   Honolulu, Hawaii 96822

[3] Pacific Islands Fisheries Science Center
   National Marine Fisheries Service
   1845 Wasp Boulevard
   Honolulu, HI 96818

About this report

The Pacific Islands Fisheries Science Center of NOAA's National Marine Fisheries Service uses the NOAA Technical Memorandum NMFS-PIFSC series to disseminate scientific and technical information that has been scientifically reviewed and edited. Documents within this series reflect sound professional work and may be referenced in the formal scientific and technical literature.

Recommended citation

Copies of this report are available from

Pacific Islands Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
1845 Wasp Boulevard, Building #176
Honolulu, Hawaii 96818

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https://repository.library.noaa.gov/

Cover: Screen shot of 2D image of coral reef illustrating outlined corals used to estimate vital rates.

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Executive Summary

Local and global stressors continue to threaten coral reef ecosystems and are expected to increase in intensity and frequency into the future. However, not all coral reefs respond similarly to the same perturbations. Therefore, understanding the underlying characteristics associated with reef resilience is imperative to protecting our coral reef ecosystems and the precious economic, cultural, and biological resources they provide. Traditional methods of tracking coral growth, recruitment, and mortality (i.e., coral vital rates), such as in situ diver surveys, coral settlement tiles, and photoquadrat analyses, are effective yet time-consuming and limited in spatial scope, reducing their widespread application and constraining our ability to draw inferences about larger reef processes that impact resilience.

Here, we outline a method of directly measuring coral vital rates via structure-from-motion (SfM) photogrammetry — an image processing technique capable of reconstructing accurate, orthorectified representations of the seafloor and the coral communities that inhabit them. By leveraging SfM technology, NOAA's U.S. National Coral Reef Monitoring Program (NCRMP) and partners are capable of generating accurate measures of coral vital rates from the scale of individual coral colonies with coverage of tens of sites and thousands of corals within a population.

In Section 1 of this technical memorandum, we provide a detailed set of Standard Operating Procedures for capturing, processing, and extracting data from SfM photogrammetry. In Section 2, we use this novel SfM approach and imagery collected at 14 sites across the Hawaiian Archipelago across time intervals from a few minutes to three years to determine how accurately we can measure coral vital rates. Specifically, we report on the four sites for which we have generated error estimates of coral colony area for corals in the genera *Porites* and *Pocillopora*, in comparison to the growth data generated from 11 of the 14 sites.

Initial analyses of error rates suggest that when diligently applied, our approach generates low, unbiased rates of error relative to the signal of colony size change we are tracking. For the most widely applicable error estimate, *Imaging Error,* 95% confidence bands of absolute area change span between $+/-$ 1.3 and 1.5 cm^2, depending on taxon. For the 'worst case' error comparing among both distinct images and annotators, i.e., *Imaging and Annotator Error*, 95% confidence bands of absolute area change span $+/-$ 2.9 and 9.9 cm^2, again depending on taxa. The upper end of this error range largely derives from cross-annotator differences, driven by a few outliers. We plan to move forward with a more robust cross-annotator QC process, increased feedback, and human-in-the-loop automation that we hope will bring these error rates even lower, allowing us to focus on the patterns of recruitment, growth, and mortality this method can provide.

We posit that SfM photogrammetry provides a robust and scalable method for extracting coral vital rates data that can support critical decisions guiding coral reef conservation, ecosystem management, restoration, and rewilding efforts. For instance, sensitivity analyses can be conducted to determine which coral species or populations are most vulnerable to perturbations and should be targeted for management interventions. Additionally, coral vital rates datasets can be used to generate a spatially-explicit "phenotype address book" for targeting restoration work, providing a foundation for phenotypically-driven explorations of the genomic bases of colony traits.

Section 1: Vital Rate Standard Operating Procedure: Field-Collection to Annotation

This section outlines the procedures used to extract colony-level vital rates data (e.g., growth, mortality, recruitment, fission, and fusion) within coral communities over time using Structure-from-Motion (SfM) technology. The Vital Rates methodology can be used to assess patterns of coral growth and recovery over time. The workflow is comprised of seven steps:

1) In-situ image collection
2) Generating 3D models in Agisoft Metashape
3) Generating 2D orthoprojections in CloudCompare[1]
4) Alignment of multi-year 2D orthoprojections in ArcMap
5) Creating random quadrats
6) Delineating live patches of coral within the boundaries of the quadrats and
7) Linking live patches across different time points to establish patch-level transitions required to estimate vital rates.

For this SOP, the following software is necessary:
- Agisoft Metashape Version 1.6 (formerly Photoscan)
- CloudCompare (version 2.10 or higher)
- ArcMap (version 10.6.1 or higher)

Spiral Drum Set Up

For imagery collection, we adopted the spiral survey protocol developed and described by Pizarro et al. (2017). This approach can be used to collect benthic imagery for the production of 3D models and 2D products, providing efficient image overlap and enabling a survey of 12 m diameter in ~20 minutes. The main component of the spiral survey is a central drum or spool that can be built using common hardware items. The drum is affixed with a length of line equal to the radius of the plot that is attached to an underwater camera. The drum is placed in the center of the plot and the camera operator swims around it while taking images of the seafloor. The line winds around the drum as the operator swims, reducing the diameter of each round. We tested methods using a variety of drum diameters, distance from the substrate, and plot sizes. In combination with our camera setup (Canon EOS Rebel SL2 with 18 mm focal length), the methods described below produced the highest quality imagery, best overlap, and plot sizes closest to previous surveys. This is the most basic version of the spiral drum. For additional spiral drum configurations using a 3D printer, refer to Appendix A: Create 3D Printed Spiral Drum.

1. To collect imagery, a camera is attached with a thin line to a central drum and images are shot 1 meter above the substrate (Fig. 1, Fig. 2, Fig. 3). If you are using a different camera and lens (Canon EOS Rebel SL2, 18 mm), refer to Pizarro et al. (2017) to calculate the correct drum size.

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[1] To maximize utility of the SOP, here we share our version using CloudCompare instead of Viscore, due to the currently limited availability of Viscore.

a. The distance between paths is equal to the drum perimeter and can be calculated using the drum diameter (for example, a nominal "6 inch" diameter PVC drum has a 53-cm space between each pass, while the "8 inch" drum has a 69-cm space).

To fabricate the Spiral drum, you will need: (all items can be found at most hardware stores)
- (1) 8-inch** diameter PVC pipe approximately 8 inches in length (**based on calculations used to determine pass spacing)
- (1) 0.75-inch × 5-foot Schedule 80 PVC Pipe (this is the standard length of Schedule 80 PVC found in hardware stores. We recommend Schedule 80 due to its sturdiness—it will not warp or weaken from sun exposure and can withstand hot and cold temperatures)
- (1) 0.75-inch PVC male threaded adapter
- (1) 0.75- inch PVC female threaded adapter
- 5–6 m of paracord or other thin line that is not stretchy (brightly colored is beneficial)
- (1) stainless steel clip
- 6 cable ties
- (2) 2-lb dive weights

2. If not purchased at 8 inches, cut the 8-inch diameter PVC pipe to 8 inches in length (this is the drum).
3. Drill a hole in the center of the drum (lengthwise). This is where you will attach the line that will connect to the camera.
4. Drill holes in the top of the drum for the 2-lb weights to attach to the inside of the drum. Do not attach the weights until the drum and pole assembly is complete.
   a. Make sure the holes are wide enough to fit cable ties through.
5. Cut the ¾ inch diameter Schedule 80 PVC pipe to a length of 15 inches.
6. Attach the now 0.75 × 15-inches PVC pipe to the inside of the drum by drilling holes in the drum and attaching the pipe using cable ties.
   a. Approximately 5 inches of pipe should extend above the top of the drum to use as a handle during the survey.
   b. To ensure the pipe does not slide inside the drum, drill two holes in the Schedule 80 PVC pipe and secure the cable tie through these holes (Fig. 1).

Figure 1. Image of the 0.75-inch PVC pipe attached to the drum using cable ties. The four holes to the right and left of the Schedule 80 pipe is where one of the two-pound weights will be attached.

7. Attach the 0.75-inch PVC male threaded adapter to the bottom of the pipe and attach the ¾-inch PVC female threaded adapter to the end of the other section of pipe. The PVC female threaded adapter side should be cut to a length that makes the center of the drum (where the line is attached) 1 m above the ground. This will allow you to maintain the camera altitude at 1 m above the substrate when the paracord is parallel with the substrate (Fig. 2).

   a. Using the threaded adapter allows you to disassemble the long PVC pipe for easier transportation.

Figure 2: Example drum. The PVC pipe connected to the bottom of the male adapter (white PVC) may vary in size to ensure that the center of the drum reaches 1 min height. Electrical tape on the drum is used to cover cable tie ends.

8. Attach 6 m (plus a little extra for attaching to the drum and camera) of line to the drum by tying a large knot at the end of the line inside the drum. Attach a clip to the other end of the line to clip onto the camera.
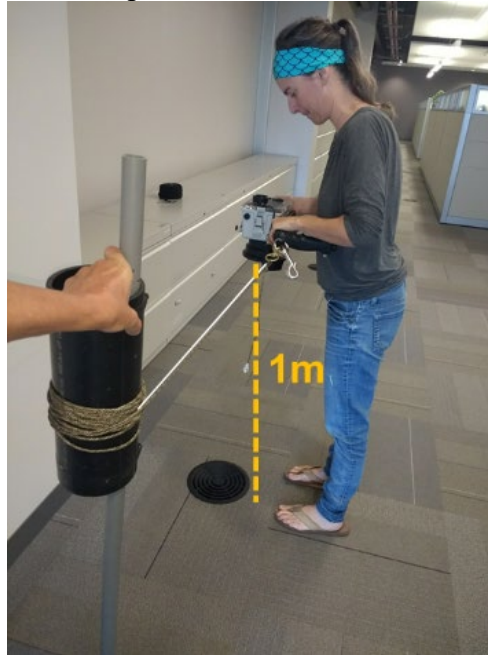
Figure 3. Example drum (black 8-inch diameter PVC) attached to a 15-inch × 0.75-inch Schedule 80 pipe (gray) with the line extending out of the center of the drum.

9. Lastly, attach the weights to the inside of the drum using cable ties (Fig. 4). The weights will provide extra stability when conducting the survey, which is especially important if a second diver is holding the drum during the survey.
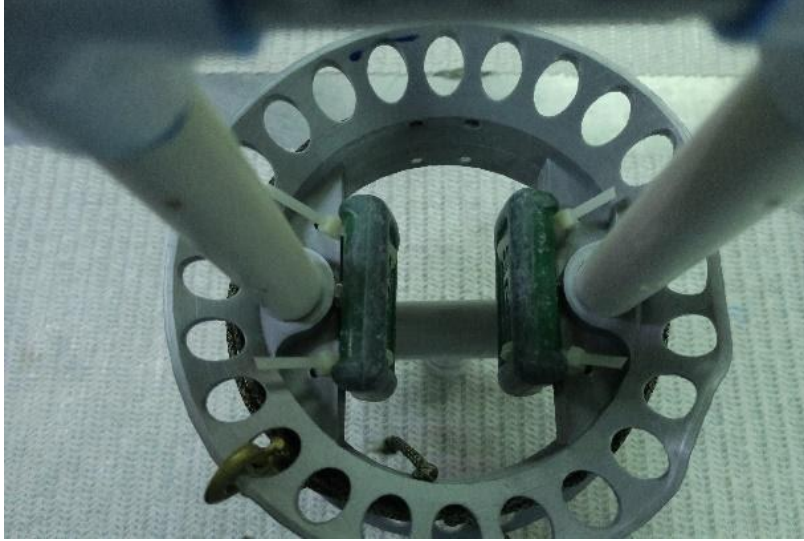
Figure 4. Drum with weights attached to inside for stabilization. Instead of a standard PVC pipe, this drum was produced using a 3D printer. For more information on creating a 3D-printed drum, see Appendix A.

For camera set-up and use see pages 3–7 in Suka et al. (2019).

Establishing New SfM Sites

There are various configurations of physical markings at fixed sites that we employ at PIFSC, many of which were marked for previous fixed site needs that we have adapted for our fixed site vital rates work. If working at an established PIFSC-ESD site, we recommend communicating with this report's authors for the specific configuration you are likely to find, as it is highly site-dependent. Some possible designs are shown in Figure 5. We present set ups for a NCRMP Climate site (Fig. 5a), a 100 Island Challenge site though our collaboration with the Sandin Lab at Scripps (Fig. 5b), or a novel PIFSC site (Fig. 5c).

However, if you are establishing a new site, or are free to re-configure your site's markings, we recommend using .025-inch stainless steel threaded rod hammered into the reef in three locations: (1) The center of the plot (mark rod with two stainless steel nuts), (2) the full distance of the drum line (i.e., 6 m in this case) along the depth contour in one direction, and (3) the full distance of the drum line along the depth contour in the other direction. This will allow you to easily re-establish the plot with maximum overlap if only two rods remain. If only one remains, it is straightforward to re-establish with reference to previous imagery/data-sheets. We recommend marking the rods with 36 inch zip-ties as they remain much more visible underwater even when fouled.

Materials Needed:
- (3) 0.25-inch × 36-inch stainless-steel threaded rods
- Hammer
- (2) 36-inch long cable ties and/or 2 heavy hex nuts (standard or square hex nuts)
- Epoxy putty
- GPS instrument
- Transect reel

- Underwater compass
- 1 dive slate with a datasheet (see Fig. 7 for example datasheet) printed on waterproof paper

1. Once a plot of reef has been selected as the fixed site, three reference stakes must be added to improve the likelihood of finding the site in future years.
   a. We recommend establishing reference pins into small fissures within coral heads, approximately 12 m apart with the 6 m midpoint between the two stakes placed at the spiral center. Hammer the three stakes into the reef substrate in one row and secure with epoxy. The two furthest pins should be 12 m from one another, and the middle pin will be located at the midpoint between them (Fig. 5c).
   b. We recommend installing reference pins into small fissures within dead substrate. It is helpful to standardize the plot set-up by orienting the reference pins in a parallel line relative to land/the depth contour. This will help orient the plot on repeat visits.
   c. Add an identifier to the middle pin by connecting one or more 36-inch long cable ties and/or screwing 2 hex nuts onto the stake. This will be the primary reference pin.
   d. Including a primary reference pin ensures that if one or two stakes are dislodged in between site visits it will be easier to determine the original plot perimeter, ensuring better imagery overlap between time points.
2. Once the reference pins are established, record the latitude and longitude of the primary reference pin, a heading from one reference pin to the primary reference pin, and draw any conspicuous site features onto the datasheet.

Plot Set Up and Survey for Established SfM Fixed Sites

At each survey site, the plot is set up by placing scale bars on the reef within the area to be surveyed. Diver 2 holds the drum in place in the center of the plot while Diver 1 holds the camera attached to the drum and swims at a slow, sustainable speed 1 m off the bottom of the reef circling the drum, continuously taking photos. The diver holding the drum should ensure that it does not spin or tilt during the survey. Next, the divers switch roles and the diver now holding the camera swims in the opposite direction to ensure all angles of the reef are captured. The methods described below were found to produce the highest quality imagery, best overlap, plot sizes closest to previous surveys, and most efficient dive times.

Materials Needed:
- Orthophoto (or any visual representation(s)) of the site you will be surveying printed on waterproof paper (it can be helpful to bring two orthophotos—one of the entire plot and another close-up version of a conspicuous section of the site)
- GPS instrument
- 1 dive slate with a datasheet (see Fig. 7 for example datasheet) printed on waterproof paper and secured onto a slate with a graphite pencil
- 3–4 scale bars of known length with Agisoft patterns at both ends (we have successfully used both 25 and 50 cm scale bars)
- 1–3 rebar caps with Agisoft pattern affixed to top
- 1 spiral drum (as discussed in "Spiral Drum Setup" section above)

- 1 camera secured in a waterproof dive housing (ESD suggests using a Canon EOS Rebel SL2 camera in an Ikelite housing due to its high image quality, superior white-balancing, small housing size, ease of use, continuous shooting, and affordability compared to other camera/housing setups)
- 18% grey card for white balancing the camera
- In case reference pins need to be added or replaced, bring all materials listed within the "Establishing New SfM Fixed Sites" section

1. Before starting the dive, record the latitude and longitude of the primary reference pin (center of the plot) on the datasheet. However, collecting imagery that overlaps with imagery from previous site visits is paramount. **Therefore, drum placement may need to be moved off-center to increase overlap across time points!**
    a. Use the best available latitude/longitude measurements. If you already have a waypoint from a previous visit that is accurate, reuse it. If previous measurements are not accurate, swim to the center of the plot and re-collect the waypoint.
2. Depending on the type of fixed site, the primary reference stake will be found in different locations.
    a. If the survey site is co-located with an ESD climate station, the primary reference stake will be in the upper left corner of the climate station when facing shore (Fig. 5a).
        i. The primary reference pin should have one or two 36-inch zip ties attached near the top of the steel rod.
        ii. All stakes except for the primary reference pin will have CAU (Calcification Accretion Unit) devices connected to them.
    b. If the survey site was established by Scripps (SIO), latitude/longitude record measurements at the reference pin on the left side of the plot when facing land (Fig. 5b).
    c. If the survey site was established by NOAA ESD as an SfM fixed site, the primary reference pin is located in the center of the plot (Fig. 5c).
        i. The primary reference pin should be flanked by two additional reference pins that indicate the max survey perimeter (Fig. 5c).
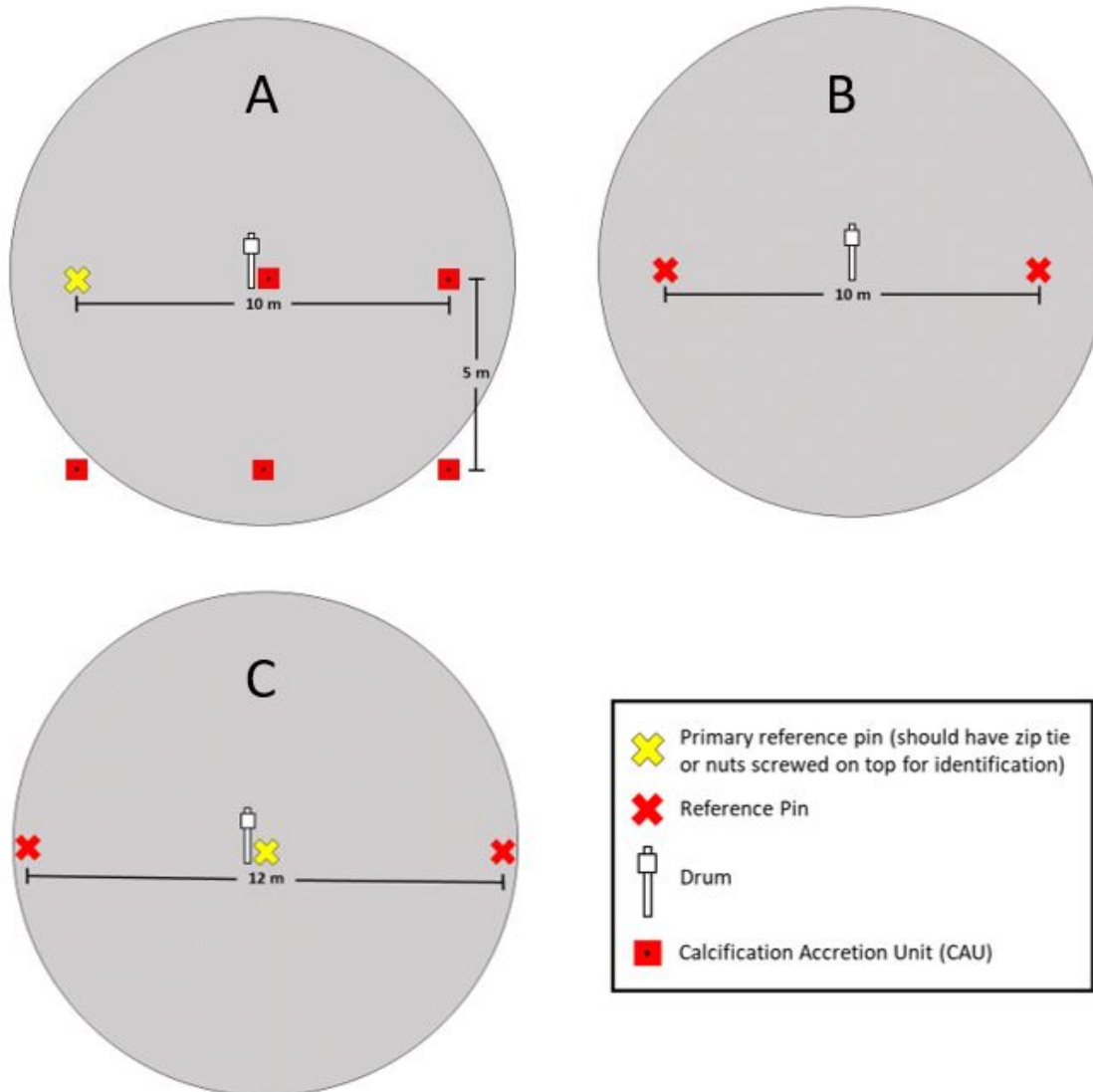
Figure 5. Diagrams of SfM plot setup within a (A) NOAA ESD climate station, (B) site originally established by SIO, and (C) site established by NOAA ESD for the sole purpose of SfM fixed site imagery collection including the location of drum placement. The shaded area indicates the region of reef surveyed. Drum placement in sites where imagery has been previously collected should be in the location that will produce the most image overlap between time points. This may or may not be the location identified within the diagram.

3. Two divers are required to set up and conduct plot surveys. Diver 1 descends to the site with the camera and scale bars and Diver 2 descends to the site with the drum and datasheet.
    a. Make sure to bring additional steel rods, 36-inch zip ties and/or hex nuts, epoxy, and a hammer in case any reference pins or zip ties are missing or need to be replaced/reinforced.
4. Once the reference pin or site identifier is located, Diver 1 places the scale bars (Ground Control Points—GCPs) 2–3 m away from the center of the plot opposite from each other and place rebar caps on each reference pin (Fig. 6).
    a. **Make sure the GCPs are facing up and are stable** (Fig. 6).

b. For further information regarding scale bars, refer to *Processing Photomosaic Imagery of Coral Reefs Using Structure-from-Motion Standard Operating Procedures* section 2.1 B (https://repository.library.noaa.gov/view/noaa/22753).
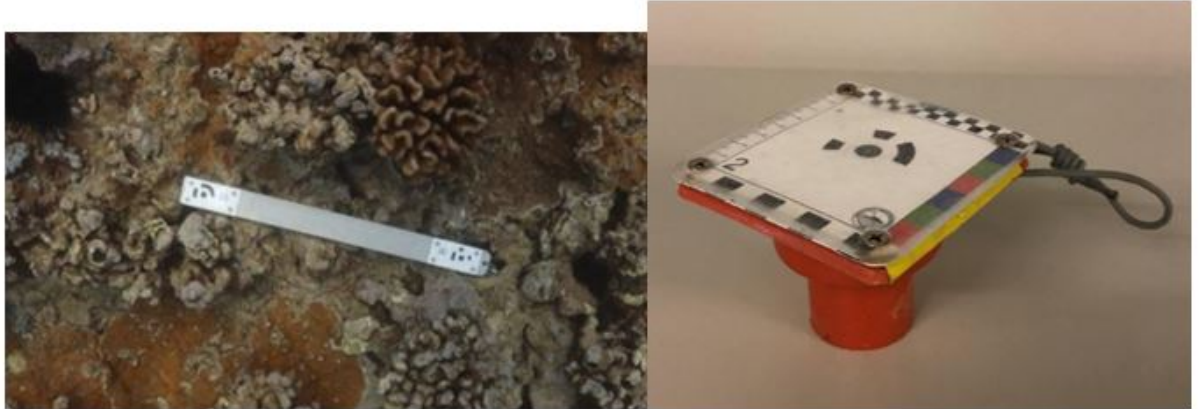
Figure 6. Picture of markers. Left: 50 cm GCP with Agisoft patterns used for scaling 3D models. Right: rebar cap with Agisoft pattern placed atop reference pins.

5. Record a heading from one of the reference pins to the other and record on the datasheet diagram (optional) (Fig. 7). It is helpful to standardize the plot set-up datasheet diagram by orienting the plot where land is labelled at the top of the datasheet. This will help orient the plot on repeat visits.
    a. If capturing imagery at a NOAA ESD climate station, take a heading from the left reference pin (when looking inshore) to the CAU (approximately 5 m away) in the center of the plot.
    b. If capturing imagery at a NOAA ESD fixed site, take a heading from the primary reference pin to one of the adjacent reference pins.
    c. If capturing imagery at a SIO site, take a heading from the primary (left, when looking inshore) reference pin to the other.
6. Using the datasheet, Diver 2 draws a rough sketch of the GCP locations (and rebar caps if used) and record the depth at the center of each scale bar, along with each corresponding marker number (Fig. 7).
    a. Add any other obvious features within the plot to the datasheet. This is crucial for sites with no pins, high disturbance, and/or where a detailed description of the benthos is necessary for achieving sufficient overlap across time points.

OCC – Spiral SFM Datasheet

DIVER 1: NP   CAMERA#: #2   DATE: 4/20/2019

DIVER 2: TW

ISLAND: OAH   SITE#: OAH_744   WAYPOINT: 007

LATITUDE: 21.43361   LONGITUDE: 155.44115   MOSAIC DIAMETER: 12M

Alongshore bearing from reference stake to CAU #1: 47°   DRUM DIAMETER: 6 inches

Underwater Checklist:

☑ Sky shot
☑ Color Balance
☑ Site image to check color balance
☑ Slate shot
☑ Record depth for each marker
☑ Record marker #s
☑ Place drum 5m from reference pin toward CAU1
☑ Take images
☑ Sky shot

36ft   38ft
12—14   65—67
Pin
PNM
CAUs
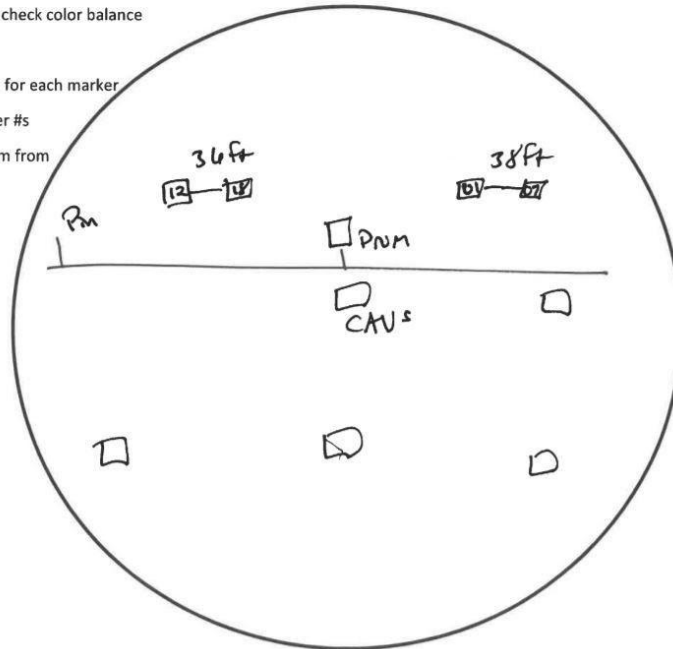
Notes:

Figure 7. Example of SfM spiral data sheet from a NOAA ESD climate station. Markers, reference pin, and other features can be drawn into the survey circle. Record GCP numbers and the depth in feet for each GCP. Land should be oriented toward the top of the page if possible.

7. As Diver 2 completes the datasheet, Diver 1 white balances the camera. We have found that the best color balanced imagery is achieved with an 18% grey card and dramatically improves the quality of the imagery and SfM products. For camera set up, refer to pages 5–6 in Suka et al. (2019).
8. Once the camera is ready, take a series of photographs of the sky or blue-water photos (aiming the camera towards the surface) to mark the beginning of the survey. In addition, Diver 2 will hold up the datasheet for Diver 1 to photograph.
   a. This is critical for differentiating images from multiple sites surveyed on the same day.
9. Diver 2 will position the drum in the center of the plot. However, collecting imagery that overlaps with imagery from previous site visits is paramount and the printed orthophoto can be used to confirm the exact location where the drum should be placed. **Therefore, drum placement may need to be moved off-center to increase overlap across time points!**

a. Examine the plot to ensure there are no high relief areas that could snag the line; if there are, move the center to the closest high point (unless the center has been established on a previous survey).

10. Diver 1 attach the camera to the clip at the end of the line and swims out to the edge of the plot so that the line is fully extended and taut.

11. As Diver 2 holds the drum fixed and stable, Diver 1 swims at a slow to moderate speed (swimming too quickly will result in blurry images), 1 m off the bottom of the reef following benthic contours while continuously pressing the shutter button. As Diver 1 swims in one direction around the drum, the line will wrap around the drum.
    a. Diver 2 should be positioned above the drum to ensure they are not obstructing the line as it wraps around the drum. **Make sure that the drum is not rotating, it must be held in a fixed position the entire survey**.
    b. Diver 2 must also keep track of Diver 1 and the line so that they can move out of the field of view and tend the line if needed.
    c. Refer to pages 10–11 in Suka et al. (2019) for further information and guidelines on image collection.

12. As Diver 1 approaches the center where Diver 2 is positioned with the drum, unclip the camera and hand the remaining line to Diver 2. Diver 2 then moves away from the center with the drum to allow the photographer to image the center of the plot. Diver 1 makes a mental note of where the drum was positioned.

13. Once the center of the plot is captured, divers switch to even out air consumption. Diver 1 places the drum in the spot it was previously located while Diver 2 reattaches the camera to the line.

14. Diver 1, positioned above the drum keeps it steady as Diver 2 starts swimming in the opposite direction, unwinding the line.

Once Diver 2 reaches the edge of the plot, they signal to Diver 1 and unclip the camera.
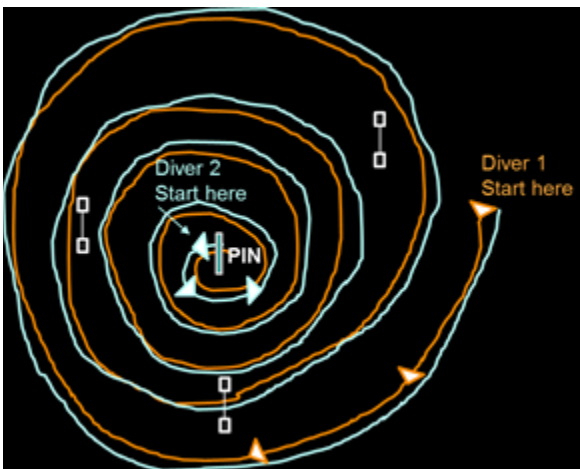
Figure 8. SfM spiral survey showing marker placement in white and reference pin in green.

15. Diver 1 reels up the line while Diver 2 takes a few series of sky or blue-water images to note the end of the survey.

16. If you have to stop the survey for any reason, make a mental note of location. When you resume the survey, begin taking photos 1 m before the point where you stopped to ensure good overlap. If you lose your place, go back to the last area that you can remember.

Figure 9. One diver holds the drum in place while the second diver swims at a moderate speed 1 m off the bottom of the reef imaging the reef.

For data management, file naming and quality control procedures, see Suka et al. (2019).

Scale, Generate, and Orient Dense Point Cloud

Once the photos have been collected and quality controlled, they can be aligned to build 3D sparse point clouds and dense point clouds (DPC) using Agisoft Metashape, This software will align the photos to build a sparse point cloud. Next, the sparse point cloud is scaled using the GCPs, and depth measurements are added to properly orient the model. Finally, a dense point cloud is built.

1. Open Agisoft Metashape.
2. Add images, filter images, and generate the sparse point cloud.
    a. Follow pages 17–21 of Suka et al. (2019).
    b. When you reach "C. Generate the 3D model" on page 19, stop after saving the project in Step 3. Do NOT build the dense point cloud at this point.
3. Scale the sparse point cloud by creating scale bars from the GCP points and adding in the distance between the two Agisoft targets that are on the same bar.
    a. If Agisoft GCP markers were used, click on Tools → Markers → Detect Markers
        i. Marker Type: circular 12 bit
        ii. Tolerance: 50
        iii. Uncheck Inverted (white on black)
        iv. Uncheck Disable parity
        v. Click OK
    b. Agisoft will automatically detect GCP markers in each image.

c. If Agisoft GCP markers were not used or Agisoft did not detect them, select a photo from the photo pane with an object that can be used to scale images (or use the GCP markers) and add a GCP according to the following steps:
   i. To place a GCP in a photo, right click on the image and choose Add Marker.
      1. Avoid GCPs that are touching the edge, at a steep angle, or blurry.
      2. A blue flag in the corner of the photo means a GCP was detected in the image.
      3. A 'grey flame' in the corner of the photo means a GCP was detected but not enabled. Click and drag the GCP on the image to enable it or ignore it if unwanted.
      4. A red dashed line may appear on the first few photos after adding a GCP; right click to Place Marker and the red line will disappear.
   ii. Rename the GCP markers in the Reference window by double clicking on the GCP name (e.g., Target ###).
      1. Once you add the same GCP in two images, Agisoft will detect those objects in the rest of the images.
   iii. Click on the Binoculars icon in the Reference toolbar to reset filter and view all of the photos again. Repeat this process for each object you want to use as a GCP.
d. When finished detecting/adding GCP markers, use the star icon in the Reference toolbar to Optimize.
   i. Click ALL the boxes EXCEPT 'Fit additional corrections.' This will calculate the error associated with each GCP marker.
   ii. Look at the Error (pix) column in the Markers pane on the far right. Each GCP marker error should be below 0.4.
   iii. If a GCP marker error is above 0.4, right click on the highest error marker and choose 'Show Info' to show the error associated with each individual photo. Sort in descending order by clicking on the Value header. Double click the image with the highest error and the photo will pop up in the model workspace. Close the Info window and remove the selected GCP marker on the image by right clicking. Select 'Optimize Cameras' (magic wand) again and observe the Error for that marker. Usually removing the top one or two highest error markers from images will suffice. Continue with this process on each marker with high error until all are at or below 0.4.
e. Under the Markers tab, choose matching marker numbers that make up a scale bar (according to the data sheet).
   i. Select both marker numbers by control and click, then right click and choose 'Create Scale Bar'.

ii. In the 'Scale Bar' pane, double click under 'Distance' to manually add the distance between the two marker numbers in meters.

iii. The single markers are not used to create scale bars, but they should be used when adding depth measurements (Step 4 below).

f. Use the star icon at the top of the Reference window to Optimize. Click Adaptive camera model fitting box.
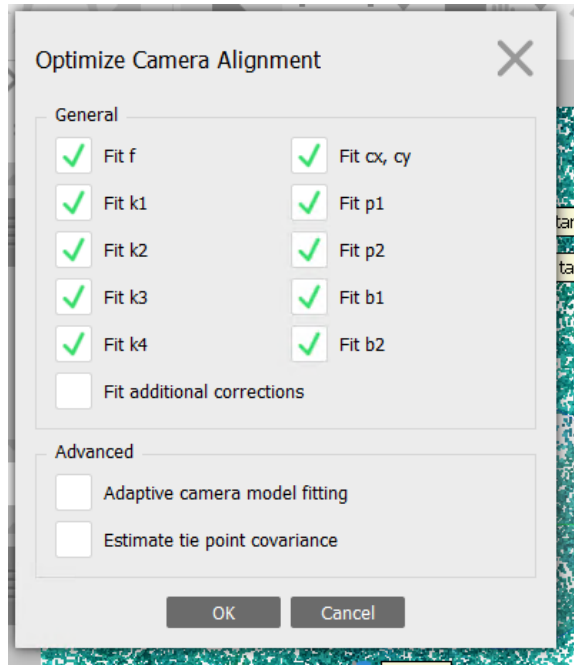
Figure 10. Screenshot of Agisoft window used to optimize camera alignment and scale the sparse point cloud.

Check the error given in the 'Scale Bar' tab—error in 'Scale Bar' tab should be no higher than 0.002. If error is too high, reevaluate GCP markers to lower their individual error, then optimize again.

g. Save the Agisoft file. The sparse point cloud is now scaled, and the tie points will be present.
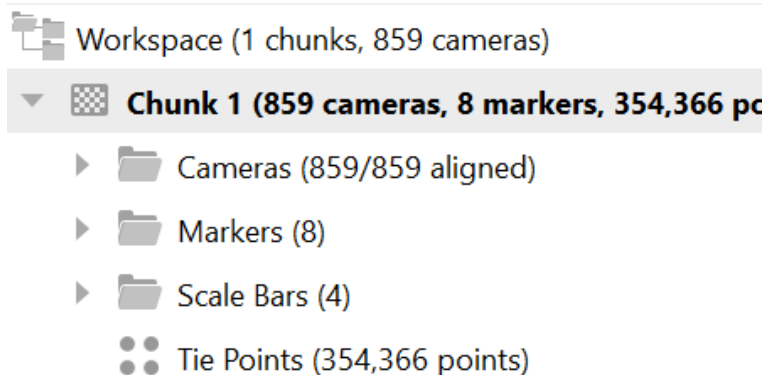
Figure 11. Agisoft window with the cameras, tie points, and markers in view.

4. Add depth measurements to the sparse point cloud.

a. Under the Markers tab, change the Z coordinate to reflect the depth measured in the field. This depth measurement should be converted to meters.

b. When adding depth measurements across time points for the same site, double check that the depth measurements make sense (i.e., measured the same point in two time points but there is a 1–2 m depth difference due to tides and/or wave action). If a depth measurement appears to be in error or is inconsistent with previous DPCs of the same site, throw out the depth measurement to remove any potential distortion and projection problems.

5. Build the dense point cloud (DPC) and export Agisoft report.

   a. Start on Step 4 on page 21 of Suka et al. (2019).

   b. When you reach Step 2 on page 22, stop and save the Agisoft document.

6. Export the DPC.

   a. Click File → Export → Export Points.

      i. File name: Site#

      ii. Save as type: Stanford PLY (*.ply)

   b. Ensure the parameters in the Export Points are correct (Fig. 12).
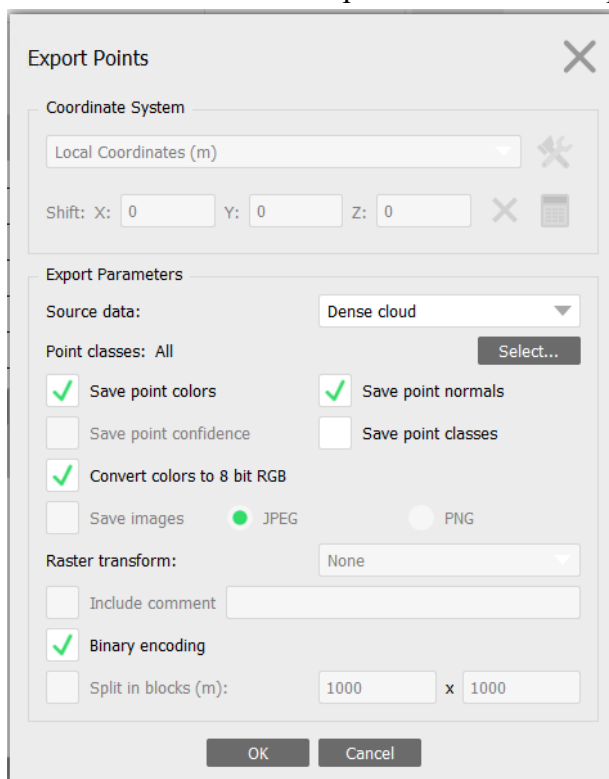
Figure 12. Screenshot of Agisoft Export Points window and the correct parameters used to export the DPC.

7. Generate and export scaled orthophoto (OPTIONAL).

   a. It is possible to create a 2D reconstruction of the reef, known as an orthophoto or orthomosaic. The orthophoto can contain significant artifacts and ghosting.

Therefore, coral demographic data may not be accurate if orthophotos are used for demographic annotation.

b. However, orthophotos can be useful if printed on waterproof paper and used in the field to help locate a fixed site.

c. To generate and export a scaled orthophoto refer to pages 22–25 of Suka et al. (2019).

File Summary:
The following files/folders should now be associated with each model and be in the Product folder for the site:

Site#.psx: Agisoft project file that opens model project
Site#.files: Agisoft project file folders containing all the data for the model
Site#.ply: Dense point cloud
Site#_report.pdf: Processing report

Exporting Orthoprojections in CloudCompare

CloudCompare (an open-source point cloud and mesh processing software) is used to produce a geometrically accurate 2D orthoprojection. The scaled DPC produced in Agisoft is uploaded to CloudCompare and exported as a 2D orthoprojection image. Orthoprojections are beneficial for extracting coral demographic data because they provide a geometrically accurate image that does not contain artifacting—a problem often found in orthophotos.

1. CloudCompare can be downloaded for free from https://www.danielgm.net/cc/.

2. Launch CloudCompare and open Site#.ply. In the Ply File Open, do not change the parameters and click Apply.

3. Rotate the DPC to create a top-down view.
   a. Make sure all time points for the same site have the same orientation. This will improve alignment in ArcMap.

4. Use the measuring tool to measure a scale bar to ensure scale is intact by clicking the point picking toolbox and clicking the distance measuring tool (Fig. 13).
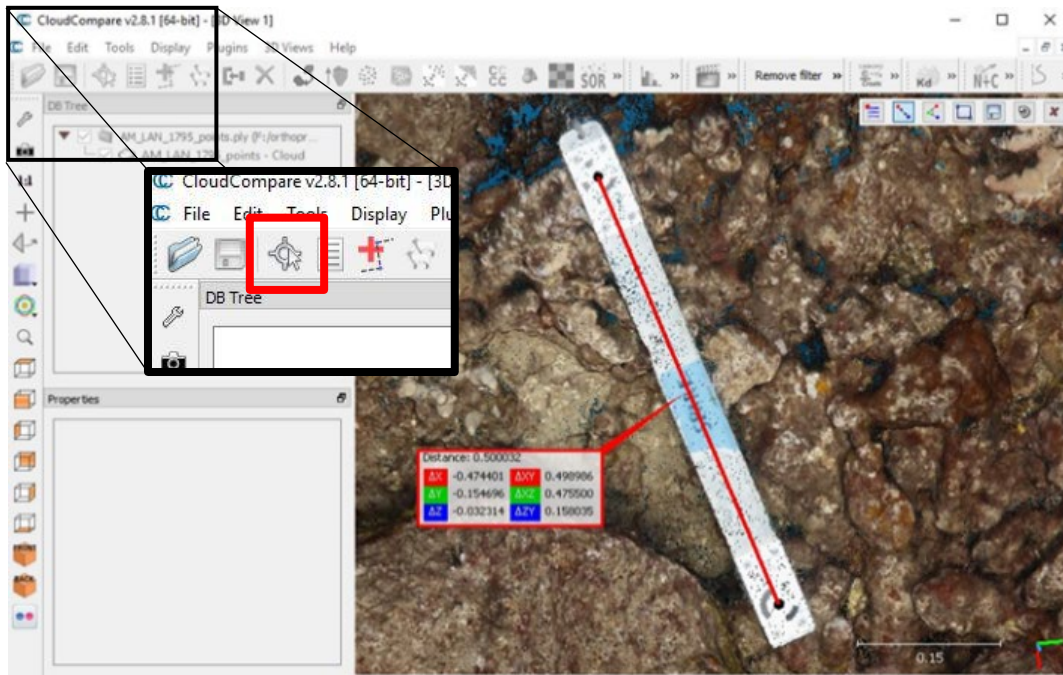
Figure 13. Screenshot of CloudCompare demonstrating use of the measurement tool.

5. Select the DPC in the DB tree on the left and at the top of the window, choose Tools > Projection > Rasterize (and contour plot).
6. Choose your desired grid step size. The grid step size refers to the resolution (e.g., 0.001 or 0.01) so that grid size is similar to DPC points.
   a. The pixel size (synonymous with grid step size in CloudCompare) can be found in the Agisoft report document.
   b. Pixel size should be the same for all images collected by the same model of camera.
7. Change the active layer to RGB and then press the Update Grid button. Click Yes.
8. If the pixel size is unknown, check that your grid size is sufficient by zooming into the DPC and ensure that the resolution is not pixelated.
9. Check average height. Click the Raster button at the bottom to export. In the Raster export options window, choose Export RGB colors and uncheck export heights. Click OK. Save as Site#_orthoprojection.tif.
   a. For further information about the rasterize tool in CloudCompare: http://www.cloudcompare.org/doc/wiki/index.php?title=Rasterize
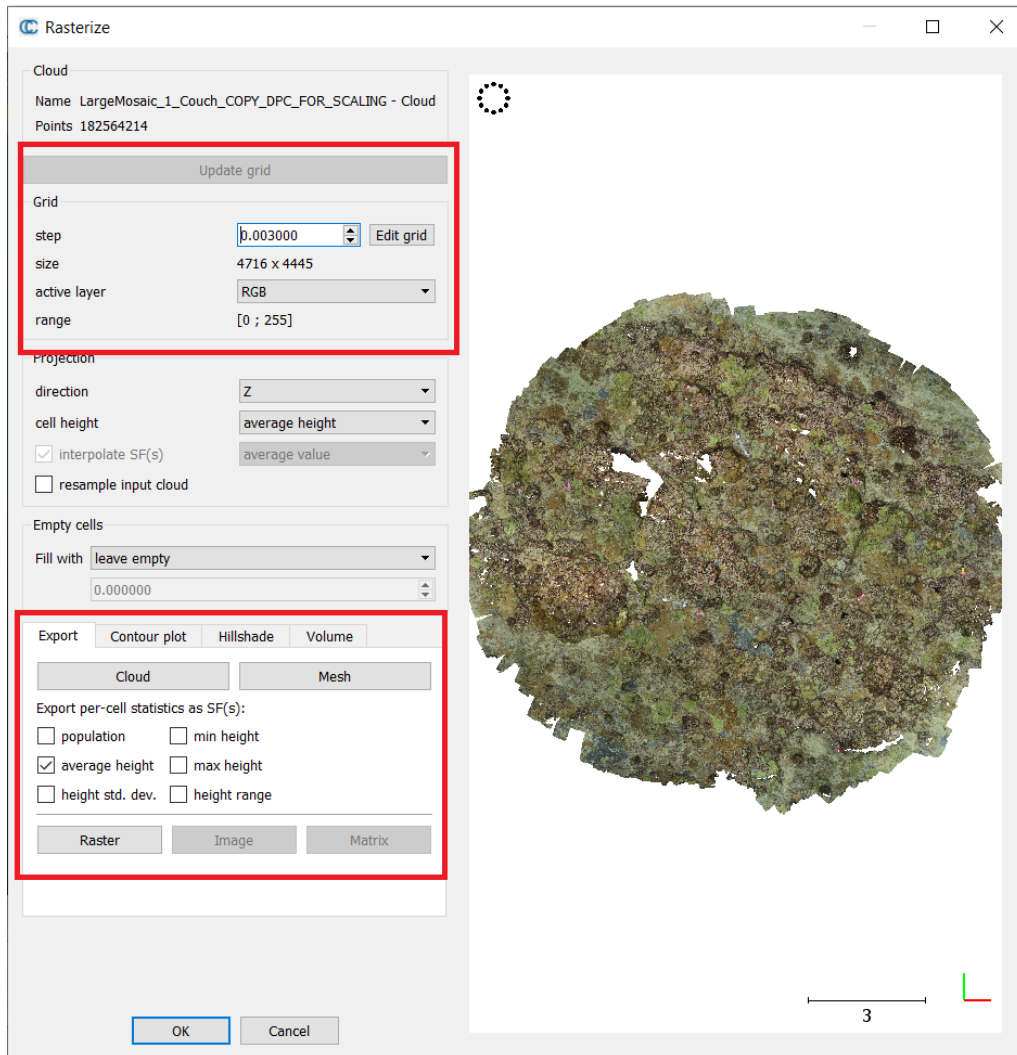
Figure 14. Screenshot in CloudCompare of the Rasterize tool used to export the 3D DPC as a 2D orthoprojection.

ArcMap Plot Setup

Using ArcMap 10.6.1, import the 2D orthoprojections for all time points in a given site to which you plan to add demographic annotations. First, orthoprojections are aligned into the same 2D space using the Georeferencing Tool. Next, using a constructed model, random points are dropped on the orthoprojections and buffered to create quadrats.

Add Exported Orthoprojection

1. Open ArcMap 10.6.1. Import the 2D orthoprojections using the Add Data button.
   a. If not previously connected, use the Connect to Folder tool to add the folder in which the orthoprojections are stored.
   b. "Unknown Spatial Reference" will pop up-- OK
2. Under View, click on Data Frame Properties
   a. Under General, change Map and Display to meters-- Apply

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b. Project coordinate system
   i. A coordinate system is necessary to make measurements in ArcMap. Any coordinate system can be chosen, but you must use the same coordinate system throughout the project. As an example, we use UTM- WGS 1984- Northern Hemisphere- WGS 1984 UTM Zone 4N.
   ii. Under Coordinate System, set to WGS 1984 UTM Zone 4N-- OK
      1. If not previously done, navigate to Projected Coordinate System- UTM- WGS 1984- Northern Hemisphere- WGS 1984 UTM Zone 4N. Right click to Add to Favorites.

3. Using the Search window on the right-hand side (if it is not already there, locate under Geoprocessing), use Define Projection (Data Management) to assign the coordinate system to all orthoprojections and the grid.
   a. Input Dataset or Feature Class: Site#_orthoprojection.tif
   b. Coordinate System: WGS 1984 UTM Zone 4
      i. Repeat until all orthoprojections and grid are defined.

4. Check to ensure your rescaled orthoprojections are correct by using the measuring tool to measure the distance between targets on the GCPs (the scale bars). They should be 0.5 m (SIO or early ESD imagery) or 0.25 m (current ESD imagery) apart.

5. The color of the rescaled file will be altered. Double click on the layer and under symbology uncheck "Apply Gamma Stretch" and change Stretch Type to None.
   a. Repeat for all orthoprojections.

6. Save the ArcMap project as Site#_VitalRates in the ARC folder in the Project folder. We name the project folder with the Site#.
   a. Pay close attention to where the saved file is located. It will automatically default to ArcGIS default Geo Database.
   b. Save all work in ArcMap to the Site#/ARC folder!

Align Orthoprojections

Orthoprojections are aligned using ArcMap to ensure that live coral patches can be efficiently tracked over time to estimate coral vital rates. The Georeferencing tool is used to drag the raster until all orthoprojections are aligned.

1. Choose a reference layer.
   a. The reference should be the orthoprojection with the most substantial overlap with other orthoprojections from the same site. All other orthoprojections will be aligned to the reference orthoprojection.

2. Under the Customize tab at the top of the screen, click Toolbars, then click Georeferencing.

3. A box will pop up. In the drop-down menu, choose the orthoprojection you want to re-align.

4. Change transparency of the layer you are re-aligning (double click on the layer, click Display, and change transparency to 50%).

5. At the far right of the georeferencing toolbar, change rotate to shift (or use the rotating tool if you need to correct the rotation).
6. Drag the layer until it is properly aligned. Use the rotate tool to rotate the layer until it is properly aligned.
   a. Repeat this process until all orthoprojections are completely aligned/overlapping. The better the alignment, the easier it will be to link the coral patches across time points.
7. Save the re-alignment using one of the following methods:
   a. Preferred method: In the toolbar, click Georeferencing and Rectify. This creates a new raster with the shifted alignment.
      i. In the Save As window, leave everything as is except change name to Site#_align.
      ii. Although the name of the aligned Site#_orthoprojection in the Table of Contents will not change, the layer has been rectified.
   b. In the toolbar, click Georeferencing and Update Georeferencing.
      i. This changes the original orthoprojection .tif file and you can NOT undo the shift.
   c. Both of these processes can take several minutes to run.
8. Save the ArcMap project.

Creating Quadrats Using Model

Due to the labor-intensive and time-consuming nature of annotation, we have adopted a randomized sub-sampling strategy that provides enough colony transitions across a wide range of size classes to fit robust demographic models and still proceed efficiently through many sites' worth of data. We do so by randomly "dropping" 25 0.5 m² quadrats and delineating colonies that fall inside them.

After constructing the model in ArcMap model builder (Appendix B), it can be used for all subsequent delineations. First, create a point and place it in the center of the overlapping area within the rescaled orthoprojections. Finally, run the model to create quadrats, and label each quadrat with consecutive numbers.

Editor Toolbar

A: Editor drop-down menu
B: Edit tool- select features
C: Edit annotation tool (not needed)
D: Segment drawing tools- these will be used when creating features
E: Point (Add point to edit sketch)
F: Edit Vertices

G: Reshape Features Tool
H: Cut Polygons
I: Split Shapefile/Polygon Tool
J: Rotate Shapefile/Polygon Tool
K: Attributes
L: Sketch Properties
M: Create Feature
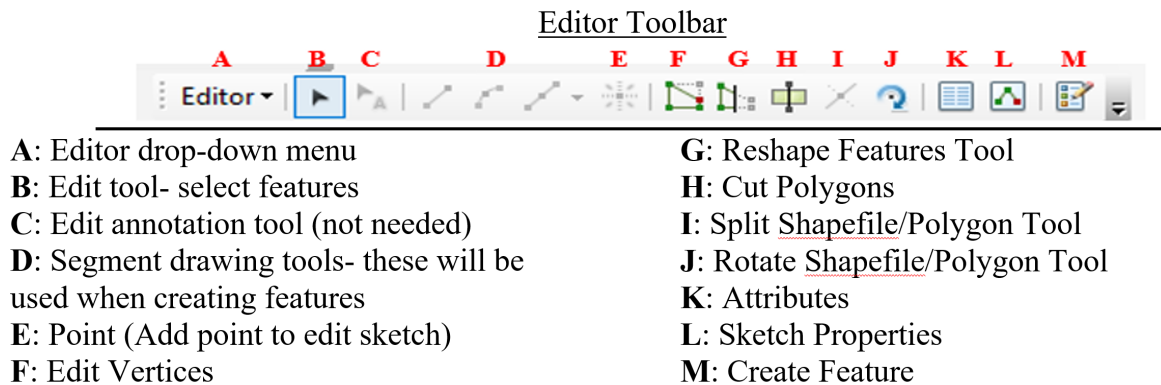
Figure 15: Editor toolbar in ArcMap.

1. In some cases, a center point does not do a good job of creating quadrats that fall in the overlapping areas.
    a. If the orthoprojections have poor overlap (i.e., only ~25% overlap exists between orthoprojections), refer to step 6.
    b. Quadrats will be placed in a ~5-m radius around the center point. If it is likely that many quadrats will not overlap with the aligned orthoprojections, refer to step 6.
2. If the orthoprojections have good overlap, create a center point for a 10 m ×10 m box that will be used in later steps:
    a. Right click on the site's ARC folder in the Catalog and select New- Shapefile…
        i. Name: Site#_centerpoint
        ii. Feature Type: Point
        iii. Spatial Reference, Description: WGS 1984 UTM Zone 4N (change this by clicking Edit…)
        iv. Leave everything unchecked-- OK
    b. Under Customize, open the Editor Toolbar (found under Toolbars).
        i. Drag to the main toolbar (this will only need to be done the first time).
    c. Drop down Editor and Start Editing (A in Editor Toolbar screenshot above).
    d. Open Create Features (M in Fig. 15), drag to the right side of your window, and pin it there (again, only needs to be done the first time opening ArcMap).
    e. Click on "Point" at the bottom of Create Features. Place your point at the center of the greatest overlap between all of your aligned orthoprojections.
    f. Once your point is drawn, drop down Editor (A), Save Edits and then Stop Editing.
3. Open up the Model_Build_Quadrats. In the Catalog under the FixedSiteProducts folder, expand the VR_Toolbox and double click on Model_Build_Quadrats.
    a. If the model is not yet built, see Appendix II.
    b. Following the examples given in the screenshot, change the inputs accordingly. Ensure that each parameter file location is saved to the **correct file location in your FixedSiteProducts/Site#/ARC folder**!
        i. Output location (ARC folder): navigate to ARC folder
        ii. Center point: click the drop-down arrow and select the centerpoint shapefile you created earlier (Site#_centerpoint)
        iii. Circle (name + output location): navigate to ARC folder and rename Site#_circle
        iv. Bounding box (name + output location): navigate to ARC folder and rename Site#_box
        v. Random points (name): rename Site#_randompoints
        vi. Circplots (name + output location): navigate to ARC folder and rename Site#_circplots
        vii. Quadrats (name + output location): navigate to ARC folder and rename Site#_quadrats

viii. Number of points [value or field] (optional): Long = 25

ix. Code block (optional): copy and paste the following:

```
rec=0
def autoIncrement():
 global rec
 pStart = 1
 pInterval = 1
 if (rec == 0):
  rec = pStart
 else:
  rec += pInterval
 return rec
```

x. Click OK.
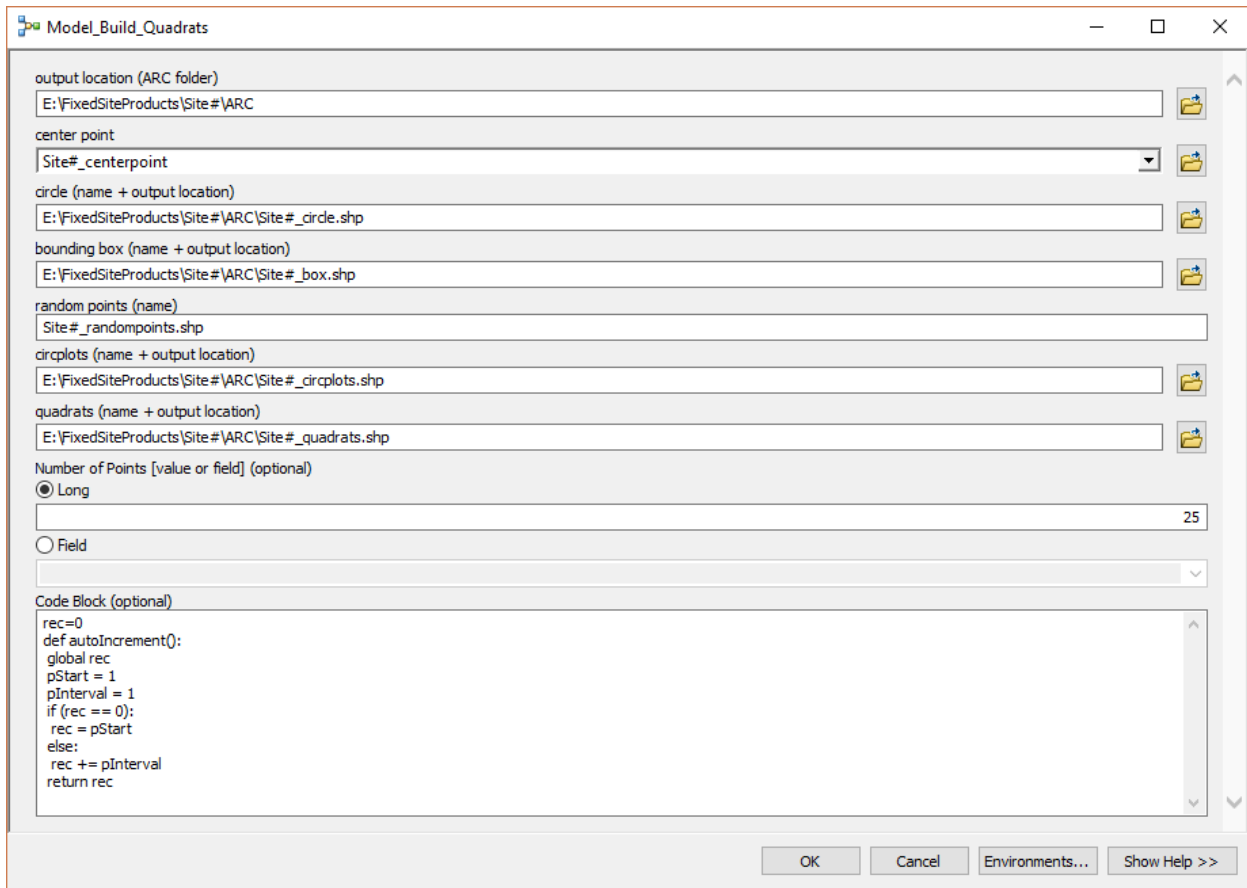
Figure 16. Screenshot of ArcMap of the Model_Build_Quadrat parameters. Change each input site name and when indicated, the output location.

4. If there is an error message and the model does not run, navigate to the Results and expand Messages to see what failed:

    a. Often the error is a result of invalid characters. ArcMap does not like hyphens (-), number signs (#), spaces, or periods in filenames. Only use underscores (_).

b. Additionally, any tool in the model run before the error will have created the file. In your Catalog, delete those files to avoid errors (e.g., "Dataset already exists") when rerunning the model.
  i. For example, if the bounding box failed, the model would have created Site#_circle. In your Catalog, navigate to the shapefile, right click, and delete. Refresh the ARC folder in the Catalog again.
c. Return to your Model_Build_Quadrats, correct the tool that caused the error, and re-run the model.

5. Once the model has run, all of the outputs will automatically be added to the Table of Contents. To reduce clutter and confusion, remove the extraneous shapefiles (optional).
  a. Right click and click remove for Site#_centerpoint, Site#_circplots, Site#_box, and Site#_circle.

6. If the orthoprojections do NOT have good overlap (i.e., multiple quadrats will not end up overlapping with the aligned orthoprojections):
  a. Right click on the site ARC folder in the Catalog and select New-Shapefile…
    i. Name: Site#_box
    ii. Feature Type: Polygon
    iii. Spatial Reference, Description: WGS 1984 UTM Zone 4N (change this by clicking Edit)
    iv. Leave everything unchecked-- OK
  b. Drop-down Editor and Start Editing (A in Editor Toolbar screenshot above).
  c. Open Create Features and choose Polygon as the construction tool. Draw a square on your aligned orthoprojections, ensuring that your square covers the areas with overlap.
    i. Once drawn, Save Edits and Stop Editing.
  d. Open up the Model_PoorOverlap_Build_Quadrats. In the Catalog under the FixedSiteProducts folder, expand the VR_Toolbox. Right click on Model_PoorOverlap_Build_Quadrats and click edit.
    i. If the model is not yet built, see Appendix II.
    ii. Following the examples given in the screenshot, change the inputs accordingly. Ensure each parameter file location is saved to the **correct file location in your FixedSiteProducts/Site#/ARC folder**!
      1. Output location (ARC folder): navigate to ARC folder
      2. Box: click the drop-down arrow and select the box shapefile you created earlier (Site#_box)
      3. Random points (name): rename Site#_randompoints
      4. Circplots (name + output location): navigate to ARC folder and rename Site#_circplots
      5. Quadrats (name + output location): navigate to ARC folder and rename Site#_quadrats

6. Number of Points [value or field] (optional): Long = 25
7. Code Block (optional): copy and paste the following

```
rec=0
def autoIncrement():
 global rec
 pStart = 1
 pInterval = 1
 if (rec == 0):
  rec = pStart
 else:
  rec += pInterval
 return rec
```

8. Click OK.
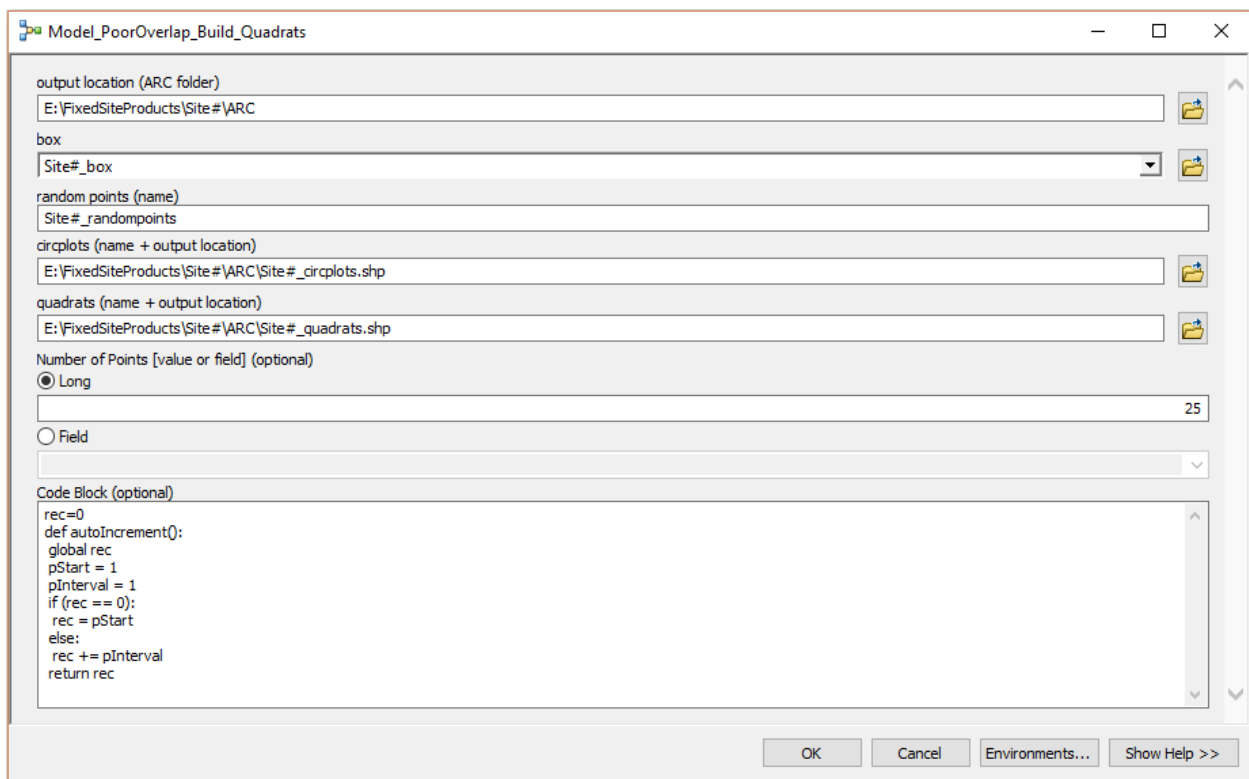
Figure 17. Screenshot in ArcMap of model parameters used for orthoprojections with minimal overlap to create and label quadrats to subsample the orthoprojections.

7. To view the polygons as perimeters rather than opaque squares, click on the colored rectangle under the layer name within the Table of Contents.
   a. Change Fill color to none
   b. Increase the Outline Width to 1
   c. Change the Outline Color to any color that is easily visible on the orthoprojection.
8. Double click the quadrats layer within the Table of Contents. In the Labels tab, check "Label features in this layer".
   a. In the Label Field box, choose the Label field (QuadNum)

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b. Change the color of the labels to the same color as the quadrat outline color
c. Change the size to 10
d. Press OK

View Raw Imagery Using Agisoft Metashape

The image view tool in Agisoft should be used in conjunction with ArcMap to view raw imagery while delineating live coral tissue in ArcMap. Viewing the original underlying images from the DPC allows the delineator to examine plot details that may not be clear in the orthoprojection, making delineations more accurate.

1. Open a new project in Agisoft and open the Site#.psx to view the DPC (Fig. 18).
2. Zoom into the area of interest. Right click and add a marker. Right click again and filter photos by point.
    a. If you wish to view another point in the model, delete the current marker and a new one.
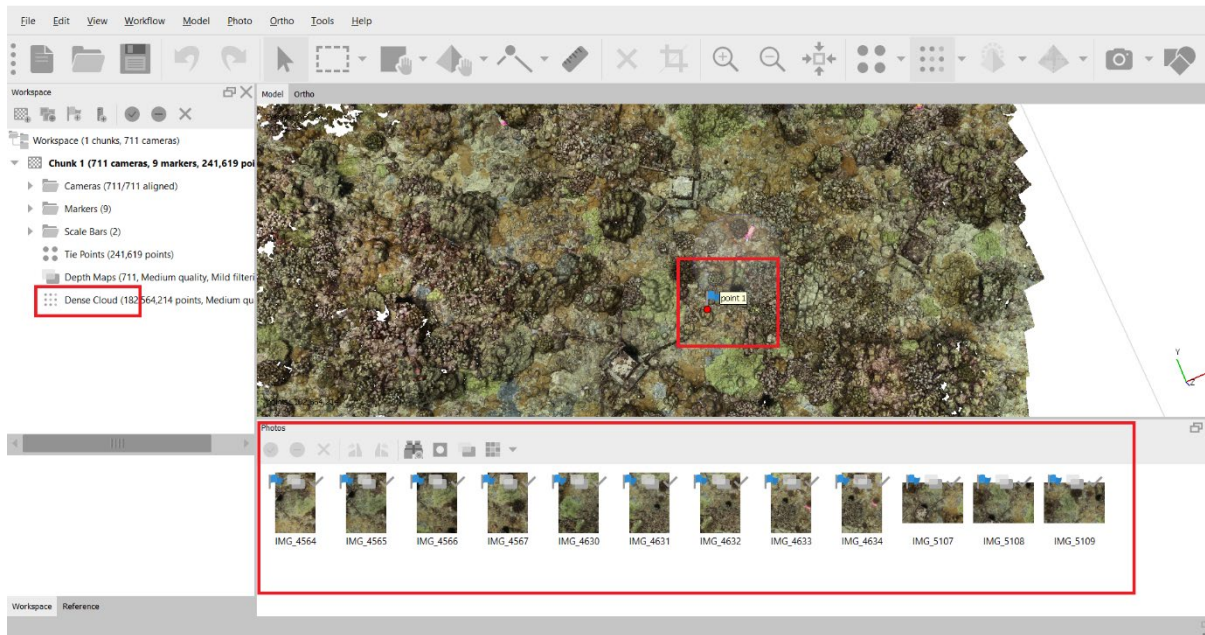
Figure 18. Screenshot of a marker added to a DPC in Agisoft.

3. Only images that contain that point will be shown in the photo pane (bottom of the screen). Double click on any of the images in the photo pane to view the photo. A flag will automatically show on the image where you placed the marker (Fig. 19).
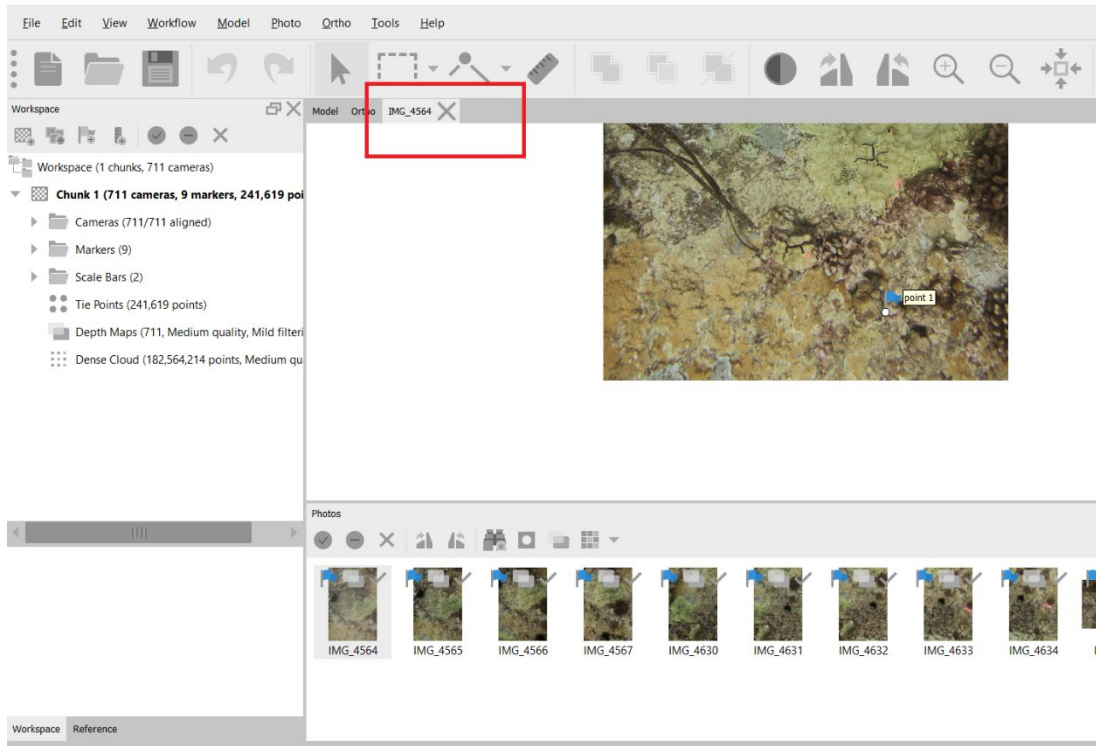
Figure 19. Screenshot of the raw images associated with the marker in Agisoft.

ArcMap Segmentation and Annotation

Using ArcMap, the analyst extracts Vital Rates demographic data using the exported orthoprojections. The analyst delineates live patches of coral within the quadrats and links the patches between years in order to build transition tables used for demographic modeling. This process consists of four steps: delineation of features, linking between time points, populating the attribute table, and exporting the attribute table.

Delineation of Features

ArcMap is used to collect growth, mortality, and recruitment data of coral populations captured within each orthoprojection. After creating a geodatabase that contains all necessary fields, live patches of coral whose centroid falls inside of the quadrats are outlined by hand. Depending on the density of the reef, this process can be very time consuming. We are currently working with several partners to incorporate automated delineation and machine learning that will significantly reduce the time to segment all live patches.

Read the entire segmentation section before beginning delineation. The sampling process is complex, and it is important to understand the entire procedure before starting.

Set up the delineation feature class:
1. If a template geodatabase has not been built, see Appendix II.
    a. Do NOT edit the VitalRateCodes in the FixedSiteProducts folder. The geodatabase uses this file and will not function without it.

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2. If a template geodatabase has already been made, navigate to the SiteName.gdb file within the FixedSiteProducts folder which has the proper attribute fields and will be used in all future annotations.
    a. Copy and paste the SiteName.gdb file into your current ARC project folder.
    b. Rename the SiteName.gdb with the proper site name.
    c. When you expand the .gdb file, there is a template feature class; right click and copy. Right click on your geodatabase and paste the template feature class into your renamed geodatabase.
    d. A data transfer window will appear. Only change template_1 under Target Name and rename template_1 to year_site#. Click OK.
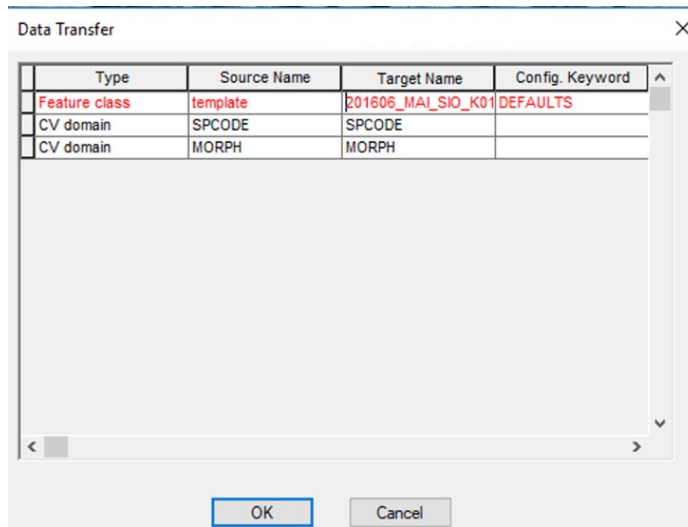
Figure 20. Screenshot in ArcMap changing the template_1 under Target Name to year_site#.

    e. Use a different feature class for each orthoprojection—copy and paste the template again and rename the feature class to year_site# until you have a feature class for each time point.
    f. Drag these feature classes into the Table of Contents.

Table 1. Definitions for each annotation column in ArcGIS attribute table.

Field Name	Type	Definition
OBJECTID		Arc will automatically assign this number.
Shape		Arc will automatically assign this number.
Site	Text	Name of the site (e.g., HAW_OCC_010).
Quadrat	Short Integer	Number of the quadrat of which the live patch is located (e.g., 1).

Field Name	Type	Definition
Date	Text	Date of image collection (e.g., 07/15/2019).
Spec_Code	Text	Drop-down list of taxon codes based on the taxa list (e.g., PMEA).
Morph_Code	Text	Drop-down list of live patch morphology codes (e.g., MD).
BLE_EXT	Short Integer	Percent of live patch that is bleached (e.g., 50).
BLE_SEV	Short Integer	Severity of bleaching (e.g., 2).
NoPatches	Text	Denotes a quadrat that has been surveyed but does not contain any of the target taxa. A square is drawn inside the quadrat and populated (e.g., EMPTY).
PatchID	Short Integer	Unique number assigned to each delineated patch (e.g., 7).
PatchName	Text	Unique patch name made up of the Site# + Quadrat# + Date + Spec_Code + PatchID (e.g., HAW_OCC_010_004_07/15/2019_PLOB_0039)
LinkTP_Bac	Text	List of PatchID(s) from the previous time points that identify the same patch(es) of tissue. If an individual patch was previously comprised of multiple patches, write all patches in the column without any spaces (e.g., 8,9,11).
LinkTP_For	Text	List of PatchID(s) in the succeeding time point that identifies the same patch of coral tissue.
Notes	Text	List any relevant notes that assist with future analyses or delineations (e.g., Spec_Code uncertain, partially beneath overhang, near hole in orthoprojections).
TimePt	Short Integer	Denotes the sequential order of the orthoprojections and their associated delineations. The oldest time point would be listed as 1.
Shape_Length	Double Integer	Patch perimeter. Arc will automatically calculate.
Shape_Area	Double Integer	Patch area. Arc will automatically calculate.

3. To make the polygons an outline rather than colored shape, double click on the colored box under the site layer name.
   a. Change fill color to "no color" and the outline width to 1.
   b. To ensure there is no confusion between each feature class/time point, change each time point to a different outline color, preferably a bright color so it stands out from the orthoprojection.
   c. Change the outline color for the oldest orthoprojection to red, orange for the second oldest orthoprojection, yellow for the orthoprojection, etc. It is easy to get confused about which orthoprojection and feature class you are using for delineation and using ROYGBIV can reduce some of the confusion.
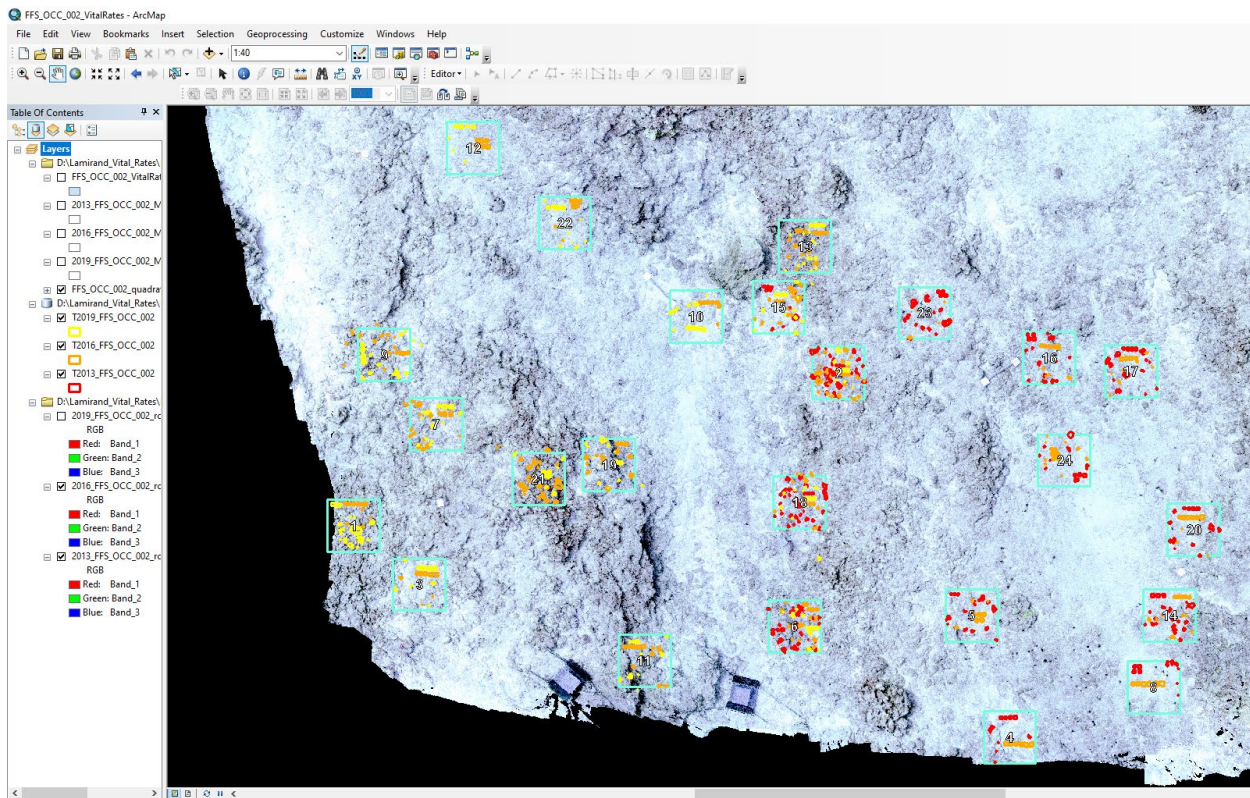
Figure 21. Screenshot in ArcMap of an orthoprojection with quadrats (in white) and the different colors used for each delineation shapefile. In this example, 2013 is delineated in red, 2016 in orange, and 2019 in yellow.

Criteria for delineating live patches:
1. Start delineations of target coral species in the oldest time point available. The oldest time point will be referred to as time point 1.
2. If the center (centroid) of a live patch is found within the boundaries of the quadrat, delineate the live patch.
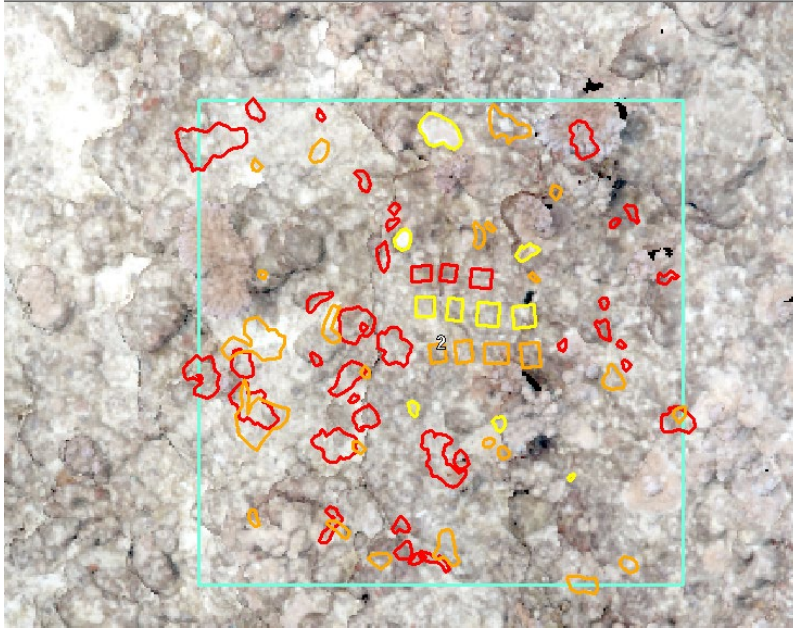
Figure 22. Screenshot in ArcMap of live patch delineations. If the center of a live patch falls within the quadrat, delineate the patch. In this example, 2013 is delineated in red, 2016 in orange, and 2019 in yellow.

    a. If the centroid of the live patch falls outside of the quadrat, do NOT delineate the live patch.

    b. To avoid biasing against large colonies, if a large live patch takes up 75% or more of a quadrat, delineate the patch even if the centroid falls outside of the quadrat.

    c. If a live patch's centroid is inside a quadrat in the first time point, yet the centroid is no longer inside the quadrat in a subsequent year(s), delineate the live patch in each time point.

    d. Similarly, if a large patch's centroid in time point 1 is not inside the quadrat, but the patch breaks into fragments in time point 2 and one or more of the fragments are inside the quadrat, delineate the patch in time point 2 and go back and delineate the large patch in time point 1.

3. Before delineating a quadrat, check all time points to ensure that none has a blank space in the quadrat or is located near the edge (Fig. 21).

    a. If one time point contains a blank space in a quadrat or is within 2 m of the orthoprojection perimeter or a large (>1-mdiameter) blank space, do not annotate within that quadrat for all time points. Instead, use the Rectangle tool to draw a square in the quadrat. In the attribute table, enter the quadrat number in the Quadrat column and in the "NoPatches" column write "EMPTY" so the quadrat is not counted in the total area surveyed.

    b. If a quadrat is within 2 m of the orthoprojection perimeter or a large (>1m diameter) blank space in the orthoprojection, choose a different quadrat to delineate for all time points if possible. If you must delineate within 2 m of the

orthoprojection perimeter or a blank space in the orthoprojection, make a note of it in the Notes column of the attribute table.

  i. These sections of the model can possess distortion that may influence our ability to extract accurate vital rates from these live patches.

  c. If you have already delineated a patch in 1+ time points and come across a time point with blank space in a quadrat, skip delineation for the time point with a blank space and write "SKIP" in the NoPatches column of the attribute table. Resume delineating in subsequent time points if there is no longer a blank space in the orthoprojection.
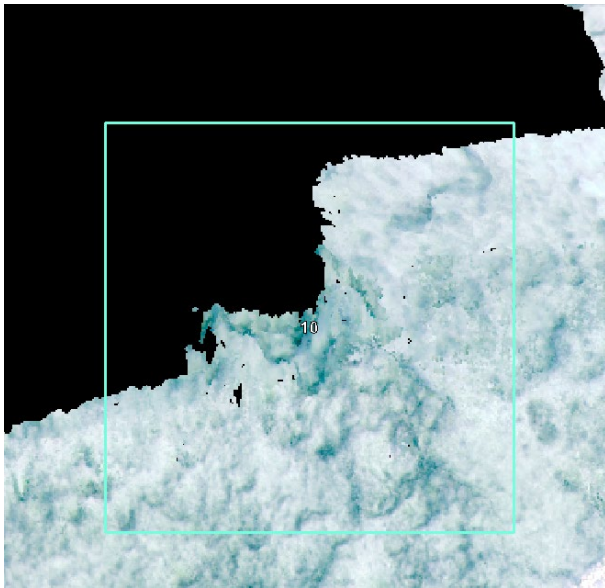
Figure 23. Example of an orthoprojection with blank spaces inside a quadrat. For this time point, the delineator would skip delineating in this quadrat.

How to delineate coral patches:

1. Drop down Editor and Start Editing (Fig. 15 A).
2. In the Create Features window, click on year_Site# feature class and make sure the selected construction tool is Free Hand.
   a. Depending on annotator preference, the Polygon tool can also be used. This tool can be useful for delineating smaller live patches.
3. Zoom into the colony you want to delineate and click once to begin your polygon, then follow the outline of the live patch. Once finished tracing, click to end the delineation.
   a. For the Freehand tool, ArcMap does not allow users to delineate at zoom levels greater than 1:2.
4. To edit the points that make up a delineation (called vertices), use the Edit Vertices tool (Fig. 15 F) to move, delete, or add points.
5. If you make an incorrect polygon during the tracing step and want to delete it:
   a. Click the black edit arrow in the toolbar.

b. Hold shift and click the polygon you want to delete. Then click the X button in the toolbar.

6. When delineating colonies located next to each other, sometimes the vertices will intersect. If this happens and an extra polygon is created, delete any of these polygons before creating the Patch IDs.
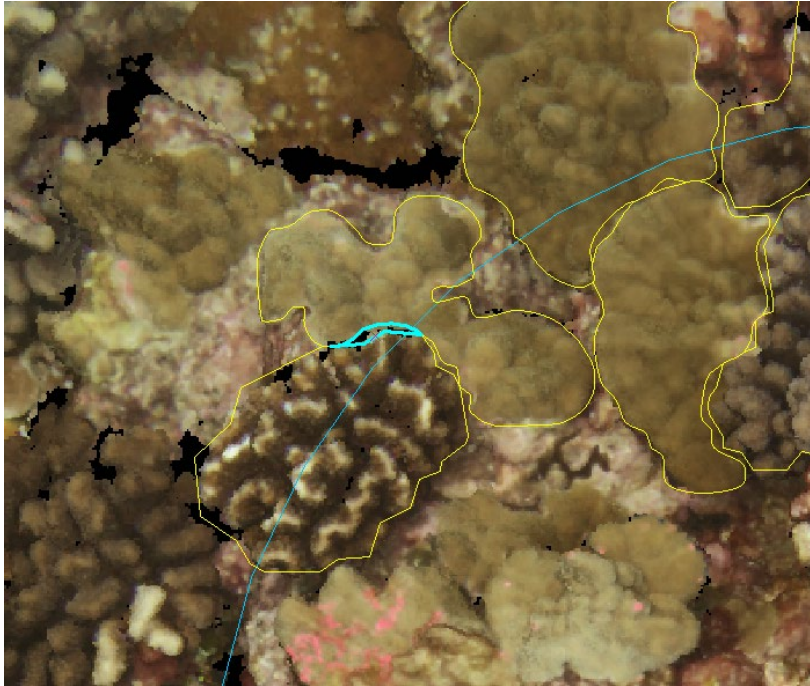
Figure 24. Screenshot in ArcMap showing a superfluous polygon that should be deleted.

4. Periodically save your edits and fill in the species codes within the attribute table.
   a. Click on the Editor toolbar drop-down menu and click Save Edits.
   b. Open the delineation shapefile attribute table and select the appropriate species codes from the drop-down menus.
   c. Species Codes:
      i. For each patch, select the species code from the drop-down menu (Appendix D).
      ii. If you cannot ID to the species level, select the genus code from the drop-down menu (Appendix D).

5. In addition to the species code, periodically fill out the morphology, bleaching extent, and bleaching severity fields.
   a. Morphology:
      i. For each patch, select the morphology code from the drop-down menu (Appendix E).
   b. Bleaching:
      i. For each patch of live coral, record the bleaching extent and severity (Appendix F).

6. If a coral has dead tissue surrounded by live tissue:
   a. Under Create Features, use the Freehand Construction tool (or Polygon tool) to outline the outermost border of the live patch.
   b. With the same tool, separately outline all of the dead portions of the live patch. These parts will be removed from the polygon.
   c. If only one dead polygon needs to be removed:
      i. In the Table of Contents window, unselect the Site#_quadrats layer so your quadrat attribute table does not get clipped.
      ii. Open the attribute table and highlight the dead patch delineation.
      iii. On the Editor toolbar, click the Editor dropdown and click Clip.
         1. Buffer Distance: 0.000
         2. When clipping features: Discard the area that intersects
         3. Click OK
      iv. In the attribute table, highlight the dead patch polygon by clicking the square on the far left of the attribute table, right click, and choose Delete Selected. You will be left with a donut polygon that is now associated with the live patch area.
   d. If multiple dead polygons need to be removed:
      i. Highlight all of the dead patches in the attribute table (NOT the live patch) by clicking the square in the far-left corner of the attribute table and dragging. Alternatively, click one patch and then press shift and click (control + click on a Mac) and click on additional patches.
      ii. Under the Editor toolbar, click Merge. In the window that pops up click OK.
      iii. Ensure that the merged dead polygons are highlighted in the attribute table and under the Editor toolbar, click Clip.
         1. Buffer Distance: 0.000
         2. When clipping features: Discard the area that intersects.
         3. Click OK.
      iv. In the attribute table, highlight the dead patch polygon and delete it.
   e. To double check that you created your donut polygons correctly, add a fill color to your delineations (Fig. 30).
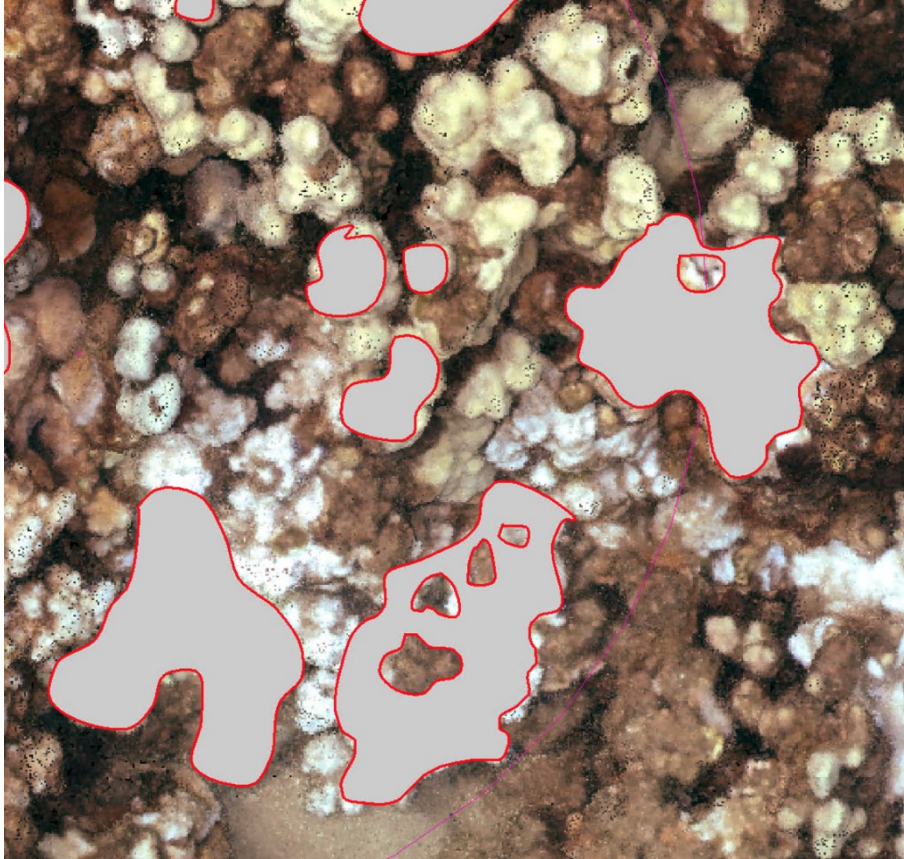
Figure 25. Example donut polygons. The two corals on the far right have partial mortality surrounded by live tissue. These non-living patches were removed to reflect the correct area of the live patch.

When to Stop Delineating:

1. For the first 10 quadrats, delineate all live patches from the target taxa list. After delineating the first 10 quadrats and reaching ~40 live patches for a target species, check its size class distribution by creating a histogram in ArcMap.
2. Before creating the histogram, separate delineations by species.
    a. At the top of the screen or within the attribute table, click Selection and click on Select by Attributes.
    b. Double click Spec_Code, then click the =.
    c. Click Get Unique Values and double click on the species of interest.
    d. Click OK.
3. To create the histogram, use the Geostatistical Analyst toolbar.
    a. If the Geostatistical Analyst toolbar is not visible, under the Customize tab on the top of the screen, click Extensions and check the box next to Geostatistical Analyst and close the window. Click Customize again, click Toolbars, and then click Geostatistical Analyst.
    b. Turn editor off.

c. On the toolbar, click Geostatistical Analyst, point to Explore Data, and click Histogram. An error message may appear. Click OK.
d. At the bottom of the window, change the Attribute field to Shape_Area.
e. Under transformation, change it to Log.
f. Change the number of bars to 6.
g. Your species of interest will appear as bright yellow or blue and the other species will appear as purple.
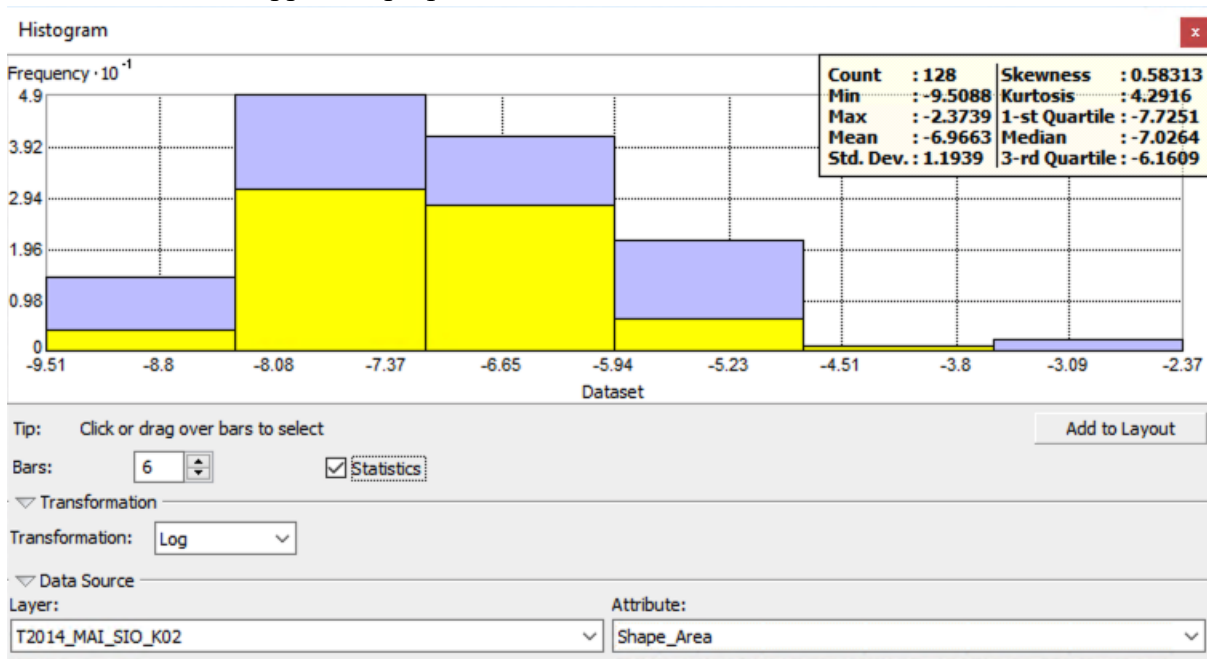
Figure 26. Histogram tool used to assess the size distribution of delineated patches. The area in yellow is the selected species and the purple area is all of the delineated colonies. The statistics are for ALL delineated colonies -- not only the selected species.

4. Use the histogram to assess if your delineations are skewed towards one size. You should aim to have a normal distribution for each target species with tails present (i.e., some small and large patches). If you reach a normal distribution, you can stop delineating that species (i.e., you can stop delineating as long as you have a few patches in the smallest and largest bins).
   i. Summary: If 40 patches of a given target species have been delineated across at least 10 quadrats and you have confirmed that they are well distributed across the size spectrum, stop delineating that species.
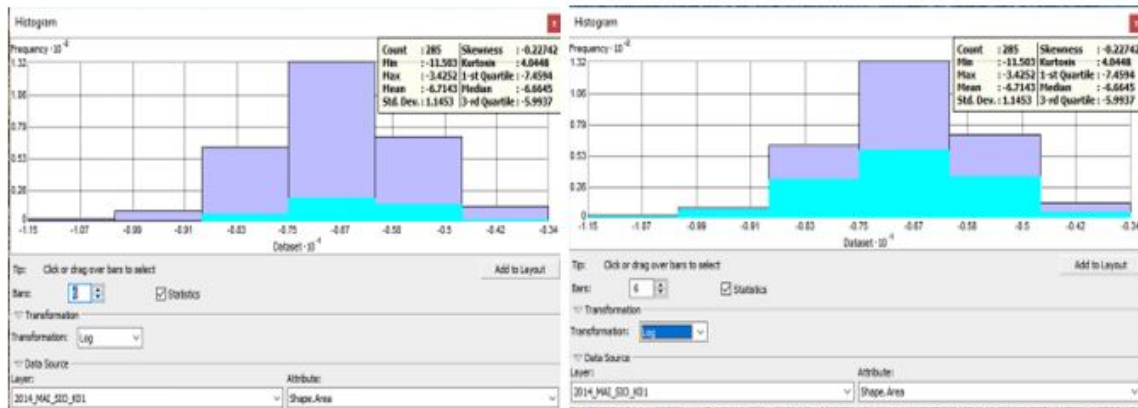
Figure 27. Example histograms in ArcMap. The histogram on the left does not have sufficient small live patches delineated (highlighted in blue) and the annotator should return to delineating. The example histogram on the right is normally distributed and has tails present. For this example, the annotator can stop delineating.

5. If you have delineated 10 quadrats but a target species has not reached a sample size of at least40 and/or does not have an appropriate size distribution, continue on to the next quadrat, but only delineate the species that are still needed.

   a. In some cases, it will not be possible to delineate40 or more live patches due to low species density at the site. In these cases, stop delineating once you reach n = 20.

      i. If a target species is absent or has an exceedingly low density (i.e., < 5 live patches in the first 10 quadrats), do not delineate this species.

   b. Check each quadrat for small patches of the target species rather than picking out the larger colonies that are more easily visible.

   c. In cases where more than 10 quadrats are required to gain an appropriate sample size for a given target species, search for and delineate live patches in order from quadrat 11–25 (or however many quadrats have been created). The quadrat with the highest label number that contains a delineation will be used to calculate sampling effort required for the target species. To properly measure sampling effort, the final quadrat surveyed must have either a live tissue delineation or a dummy delineation present.

      i. Ex: To reach n = 20 for a rare species, 25 quadrats are surveyed; in the last quadrat (quadrat 25), locate and delineate the species present in each. Therefore, we know that sampling effort required $25 \times 0.5 \text{ m}^2$ of reef.

      ii. Ex: To reach n = 20 for a rare species, 25 quadrats are surveyed; in the 20th quadrat (quadrat 20), locate and delineate the species. However, continue looking for the rare species in the remaining 5 quadrats. If no dummy delineation is placed in quadrat 25, it will be assumed that only 20

$\times$ 0.5 m² of reef was surveyed for this particular species, rather than 25 $\times$ 0.5 m². To remedy this, a dummy delineation must be placed in the final quadrat searched.

      iii.   Ex: When searching for a rare species past quadrat 10, you can choose to delineate 5 additional quadrats until you reach an adequate sample size. However, if you chose to survey 5 quadrats haphazardly this could cause problems. For example, if you delineated quadrats 20–25, but not 11–19, even though your sampling effort only increased by 5 $\times$ 0.5 m², it will appear as though sampling effort increased by 15 $\times$ 0.5 m² because quadrat 25 was delineated.

6. When a quadrat contains no live patches of any target taxa, create a dummy delineation in the quadrat to confirm that this area of the plot has been surveyed.
   a. Under Create Features, choose the rectangle construction tool and create a square in the quadrat containing the missing coral species.
   b. In the attribute table, fill in the species code and write "EMPTY" in the NoPatches and Notes column. Fill out the Quadrat column with the number of the quadrat (e.g., 3). Leave all other columns blank.
   c. If you increased sampling effort past 10 quadrats for only some species, do NOT add a dummy delineation for species you have stopped searching for.

7. If you have annotated all of the 25 quadrats and have not reached at least 20 live patches for a given species, add additional quadrats. This should only be done if adding more quadrats is likely to increase the number of delineations to at least 20. If you are unlikely to find more live patches with the addition of 10 or less quadrats, stop delineating. To create additional quadrats:
   a. Re-run Model_Build_Quadrats using the following guidelines:
      i.   In the Catalog under the FixedSiteProducts folder, expand the VR_Toolbox and double click on Model_Build_Quadrats.
      ii.   Following the examples given in the screenshot, change the inputs accordingly. Ensure each parameter file location is saved to the **correct file location in your FixedSiteProducts/Site#/ARC folder**!
         1. Output location (ARC folder): navigate to ARC folder
         2. Center point: Click the drop-down arrow and select the centerpoint shapefile you created before (Site#_centerpoint)
         3. Circle (name + output location): navigate to ARC folder and rename Site#_circle_2
         4. Bounding box (name + output location): navigate to ARC folder and rename Site#_box_2
         5. Random points (name): rename Site#_randompoints_2
         6. Circplots (name + output location): navigate to ARC folder and rename Site#_circplots_2

7. Quadrats (name + output location): navigate to ARC folder and rename Site#_quadrats_2
8. Number of Points [value or field] (optional): Long = 20 (or more)
9. Code Block (optional): copy and paste the following **(BE AWARE OF THE pStart CHANGE)**

```
rec=0
def autoIncrement():
 global rec
 pStart = 26
 pInterval = 1
 if (rec == 0):
  rec = pStart
 else:
  rec += pInterval
 return rec
```

10. Click OK
    a. If using the Model_PoorOverlap_Build_Quadrats model, make the changes similarly to above.
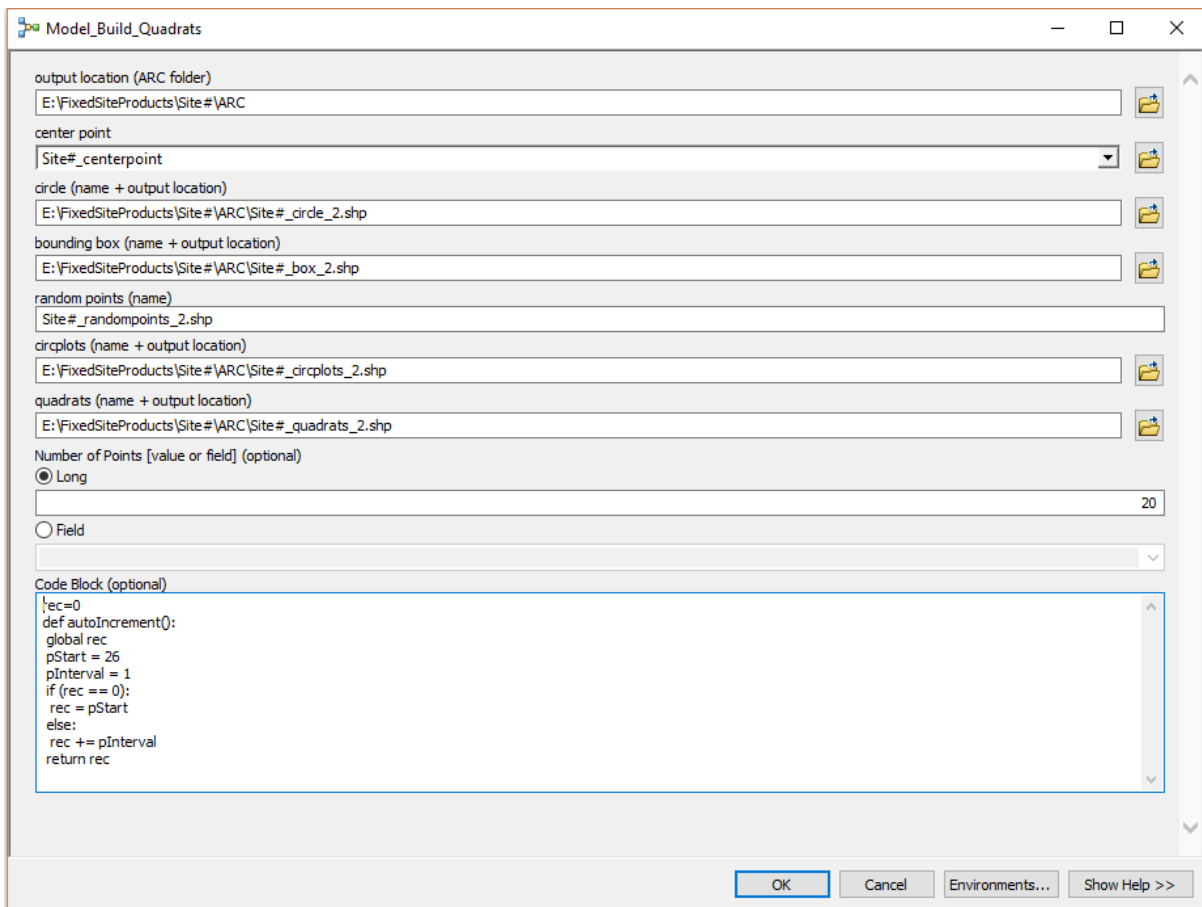
Figure 28. The model parameters with a changed output name for the quadrats. This ensures that the additional quadrats you will add to the model do not erase the quadrats that have already been annotated.

8. If any new quadrats overlap with the originals, they need to be removed (begin editing, highlight the new quadrat you want to remove, and delete).
   a.   Once the overlapped quadrats have been removed, renumber the remaining quadrats:
      i. Right click on the Site#_quadrats_2 and click Open Attribute Table.
      ii. Turn on Editor.
      iii. Highlight the QuadNum, right click and choose Field Calculator.
      iv. Click Python and click Show Codeblock.
      v. Copy and paste the following into the Pre-Logic Script Code **(BE AWARE OF THE pStart CHANGE)**:

```
rec=0
def autoIncrement():
    global rec
    pStart = 26
    pInterval = 1
    if (rec == 0):
        rec = pStart
    else:
        rec += pInterval
    return rec
```

   vi. In the QuadNum box below, copy and paste the following:
   ```
   autoIncrement()
   ```
   vii. Click OK.
   viii. Double click the quadrats layer within the Table of Contents. In the Labels tab, check "Label features in this layer".
   ix. In the Label Field box, choose the Label field (QuadNum). Press OK.
9. Once 40 live patches from each target species have been delineated and the patches cover a range of sizes, repeat with the next time point.
   a. You will "follow" each delineated coral through each time point and delineate the same coral in each time point in order to capture the patch's transition between each time point.
10. Once you have finished delineating, Save Edits and Stop Editing.

Linking Between Time Points

Once all target taxa have been delineated in every time point, the annotator will fill out the attribute table for each year. The Patch ID field is populated with consecutive numbers; this number is used to link patches across time points. Patch linkage will be used to analyze growth, mortality, fission, fusion, and recruitment.

1. Once all live patches have been delineated in each time point, left click on your shapefile, and click Open Attribute Table.
2. Although all fields will eventually be populated, start with the Patch ID and link the patches between years. Each live patch will receive a unique number for the site. This

number will be used to link patches between time points to ascertain how the patch changed over time. To populate the Patch ID field:

    a. Highlight the Patch ID field, right click, and select Field Calculator.

    b. Click Python.

    c. Click on Show Codeblock and in the Pre-Logic Script Code copy and paste:

```
rec=0
def autoIncrement():
 global rec
 pStart = 1
 pInterval = 1
 if (rec == 0):
  rec = pStart
 else:
  rec += pInterval
 return rec
```

    d. In the box below, copy and paste: `autoIncrement()`

    e. Click OK.

    f. For the attribute tables in subsequent time points, change the pStart number to the last number used so that the auto increment begins at the highest number and no numbers are re-used.

        i. Example: If there were 32 patches in the first time point, your code for the following time point will read as follows:

```
rec=0
def autoIncrement():
 global rec
 pStart = 33
 pInterval = 1
 if (rec == 0):
  rec = pStart
 else:
  rec += pInterval
 return rec
```

3. To link time points in the attribute table:

    a. Make sure both time point layers are visible.

    b. Use the Select Features by Lasso tool (white and blue square with arrow in the top left corner) and draw a lasso around the two polygons.

    c. Open up both Attribute tables. The selected polygons are highlighted in blue.

    d. Fill in the PatchID number for both the forward and backwards time point columns.

A

AW_SIO_K08

OBJECTID*	Shape*	Site	Circrat	Date	Spec_Code	Morph_Code	BLE_EXT	BLE_SEV	ColonyID	PatchID	PatchName	LinkTP_Bac	LinkTP_For	Notes
15	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	11	HAW_SIO_K08_02	NA	186	<Null>
16	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	12	HAW_SIO_K08_02	NA	-99.1	mortality
17	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	13	HAW_SIO_K08_02	NA	258,261	fission
18	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	14	HAW_SIO_K08_02	NA	262	<Null>
20	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	15	HAW_SIO_K08_02	NA	257	<Null>
21	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	16	HAW_SIO_K08_02	NA	265,266	fission
22	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	17	HAW_SIO_K08_02	NA	263	<Null>
23	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	18	HAW_SIO_K08_02	NA	255	<Null>
24	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	19	HAW_SIO_K08_02	NA	250	<Null>
25	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	20	HAW_SIO_K08_02	NA	248	<Null>
26	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	21	HAW_SIO_K08_02	NA	-99.1	mortality
27	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	22	HAW_SIO_K08_02	NA	237	<Null>
28	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	23	HAW_SIO_K08_02	NA	226	<Null>
29	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	24	HAW_SIO_K08_02	NA	-99.1	mortality
30	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	25	HAW_SIO_K08_02	NA	231	<Null>
31	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	26	HAW_SIO_K08_02	NA	225	<Null>
32	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	27	HAW_SIO_K08_02	NA	273	<Null>
38	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	29	HAW_SIO_K08_02	NA	248,250,251,252,253,254,274	fission
39	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	30	HAW_SIO_K08_02	NA	275	<Null>
40	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	31	HAW_SIO_K08_02	NA	224	<Null>
41	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	32	HAW_SIO_K08_02	NA	-99.1	mortality
42	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	33	HAW_SIO_K08_02	NA	286	<Null>
44	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	34	HAW_SIO_K08_02	NA	216,217,218,219,221	fission
45	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	35	HAW_SIO_K08_02	NA	223	<Null>
46	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	36	HAW_SIO_K08_02	NA	229,230,242	fission
48	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	37	HAW_SIO_K08_02	NA	214,215,248	fission
49	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	38	HAW_SIO_K08_02	NA	183,184,187,188,189,190,191,192,193,276,277,278	fission
50	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	39	HAW_SIO_K08_02	NA	279,280,281	fission
51	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	40	HAW_SIO_K08_02	NA	195,196,197,198,199,200,201,202,203,204	fission
52	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	41	HAW_SIO_K08_02	NA	205,306	fission
53	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	42	HAW_SIO_K08_02	NA	259,260,400	fission
54	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	43	HAW_SIO_K08_02	NA	264	<Null>
55	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	44	HAW_SIO_K08_02	NA	256,257,267,268,269,270	fission
56	Polygon	HAW_SI	2	04/13/20	PLOB	MD	<Null>	<Null>	<Null>	45	HAW_SIO_K08_02	NA	238,240,241,242,243,244,246,247,249,271	fission

(0 out of 183 Selected)

V_SIO_K08 | T2017_HAW_SIO_K08 | T2019_HAW_SIO_K08

22.224

Table

T2017_HAW_SIO_K08

OBJECTID*	Shape*	Site	Circrat	Date	Spec_Code	Morph_Code	BLE_EXT	BLE_SEV	ColonyID	PatchID	PatchName	LinkTP_Bac	LinkTP_For	Notes	TimePt	Shape_Length	Notes
1	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	183	HAW_SIO_K08	38	495,496	fission	2	0.214884	
2	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	184	HAW_SIO_K08	38	498	<Null>	2	0.097907	ity
3	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	185	HAW_SIO_K08	-99.1	-99.2	recruitment,mort	2	0.060743	
4	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	186	HAW_SIO_K08	11	495	<Null>	2	0.124967	
5	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	187	HAW_SIO_K08	38	492	<Null>	2	0.06463	
6	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	188	HAW_SIO_K08	38	493	<Null>	2	0.11302	
7	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	189	HAW_SIO_K08	38	494	<Null>	2	0.198288	
8	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	190	HAW_SIO_K08	38	494	<Null>	2	0.142942	
9	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	191	HAW_SIO_K08	38	499	<Null>	2	0.251882	
10	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	192	HAW_SIO_K08	38	500	<Null>	2	0.127896	
11	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	193	HAW_SIO_K08	38,4	505,504	fusion,fission	2	0.754799	
12	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	194	HAW_SIO_K08	38	546	<Null>	2	0.14187	
13	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	195	HAW_SIO_K08	40	550	<Null>	2	0.217138	
14	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	196	HAW_SIO_K08	40	551	<Null>	2	0.314322	ity
15	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	197	HAW_SIO_K08	40	549	<Null>	2	0.168152	
16	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	198	HAW_SIO_K08	40	548	<Null>	2	0.074421	
17	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	199	HAW_SIO_K08	40	547	<Null>	2	0.161897	
18	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	200	HAW_SIO_K08	40	545	<Null>	2	0.091095	
19	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	201	HAW_SIO_K08	40	546	<Null>	2	0.158587	
20	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	202	HAW_SIO_K08	40	546,544	fission	2	0.559067	
21	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	203	HAW_SIO_K08	40	560	<Null>	2	0.291353	ity
22	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	204	HAW_SIO_K08	40	560,510	fission	2	0.278915	
23	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	205	HAW_SIO_K08	41	509	<Null>	2	0.106304	
24	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	206	HAW_SIO_K08	7	511	<Null>	2	0.184717	
25	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	207	HAW_SIO_K08	7	511	<Null>	2	0.143854	
26	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	208	HAW_SIO_K08	7	543	<Null>	2	0.270864	
27	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	209	HAW_SIO_K08	8	-99.2	mortality	2	0.045693	
28	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	210	HAW_SIO_K08	8	-99.2	mortality	2	0.071094	
29	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	211	HAW_SIO_K08	6	513	<Null>	2	0.337119	
30	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	212	HAW_SIO_K08	5	513	<Null>	2	0.103607	
31	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	213	HAW_SIO_K08	5	513	<Null>	2	0.290826	
33	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	214	HAW_SIO_K08	37	512	<Null>	2	0.069859	
34	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	215	HAW_SIO_K08	37	512	<Null>	2	0.240859	
35	Polygon	HAW_SI	2	04/08/20	PLOB	MD	<Null>	<Null>	<Null>	216	HAW_SIO_K08	34	483,513	fission	2	0.747505	

(0 out of 269 Selected)

T2015_HAW_SIO_K08 | T2017_HAW_SIO_K08 | T2019_HAW_SIO_K08

22.224

Figure 29. Screenshot of attribute tables in ArcMap demonstrating how to link patches between three time points. Use the Patch ID to link patches from the first time point to the next time point. (A) Shows the first time point with all of the Link Forward column filled in while (B) shows the middle time point that has been linked both backwards and forwards and (C) shows the latest time point that is only linked backwards.

OBJECTID*	Shape*	Site	Circrat	Date	Spec_Code	Morph_Code	BLE_EXT	BLE_SEV	ColonyID	PatchID	PatchName	LinkTP_Bac	LinkTP_For	Notes
1	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	457	HAW_SIO_K08	264,267	NA	fusion
2	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	458	HAW_SIO_K08	263	NA	<Null>
3	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	459	HAW_SIO_K08	265	NA	<Null>
4	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	460	HAW_SIO_K08	268	NA	<Null>
5	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	461	HAW_SIO_K08	269	NA	<Null>
6	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	462	HAW_SIO_K08	-99.2	NA	recruitment
8	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	463	HAW_SIO_K08	246,247	NA	fusion
9	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	464	HAW_SIO_K08	245	NA	<Null>
10	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	465	HAW_SIO_K08	249	NA	<Null>
11	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	466	HAW_SIO_K08	237,238,239,240,243,24	NA	fusion
12	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	467	HAW_SIO_K08	243	NA	<Null>
16	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	468	HAW_SIO_K08	241,242,244	NA	fusion
17	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	469	HAW_SIO_K08	240	NA	<Null>
18	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	470	HAW_SIO_K08	242	NA	<Null>
19	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	471	HAW_SIO_K08	242	NA	<Null>
20	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	472	HAW_SIO_K08	230,401	NA	fusion
21	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	473	HAW_SIO_K08	229	NA	<Null>
23	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	474	HAW_SIO_K08	226	NA	<Null>
24	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	475	HAW_SIO_K08	225	NA	<Null>
25	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	476	HAW_SIO_K08	-99.2	NA	recruitment
26	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	477	HAW_SIO_K08	272,273	NA	fusion
27	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	478	HAW_SIO_K08	223,224	NA	fusion
28	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	479	HAW_SIO_K08	222	NA	<Null>
29	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	480	HAW_SIO_K08	228	NA	<Null>
30	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	481	HAW_SIO_K08	228	NA	<Null>
31	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	482	HAW_SIO_K08	218,219	NA	fusion
32	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	483	HAW_SIO_K08	216,221	NA	fusion
33	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	484	HAW_SIO_K08	274	NA	<Null>
34	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	485	HAW_SIO_K08	256,257	NA	fusion
35	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	486	HAW_SIO_K08	259	NA	<Null>
36	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	487	HAW_SIO_K08	259,260,261	NA	fusion
37	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	488	HAW_SIO_K08	266	NA	<Null>
38	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	489	HAW_SIO_K08	259,400	NA	fusion
39	Polygon	HAW_SI	2	07/19/20	PLOB	MD	<Null>	<Null>	<Null>	490	HAW_SIO_K08	260	NA	

0 ▸ ▸ (0 out of 223 Selected)

T2015_HAW_SIO_K08 T2017_HAW_SIO_K08 T2019_HAW_SIO_K08

e. For complete mortality or recruitment, record −99.n (where n represents the time point number) and write mortality or recruitment in the notes section. The −99 represents the patch that isn't there and the n is the time point in which it should be there.

f. As a reminder, time point 1 is the oldest year, time point 2 is the next oldest year, etc.

g. Ex: Patch ID 1 in 2016 is the same patch as Patch 34 in 2019. In the 2016 layer attribute table, record 34 in the LinkTP_For column. In the 2019 layer attribute table, record 1 in the LinkTP_Bac column.

h. Ex: If a coral appears in time point 2, it is recruitment. Record −99.1 (the 1 signifies that recruitment occurred because there was no coral in time point 1) in LinkTP_Bac for the delineated patch.

i. Ex: If a coral dies in time point 2, it is mortality. Record −99.2 (the 2 signifies that mortality occurred by time point 2) in the LinkTP_For column for the delineated patch.

j. Ex: If there is no coral in time point 1, a hole in the DPC in time point 2, and a coral appears in time point 3, record −99.1 in the LinkTP_Bac column for the delineated patch (the 1 signifies that we could confirm that there was no coral present in time point 1).

42
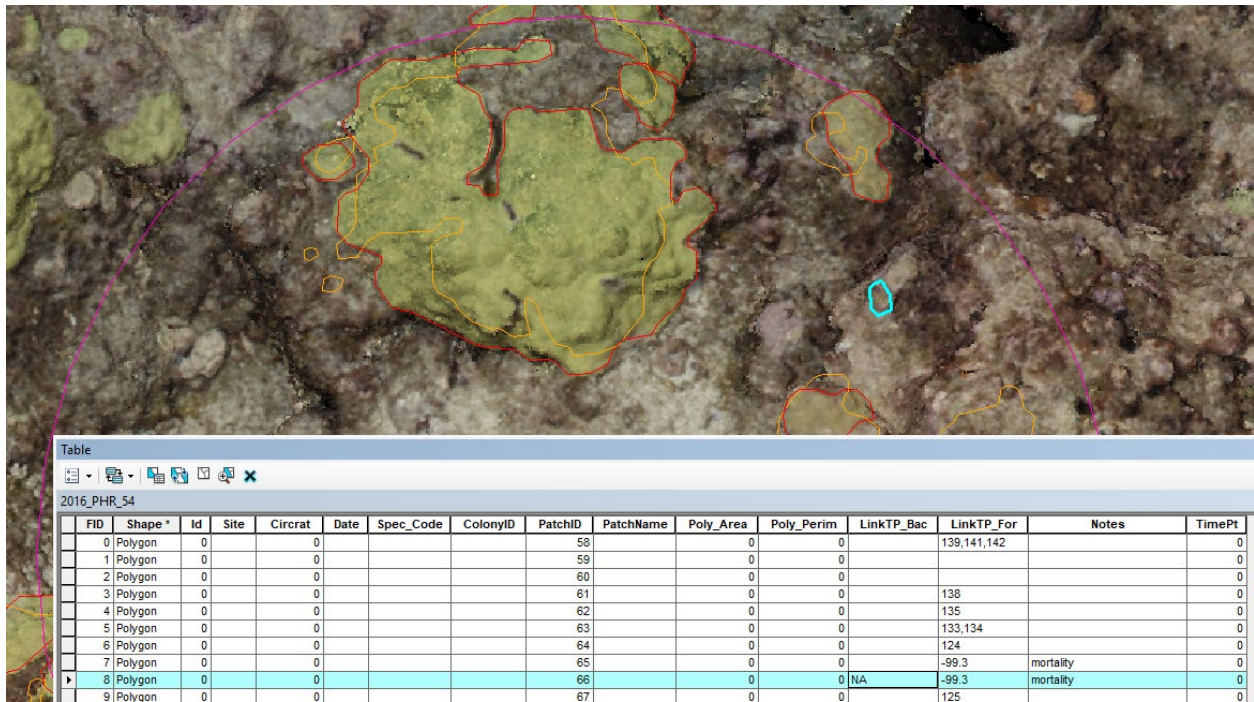
Figure 30. Screenshot in ArcMap depicting a mortality event. In 2016, there was a coral (highlighted in blue) which, by 2019, had died. Mark −99.3 because the coral died in time point 3.

k. If a single live patch breaks into multiple live patches in a subsequent time point, record possible fission in the Notes column. Similarly, if several live patches in an earlier time point fuse into one coral colony in a later time point, write possible fusion in the Notes column.
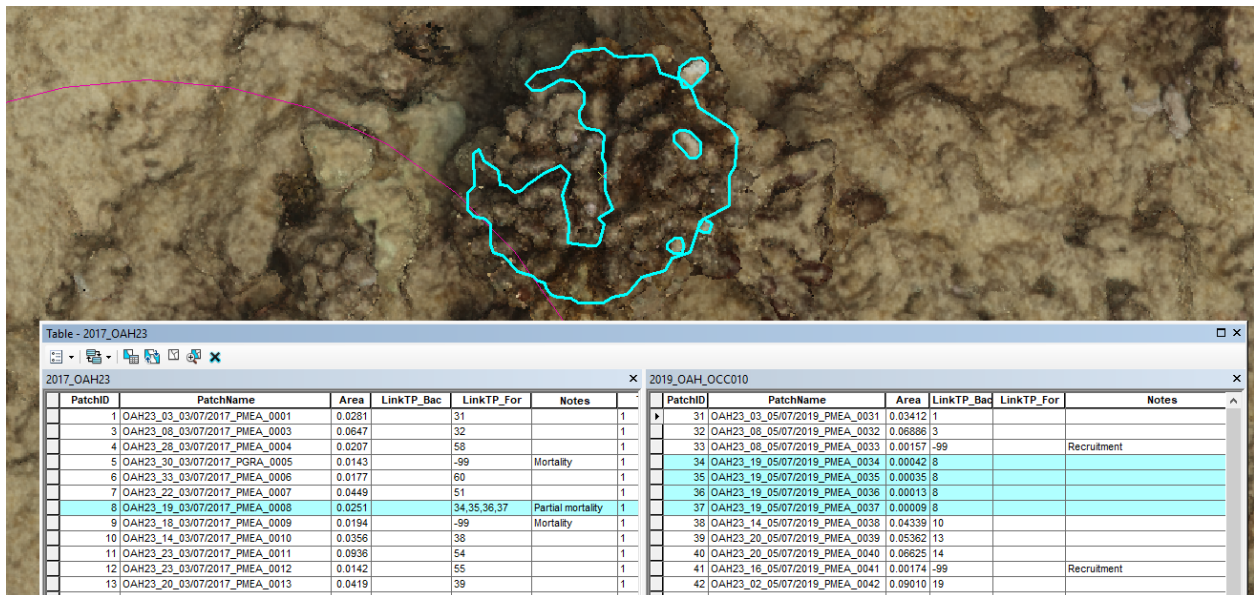
Figure 31. Example of partial mortality. In this example, Patch ID 8 in 2017 split into four smaller live patches (Patch ID 34–37) in 2019.

l. If a patch dies in a subsequent time point, record possible mortality in the Notes section.

m. When several live patches correspond to one live patch from a different time point, record the Patch IDs with commas and no spaces (ex: 34,35,36,37).

n. In the first sampling year, record NA in the LinkTP_Bac column because there are no data before the first sampling effort. For the last/most recent year, record NA in the LinkTP_For column because there are no data.

2. Save your edits and save the ArcMap file.

Populating the Attribute Table

Once all target taxa have been delineated in every time point and the patches have been linked across time points, the annotator will also identify coral taxon and in which quadrat the patch is located. Finally, calculate the maximum diameter by creating a feature class containing circular polygons around delineated plots.

1. Once you have linked all delineations between all available time points, annotate the other fields within the attribute table. Do not fill other columns until all delineations have been linked!

    a. Turn on Editing

    b. To populate an entire field in the attribute table:

        i. Right click the field to highlight the entire column and click Field Calculator.

        ii. Click python on the top.

        iii. In the text box add 'text you want to add'

        iv. Example: 'OAH22'

2. To populate the Quadrat field:

    a. Select features by lasso and use it to circle all polygons within a single quadrat.

    b. In the attribute table, the polygons will be highlighted in blue.

    c. To change multiple polygon's Quadrat field at once, click on the Show Selected Records tab in the attribute table. Next, right click on the Quadrat column and then click on Field Calculator.

    d. Type in the number without any quotation marks.
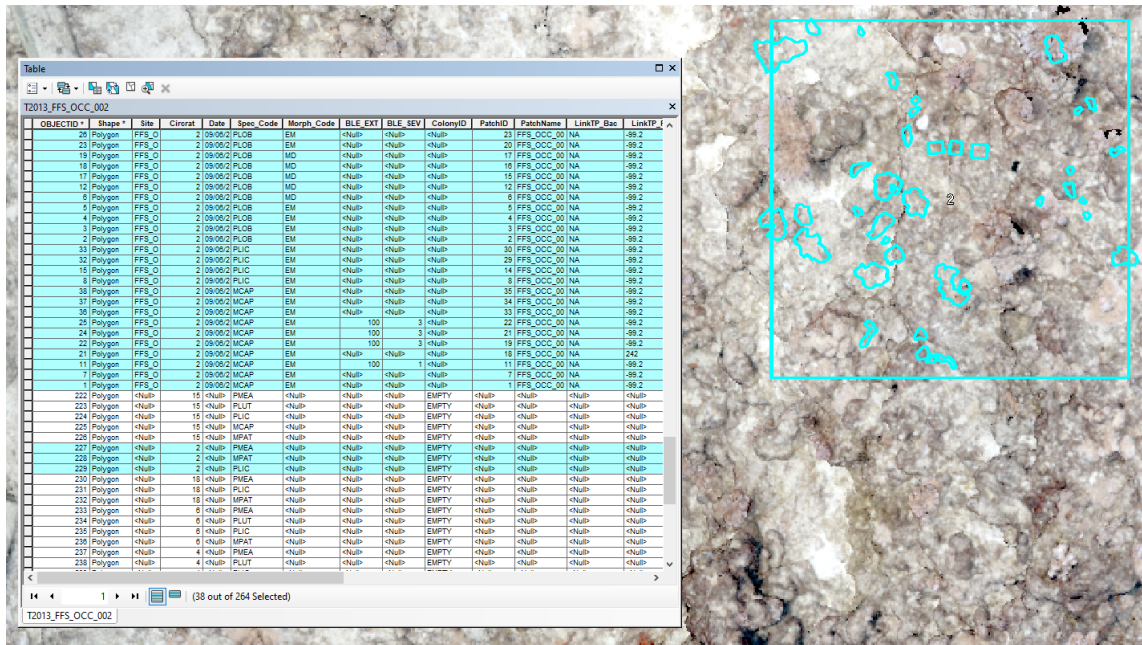
Figure 32. Screenshot in ArcMap using the lasso tool to highlight all the live patches within one quadrat. The quadrat column is filled in with the number of the quadrat.

3. To populate the Date field:
   a. Open the Field calculator and write in the date of imagery collection.
   b. Use the format 'MM/DD/YYYY' (ex: 01/05/2019).
4. To populate the Patch Name field:
   a. Highlight the field and click Field Calculator. Change to Python.
   b. Enter the following code in the PatchName block:

```
!Site! + "_" + str(!Quadrat!).zfill(2) + "_"
+ !Date! + "_" + !Spec_Code! + "_" +
str(!PatchID!).zfill(4)
```

5. To populate the TimePt field:
   a. Highlight the field and click Field Calculator.
   b. Enter a 1 for the earliest year, a 2 for the subsequent year, etc.
6. To populate the Max Diameter field:
   a. Create a circular polygon around your delineations:
      i. Search Minimum Bounding Geometry (Data Management Tool).
         1. Input: Delineation shapefile
         2. Output Feature Class: year_site#_MBG
         3. Geometry Type: CIRCLE
         4. Group Option: NONE
         5. Check Add geometry characteristics as attributes to output
         6. Click OK
   b. The shapefile should automatically load onto the delineated patches. If needed, change the fill color to no fill.

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Exporting the Attribute Table

After completing the annotation and ensuring there are no errors in the attribute table, export the table as a .txt file. This file will be analyzed using R statistical software.

1. Open the year_site_MBG shapefile with all of your delineations. This will be the file you export.

OBJECTID*	Shape*	Site	Circrat	Date	Spec_Co	Morph	BLE_EX	BLE_S	Colo	PatchID	PatchNa	LinkTP_	LinkTP_For	Notes	TimePt	Shape_Lengt	Shape_Area
2	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	3	<Null>	333	MAI_SIO_ 12	664		<Null>	2	0.20062	0.000832
3	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	3	<Null>	334	MAI_SIO_ 11	644		Fission	2	0.181631	0.001051
4	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	335	MAI_SIO_ 4	651		<Null>	2	0.302719	0.004193
7	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	336	MAI_SIO_ 3	647,649,650		<Null>	2	0.530684	0.005662
10	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	337	MAI_SIO_ 15	665		<Null>	2	0.360324	0.002513
18	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	338	MAI_SIO_ 5,6	652,653,654		Fusion	2	0.839329	0.006397
20	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	339	MAI_SIO_ 7	667		<Null>	2	0.4044	0.007335
26	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	95	3	<Null>	340	MAI_SIO_ 13,16	656,657,658,659		Fusion	2	0.866034	0.009912
28	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	341	MAI_SIO_ 14	641		<Null>	2	0.652505	0.006658
29	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	342	MAI_SIO_ 10	642,643		<Null>	2	0.268689	0.002182
30	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	343	MAI_SIO_ 322	677		<Null>	2	0.168461	0.001414
31	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	344	MAI_SIO_ 17	646		<Null>	2	0.190284	0.001592
32	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	345	MAI_SIO_ 18,320	643		Fusion	2	0.34042	0.004133
33	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	3	<Null>	346	MAI_SIO_ 11	645		fission	2	0.072931	0.000343
34	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	1	<Null>	347	MAI_SIO_ 37	-99.3		Mortality	2	0.191771	0.001091
35	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	2	<Null>	348	MAI_SIO_ 35,36	663		Fusion	2	0.426118	0.004481
41	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	90	2	<Null>	349	MAI_SIO_ 36,38,39,	691		Fusion	2	0.538949	0.004363
42	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	3	<Null>	350	MAI_SIO_ 49	673		<Null>	2	0.140166	0.000906
43	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	2	<Null>	351	MAI_SIO_ 34	669		<Null>	2	0.125832	0.000942
44	Polygon	MAI_SIO_K01	1	07/10/2015	PLOB	MD	0	0	<Null>	352	MAI_SIO_ 53	697		<Null>	2	0.213402	0.002497
51	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	3	<Null>	353	MAI_SIO_ 617	-99.3		Mortality	2	0.165759	0.000599
52	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	96	2	<Null>	354	MAI_SIO_ 43,45,47	669		Fusion	2	0.456832	0.003448
53	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	85	2	<Null>	355	MAI_SIO_ 42	668,670		<Null>	2	0.563478	0.003664
54	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	3	<Null>	356	MAI_SIO_ 329,330	686		Fusion	2	0.36127	0.002096
55	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	2	<Null>	357	MAI_SIO_ 54	683		<Null>	2	0.056142	0.000164
57	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	2	<Null>	358	MAI_SIO_ 325	695		<Null>	2	0.08576	0.000255
58	Polygon	MAI_SIO_K01	1	07/10/2015	MCAP	EC	100	2	<Null>	359	MAI_SIO_ 325	699		<Null>	2	0.221429	0.000869

Figure 33. Screenshot in ArcMap of a completed Attribute Table.

2. Ensure there are no spaces before any of the completed cells in the attribute table and that all fields have been filled out. Double check that all patches have a link forward and/or backward and that there are no accidental polygons created as a result of overlap between two polygons.
   a. The data will be exported to R statistical software and must be clean in order to run properly in R.
3. Save your ArcMap project.
4. Search for the "Merge (Data Management)" Tool.
   a. Input datasets: Highlight all of your year_Site#_MBG files then drag and drop
   b. Output dataset: navigate to the desired save location
   c. Name: Site#_VitalRates
   d. Save as type: Feature classes
   e. Leave everything as shown in 'Field Map'
5. Once complete a new shapefile will appear in your Table of Contents.
6. Right click on the shapefile to open the Attribute Table. In the top left corner of the Attribute Table, click Table Options and then Export.
   a. Export: All records
   b. Output: Save to your ARC folder. Name: Site#_exportdate
   c. Save as Type: Text file
      i. delete the .txt at the end
   d. Click Save. Click OK

    e.   A window will pop up and ask, "do you want to add the new table to the current map?" Click No.

7. Upload your Site#_exportdate CSV file to the ArcMap Exports folder on the VitalRatesData Google Drive.

Section 2: Error Analysis

Introduction—Error Analysis

Local and global stressors continue to threaten coral reef ecosystems and are expected to increase in intensity and frequency into the future (Hoegh-Guldberg et al. 2018). Scleractinian corals form the foundation of coral reefs and changes in their growth, reproduction, and mortality have direct consequences on the structure and function of coral reef ecosystems (Done 1992; Edmunds and Riegl 2020). However, not all coral reefs respond similarly to the same perturbations (Cinner et al. 2016). Therefore, understanding the underlying characteristics associated with reef resilience is imperative to protecting our coral reef ecosystems and the precious economic, cultural, and biological resources they provide.

NOAA's Ecosystem Sciences Division (ESD), formerly the Coral Reef Ecosystem Division, has been monitoring Pacific coral populations and benthic communities since the early 2000s and has done so under the National Coral Reef Monitoring Program (NCRMP) in the Pacific since 2013. Historically, ESD has used in situ visual assessments of coral communities and benthic photoquadrat imagery to generate coral demographic metrics. Although these methods are effective at assessing broad variables such as coral cover and density, they are spatially randomized. Therefore, they do not provide a platform to directly track colony-level changes in coral growth, mortality, or recruitment over time, constraining our ability to draw inferences about larger reef processes that impact ecosystem health.

To address these limitations, our program has engaged with a diverse academic collaboration including Dr. Stuart Sandin (Scripps Institution of Oceanography), Dr. John Burns (University of Hawaii at Hilo), and Dr. Joshua Madin (Hawaii Institute of Marine Biology) with the shared goal of extracting benthic metrics from large-area imagery (60–120 m^2) using Structure-from-Motion photogrammetry (SfM). SfM generates 3D models and 2D mosaics of a given area by aligning hundreds to thousands of still images. This technique is more cost effective and easier to conduct than alternative 3D technologies such as LIDAR (Burns et al. 2020). Consequently, it has been widely applied across a variety of fields and more recently has gained utility in coral reef assessment (Fox et al. 2019; Burns et al. 2020; Kodera et al. 2020; Lange and Perry 2020). The 3D and 2D products generated through SfM show robust imaging and millimeter-scale resolution, thus providing a powerful means to track coral growth, mortality, fission, fusion, and recruitment. Unlike earlier efforts to track vital rates, the cost-effective scale of SfM allows us to potentially track thousands of colonies across tens to hundreds of sites, providing the ecological and spatial replication necessary to build multivariate statistical models linking these vital rates to environmental patterns.

SfM presents impressive potential to track colony-scale changes, but like any novel tool, we need to accurately document any errors produced during image collection, model generation, model alignment across time points, and model annotation. To address these issues in the context of ESD's methodology, we extracted vital rate measurements from a statistically robust subset of colonies, from 5 coral species in 2 genera (*Pocillopora* and *Porites*) at 14 sites throughout the Hawaiian Archipelago. All sites were surveyed at least twice, and image collection intervals ranged from a few minutes (for error estimation) to 1–3 years apart. Here, we demonstrate our technical and annotator error and suggest that relative to observed patterns of growth, the

methodology's error is low, making it possible to track coral vital rates over time. We also lay out a strategy to minimize detected errors as we move from pilot scale to operational scale in our coral vital rates program.

Methods—Error Analysis

Study Site

Surveys were conducted in both the main Hawaiian Islands and Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands as a part of NCRMP missions and by collaborators in the 100 Island Challenge from Scripps Institution of Oceanography. Fourteen sites were surveyed at least twice between September 2013 and September 2019, with five sites on Hawaii Island, five on Oahu (two in which we measured growth, and four in which we assessed error rates), two on Maui, one on Pearl and Hermes Atoll, and one on Kure Atoll. All sites were located on the forereef between 10 and 15 m depth, with one site at 6 m. Each survey covered 100–113 m^2 of reef.
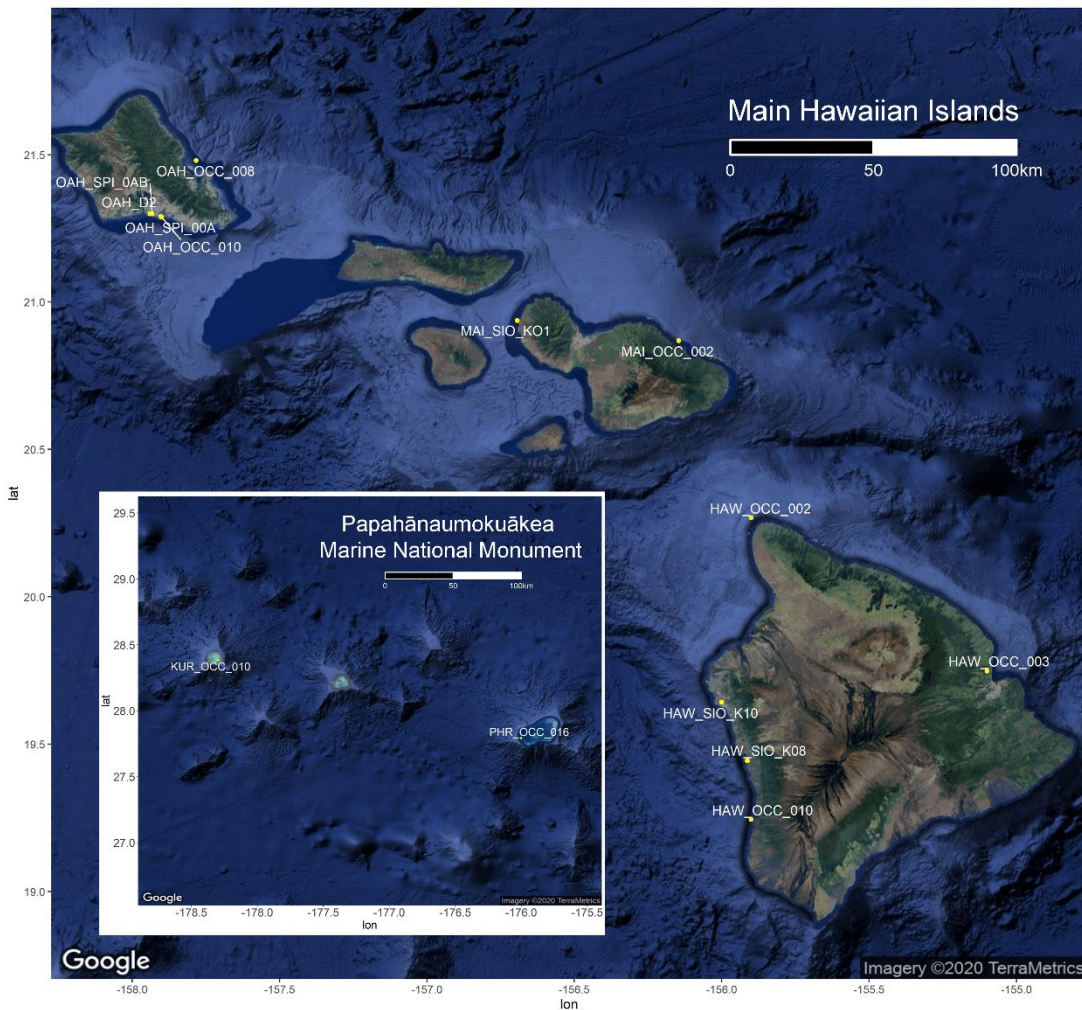

Figure 34: Map of fixed sites across the Hawaiian Archipelago.

Surveys

Imagery was collected using methods described in *Plot Set Up and Survey for Established SfM Fixed Sites* ([Section 1](#), above).

SfM Analyses

SfM 3D dense point cloud (DPC) models were generated using methods described in *Scale, Generate, and Orient Dense Point Cloud, ArcMap Plot Setup*, and *ArcMap Segmentation and Annotation* ([Section 1](#), above). Prior to importing imagery into ArcMap, the 3D DPCs were imported into Viscore, a custom developed software (Petrovic et al. 2014; Naughton et al. 2015) in which the imagery was scaled, oriented, aligned, and exported as a 2D orthoprojection. Five of the most common coral species in the Hawaiian archipelago in two coral genera, *Porites* (*P. lutea, P. lobata*) and *Pocillopora* (*P. meandrina, P. grandis, P. ligulata*), were selected and delineated across each site due to their widespread occurrence throughout the Hawaiian Archipelago and differences in life history strategy (Darling et al. 2012). These differences include branching vs. mounding growth form, "stress-tolerant" vs. "competitive" or "weedy" life history (Darling et al. 2012), and a tendency to live in a single contiguous patch (*Pocillopora*) vs. a collection of patches frequently fissioning and fusing (*Porites*).

For this presentation of error rates, we delineate live, contiguous coral tissue and refer to this unit synonymously as both "coral patch" and "coral colony". To focus our results on adults, we analyze all patches greater than 20 cm^2. For more information regarding set up and delineation within ArcMap, please refer to sections *ArcMap Plot Setup* and *ArcMap Segmentation and Annotation* ([Section 1](#), above).

Error Assessment—Imaging and Annotation

The four sites used for error analyses were imaged twice, with collections separated by intervals from minutes to a few hours. From each set of images, we separately generated DPCs in Agisoft, aligned site DPCs, and delineated patches to measure errors associated with SfM processing methodology and differences among annotators, i.e., humans delineating live coral tissue.

For our Vital Rates Pilot, 8 annotators work together and divide work by site so that one annotator delineates all colonies across the site. Although infrequent, at some multi-time point sites (i.e., sites with six or seven time points), two annotators will divide the site and one annotator will work on the earlier time points and the other will annotate the later time points. Annotators were trained on the detailed SOP ([Section 1](#)), and initial delineations, species identifications, and data entry procedures were reviewed at a weekly meeting of the Vital Rates Team. To compare difference between annotators, we asked two annotators to delineate the same colonies across the two different rounds of imaging. The first annotator randomly generated quadrats and delineated colonies selected as described in the SOP. All subsequent delineations then followed the same colonies which were marked only with a point and an identification label and were delineated by the second annotator. Post-delineation, we compared planar colony areas from colonies linked across sampling bouts to document error associated with measuring an assumed change of zero.

We classify process errors as *Imaging Error*, which compares delineations of the same colony performed by a single annotator across two distinct imaging efforts; *Cross-Annotator Error*

which compares delineations of the same colony by two different annotators using the same imagery; and *Imaging & Annotator Error* which compares colony delineations from two distinct annotators using different imagery (Table 3, Table 4). *Cross-annotator Error* estimates were generated by comparing the work of just two distinct annotators, and annotator identity was conserved in the sign of error estimates, so any bias shown in the data reflects differences between the two annotators' individual tendencies.

Here we compare both absolute change in coral colony area (cm^2) and percentage change in coral colony area (Δ cm^2/initial cm^2). As we are examining the scale of observation errors, not documenting rates for this analysis, we present absolute and percentage change, ignoring the time elapsed between measurements, and do not attempt to present rates of change. In our QC process, a small number of extreme outliers would be flagged and reviewed; here we similarly mark and remove outliers falling three standard deviations beyond a metric's mean (area change, percent area change) from calculation of means and error bounds. These outliers largely represent colonies where the two annotators disagreed on a colony boundary, i.e., lumping or splitting portions of a colony. These points are marked in the figures to follow (as Xs) but removed from the tabular summaries. We test each error category for significant bias away from zero using a one sample, two-sided t-test assuming a mean of 0.

Table 2: Number of sites and colony count by error category and taxon.

Genus	Error Category	N. Sites	N. Colonies
Pocillopora sp.	Growth Data	7	173
	Imaging Error	4	114
	Cross-Annotator Error	6	263
	Imaging & Annotator Error	4	112
Porites sp.	Growth Data	11	301
	Imaging Error	3	82
	Cross-Annotator Error	5	204
	Imaging & Annotator Error	3	78

Results—Error Analysis

Comparing Growth Data to Error Estimates By Category

The following tables and figures compare adult coral colony-scale area change (i.e., growth) across samples separated by 1–3 years (i.e., *Growth Data*) to area change estimates from imaging rounds separated by less than 3 hours (i.e., three *Error* categories). Species-specific data were pooled by genera to simplify presentation of the error rates. Across all four error categories, we compared 1,327 coral colonies from two genera across 14 sites in the main Hawaiian Islands and the Northwestern Hawaiian Islands (which includes the Papahānaumokuākea Marine National Monument, Fig. 1).

The multi-year *Growth Data* show broad variability and a clear non-zero bias in both absolute and percentage growth, as would be expected for coral experiencing a few years of growth. For *Pocillopora* data, the pattern of growth was positive biased with a mean of 62.67 cm^2 colony size increase, or +50.78% growth (Table 3, Table 4). *Porites* showed significant bias, but its mean growth was comparably moderate (+14.77 cm^2 or +24.06%) (Table 3, Table 4).

In comparison to *Growth Data*, all three error estimate categories showed no significant non-zero bias in absolute area change (Table 3), but the category with the highest aggregate error (*Imaging and Annotator Error*) did show small but significant positive bias for the percentage area change metric (Table 4).

Measured errors were substantially smaller than patterns shown in *Growth Data* and tended to be smallest when considering only *Imaging Error*, while adding in annotator errors increased the deviance from the expected zero area change. For *Imaging Error* alone (i.e., a single annotator delineates the same coral colonies captured into separate rounds of imaging and processing), we saw small mean errors (i.e., 0.19/0.81 cm^2, 0.44/0.19 %, *Pocillopora*/*Porites*, respectively) with confidence intervals straddling zero for both absolute and percentage area change metrics (Table 3, Table 4).

In comparing *Cross-Annotator* error (i.e., two annotators delineating colonies using the same imagery), we observed small, zero-straddling errors, but somewhat increased error rates, (i.e., means of 1.48 / 2.17 cm^2, 0.72 / 3.07%, *Pocillopora* / *Porites*, respectively). In the most

inclusive error metric, *Imaging and Annotator Error* (i.e., two different annotators each annotating images of the same colony collected on separate imaging rounds), we saw the largest error estimates of any of our error categories (i.e., means of 2.00 / 6.02 cm^2, 2.41/8.34%, *Pocillopora / Porites*, respectively; Table 3, Table 4). For absolute area change, *Imaging and Annotator Error* remained non-biased, with zero-overlapping confidence intervals. However, for percentage error, we observed a significant positive bias for both *Pocillopora* and *Porites.* This bias became non-significant if we only examined colonies 8 cm diameter or greater (50.3 cm^2) instead of our standard adult diameter of less than 5 cm (19.6 cm^2; Fig. 38).

Table 3: Absolute area change by error category and taxon. Significance marked by asterisks (p < 0.05 *; p < 0.001 ***).

Genus	Error Category	No. Colonies	Mean Colony Area Change (cm^2)	+/- 95% CI	Non-Zero Bias P-value
Pocillopora sp.	Growth Data	173	62.67	10.59	**0.0000- *****
	Imaging Error	113	0.19	1.48	0.8004–NS
	Cross-Annotator Error	260	1.48	2.12	0.1715–NS
	Imaging & Annotator Error	111	2.00	2.88	0.1761–NS
Porites sp.	Growth Data	299	14.77	6.73	**0.0000 - *****
	Imaging Error	81	0.81	1.32	0.2363–NS
	Cross-Annotator Error	200	2.17	5.01	0.3962–NS
	Imaging & Annotator Error	76	6.02	9.89	0.2364–NS

Table 4: Percent area change by error category and taxon. Significance marked by asterisks (p<0.05 *; p<0.001 ***).

Genus	Error Category	No. Colonies	Mean Colony Area Pct. Change (% cm^2)	+/- 95% CI	Non-Zero Bias P-value
Pocillopora sp.	Growth Data	169	50.78	8.91	**0.0000 - *****
	Imaging Error	111	0.44	0.92	0.3506–NS
	Cross-Annotator Error	259	0.72	1.12	0.2064–NS
	Imaging & Annotator Error	110	2.41	1.52	*0.0024˜ **
Porites sp.	Growth Data	294	24.06	5.72	**0.0000 - *****
	Imaging Error	81	0.19	1.38	0.7912–NS
	Cross-Annotator Error	202	3.07	3.29	0.0691–NS
	Imaging & Annotator Error	76	8.34	5.80	*0.0062– **

Examining these patterns of error as X-Y plots (Fig. 35) and error histograms (Fig. 36, Fig. 37) underscores the results described above. *Growth Data* showed a clear positive bias, especially in *Pocillopora,* with partial mortality in *Porites* balancing growth to generate more net-zero change (Fig. 35). *Imaging Error* alone shows the lowest error rate, but all error estimates are low with respect to growth patterns, and the majority show no significant bias (Fig. 35). *Cross-Annotator Error* and *Imaging and Annotator Error* show larger errors than imaging alone, but all mean error estimates remain in the single digit cm^2 or % cm^2. The aggregate *Imaging and Annotator Error* does show small but significant positive non-zero bias in percentage growth metrics (Fig. 37, Fig. 38), but this bias is absent in absolute metrics (Fig. 36). In examining Figure 38, this bias presents as positive LOESS fit lines in *Cross-Annotator Error* and *Imaging and Annotator Error*

at small colony sizes that shift back to zero, i.e., no bias, as the colony size gets larger than 20–50 cm^2 (i.e., further along the x-axis, but vertical hashed lines at 20 and 50 cm^2).
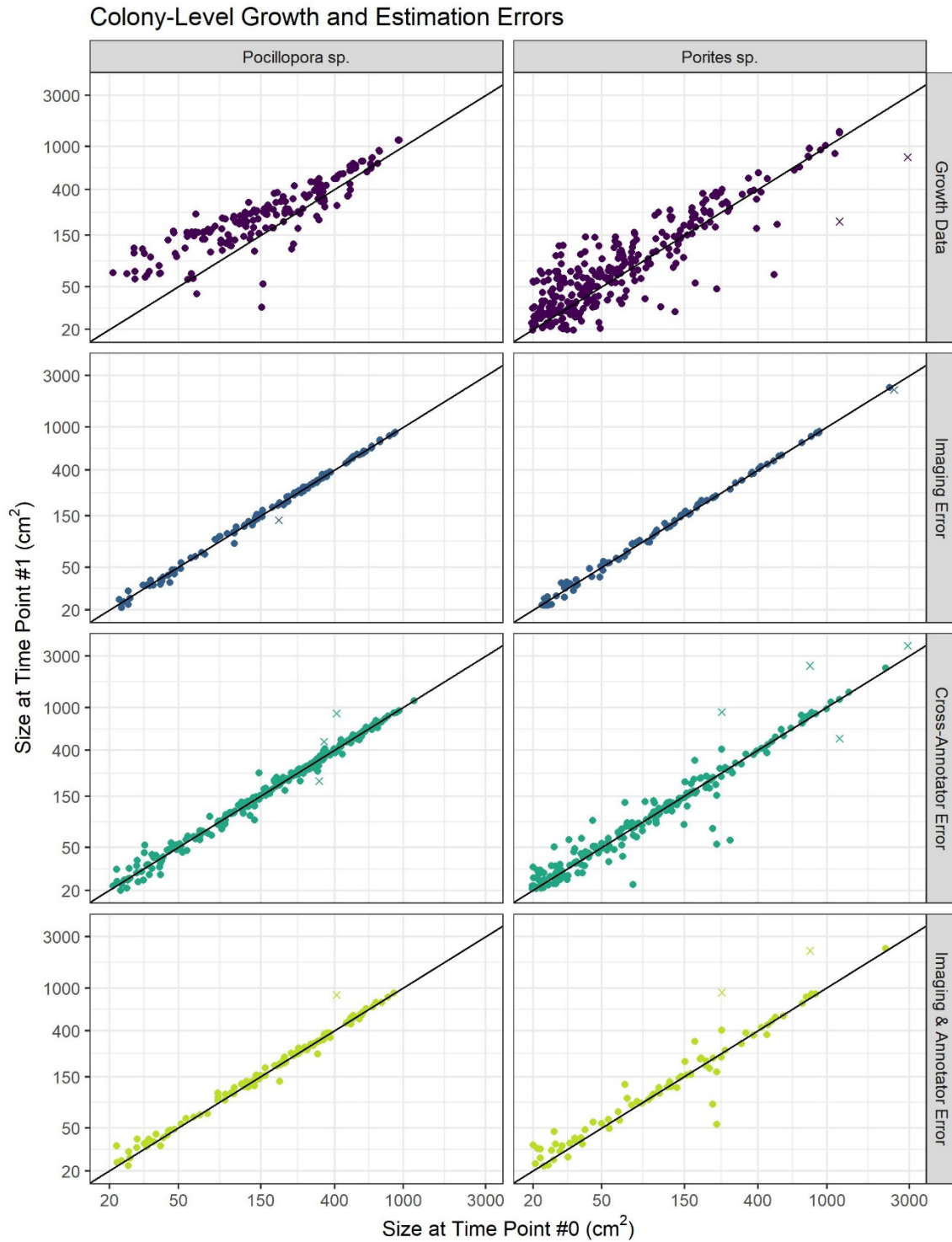
Figure 35: Colony size comparison. Scatter plot of observed change in planar area and error estimate of *Pocillopora* and *Porites* between time points #0 and #1. The Xs indicate outliers that were not included in statistical analyses.

Figure 36: Absolute change in planar area. Histograms of observed absolute change in planar area and error estimate of *Pocillopora* and *Porites* between time points #0 and #1. The Xs indicate outliers that were not included in statistical analyses. Grey bars indicate 95% confidence interval of the mean.

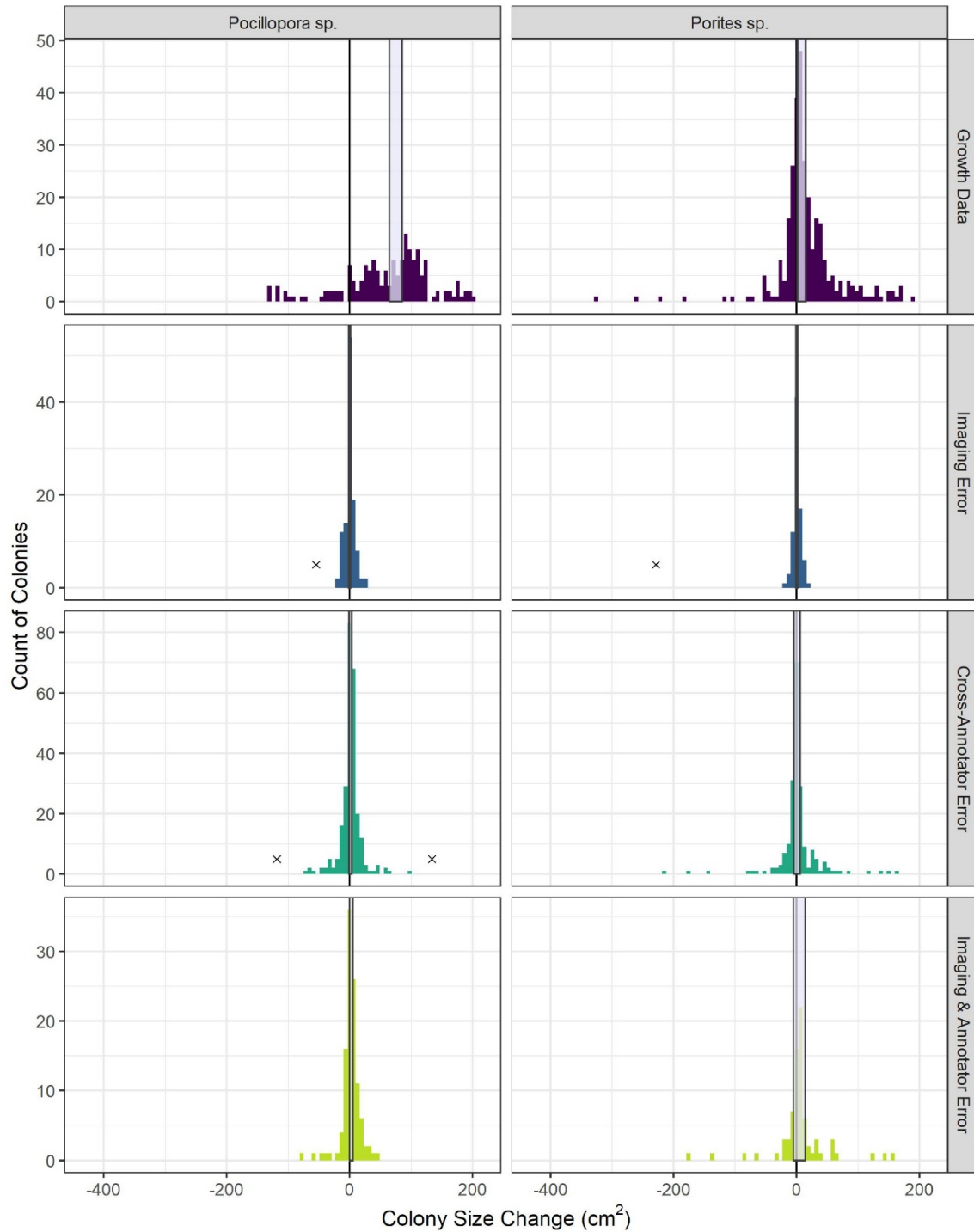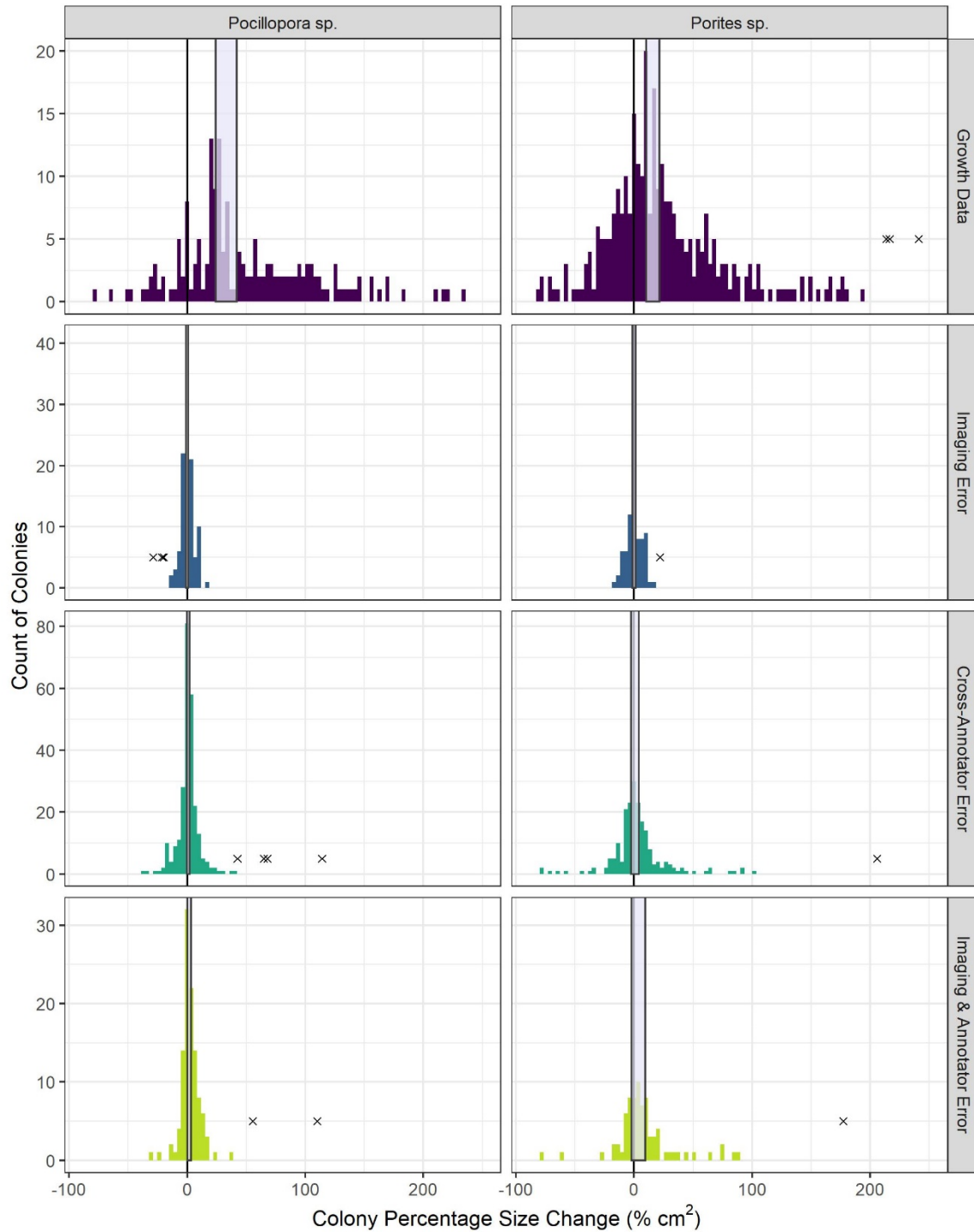**Figure 37: Percentage change in planar area.** Histograms of observed percentage change in planar area and error estimate of *Pocillopora* and *Porites* between time points #0 and #1. The Xs indicate outliers that were not included in statistical analyses. Grey bars indicate 95% confidence intervals of the mean.
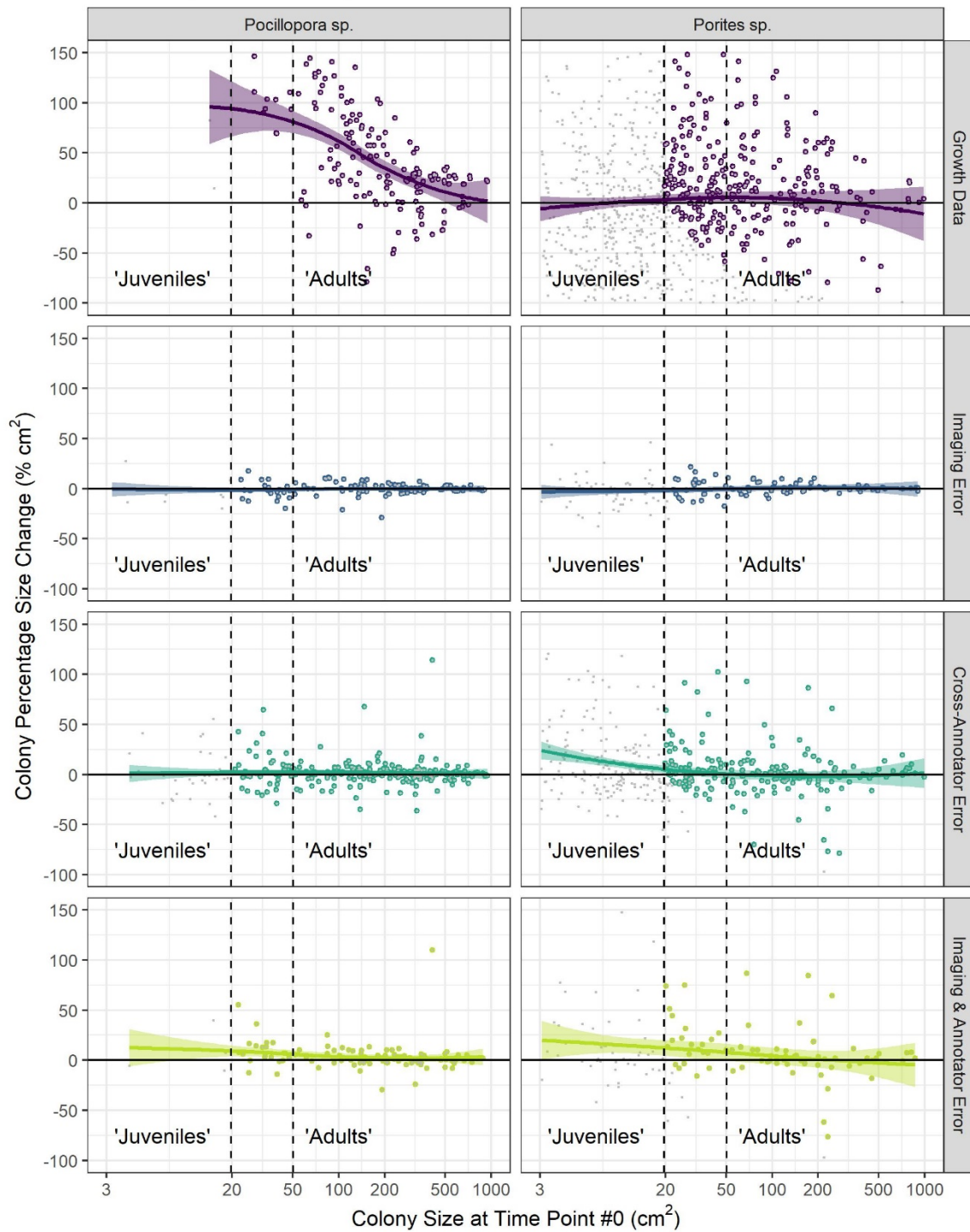
Figure 38: Percent size change by initial coral size and error category. Lines indicate LOESS fit to each data category with transparent bands indicating standard errors. Line at 20 cm² underscores break between our defined "Juvenile" and "Adult" categories. Line at 50 cm² placed to support discussion of small-size bias.

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Discussion–Error Analyses

Our analyses demonstrate that the photogrammetric imaging and annotation methodology detailed above can accurately and repeatedly estimate coral colony size, and thereby estimate growth rates (i.e., change in colony size between time points). Error rates from imaging and annotation are low relative to multi-year growth observations for adult colonies. The patterns of error and bias observed, however, suggest that applying these methods to corals of small size classes (i.e., juveniles) can disproportionately impact size estimate precision.

We noted the lowest error estimates in the category *Imaging Error*, which is not a metric of purely imaging performance, but instead is an end-to-end metric of our imaging and human annotation workflow. In this case, a single human annotator delineated the same coral colony in two separate imaging and model generation rounds, and the resulting colony area estimates are compared. This type of error includes error associated with collecting the imagery, generating the models, and 2D orthoprojections as well as the annotation error for a single annotator. Our pure imaging metrics, like ground sample distance (Felipe-García et al. 2012), which reports the spatial resolution per pixel, showed robust performance, ranging between around 2–4 mm/pix. The more inclusive *Imaging Error* is much more relevant to gauging how well we can measure colony change.

For any given coral colony in our dataset, *Imaging Error* is likely the most appropriate error category as individual annotators usually complete all time points collected for a single site. Therefore, the low, unbiased error rates (zero-spanning bands of 1–1.5%) seen in *Imaging Error* (Table 1, Table2, Fig. 2, Fig. 3, Fig. 4) are the most widely applicable rates for the majority of the study. That said, other patterns in the data raise two major categories of concern: cross-annotator error, and small colony sizes.

Annotator Errors: As shown in the categories *Cross-Annotator Error* and *Imaging and Annotator Error*, error estimates grew with more annotators working on the same colonies.

In our current effort, we have a total of 8 annotators working together, mostly dividing work by site, which implies that in most contexts, the *Imaging Error* model applies. However, in some multi-time point sites (i.e., the West Maui sites included here), we have multiple annotators dividing work within a site by time points. For example, in a six time-point site, two annotators may divide work with one annotator taking the first three time-points, and a second annotator taking the latter three. In this case, *Imaging Error* category would apply within the set of the initial three or latter three time points, but corals followed between time points three and four would be better interpreted in the light of the *Imaging and Annotator Error* results.

To mitigate cross-annotator error, we propose several strategies. First, whenever possible, only one annotator will delineate all time points for a given site. Second, we intend to include a series of more thorough annotator checks as we move out of pilot phase and operationalize our vital rates program. Generally, these efforts will include (1) outlier re-checks, (2) random-spot checks of delineations, (3) a percentage of colonies that will be double-annotated to isolate and track cross-annotator error, and (4) a standardized annotator training incorporating feedbacks to better allow annotators to train-away individual tendencies toward over or under delineating colony boundaries, including their tendency to lump vs. split in situations of uncertain colony boundaries. As an example of this kind of feedback, we will establish a set of baseline colonies

randomly selected from the dataset that all annotators will need to delineate, then compare across all annotators to document biases. Not only will this be useful for re-training but could also be used to statistically document annotator tendencies that we could offset in mixed models of colony growth.

Small Colonies: While error rates for absolute area change consistently and show no significant bias from zero regardless of size class (Table 2), our estimate of percentage change between two different annotators skews positive for small colonies (Fig. 38). This reflects a tendency for one annotator to delineate colonies slightly larger than the other, and the percentage metric is simply more sensitive to this skew for smaller colonies. This raises a greater level of concern for tracking changes in small area colonies. We will proceed with due skepticism and transparent presentation of uncertainties. Further, we will consider binning small colony transitions, post-annotation, into bins with widths proportional to our measured error.

Conclusion

The pilot effort for tracking coral vital rates now has a robust, evolving Standard Operating Protocol (SOP), and initial analyses of error rates suggest that when diligently applied, the SOP generates low, unbiased rates of error relative to the signal of colony growth we are tracking. For the most widely applicable error estimate, *Imaging Error,* 95% confidence bands of absolute area change span between +/− 1.3 and 1.5 cm^2, depending on taxon. For the 'worst case' error comparing among both distinct images and annotators, i.e., *Imaging and Annotator Error*, 95% confidence bands of absolute area change span +/− 2.9 and 9.9 cm^2, again depending on taxon. The upper end of this error range largely derives from cross-annotator differences, driven by a few outliers. We plan to move forward with a more robust cross-annotator QC process, increased feedback, and human-in-the-loop automation that we hope will bring these error rates even lower, allowing us to focus on the fascinating patterns of recruitment, growth, and mortality this method can provide.

Literature Cited

Burns JHR, Weyenberg G, Mandel T, Ferreira SB, Gotshalk D, Kinoshita CK, Marshall MJ, Del Moral NA V., Murphy SJ, Pascoe KH, et al. 2020. A Comparison of the Diagnostic Accuracy of in-situ and Digital Image-Based Assessments of Coral Health and Disease. Front Mar Sci. doi:10.3389/FMARS.2020.00304.

Cinner JE, Huchery C, MacNeil MA, Graham NAJ, McClanahan TR, Maina J, Maire E, Kittinger JN, Hicks CC, Mora C, et al. 2016. Bright spots among the world's coral reefs. Nature. doi:10.1038/nature18607.

Darling ES, Alvarez-Filip L, Oliver TA, McClanahan TR, Côté IM. 2012. Evaluating life-history strategies of reef corals from species traits. Bellwood D, editor. Ecol Lett. doi:10.1111/j.1461-0248.2012.01861.x.

Done TJ. 1992. Phase shifts in coral reef communities and their ecological significance. Hydrobiol 2471. doi:10.1007/BF00008211.

Edmunds PJ, Riegl B. 2020. Urgent need for coral demography in a world where corals are disappearing. Mar Ecol Prog Ser. doi:10.3354/MEPS13205.

Felipe-García B, Hernández-López D, Lerma JL. 2012. Analysis of the ground sample distance on large photogrammetric surveys. Appl Geomatics. doi:10.1007/S12518-012-0084-2.

Fox MD, Carter AL, Edwards CB, Takeshita Y, Johnson MD, Petrovic V, Amir CG, Sala E, Sandin SA, Smith JE. 2019. Limited coral mortality following acute thermal stress and widespread bleaching on Palmyra Atoll, central Pacific. Coral Reefs. doi:10.1007/s00338-019-01796-7.

Hoegh-Guldberg O, Kennedy E V., Beyer HL, McClennen C, Possingham HP. 2018. Securing a Long-term Future for Coral Reefs. Trends Ecol Evol. doi:10.1016/J.TREE.2018.09.006.

Kodera SM, Edwards CB, Petrovic V, Pedersen NE, Eynaud Y, Sandin SA. 2020. Quantifying life history demographics of the scleractinian coral genus Pocillopora at Palmyra Atoll. Coral Reefs. doi:10.1007/s00338-020-01940-8.

Lange ID, Perry CT. 2020. A quick, easy and non-invasive method to quantify coral growth rates using photogrammetry and 3D model comparisons. Methods Ecol Evol. doi:10.1111/2041-210X.13388.

Naughton P, Edwards C, Petrovic V, Kastner R, Kuester F, Sandin S. 2015. Scaling the annotation of subtidal marine habitats. In: 10th ACM International Conference on Underwater Networks & Systems. WUWNet 2015.

Petrovic V, Vanoni DJ, Richter AM, Levy TE, Kuester F. 2014. Visualizing high resolution three-dimensional and two-dimensional data of cultural heritage sites. Mediterr Archaeol Archaeom. doi:10.5281/zenodo.13709.

Pizarro O, Friedman A, Bryson M, Williams SB, Madin J. 2017. A simple, fast, and repeatable survey method for underwater visual 3D benthic mapping and monitoring. Ecol Evol. 7(6):1770–1782. doi:10.1002/ece3.2701.

Suka R, Asbury M, Couch C, Gray A, Winston M, Oliver T. 2019. Processing Photomosaic Imagery of Coral Reefs Using Structure-from-Motion Standard Operating Procedures. US Dept Commerce, NOAA Technical Memorandum NOAA-TM-NMFS_PIFSC-93. doi:10.25923/h2q8-jv47.

Swanson DW, Bailey H, Schumacher B, Ferguson M, Vargas-Ángel B 2018. Ecosystem Sciences Division Standard Operating Procedures: Data Collection for Rapid Ecological Assessment Benthic Surveys. NOAA Tech. Memo. NMFS-PIFSC-71. doi:10.25923/39JH-8993.

Appendix A: Create 3D Printed Spiral Drum

This version of the spiral drum includes a barrier that keeps the line from slipping off the edges of the drum. Additionally, it has a handle at the top of the drum providing better control during the survey.

List of required hardware is identical to "Spiral Drum Set Up" in addition to:
- PVC glue
- 4 right angle bend 0.75-inch PVC connectors
- 1 threaded T-connector PVC connector
- (1) 8-inch** diameter 3D-printed drum made from strong, heat resistant plastic
- ? ft Schedule 80 0.75-inch PVC pipe

** based on calculations used to determine the drum diameter needed. See "Spiral Drum Setup" section for more information

(The 8-inch diameter PVC pipe is NOT needed for this drum version)

1. Use a standard 3D printer to create the drum. Software such as AutoCAD should be used to create a blueprint of the drum that meets your specific needs. Follow the data files associated with this report to find our 3D print file.
    a. We recommend using Ultimaker polycarbonate plastic due to its strength and heat resistance (https://ultimaker.com/materials/pc).
    b. We recommend adding holes to the rim of the drum (Fig. 39) because it reduces the amount of material needed and provides a convenient place to clip the line when not connected to the camera (do not clip other, heavier objects onto these holes).
2. Cut two lengths of Schedule 80 PVC pipe to 13 inches.
3. Cut two lengths of Schedule 80 PVC pipe wide enough to fit tightly inside of the drum.
    a. Keep in mind that the connectors increase the total length.
4. Using the right-angle connectors and the T-connector, attach all Schedule 80 PVC pipe pieces together and PVC glue all connectors.
5. Secure the Schedule 80 PVC pipe to the inside of the drum (Fig. 39).
    a. Approximately 5 inches of the Schedule 80 pipe should extend above the top of the drum to use as a handle during the survey.
6. Attach a short section of 0.75-inch PVC to the end of the T-connector and attach the 0.75-inch PVC male threaded adapter to the end. Attach the 0.75-inch PVC female threaded adapter to the end of the remaining 0.75-inch PVC.
    a. The PVC with the female threaded adapter should be cut to a length that makes the center of the drum (where the line is attached) reach 1 m above the ground. This will allow you to fly the camera 1 m above the substrate.
7. On one end of the line, attach the camera clip and connect the other end to the drum.

Figure 39. Image showing the construction of the drum using PVC pipe handles and a 3D printed drum.

Appendix B: Create A Model to Build Quadrats

This process will create 25 quadrats on the orthoprojections. All delineations will be done within these quadrats until a minimum of 40 live patches per species are annotated. There are three steps to making the quadrats: creating a box that encapsulates the greatest overlapping area between the aligned orthoprojections, creating 25 random points within this box, and buffering around these points to create 0.5 square meter quadrats. These steps can be done efficiently by constructing a model in ArcMap to use at all future sites.

Creating a 10 × 10m Bounding Box

1. In the main toolbar, click model builder   . An empty Model window will open.
2. Using the search window, search for the Buffer (Analysis) tool and drag the tool into the model window. Double click on Buffer within the model window to edit.
   a. Input Features: Site#_centerpoint
   b. Output Feature Class: leave as is (will change in later step)
   c. Linear Unit: 5 m
   d. Side Type: FULL
   e. End Type: FLAT
   f. Method: PLANAR
   g. Dissolve Type: NONE -- OK
3. Right click on Site#_centerpoint bubble and choose rename. Change to "center point".
4. Right click on the Buffer output bubble (bubble after Buffer) and choose rename. Change to "circle (name + output location)".
5. Again using the search window, search for the Minimum Bounding Geometry (Data Management) tool and drag the tool into the model window. Double click to edit.
   a. Input Features: use the drop-down menu to choose "circle (name + output location)"
   b. Output Feature Class: leave as is (will change in later step)
   c. Geometry type: Envelope
   d. Group Option: NONE -- OK
6. Right click on the Minimum Bounding Geometry output bubble and choose rename. Change to "bounding box (name + output location)".
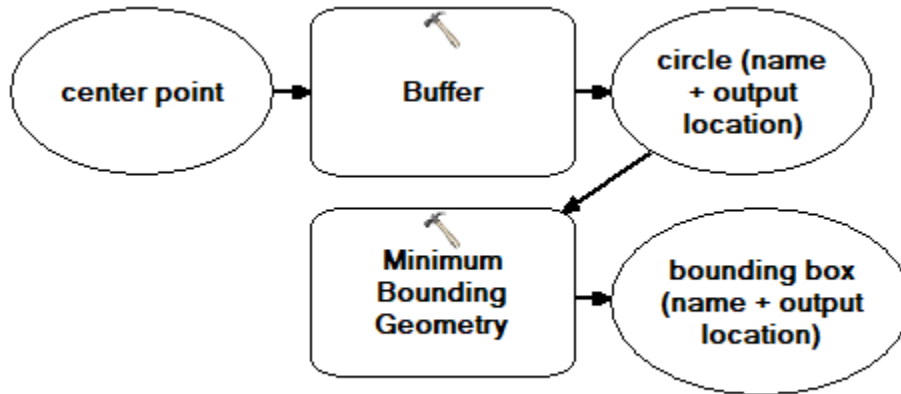7. Save the model as "Model_Build_Quadrats".

Figure 40. Screenshot in ArcMap of the first two tools in the Model_Build_Quadrats model.

Creating Random Points

1. Using the search window, search for the Create Random Points (Data Management) tool. Drag and drop into the model window and double click to edit the tool.
   a. Output Location: leave as is
   b. Output Point Feature Class: Site#_randompoints
   c. Constraining Feature Class: use the drop-down menu to choose "bounding box (name + output location)
   d. Long: 25 (number of random points)
   e. Linear unit: 1 m -- OK
2. Right click on the Create Random Points input bubble and rename. Change to "output location (ARC folder)".
3. Right click on the Create Random Points output bubble and rename. Change to "random points".
4. Right click on the Create Random Points tool within the model and choose Make Variable -- From Parameter-- Output Point Feature Class.
5. Right click the Output Point Feature Class bubble and rename "random points (name)".
6. Right click on the Create Random Points tool within the model and choose Make Variable -- From Parameter -- Number of Points [value or field].
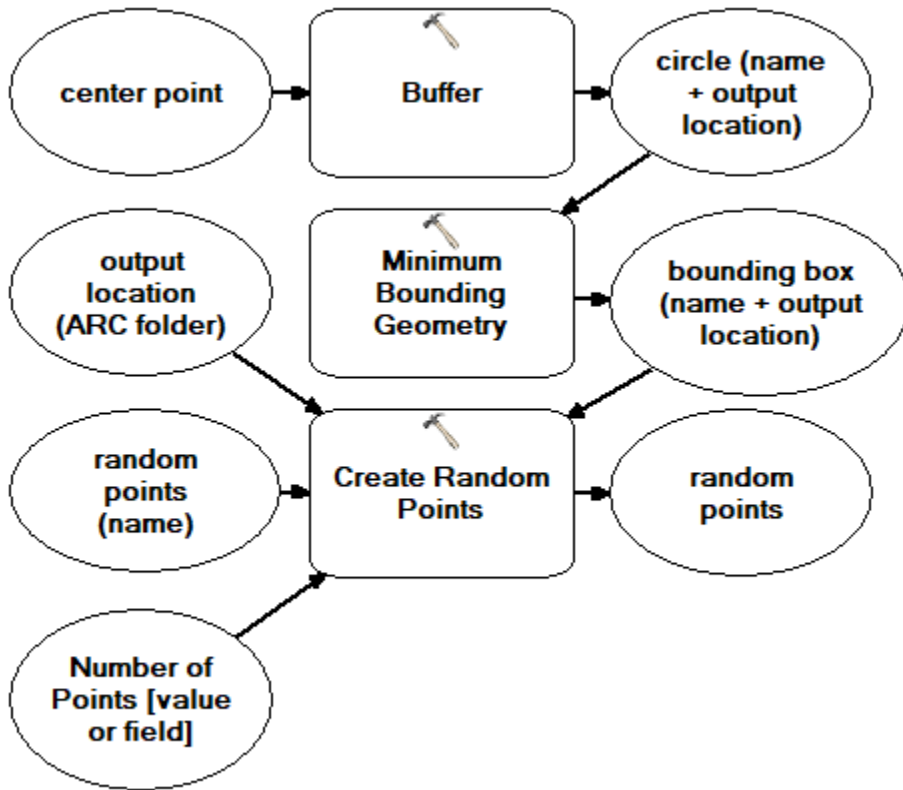7. Save the model.

Figure 41. Screenshot in ArcMap of the Model_Build_Quadrats model with the first three tools.

Creating Quadrats

1. Using the search window, search for the Buffer (Analysis) tool and drag the tool into the model window. Double click to edit.
    a. Input features: use the drop-down menu to choose "random points"
    b. Output Point Feature Class: leave as is
    c. Linear unit: 35.35 cm
    d. Side Type: FULL
    e. End Type: ROUND
    f. Method: PLANAR
    g. Dissolve Type: NONE -- OK
2. Right click the Buffer (2) output bubble and rename "circplots (name + output location)".
3. Using the search window, search for the Feature Envelope to Polygon (Data Management) tool. Drag and drop into the model window. Double click to edit.
    a. Input Features: use the drop-down menu to choose "circplots (name + output location)"
    b. Output Feature Class: leave as is
    c. Check Create multipart features (optional) -- OK

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4. Right click the Feature Envelope to Polygon output bubble and rename "quadrats (name + output location)".
5. Save the model.
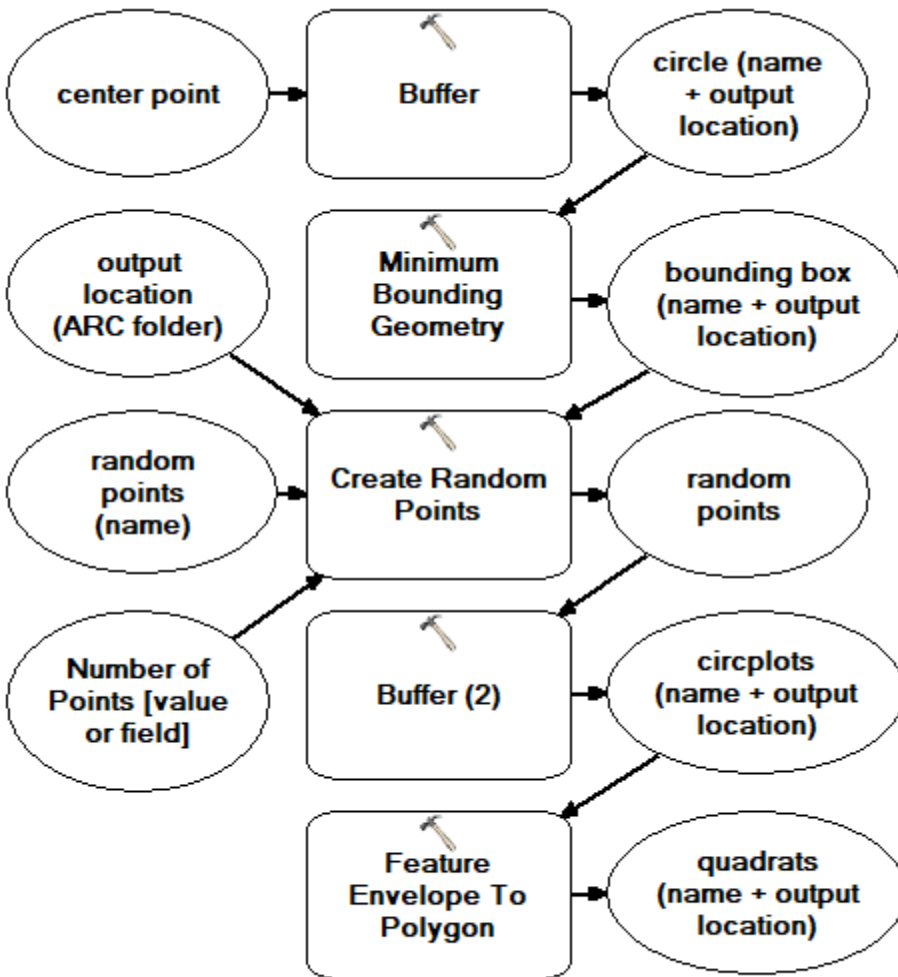
Figure 42. Screenshot in ArcMap of the five tools used to create the quadrats in the Model_Build_Quadrats model.

Label Quadrats and Set Model Parameters

1. Using the search window, search for the Add Field (Data Management) tool and drag into the model window.
2. Double click to edit.
    a. Input table: use the drop-down menu to choose "quadrats (name + output location)
    b. Field Name: QuadNum
    c. Field Type: SHORT
    d. Field Precision: 2 -- OK

3. Right click the Add Field output bubble and rename "quadrat ID".
4. Again using the search window, search for the Calculate Field (Data Management) tool and drag into the model window. Double click to edit.
   a. Input Table: use the drop-down menu to choose "quadrat ID"
   b. Field Name: QuadNum
   c. Expression (type this out): `autoIncrement()`
   d. Expression Type: PYTHON_9.3
   e. Code Block (copy and paste the following):

```
rec=0
def autoIncrement():
 global rec
 pStart = 1
 pInterval = 1
 if (rec == 0):
  rec = pStart
 else:
  rec += pInterval
 return rec
```

5. Right click on the Calculate Field output bubble and rename "quadrat numbers".
6. Right click on the Calculate Field tool within the model and choose Make Variable -- From Parameter-- Code Block.
7. Save the Model.
8. Right click on the following bubbles and choose "Model Parameter". Adding model parameters allows for easier use of the model while minimizing error:
   a. center point
   b. circle (name + output location)
   c. bounding box (name + output location)
   d. random points (name)
   e. output location (ARC folder)
   f. Number of Points [value or field]
   g. circplots (name + output location)
   h. quadrats (name + output location)
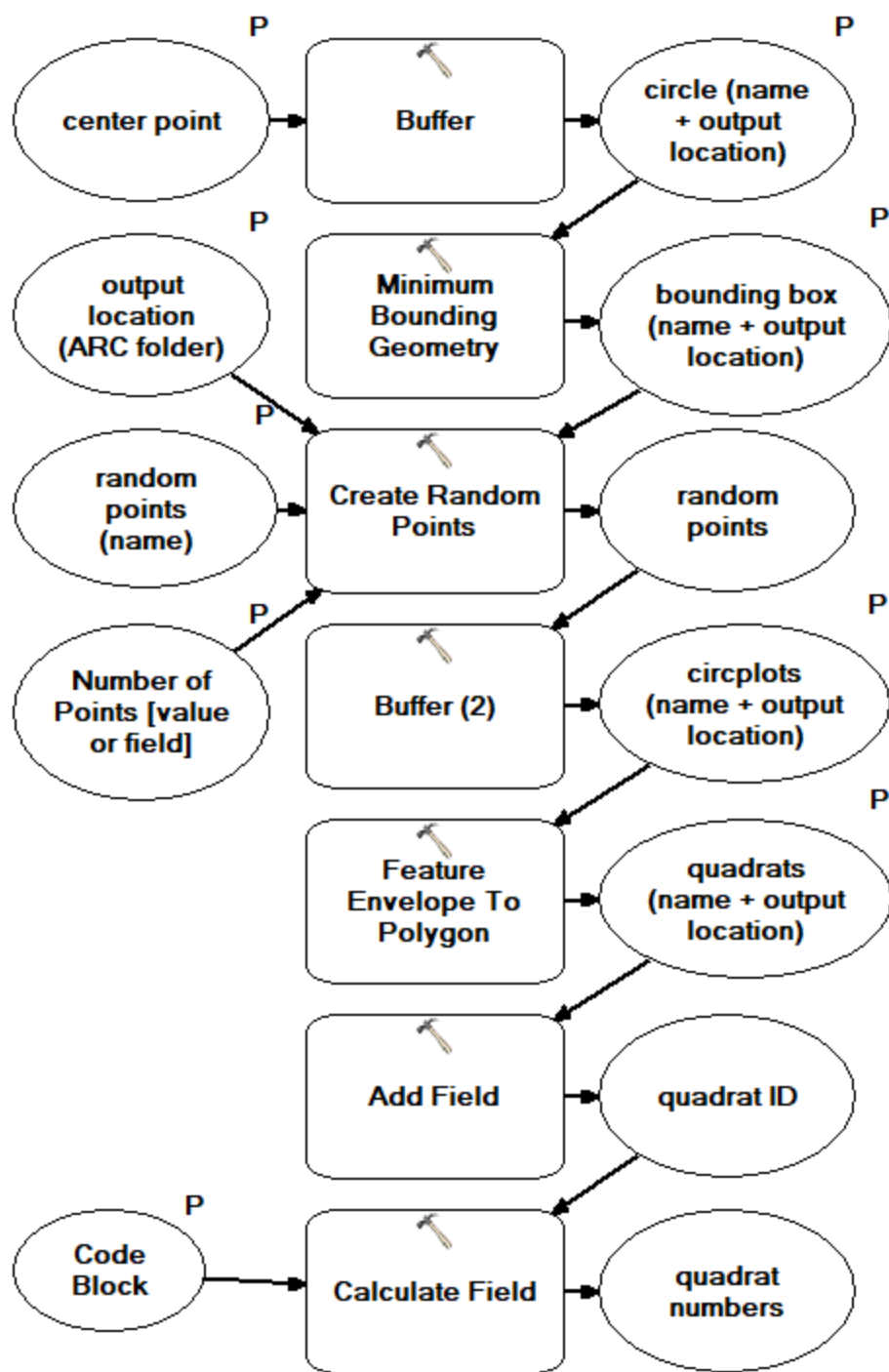   i. Code Block

Figure 43. Screenshot in ArcMap of the completed Model_Build_Quadrats. The first five tools create the quadrats, and the last two tools assign numbered labels to each quadrat. Each P represents a model parameter that the annotator will edit.

9. Save and close the model.

10. Navigate to the model in the catalog and double click to open. All model parameters should be listed.

Create Model to Build Quadrats for Poor Overlap Between Orthoprojections

1. In the main toolbar, click model builder [icon] . An empty Model window will open.
2. Using the search window, search for the Create Random Points (Data Management) tool. Drag and drop into the model window and double click to edit the tool.
   a. Output Location: leave as is
   b. Output Point Feature Class: Site#_randompoints
   c. Constraining Feature Class: leave as is
   d. Long: 25 (number of random points)
   e. Linear unit: 1 Meters -- OK
3. Right click on the Create Random Points input bubble and rename. Change to "output location (ARC folder)".
4. Right click on the Create Random Points output bubble and rename. Change to "random points".
5. Right click on the Create Random Points tool within the model and choose Make Variable -- From Parameter -- Constraining Feature Class.
6. Right click on the Constraining Feature Class bubble and rename "box".
7. Right click on the Create Random Points tool within the model and choose Make Variable -- From Parameter-- Output Point Feature Class.
8. Right click the Output Point Feature Class bubble and rename "random points (name)".
9. Right click on the Create Random Points tool within the model and choose make Variable -- From Parameter -- Number of Points [value or field].
10. Save the model as Model_PoorOverlap_Build_Quadrats.
11. Complete the model by adding the "CREATING QUADRATS"and "LABEL QUADRATS AND SET MODEL PARAMETERS" sections above.
    a. Set the following bubbles as model parameters:
       i. box
       ii. output location (ARC folder)
       iii. random points (name)
       iv. Number of Points [value or field]
       v. circplots (name + output location)
       vi. quadrats (name + output location)
       vii. Code Block
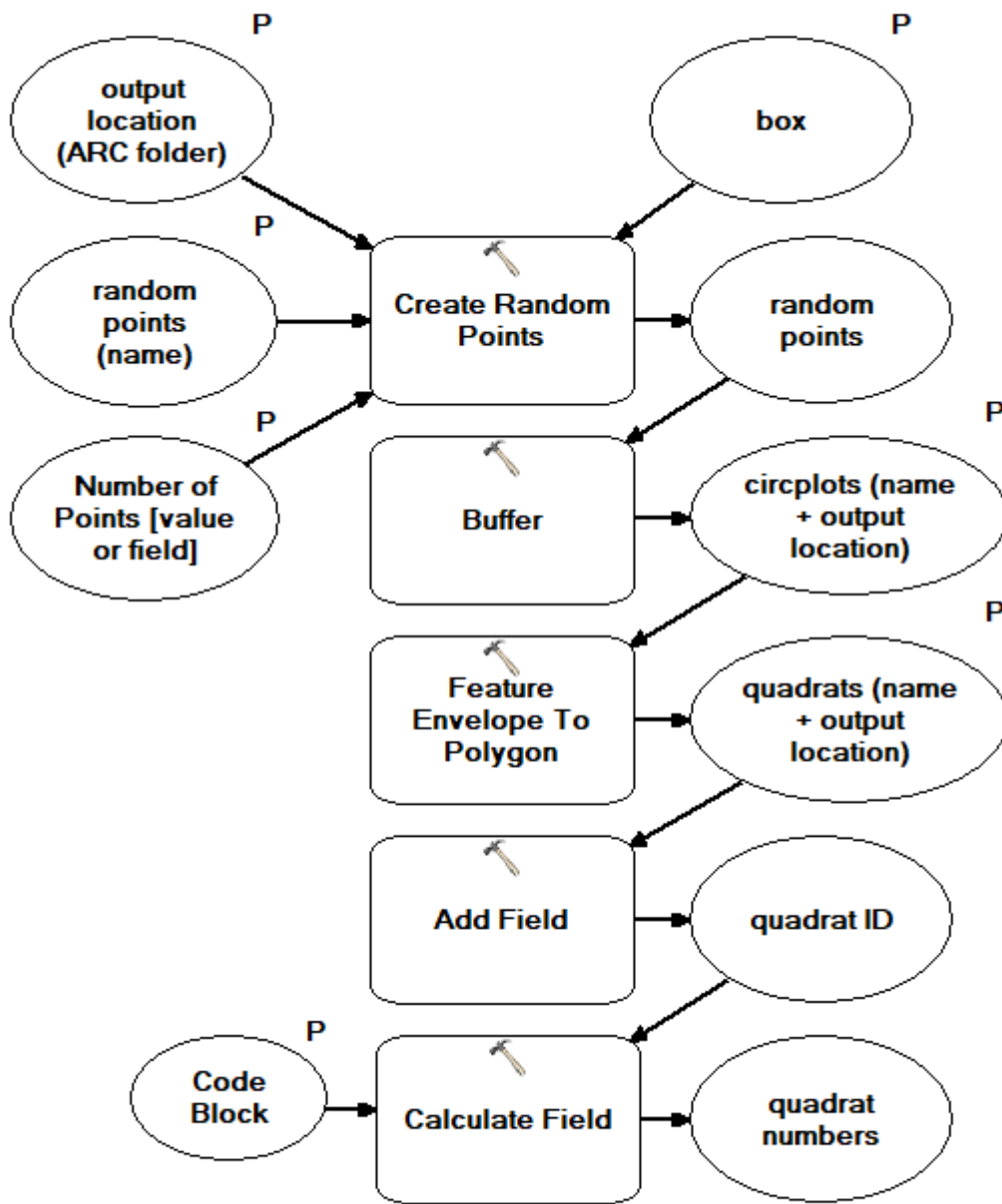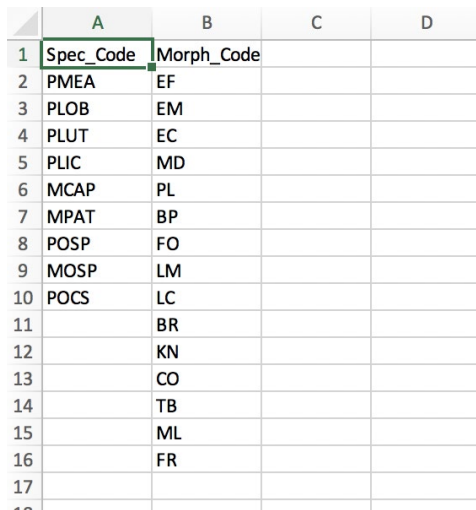12. Save the model as "Model_PoorOverlap_Build_Quadrats and close.

Figure 44. Screenshot in ArcMap of the completed Model_PoorOverlap_Build_Quadrats.
The first three tools create the quadrats, and the last two tools assign numbered labels to each quadrat. Each P represents a model parameter that the annotator will edit.0

Appendix C: Setting Up the Geodatabase

Create a geodatabase and build a template feature class that will allow for delineations to be organized by site. Each site-level geodatabase will be used for all coral patch delineations for each time point and includes drop-down menus for applicable columns. Eventually the geodatabase will be exported to R for data manipulation.

1. Create a File Geodatabase using the Create File GDB (Data Management) tool.
    a. File GDB Location: path where the geodatabase will be stored
    b. File GDB Name: Name of GDB (e.g., SiteName.gdb)
    c. File version: CURRENT
        i. We utilize a GDB for each site and arbitrarily name it SiteName.gdb, which allows us to copy and rename according to site.
2. Open a blank Excel spreadsheet and create your attribute domains. Attribute domains are rules within the geodatabase that constrain the values allowed within a particular attribute and the analyst to utilize a standardized drop-down menu. We use attribute domains for species and morphology, as shown in Fig. 39.
    a. Save the document as a csv file with the title: VitalRatesCodes.csv

	A	B	C	D
1	Spec_Code	Morph_Code		
2	PMEA	EF		
3	PLOB	EM		
4	PLUT	EC		
5	PLIC	MD		
6	MCAP	PL		
7	MPAT	BP		
8	POSP	FO		
9	MOSP	LM		
10	POCS	LC		
11		BR		
12		KN		
13		CO		
14		TB		
15		ML		
16		FR		
17				

Figure 45. Screenshot of the VitalRatesCodes.csv file with the Attribute Domains that require a drop-down menu and their associated codes.

3. Back in ArcMap, import the attribute domains (the drop-downs) into the geodatabase by searching for the Table to Domain (Data Management) tool.
    a. Input Table: VitalRatesCodes.csv
    b. Code Field: use the drop-down to choose one of the attribute domain names
    c. Description Field: same as Code Field
    d. Input Workspace: navigate to the GDB created in step 1 (e.g., SiteName.gdb)
    e. Domain Name: same as Code Field
    f. Domain Description (optional): same as Code Field

g. Update Option (optional): APPEND
   i. Repeat this for all your Attribute Domains
4. Once all the attribute domains are imported, create a template feature class in the geodatabase by searching for the Create Feature Class (Data Management) tool.
   a. Feature Class Location: navigate to the GDB created in step 1 (e.g., SiteName.gdb)
   b. Feature Class Name: template
   c. Geometry Type (optional): POLYGON
   d. Template Feature Class (optional): leave blank
   e. Has M (optional): DISABLED
   f. Has Z (optional): DISABLED
   g. Coordinate System (optional): WGS1984 UTM Zone 4N
5. The template feature class will automatically be dropped into the Table of Contents
6. Search for the Add Field (Data Management) tool. Use this tool to add fields to the template feature class (Input Table). We enter the following fields in the listed order. Remember to add field domains (drop-downs) when applicable. The Field Domain must be identical to the name used in the Table to Domain tool:
   a. Refer to Table 1 on page 3 for field meanings.

Table 5. Settings used for each field of the geodatabase.

Field Name	Field Type	Field Precision	Field Length	Field Domain
Site	TEXT		15	
Quadrat	SHORT	2		
Date	TEXT		10	
Spec_Code	TEXT		10	Spec_Code
Morph_Code	TEXT		10	Morph_Code
BLE_EXT	SHORT	2		
BLE_SEV	SHORT	2		
NoPatches	TEXT		50	
PatchID	SHORT	2		
PatchName	TEXT		50	
LinkTP_Bac	TEXT		200	
LinkTP_For	TEXT		200	

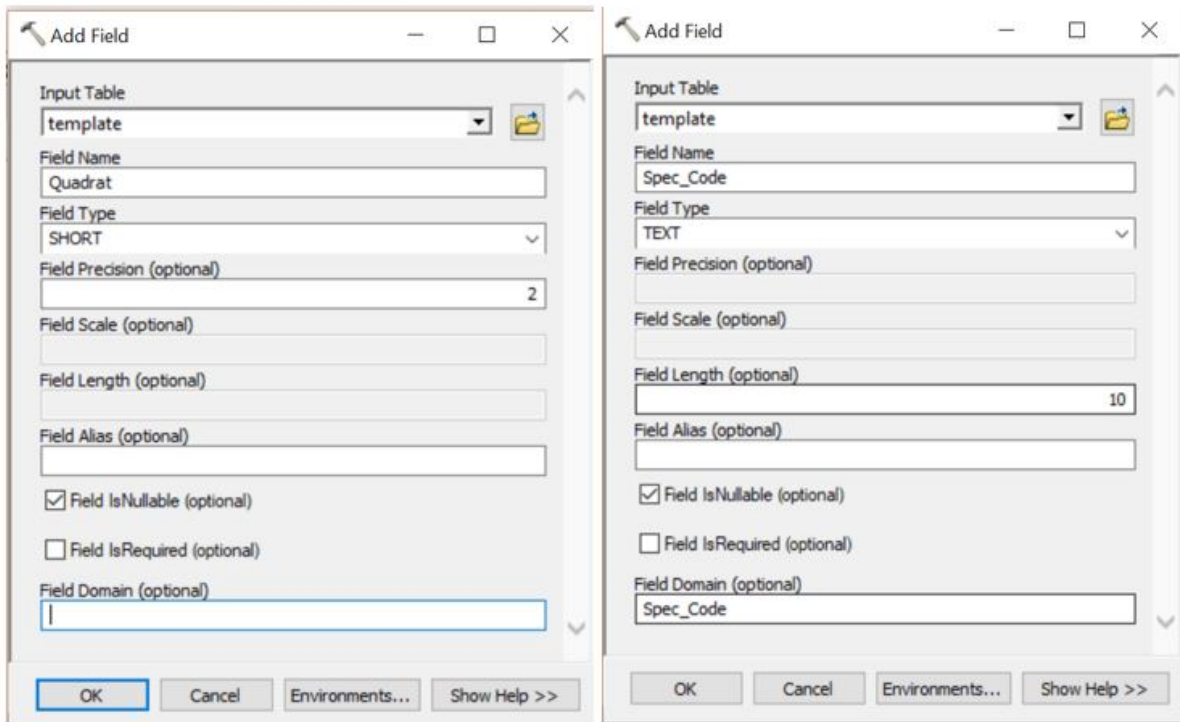| Notes	TEXT		200	
TimePt	SHORT	2		

Figure 46.Screenshot of different variations of the Add Field tool in ArcMap.

7. Once all fields are added, the template and geodatabase are complete.
   Remember that future annotations are created using a copy of the template feature class. Do not annotate using the template feature class.

Appendix D: Species Codes

List of target Hawaiian coral taxa and their corresponding species codes by the NOAA ESD Vital Rates team. Target taxa may change based on geographic region.

1. Species codes:
    a. For each patch, select the species code from the drop-down menu.
    b. PMEA: *Pocillopora meandrina*
    c. PLIG: *Pocillopora ligulata*
    d. PLOB: *Porites lobata*
    e. PLUT: *Porites lutea*
    f. PLIC: *Porites lichen*
    g. MCAP: *Montipora capitata*
    h. MPAT: *Montipora patula*
2. If you cannot ID to the species level:
    a. POSP - *Porites sp.*
    b. MOSP- *Montipora sp.*
    c. POCS - *Pocillopora sp*

Appendix E: Morphology

List of coral morphology types and associated codes and descriptions used by the NOAA ESD Vital Rates team. Morphology codes may change based on geographic region.

1. Morphology should be determined based on the general shape of the live contiguous patch, not of the entire "colony" or the morphology by which a given species is typically characterized.

Table 6. Morphology types, codes, and descriptions used by the NOAA ESD Vital Rates team.

Morphology	Code	Description
Encrusting	ENC	Adheres to a flat or mounding surface. "Pancake glued to the bottom or frosting on a cake"
Encrusting Columnar	EC	Adheres to a flat surface and also has columns; encrusting or spread out base or portion of the colony with branches, knobs, or columns
Mounding	MD	Solid and similar in shape in all dimensions; Ellipsoid—small or large, sometimes spherical
Plating/Laminar	PLL	Forms simple plate extending outwards from the benthic substrate, akin to a shingle on a roof OR multiple plates on a larger structure; "shingles on a mound"
Laminar-columnar	LC	Combination of laminar and columnar morphologies, multiple plates on a larger structure with columns protruding from the top; "candles on a tiered birthday cake"; common for *Porites rus* and *M. capitata*
Branching	BR	Bifurcated or finger-like branching; "fingers"
Knobby	KN	Stubby branches; "knuckles"
Columnar	CO	Forms columns of stumps that often do not share a common base like branching corals generally do

Morphology	Code	Description
Table	TB	Forms a table with one central leg attached to the substrate, mostly *Acropora* such as *A. cytherea*

For example photos of each morphology, see pages 24–25 of Swanson et al. (2018).

Appendix F: Bleaching Extent and Bleaching Severity

This section summarizes the methodology used by the NOAA ESD Vital Rates team to assign bleaching extent and severity to live tissue patches.

1. To assign bleaching extent:
   a. Record the percentage of the live patch that is bleached.
   b. Record as 0–100% bleaching in increments of 1% for percentages between 1–5% and 95–100%. All extents between 5–95% should be recorded in increments of 5%.
   c. If there are multiple regions of bleached tissue in one contiguous live patch, total the bleached patches
      i. If 20% of the patch is slightly pale, 50% of the patch is stark white, and 5% of the patch has significant loss of pigment, record 75% extent.
2. To assign bleaching severity:
   a. Severity is recorded on a scale of 1–3
      i. 1: slight paling
      ii. 2: significant loss of pigmentation
      iii. 3: almost or completely stark white
      iv. If the patch is not bleached, you do not need to record a 0; ArcMap will automatically fill in the blank with 0.
   b. When in doubt, if choosing between two severity levels, be conservative in your estimate.
   c. If there are different bleaching severities within a contiguous live patch, take the average of the severities. Do not take the non-bleached areas into account when determining bleaching severity. For example:
      i. If 50% of a patch is not bleached and 50% of the patch is bleached with severity = 3 Do not average 0 and 3. Instead, the severity level should be written as 3
      ii. If a live patch has 20% severity 1, 20% severity 2, and 20% severity 3, a severity of 2 should be recorded
      iii. If 80% of the live patch is severity 2 and 10% of the live patch is severity 1, record a severity level of 2
      iv. If 50% of the live patch is severity 1, 25% is severity 2, and 25% is severity 3, record a severity level of 2
   d. Some genera lose color more than others. For example, *Porites* do not always bleach completely white. A good rule of thumb is to track the colony in question across time points to get a general baseline of live patch pigmentation and if discoloration is due to image overexposure or "casual paling" rather than coral bleaching.

Appendix G: Replace a Deleted Quadrat

If you accidentally delete one of the quadrats, follow this procedure to create a new set of quadrats in the exact same place.

1. From the Catalog menu, drag and drop the Site#_randompoint.shp file onto your viewing window where the orthoprojection(s) is visible (or drag into the table of contents).
2. Using the search window, search for the Buffer (Analysis) tool.
   a. Input features: use the drop-down menu to select Site#_randompoint.shp
   b. Output Point Feature Class: Change the output location to your FixedSiteProducts/Site/ARC folder and save it as Site#_corrected_circplots.shp
   c. Linear unit: 35.35 cm
   d. Side Type: FULL
   e. End Type: ROUND
   f. Method: PLANAR
   g. Dissolve Type: NONE -- OK
3. Using the search window, search for the Feature Envelope to Polygon (Data Management) tool.
   a. Input Features: use the drop-down menu to choose the Site#_corrected_circplots.shp you just created
   b. Output Feature Class: Change the output location to your FixedSiteProducts/Site/ARC folder and save it as Site#_corrected_quadrats
   c. Check Create multipart features (optional) -- OK
3. Drop this new Site#_corrected_quadrats file onto your orthoprojection(s) viewing window and remove the old shape file that contained the deleted quadrat from the Table of Contents.
4. Right click on the Site#_corrected_quadrats file in the Table of Contents and click Open Attribute Table.
5. Click the arrow on the top left icon (Table Options) and choose Add Field (Editor must be turned off).
   a. Name: QuadNum
   b. Type: Short Integer
   c. Precision: 2
6. To populate the QuadNum field:
   a. Start editing
   b. Highlight QuadNum column and right click and choose Field Calculator
   c. Click Python and Show Codeblock
   d. Copy and paste the following code into Pre-Logic Script Code:
   ```
   rec=0
   def autoIncrement():
    global rec
    pStart = 1
    pInterval = 1
   ```

```
if (rec == 0):
 rec = pStart
else:
 rec += pInterval
return rec
```

  e. In the QuadNum box below, copy and paste:

```
autoIncrement()
```

  f. Click OK

  g. If an error message appears, delete any extra spaces at the end of the codeblock

7. Format and label the quadrat according to the SOP (steps 6–7 on page 25).