Coral Reefs
https://doi.org/10.1007/s00338-023-02367-7

NOTE

3D photogrammetry improves measurement of growth and biodiversity patterns in branching corals

Joseph S. Curtis[1,2] · Journ W. Galvan[1] · Alexander Primo[3] · Craig W. Osenberg[3] · Adrian C. Stier[1,2]

Received: 12 October 2021 / Accepted: 5 March 2023
© The Author(s), under exclusive licence to International Coral Reef Society (ICRS) 2023

Abstract Photogrammetry is an emerging tool that allows scientists to measure important habitat characteristics of coral reefs at multiple spatial scales. However, the ecological benefits of using photogrammetry to measure reef habitat have rarely been assessed through direct comparison to traditional methods, especially in settings where manual measurements are more feasible and affordable. Here, we applied multiple methods to measure coral colonies (*Pocillopora* spp.) and asked whether photogrammetric or manual observations better describe short-term colony growth and links between colony size and the biodiversity of coral-dwelling fishes and invertebrates. Using photogrammetry, we measured patterns in changes in coral volume that were otherwise obscured by high variation from manual measurements. Additionally, we found that photogrammetry-based estimates of colony skeletal volume best predicted the abundance and richness of animals living within the coral. This study highlights that photogrammetry can improve descriptions of coral colony size, growth, and associated biodiversity compared to manual measurements.

Keywords 3D modeling · Biodiversity · Branching coral · Microhabitat · Moorea · Reef ecology

Introduction

Successful integration of new technology into ecological research requires clear understanding of how it can improve predictions of biological processes. Photogrammetry is a tool that renders detailed models of landscapes and organisms from images, enabling sophisticated examination of habitat structure (Burns et al. 2015; Ferrari et al. 2021). However, photogrammetric applications can be more expensive than traditional data collection methods in terms of equipment, time, and training (Young et al. 2017; Couch et al. 2021; Urbina-Barreto et al. 2021). Despite such costs, photogrammetric measurements of basic habitat characteristics may be very similar to data collected using traditional surveys (Raoult et al. 2016; Million et al. 2021). Studies that explicitly measure the same ecological phenomena using photogrammetry and manual approaches are therefore needed to critically examine the benefits of this emerging technique.

Photogrammetry may provide an especially useful research tool in settings where interactions among animals and structurally complex habitats govern ecosystem function, such as coral reefs (Burns et al. 2015; Lavy et al. 2015). For example, photogrammetry has helped to measure connections between reef habitat and fish communities (Gonzalez-Rivero et al. 2017; Urbina-Barreto et al. 2020), assess patterns in coral growth (Ferrari et al. 2017; Conley and Hollander 2021), and generate novel descriptions of coral geometry (Reichert et al. 2017; Aston et al. 2022). Among studies that have included both manual and photogrammetric measurements, most have focused on the accuracy of

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00338-023-02367-7.

Joseph S. Curtis
joseph_curtis@ucsb.edu

[1] Department of Ecology, Evolution, and Marine Biology, University of California Santa Barbara, Santa Barbara, CA 93106, USA

[2] Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA 93106, USA

[3] Odum School of Ecology, University of Georgia, 140 E Green St, Athens, GA 30602, USA

Published online: 20 March 2023

photogrammetry, which has been robustly demonstrated (Courtney et al. 2007; Veal et al. 2010; Figueira et al. 2015; Lavy et al. 2015). However, few studies have quantified differences in analogous ecological measurements derived from photogrammetric and traditional measurements of reef habitat, likely because photogrammetry is often used to describe large-scale characteristics when no practical manual equivalent is available (Reichert et al. 2017; Aston et al. 2022).

Some direct comparisons of ecological interpretations derived from manual and photogrammetric approaches indicate that photogrammetry can provide more accurate estimates of coral growth (Kikuzawa et al. 2018; Conley and Hollander 2021) and stronger predictions of links between fish biodiversity and reef-scale habitat complexity (Gonzalez-Rivero et al. 2017). However, photogrammetric measurements do not always lead to different conclusions than comparable field-based estimates. For example, Million et al. (2021) measured nearly identical colony growth using photogrammetric and manual methodologies, while Agudo-Adriani et al. (2016) observed that simple, manually measurable colony features drove more variation in fish communities than complex, photogrammetry-derived habitat characteristics.

In this paper we explore whether photogrammetry improves measurements of growth and habitat provisioning of branching cauliflower corals (*Pocillopora* spp.) over traditional approaches. Specifically, we asked: (1) Do manual or photogrammetric methods better describe short-term, volumetric growth across a range of coral sizes, and (2) Does photogrammetry improve our ability to predict the abundance and biodiversity of coral-associated animal communities?

Methods

We collected data in Moorea, French Polynesia, as part of a study of feedbacks between *Pocillopora* spp. and coral-associated fishes and invertebrates (CAFI). Although CAFI diversity and abundance have been shown to increase with host colony size, these relationships were previously modeled using coarse geometric measurements (Caley et al. 2001). We hypothesized that photogrammetry would better quantify linkages between coral volume and CAFI community characteristics.

We initiated an experiment in August 2019 consisting of 60 *Pocillopora* colonies (5–50 cm diameter). Corals were removed from the reef and sorted into control (n = 30) and CAFI-removal treatments (n = 30), then deployed into an experimental array (see Supplement). Directly after deployment, we measured coral size using both manual and photogrammetric approaches (Fig. S1). For manual measurements, a single observer used a flexible tape to estimate colony length (*L*, longest horizontal axis), width (*W*, longest perpendicular measurement to length), and height (*H*, perpendicular to *L* and *W*). We calculated manual coral volume as a hemi-ellipsoid:

$$V_{ellipsoid} = \frac{4}{3}\pi\frac{L}{2}\frac{W}{2}\frac{H}{2} \tag{1}$$

a measurement previously used to relate *Pocillopora* spp. volume to CAFI biodiversity (Caley et al. 2001; McKeon et al. 2012).

For photogrammetric measurements, we used Agisoft Metashape (v1.6.2; Agisoft LLC, St. Petersburg, Russia) to create 3D models of coral colonies, following the protocol outlined by Ferrari et al. (2017). Full details are outlined in the Supplement, and in our online protocol (https://github.com/stier-lab/Stier-Coral-Morphometrics-2020). Using our complete and isolated 3D models, we estimated skeletal volume (V_{skeleton}), as well as length, width and height of each colony in Metashape. From photogrammetric linear dimensions we calculated photogrammetric ellipsoid volume ($V_{\text{photo\_ellipsoid}}$) to directly approximate manual volumetric measurements ($V_{\text{ellipsoid}}$). We also used Meshlab (v2020.06; Cignoni et al. 2008) to estimate convex hull volume (V_{hull}), the size of the smallest convex 3D object that can encase a coral colony. Convex hulls provided an additional semi-elliptical measurement of exterior coral volume, but one that is not based on geometric calculation from multiple observer-based component measurements. To assess coral growth, we remeasured colonies after 105 days in December 2019 using the same observers.

We excluded six corals (of 60) from all analyses which did not yield high-quality photogrammetric models, due largely to incomplete photo coverage and turbidity. We also excluded 21 colonies from growth measurements that by December had experienced partial mortality or attracted dense fish aggregations which obscured the coral in photographs. In total, we analyzed n = 33 colonies for coral growth (measured at both time points) and n = 26 colonies to link CAFI biodiversity and coral volume (using data from August).

Analysis

We estimated growth as the proportional change in volume, calculated as $(V_{i,\text{December}} - V_{i,\text{August}})/V_{i,\text{August}}$ where i represents measurement method (manual ellipsoid, photogrammetric ellipsoid, hull, or skeleton). We used correlation analysis to compare manual and photogrammetric estimates of colony size and growth. We compared mean growth estimates using a repeated-measures ANOVA with a Greenhouse–Geisser correction and a post hoc Tukey HSD test (Bathke et al. 2009). We measured whether August colony volume predicted growth by performing linear regression on colony-wise growth and initial volume measurements. To measure the link between colony volume and CAFI biodiversity, we performed power-law regressions of CAFI abundance and richness against all four volumetric measurements (see Supplement). We compared goodness of fit among regressions of the same response variable using AIC and root mean square error (RMSE) values (Chai and Draxler 2014). We performed analyses using R v3.6.3 (R Core Team, 2022) at a significance threshold of $\alpha = 0.05$.

Results and discussion

Manual measurements of colony size and volume were strongly correlated to photogrammetric measurements (Table S1; Fig. S2). In contrast, manual growth estimates ($V_{ellipsoid}$) were not correlated with any of the three photogrammetric growth estimates, whereas all three photogrammetric estimates of growth were positively correlated with each other (Table S1). Average proportionate growth varied slightly among the four methods (ANOVA: $F_{3,126} = 4.9$, $p = 0.014$, Fig. 1), with the only pairwise difference being between photogrammetric ellipsoid growth and manual ellipsoid growth (Diff (95% CI) = 14.6% (2.2%, 27.1%), $t_{32} = 14.6$, $p = 0.014$). Changes in ellipsoid volume (both manual and photogrammetric) were over twice as variable ($SD_{ellipsoid} = 23.9\%$, $SD_{photo\_ellipsoid} = 25.6\%$) as growth estimates derived from photogrammetric measurements of $V_{skeleton}$ and V_{hull} ($SD_{skeleton} = 9.99\%$, $SD_{hull} = 12.7\%$). Over a third of manual growth measurements were negative (13/33), whereas only 4/33 photogrammetric ellipsoid measurements, 2/31 photogrammetric hull measurements and 0/33 photogrammetric skeletal measurements were negative. Finally, all photogrammetric growth measurements were positively correlated with initial coral volume, whereas manual ellipsoid growth was uncorrelated with initial volume (Fig. S3).

All volumetric measurements, including manual ellipsoid volume, suggested that CAFI abundance and richness increased with coral size (Fig. 2). However, photogrammetry-based measurements of $V_{skeleton}$ provided better predictors of CAFI abundance and biodiversity than manual estimates ($\Delta AIC_{abundance} = -5.8$, $\Delta AIC_{richness} = -3.6$; RMSE reduced by ~ 10%; Table S2). In contrast, all other photogrammetric estimates performed similarly to each other and to manual ellipsoid volume (Table S2).

Our findings demonstrate that photogrammetry can yield useful descriptions of coral colony structure and growth, and quantify the value of its application over traditional measurement methods. The tight correlation of manual and photogrammetric measurements corroborates that both approaches provide consistent assessments of coral linear dimensions and exterior volume (Courtney et al. 2007; Veal et al. 2010; Lavy et al. 2015; Fig. S2).

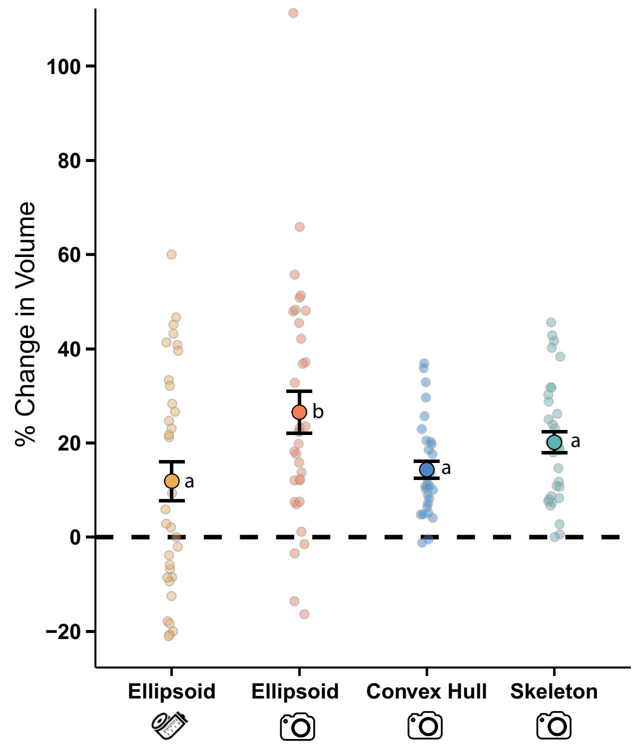

Fig. 1 Mean (±*SE*) proportional change in coral volume between August and December 2019 derived from manual measurements of ellipsoid volume (yellow) and photogrammetric measurements of ellipsoid (red), convex hull (blue), and skeletal volume (green). **a**, **b** indicate statistically significant differences based upon ANOVA followed by Tukey's HSD tests

However, photogrammetric measurements of skeleton and convex hull volume yielded the least variable and most biologically realistic (i.e., moderate and positive) estimates of growth over our three-month experimental period. Conversely, ellipsoid-based calculations (both manual and photogrammetric) provided more extreme and variable growth measurements, possibly due to error propagation when multiplying component linear measurements (Kikuzawa et al. 2018, see Supplementary material). In particular, our inclusion of large corals may have led to error in both manual and photogrammetric ellipsoid-based calculations due to increased departure from an elliptical shape (Conley and Hollander 2021; Million et al. 2021). Despite their high levels of variability, photogrammetric ellipsoid growth, unlike manual ellipsoid growth, was correlated to other photogrammetric growth measurements, possibly due to reduced error in component photogrammetric linear measurements compared to manual equivalents (Couch et al. 2021). In addition, all three photogrammetric volume measurements better described the expected allometry between growth and colony size (See Supplement, Fig. S3). Therefore, photogrammetric growth measurements were more broadly consistent and informative

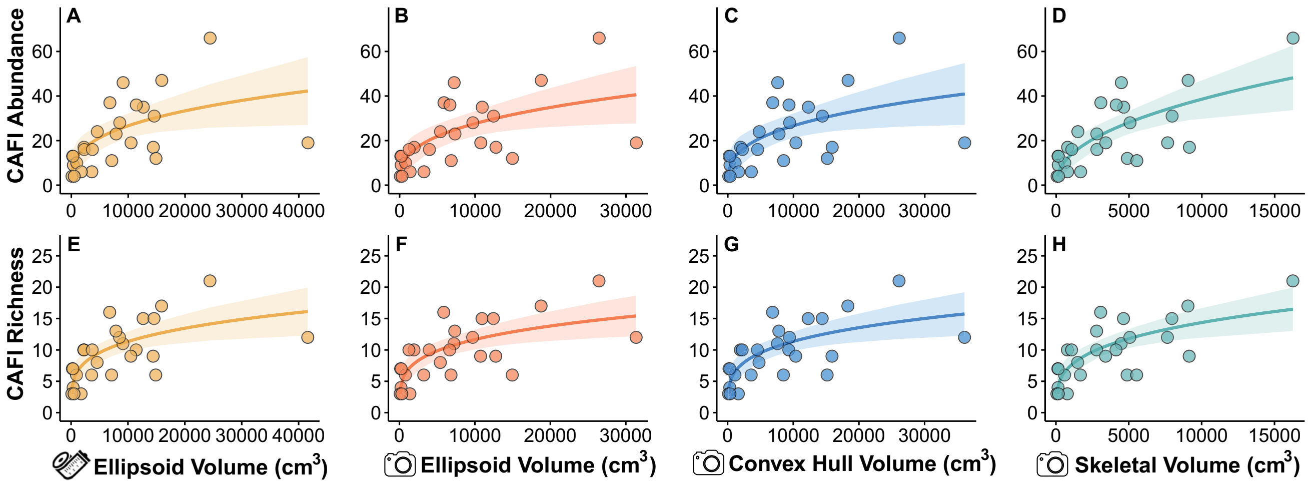

Fig. 2 Power-law regressions of CAFI abundance (**A**–**D**) and richness (**E**–**G**) against manual coral ellipsoid volume (**A**, **D**, yellow) and three photogrammetry-derived measurements: ellipsoid (**B**, **E**, red), convex hull (**C**, **F**, blue), and skeletal volume (**D**, **G**, green). Shaded areas are 95% CIs of fitted regressions (Table S2)

than manual growth estimates, even at monthly timescales and across a wide range of colony sizes.

Additionally, photogrammetric skeletal volume most strongly predicted CAFI abundance and richness, outperforming manual ellipsoid volume and other photogrammetry-based measurements. The similarity in performance of photogrammetric ellipsoid volume, hull volume, and manual ellipsoid volume suggests that any methodological differences in accuracy did not yield improvements in modeled relationships with CAFI biodiversity. Instead, the advantage of photogrammetry was its ability to describe habitat in ways that are difficult using noninvasive manual techniques, in this case through estimates of skeletal volume. Although coral skeletal volume can also be measured by buoyant weighing or CT-scanning, these techniques are generally destructive and challenging to perform on large corals (Conley and Hollander 2021). Our photogrammetric measurements offer the first linkages of CAFI biodiversity to *Pocillopora* spp. skeletal volume, improving resolution of habitat-biodiversity relationships over our best available manual approximation of coral volume.

The application of photogrammetry to nondestructively measure 3D coral colonies in situ offers an exciting opportunity for researchers to study the ecology and structure of corals across a broad range of sizes. We conclude that photogrammetry may be especially valuable when 3D measurements are desirable but hard to obtain using field-based approaches, or where repeated measurements are required. By allowing noninvasive description of habitat characteristics, photogrammetry can generate tremendous value for studies of reef ecology and coral-animal interactions, even in settings where more affordable in situ measurements are available.

Acknowledgements This research was funded by a U.S. National Science Foundation Grant OCE 2224354 to the Moorea Coral Reef LTER, OCE #1851510, 1851032 to our research groups, as well as a generous gift from the Gordon and Betty Moore Foundation. Research was completed under permits issued by UCSB IACUC (Protocol #926), the Territorial Government of French Polynesia (Délégation à la Recherche) and the Haut-Commissariat de la République en Polynésie Francaise (DTRT) (MCR LTER Protocole d'Accueil 2005–2022; Stier Protocole d'Accueil 2019-2022), and we thank the Délégation à la Recherche and DTRT for their continued support. We thank Matthew Gottlieb, the Moorea Coral Reef LTER, UCSB Ocean Recoveries Lab, and Gump Research Station staff for their insight and technical assistance. Finally, we acknowledge the people of Tahiti for their environmental stewardship and for the honor of studying their reefs.

Author contributions CO and AS designed the research; JC and AP collected field data; JG developed the photogrammetry protocol; JC and JG analyzed data; JC led manuscript writing. All authors contributed critically to drafts and gave final approval for publication. On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability Data, code, and detailed photogrammetry protocols are available at: https://github.com/stier-lab/Stier-Coral-Morphometrics-2020.

References

Agudo-Adriani EA, Cappelletto J, Cavada-Blanco F, Croquer A (2016) Colony geometry and structural complexity of the endangered species *Acropora cervicornis* partly explains the structure of their associated fish assemblage. PeerJ 4:e1861

Aston EA, Duce S, Hoey AS, Ferrari R (2022) A protocol for extracting structural metrics from 3D reconstructions of corals. Front Marine Sci. https://doi.org/10.3389/fmars.2022.854395

Bathke AC, Schabenberger O, Tobias RD, Madden LV (2009) Greenhouse-geisser adjustment and the ANOVA-type statistic: cousins or twins? Am Stat 63:239–246

Burns J, Delparte D, Gates R, Takabayashi M (2015) Integrating structure-from-motion photogrammetry with geospatial software as a novel technique for quantifying 3D ecological characteristics of coral reefs. PeerJ 3:e1077

Caley JM, Buckley KA, Jones GP (2001) Separating ecological effects of habitat fragmentation, degradation, and loss on coral commensals. Ecology 82:3435–3448

Chai T, Draxler RR (2014) Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. Geoscient Model Devel 7:1247–1250

Cignoni P, Callieri M, Corsini M, Dellepiane M, Ganovelli F, Ranzuglia G (2008) MeshLab: an open-source mesh processing tool. Eurographics Italian Chapter Conference, 8 p

Conley DD, Hollander ENR (2021) A non-destructive method to create a time series of surface area for coral using 3D photogrammetry. Front Marine Sci. https://doi.org/10.3389/fmars.2021.660846

Couch CS, Oliver TA, Suka R, Lamirand M, Asbury M, Amir C, Vargas-Ángel B, Winston M, Huntington B, Lichowski F, Halperin A, Gray A, Garriques J, Samson J (2021) Comparing coral colony surveys from in-water observations and structure-from-motion imagery shows low methodological bias. Front Marine Sci. https://doi.org/10.3389/fmars.2021.647943

Courtney LA, Fisher WS, Raimondo S, Oliver LM, Davis WP (2007) Estimating 3-dimensional colony surface area of field corals. J Exp Mar Biol Ecol 351:234–242

Ferrari R, Figueira WF, Pratchett MS, Boube T, Adam A, Kobelkowsky-Vidrio T, Doo SS, Atwood TB, Byrne M (2017) 3D photogrammetry quantifies growth and external erosion of individual coral colonies and skeletons. Sci Rep 7:16737

Ferrari R, Lachs L, Pygas DR, Humanes A, Sommer B, Figueira WF, Edwards AJ, Bythell JC, Guest JR (2021) Photogrammetry as a tool to improve ecosystem restoration. Trends Ecol Evol 36:1093–1101

Figueira W, Ferrari R, Weatherby E, Porter A, Hawes S, Byrne M (2015) Accuracy and precision of habitat structural complexity metrics derived from underwater photogrammetry. Remote Sens 7:16883–16900

Gonzalez-Rivero M, Harborne AR, Herrera-Reveles A, Bozec Y-M, Rogers A, Friedman A, Ganase A, Hoegh-Guldberg O (2017) Linking fishes to multiple metrics of coral reef structural complexity using three-dimensional technology. Sci Rep 7:13965

Kikuzawa YP, Toh TC, Ng CSL, Sam SQ, Taira D, Afiq-Rosli L, Chou LM (2018) Quantifying growth in maricultured corals using photogrammetry. Aquac Res 49:2249–2255

Lavy A, Eyal G, Neal B, Keren R, Loya Y, Ilan M (2015) A quick, easy and non-intrusive method for underwater volume and surface area evaluation of benthic organisms by 3D computer modelling. Methods Ecol Evol 6:521–531

McKeon CS, Stier AC, McIlroy SE, Bolker BM (2012) Multiple defender effects: synergistic coral defense by mutualist crustaceans. Oecologia 169:1095–1103

Million WC, O'Donnell S, Bartels E, Kenkel CD (2021) Colony-level 3D Photogrammetry reveals that total linear extension and initial growth do not scale with complex morphological growth in the branching coral. Acropora Cervicornis Front Mar Sci 8:646475

Raoult V, David PA, Dupont SF, Mathewson CP, O'Neill SJ, Powell NN, Williamson JE (2016) GoPros™ as an underwater photogrammetry tool for citizen science. PeerJ 4:e1960

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. More information is available here: https://intro2r.com/citing-r.html

Reichert J, Backes AR, Schubert P, Wilke T (2017) The power of 3D fractal dimensions for comparative shape and structural complexity analyses of irregularly shaped organisms. Methods Ecol Evol 8:1650–1658

Urbina-Barreto I, Chiroleu F, Pinel R, Fréchon L, Mahamadaly V, Elise S, Kulbicki M, Quod J-P, Dutrieux E, Garnier R, Henrich Bruggemann J, Penin L, Adjeroud M (2020) Quantifying the shelter capacity of coral reefs using photogrammetric 3D modeling: From colonies to reefscapes. Ecol Ind 121:107151

Urbina-Barreto I, Garnier R, Elise S, Pinel R, Dumas P, Mahamadaly V, Facon M, Bureau S, Peignon C, Quod J-P, Dutrieux E, Penin L, Adjeroud M (2021) Which method for which purpose? A comparison of line intercept transect and underwater photogrammetry methods for coral reef surveys. Front Marine Sci 8:636902

Veal CJ, Holmes G, Nunez M, Hoegh-Guldberg O, Osborn J (2010) A comparative study of methods for surface area and three-dimensional shape measurement of coral skeletons: Surface area measurements of corals. Limnol Oceanogr Methods 8:241–253

Young GC, Dey S, Rogers AD, Exton D (2017) Cost and time-effective method for multi-scale measures of rugosity, fractal dimension, and vector dispersion from coral reef 3D models. PLoS ONE 12:e0175341

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.