



A protocol for the large-scale analysis of reefs using Structure from Motion photogrammetry

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Abstract

1. Substrate complexity is an essential metric of reef health and a strong predictor of several ecological processes connected to the reef, including disturbance, resilience, and associated community abundance and diversity.
2. Underwater Structure from Motion (SfM) photogrammetry has been growing rapidly in use over the last 5 years due to advances in computing power, reduced costs of underwater digital cameras and a push for reproducible data. This has led to the adaptation of an originally terrestrial survey technique into the marine realm, which can now be applied at the habitat scale.
3. This technique allows researchers to make detailed 3D reconstructions of reef surfaces for morphometric analysis of reef physical structure and perform large-scale image-mosaic mapping. SfM is useful for both reef-scale and colony-scale assessments, where visual or acoustic methods are impractical or not sufficiently detailed.
4. Here we provide a protocol for the collection, analysis and display of 3D reef data, focussing on large-scale habitat assessments of coral reefs using primarily open-source software. We further suggest applications for other underwater environments and scales of assessment, and hope this standardized protocol will help researchers apply this technology and inspire new avenues of ecological research.

KEYWORDS

complexity, coral, photogrammetry, reefs, rugosity, Structure from Motion

1 | INTRODUCTION

The 3D structure of temperate and tropical reef ecosystems is a key predictor of benthic and demersal community structure, and of ecosystem disturbance and resilience (Ferrari, Bryson, et al., 2016; Graham & Nash, 2013; Zawada, Madin, Baird, Bridge, & Dornelas, 2019). Traditionally, this component of the underwater environment has been recorded visually on a graded scale (Wilson, Graham, & Polunin, 2007), or using in-situ measures like the 'tape-and-chain' method (English, Baker, Wilkinson, & Wilkinson, 1997), or

determined via a combination of visual and directly measured elements (Gratwicke & Speight, 2005). However, while these methods have proved useful for ecological studies, there is potential for observer bias, high variation according to placement and non-repeatability (Bayley, Mogg, Koldewey, & Purvis, 2019).

The recent development of new technologies to record physical structures digitally, alongside rapid increases in computing power have allowed these traditional methods to be substantially improved upon. 'Structure from Motion' (SfM) photogrammetry (Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012) now allows us to

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create a detailed non-destructive 3D digital model of the physical environment from overlapping camera images. Models can be morphometrically analysed in a range of ways, and can be archived for future analysis and comparison by multiple observers (Anderson, Westoby, & James, 2019; Bayley & Mogg, 2019).

As this technology expands its use into underwater survey and research (from a largely terrestrial starting point), a range of methodologies are developing for creating and analysing 3D reef models, primarily over a small scale. However, there is still uncertainty for researchers new to this field over how to create their own models given the range of options available, and therefore a barrier to its standardized use in this setting from the initial training hurdles.

We present an end-to-end protocol for how to create large-scale 3D models of reefs, common options for analysis of such models, and best practice for storage and presentation of the outputs. We hope to aid researchers new to this approach by providing clear guidance to help fast-track and standardize the applications of photogrammetry within the community. We also hope it will inspire new avenues of ecological research, by summarizing a range of approaches already in use.

2 | ECOLOGICAL APPLICATIONS

This paper specifically deals with the creation of models created from reef environments; however, the SfM technique has been shown to be accurate and repeatable at a range of scales and across various habitat types above and below water (Anderson et al., 2019; Bayley, Mogg, Koldewey, et al., 2019; Bryson et al., 2017; Ferrari, McKinnon, et al., 2016; Raoult, Reid-Anderson, Ferri, & Williamson, 2017).

Within the sphere of marine ecological research, this technology is being applied to analyse reef benthic community composition and habitat condition (Bayley, Mogg, Purvis, & Koldewey, 2019; Burns et al., 2020; Carlot et al., 2020; Edwards et al., 2017; Fukunaga, Burns, Craig, & Kosaki, 2019; Fukunaga, Burns, Pascoe, & Kosaki, 2020), to inform associated community dynamics, and species behavioural interactions (Bayley & Rose, 2020; González-Rivero et al., 2017; Palma et al., 2019; Tebbett, Streit, & Bellwood, 2020), and to assess changes in morphological complexity or growth through time (Bayley, 2019; Ferrari, Bryson, et al., 2016; Ferrari et al., 2017; Lange & Perry, 2020; Lavy et al., 2015; Magel, Burns, Gates, & Baum, 2019; Rossi, Castagnetti, Capra, Brooks, & Mancini, 2020). The technique is also being usefully applied to inform analysis of other marine and coastal systems, using drones and remotely operated vehicles (Casella et al., 2017; Castellanos-Galindo, Casella, Mejía-Rentería, & Rovere, 2019; Chirayath & Instrella, 2019; Palma et al., 2018; Price et al., 2019; Teague & Scott, 2017; Varela et al., 2019), making this a rapidly evolving and adaptable tool. The recent application of machine learning and convolutional neural networks to aid habitat/species classification of 3D mapped outputs will likely further widen the scope of this tool (Chirayath & Instrella, 2019; Hopkinson et al., 2020; Mohamed, Nadaoka, & Nakamura, 2020).

3 | LIMITATIONS

Unlike laser or acoustic-based methods of structural assessment, SfM is primarily limited by lighting, visibility and resolution as it is image-based. This can result in the loss of detail/accuracy in highly complex substrates due to objects creating areas of occlusion (i.e. obscured/shadowed areas where we cannot see, such as the centre of a densely branching coral stand). Adequate lighting, survey coverage, image overlap and camera equipment are therefore essential for creating accurate reef reconstructions (Aber, Marzoff, Ries, & Aber, 2019). Official ISO data collection standards are however still being developed for this technique (Kresse, 2010); therefore, the level of consistency/comparability across outputs from varying cameras, operators and conditions is still to be fully explored. Finally, the size of current individual surveys is generally restricted to hundreds of square metres, primarily due to computer processing power limitations and time constraints (Bayley, Mogg, Koldewey, et al., 2019; D'Urban Jackson, Williams, Walker-Springett, & Davies, 2020).

4 | PRE-FIELDWORK PREPARATION

4.1 | Computer storage/power

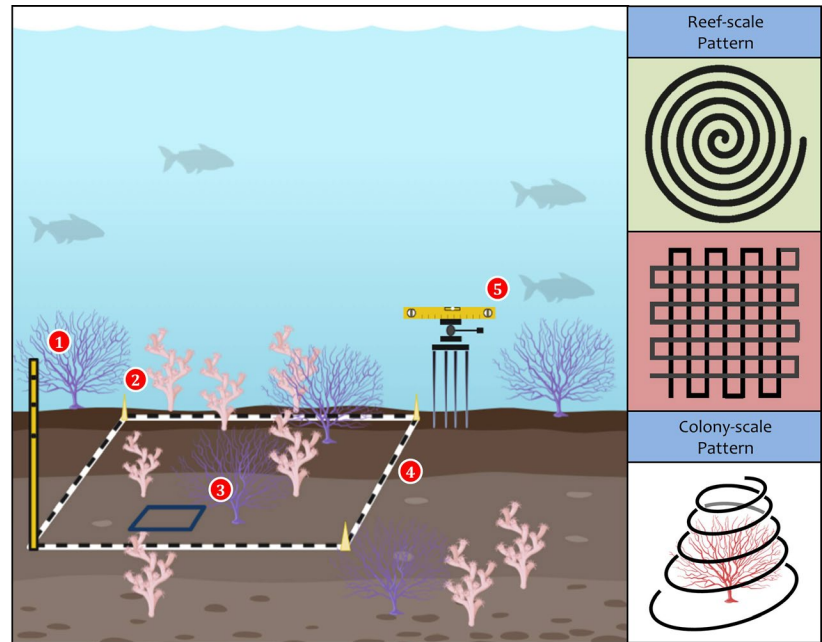
Photographic inputs for SfM can be relatively data-intensive (i.e. multiple gigabytes of data per survey), with reef-scale surveys averaging several thousand images and even small-scale reconstructions of complex objects requiring tens to hundreds of images. However, photographic detail is important, with higher-resolution cameras enabling greater data capture and point-matching per image, as well as greater stand-off distances in clear waters. Adequate computing power is therefore essential as ~100 m² of complex seabed may require ~1,000 images to produce a sufficiently detailed surface model. These data require large amounts of RAM (≥32 GB), a powerful GPU (e.g. Nvidia GeForce range) and multi-core CPU (e.g. Quad-core Intel i7 or higher) to process in a sensible time period (i.e. hours vs. days). Cluster processing the work over multiple nodes can considerably reduce processing time.

5 | IMAGE COLLECTION METHOD FOR SFM

5.1 | Survey area set-up (the 're-construction site')

To mark out the site, we recommend initially tying off a Surface Marker Buoy (line taut to surface) with an attached waterproof GPS unit, to a non-living object (or to a fixed steel rebar stake/concrete block, if intending to re-survey over time). Note that while having multiple GPS-marked points is useful, in the field/at depth, this can be impracticable and time-consuming. Instead, one good GPS point, with recorded size and site orientation of the plot around this point, is preferable. Working from this initial point, lay a rough survey area using a reeled measuring-tape (Figure 1). This tape-laying element is optional but can help visualization of the area during survey,

FIGURE 1 The typical conceptual layout of equipment over the substrate in preparation for photogrammetric survey. (1) A permanent visible marker (taped steel rebar) standing ~1 m proud of the reef; (2) small corner-marker tags to aid re-location of the survey area; (3) in-situ markers/Ground Control Points (GCPs) of known XYZ (3D) dimensions; (4) measuring tape detailing the survey extent and (5) in-situ spirit-level and compass for calibration and additional scaling to XYZ planes. Right panels show the direction of movement (black line) by the surveyor for a reef- or colony-scale assessment. Reef-scale patterns are depicted as from above



particularly in low-visibility situations (i.e. visibility < site width). Next, distribute multiple objects/Ground Control Points (GCPs) of known dimensions (that are visible, non-mirrored and weighted) across the survey area. Finally, set up a spirit level (using a stable tripod), and take the depth and time at the top of the level. Inclusion of a spirit level with compass allows accurate assessment of site slope three-dimensional (XYZ) orientation and cardinal direction. Where using an ROV/drone, paired lasers can be used for size calibration.

5.2 | Image collection/swim pattern

Swim over the area, pointing the camera down towards the substrate at a roughly perpendicular/oblique angle, 1–2 m above the substrate for habitat-scale assessments. Photograph the area of interest, spirit level and markers/GCPs, with the sequential images overlapping by 50%–75%. The initial image should capture a slate, detailing survey site, replicate, date, time and depth.

The survey pattern used to collect underwater imagery will vary according to the scale of survey (colony vs. reef), the reef complexity and the angle of slope. Common approaches apply a ‘lawn-mower’ pattern zig-zagging over the substrate (Burns, Delparte, Gates, & Takabayashi, 2015), or an expanding spiral pattern (Pizarro, Friedman, Bryson, Williams, & Madin, 2017), which can be beneficial in lower visibility environments (Figure 1). The exact angle of shots will vary according to the substrate, with the techniques all aiming to attain good coverage while minimizing occlusion and blue-water image space.

5.3 | Scale: Habitat versus colony

Survey area coverage will vary according to the aims of the study (Lechene, Haberstroh, Byrne, Figueira, & Ferrari, 2019), ranging from

a few cm² (assessing individual colonies or polyps) to many hundred m² (assessing habitat-scale/multi-colony changes). Within a 1-hr dive in clear still conditions, a buddy team can expect to be able to survey at least 400 m² planar area of contiguous moderately complex substrate. Site-specific hydrology, lighting, structure, depth and slope conditions will all affect the total amount of time needed and therefore the feasible survey coverage. Scale of assessment and associated detail will also affect the outputs, with the number of photos needed per m² increasing as scale decreases (i.e. as the need for fine-scale detail increases).

5.4 | Camera settings for image capture

Structure from Motion photogrammetry can be conducted using a single camera; however, an array of linked (e.g. remote release connected DSLRs) or time-lapsing cameras of the same model and settings can also be used to increase area coverage within the survey time (Figure 2). Photogrammetry software such as Agisoft Metashape will automatically calibrate (and group) cameras during optimization providing EXIF data are present. If not, parameters must be added manually.

Multiple camera types are now available for underwater photography (Neyer, Nocerino, & Gruen, 2019; Nocerino et al., 2019). While GoPros are ideal for rapid and affordable assessment in optimal conditions, for the best quality outputs in terms of resolution, alignment and adaptability, we broadly recommend a DSLR with a large, high MegaPixel image sensor (ideally full frame/≥1” with global shutter), and a flat, fixed focal length ‘prime’ wide-angle lens (i.e. ~20 mm) with auto-focussing. This allows adaptability to varying underwater environments and wide field of view. Ensure the same camera model and lens focal length are used for any one survey, as variations will cause processing issues (Lavy et al., 2015).

Take care with image exposure and re-assess frequently. A good aperture for images is ~5.6, with a fast shutter speed to limit

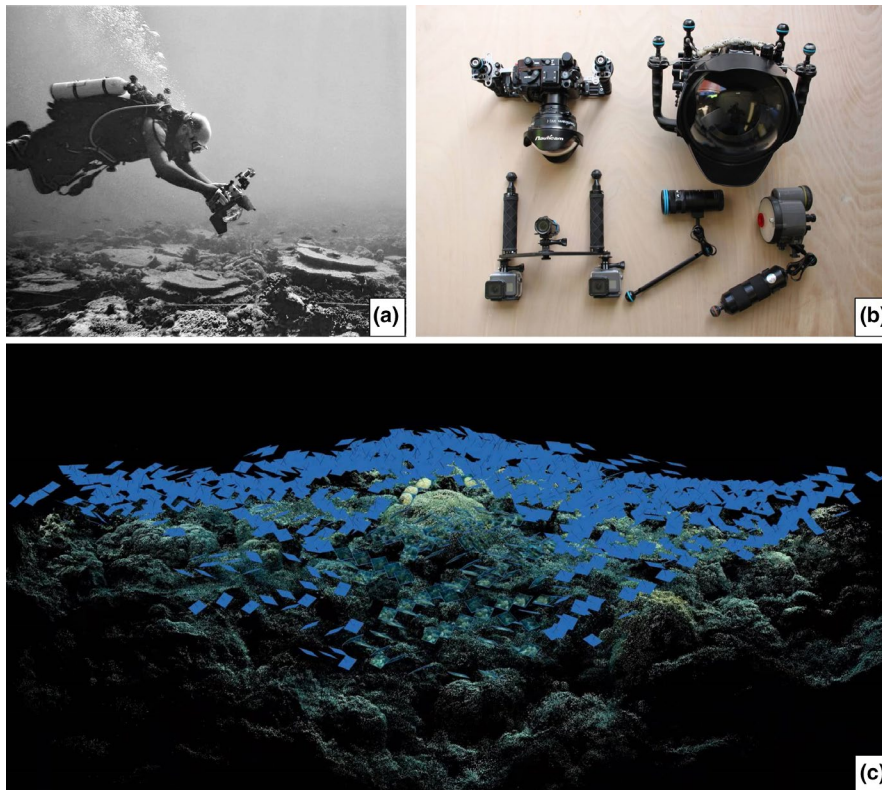


FIGURE 2 (a) A diver using a handheld DSLR camera to survey a coral reef using the SfM technique; (b) example camera configurations for short-range photogrammetry underwater (wide-angle DSLR/compact/paired action-cameras, with video lights/strobes); (c) resulting dense pointcloud layer of a 100 m² reef section, with individual photo locations shown in blue

low-light image blur (i.e. 1/125 or faster, altered frequently as ambient light changes), and moderate ISO (i.e. 200–400) to compensate without adding grain. White-balance needs to be set at the start of each survey to an in-situ colour reference. Adequate strobe lighting becomes essential at increased depth or within more turbid waters. Ensure the angle of the lighting is oblique rather than directly on to the subject, and use a diffuser to minimize backscatter and give even illumination.

In clear water conditions with adequate ambient or video-lighting, quality wide-angle action cameras such as GoPro (with large image sensors) can be used, typically applying the time-lapse function (~1 frame/second). Video footage can also be used; however, this involves an additional step of ‘frame-grabbing’, which can take time and reduce image quality. With older video cameras, it is advisable to use a non-interlacing video format to retain high-quality outputs.

Ensure any underwater equipment is washed daily and is periodically inspected to ensure continued use throughout a survey campaign, with no loss of data, quality or time.

6 | PHOTOGRAMMETRIC PROCESSING

6.1 | Processing of images

A range of commercial and open-source software is now available for creating topographic 3D models through SfM (Anderson et al., 2019). Popular commercial tools currently include Agisoft Metashape (previously ‘Photoscan’), Pix4D, Autodesk and Photomodeler. Open-source tools, including VisualSfM, COLMAP, Regard3D,

OpenDroneMap and Bundler, each vary in the degree of user control, outputs available, photo number-limit and processing time. We recommend the use of Agisoft Metashape for SfM processing of reef imagery, due to its affordable price, wide use, good technical support and easy control over processing and outputs. Table 1 details our recommended process for SfM-derived reef model creation. For in-depth discussion on camera trade-offs, optimal calibration, processing/alignment error mitigation and post-process error reduction while using underwater SfM techniques (see Agisoft LLC, 2020; Bryson et al., 2017; James & Robson, 2014; Lange & Perry, 2020; Lavy et al., 2015; Marre, Holon, Luque, Boissery, & Deter, 2019; Neyer et al., 2019; Nocerino et al., 2019; Shortis, 2019; Suka et al., 2019).

7 | MORPHOMETRIC ANALYSIS OF REEFS

7.1 | Surface/community analysis

There are a diverse array of outputs and approaches possible for reef ecology using SfM, summarized in Figure 3. A number of methods are now available to analyse the resulting SfM-derived 3D surface morphometrics, which range in complexity, software cost and user-training: ArcGIS (Burns et al., 2015; Fukunaga et al., 2019); SLAM/Python-based (Ferrari, McKinnon, et al., 2016; Friedman, Pizarro, Williams, & Johnson-Roberson, 2012; González-Rivero et al., 2017); Fledermaus (Storlazzi, Dartnell, Hatcher, & Gibbs, 2016); Rhino (Young, Dey, Rogers, & Exton, 2017); GeoMagic (Ferrari et al., 2017); Meshlab/Blender (House et al., 2018); R (Schlager, 2019) or machine

TABLE 1 A workflow detailing the steps recommended to create a 3D reef pointcloud using SfM, following initial image collection

Model creation workflow	
Project creation and image alignment	
Step	Action
1	Collect field imagery (label images sequentially as captured) and back-up the data
2	Import imagery to an Agisoft Metashape project (1 reef or colony of interest per chunk). Camera and lens type are detected automatically from image EXIF metadata, but can be specified further to increase accuracy (Tools > Camera calibration)
3	Save the project with a sensible and informative naming convention i.e. 'SiteName_Block#_Depth#_Replicate#.psx'
4	Align imagery to create a sparse pointcloud (Workflow > Batch process > Add > Job type = <i>Align Photos</i> > Apply to = <i>All/unprocessed/selected chunks</i> , Save project after each step = <i>True</i>)
-	Default settings (Accuracy = <i>High</i> , Generic preselection = <i>Yes</i> , Key point limit = 40,000, Tie point limit = 4,000). All batch job settings can be saved as an.xml file.
-	For difficult to align models deselect 'generic preselection', change key and tie points to = 0 (infinite). Note processing time will significantly increase
Error reduction and scaling	
Step	Action
5	Optimize camera alignment (Workflow > Batch process > Add > Job type = <i>Optimize alignment</i> > Apply to = <i>All/unprocessed/selected chunks</i> . Save project after each step = <i>True</i> , Settings = <i>Default</i>)
6	Reduce model errors and increase accuracy using (Model > Gradual Selection). <i>Reconstruction Uncertainty</i> (Level aim = ~10, max 50); <i>Projection Accuracy</i> (Level aim = ~3)
-	For both error reduction stages in Step 6, if more than 50% of points are selected, increase the level to a higher value and then repeat iteratively. Repeat Step 5 after each error reduction
7	Add reference markers to in-situ 'Ground Control Points' within the photo view (right click > Add marker). Ensure correct placement of markers on visible 'GCPs' in all overlapping photos
-	Note, reference markers can also be added to in-situ 'Ground Control Points' within the model view following dense cloud creation, which is faster but can lead to increased calibration error
8	Scale model using at least three marker pairs (select two marker points > right click > Create scale bar > add distance in metres > update model). Scale Bars Error should be ≤ 0.005 m, aiming for ~0.002 m over a >10 m site. Include known Z value (depth) if available
-	Note that stationary in-situ Agisoft-generated 'coded targets' can also be used to automate this scaling process and aid alignment (Tools > Markers > Detect Markers)
9	Reduce RMS reprojection error. (Model > Gradual Selection > Reprojection Error, Level aim = ~0.3). If more than 10% selected, increase level. Repeat iteratively until level reached
-	We recommend completing stage 5–9 manually. For a fuller description of this process see: https://uas.usgs.gov/nupo/pdf/USGSA_gisoftPhotoScanWorkflow.pdf
10	Complete processing steps 4–9 first and check results before moving on to next steps if using the batched workflow. Steps 5 and 6 are non-essential but will reduce systematic errors and are therefore recommended
Dense cloud creation, cleaning and orientation	
Step	Action
11	Build dense cloud (Batch process > Add > Job type = <i>Build dense cloud</i> > Apply to = <i>All/unprocessed/selected chunk</i>)
-	Default settings (Quality = <i>High</i> *, Depth filtering = <i>Aggressive</i> , Calculate point colours = <i>Yes</i> , Calculate point confidence = <i>Yes</i>) * settings changeable depending on required level of detail
-	For highly complex surfaces 'Moderate' depth filtering may be more appropriate
-	This step (and steps 16–18) can be run as a single batch file for multiple 'chunks' (i.e. multiple reef surveys) in a single project, and run overnight
12	Select & crop the Dense Cloud to the area of interest (reducing file size/process time), for example (Model > Rectangle Selection; Edit > Crop Selection)
13	Clean surface layer by selecting and deleting anomalous point scatter (rotate object with mouse > Free-form selection tool > select anomalies > Delete selection). To automate filtering out low confidence points/noise (Tools > Dense cloud > Filter by confidence, adjust tolerance as required. Low confidence limit = approximately ≥ 2)

(Continues)

TABLE 1 (Continued)

Dense cloud creation, cleaning and orientation	
Step	Action
14	Reset View. Resize region to encompass full model, if required (Model > Transform Region). Rotate Object for a bird's eye view of the surface (Model > Transform Object > Rotate Object); Y = up (North), X = right (East), Z = vertical. If using a spirit level, place markers (in model view) on top of the level and input relative X, Y and Z values in Reference pane (Z values should all be equal, and relate to depth in metres)
15	Export surface layer (File > Export points > Save Type = XYZ point cloud (*.txt) > Source data = Dense cloud > point colours & normals = selected)
Additional model outputs (DEM/orthophoto/textured mesh/shapes)	
Step	Action
16	Create DEM (Batch process > Add > Job type = Build DEM > Source data = Dense cloud > Apply to = All/unprocessed/selected chunk)
17	Create Orthomosaic (Batch process > Add > Job type = Build Orthomosaic > Surface = DEM or Mesh > Blending mode = Mosaic > Apply to = All/unprocessed/selected chunk)
18	Create a Triangulated Irregular Network (TIN) mesh and textured surface for visualization and display (Batch process > Add > Job type = Build Mesh (Default settings, source data = dense cloud, quality = High) > Apply to = All/unprocessed/selected chunk); Add > Job type = Build Texture (default settings, blending mode = Mosaic, Texture size/count = 16,384) > Apply to = All
19	Shapes delineating areas/features of interest in the model can be created and exported as.SHP files (i.e. Model > Draw polyline/Polygon/Point; File > Export>Export Shapes)
20	All above elements can be integrated within a Python workflow

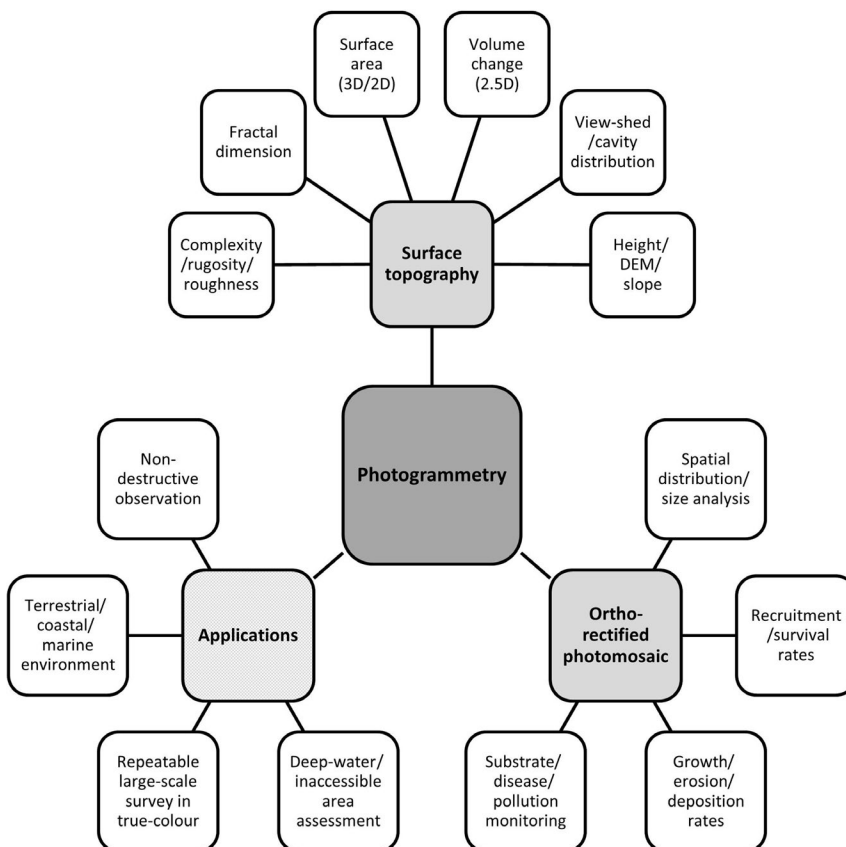


FIGURE 3 A non-exhaustive summary of applications and outputs available from the use of Structure from Motion photogrammetry for coastal and marine science

learning/neural network classification (Chirayath & Instrella, 2019; Hopkinson et al., 2020; Mohamed et al., 2020).

We recommend using the open-source software 'Gwyddion' (Nečas & Klapetek, 2012) for 3D surface analysis, which produces

a wide diversity of topographic outputs. The software has extensive online documentation, and can be integrated to open-source workflow pipelines such as Python/R. It is important to note however that this method creates an interpolated/rasterized layer

TABLE 2 A workflow detailing the steps recommended to analyse a 3D reef surface model, using a virtual transect or virtual quadrat method

3D surface analysis workflow	
Data import and conversion	
Step	Action
1	Import the exported XYZ layer (.txt) file to Gwyddion—64 bit (File > Open > [Browse/select file] > Lateral units = m, value units = m). Note down X, Y and Z distance ranges
-	Ensure 'XYZ file type' is selected rather than auto-detect option
-	Note that the 64-bit version is more stable for larger files sizes (i.e. 500 MB+), but the 32-bit version allows Python integration
2	Convert XYZ data to interpolated layer (XYZ data > Rasterize > Horizontal size = (link length required in px/m) > Make pixels square > Interpolation type = Average > Exterior type = Mirror)
3	Level dataset's relative height so that the lowest point = 0 (Data process > Shift minimum data value to zero)
4	If required, flip the layer to match original orientation (Data process > Basic Operations > Flip vertically/horizontally/both)
Virtual transect (2D) method	
Step	Action
<i>Virtual transect (2D) method:</i>	
5	Extract linear surface data (Tools > Calculate roughness parameters > Cut-off = 0 (typically), Thickness = 10 px (points averaged), Interpolation type = Linear > Result formatting = CSV).
6	[Click/select a profile line on the separate rasterized topography window from step 2] > Save results to file [naming = '####.csv'] > Repeat profile lines as required
7	Use R script (supplementary data) to amalgamate multiple individual CSV files to one spreadsheet—or do so manually
Virtual quadrat (3D) method	
Step	Action
8	Extract 3D surface data (Tools > Statistical Quantities [specify location (X/Y) and size (width/height) of area over rasterized topography window] > Resulting format = CSV > Save results to file [naming = '####.csv'] as above > repeat as required)
9	Extract Fractal dimension of whole surface (Data Process > Statistics > Fractal Dimension > Method = Power spectrum/Triangulation/Cube counting/Partitioning > Result formatting = CSV > Save results to file [naming = '####.csv'])
-	If subsampling the rasterized surface layer (Tools > Crop > [Select area of interest] > Create a new image = Selected > OK)
10	Use R script (Supplementary data) to amalgamate multiple individual CSV files to one spreadsheet—or do so manually

based on point height, and will therefore not fully account for overhanging objects (similarly to topobathic Lidar/Sonar techniques). We recommend a protocol for reef surface analysis in Table 2 using Gwyddion. This method assesses reef surfaces using both a virtual transect and virtual quadrat, resulting in a wide range of possible output metrics.

For analysis of substrate community composition/distribution/cover, etc., HD ortho-rectified image-mosaics and Digital Elevation Models (DEMs) can also be exported from Agisoft Metashape (Table 1) and integrated into commonly used workflows, such as 'Coral Point Count (CPCe)' software in JPG format, or within ArcGIS in ASCII/GeoTIFF format, respectively.

7.2 | Volumetric analysis

We recommend using the open-source software 'Cloudcompare' to simply align multiple reef surface models and to calculate the 2.5D volume change between pointcloud layers (Table 3).

8 | DATA STORAGE/ACCESSIBILITY

8.1 | Structure and metadata

For efficient storage of raw and processed data, we recommend following established ISO compliant folder structure systems, such as the British Geological Society marine survey system (<https://www.bgs.ac.uk>), and following MEDIN (or similar) metadata standards (<https://www.medin.org.uk/data-standards>). We recommend the daily download of all captured data in the field, followed by the creation of back-up copies. Labelling and filing of imagery should be completed on the day of collection to avoid confusion, along with formatting of camera memory cards before each reuse.

8.2 | Data sharing/storage platforms

For increased accessibility and data sharing of 3D layers, alongside traditional storage solutions there are a number of online

TABLE 3 A workflow detailing the steps recommended to analyse volumetric change between two reef models over time

Volume change analysis workflow	
Data import, alignment and calculation	
Step	Action
1	Import two XYZ surface layers (.txt files) of interest into Cloudcompare
2	Roughly align the two layers using the 'Equivalent point pairing' tool ([select both clouds of interest] > Tools > Registration > align (point pairs picking) > Choose 'reference' and 'aligned' roles for layers (oldest/before layer typically the reference)> [Select at least 4 matching point pairs based on fixed in-situ markers or objects])
-	Note that the alignment points/markers need to be arranged in a nonlinear pattern, dispersed around the area of interest (i.e. four rebar markers placed at each corner of the quadrat)
	Note, layers should ideally be the same size. If one layer is larger than the other, this should preferably be the bottom layer; therefore, additional cropping may be needed
-	Note, If you need to reduce the layer file size, select 'subsample a point cloud' and choose the minimum resolution needed
3	Finely align the two pointcloud layers using the 'Iterative Closest Point' tool (Tools > Registration > Fine registration (ICP) > [select reference/aligned layers] > [select RMS difference] typically = $1.0e-5$)
4	Crop to the area of interest, including only the regions with a top and bottom pointcloud area (Edit > Segment)
5	Compute 2.5D volume difference between layers with the reference layer typically the earliest of the two surveys or the 'before' layer (Tools > Volume > Compute 2.5D volume > [Select floor and ceiling layer] > Empty cells = interpolate > Grid step = [resolution of layers in metres, i.e. 0.005] > Projection direction = Z > cell height = average > Update)
-	To visualize results: select 'Export grid as cloud' and use the properties for the new height difference raster to adapt the colour and parameters
-	Graph the height differences using (show histogram)
-	Save/export results and outputs by selecting your layers of interest

platforms designed to accommodate this specific data type, such as Morposource (morphosource.org), 3Dmapping (3dmapping.cloud), Pointbox (pointbox.xyz) and Dronelab (dronelab.io), which allow users to store and view meshes, pointclouds and orthomosaics online for low to no cost.

8.3 | Visualization

A number of online platforms now exist for sharing interactive 3D models (e.g. Sketchfab, Sketchup, ArcGIS online and Oculus Unity), though models must typically be decimated to be uploaded, losing detail. Models must be further decimated to create virtual reality (VR) compatible outputs, so maintaining high mesh texture sizes is essential.

For science communication, Metashape's animation pane allows users to create either a basic rotational animation or a more complex flightpath. Animated fly-throughs can alternatively be created using previously mentioned software options, such as CloudCompare, Blender and Fledermaus. We recommend exporting the resulting capture at $3,840 \times 2,160$ (16:9) resolution to produce high-quality animations.

9 | CONCLUSIONS

The 3D analysis and mapping of reefs using SfM modelling is likely to revolutionize marine monitoring and rapidly become standard

practice, allowing a suite of new questions to be quantitatively assessed (Obura et al., 2019). Detailed substrate data can be captured and stored indefinitely allowing interrogation with constantly evolving analytical tools, and integration within large-scale assessments (Madin, Darling, & Hardt, 2019). The initial capture methods must therefore be rigorous and methodological, and care must be taken whilst planning long-term surveys to ensure direct comparisons can be made over time. The protocol described here has been developed over several years and is focused on providing a low-cost and efficient workflow for the production of structural data to a high quality. However, this technology and the range of applications to which it can be applied are of course still relatively young and so are rapidly evolving. Protocols such as ours will consequently continue to develop and change at pace as more of the marine community uses the technology. As camera equipment improves and both the costs and time of processing decrease, we hope to see this technology become even more widespread and a standard tool within ecological survey.

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AUTHORS' CONTRIBUTIONS

D.T.I.B. and A.O.M.M. conceived the ideas and methodology; D.T.I.B. led the writing of the manuscript. Both authors contributed critically to the drafts and gave final approval for publication.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

No data were used for this manuscript.

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REFERENCES

- Aber, J. S., Marzoff, I., Ries, J. B., & Aber, S. E. W. (2019). *Small-format aerial photography and UAS imagery. Small-format aerial photography and UAS imagery: Principles, techniques and geoscience applications*. Elsevier. <https://doi.org/10.1016/C2016-0-03506-4>
- Agisoft LLC. (2020). *Agisoft metashape user manual: Standard edition*. Retrieved from https://www.agisoft.com/pdf/metashape_1_6_en.pdf
- Anderson, K., Westoby, M. J., & James, M. R. (2019). Low-budget topographic surveying comes of age: Structure from motion photogrammetry in geography and the geosciences. *Progress in Physical Geography: Earth and Environment*, 43(2), 163–173. <https://doi.org/10.1177/0309133319837454>
- Bayley, D. T. I. (2019). *Empirical and mechanistic approaches to understanding and projecting change in coastal marine communities*. University College London. Retrieved from <https://discovery.ucl.ac.uk/id/eprint/10077839/>
- Bayley, D. T. I., & Mogg, A. O. M. (2019). New advances in benthic monitoring technology and methodology. In C. R. C. Sheppard (Ed.), *World seas: An environmental evaluation* (pp. 121–132). Elsevier. <https://doi.org/10.1016/B978-0-12-805052-1.00006-1>
- Bayley, D. T. I., Mogg, A. O. M., Koldewey, H., & Purvis, A. (2019). Capturing complexity: Field-testing the use of 'structure from motion' derived virtual models to replicate standard measures of reef physical structure. *PeerJ*, 7, e6540. <https://doi.org/10.7717/peerj.6540>
- Bayley, D. T. I., Mogg, A. O. M., Purvis, A., & Koldewey, H. J. (2019). Evaluating the efficacy of small-scale marine protected areas for preserving reef health: A case study applying emerging monitoring technology. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(12), 2026–2044. <https://doi.org/10.1002/aqc.3215>
- Bayley, D. T. I., & Rose, A. (2020). Multi-species co-operative hunting behaviour in a remote Indian Ocean reef system. *Marine and Freshwater Behaviour and Physiology*, 53(1), 35–42. <https://doi.org/10.1080/10236244.2020.1746658>
- Bryson, M., Ferrari, R., Figueira, W., Pizarro, O., Madin, J., Williams, S., & Byrne, M. (2017). Characterization of measurement errors using structure-from-motion and photogrammetry to measure marine habitat structural complexity. *Ecology and Evolution*, 7(15), 5669–5681. <https://doi.org/10.1002/ece3.3127>
- Burns, J. H. R., 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. <https://doi.org/10.7717/peerj.1077>
- Burns, J. H. R., Weyenberg, G., Mandel, T., Ferreira, S. B., Gotshalk, D., Kinoshita, C. K., ... Pelayo, R. (2020). A comparison of the diagnostic accuracy of in-situ and digital image-based assessments of coral health and disease. *Frontiers in Marine Science*, 7(May). <https://doi.org/10.3389/fmars.2020.00304>
- Carlot, J., Rovère, A., Casella, E., Harris, D., Grellet-Muñoz, C., Chancerelle, Y., ... Parravicini, V. (2020). Community composition predicts photogrammetry-based structural complexity on coral reefs. *Coral Reefs*, 39(4), 967–975. <https://doi.org/10.1007/s00338-020-01916-8>
- Casella, E., Collin, A., Harris, D., Ferse, S., Bejarano, S., Parravicini, V., ... Rovere, A. (2017). Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. *Coral Reefs*, 36(1), 269–275. <https://doi.org/10.1007/s00338-016-1522-0>
- Castellanos-Galindo, G. A., Casella, E., Mejía-Rentería, J. C., & Rovere, A. (2019). Habitat mapping of remote coasts: Evaluating the usefulness of lightweight unmanned aerial vehicles for conservation and monitoring. *Biological Conservation*, 239(November), 108282. <https://doi.org/10.1016/j.biocon.2019.108282>
- Chirayath, V., & Instrella, R. (2019). Fluid lensing and machine learning for centimeter-resolution airborne assessment of coral reefs in American Samoa. *Remote Sensing of Environment*, 235(October), 111475. <https://doi.org/10.1016/j.rse.2019.111475>
- D'Urban Jackson, T., Williams, G. J., Walker-Springett, G., & Davies, A. J. (2020). Three-dimensional digital mapping of ecosystems: A new era in spatial ecology. *Proceedings of the Royal Society B: Biological Sciences*, 287(1920), 20192383. <https://doi.org/10.1098/rspb.2019.2383>
- Edwards, C. B., Eynaud, Y., Williams, G. J., Pedersen, N. E., Zgliczynski, B. J., Gleason, A. C. R., ... Sandin, S. A. (2017). Large-area imaging reveals biologically driven non-random spatial patterns of corals at a remote reef. *Coral Reefs*, 36(4), 1291–1305. <https://doi.org/10.1007/s00338-017-1624-3>
- English, S. A., Baker, V. J., Wilkinson, C. R., & Wilkinson, C. R. (1997). *Survey manual for tropical marine resources*. Australian Institute of Marine Science. Retrieved from <https://books.google.co.uk/books?id=bNoQAQAIAAJ>
- Ferrari, R., Bryson, M., Bridge, T., Hustache, J., Williams, S. B., Byrne, M., & Figueira, W. (2016). Quantifying the response of structural complexity and community composition to environmental change in marine communities. *Global Change Biology*, 22(5), 1965–1975. <https://doi.org/10.1111/gcb.13197>
- Ferrari, R., Figueira, W. F., Pratchett, M. S., Boube, T., Adam, A., Kobelkowsky-Vidrio, T., ... Byrne, M. (2017). 3D photogrammetry quantifies growth and external erosion of individual coral colonies and skeletons. *Scientific Reports*, 7(1), 16737. <https://doi.org/10.1038/s41598-017-16408-z>
- Ferrari, R., McKinnon, D., He, H. U., Smith, R., Corke, P., González-Rivero, M., ... Upcroft, B. (2016). Quantifying multiscale habitat structural complexity: A cost-effective framework for underwater 3D modelling. *Remote Sensing*, 8(2), 113. <https://doi.org/10.3390/rs8020113>
- Friedman, A., Pizarro, O., Williams, S. B., & Johnson-Roberson, M. (2012). Multi-scale measures of rugosity, slope and aspect from benthic stereo image reconstructions. *PLoS ONE*, 7(12), e50440. <https://doi.org/10.1371/journal.pone.0050440>
- Fukunaga, A., Burns, J. H. R., Craig, B., & Kosaki, R. (2019). Integrating three-dimensional benthic habitat characterization techniques into ecological monitoring of coral reefs. *Journal of Marine Science and Engineering*, 7(2), 27. <https://doi.org/10.3390/jmse7020027>
- Fukunaga, A., Burns, J. H. R., Pascoe, K. H., & Kosaki, R. K. (2020). Associations between benthic cover and habitat complexity metrics obtained from 3D reconstruction of coral reefs at different resolutions. *Remote Sensing*, 12(6), <https://doi.org/10.3390/rs12061011>
- González-Rivero, M., Harborne, A. R., Herrera-Reveles, A., Bozec, Y.-M., Rogers, A., Friedman, A., ... Hoegh-Guldberg, O. (2017). Linking fishes to multiple metrics of coral reef structural complexity using three-dimensional technology. *Scientific Reports*, 7(1), 13965. <https://doi.org/10.1038/s41598-017-14272-5>
- Graham, N. A. J., & Nash, K. L. (2013). The importance of structural complexity in coral reef ecosystems. *Coral Reefs*, 32(2), 315–326. <https://doi.org/10.1007/s00338-012-0984-y>

- Gratwicke, B., & Speight, M. R. (2005). The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. *Journal of Fish Biology*, 66(3), 650–667. <https://doi.org/10.1111/j.0022-1112.2005.00629.x>
- Hopkinson, B. M., King, A. C., Owen, D. P., Johnson-Roberson, M., Long, M. H., & Bhandarkar, S. M. (2020). Automated classification of three-dimensional reconstructions of coral reefs using convolutional neural networks. *PLoS ONE*, 15(3), 1–20. <https://doi.org/10.1371/journal.pone.0230671>
- House, J. E., Brambilla, V., Bidaut, L. M., Christie, A. P., Pizarro, O., Madin, J. S., & Dornelas, M. (2018). Moving to 3D: Relationships between coral planar area, surface area and volume. *PeerJ*, 6, e4280. <https://doi.org/10.7717/peerj.4280>
- James, M. R., & Robson, S. (2014). Mitigating systematic error in topographic models derived from UAV and ground-based image networks. *Earth Surface Processes and Landforms*, 39(10), 1413–1420. <https://doi.org/10.1002/esp.3609>
- Kresse, W. (2010). *Status of ISO standards for photogrammetry and remote sensing*. International Archives of ISPRS. Retrieved from http://www.isprs.org/proceedings/XXXVIII/Eurocow2010/euroCOW2010_files/papers/24.pdf
- Lange, I. D., & Perry, C. T. (2020). A quick, easy and non-invasive method to quantify coral growth rates using photogrammetry and 3D model comparisons. *Methods in Ecology and Evolution*, 2020(March), 1–13. <https://doi.org/10.1111/2041-210X.13388>
- 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 in Ecology and Evolution*, 6(5), 521–531. <https://doi.org/10.1111/2041-210X.12331>
- Lechene, M. A. A., Haberstroh, A. J., Byrne, M., Figueira, W., & Ferrari, R. (2019). Optimising sampling strategies in coral reefs using large-area mosaics. *Remote Sensing*, 11(24), 2907. <https://doi.org/10.3390/rs11242907>
- Madin, E. M. P., Darling, E. S., & Hardt, M. J. (2019). Emerging technologies and coral reef conservation: Opportunities, challenges, and moving forward. *Frontiers in Marine Science*, 6(December), 1–7. <https://doi.org/10.3389/fmars.2019.00727>
- Magel, J. M. T., Burns, J. H. R., Gates, R. D., & Baum, J. K. (2019). Effects of bleaching-associated mass coral mortality on reef structural complexity across a gradient of local disturbance. *Scientific Reports*, 9(1), 1–12. <https://doi.org/10.1038/s41598-018-37713-1>
- Marre, G., Holon, F., Luque, S., Boissery, P., & Deter, J. (2019). Monitoring marine habitats with photogrammetry: A cost-effective, accurate, precise and high-resolution reconstruction method. *Frontiers in Marine Science*, 6(May), 1–15. <https://doi.org/10.3389/fmars.2019.00276>
- Mohamed, H., Nadaoka, K., & Nakamura, T. (2020). Towards benthic habitat 3D mapping using machine learning algorithms and structures from motion photogrammetry. *Remote Sensing*, 12(1), 127. <https://doi.org/10.3390/rs12010127>
- Nečas, D., & Klapetek, P. (2012). Gwyddion: An open-source software for SPM data analysis. *Open Physics*, 10(1). <https://doi.org/10.2478/s11534-011-0096-2>
- Neyer, F., Nocerino, E., & Gruen, A. (2019). Image quality improvements in low-cost underwater photogrammetry. *ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W10, 135–142. <https://doi.org/10.5194/isprs-archives-XLII-2-W10-135-2019>
- Nocerino, E., Neyer, F., Gruen, A., Troyer, M., Menna, F., Brooks, A., ... Rossi, P. (2019). Comparison of diver-operated underwater photogrammetric systems for coral reef monitoring. *ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W10(3), 143–150. <https://doi.org/10.5194/isprs-archives-XLII-2-W10-143-2019>
- Obura, D. O., Aeby, G., Amornthammarong, N., Appeltans, W., Bax, N., Bishop, J., ... Wongbusarakum, S. (2019). Coral reef monitoring, reef assessment technologies, and ecosystem-based management. *Frontiers in Marine Science*, 6(SEP), 1–21. <https://doi.org/10.3389/fmars.2019.00580>
- Palma, M., Casado, M. R., Pantaleo, U., Pavoni, G., Pica, D., & Cerrano, C. (2018). SfM-based method to assess gorgonian forests (*Paramuricea clavata* (Cnidaria, Octocorallia)). *Remote Sensing*, 10(7), 1–21. <https://doi.org/10.3390/rs10071154>
- Palma, M., Magliozzi, C., Rivas Casado, M., Pantaleo, U., Fernandes, J., Coro, G., ... Leinster, P. (2019). Quantifying coral reef composition of recreational diving sites: A structure from motion approach at seascape scale. *Remote Sensing*, 11(24), 1–21. <https://doi.org/10.3390/rs11243027>
- Pizarro, O., Friedman, A., Bryson, M., Williams, S. B., & Madin, J. (2017). A simple, fast, and repeatable survey method for underwater visual 3D benthic mapping and monitoring. *Ecology and Evolution*, 7(6), 1770–1782. <https://doi.org/10.1002/ece3.2701>
- Price, D. M., Robert, K., Callaway, A., Lo Iacono, C., Hall, R. A., & Huvenne, V. A. I. (2019). Using 3D photogrammetry from ROV video to quantify cold-water coral reef structural complexity and investigate its influence on biodiversity and community assemblage. *Coral Reefs*, 38(5), 1007–1021. <https://doi.org/10.1007/s00338-019-01827-3>
- Raoult, V., Reid-Anderson, S., Ferri, A., & Williamson, J. (2017). How reliable is Structure from Motion (SfM) over time and between observers? A case study using coral reef bommies. *Remote Sensing*, 9(7), 740. <https://doi.org/10.3390/rs9070740>
- Rossi, P., Castagnetti, C., Capra, A., Brooks, A. J., & Mancini, F. (2020). Detecting change in coral reef 3D structure using underwater photogrammetry: Critical issues and performance metrics. *Applied Geomatics*, 12(S1), 3–17. <https://doi.org/10.1007/s12518-019-00263-w>
- Schlager, S. (2019). 3D data analysis using R. In N. Seguchi & B. B. T.-3D D. A. for B. Dudzik Forensic Anthropology, and Archaeology (Eds.), *3D data acquisition for bioarchaeology, forensic anthropology, and archaeology* (pp. 131–159). Elsevier. <https://doi.org/10.1016/B978-0-12-815309-3.00007-3>
- Shortis, M. (2019). Camera calibration techniques for accurate measurement underwater BT – 3D recording and interpretation for maritime archaeology. In J. K. McCarthy, J. Benjamin, T. Winton, & W. van Duivenvoorde (Eds.), *3D recording and interpretation for maritime archaeology* (Vol. 31, pp. 11–27). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-03635-5_2
- Storlazzi, C. D., Dartnell, P., Hatcher, G. A., & Gibbs, A. E. (2016). End of the chain? Rugosity and fine-scale bathymetry from existing underwater digital imagery using structure-from-motion (SfM) technology. *Coral Reefs*, 35(3), 889–894. <https://doi.org/10.1007/s00338-016-1462-8>
- Suka, R., Asbury, M., Couch, C. S., Gray, A. E., Winston, M., & Oliver, T. (2019). *Processing photomosaic imagery of coral reefs using structure-from-motion standard operating procedures*. NOAA Technical Memorandum NOAA-TM-NMFS-PIFSC-93. <https://doi.org/10.25923/h2q8-jv47>
- Teague, J., & Scott, T. B. (2017). Underwater photogrammetry and 3D reconstruction of submerged objects in shallow environments by ROV and underwater GPS. *Journal of Marine Science Research and Technology*, 1, 5.
- Tebbett, S. B., Streit, R. P., & Bellwood, D. R. (2020). A 3D perspective on sediment accumulation in algal turfs: Implications of coral reef flattening. *Journal of Ecology*, 108(1), 70–80. <https://doi.org/10.1111/1365-2745.13235>
- Varela, M. R., Patrício, A. R., Anderson, K., Broderick, A. C., DeBell, L., Hawkes, L. A., ... Godley, B. J. (2019). Assessing climate change associated sea-level rise impacts on sea turtle nesting beaches using

- drones, photogrammetry and a novel GPS system. *Global Change Biology*, 25(2), 753–762. <https://doi.org/10.1111/gcb.14526>
- Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179, 300–314. <https://doi.org/10.1016/j.geomorph.2012.08.021>
- Wilson, S. K., Graham, N. A. J., & Polunin, N. V. C. (2007). Appraisal of visual assessments of habitat complexity and benthic composition on coral reefs. *Marine Biology*, 151(3), 1069–1076. <https://doi.org/10.1007/s00227-006-0538-3>
- Young, G. C., Dey, S., Rogers, A. D., & Exton, D. (2017). Cost and time-effective method for multiscale measures of rugosity, fractal dimension, and vector dispersion from coral reef 3D models. *PLoS ONE*, 12(4), 1–18. <https://doi.org/10.1371/journal.pone.0175341>
- Zawada, K. J. A., Madin, J. S., Baird, A. H., Bridge, T. C. L., & Dornelas, M. (2019). Morphological traits can track coral reef responses to

the Anthropocene. *Functional Ecology*, 33(6), 962–975. <https://doi.org/10.1111/1365-2435.13358>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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