Australian Government

Australian Institute of Marine Science

Field photogrammetry in 4D: *Overview & in-field workflow*

Reef Restoration and Adaption Program (EcoRRAP)

Standard Operational Procedure Number 14 (No. 1 of series)

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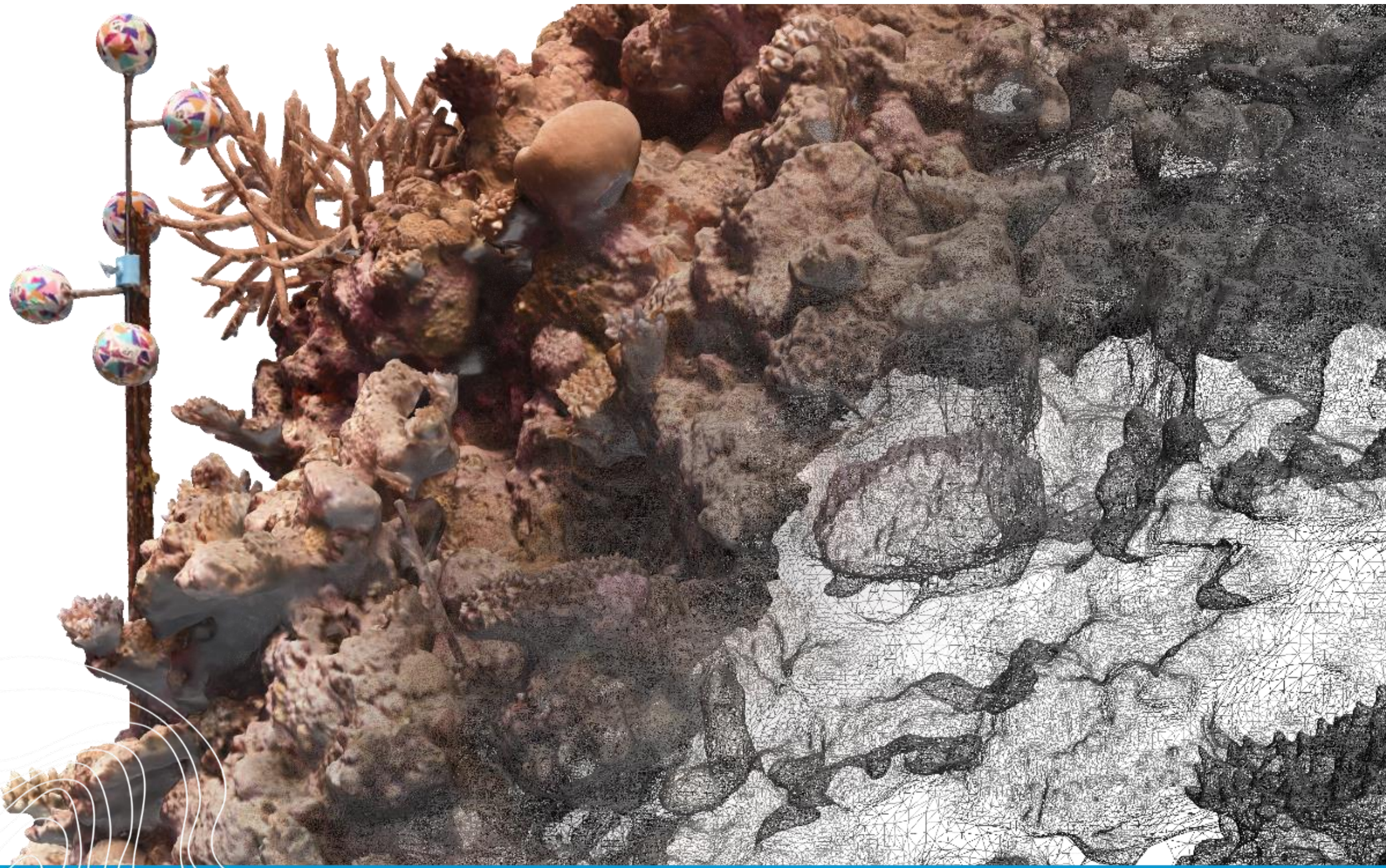

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Cover photo: A composite image showing underlying points and wire-mesh model frame and overlaid textured model of reef substrate and sphere tree. Image credit: M. Lechene.

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.
We specifically acknowledge and thank the following Traditional Owners of sea Country that this report relates to:

Location	**Traditional Owner Group**
Torres Strait	Masigalgal, Porumalgal, Warraberalgal
Northern Great Barrier Reef	Gunggandji, Ngurruumungu, Gingaal
Central Great Barrier Reef	Manbarra, Bindal
Southern Great Barrier Reef	Woppaburra, Bailai, Gurang, Gooreng Gooreng, Taribelang Bunda

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Appendix 3. Equipment designed and manufactured for EcoRRAP workflow and corresponding schematic file name. Schematic designs for fabricating all items can be found on the AIMS Metadata repository (EcoRRAP Photogrammetry Equipment Schematics - AIMS). Descriptions of each item and it's use are provided in Appendix 4, Tables 6,7,8,9,11,12,14, and Figs. 8,10.

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SUMMARY

The Australian Institute of Marine Science's (AIMS) Ecological Intelligence for Reef Restoration and Adaptation Program (EcoRRAP) quantifies natural rates of ecological and genetic reef recovery and adaptation in response to acute and chronic disturbances, as well as key environmental variables related to different coral reef communities. This information is used to inform the Reef Restoration and Adaptation Program (RRAP) restoration interventions, the largest reef restoration program in the world as of 2020. The RRAP is a collaboration across many research institutes and experts, managed by AIMS.

This document is the Standard Operational Procedure Volume 1, produced by the EcoRRAP sub-program at the Australian Institute of Marine Science. It details photogrammetry standard procedures for collecting images to reconstruct three-dimensional (3D) models and two-dimensional (2D) orthomosaics to quantify benthic communities over time (the fourth dimension, '4D'). The reconstructions created by this workflow exhibit sub-mm resolution, span extents of 75 - 1500 square meters, and use high-precision temporal co-registration techniques.

Details for other surveying methods used by EcoRRAP, including image processing post fieldtrip (SOP 2), can be found in a series of Standard Operational Procedures described in Table 1 and are published online at: AIMS's SOP page (Reef monitoring sampling methods | AIMS), EcoRRAP Metadata records Reef monitoring sampling methods | AIMS), EcoRRAP Metadata records (EcoRRAP Metadata), and the EcoRRAP Website (EcoRRAP (gbrrestoration.org).

Table 1. EcoRRAP 3D photogrammetry tasks and associated standard operating procedures (SOPs).

Task	Associated SOP
Overview and in-field workflow	Field photogrammetry in 4D: No. 1 of series (current doc.)
Model processing	Field photogrammetry in 4D: No. 2 of series
Digitisation and metric extraction	Field photogrammetry in 4D: No. 3 of series

Information regarding data generated by the EcoRRAP program can be accessed through the Australian Institute of Marine Science's metadata records (EcoRRAP Metadata). Additional links to project outputs can be found throughout this document. The EcoRRAP Database (internal document) and data management files and folder templates: EcoRRAP Data Management Templates. Processing scripts are located on the EcoRRAP GitHub: GitHub AIMS/EcoRRAP.

1 INTRODUCTION

1.2 Ecological Intelligence for Reef Restoration and Adaptation (EcoRRAP)

The Reef Restoration and Adaptation Program (RRAP) brings together leading experts from Australia and around the world to help protect the future of the Great Barrier Reef, other Australian reefs, and coral reefs globally. The 'EcoRRAP' subprogram aims to maximise the success of restoration interventions by advising on the 'what', 'where', and 'when' of interventions, and by filling crucial gaps in ecological knowledge of the Great Barrier Reef (GBR). EcoRRAP's objectives are to: (1) Provide location-specific knowledge on natural limitations to reef recovery from disturbances (without human interventions), and to; (2) Deliver knowledge about the natural processes and speed of adaptation to a changing environment (Fig. 1; EcoRRAP (ecological intelligence for reef restoration) - Reef Restoration and Adaptation Program (gbrrestoration.org)).

The EcoRRAP team has designed and implemented a field-program spanning six reference 'reef clusters' in the GBR and Torres Strait. This program aims to generate a baseline of empirical data comprised of important environmental variables, biological, and ecological data. EcoRRAP uses state-of-the art technology, such as photogrammetry, to quantify key limitations to reef recovery and adaptation. Some of the key questions this data will answer are: (1) What are the agents of mortality for recruit, juvenile, and adult coral? (2) What are the most suitable areas of the reef for enhancing coral growth and survival? (3) What are the most important traits driving natural recovery and adaptation to disturbances (i.e. bleaching)? This project will also investigate spatiotemporal, environmental, and taxa-specific variation in these traits.

1.1 Landscape, population, and community ecology on coral reefs

Habitat structure is a key driver of resilient marine ecosystems. Biodiversity, function, and the trajectory of reef communities are inextricably linked to the success of ecosystem engineers, such as corals, creating structure and refuge for fish and other reef organisms (Gratwicke and Speight 2005a, Gratwicke and Speight 2005b, Harborne et al. 2012). There is increasing evidence that coral reef resilience to climate change is positively related to a reef's 3D structure (Bozec & Mumby 2015, Graham et al. 2015). For example, as coral reefs begin flattening after disturbances, fish that perform vital services to the reef have difficulty finding refuge and may move away from these less complex reef areas.

Our ability to predict and manage the impacts of environmental change on reefs is impeded by a lack of data on the relationship between 3D structural complexity and biotic assemblages across spatial and temporal extents (Pygas et al. 2020). The life history of corals is also limited by data availability; empirical data is extremely limited on 'how', 'where,' and 'why' corals recruit on specific surfaces, grow faster, or die less, in specific habitats and depths. Population and community dynamics are well understood on shallow flanks on the GBR after more than 30 years of long-term monitoring, yet we are only scratching the surface of understanding community turnover in other habitats and depths (Castro-Sanguineo et al. 2021). Digitising reefs of the GBR across space and time, including in different habitats and depths, will help fill these key knowledge gaps and advance our fundamental understanding of how to improve the climate adaptation potential of coral reefs (Calders et al. 2020). Such data is also vital to improve the success of restoration interventions (Ferrari et al. 2021).

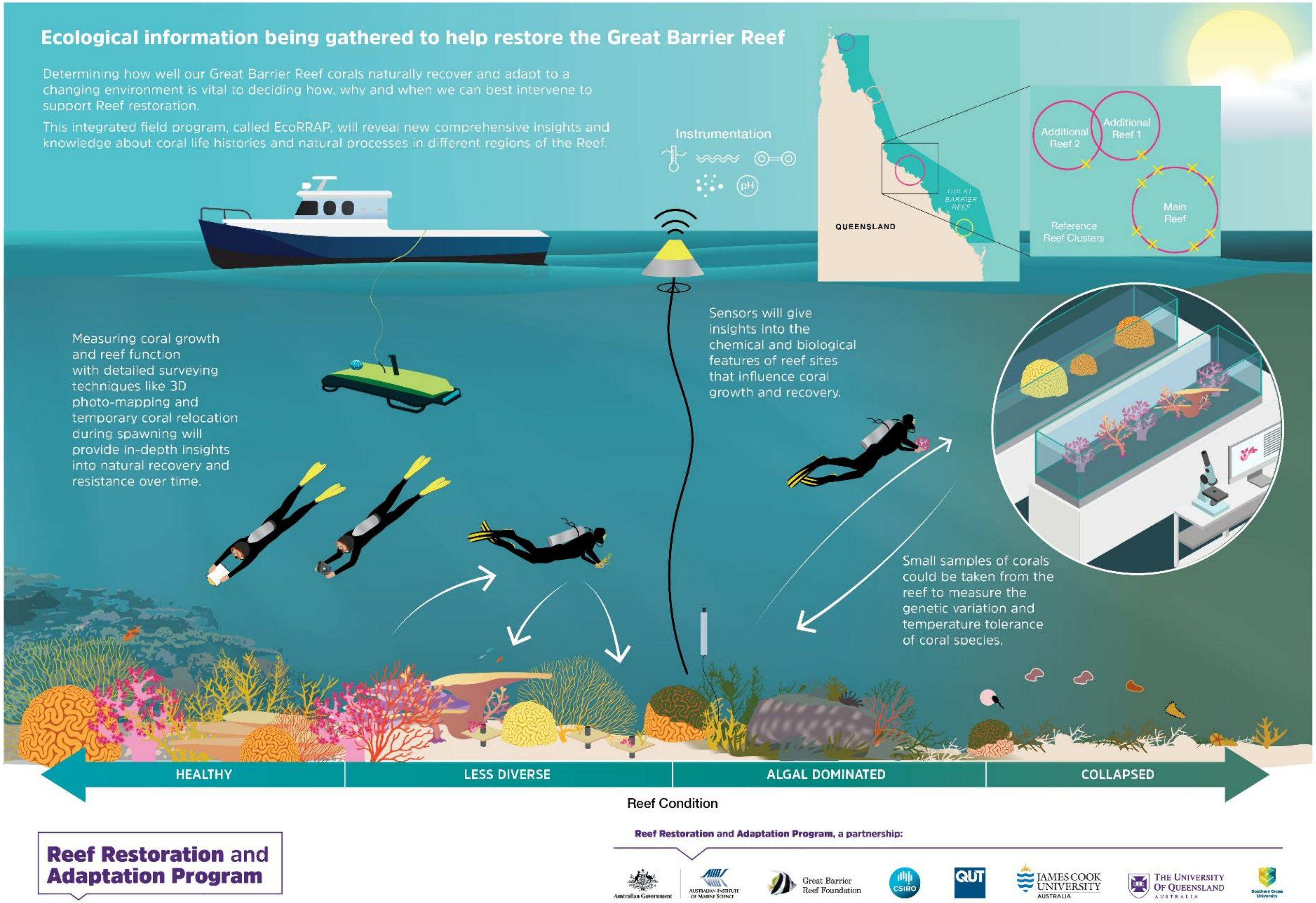


Figure 1. A visual summary of research focuses and approaches used by the EcoRRAP subprogram of RRAP. Image: EcoRRAP.

1.2 Photogrammetry sampling and products

EcoRRAP uses close-range photogrammetry to quantify structural complexity, benthic communities, and demographic rates of coral reefs across spatial and temporal scales. Two key outputs are created from the images collected by EcoRRAP: (1) 3D digital surface models (DSMs), and: (2) 2D orthomosaics. The 3D DSMs are used to quantify landscape metrics, such as structural complexity, and the demographic rates of complex coral morphologies (i.e. staghorn *Acropora spp.* corals)(Fig. 2a; EcoRRAP Digital Surface Models - AIMS). The 2D orthomosaics are used to quantify benthic community composition and demographic rates of simpler coral morphologies (i.e. tabulate *Acropora spp.* corals)(Fig. 2b; EcoRRAP Benthic Orthomosaics - AIMS).

One EcoRRAP 'site' includes approximately 575 square meters of reef area captured by high resolution DSLR images (0.3 mm per pixel in outputs) and approximately 3000 square meters of reef area captured by medium resolution action camera images (5 mm per pixel in outputs). To image each site, sequential images are collected on SCUBA using a diver-rig comprised of two Nikon D850 DSLRs and three action cameras (Fig. 3). The resulting images are processed using Agisoft Metashape Professional (v.1.8) to build models and generate 3D and 2D products. These 3D and 2D products are exported and subsequently used for colony annotation and metric extraction in other software platforms (EcoRRAP SOPs 2,3, Table 1). At most EcoRRAP reefs, the reef flat adjacent to each EcoRRAP site is also imaged by 'ReefScan.' The ReefScan project uses a six-camera Transom array to capture images of the reef flat from aboard a vessel, similar to that described in Hatcher et. al. (2020). These images are also used for photogrammetry and produce lower-resolution 2D outputs covering reef areas of approximately 5000 square meters (EcoRRAP Large Area Survey Processing Methodology SOP, Table 1).

1.3 Structure from Motion (SfM) close-range underwater photogrammetry

The 3D and 2D products produced by EcoRRAP are a representation of reef topography and area produced from overlapping two-dimensional images using Structure from Motion (SfM) photogrammetry algorithms (Ferrari et al. 2016). Structure from Motion (SfM) is a close-range photogrammetric technique that finds correspondence between images and tracks common features (edges, shapes, etc.) from one image to the next. Feature trajectories are then used to reconstruct their location in the 3D space and create a high-resolution (millimetric scale) tridimensional representation of the reef topography.

To recreate the 3D models, the algorithm searches for common points (at pixel scale) in overlapping frames, matches them, and determines the position of the camera for each frame. The next steps build point clouds and depth maps based on the estimated camera positions and pictures (Ferrari et al. 2016). Points are then joined to create a 3D mesh made of triangular faces, over which the texture (colour information) of the 2D images, on a pixel-by-pixel basis, is overlaid to create a textured 3D DSM. Metrics are extracted either from the point cloud or the 3D DSM. The final textured 3D DSM is also useful for visualisation and 3D segmentation (Fig. 4; Ferrari et al. 2016).

Previous evaluations of the accuracy of 3D reconstructions using this methodology suggest that the technique can replicate the 3D structure of coral reefs within millimetres of error (Figueira et al. 2015). From these models, structural complexity is estimated by computing the rugosity index over the 3D meshes or point clouds, using approach as those described in González-Rivero et al. (2017) and Friedman et al (2012). 'Rugosity index' is a measure of the deformation of a surface relative to its

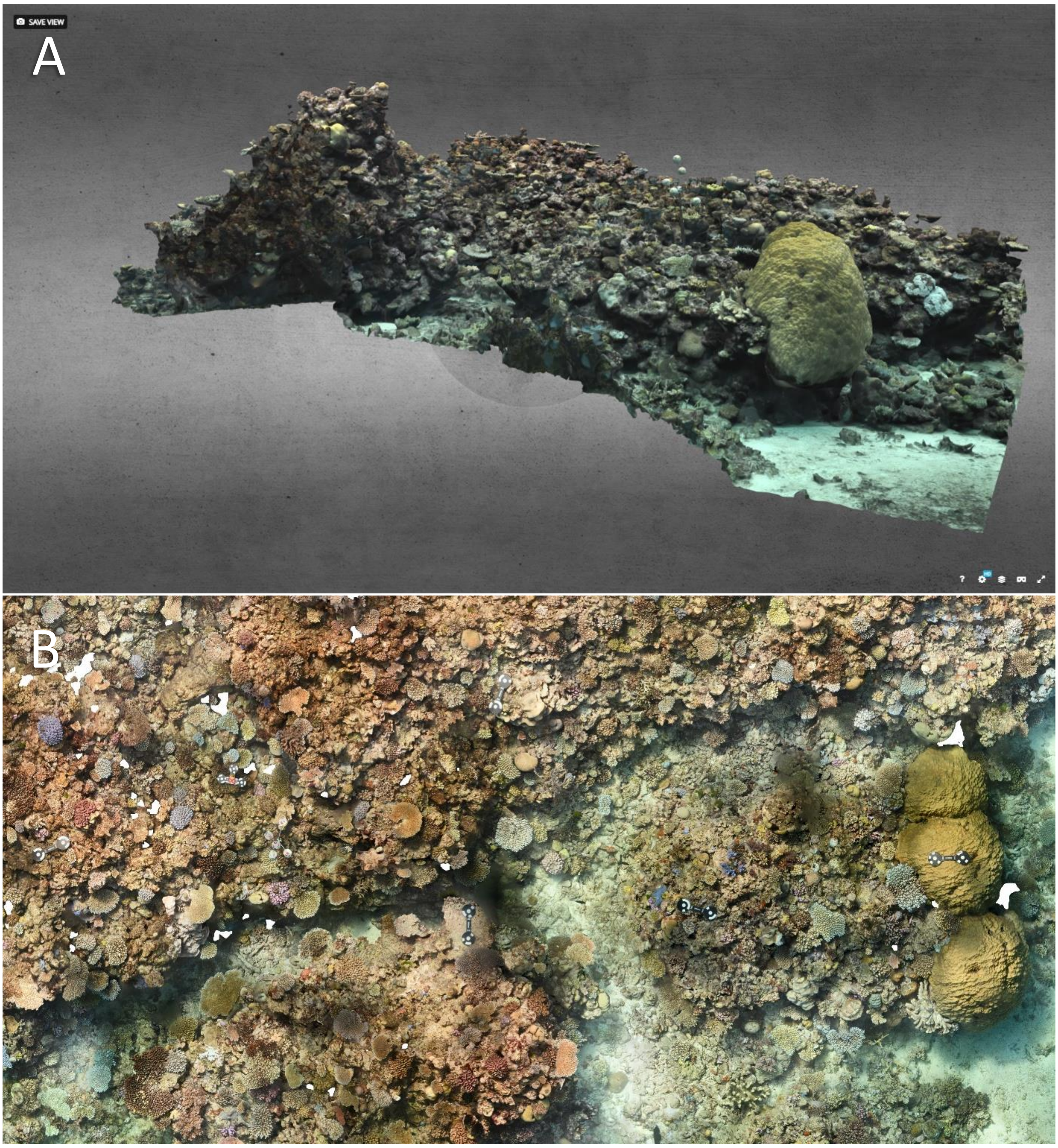


Figure 2. Three- and two-dimensional representations of the reef topography at an EcoRRAP plot produced using Structure from Motion (SfM) techniques: (A) a 3D digital surface model (DSM), and; (B) a 2D orthomosaic. Image: S. Gordon.

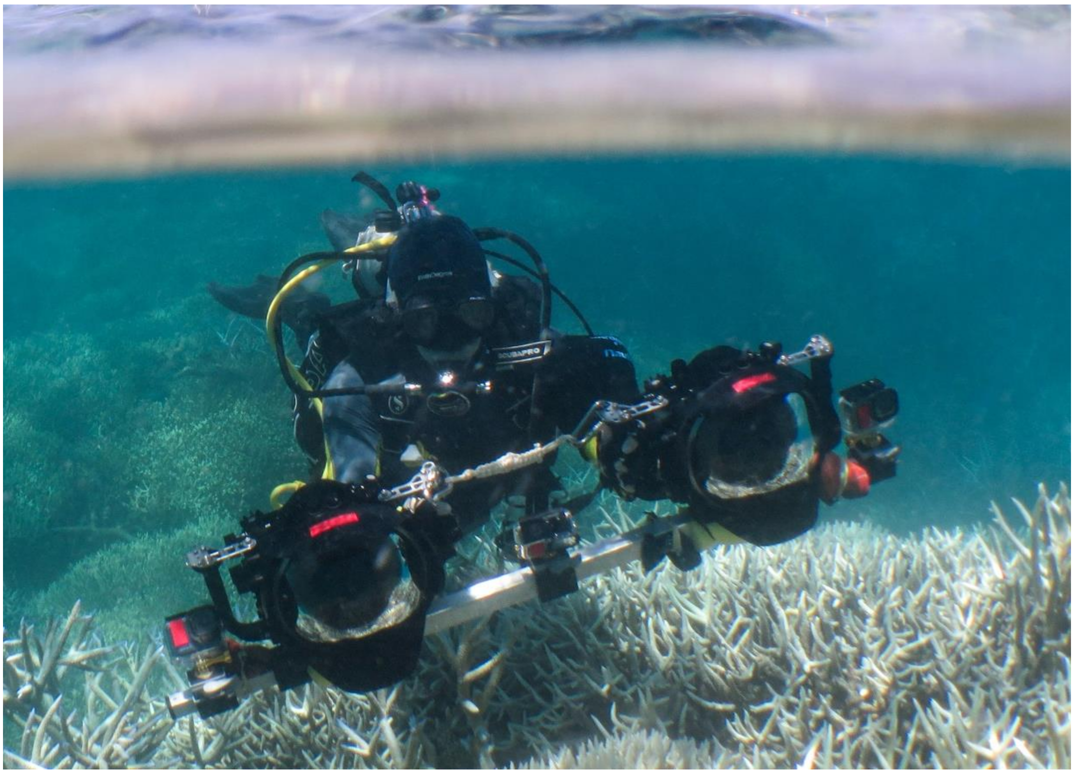


Figure 3. A diver rig consisting of two Nikon D850 DSLRs and three action cameras used to conduct EcoRRAP photogrammetry surveys. Note that the two outer action cameras are mounted on telescopic poles to allow them to be extended to the required distance when imaging. Photo: M. Panero.

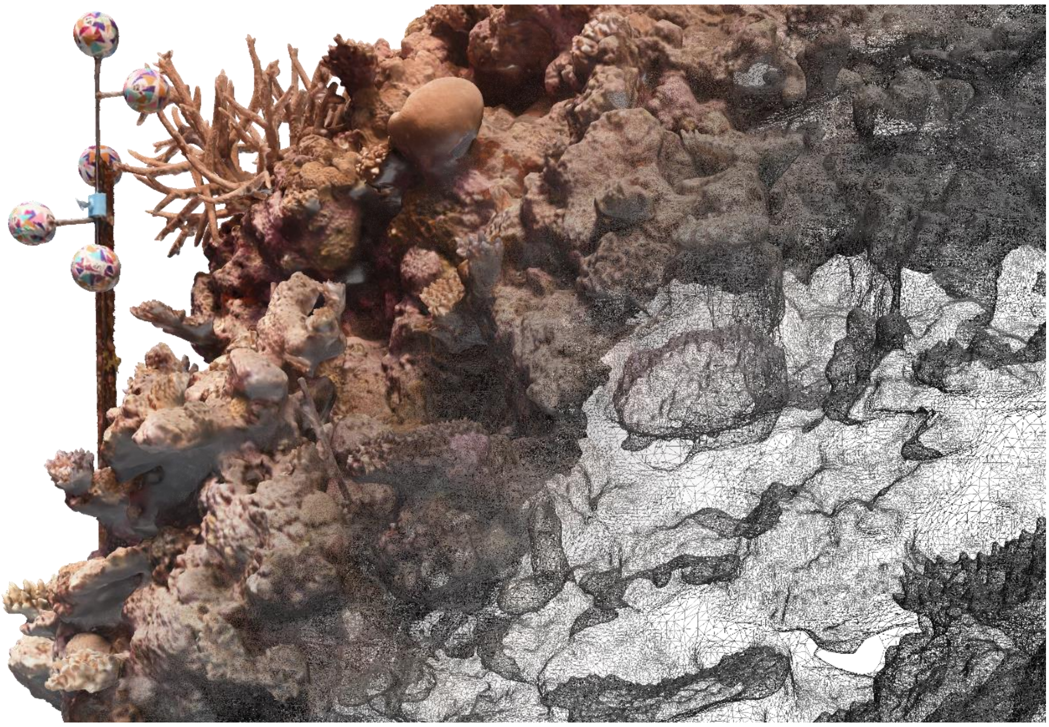


Figure 4. A composite image of a 3D digital surface model (DSM) showing the textured digital model on the left and the underlying model structure comprised of points and triangular faces on the right. Image: M. Lechene.

planar projection and is a common metric used to characterize the topographical complexity of marine habitats (Graham and Nash 2013). This index uses a value of 1.0 to depict a perfectly flat surface and the increases with the complexity of surface convolutions. Additional metrics are also derived from the 2D and 3D maps to capture a more complete picture of the habitat structural complexity, community composition, and demographic rates over time (Aston et al. 2022). These metrics include curvature, range of heights, slope, coral recruitment, growth, and mortality among others, and are covered in detail in EcoRRAP SOPs 2 and 3 (Table 1).

A key contribution of this SOP is the design and successful implementation of hardware and workflows to achieve temporal co-registration of 3D models. Temporal co-registration can represent a substantial hurdle to the application of close-range photogrammetry to coral reef monitoring. The current SOP presents the first detailed, successful, method for temporal co-registration of 3D models and orthomosaics (but see Yuval et al. (2021) for similar approaches from which current methods were derived).

1.4 How to use this Standard Operational Procedure (SOP)

The EcoRRAP photogrammetry workflow consists of three key stages, here presented in three SOPs (Fig. 5, Table 1): 1) Field-based data collection and model building; 2) Office-based model building, and; 3) Metric extraction. The current SOP describes the sampling design, equipment, preparation procedure, data collection workflow, data management protocol, and initial model processing steps used by EcoRRAP to monitor reefs using photogrammetry. Consequently, some aspects of this manual are specific to the equipment and requirements of this program. This SOP also contains general user information and is intended to act as a guide for other users who wish to use photogrammetry to map and monitor habitat structural complexity and demographic rates of benthic communities on coral reefs. The following two stages of the EcoRRAP photogrammetry workflow are provided in SOPs 2 and 3 (Fig. 5, Table 1). Is it recommended to use and refer to SOP 2 for additional background information regarding model building during field-based model building steps.

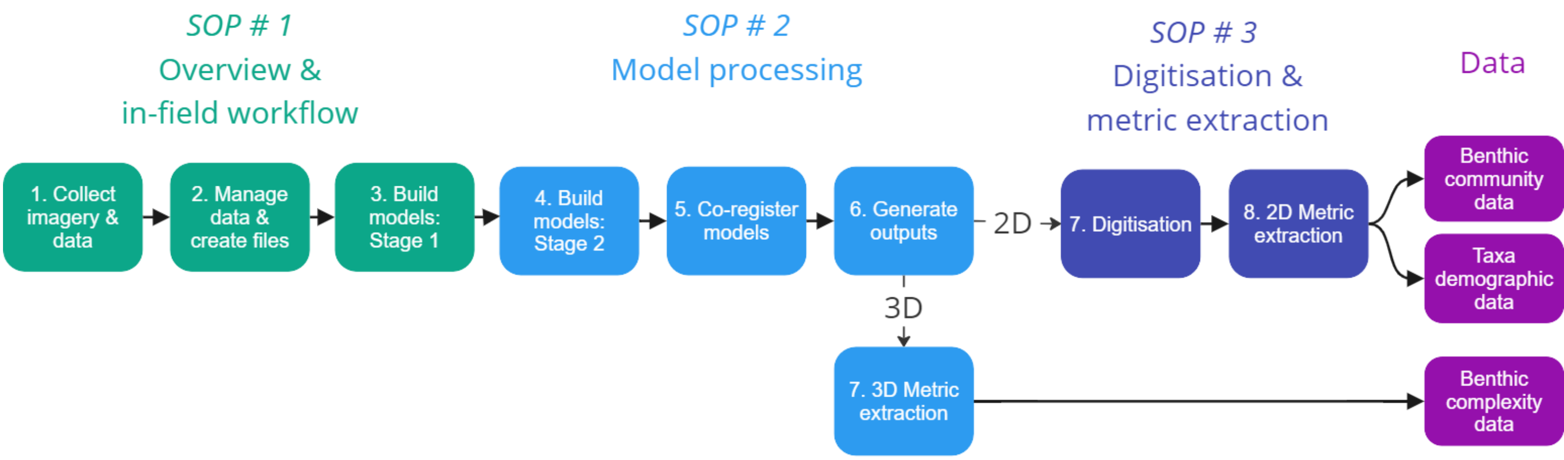


Figure 5. EcoRRAP photogrammetry workflow, related SOPs, and key data outputs. Image: S. Gordon.

2 STUDY DESIGN

2.1 Sampling location and design

EcoRRAP study sites encompassed a range of environmental conditions within the GBR and Torres Strait, spanning latitudinal temperature gradients, and cross-shelf gradients in water quality and wave exposure. The following nested sampling design and replication was used, with the levels and locations described further in Fig. 6, Tables 2,3, and Appendix 1:

Reef Cluster (6) > Reef (17) > Site (64) > Zone (88) > Plot (352).

EcoRRAP study sites spanned six 'reef clusters,' from the Torres Strait in the north, to Lady Musgrave Island in the south. Within each reef cluster, reefs were selected and categorised as either 'main' or 'additional' reefs to dictate their sampling regime. EcoRRAP's primary research priority was to understand natural limitations to recovery and adaptation between habitats *within* reefs, therefore sampling locations also spanned within-reef exposure gradients ('sites') and depths ('zones'). As there is little know about recovery and adaptation rates beyond approximately nine meters depth on the GBR (Castro-Sanguineo et al. 2021), the sampling design included depths of approximately 5 and 12 meters ('shallow' and 'deep' sites, respectively) within each reef cluster. 'Main reefs' were sampled at both shallow and deep zones, while 'additional reefs' were only sampled at shallow zones. Oceanographic logger array deployment and other aspects of EcoRRAP procedures also varied between main and additional reefs (see other EcoRRAP SOPs for more information, Table 1). EcoRRAP 'zones' consisted of an area of reef approximately 100 x 15 m in size (1500 square meters). Each zone encompassed four 12 x 6 m 'plots' (72 square m) laid horizontally in a line following the 5 or 12 m depth contour (for shallow and deep sites, respectively) (Fig. 7). Plots were spaced at an approximate distance of 10 m between each plot (Fig. 7). Study locations were sampled every 12 months from 2021 - present. If disturbance events occurred (e.g. the 2022 mass Central GBR bleaching event) sites were sampled as soon as possible following the disturbance.

2.2 Study location selection

Reef clusters, and main and additional reefs, were selected from a list of candidate reefs compiled though multiple consultation workshops with RRAP researchers, AIMS monitoring teams, statisticians, stakeholders, traditional owners, and restoration practitioners. Numerous factors including ecological status, logistical constraints, and the utility of resultant data to inform restoration interventions were considered when selecting reefs and determining their classification and cluster grouping. Once reefs were selected, high resolution maps of water flow (wave and wind exposure, and bottom stress) of each reef were used to identify three to six sites around the perimeter of the reef to capture a water flow gradient. The exact number of sites selected per reef were reef-specific and depended on ecological and logistical trade-offs but aimed to represent the range of habitat types present (e.g. reef fronts, flanks, backs, and lagoons). For each site, one to two depth zones (shallow and deep) were established depending on the reef classification. Visual checks on snorkel or SCUBA were completed to confirm the suitability of the identified zones for establishment and monitoring. Zones were considered suitable if they had: (1) a benthic habitat dominated by hard substrate (reef matrix), as opposed to loose rubble or sand; (2) the presence of live hard coral, and; (3) were safe and feasible to work at.

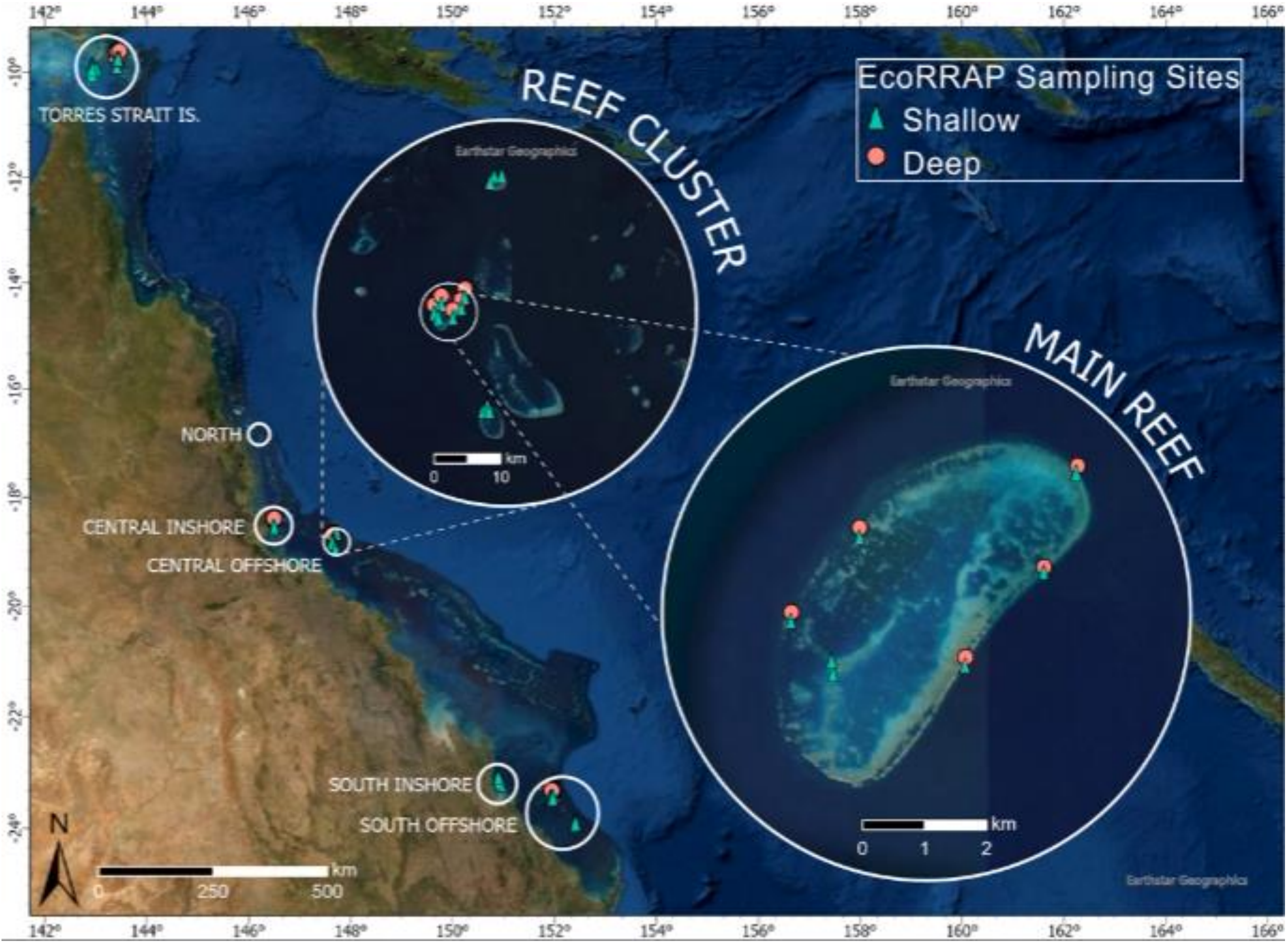


Figure 6. EcoRRAP sampling design showing reef clusters and examples of reef, site, and zone locations within the central offshore reef cluster. Image: M. Lechene.

Table 2. EcoRRAP sampling design, levels, and replication.

Rank	Factor	Levels	Replication	Comment
1	Reef cluster	Torres strait Offshore Northern Offshore Central Inshore Central Offshore Southern Inshore Southern	NA	
2	Reef	Main Additional	1 Main reef per Reef cluster 1-2 Additional Reefs per Reef cluster	See reef names in Table 3
3	Site	Reef front Reef flank Reef back Lagoon	1-2 of each Site per Reef*	
4	Zone	Shallow (5 m) Deep (12 m)	Main Reef: 1 Shallow and 1 Deep per Site* Additional Reef: 1 Shallow per Site	1500 square m in size
5	Plot	Numbered 1-4	4 Plots per Zone	72 square m in size

* In some locations this was not possible due to the geographic nature of the reef, e.g. Some reefs did not possess a lagoon so therefore could not be sampled, while some sites did not have suitable habitats or depths to establish deep zones.

Table 3. EcoRRAP sampling locations showing study sites and the number of plots imaged.

Reef cluster	Reef	Latitude	Longitude	Sites	Zones	Plots
Torres strait (TS)	Masig* (MA)	-9.762	143.421	6	10	40
	Aukane (AU)	-9.882	143.394	5	6	24
	Dungeness (DU)	-9.931	143.005	6	6	24
	Total			**17**	**22**	**88**
Offshore Northern GBR (ON)	Lizard (LI)	-14.688	145.465	6	7	28
	Moore* (MO)	-16.860	146.226	6	12	48
	Total			**12**	**19**	**76**
Inshore Central GBR: Palm Islands (PA)	Pelorus* (PE)	-18.541	146.489	3	6	24
	Orpheus* (OR)	-18.572	146.495	1	2	8
	Total			**4**	**8**	**32**
Offshore Central GBR (OC)	Chicken (CH)	-18.653	147.709	3	3	12
	Davies* (DA)	-18.831	147.653	8	12	48
	Little Broadhurst (LB)	-18.949	147.702	3	3	12
	Total			**14**	**18**	**72**
Inshore Southern GBR: Keppel Islands (KE)	North Keppel (NK)	-23.084	150.886	2	2	8
	Miall (ML)	-23.151	150.903	1	1	4
	Middle (MD)	-23.162	150.921	1	1	4
	Great Keppel (GK)	-23.197	150.937	1	1	4
	Halfway (HW)	-23.202	150.967	1	1	4
	Total			**6**	**6**	**24**
Offshore Southern GBR: Capricorn Bunkers (CB)	Heron* (HE)	-23.454	151.969	6	10	40
	Lady Musgrave (LM)	-23.896	152.413	5	5	20
	Total			**11**	**15**	**60**
All Clusters	All Reefs			64	88	352

*Denotes 'Main reefs.' All other reefs are 'Additional' reefs.

2.3 Establishing zones and plots

Once a zone was identified, suitable locations for the four permanent plots were selected and marked with eight star-pickets (two per plot). Plot location followed the spacing shown in Fig. 7 and described in section 2.2 and was also determined by small-scale habitat suitability. Plots were located closer together in zones with poor visibility and farther apart when suitable reef habitat was sparse (e.g. dispersed patch reefs on sand). Star-pickets were installed into the substrate along the centre horizontal axis of the plot at meters 2 and 10 of the 12 m plot (6 m between pickets). Star-pickets were labelled with unique numbers in batches of 1-8 and GPS marked to aid navigation, diver orientation, and minimise measurement error. Personnel roles, tasks, required equipment, and considerations for establishing EcoRRAP plots are provided in Table 4. Most EcoRRAP zones used 165 cm steel star-pickets, however 'reef stakes' (Appendices 2,3) were used at zones with very compacted reef substrates. During EcoRRAP zone establishment, additional deployments included a selection of: (1) oceanographic loggers; (2) coral settlement tiles; (3) permanent coral recruit quadrats, and: (4) bioerosion blocks (see other SOPs for more info, Table 1).

Figure 7. Example layout of EcoRRAP plots within a shallow reef zone. Stars indicate locations of deployed star-pickets. Image: S. Gordon.

Table 4. Personnel, roles, and equipment required for setup of an EcoRRAP zone (four plots).

No. divers	Role	Task	Equipment required	Considerations
1-2	Site scout	• Determine suitable plot locations • Roll out transect tape to measure distances • Lay out start-pickets in selected locations • GPS mark star-pickets	• Tape measure • 8 x star-pickets or 'reef stakes' • 8 x numbered cattle tags (attached to pickets)	• Star-picket locations can be GPS marked by a snorkeller in the water if visibility allows, or via the use of a float line and diver signals • The type of picket used (star-picket or reef stake) should also be recorded for future reference
1-3	Star-picketer	• Hammer star-picket into substrate • *Note:* - This task is very physically exerting and requires strong persons - More divers and/or more dives will be required to instal star-pickets at deep zones and in locations with hard reef substrates	• 1 x sledgehammer	Star-pickets should be: • Located in reef areas free of live coral • Driven into the reef until they are very solidly secured (not able to be shaken loose) • Located at least ~1 m from surrounding objects to ensure sufficient space for the camera rig (1 m in length) to circle star-pickets during imaging • Oriented so the small angle between picket flanges faces upwards if star-pickets are installed on a reef wall

3 PHOTOGRAMMETRY TECHNIQUES

3.1 Workflow design

The following photogrammetry workflow was used to collect imagery to generate 3D and 2D habitat reconstructions of sessile benthic communities at all EcoRRAP study zones. These techniques were designed to maximise: (1) in-water image capture efficiency; (2) resultant 2D and 3D model quality, and; (3) enable accurate and precise quantifications of benthic structural complexity, community composition, and coral demographic rates. Specifically, time-series photogrammetry techniques were used to examine temporal variation in benthic habitat metrics and community composition, and to quantify demographic rates of coral taxa to a high level of accuracy and precision. The current techniques are the result of over three years of development, field-testing, and refinement of equipment and procedures to optimize in-water workflows and maximise the quality of resultant models and derived metrics. While the techniques described are specifically tailored to the objectives, sampling design, and equipment used in the EcoRRAP program, they may be easily modified to satisfy other research objectives and requirements.

Two different photogrammetry techniques were developed to best suit differences in ecological information and spatial scales between plots (72 square m per plot) and zones (~2000 square m per zone). At the scale of EcoRRAP plots, DSLR cameras and associated in-water imaging techniques were used to construct high resolution outputs (0.3 mm per pixel) of reef areas. In contrast, medium resolution action cameras and less complex in-water imaging techniques were employed to image reefs at the zone-scale. In addition to different field-based techniques, these two photogrammetry workflows also follow different model processing and metric extraction procedures (see other SOPs, Table 1). Most photogrammetry techniques described in the following sections are applicable both when imaging newly established plots and re-imaging plots in subsequent years, and for imaging at both plot and zone scales, however where differences exist they are noted.

3.2 Photogrammetry workflow overview

Successful implementation of the current workflow requires an understanding of: (1) pre-dive preparation; (2) in-water workflows, and; (3) post-dive data management and pack-down procedures. The general steps involved in photogrammetry data collection and each of the above topics are described in the Table 5 and the following sections. Additional information is provided in both detailed and 'quick reference' formats in Appendices 7,9,10. The current workflow is not complex in nature, however *it does* require careful planning, preparation, and maintenance of a large range of equipment. To successfully conduct the current photogrammetry workflow it is essential to be familiar with the range of equipment used and to ensure all items are packed and operational prior to, throughout, and at the completion of, data collection. The current section provides a description of photogrammetry-specific equipment for new users and provides checklists and tips to assist with all steps of the data collection workflow. Schematic designs for fabricating equipment used in this SOP are listed in Appendix 3.

Table 5. General steps involved in collection of photogrammetry imagery for 3D and 2D habitat reconstructions of benthic communities.

Order	Step	Key tasks	Quick reference
1	Pre-dive preparation	Prepare and pack all required equipment Discuss planned dive activities and dive teams	Tables 4,7,8,9,10 Fig. 10 Appendices 4,5,6,7
2	In-water workflow	Deploy photogrammetry equipment (GPCs) Record depth measurements and zone metadata Collect DSLR and action camera imagery Retrieve photogrammetry equipment (GPCs)	Tables 11, 12, 13 Fig. 10
3	Post dive data management and pack-down	Download images from cameras Enter data and metadata Back up and manage data Start initial model processing (Agisoft Metashape)	Appendices 9,10 Tables 14, 15 Fig. 13 SOP No. 2 (Table 1)
4	Model processing	*Not covered in the current document*	SOP No. 2 (Table 1)

3.3 Pre-dive preparation

Pre-dive preparation involves checking, packing, and preparing all photogrammetry equipment. General equipment required to conduct most underwater photogrammetry surveys includes: (1) camera equipment; (2) ground control points (GPCs); and (3) computer equipment. A list of all equipment required to conduct the current photogrammetry workflow is provided in detail with explanations of each item's use in Appendix 2, and as a **quick reference packing list in Appendix 4.** These lists contain all equipment required to conduct imaging at both plot (DSLR) and zone (action camera) scales. While most users will likely have some experience using cameras and computer equipment, personnel new to photogrammetry may not have previously used GPCs or photogrammetry software. Ground control points (GPCs) are tools used to incorporate spatial data, scaling, and orientation into 3D reconstructions. Data incorporated into models via the use of GPCs in the current workflow is summarised in Table 6, and examples of each GPC type is shown in Fig. 8. Software used for 3D model processing used in the current workflow was Agisoft Metashape (v.1.8). Steps and checklists for preparing photogrammetry equipment is provided below in a mix of tables and Appendices to help assist in understanding and remembering tasks to be completed prior to data collection.

The current section provides information on the setup and use of: (1) Nikon D850 DSLRs in Nauticam housings (Table 7; Fig. 8, Appendix 5); (2) GoPro Hero 9 action cameras (Table 8, Appendix 6), and; (4) GPCs (Table 9), and; (5) computer equipment (Table 10). All sections describe the exact settings and steps used to conduct the current photogrammetry workflow, however only some tables and appendices may apply to altered workflows**. A 'pre-dive' quick reference checklist is provided in Appendix 7** to guide and prompt preparation steps in the field.

Table 6. Ground control point (GPC) types used in the current workflow and their applications. Schematic designs and associated files are provided in Appendix 3.

GPC name	Construction	Application
Dumbbell (Fig. 8a)	Flat aluminium shape consisting of two 12-bit markers spaced at a known distance	Enables 2D and 3D model scaling (X-Y-Z axis)
Triad (Fig. 8a)	Standing aluminium shape consisting of three 12-bit markers spaced at known distances, with a bi-directional bubble level mounted on the base	Enables 2D and 3D model scaling (X-Y-Z axis) and provides model orientation relative to 'real-world up'
Sphere tree (Fig. 8c)	Five spherical stainless-steel shapes with patterned decals attached to branched a central pole. Sphere trees are temporarily attached to permanently deployed star-pickets with clamps (shown in blue, Fig. 8c)	Spatial reference for temporal co-registration of 3D models between years. Note: Sphere trees must be placed in the *exact* same position and orientation each year to be used as a co-registration reference

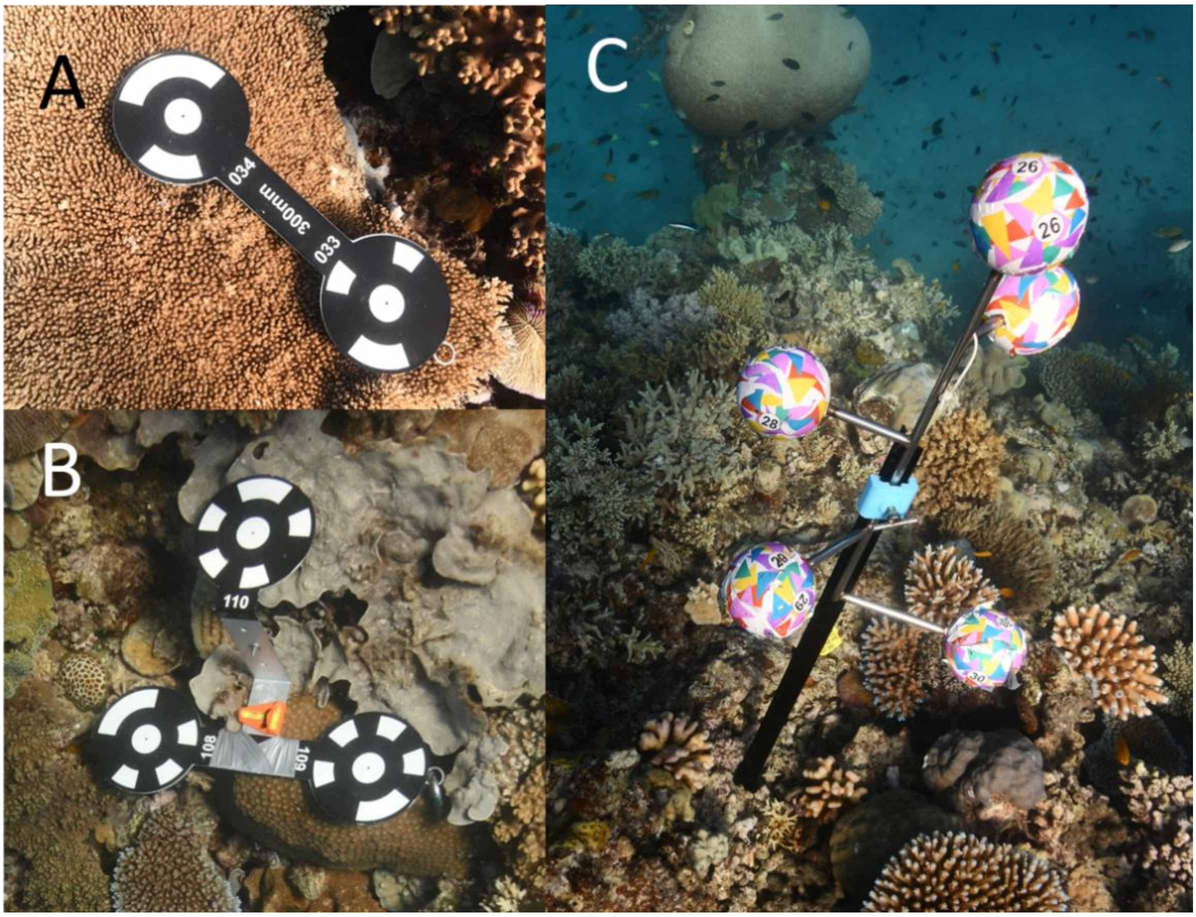


Figure 8. Photogrammetry ground control points used in the current workflow; (A) dumbbells; (B) triads, and; (C) sphere trees. Image: S. Gordon.

Table 7. Set up steps and settings for Nikon D850 DSLRs in Nauticam housings.

Step	Part/consideration	Key tasks	Additional info
Prepare DSLR (Nikon D850)	Camera hardware	• Check camera battery full and charge spares • Check SD and XQD card inserted and formatted • Clean lens, clean with Kim wipe or lens pen if dirty	Nikon D850 user manual: D850UM_NT(En)06.pdf (nikonimglib.com)
	Settings	• Check camera settings match recommendations in Appendix 5 • Refer to Fig. 9 for a visual check • Set date and time • Format memory card to delete all files	Appendix 5 Fig. 9
Prepare Nauticam housing	Housing and o-rings	• Check housing for rust, damage, cracks, and loose fittings • Wash O-rings with soap and water to clean and hang to dry • Inspect for cracks and chips and replace if required • Once dry, grease O-rings with a small amount of Nauticam silicone grease (white) and re-install • NOTE: This process is only required on the first day of operations, in following days O-rings only require a visual check and minor grease application unless dirty	Video demonstrations of steps: https://vimeo.com/246180473
	Dome ports	• Inspect dome for scratches on outside and dust on inside • If scratches are present on the outside of the dome, polish with Novus acrylic polishing fluid and microfibre cloths • Polishing solutions should be applied in descending order: solution three (only for small spot application if needed, very coarse), then two (less coarse), and one (to wash) • Ensure different cloths are used for each solution • If dust, hairs, or smudges are present inside the dome, clean with a lens pen or KimWipe but NEVER polish the inside of the dome • Cover dome with neoprene cover	Novus acrylic polish video: Novus Cleaning and Polishing Kit - YouTube

Assemble Nauticam housing	Attach dome port to housing	• Open red lever on housing to remove dome-port cover • Inspect O-ring seat and dome-port O-ring for dirt and hairs • Wipe seat and O-ring with KimWipe and grease O-ring with a small amount of silicone grease if required • Line up white circle on back of dome-port with white circle on top of housing opening • Carefully push down dome-port into housing until it drops into groove, no O-ring should be protruding from the join • <u>Do not</u> turn the dome port to insert it into the housing • Close the red housing lever, this should require very little pressure, if the lever feels forced, check for correct seating of dome-port • NOTE: This process is only required on the first day of operations. Unless there is reason to do so, domes should remain attached to the housing for the duration of operations to minimise flooding risk	Video demonstrations of steps: https://vimeo.com/246180473
	Place DSLR in housing	• Lift back screen out slightly to fit camera mount on and screw in at camera base with flat-head screw driver • Ensure camera Autofocus/Manual focus switch and On/Off switch are correctly aligned with mount as <u>these settings cannot be changed when in housing</u> • Ensure the flash cable is lifted out and attached to the camera while sliding to avoid pinching • Slide DSLR in mount into housing and clip closed with bottom lever • Connect the flash cable to top of DSLR camera to keep it in place even if no flash will be used	Video demonstrations of steps: https://vimeo.com/246180473
	Check housing pressure and flood alarm	• Open housing by simultaneously pressing and sliding the 2 locks on either side of the housing • Place one coin battery (CR 2032) into bottom, inside holder	Video demonstrations of steps: https://vimeo.com/246180473

Assemble Nauticam housing cont.	Check housing pressure and flood alarm cont.	• Turn on switch inside housing back, a blue light will flash if operational • Lick finger and place on bottom electrodes inside housing, a loud broken "beep" will sound if operational • If the "beep" is constant and not broken it is an indication that the coin battery is low and needs to be replaced • Turn switch off to clear error, then turn on before pressurising	Video demonstrations of steps: https://vimeo.com/246180473
	Close housing and pressurise	• Inspect housing O-ring and O-ring seat for dirt and hair, clean and grease if needed • Close housing with both levers simultaneously • Remove pump cap and use pump to remove air from housing until indicator light turns from red, to yellow, then to green, this should take ~10 seconds of pumping • If you feel significant resistance while pumping stop and check the housing or indicator light • If you need to purge the housing, push down the red button to open it • Return pump cap and inspect indicator light a minimum of 20 mins after pumping to ensure there are no leaks	
Attach cameras to rig	Attach camera mounts to base of housing	• Screw in large sliding plate to base of housing using two screws • The plate should be positioned as far to the right of the housing as possible on the housing to be mounted on the left of the rig, and as far to the left as possible on the housing mounted on the right. • NOTE: This process is only required on the first day of operations	Camera mounts: Rapid Connect Adapter With Sliding Mounting Plate 357Pl - 357-1 | Manfrotto AU
	Slide camera mounts onto rig	• Tighten screw level all the way, then turn back half a turn • Slide camera mounts into rig bar mounts and tighten screw as much as possible	

	Slide camera mounts onto rig cont.	• Pull the lever towards you to reposition of the screw if it is obstructed by the mount • Ensure latch of camera mount is greased and working • Secure cameras together using a rope with carabiners to ensure cameras cannot slide out of mounts	
	Place camera rig in stand to transport in vessel	• Camera rig will fit into stand in upright or down-facing position • Ensure handle fit into cut-out of stand • Cameras in housings should always be either on the desk in the office (on top of towels) or mounted on the rig and sitting in the stand to avoid damage to housings	

Table 8. Set up steps and settings for GoPro Hero9/10.

Step	Part/consideration	Key tasks	Additional info
Prepare GoPro	Camera hardware	• Check battery is > 80 % full • Check camera lens and housing clean • Wipe with KimWipe if dirty	GoPro Hero9 user manual: HERO9Black_UM_ENG_REVB.pdf (gopro.com)
	Settings	• Turn on GoPro and connect to GoPro Quik App • Select ‘Set date and time’ to update time • Select ‘Delete all files’ to format SD card • Check camera setting match recommended settings described in Appendix 6	Appendix 6
	Housing	• Inspect housing O-ring and seat for damage, dirt, and hairs • DO NOT grease GoPro O-rings • Place GoPro in underwater housings and clip closed • Check camera mounts are securely attached to housing • Attach cameras to camera rig and ensure locking pin is closed	

Prepare GoPro cont.	Housing cont.	• Cover GoPro with stubby coolers to protect GoPros from damage when not in use	
Attach GoPros to rig	Attach camera mounts to base of housing	• Screw in camera mount plate to base of GoPro using tripod adapter • Ensure quick release latch of camera mount is greased and working • NOTE: This process is only required on the first day of operations	Camera mounts: Manfrotto Quick Release Adapter 323 (Q2-RC2) incl 200PL plate | Buy at digiDirect | digiDirect
	Clip camera mounts into rig	• Clip GoPro on mount plate into holder on rig and lock closed • Cover GoPro with stubby cooler cover	

Table 9. Set up of ground control points and other items.

GPC	Part/consideration	Key tasks	Additional info
Dumbbells and triads	Check sticker quality	• Check marker stickers on dumbbells and triads are clean and free from discolouration and scratche • Replace stickers in poor condition (to ensure detection during processing)	Dumbbell and triad sticker print designs and laser cut diagrams (Appendix 3)
	Check triads are square	• Ensure triads are not bent out of shape (bends should be 90°) • Re-bend if incorrect	
Sphere trees	Check sticker quality	• Check stickers on spheres have not peeled off to reveal raw stainless-steel or distort the sphere outline • If so, apply new stickers and/or cut off excess sticker edges then apply a coat of epoxy over the sticker	Sphere sticker print design and fabrication diagrams (Appendix 3)
Pack	Dumbbells, triads, sphere trees, clamps, data sheet, dive gear, dump weights	• Pack the required number of GPCs per zone (see Table 12) in a catch bag with a carabiner to prepare for deployment • Pack marker data sheets, slate, pencil, and dive computer • Pack all dive gear and dump weights	Table 12

A

B

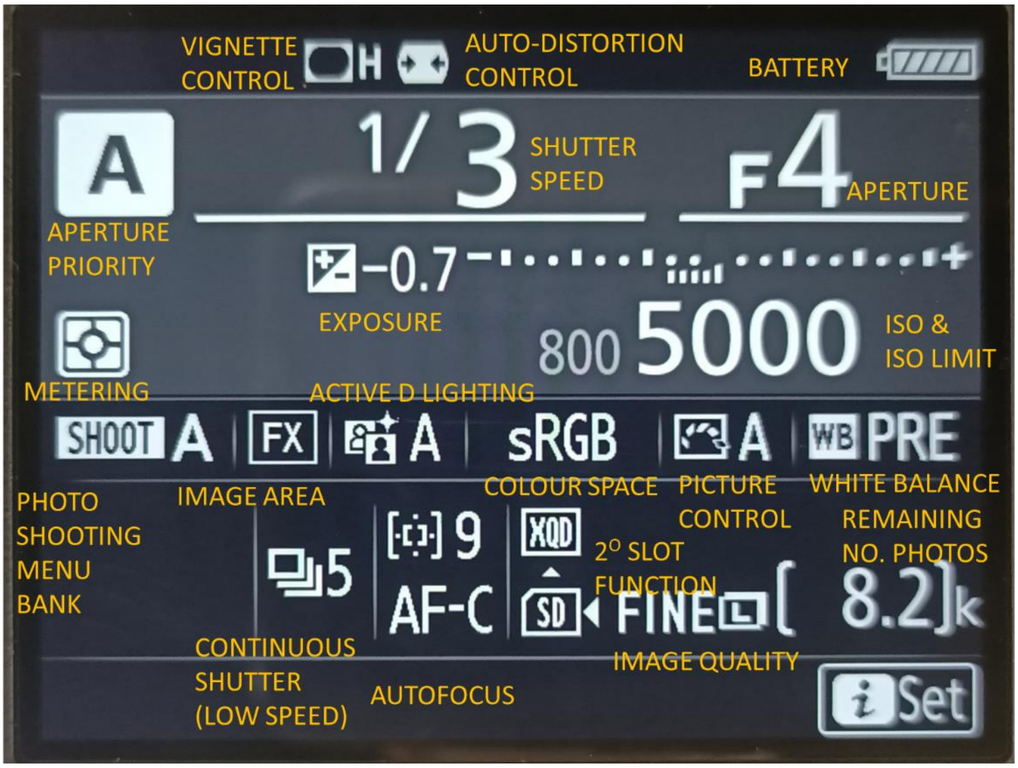


Figure 9. Photo of info display of Nikon D850 with recommended settings: (A) unlabelled, and; (B) labelled. Image: S.Gordon.

Table 10. Computer equipment setup and pack list.

Step	Part/consideration	Key tasks	Additional info
Pack computer	Pack equipment	• Use either powerful laptop or desktop with good CPU and GPU • Pack additional screens, mouse, keyboard as required	Minimum computer requirement (equivalence): • Processor: Intel core i9, 16 core • Memory: 64 GB • GPU: NVIDIA RTX A4500 16 GB equivalent • Storage: 2TB
	Pack HDD/SSDs	• Pack a sufficient number and storage capacity to ensure three separate copies of all data (one copy = approx. 8-12 TB per Reef Cluster) • Pack two small SSD drives to store master files (e.g. Access Database) and to transfer files for processing	
Prepare software and files	Software	• Ensure Agisoft Metashape (3D processing software) is installed and check-out offline licence • Ensure GoodSync (backup software) is installed and activated • Ensure GoPro app installed and updated one mobile phones • Check for updates for GoPros and DSLRS	
	Files	• Download most recent EcoRRAP Access database file • Download 'data' and 'projects' folder structures and rename for relevant reefs and dates • Download the most recent copy of all Agisoft Metashape processing scripts	Database (internal document) and folder templates: EcoRRAP Photogrammetry Data Management Templates - AIMS Scripts: GitHub - open-AIMS/EcoRRAP: Useful scripts produced by EcoRRAP, a subprogram of the Reef Restoration and Adaptation Program (RRAP)

3.4 In-water workflow

The EcoRRAP in-water photogrammetry workflow consists of three main steps: (1) plot setup and measurements; (2) imagery, and; (3) pack-up. This workflow commences after all 'pre-dive preparation' steps have been completed (Appendix 7, Tables 7,8,9,10) and the dive team has arrived at the location of the EcoRRAP zone to be imaged. A team of five to six SCUBA divers and two boats is recommended to conduct this workflow, however a minimum of three personnel may be sufficient at shallow, low-current, sites where dive profiles allow sufficient bottom time. Detailed descriptions of diver tasks, equipment, and considerations to complete this workflow are provided in Table 11 and summarized below. The current workflow allows sufficient surface intervals and dive time for approximately two zones (8 plots) to be imaged per day of diving (approx. 6 hours) if both deep and shallow zones are imaged, or 2-3 zones (8-14 plots) per day if only shallow zones are imaged. This workflow may be altered to image fewer or more zones per day depending on specific project and imaging requirements.

On arrival at the zone to be imaged, personnel carefully deploy a surface float-line with a weight at the GPS mark and the boat is anchored outside of the zone extent (see Table 11). SCUBA divers then deploy ground control points (GPCs) throughout all four plots following the arrangement and quantities described in Fig. 10 and Table 12. Each type of GPC used is essential for scaling and referencing the resultant habitat reconstructions in different ways (described in Table 6). The use of GPCs is particularly important in the current workflow since all imagery is collected underwater and cannot utilize real-time GPS positioning information. Accordingly, the number, size, and arrangement of GPCs used in this workflow was determined through repeated field testing and analyses and represents a balance of both logistical considerations and model processing requirements. Once deployed, each GPC requires specific information to be measured and recorded (described in Table 12, Appendix 8) to be used later in model processing (Section 3.5).

Once all GPCs have been deployed, the area of interest is imaged using two photogrammetry techniques: (1) Plot-level DSLR imaging (four replicate 72 square m areas; Figs. 7,10,11), and; (2) Zone-level GoPro imaging (one ~1500 square m area; Figs. 7,12). Both imaging techniques involve capturing continuous (0.5 second interval) imagery of the benthic reef habitat using a camera rig at a standard distance ('flying height,' or 'altitude') and angle to the reef, while swimming in an pre-determined pattern. The two in-water imaging techniques are described in detailed steps in Table 11, and differences between the techniques are presented in Table 13 and Figs. 11,12. The selected parameters of each imaging technique have been optimized to yield high quality images with an overlap of 80 and 60 % between temporally and spatially adjacent images, respectively (Figs. 11,12). Where in-water visibility is reduced, both flying height and distance between cameras is reduced to ensure image quality and overlap is conserved (Table 13). Following the completion of imaging, all GPCs are collected and returned to the boat to deployed again at the next zone. Note that the only items that remain deployed between imaging events are star-pickets (Fig. 7).

Table 11. Personnel and roles required for 3D habitat imaging.

No. divers	Role	Task	Equipment required	Steps and considerations
2	Plot set-up	1. Navigate to zone with required equipment 2. Mark zone with float line with weight 3. Anchor boat at up-current end of zone 4. Transport/lower equipment to plot 5. Position dumbbells and triads (Table 12) 6. Level triads 7. Measure depth of markers (one per dumbbell and top marker of triad) 8. Clean star-pickets with scraper if fouled and assess stability 9. Attach sphere trees to star-pickets with clamps 10. Deploy float lines at start of Plot 1 and between Plots 2 and 3 11. Record zone metadata (current strength, wind strength and direction, reef structure, benthic community, issues with plot set-up (e.g. moving dumbbells) or cameras)	• Slate and pencil • Marker datasheet • Depth gauge • Catch bags with carabiners • Spare cattle tags (to replace missing) • 20 Dumbbells • 4 Triads (3 small, 1 large) • 8 Sphere trees • 8 Tree clamps (+ spare) • 2 Float lines	• Care should be taken to drop the float line weight in an area clear of coral, or for a snorkeller to guide it down to avoid damaging coral colonies • The boat should be anchored at the up-current end of the zone to avoid anchoring in plots to be imaged or in the adjacent depth zone (shallow or deep) • Depth measurements should be recorded in the 'marker data sheet' (Appendix 8) • If star-pickets are wobbly they will need to be hammered further into the reef or replaced following imaging • Zone metadata can be recorded during and after dives
1-2	Plot imagery	1. Set DSLR white balance • Hold down WB button • Check D-6 (or preferred slot) selected • Place white slate on reef and centre in camera viewfinder, select OK • 'Data acquired' will show If successful • Press WB button to exit 2. Set ISO • Set ISO sensitivity defaults to 2400 for deep and 1600 for shallow zones	• Slate • Camera rigs	• One diver can complete this task in shallow zones, however two divers are required at deep zone due to air and bottom time limitations • Divers should start their dive when plot set up is nearly complete to avoid divers getting in the way of imaging • See section Table 13 and Figs. 11, 12 for swim patterns

		• Ensure ISO < 3200 3. Set aperture • Range approx. 5-13 • Ideal: 11 or higher • Take photo and examine shape of histogram, should be centred • Ensure shutter speed not dropping < 1/500 and ISO > 3200 4. Image zone with GoPros (~10 min) 5. Image plots with DSLRs (10-15 min per plot) 6. Assist in plot pack up		• If white balance is unsuccessful, and 'error message' shown, try to: ○ Move slate closer/further from lens ○ Move a little shallower and repeat ○ Or use pre-saved images in other slots (e.g. D-1, D-2)
1-2	Pack up plot	1. Pack up dumbbells and triads into catch bags Note: Markers should <u>ONLY</u> be removed when imagers confirm that plot imaging is complete 2. Clip catch bag to float line (later lifted from surface) 3. Remove sphere trees from pickets and carry to surface	• Catch bag (left on bottom by setup divers)	• Two divers are required at deep zones due to air and bottom time limitations, while in shallow sites one diver can buddy with plot imagers to assist with plot pack-up • Depending on dive time, this task can be completed by the same divers who completed initial plot setup • Divers can descend approx. 15-20 mins after imaging team starts dive

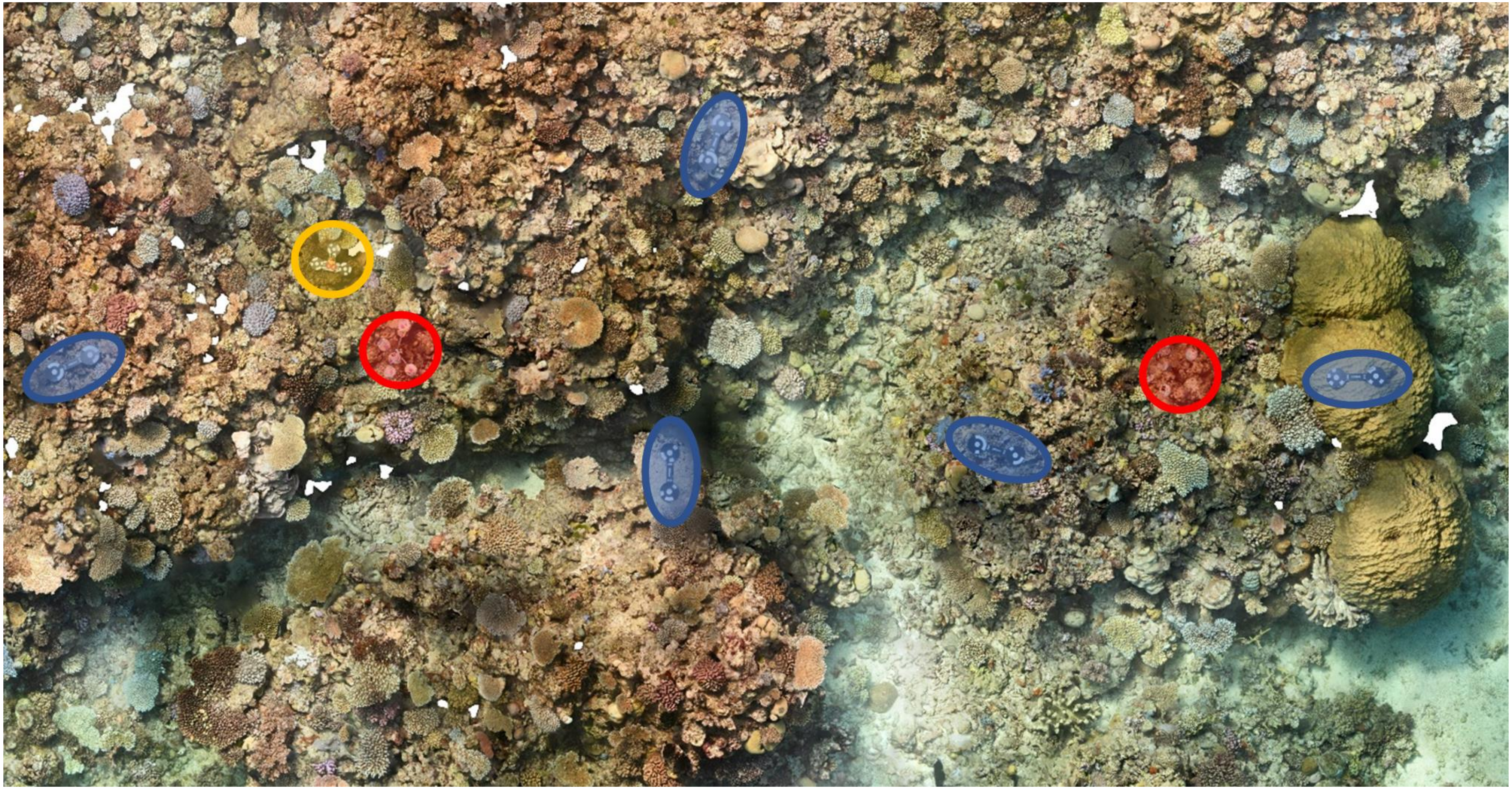


Figure 10. Example arrangement of equipment in a standard 12 x 6 m EcoRRAP plot: two sphere trees (red), one triad (yellow), and five dumbbells (blue). Image: S. Gordon.

Table 12. Number and arrangement of equipment required for 3D imaging of one EcoRRAP plot (four plots per zone). Measurements are recorded in the 'Marker datasheet' template (Appendix 8) using a pencil, depth gauge, and underwater paper.

No.	Item	Description of placement	Measurements required
2	Star-picket	• Spaced ~6 m apart • Labelled with uniquely numbered cattle tags	• Picket integrity (does it require replacing or hammering?)
2	Sphere tree	• Attached to star-pickets in standardized orientation using clamps: i.e. Positioned on the picket so the two bottom arms sit flush against the two small flanges of picket and 3rd branch sits touching top of star-picket (Fig. 8c). • Attached to star-pickets positioning the tree in the described orientation then sliding the tree clamp along the trunk of the tree downwards so the cut-out fits the small flanges. The metal screw of the clamp is then tightened • Note: Sphere trees must be placed in the *exact* same position and orientation each year to be used as a co-registration reference. A minimum of three spheres is required for the co-registration workflow, the use of two sphere-trees with five spheres (10 total) provides redundancy during co-registration	• Depth of top sphere (picket number is ID)
5	Dumbbell	• Two approx. 1 m wider of the sphere trees (along x-axis of plot) • Three between the sphere trees, spaced evenly along the x-axis of the plot and 0.5-2 m wider than sphere trees (along the y-axis of the plot) • Placement of dumbbells should aim to cover plot depth ranges • Attach a weight to dumbbells if there is strong surge or current that may make them unstable • All dumbbells and triads are placed in locations where they are: • Stable and cannot move, fall, or teeter • Clear of occlusion by corals, macroalgae, rocks, spheres, sand, or other obstructions • Ideally not on living coral or large canopy macroalgae, if this is not possible, then not on the growing margin of the colony • Note: A minimum of three detectable dumbbells are needed to successfully scale each plot, so it is recommended that five dumbbells are deployed for redundancy	• Depth and ID of one to two markers per dumbbell • Note: Depth of two markers should be recorded if dumbbell is on a steep slope marker depth differs by >20 cm.

1	Triad	• Note: It is recommended that Plots 1,2,4 use a 100mm triad and Plot 3 uses 300mm triad* • Placed near to a sphere tree/picket when possible • Attach a weight (in holder) to the base of all triads to improve stability • Triads are on a level on x-y axis using the attached bubble level as a reference (Fig. 8b)	• Depth and ID of top marker

*100 mm triads are suitable for DSLR imagery and are easier to manipulate underwater and balance. In contrast, 300 mm triads are suitable for both DSLR and GoPro imagery but are harder to manipulate and balance therefore only one is used per zone (four plots).

Table 13. Plot imaging swim pattern.

Scale	Camera	Distance between cameras	Flying height	No. photos collected	Time	Diver coordination	Swim pattern
Plot	DSLR	Good visibility: • 57 cm Poor visibility: • 50 cm	Good visibility: • 1-1.5 m Poor visibility: • 0.5-1 m	1700 – 2700 per plot	10-15 m per plot	• Divers image plots independently • Each diver images 2 plots • Divers image adjacent plots simultaneously to ensure buddy pairs can be maintained	• Divers use 'lawn mower pattern'(Fig. 11) of: ○ 5 longitudinal passes in-line with transect ○ 6 passes perpendicular to the transect ○ 'Spirals' or 'slices' around sphere trees ○ Additional passes should be made around complex structures • Horizontal passes are used to capture nadiral images (relative to reef), while perpendicular passes aim to capture 3D oblique imagery • Passes should extend approx. 2 m past the plot extent (12 x 6 m, e.g. 14 x 8 m imaged)
Zone	GoPro	Good visibility: • 90 cm Poor visibility: • 70 cm	Good visibility: • 1.5 – 3 m Poor visibility: 1-1.5 m	5000-7000 per zone	~10 m per zone	• Divers image plots together • Divers image whole zone at once	• Divers swim two horizontal passes in-line with transect spaced side-by-side to ensure sufficient overlap between cameras (Fig. 12) • Imagery is nadiral relative to the reef

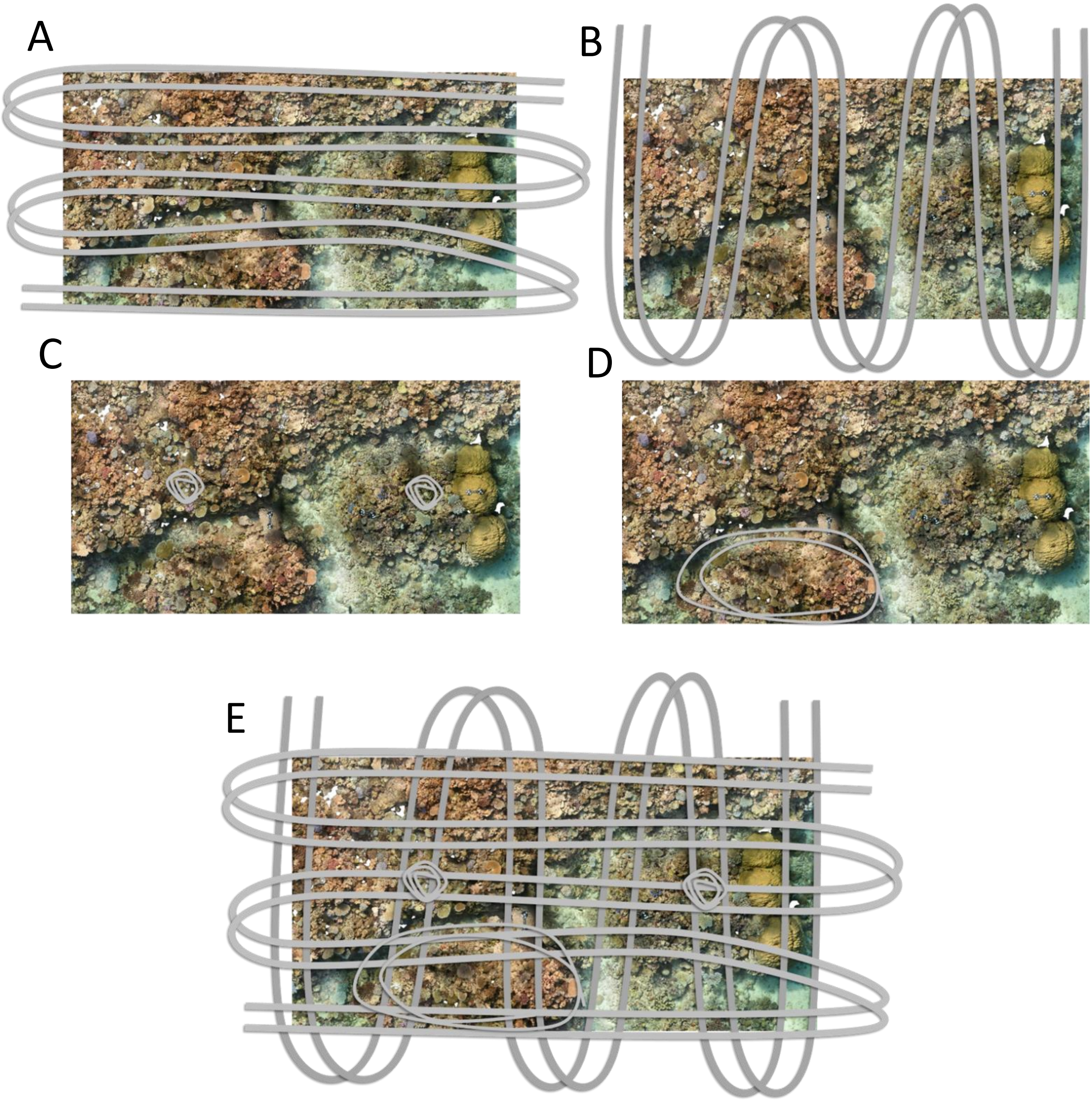


Figure 11. Single diver imaging swim pattern showing DSLR camera passes on an EcoRRAP plot (12 x 6 m): (A) five longitudinal nadiral passes in line with transect; (B) six oblique passes perpendicular to the transect; (C) Spirals' or 'slices' around sphere trees at varying angles (avoid blue water or pointing cameras upwards past 90 degrees); (D) additional around complex structures, and; (E) combined whole plot coverage. Note that each line represents the track of a single camera. Image: S. Gordon.

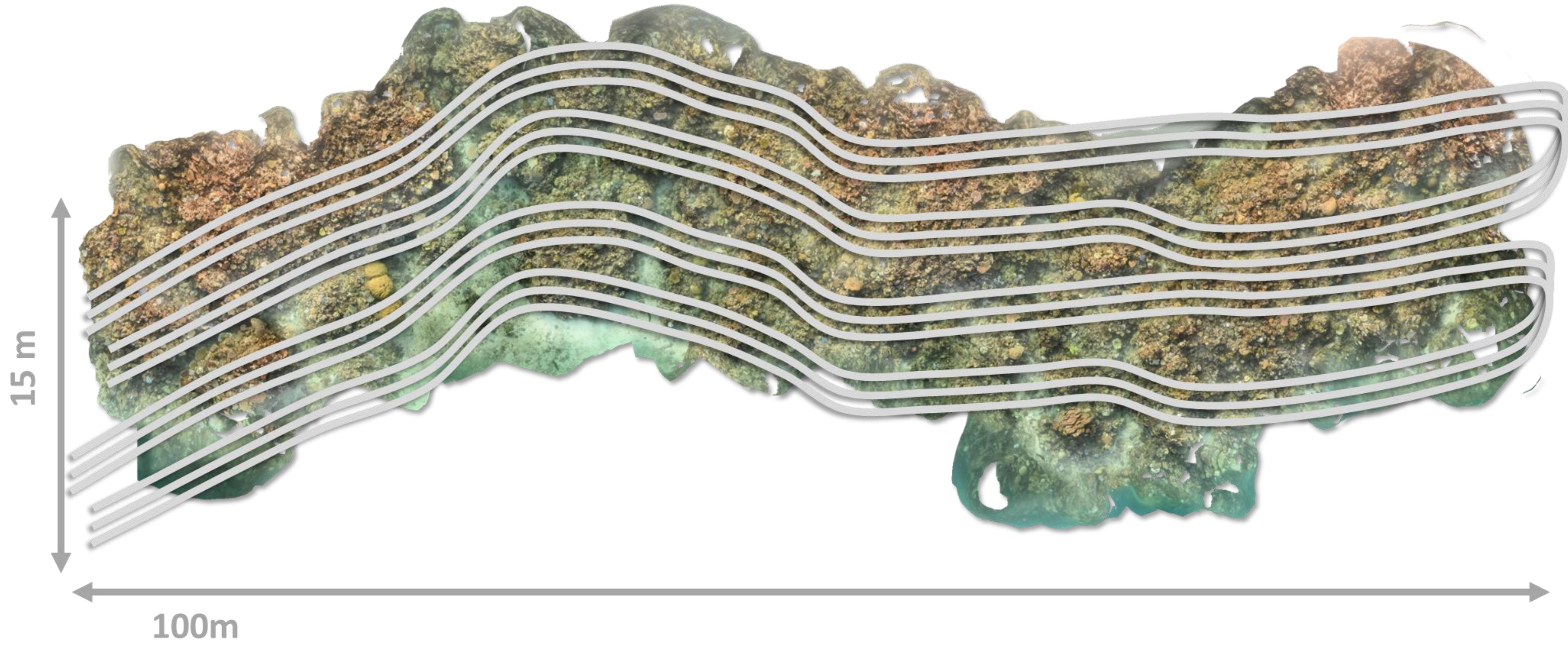


Figure 12. Two-diver imaging swim pattern showing GoPro camera passes on an EcoRRAP zone (100 x 15 m) showing two longitudinal nadiral passes in line with transect. Note that each line represents the track of a single camera. Image: S. Gordon.

3.5 Post-dive data management and pack-down

Post-dive data management and pack-down workflow involves: (1) downloading and organising camera imagery; (2) entering metadata and GPC data; (3) conducting initial 3D processing steps; (4) backing-up files, and; (5) disassembling and servicing equipment. Steps 1-4 are designed to be repeated daily and are described in detail in Tables 14 and 15 and as a **'post-dive' quick reference checklist in Appendix 9.** In contrast, step 5 (disassembling and servicing equipment) is completed at the completion of fieldwork and is described in the **'pack-down' quick reference checklist in Appendix 10.** The current workflow is designed to ensure daily data management and QA/QC and requires approximately 2-3 hours of work by 1-2 staff members following the completion of image collection for the day. Accordingly, this workflow can be altered (e.g. postponing 3D processing until after the completion of fieldwork) if required to suit specific time, personnel, or equipment limitations. **As EcoRRAP's imaging workflow can result in the production of tens of thousands of images, associated metadata, and Agisoft Metashape project files, <u>careful and methodical data management is essential to avoid data loss and errors.</u>**

The post-dive workflow commences when divers have completed the 'in-water workflow' (Section 3.5) and have returned to wash-down equipment (Table 14). The first steps are similar for both DSLR and actions cameras and involve: washing, drying, and stowing camera housings, and removing cameras, camera batteries, and memory cards. Images from camera memory cards are then copied to a computer following the folder structure recommended in Table 14. While images are downloading, collected metadata and GPC measurements should be entered into their respective locations in the master access database file (Fig. 13, Table 14). At this time, Agisoft Metashape (Metashape) projects can also be created, and imagery imported to create one project per plot (DSLR imagery) and one project per zone (GoPro imagery) using the file naming conventions described in Table 14.

It is recommended to conduct the initial stages of 3D model processing in Metashape (described in Table 15) to assist with in-field QA/QC and to optimize post-field processing workflow. Metashape processing steps help to identify if in-water errors (e.g. incorrect camera settings or swim pattern), or data-management errors (e.g. incorrect data storage or file deletion) have occurred and identify if re-imaging of plots is required (Table 15). Metashape processing is completed via use of a python script to optimize processing efficiency, minimize user input, and allow processing to run unattended overnight (Table 15). **Detailed information about Metashape processing is provided in SOP 2 'Model processing' (Table 1), which should also be packed for use in field.** At the completion of each day all data should be backed-up to an appropriate number of internal and external drives using a back-up software (see steps in Table 14) to ensure data integrity prior to clearing camera memory cards.

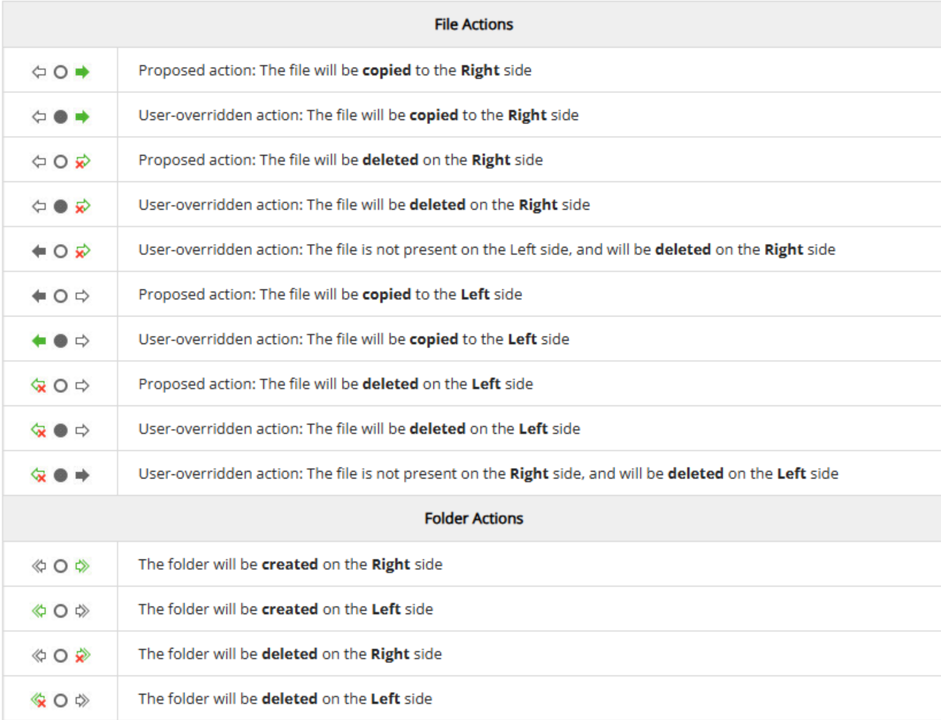
Steps for the pack-down at the conclusion of imaging involve many of steps and checks involved in the pre-dive workflow (Appendix 10). These include camera equipment disassembly and servicing (Tables 7 and 8), GPC checks (Table 9), and use of the packing list (Appendix 4). It is also vital to ensure all data has been entered, backed-up, and processing progress has been recorded (Table 15).

Table 14. Post-imaging data management and pack down.

Step	Part/consideration	Key tasks	Additional info
Download DSLRs and GoPros	Rinse camera housing	• Remove cameras from camera rig mounts • Rinse cameras in housings in freshwater • Turn cameras off and press all buttons and levers in freshwater • Press buttons and levers again once out of water • Allow housings to dry • Purge housing pressure and replace cap (for DSLRs) then open housings • Check housings for water intrusion, wipe dry, and re-close to keep clean	Video of some DSLR steps: https://vimeo.com/246180473
	Remove camera and SD card	• Remove cameras from housing • Remove SD cards and prepare to copy data to computer (SSD fastest) • Remove camera batteries and charge	**Note**: Maintaining consistency in data management and collection protocols, e.g. which cameras each diver uses and which plot they image, significantly assists clarity and ease in file management (especially after a long day of diving)
	Prepare and copy to standard file structure	• Ensure 'data' folder naming structure is correct Folder structure: EcoRRAP\data\DATE\REEF\SITE\ZONE\PLOT • Copy photos into respective plot folder • Images from DSLRs are named relative to the camera (e.g EC1…) and will be automatically saved into SD card folders when imaging is stopped and started • Images from GoPros will not be named by camera or sorted into folders by imaging period. Accordingly, care should be taken to check capture time and keep track of SD card numbers to help with clarity during downloading	
Database	Enter sample event information (Fig. 13a)	• Open EcoRRAP Access Database • Navigate to the form 'FrmDataEntry' > 'Reef' tab and alter any changes to reef clusters, reefs, sites, zones, GPS locations and picket numbers • Navigate to the form 'FrmDataEntry' > 'Sample' tab and select the reef, site, zone, and plot information from the drop-down menu related to the data to be entered • Fill in all information required for the sample in a new row	EcoRRAP Access Database (internal document): EcoRRAP Photogrammetry Data Management Templates - AIMS

	Enter marker data (Fig. 13b)	• Navigate to the form 'FrmDataEntry' > 'Markers' tab and select the reef, site, zone, plot, and sample information from the drop-down menu related to the data to be entered • Enter marker depth information (one depth per row) ensuring to complete all drop-down categories	Triad names • 'Small' triads = 'Triad100' • 'Large' triads ='Triad150'
	Export marker depth CSV (Fig. 13c,d)	• Navigate to the 'target_depth_all' query • Filter the first two columns for the plots and sample required • Select cells to be copied (all columns from columns 'target' to 'z-error'), the right click and select 'copy' • Paste cells into an excel file and delete row heading • Save file as a CSV named as per file naming convention: REEF_SITEZONE_PLOT_YEARMONTH e.g. OCDA_FR1S_P1_202401 **NOTE:** For general users not using the EcoRRAP database, ensure metadata is entered in your desired format and save depth/coordinate information in the same format as the 'Depth csv template file' for input into Metashape (see example selected cells in Fig. 13d)	Depth csv template: EcoRRAP Photogrammetry Data Management Templates - AIMS
Agisoft Metashape processing	Create Metashape project file	• Create new Metshape project file (one file per DSLR 'plot' or GoPro 'zone') • Save project with the following naming convention in the following folder structure: DLSR project: 'REEF_SITEZONE_PLOTNUMBER_DATE.psx' GoPro project: 'REEF_SITEZONE_DATE_GoPro.psx' Folder structure: EcoRRAP\projects\REEF\SITE\ZONE\DATE	**Note:** Folder structure for data and projects is slightly different (note location of 'date' folder in each). This is to allow easy coping of all data to a central location on return from the field. Take care when creating folders to ensure consistent paths.
	Import photos into project	• Import all plot photos into project by dragging and dropping the folder containing plot photos into the 'Photos' pane of Metashape	

	Start initial processing	• Run processing script: ‘Chain 1’ and follow script prompts • If first time using script, navigate to script and right click to open in IDLE or alternative viewer and read initial script lines to understand functionality, required user inputs, and default values used • Confirm default settings and file paths within the script are correct e.g. scalebarpath = 'C:/scripts/EcoRRAP/scalebars.txt' • Navigate to Tools > Run Script (or press Ctrl + R) to run script • When prompted, click the Browse button (folder icon) and navigate to and select script ‘Chain 1’ • Click ‘no’ to network processing (if prompted) • A pop-up will then prompt you to locate the folder containing the target depth CSV file for the project (exported in previous steps). • The script will automatically begin processing (run time 4-8 hours) and will complete the jobs listed in Table 15	**Note:** While script is running, monitor progress and computer performance through the dialogue box in Metashape and through Windows Task Manager (CPU, GPU, and memory usage). Chain 1 can be run locally on approx. 3-4 x DSLR, or 2 x GoPro projects simultaneously on computers with specifications as per Table 2
Back up files	Create copies of files with GoodSync (or alternative back-up software)	• Once photos are downloaded from SD cards to a computer SSD, a back-up should be run from the computer to an external drive • An additional copy may also be sent to copy overnight to ensure there are a minimum of 2-3 copies of the data before SD cards are formatted the following morning (or swapped if more available) • Backups of metadata and Metashape projects should be completed daily • If files are deleted from the local computer drive (i.e. space runs out) ensure that you un-check any files that GoodSync (or other back-up software) identifies as ‘files to be deleted’ by clicking the little circle next to the ‘do not copy’ text • Ensure there are no listings in the ‘files to be deleted’ tab before proceeding with the sync	GoodSync manual: GoodSync Tutorial **Note:** Coordination of file backups is generally best coordinated by one person to minimise errors due to miscommunication. Use of back-up software is very helpful but <u>can propagate deletions throughout copies so use with care!</u>



	File Actions
	Proposed action: The file will be **copied** to the **Right** side
	User-overridden action: The file will be **copied** to the **Right** side
	Proposed action: The file will be **deleted** on the **Right** side
	User-overridden action: The file will be **deleted** on the **Right** side
	User-overridden action: The file is not present on the Left side, and will be **deleted** on the **Right** side
	Proposed action: The file will be **copied** to the **Left** side
	User-overridden action: The file will be **copied** to the **Left** side
	Proposed action: The file will be **deleted** on the **Left** side
	User-overridden action: The file will be **deleted** on the **Left** side
	User-overridden action: The file is not present on the **Right** side, and will be **deleted** on the **Left** side
	Folder Actions
	The folder will be **created** on the **Right** side
	The folder will be **created** on the **Left** side
	The folder will be **deleted** on the **Right** side
	The folder will be **deleted** on the **Left** side

QA/QC check and log	Record processing progress in log	• Once Chain 1 processing is complete, check output for errors • Fill in the 'Process log' of with results of Chain 1 • Perform a check of photos and model to ensure: camera settings are correct and photos are good quality, sparse-cloud generation has been successful and cloud shape is a realistic and representative of area imaged, enabled markers are well distributed throughout the area, and alignment is > 80 % • If the above requirements are not achieved conduct troubleshooting (see SOP 2 for more detail) and determine whether plots require re-imaging	Process log: EcoRRAP Photogrammetry Data Management Templates - AIMS

Table 15. Metashape processing steps involved in processing Chain 1.

Job name	Job description	Settings used (DSLR and GoPro, **(bolded if GoPro differs**)
Quality check	• Assesses the quality of photos and removes photos below the quality threshold • Repeatedly disables, counts, and adjusts (if required) the quality threshold to retain the 'targeted number of photos' of the maximum quality • Begins process using the 'initial quality' threshold and reduces the quality threshold (as required) by the 'quality step value,' until ≥ the 'minimum quality' threshold is reached • If the 'target number of photos' is not achieved by the 'minimum quality threshold', an error message is displayed, and processing will be paused until 'OK' is clicked • The threshold and number of photos prior to and after deletion is logged	• Target number of photos (to retain): > 2000 for 1 'plot' **(1500 for 1 'zone')** • Initial quality: 0.50 • Minimum quality: 0.35 • Quality step value: 0.05 • Note: GoPro images with a quality value of '0.0' can be used for analysis if the target number of photos is not reached and a visual assessment of image quality is OK
Lowest quality alignment	• Aligns photos to create a sparse-cloud of pixel positions in 3D space • Error message displayed and processing stopped if alignment is ≤ 80 % ('minimum alignment' threshold) • See SOP 2 'Model processing' for troubleshooting workflow if 'minimum alignment' is not achieved	• Accuracy: Lowest • Generic preselection: Yes • Reference preselection: Source • Key point limit: 40,000 • Tie point limit: 10,000 • Exclude stationary tie points: Yes • Guided image matching: No • Adaptive camera model fitting: No • Reset alignment: Yes • Minimum alignment: 80 %
Detect markers	• Detects markers using 'initial tolerance' and removes: - Marker projections ≥ the 'marker projection error' threshold, and; - Markers with projection numbers < the 'minimum marker projections' threshold	• Target type: Circular Target 12 bit • Initial marker tolerance: 25 **(85)** • Secondary marker tolerance: 50 **(95)** • Marker projection error: 50 pix • Minimum marker projections: 5 **(10)** • Filter mask: False • Inverted: True • No parity: False

		• Maximum residual: 5 • Minimum size: 0 • Minimum distance: 5

Add and check scale bars	• Adds scale bars based on marker number pairings in ‘scalebars.txt’ file
	• Checks the number of scale bars is ≥ the ‘minimum scalebars’ threshold, if < the threshold:
	    • Marker are re-detected at the ‘secondary marker tolerance’
	    • Projection errors tests are rerun
	    • Scale bars are re-added
	    • A dialogue box is displayed and processing is paused until ‘OK’ is clicked
	• If the number of scale bars is ≥ the ‘minimum scalebars’ threshold after above steps, processing is paused until ‘OK’ is clicked and scale bars should be added manually
	• Calculates the overall scalebar error
	• Checks overall scalebar error is < the ‘maximum scale bar error’
	• An error message is displayed if scale bar error is > the ‘maximum scale bar error’ prompting to manually check error
		• Minimum scalebars: 3 **(7)**
		• Maximum scalebar error (m): 0.01 **(0.02)**

Import depths	• Imports marker X and Y coordinates, depth values (Z), and related accuracies into reference pane (CSV file saved in previous step, Table 14)	
Generate log and save project file	• Automatically generates a processing log and deposits processing information in file	

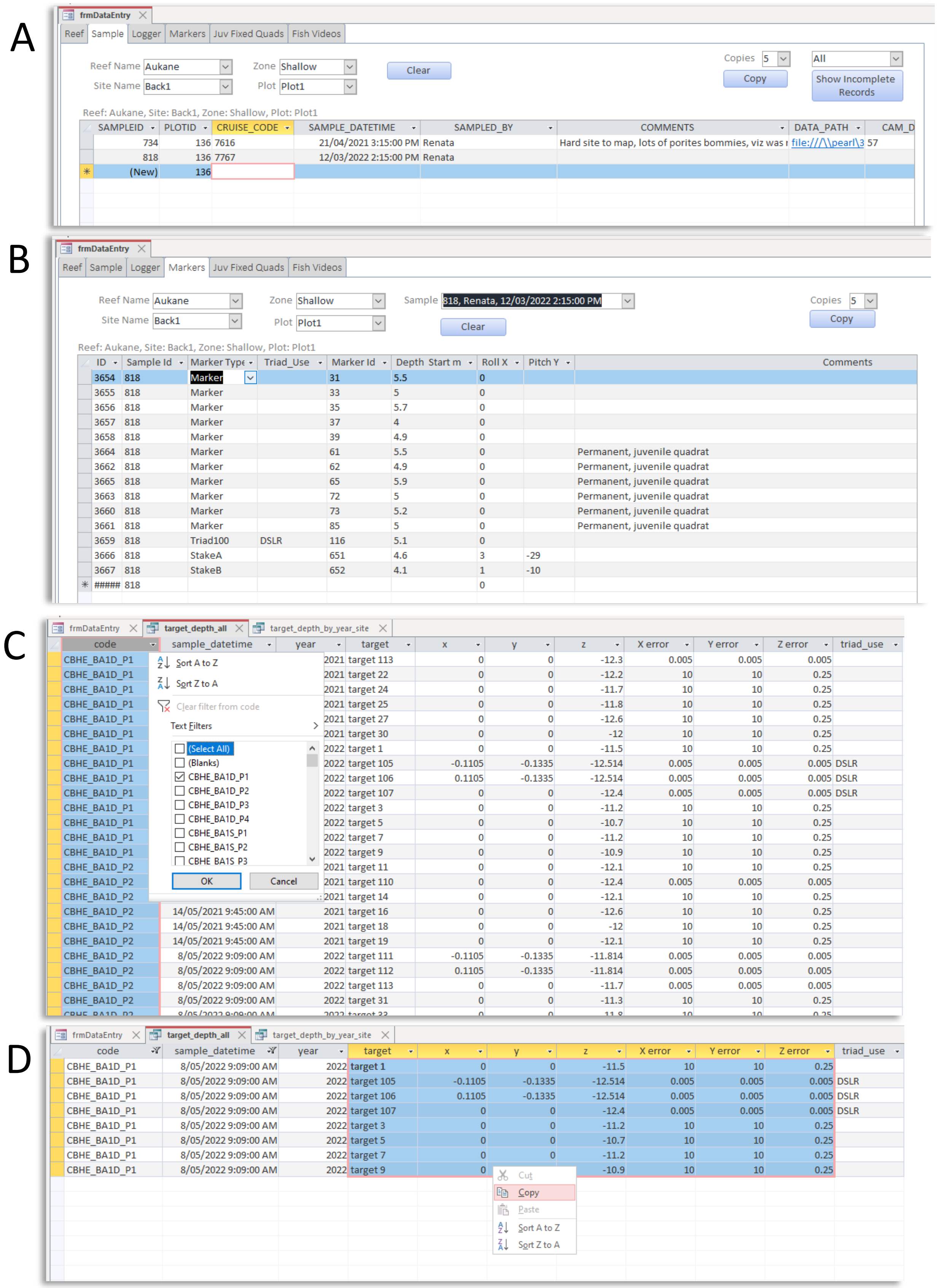


Figure 13. EcoRRAP database steps for: (A) entering sample information; (B) entering marker depth data; (C) filtering marker depth information, and; (D) extracting marker depth information to save as a CSV file for later import into Metashape (described in Table 14). Image: S. Gordon.

4 NEXT STEPS AND ADDITIONAL RESOURCES

4.1 Workflow continued…

Please see the following SOPs in the current series (Table 1, Figure 5) for next steps in:

- 3D model processing (SOP #2)
- Coral digitisation and metric extraction (SOP #3)
- Extracting 3D habitat metrics (SOP #4)

4.2 Additional resources/quick links

- EcoRRAP links
  - Website: EcoRRAP (ecological intelligence for reef restoration) - Reef Restoration and Adaptation Program (gbrrestoration.org)
  - SOPs: Reef monitoring sampling methods | AIMS
  - Metadata: Ecological Intelligence for Reef Restoration and Adaptation Project (EcoRRAP) - AIMS
  - Data management templates: EcoRRAP Photogrammetry Data Management Templates - AIMS
  - EcoRRAP Equipment Schematics: EcoRRAP Photogrammetry Equipment Schematics - AIMS
  - GitHub: GitHub - open-AIMS/EcoRRAP: Useful scripts produced by EcoRRAP, a subprogram of the Reef Restoration and Adaptation Program (RRAP)

- Metashape
  - Download software: https://www.agisoft.com/downloads/installer/
  - Manual/Resources: https://www.agisoft.com/downloads/user-manuals/
  - GitHub: https://github.com/orgs/agisoft-llc/repositories?type=all

- CloudCompare
  - Download software: https://www.cloudcompare.org/main.html
  - Manual/Resources: https://www.cloudcompare.org/main.html

- Python
  - Download software: https://www.python.org/downloads/
  - Manual/Resources: https://www.python.org/doc/

- Goodsync
  - Download: https://www.goodsync.com/

APPENDICES

Appendix 2. EcoRRAP study site GPS locations. See Table 3 for reef zone codes. Zone codes with the suffix 'F' refer to shallower reef flat zones where EcoRRAP data collection other than diver-rig photogrammetry occurred (e.g. ReefScan surveys, settlement tiles, and oceanographic loggers).

Zone code	Latitude	Longitude	Zone code	Latitude	Longitude
CBHE_BA1D	-23.4281	151.9522	OCCH_LA1F	-18.6604	147.7027
CBHE_BA1F	-23.4288	151.9525	OCCH_LA1S	-18.6604	147.7027
CBHE_BA1S	-23.4285	151.9524	OCDA_BA1D	-18.8259	147.6274
CBHE_BA2D	-23.434	151.9204	OCDA_BA1F	-18.8259	147.6271
CBHE_BA2F	-23.4341	151.9209	OCDA_BA1S	-18.8259	147.6273
CBHE_BA2S	-23.434	151.9209	OCDA_BA2D	-18.8143	147.6372
CBHE_FL1F	-23.456	151.9257	OCDA_BA2S	-18.8145	147.6372
CBHE_FL1S	-23.4561	151.9257	OCDA_FL1D	-18.8059	147.6688
CBHE_FR1D	-23.4721	151.978	OCDA_FL1F	-18.8062	147.6686
CBHE_FR1F	-23.4716	151.9775	OCDA_FL1S	-18.8058	147.6686
CBHE_FR1S	-23.472	151.9777	OCDA_FR1B	-18.8197	147.6639
CBHE_FR2D	-23.4709	151.9511	OCDA_FR1D	-18.8197	147.6639
CBHE_FR2F	-23.4704	151.951	OCDA_FR1F	-18.8162	147.6638
CBHE_FR2S	-23.4705	151.9509	OCDA_FR1S	-18.8192	147.6639
CBHE_LA1S	-23.4539	151.9686	OCDA_FR2D	-18.8318	147.6527
CBLM_BA1F	-23.9008	152.3937	OCDA_FR2F	-18.8317	147.6522
CBLM_BA1S	-23.9003	152.3934	OCDA_FR2S	-18.8319	147.6525
CBLM_BA2F	-23.8948	152.4042	OCDA_LA1F	-18.8329	147.6337
CBLM_BA2S	-23.8944	152.404	OCDA_LA1S	-18.8329	147.6334
CBLM_FL1S	-23.8851	152.4137	OCDA_LA2S	-18.8313	147.6332
CBLM_FL2F	-23.9171	152.3922	OCLB_BA1F	-18.9494	147.693
CBLM_FL2S	-23.9175	152.3924	OCLB_BA1S	-18.9492	147.693
CBLM_LA1S	-23.8963	152.4139	OCLB_FL1F	-18.944	147.6992
KEGK_BA1F	-23.1964	150.9373	OCLB_FL1S	-18.944	147.6992
KEGK_BA1S	-23.1966	150.9368	OCLB_LA1S	-18.9494	147.702
KEHW_BA1F	-23.2016	150.9672	ONLI_BA1F	-14.6507	145.4502
KEHW_BA1S	-23.2017	150.9666	ONLI_BA1S	-14.6507	145.4502
KEMD_BA1F	-23.162	150.9205	ONLI_BA2F	-14.6678	145.4424
KEMD_BA1S	-23.1619	150.9207	ONLI_BA2S	-14.6678	145.442
KEML_FL1D	-23.1504	150.9028	ONLI_FL1F	-14.6981	145.4455
KEML_FL1F	-23.1507	150.9028	ONLI_FL1S	-14.6981	145.4454
KEML_FL1S	-23.1506	150.9028	ONLI_FR1D	-14.6911	145.4695
KENK_BA1F	-23.0843	150.886	ONLI_FR1F	-14.6913	145.4693
KENK_BA1S	-23.0843	150.8854	ONLI_FR1S	-14.6914	145.4694
KENK_FL1F	-23.0851	150.8989	ONLI_FR2F	-14.6496	145.4928
KENK_FL1S	-23.0853	150.8991	ONLI_FR2S	-14.6494	145.4929
OCCH_BA1F	-18.6532	147.7087	ONLI_LA1F	-14.6876	145.4653
OCCH_BA1S	-18.6532	147.7086	ONLI_LA1S	-14.6877	145.4652
OCCH_FL1F	-18.6521	147.7185	ONMO_BA1D	-16.8472	146.2174
OCCH_FL1S	-18.6521	147.7185	ONMO_BA2D	-16.8818	146.184

Zone code	Latitude	Longitude	Zone code	Latitude	Longitude
ONMO_BA1F	-16.8473	146.2176	TSDU_BA2F	-9.87865	142.933
ONMO_BA2F	-16.8819	146.184	TSDU_BA2S	-9.87852	142.9329
ONMO_BA1S	-16.8471	146.2174	TSDU_BA3F	-9.98513	142.9088
ONMO_BA2S	-16.8819	146.184	TSDU_BA3S	-9.9853	142.9086
ONMO_FL1D	-16.8484	146.2373	TSDU_FR1F	-9.93117	143.0053
ONMO_FL1F	-16.8486	146.2372	TSDU_FR1S	-9.9312	143.0054
ONMO_FL1S	-16.8485	146.2373	TSDU_FR2S	-10.0372	142.9265
ONMO_FR1D	-16.8719	146.2537	TSDU_LA1F	-9.93386	142.9227
ONMO_FR1F	-16.872	146.2534	TSDU_LA1S	-9.93405	142.9228
ONMO_FR1S	-16.872	146.2536	TSMA_BA1D	-9.74876	143.3999
ONMO_FR2D	-16.8831	146.2446	TSMA_BA1F	-9.74886	143.4001
ONMO_FR2F	-16.8826	146.2446	TSMA_BA1S	-9.74877	143.3999
ONMO_FR2S	-16.8828	146.2446	TSMA_BA2D	-9.74405	143.4157
ONMO_LA1D	-16.86	146.2255	TSMA_BA2F	-9.74463	143.4159
ONMO_LA1F	-16.8599	146.2254	TSMA_BA2S	-9.74423	143.4158
ONMO_LA1S	-16.86	146.2255	TSMA_FL1F	-9.75989	143.3982
PAOR_FR1D	-18.5715	146.4956	TSMA_FL1S	-9.75998	143.398
PAOR_FR1F	-18.5726	146.495	TSMA_FR1D	-9.7639	143.4172
PAOR_FR1S	-18.5722	146.4954	TSMA_FR1S	-9.76227	143.4214
PAOR_FR2D	-18.5715	146.4956	TSMA_FR2D	-9.7462	143.4603
PAOR_FR2F	-18.5726	146.495	TSMA_FR2F	-9.74817	143.4583
PAOR_FR2F	-18.5726	146.495	TSMA_FR2S	-9.74831	143.4585
PAOR_FR2S	-18.5722	146.4954	TSMA_LA1S	-9.73419	143.435
PAPE_BA1D	-18.5505	146.4882			
PAPE_BA1F	-18.5508	146.4886			
PAPE_BA1S	-18.5508	146.4884			
PAPE_BA2D	-18.541	146.4884			
PAPE_BA2F	-18.541	146.4891			
PAPE_BA2S	-18.541	146.4886			
PAPE_FR1D	-18.5391	146.4992			
PAPE_FR1F	-18.54	146.4989			
PAPE_FR1S	-18.5395	146.499			
TSAU_BA1F	-9.86777	143.3894			
TSAU_BA1S	-9.86766	143.3893			
TSAU_BA2F	-9.8753	143.3887			
TSAU_BA2S	-9.87567	143.3885			
TSAU_FL1F	-9.88172	143.3944			
TSAU_FL1S	-9.882	143.3944			
TSAU_FR1F	-9.87976	143.4097			
TSAU_FR1S	-9.87995	143.4101			
TSAU_FR2D	-9.88355	143.4073			
TSAU_FR2F	-9.88335	143.4068			
TSAU_FR2S	-9.88363	143.407			
TSDU_BA1F	-9.88176	142.9253			
TSDU_BA1S	-9.88165	142.9252			

Appendix 2. EcoRRAP 3D photogrammetry equipment list and item description. Items with Asterix (*) additionally required for fish RUV (Table 1).

Category	Item	Description/use
Plot set up	Star picket / reef stake	Secured into reef to mark permanent plot and to attach sphere tree to in standardized position for use as temporal co-registration reference. Note: Reef stakes are used in locations where the reef substrate is too compacted to install star-pickets
	Sledge-hammer	To install star-pickets and reef stakes into the reef
Camera rig	Camera bar	Aluminium telescopic bar on which cameras are mounted
	Foam mat	Placed on deck below cameras and ground control points to prevent damage
	Bar mount	Component of camera mount secured to camera bar using custom made brackets
	Camera mount	Component of camera mount secured to camera (double size for DSLR, single for GoPro)
	Dive computer	To monitor depth/altitude of camera rig during imaging
	Camera rig stand	PVC stand used to hold camera rig for transport and prevent weight bearing on dome hoods
Computer	Field computer	To download files, enter data, and create Metashape projects in the field
	Monitor, keyboard, & mouse	To use with field computer (if required)
	External harddrive	To back-up files in the field
	Agisoft Metashape licence	To create Metashape projects and conduct preliminary processing Needs to be checked-out as offline licence
	Access database	To enter metadata
	UPS	To prevent power loss and surges (if required)
DSLR	Nikon D850 body	Preferred DSLR used for imaging
	Nikor 20 mm, f1.8 lens	Preferred lens used for imaging
	Lens bag and caps	To protect lens and body when separated
	Nauticam 8.5" dome port	Preferred dome port for imaging
	Dome bag, caps, & neoprene cover	To protect dome port in water, transport, and storage
	Nauticam 17222 NA-D850 housing	Preferred DSLR housing for imaging
	Housing accessories	Vacuum pump, spare O-rings, port screws
	Lens pen kit	To clean lens and dome

	XQD card	DSLR image storage (overflow)
	512 GB micro SD & SD converter	DSLR image storage (primary)
	256 GB SD	DSLR image storage (spares)
	Nikon batteries	Two per camera
	Nikon battery charger	One per camera
	Nikon D850 manual	For troubleshooting and info in the field
	Acrylic polish kit & cloth	Novus polish kit and microfibre cloths (colour-coded) for polishing domes
GoPro	SD & MicroSD card reader	USB-C connection if possible
	MicroSD-SD adapter	Depending on card reader available
	128 GB micro SD	GoPro image storage (128 GB preferred but 64 GB sufficient)
	GoPro Hero 9/10	Preferred GoPro used for imaging
	Soft zip case	To store and transport GoPros
	GoPro underwater housing	To protect GoPros from flooding and damage while underwater
	USB-C cable	To charge GoPros
	GoPro battery	Two per GoPro
	GoPro battery charger	One per two GoPro
	Stubby cooler	Secured to camera rig to protect GoPros from scratches when in water and not in use
	Gold metal mounts	To attach underwater housings to single camera mounts (tripod screw)
	GoPro manual & App	For troubleshooting and info, GoPro Quik App on phones for quick access of camera settings
	GoPro clamps & gooseneck*	To attach GoPro to star-picket to record fish video footage
	GoPro floats & line*	To retrieve GoPro from surface once fish video footage recording complete
Maintenance	Kim wipe, paper towel, alcohol wipe	To clean camera lens, housings, GPCs, etc.
	Tool kit (Allen keys, screw drivers)	To attach/adjust mounts, camera rig, etc.
	Cotton tips	To clean housings, camera rig, and mounts etc.
	Elastic bands	To attach stubby coolers to camera rig and attach datasheet to slate
	Cable ties	General use

	Vaseline grease (not for O-ring)	To lubricate screws and latches in camera rig and mounts
	WD40	To lubricate screws and latches in camera rig and mounts
	O-ring pick and lubricant	To remove and lubricate Nauticam DSLR housing O-rings
	Quick-dry towels	To shade cameras during transit in tender and absorb water when handling in office
Packing	Pelican cases	To store cameras, computer, Nauticam DSLR housings, and housing domes
	Nelly bin/ tubs	To pack durable / water resistant equipment
	Maintenance/battery toolbox	To store regularly used tools and equipment
GPCs	Dumbbell	Flat aluminium shape with two marker stickers with a known distance between
	Triad	Standing aluminium shape with three marker stickers with a known distance between.
	Clip / carabiner	Used to connect dumbbells together and assist with transport of GPCs
	Sphere tree	Stainless steel rods with spherical projections covered in unique sticker patterns
	Cattle tags (bag)	Used to label star-pickets
	Tree clamp	Plastic clamp with stainless screw used to attach sphere trees to star-pickets
	Dumbbell weights and holders	PVC brackets used to hold small lead weights to underside of dumbbells and triads to minimise GPC movement
	Marker datasheets	To record depths of markers and star-pickets
	Spare dumbbell stickers	To replace scratched/ damaged stickers
	Spare sphere stickers	To replace scratched/ damaged stickers

Appendix 3. Equipment designed and manufactured for EcoRRAP workflow and corresponding schematic file name. Schematic designs for fabricating all items can be found on the AIMS Metadata repository (EcoRRAP Photogrammetry Equipment Schematics - AIMS). Descriptions of each item and it's use are provided in Appendix 4, Tables 6,7,8,9,11,12,14, and Figs. 8,10.

Item	File name
Reef stakes	Reef stake.pdf
Camera rig (telescopic)	Camera rig_2D.pdf, Camera rig_3D.pdf
Camera mounts (for rig)	Camera mount_2D.pdf
Dumbbells	300 mm dumbbell.pdf
'Small' triad (100 mm radius)	Triad 100 mm_2D.pdf, Triad 100 mm_3D.pdf
'Large' triad (150 mm radius)	Triad 150 mm_2D.pdf, Triad 150 mm_3D.pdf
Dumbbell and triad stickers	Target stickers.pdf
Sphere tree + picket placement	Sphere tree_3D.pdf
Sphere tree stickers	Sphere tree sticker.pdf
Tree clamps – Steel picket	Steel tree clamp_3D.pdf
Tree clamps – Stainless picket	Stainless tree clamp_3D.pdf
Weight holder	Weight holder_3D.pdf

Appendix 4. EcoRRAP 3D Photogrammetry equipment pack list. Items with Asterix (*) considers additional equipment required for fish RUV (Table 1).

Category	Item	No. (suggested)	Packed (Y/N)	Comments
Plot setup	Star-pickets	As req.		2 per plot (setup) + spares (re-imaging)
	Reef stakes	As req.		Substrate-dependant
	Sledge-hammer	2		
Camera rig	Camera bar	2		
	Foam mat	2		
	Spare bar mounts	3 each		
	Spare camera mounts	3 each		
	Dive computer	2		
	Camera rig stand	2		
Computer	Monitor, keyboard and mouse	2 each		
	Field computer	2		
	External harddrive	1-3		
	Agisoft Metashape licence	1-3		
	Access database	1		
	UPS	1		
	SD/MicroSD card reader	2		
DSLR	Nikon D850 body	5		
	Nikor 20 mm lens	5		
	Lens bag and caps	5		
	Nauticam dome port	5		
	Dome bag, caps, and cover	5		
	Nauticam 17222 NA-D850 housing	5		
	Housing accessories	5		
	Lens pen kit	5		
	XQD card	5		
	512 GB micro SD	10		
	Nikon batteries	10		
	Nikon battery charger	5		
	Acrylic polish kit & cloths	1		
GoPro	Micro SD-SD adapter	5		
	128 GB micro SD	8/16*		
	GoPro 9	7/14*		
	Soft zip case	7/14*		
	GoPro housing	7/14*		
	USB-C cable	9/16*		
	GoPro battery	14/30*		
	GoPro battery charger	7/15*		
	Stubby cooler	8/16*		
	Gold metal mounts (tripod attach)	8		
	Plastic mounts (GoPro attach)	10*		
	GoPro clamps	5*		

	GoPro goosenecks	9*		
	GoPro floats and line	9*		
Maintenance	Kim wipe, paper towel, alcohol wipe	2 box each		
	Tool kit (allen keys, screw drivers)	2 each		
	Cotton tips	2 box		
	Elastic bands	1 bag		
	Cable ties	Assorted		
	WD40	1		
	Vaseline and O-ring grease	2 each		
	Quick dry towels	6		
Packing	Pelican cases	3		
	Nelly bin/ tubs	3		
	Maintenance/battery toolbox	2		
GPCs	Dumbbell	30		
	Triad (large, small)	4, 6		
	Clip / carabiner	10		
	Sphere tree	11		
	Cattle tags (bag)	1		
	Tree clamp	16		
	Dumbbell weights and holders	30		
	Marker datasheets	1 per site		
	Spare dumbbell stickers	1 each		
	Spare sphere stickers	1 each		
Manuals	Nikon D850			
	GoPro			
	SOP #1 (Current document)			
	SOP #2 (3D Model Processing)			

Appendix 5. EcoRRAP camera settings for 3D photogrammetry using Nikon D850 DSLR.

Table 1. Recommended settings for setup of Nikon D850 DSLR. Establishes FN2 shortcut to interval shooting menu.

Menu	Submenu	Recommended setting
MY MENU	Add items	Photoshooting menu > Interval timer shooting (OK)
CUSTOM SETTINGS MENU	Controls > f1 Custom control assignment	Select f2 Select 'Access top item in MY MENU'

Table 2. Recommended manual settings (accessible only via camera buttons) for Nikon D850 DSLR. Bolded text identifies key setting that can be manipulated in-water by users to suit conditions.

Menu	**Submenu**	**Recommended setting**
Exposure Mode (Press 'Mode' button on 'Mode dial' and scroll 'Main command dial')	Exposure Mode	Aperture priority (A) Note: Aperture range should be approx. 5-13 (11 ideal).
Release Mode (Press **'Mode dial lock release'** button and scroll 'Mode dial')	Release Mode	Continuous Low Speed (CL)
Autofocus (Move 'AF mode selector')	Autofocus	Autofocus (AF)
Autofocus mode (Press 'AF-Mode button' and scroll 'Main command dial'), and set AF-area by presseing lever and using front scroll wheel to set to AF-9	Autofocus mode	continuous (AF-C)
Exposure compensation (Press 'Exposure compensation button' and scroll 'Main command dial'	**Exposure compensation**	**-0.7**, but if very low light this can be changed to ---0.3, if very high light or bleaching this can be changed to -1.0
PHOTO SHOOTING MENU	**ISO sensitivity settings**	**ISO sensitivity: 1600 (light sites) – 2500 (dark sites)** Auto ISO sensitivity: ON Maximum sensitivity: 5000 Max sensitivity with flash: 5000

		Minimum shutter speed: 1/500, in very dark conditions (inshore rainy or windy) should be changed to 1/250
	White Balance	PRE: d-6 Note: Re-write d-6 at every dive - Save offshore deep zone white balance in d-1, and inshore deep zone white balance in d-2, to use if white balance in water not possible at depth
	Interval timer (F2 Shortcut)	Interval: 00:00'00.5" Intervals x shots/interval: 9999x1 Exposure smoothing: OFF Silent photography: OFF Interval priority: OFF Starting storage folder: Tick new folder, do not tick reset file numbering

Table 3. All recommend menu camera settings for Nikon D850 DSLR. Bolded settings indicate most important settings or changes from default settings.

Menu	Submenu	Recommended setting
PLAYBACK MENU	Playback folder	ALL
	Playback display options	Tick Overview (2nd page)
	Image review	ON
	Auto image rotation	**OFF**
	Rotate tall	**OFF**
PHOTO SHOOTING MENU	Photo shooting menu bank	A
	Extended photo menu banks	OFF
	Storage folder	**ECON1 (number = camera number, i.e. 1-5)**
	File naming	**EC3 (number = camera number, i.e. 1-5)**
	Primary slot selection	**SD**
	Secondary slot function	**overflow**
	Image area	**FX**
	Image quality	**FINE**
	Image size	**JPEG/TIFF Large (8256x5504; 45.4M)**
	ISO sensitivity settings	**ISO sensitivity: 1600 - 2500** **Auto ISO sensitivity: ON** **Maximum sensitivity: 5000** **Max sensitivity with flash: 5000** **Minimum shutter speed: 1/500 or 1/250**
	White Balance	**PRE: d-6**
	Set picture control	Auto
	Colour space	RGBs
	Active D-Lighting	**Auto**
	High ISO NR	**High**

	Vignette control	**High**
	Auto distortion control	**On**
	HDR	OFF
	Interval time shooting	OFF** you start it every time and need to set it according to Table A3.1
	Focus shift shooting	OFF
	Silent live view photography	OFF
MOVIE SHOOTING MENU	Leave all as default	
CUSTOM SETTING MENU (bank A)	Autofocus (a)	**1. AF-C priority selection (Release)** 2. AF-S priority selection (Release) 3. Focus tracking with lock-on - default 4. 3D tracking face-detection OFF 5. 3D tracking watch area NORM 6. Number of focus points AF55 **7. Store by orientation OFF** 8. AF activation ON **9. Limit AF-area mode selection** – **Dynamic-area AF (9 points)** 10. **Autofocus mode restrictions –AF-C – see Fig 14 below this table** 11. Focus point wrap-around-OFF Focus point options - default
	Metering/exposure (b)	1. ISO sensitivity step value: 1/3 2. EV steps for exposure ctrl: 1/3 3. Exp/flash comp. step value: 1/3 4. Easy exposure compensation: OFF **5. Matrix metering: face det OFF** **6. Center-weighted area: 20** **12.** Fine-tune optimal exposure --
Timers/AE lock, Bracketing and flash & Movie settings	All default	7.
	Shooting display	1. CL mode shooting: 5 2. Max continuous release: 200 3. ISO display: OFF 4. Sync. Release mode options: Sync 5. Exposure delay mode: OFF 6. Electronic front-curtain shutter: OFF 7. File number sequence: ON 8. Peaking highlight color: R 9. /viewfinder grid display: OFF 10. LCD illumination: OFF

		8. Live view in continuous mode: ON
	Controls	1 – 7 defaults 8. Live view button options: ON 9. Switch: LCD 11. Assign MB-D18 buttons: default
SET UP MENU (only relevant settings)	Time zone and date	Check that it is correct
	Non-CPU lens data	20 mm, 1.8
	Wifi, Bluetooth and any other connectivity setting	OFF
MY MENU	**Interval timer shooting**	**OFF**

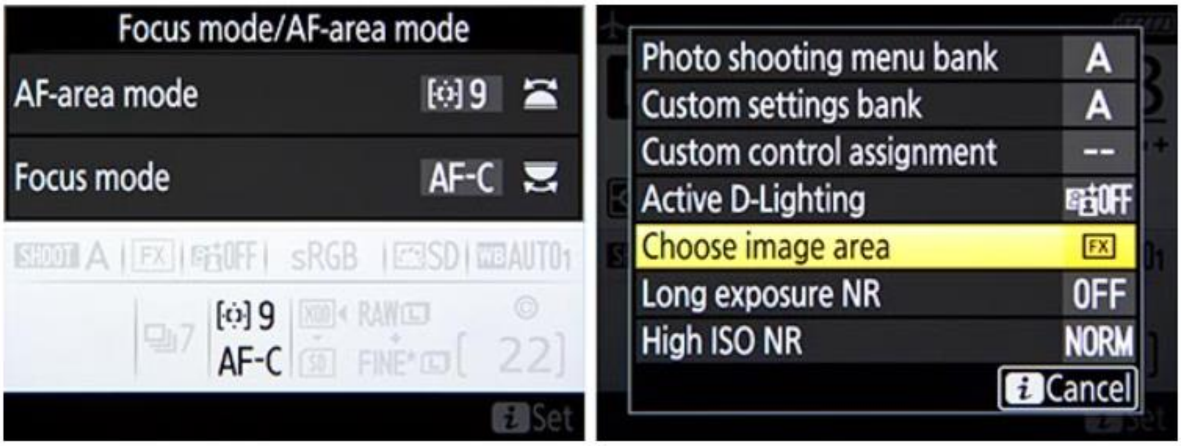


Figure 14 To change the AD-C symbol for AF-area mode –first ensure that the lever on the left front of the camera is on AF (NOT M), then press the button on the AF lever and use the scroll will to change to AF-are mode desired (AF-9).

Appendix 6. Recommend camera settings for GoPro Hero9/10

Menu	Recommended setting
Autorotation	Off
Field of view	Wide
Timelapse	Photo
Interval	0.5s
Beep	On
Brightness	50 %
Voice activation	Off
Bluetooth	Off
Wi-Fi	Off
GPS	Off
All other settings	Default
White balance (Timelapse > Settings > Protune > White balance)	Native

Appendix 7. Pre-dive checklist

DLSR

- ☐ Check camera lens and dome port clean
- ☐ Cover dome with neoprene cover
- ☐ Place DLSR in housing
- ☐ Test flood alarm (alarm should sound when damp finger touches electrodes) and leave on
- ☐ Check O-ring and seat clean
- ☐ Vacuum pump housing until indicator light is green
- ☐ Ensure pump cap replaced
- ☐ Check camera battery full
- ☐ Format SD card (Settings menu)
- ☐ Check camera time correct and synced
- ☐ Leave housing for 20 and check pump light indicator still green (indicates no leaks)
- ☐ Attach cameras in housings to rig and place rig in stand
- ☐ Pack dive slates for white balance

GoPro

- ☐ Check camera and housing lens clean
- ☐ Connect to GoPro with App (GoPro Quick) from device
- ☐ Check camera battery full
- ☐ Synchronize time (Settings menu)
- ☐ Format SD card (Settings menu)
- ☐ Check camera and housing lens clean
- ☐ Check O-ring and seat clean
- ☐ Place GoPro in housing
- ☐ Attach GoPros in housing to rig in stand

Other

- ☐ Check zone information in Access database (e.g. picket numbers, previous conditions)
- ☐ Collect GPS and check zone position available
- ☐ Prepare and pack GPCs into catch bags
- ☐ Prepare marker data sheet
- ☐ Pack float lines and any additional required equipment

Appendix 8. Marker depth datasheet

Date		**Zone code**		**Date**		**Zone code**	
Plot	**Marker no.**	**Depth**	**Comment**	**Plot**	**Marker no.**	**Depth**	**Comment**

Appendix 9. Post-dive checklist

- ☐ Wash and dry all camera housings and check for damage
- ☐ Replace all camera batteries, charge used batteries
- ☐ Copy images from memory cards to 'master' drive (SSD ideal) in 'Data' folder structure
    - o EcoRRAP\data\DATE\REEF\SITE\ZONE\PLOT\
    - o Check for errors in coping by:
        - Comparing numbers of files in all folders against memory cards
        - Visually inspecting cattle tag numbers of star-pickets in photos if needed
- ☐ Enter metadata in database
    - o Reef/Site/Zone/Sample info
    - o Marker measurements
    - o May also include fish video and coral juvenile quadrat data depending on workflow
- ☐ Replace cameras in housings
    - o Check camera lens, housing and dome port clean and free from scratches
    - o Polish dome port with acrylic polish if required
    - o Check O-ring and seat clean, re-grease if required
- ☐ Make Metashape file in 'Projects' folder and import images
    - o Use 'Projects' folder structure and project file naming structure
        - Folder structure: EcoRRAP\projects\REEF\SITE\ZONE\DATE\
        - DLSR project: 'REEF_SITEZONE_PLOTNUMBER_DATE.psx'
        - GoPro project: 'REEF_SITEZONE_ PLOTNUMBER_DATE_GoPro.psx'
    - o Create one separate files for each plot (DSLR) and each zone (GoPro)
- ☐ Run initial Metashape processing steps
    - o Run jobs overnight
    - o Log progress and use results for QA/QC and to determine if plots require re-imaging
- ☐ Back-up all files using GoodSync or other back up software
    - o Back up Data, Projects, and Metadata folders so there are at least three copies before formatting any camera memory cards
- ☐ Spray camera mounts and latches on camera rig with WD40

Appendix 10. Pack-down checklist

General

- ☐ Rinse all equipment with fresh water and allow to dry
- ☐ Ensure all data entry complete
- ☐ Ensure all data backed-up to min. three locations (master, back-up, and additional copy)

- ☐ Check pack-list to ensure all equipment accounted for

DLSR and GoPro

- ☐ Remove batteries, check all charged
- ☐ Remove SD cards, check all downloaded and formatted
- ☐ Check lens clean and un-damaged

DLSR

- ☐ Attach lens cap and store in hard case (detach lens from body if required)

GoPro

- ☐ Store in GoPro soft cases in hard case

DLSR housing

- ☐ Rinse housing in warm water and press all buttons to dissolve/ work-out any remaining salt
- ☐ Allow housing to dry and press all buttons to remove remaining freshwater
- ☐ Remove and wash O-rings (warm water and mild soap)
- ☐ Remove and polish dome ports with acrylic polish
- ☐ Inspect housing for rust and salt build-up
- ☐ Store dome port in material bag in hard case
- ☐ Store housing body in soft padded bag in hard case

Camera rig

- ☐ Disassemble camera rig and wash thoroughly
- ☐ Disassemble camera mounts where possible, clean grease, and replace springs as required

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