Australian Government

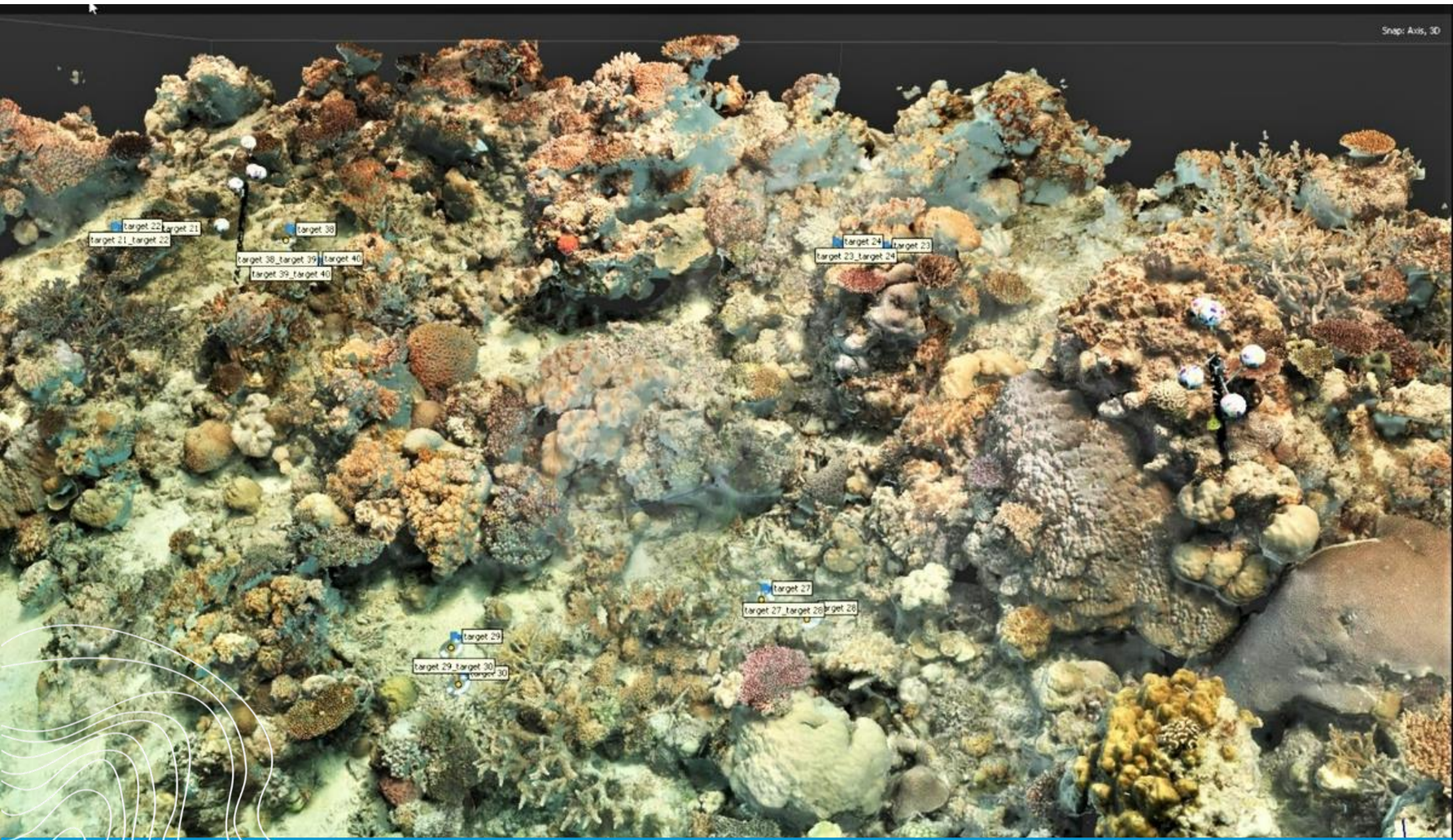
AUSTRALIAN INSTITUTE OF MARINE SCIENCE

Field photogrammetry in 4D: *Model processing*

Reef Restoration and Adaption Program (EcoRRAP)

Standard Operational Procedure Number 15 (No. 2 of series)

Sophie Gordon, Eoghan Aston, Marine Lechene, Tiny Remmers, Agustina Piccaluga, Ean Brinker, Zal Cowasji, Januar Harianto, Peran Bray, Geoff Millar, Ben Watkin, Will Figueira, Manuel Gonzalez Rivero, Renata Ferrari



AIMS: Australia's tropical marine research agency.

www.aims.gov.au

Australian Institute of Marine Science

PMB No 3
Townsville MC Qld 4810

PO Box 41775
Casuarina NT 0811

Indian Ocean Marine Research Centre
University of Western Australia, M096
Crawley WA 6009

This report should be cited as:
Gordon S., Aston E., Lechene M., Remmers T., Piccaluga A., Brinker E., Cowasji Z., Harianto J., Bray P., Millar G., Watkin B., Figueira W., Gonzalez Rivero M., Ferrari Legorreta R. (2024) Field photogrammetry in 4D: Model Processing. Reef Restoration and Adaption Program (EcoRRAP). Standard Operational Procedure 15 (2 of series): Model processing. Australian Institute of Marine Science, Townsville. (57 pp) https://doi.org/10.25845/mwkv-ez70

Project Leader shall ensure that documents have been fully checked and approved prior to submittal to client				
Revision History:		*Name*	*Date*	*Comments*
1	Prepared by:	Sophie Gordon	8/5/2024	
	Contributed by:	Renata Ferrari, Agustina Piccaluga, Ean Brinker, Marine Lechene, Eoghan Aston, Tiny Remmers, Zal Cowasji, Januar Harianto, Peran Bray, Geoff Millar, Benjamin Watkin, William Figueira	8/5/2024	
	Reviewed by:	Renata Ferrari	14/06/2024	
	Reviewed by:	Manuel Gonzalez Rivero	2/12/2024	
	Approved by:	David Wachenfeld	2/12/2024	

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.

Acknowledgement

This work was undertaken by the Ecological Intelligence for Reef Restoration and Adaptation subprogram (EcoRRAP) of the Reef Restoration and Adaptation Program (RRAP). Funded by the partnership between the Australian Governments Reef Trust and the Great Barrier Reef Foundation, partners include: the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, Southern Cross University, the University of Queensland, Queensland University of Technology and James Cook University.

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

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Appendix 1. Overview of EcoRRAP 3D model processing workflow. All steps are described in detail in Tables 7-12, reproduced from Table 6 in text.

Appendix 2. Triad coordinate values used in model scaling. Note: ‘Small’ triads are generally used for DSLR model scaling, while ‘large’ triads are used for GoPro model scaling. Each EcoRRAP site contains 3 x small triads and 1 x large triad.

Appendix 3. Visual representation of triad coordinate values used in model scaling.

Appendix 4. Marker accuracy values used in model scaling. See descriptions of GCP (ground control points) in SOP 1 (Table 1).

Appendix 5. EcoRRAP model processing troubleshooting steps.

Appendix 6. Steps to decimate 3D models and upload to Sketchfab.

Appendix 7. Steps to colour-correct GoPro orthomosaics.

Appendix 8. Complexity metrics definitions from Mitch Bryson ('ComplexityMetrics' tool) and Ryan Krensel ('MetricsCalc' tool).

SUMMARY

The Ecological Intelligence for Reef Restoration and Adaptation Program (EcoRRAP) team at the Australian Institute of Marine Science (AIMS) 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 2, 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 (Lechene et al. 2024).

An introduction to the aims, theoretical background, and sampling design of EcoRRAP is provided in the first SOP of this series (SOP 1, Table 1). Details for other surveying methods used by EcoRRAP, including image processing during fieldtrips 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 (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
Model processing	Field photogrammetry in 4D: No. 2 of series (current doc.)
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

1.1 Overview

***Note**: A detailed overview of the EcoRRAP subprogram, sampling design, and image collection techniques used are provided in the first SOP of this series "SOP 1: Overview and in-field workflow" (Gordon et al. 2023).*

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).

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), used to quantify landscape metrics, and: (2) 2D orthomosaics, used to quantify benthic community composition and demographic rates of corals of several taxa and morphologies. All photogrammetry outputs are generated using Structure from Motion (SfM) algorithms (Ferrari et al. 2016, Aston et al. 2022, Aston et al. 2023) which locate and track correspondence between images and use these trajectories to reconstruct their location in 3D space and thereby create representations of reef topography. The incorporation of model co-registration techniques further enables changes in 2D and 3D outputs to be precisely examined to describe changes in landscape metrics and community compositions, and to quantify demographic rates of benthic taxa with mean precision of 1.37 mm (Lechene et al. 2024).

1.2 How to use this Standard Operational Procedure (SOP)

The EcoRRAP photogrammetry workflow consists of three key stages, here presented in three SOPs (Fig. 1, Table 1): 1) Field-based data collection and model building; 2) Office-based model building using HPC systems, and; 3) Model annotation and metric extraction. The workflow described in this SOP begins once imagery has been collected, downloaded, Metashape projects have been created, and field processing for QCQA have been completed (described in SOP 1). An essential component of this time-series workflow is the process of aligning models from different time-points, or epochs, to the same 3D coordinate space and orientation, a process called 'co-registration' (Figs. 1,2; Lechene et al. 2024).

'Co-registration' uses one model as the 'reference' (i.e. T_1) to which other subsequent model time-points (e.g. T_2, T_3) are spatially aligned (Fig. 2). The orientation of the 'reference' model is specified using a series of steps (see section 3.3.1, Table 9) before 'reference' outputs are generated (e.g. 2D orthomosaics and 3D DSMs, Fig. 2). For subsequent time-points, co-registration with the reference model is required before outputs are generated (Fig. 2). This step is essential to ensure models are precisely aligned in 3D-space to allow accurate and precise quantification of change over time of different spatial metrics (e.g. colony growth or rugosity changes).

As for SOP 1, some aspects of this manual are specific to the equipment and aims of this program, however the document also presents useful information for a wide range of photogrammetry users.

The final stage of the EcoRRAP photogrammetry workflow, model annotation and metric extraction, is covered for 3D DSM complexity metrics in the current document (see section 3.7.1) and for 2D orthomosaics in SOP 3 'Digitisation and metric extraction' (Figs, 1,3, Table 1). Metric extraction is described in SOP 2 and 3, as steps in SOP 3 are significantly more involved and may only be of interest to a specific audience. In contrast, deriving 3D structural complexity metrics from photogrammetric outputs is more general in application.

At the time of writing, Agisoft Metashape v.1.7.6 is in use and instructions are reflective of this. Future versions of Metashape will likely require updating of python scripts and revision towards more efficient workflows. Reviews of this SOP will be conducted during the life of the sub-program as required (see disclaimer page). Procedures that are regularly updated, and/or are AIMS-specific, are described in the AIMS 3D Modelling Onenote (internal link). See this link for AIMS-specific IT considerations (AIMS server access, VPN, etc). If you are using your own network you will need to ensure correct setup is complete before following the steps in this SOP.

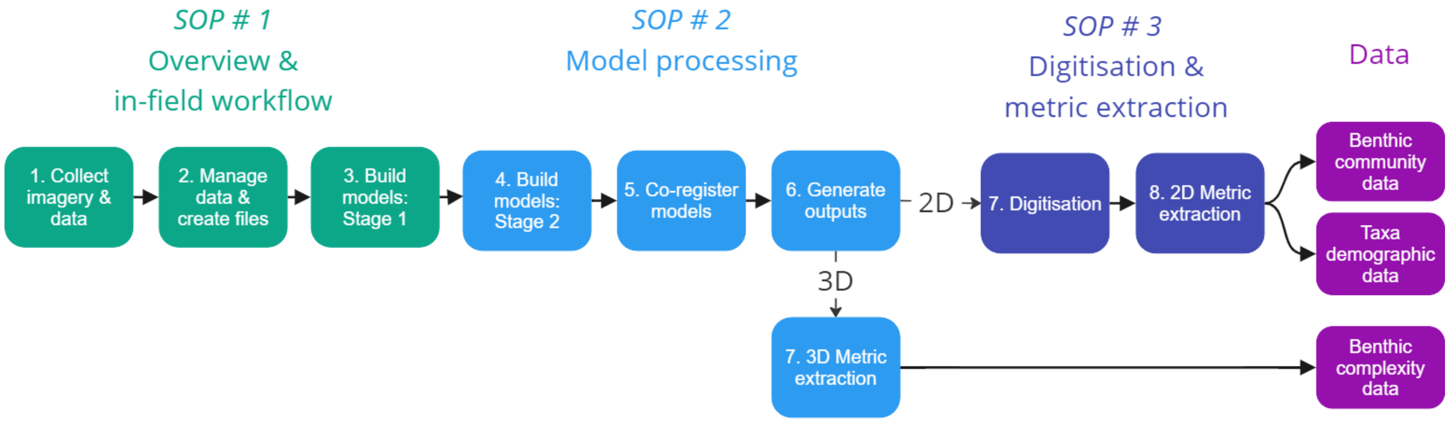


Figure 1. EcoRRAP photogrammetry workflow, related SOPs, and key data outputs. Image: S. Gordon, reproduced from SOP 1.

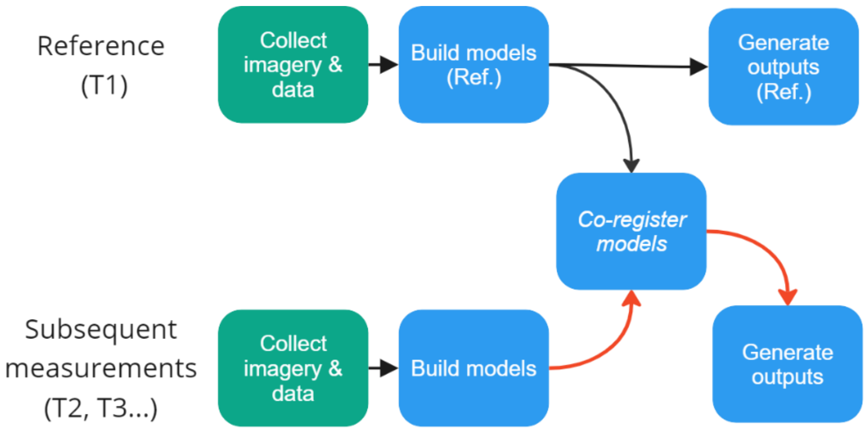


Figure 2. Co-registration workflow considerations for 'reference' (T_1) and subsequent ('non-reference', T_2, T_3...) models. Note that if only one time-point is measured (T_1), model orientation is set but co-registration is not required before generating outputs (2D orthomosaics and 3D digital surface models). When multiple time-points are measured, co-registration is an essential step required prior to generating outputs (see red arrows). Image: S. Gordon.

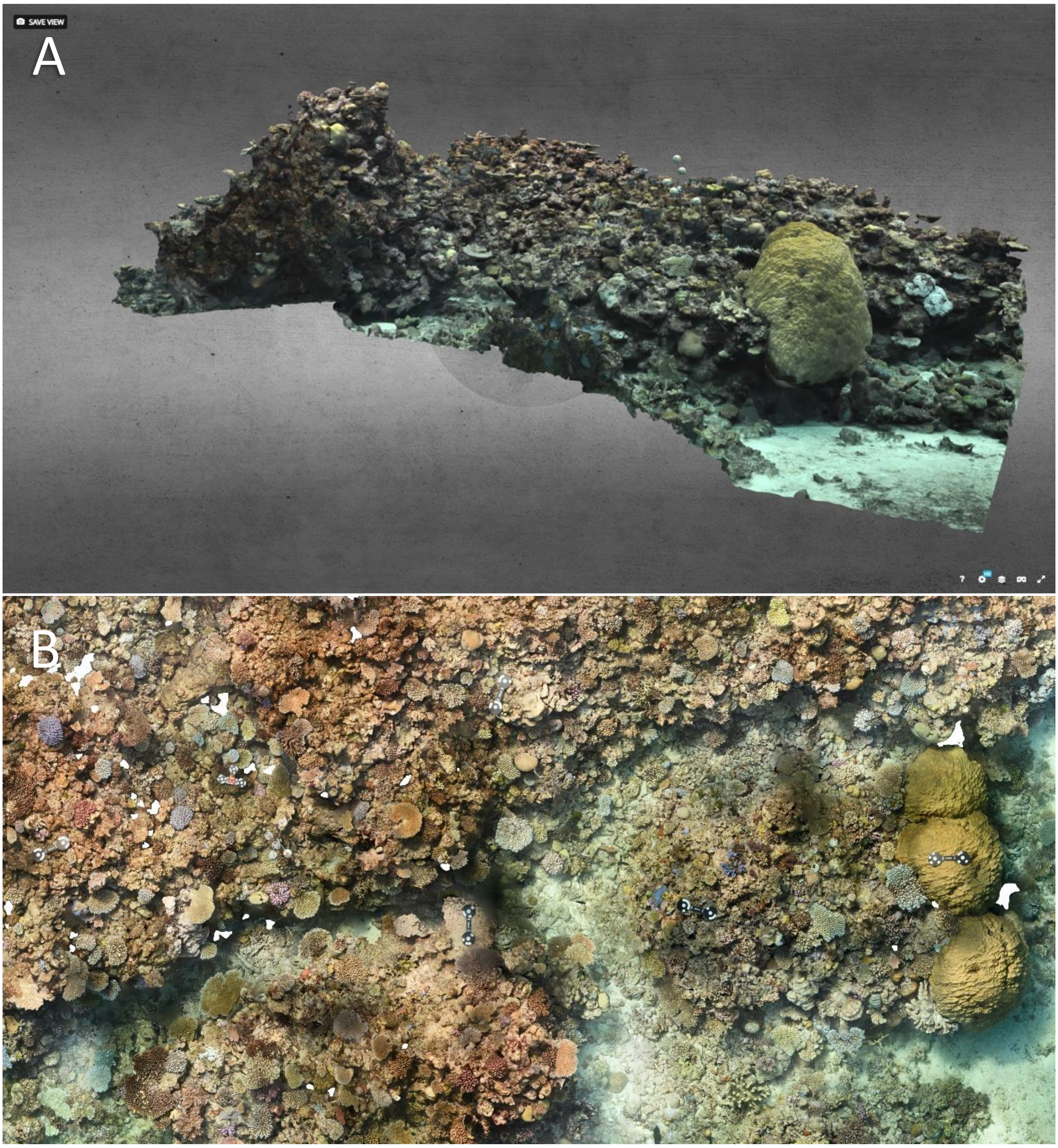


Figure 3. Three- and two-dimensional representations of the reef topography at an EcoRRAP plot produced using Structure from Motion (SfM) techniques: a) a 3D digital surface model (DSM), and; b) a 2D orthomosaic. Image: S. Gordon, reproduced from SOP 1.

2 HARDWEAR AND SOFTWARE

2.1 Hardware

The current EcoRRAP 3D-processing workflow represents a variety of trade-offs between output quality and processing efficiency. All steps and settings recommended are the result of rigorous testing and are strongly influenced by available computing capacity. All processing steps were designed to be completed locally on consumer-grade desktop computers or high-powered laptops. While all processing *can* be completed locally on desktops or laptops, the use of high-powered computing (HPC) nodes increases processing efficiency significantly and is therefore recommended if available (particularly for 'office-based steps', Table 2). Specifications for computers and HPC nodes used in the current workflow are described in Table 2. Computers with lower specifications than Table 2 may also be able to follow the described workflow, however alterations may be needed to make this feasible (e.g. decreasing the number of photos used or the quality settings selected).

Table 2. Computing specifications used for model processing with the current workflow.

Specification	'In-field' processing	'Office-based' processing	
Processing location	Local	Network	Network
Computer type	Laptop	HPC **CPU** node	HPC **GPU** node
Model	Dell Latitude (7780)	NA (as below)	NA (as below)
Processor (CPU)	Intel Core i9 16 Core, 32 threads 64 GB RAM, 36 MB cache 5.5 GHz, 55 W	AMD EPYC 7643 48 core, 96 threads 512 GB RAM, 256 MB Cache 2.3 GHz, 225 W	Intel Xeon w5-3435X 16 core, 32 threads 128 GB RAM, 45 MB cache 4.7 GHz, 270 W
Video card (GPU)	NVIDIA RTX A4500 20 GB G DDR6	NA	Quad (x4) NVIDIA RTX A4500 20 GB G DDR6
Hard drive / storage	4TB SSD	NA – Network storage	NA – Network storage

2.2 Software and applications

All software applications used in the EcoRRAP 3D-processing workflow and their purpose is listed in Table 3. 'Agisoft Metashape Professional' is the primary software used for 3D model processing, while addition software is used for model co-registration and output manipulation. Updated download sources and manuals for applications listed in Table 3 are available in section 4.2 and internally here.

Table 3. Software and applications used in EcoRRAP 3D-processing workflow. Software marked with an Asterix(*) require a paid licence.

Provider	Software	Use in workflow
Agisoft	Metashape Professional*	Build 3D models from images, produce 3D digital surface models (DSMs) and 2D orthomosaics
Agisoft	Network monitor*	Monitor progress of jobs sent for network processing
CloudCompare	CloudCompare	Co-register and compare DSMs between years
Python	Python	Write/edit code to automate processing in Metashape
ESRI	ArcGIS Pro*	Check and clip 2D orthomosaics prior to annotation

2.3 Model processing scripts, 'chains,' locations, and logs

The current processing workflow minimizes user input while ensuring high-quality, standardised outputs though a combination of semi-automated scripts and manual quality checks. The EcoRRAP model processing pipeline uses three main processing 'chains,' each consisting of multiple functions, and the use of additional single-task scripts (Table 4). All scripts are designed to be run within Metashape (e.g. using 'CRTL+R' shortcut), however can be adapted for use without launching Metashape (i.e. python-only workflows). User input and quality checks are generally required before and after running each chain, but no manual input is required while each chain is running.

Note*: Before running any chain for the first time, it is important to open the script (in any text viewer or script editing software) and read the summary of steps involved and any user input required.*

Metashape model processing steps, or 'jobs,' can be run 'locally' (directly on a computer) or via 'network processing' (sent to a group of networked computers, servers, and/or HPC nodes). The recommended processing location for each job is dependent on the stage of processing, task duration, and computing power requirements. All initial 'in-field' processing steps are designed to be run locally on laptop computers (Tables 2,4) as internet-based network processing is generally limited in the field (however network-adapted versions of 'in-field' chains are also provided). Many 'in-office' processing steps have greater computing requirements and are therefore largely network-processed using networked computers or HPC nodes if available (Table 2,4). Most small/single jobs, such as exporting outputs, are also generally best run locally.

All scripts required for the current workflow are available in the AIMS EcoRRAP GitHub: GitHub AIMS/EcoRRAP3D. Scripts are provided for both DSLR and GoPro processing pipelines and in local and network processing formats. See section 1.2 for more information regarding script versioning and updates. The software 'Agisoft Network Monitor' is used to monitor the progress of Metashape jobs run via network processing. Agisoft Network Monitor logs and estimates processing time, reports errors, and allows jobs to be paused, aborted, and ranked in order of priority (Agisoft Metashape: User Manuals, Table 3). Information about Metashape network set-up and management is provided in the relevant Agisoft Metashape user manual: Agisoft Metashape: User Manuals.

Throughout model processing, progress and metadata are recorded in the EcoRRAP Access Database and EcoRRAP Processing Log (EcoRRAP Data Management Templates). Key scripts and logs used for EcoRRAP model processing are described in Table 5. Where differences in DSLR and GoPro processing occur it is noted throughout this document.

Table 4. Summary of python chains and scripts used in the EcoRRAP 3D processing workflow. Note that script applications and order of use differ between 'reference' models (T_1) and subsequent time-points (T_2, $T_{3...}$)(see Fig. 2). All script files are named with the suffixes 'Local' or 'Network, and 'DSLR' or 'GoPro' to differentiate between processing locations and cameras (e.g. 'Chain1_Local_DSLR.py'), steps that differ between DSLR and GoPro processing are marked with an Asterix(*).

Model	Order	File name (.py)	Application	Recommended processing location
Reference (T_1)	1	Chain1	In-field processing steps	Local
	2	Chain2.1	In-office processing steps part 1	Network
	3	PS170_geobit_helper (AccuPixel 2021)	Launch function to orient reference model	Local
	4	Chain2.2	In-office processing steps part 2	Network
Subsequent timepoints ($T_{2,..}$)	1	Chain1	In-field processing steps	Local
	2	Chain2	In office-processing steps	Network
	3	Chain3	Apply co-registration, apply reference bounding-box*	Local

Table 5. Summary of files used in EcoRRAP 3D processing workflow and associated access locations.

File name	File	Description	File location
Multiple (see Table 4)	.py	Python scripts used to run a Metashape processing steps	GitHub AIMS/EcoRRAP3D
EcoRRAP_Database	.db	EcoRRAP Access Database used for metadata, sampling event information, and marker data entry (AIMS internal access only)	EcoRRAP Data Management Templates
EcoRRAP_Processing Log	.xlx	Log file used to record model statistics, processing progress, and model QA/QC	
Multiple (see Table 1)	.pdf	SOPs used to inform and standardise processing (e.g. current document)	Reef monitoring sampling methods | AIMS)

3 WORKFLOW

3.1 Summary

The current section summarises the main stages in the EcoRRAP 3D model processing workflow (Fig. 1 and Table 6, Appendix 1), from photo input to the export of 2D and 3D products. Each step is explained in detail in subsequent sections. While most processing steps are similar for camera types and 'reference' (i.e. T_1) and subsequent models (i.e. T_2, T_3, etc.) there are a few important considerations and exceptions described in section 3.2.

Table 6. Overview of EcoRRAP 3D model processing workflow. All steps are described in more detail in Tables 7-12, also available in Appendix 1.

Step	Platform	Key tasks
Model processing (in-field)	File management	• Copy image files to computer
	Microsoft Access	• Enter metadata and marker depth data into database • Export and save 'Marker depth' CSVs from database
	Agisoft Metashape	• Create Metashape project file and import photos • Run processing script: 'Chain 1' (Local processing) • Conduct manual QA/QC checks
Model processing (in-office)	Agisoft Metashape	• Save photos and Metashape projects to network drive • Open Agisoft Network monitor and prepare network processing • Reference models (T_1) - Run Chain 2.1 (Network processing if available) - Set reference model orientation (use associated script) - Run Chain 2.2 (Network processing if available) • Subsequent timepoints (T_2, T_3…) - Run Chain 2 (Network processing if available) • Conduct manual QA/QC check • Export 3D models
	CloudCompare	• Load 'reference' and 'test' (subsequent timepoint) models • Complete model co-registration and QA/QC • Export transformation matrix
	Agisoft Metashape	• Subsequent timepoints (T_2, T_3…) - Load project and run 'Chain 3' (Local processing)
Output generation	Agisoft Metashape	• Generate orthomosaic • Export orthomosaic (.tif) as 2D output (<u>final ref. 2D output</u>) • Export 3D model (.ply) as <u>final 3D output</u> (ref. and subs.)
	ArcGIS *(DSLR only)*	• Clip orthomosaics from subsequent timepoints (T_2, T_3…) to reference extent in ArcGIS and save <u>final subs. 2D output</u>

3.2 General processing considerations

Before starting the EcoRRAP 3D model processing workflow it is important to take note of a few important considerations:

- Some steps differ between 'reference' (i.e. T_1) and subsequent models (i.e. $T_{2,}$ $T_{3,}$ etc.)(Fig. 2)
- Some steps differ between DSLR and GoPro processing workflows
- All files and folders are recommended to be saved as per file/folder naming structures specified
- Progress throughout processing stages should be recorded in logs for on-going QA/QC (Table 5)
- See SOP 1 for a description of the EcoRRAP sampling design and definitions of 'Plots' and 'Zones'

In addition to this, a few key concepts that may influence processing design and planning are described below.

3.2.1 Processing time and manual input considerations

Model processing time can vary significantly depending on computing resources and may range from as little as 1-2 hours per job if multiple HPC nodes are available to >24 hours per job if processed locally. Similarly, although the current workflow is designed to minimise manual user input, depending on the number of sites and/or time-points measured this can multiply out to be a large workload (i.e. EcoRRAP has > 350 sites). Accordingly, efficient planning, management, and QA/QC is important and best achieved by progressing multiple (or all) projects through to the same processing stage before moving the next. For example, process all projects to the end of Chain 2 before starting co-registration, rather than processing one project all the way to completion. This also allows QA/QC to be completed more effectively, as model characteristics and statistics can be compared between projects and help detect potential issues. Tasks requiring the most significant manual user input in the workflow are:

- **Quality checks**

  It is essential that quality checks are performed after each processing step is completed to ensure that any issues with reconstructions are resolved before processing is continued. This minimises down-stream issues (i.e. issues with reference models will affect all subsequent models) and the need to re-run processing steps. **Some of the most important quality checks relate to model alignment:**

  - If model alignment is <80 % and/or models do not look representative of the reef habitat mapped, <u>processing cannot not be continued without troubleshooting</u>
  - <u>Issues with alignment cannot be resolved in subsequent steps</u> and may indicate a fundamental problem (see Fig. 5, Troubleshooting in Appendix 5)

- **Reference model orientation**

  Manual user input is required to orient the reference (i.e. T_1) model, rotate (if required), and place the bounding box in the position of interest. Once set, the reference model orientation and extent will be applied to all future timepoints (models). Accordingly, all 'reference only' steps only need to be completed for one timepoint of each 'plot' (unique spatial area).

- **Model co-registration**

Manual user input is required to identify and select common features (spheres and points) in models within the software (CloudCompare) to co-register models in 3D space. This step can require the largest amount of manual user input in the current workflow. The amount of manual input required to co-register one model can range from approx. 10-20 minutes per model (plus troubleshooting if there are issues with reference marker movement or reconstruction).

- **Troubleshooting**

One of the most time-consuming, but essential, manual tasks in the current workflow involves troubleshooting issues with individual models. These issues are generally caused by user error and/or issues with image collection (e.g. wrong camera settings or very low visibility conditions), file storage and management (e.g. files saved in wrong folder, co-registering wrong files), and processing mistakes (e.g. forgetting to complete a step or run a script before progressing). Additional troubleshooting can also be required if errors occur during model-building (e.g. low percentage alignment or abnormalities in model reconstruction shape). Troubleshooting tips for frequently encountered errors are provided in Appendix 5 and can best be avoided by careful, documented processing, and ongoing QA/QC throughout the workflow.

3.2.2 DSLR and GoPro processing

While many steps in the EcoRRAP model processing workflow are consistent for DSLR and GoPro imagery, it is important to note that there are a few key differences. Although it is not feasible to explain all differences here, general examples of these are:

- **Differences in settings**

Example 1: 'Lowest-' and 'medium-'quality alignment is used for initial model processing of DSLRs and GoPro imagery, respectively. This reflects a trade-off between computing time requirements, and the quality and utility of resultant sparse clouds, e.g.:

- DSLR models: 'Lowest' quality sparse clouds (4-8 hours local processing using a laptop and ~2500 x 40 MP images) are sufficient to detect issues with alignment and are good predictors of 'high'-quality alignment rate (i.e. models with ≥ 80 % alignment at lowest quality generally have ≥ 80 % alignment at 'high' quality).
- GoPro models: 'Lowest' quality sparse clouds are poor indicators of GoPro model issues and predictors of 'high'-quality alignment rate, therefore 'medium' quality alignment (6-10 hours local processing using a laptop and ~6000 x 20 MP images) is used.

- **Differences in processing steps and project structure**

Example 1: The bounding box (model extent) of reference models is automatically re-sized (to 12 x 6 x 10 m in length, width, and height, respectively) for DSLR models but not GoPro models. This step standardizes DSLR model extent but is not suitable for larger GoPro models where shape and extent is not uniform and can vary significantly depending on reef structure and shape.

Example 2: DSLR 'plots' (72 sq. m areas) are imaged individually, saved, and processed individually as one plot per Metashape project. In contrast, GoPro 'zones' are imaged as one large area (containing all DSLR plots), saved as one Metashape project, and then are split into two halves (plots 1 &2, and plots 3 &4). These differences in workflow are designed to achieve multiple objectives: minimizing DSLR project size, improving script simplicity, maximising efficiency of in-water DSLR and GoPro data collection, and improving quality of GoPro model co-registration.

3.3 In-field model processing

The following text (section 3.2 and referenced tables and images) is adapted from Section 3.5 of SOP 1: Overview and in-field workflow (Gordon et al. 2023) and commences post-dive, once imaging has been completed. For more information and background on imagery collection see SOP 1.

In-field data management and model processing involves the following general steps: 1) downloading and organising camera imagery; 2) entering metadata and ground control point (GPC) data; 3) conducting initial 3D processing steps (Chain 1), and; 4) backing-up files. All steps are designed to be conducted daily and are described in detail in Tables 6 and 7. The current workflow 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.

Note*: The EcoRRAP imaging workflow can result in the production of tens of thousands of images, associated metadata, and Metashape project files. Accordingly careful and methodical data management is essential to avoid data loss and errors.*

Post-dive workflow commences when divers have completed the 'in-water workflow' (SOP 1) and have washed down camera equipment (see SOP 1). Images from camera memory cards are then copied to a computer following the folder structure recommended in Table 7. While images are downloading, collected metadata and GPC measurements should be entered into their respective locations in the master access database file (Fig. 4, Table 7). At this time, Metashape projects can also be created, and imagery imported to create one project per 'plot' (72 sq. m area, DSLR imagery) and one project per 'zone' (~1500 sq. m area containing all four 'plots', GoPro imagery) using the file naming conventions described in Table 7.

It is recommended to conduct the initial stages of 3D model processing in Metashape (described in Table 8) to assist with in-field QA/QC and to optimize post-field processing workflow. In-field processing steps are designed to help identify image collection errors (e.g. incorrect camera settings or swim pattern), data-management errors (e.g. incorrect file storage or file deletion) and identify if re-imaging of plots is required (Table 8). At the completion of each day all data should also be backed-up to an appropriate number of internal and external drives using a back-up software (see steps in Table 7) to ensure data integrity prior to clearing camera memory cards.

Table 7. Post-imaging data management and pack down (reproduced from SOP 1 (Gordon et al. 2023), Table 1).

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 are not automatically named by camera or sorted into folders by imaging period. Accordingly, care should be taken to check capture time, rename downloaded files (e.g. GP1…) and keep track of SD card numbers to help with clarity during downloading	
Database	Enter sample event information (Fig. 4a)	• 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. 4b)	• 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. 4c,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. 4d)	Depth csv template: EcoRRAP Data Management Templates Scaling coordinates and error details in Appendices 2,3,4
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 - Use the 'local' version of the script if processing locally on a single computer (most common when in field) or the 'network' version if jobs are being sent to a group of networked computers, servers, and/or HPC nodes (most common when in office) • 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 • In Metashape, navigate to Tools > Run Script (or Ctrl + R) to run script • When prompted, click the Browse button (folder icon) and navigate to and select the version of 'Chain 1' required • 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 8	**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 to 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 completed by one person to minimise errors due to miscommunication. Use of back-up software is very helpful but can propagate deletions throughout copies so use with care!

QA/QC check and log	Record processing progress in log	• Once Chain 1 processing is complete, check for issues/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 (Fig. 5) - A sufficient number of photos are enabled (see Table 8) - Alignment is > 80 % of enabled photos - Sparse cloud shape is a realistic and representative of area imaged - The minimum number and error of markers is achieved (see Table 8) - The minimum number and error of scalebars is achieved (see Table 8) • If the above requirements are not achieved conduct troubleshooting (Appendix 5) and determine whether plots require re-imaging	Process log: EcoRRAP Data Management Templates

Table 8. Metashape processing steps involved in processing Chain 1 (reproduced from SOP 1 (Gordon et al. 2023), Table 1).

Job name	Job description	Settings used for DSLR and GoPro **(bolded if GoPro differs)**
Quality check	• Assesses the quality of photos and removes photos below the quality threshold • Disables, counts, and adjusts (if required) the quality threshold to retain the targeted number of photos • Begins using a quality threshold of 0.5 and reduces this value (if required) by 0.05 until the target minimum number of photos is reached or the minimum quality threshold is reached (0.35) • The quality threshold and number of photos prior to and after disabling is logged	• Target number of photos (to retain): - 2000 for 1 x DSLR 'plot', - 2000 for 1 x GoPro 'zone' (4 x DSLR plots • 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
Initial alignment	• Aligns photos to create a sparse-cloud of pixel positions in 3D space • See Appendix 5 for troubleshooting workflow if 'minimum alignment' is not achieved	• Accuracy: Lowest, **Medium** • 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’ threshold and: - Removes marker projections with ≥ ‘marker projection error’ pixel threshold, - Disables markers with projection numbers < ‘minimum marker projections’ threshold	• Target type: Circular Target 12 bit • Initial marker tolerance: 25 **(85)** • Secondary marker tolerance: 50 **(95)** • Marker projection error: 50 **(150)** • Minimum marker projections: 5 **(10)** • Filter mask: False • Inverted: True • No parity: False • Maximum residual: 5 • Minimum size: 0 • Minimum distance: 5
Import depths	• Imports marker X and Y coordinates, depth values (Z), and related accuracies into reference pane (CSV file saved in previous step, Table 7) • See Appendix 2 for marker accuracy values	

Add and check scale bars	• Adds scale bars based on marker number pairing and distances specified
	• Checks the number of scale bars is ≥ the ‘minimum scalebars’ threshold,
	if < threshold:
	  • Marker are re-detected at ‘secondary marker tolerance’
	  • Projection error tests are rerun
	  • Scale bars are re-added
	• Calculates the overall scalebar error
	• Checks overall scalebar error is < the ‘maximum scale bar error’
		• Minimum scalebars: 3 **(7)**
		• Maximum scalebar error (m): 0.01 **(0.02)**
		• Scaling coordinates and error details in Appendices 2,3,4

Warnings	• If alignment is ≤ 80 % ('minimum alignment' threshold) • If scale bar error is > the 'maximum scale bar error'
Generate log and save project file	• Automatically generates a processing log and deposits processing information in file

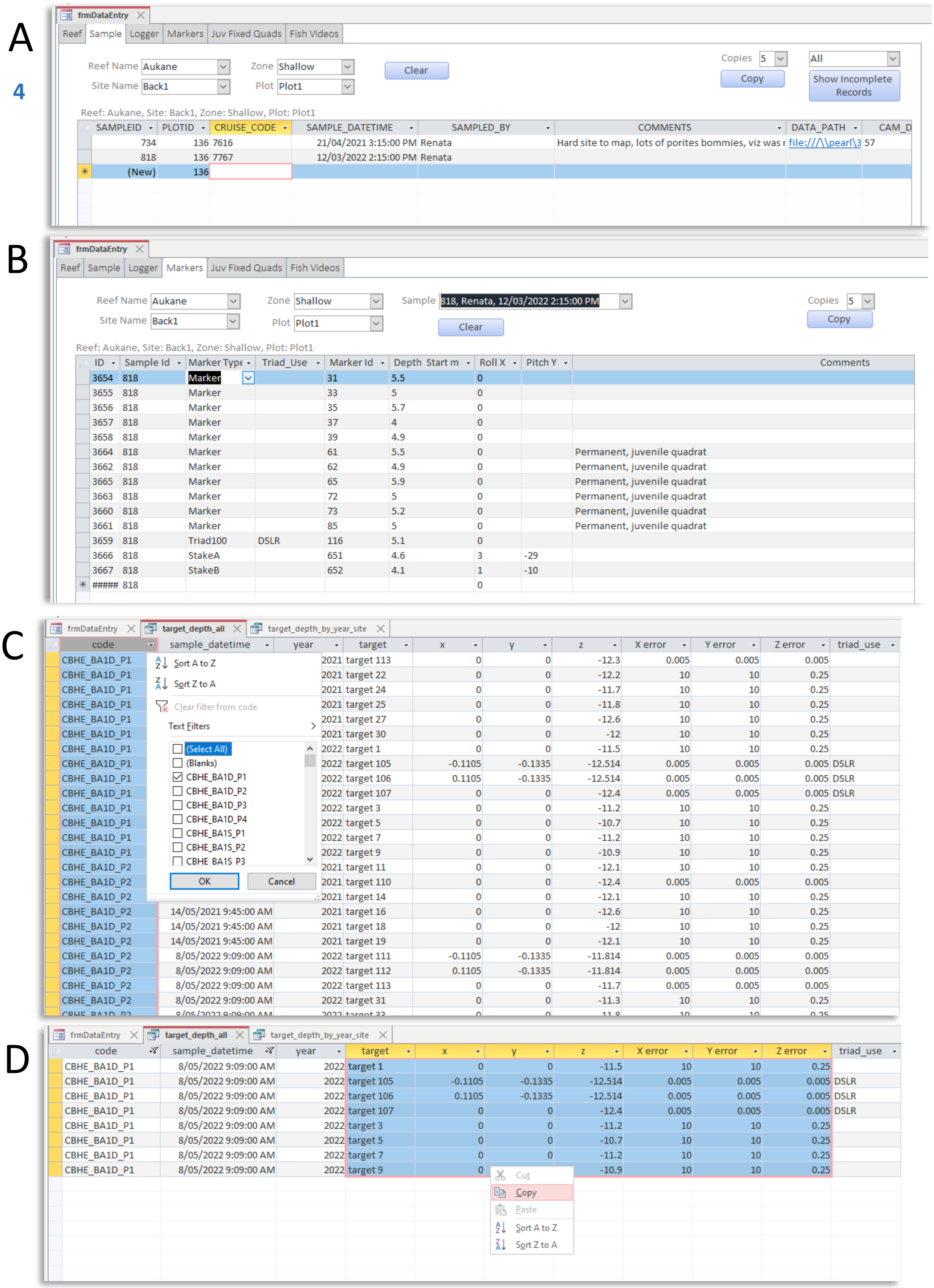


Figure 4. EcoRRAP database steps for: a) entering sample information; b) entering marker depth data; c) filtering marker depth information, and; d) extracting marker depth information to save as a CSV file for later import into Metashape (described in Table 7). Image: S. Gordon (reproduced from SOP 1 (Gordon et al. 2024), Table 1).

4.1 In-office model processing

'In-office' processing commences after all 'in-field' model processing steps are complete and users have access to network storage and/or increased computing power. If these resources are not available all steps can be completed on a local device, however processing time will be significantly longer. Furthermore, depending on the outputs required and intended applications, certain steps may be omitted (e.g. if orthomosaics are not needed then ArcGIS steps are not required). The current in-office processing steps are designed to create outputs ready and suitable for analyses and metric extraction described in SOP 3 (Table 1) and Section 3.7. All steps are described in Tables 9 and 10 and Figures 1-3. See Appendix 5 for troubleshooting information.

Note: Keep in mind the general processing considerations outlined in section 3.2 during in-office model processing.

4.2 Model co-registration

Model co-registration takes place following the completion of model processing Chains 1 and 2, after setting the orientation of 'reference' models, and exporting all textured meshes. Model co-registration involves: 1) importing 'reference' (T_1) and 'test' (subsequent timepoint, T_2…) models into the software CloudCompare; 2) co-registering models in 3D space; 3) exporting and saving the coordinate transformation matrix as a text file (.txt), and; 4) applying this transformation matrix to the 'test' project in Metashape to apply the model orientation in coordinate space. These steps are described in detail in Table 11 and Figs. 10 and 11.

Because co-registration can be relatively time consuming (10-20 minutes per model) It is important to take care when loading, saving, exporting, and applying files to avoid errors in model co-registration and output orientation (section 3.5).

Model co-registration is essential to ensure models of all time-points from the same reef area are positioned in the same 3D coordinate space. This enables changes to be directly compared over time accurately and effectively, e.g. growth of individual corals can be measured and tracked in 2D orthomosaics or 3D models (see SOP 3, Table 1). The co-registration method presented achieves a precision of 1.37 ± 16.55 mm (change < 0.0001%) for DSLR models across an extent of 72 m^2 (see Lechene et al. (2024) for a detailed examination co-registration error).

Note that slightly different co-registration procedures are required for DSLR and GoPro models. While DSLR co-registration may only require the use of spheres as reference objects, GoPro co-registration also requires the use of reef points to ensure accurate co-registration (see Table 11, Fig. 11). These differences improve co-registration over the larger spatial extent of GoPro models. See co-registration troubleshooting tips in Appendix 5.

Table 9. In-office model processing workflow.

Step	Part/consideration	Key tasks	Additional info
Transfer files	Save photos to AIMS network drive	• Use GoodSync (or alternative back-up software) to transfer photos from the date-level folder (EcoRAPP\data\DATE) of the field HDD to the following location in the network drive: \\pearl\3d-ltmp\EcoRRAP\data • Ensure to use a 'one-way' back up (not sync) to copy files	• GoodSync manual: GoodSync Tutorial
	Save Metashape projects to AIMS network drive	• Manually copy project folders from each date-level folder (EcoRAPP\projects\REEF\SITE\ZONE\DATE) of the field HDD the respective folder in the network drive: e.g. \\pearl\3d-ltmp\EcoRRAP\projects\REEF\SITE\ZONE	
	Save metadata to network drive	• Save the most recent copy of the database to \\pearl\3d-ltmp\EcoRRAP\database • Save any other trip files or metadata to the network drive and any other required Sharepoint locations - \\pearl\3d-ltmp\EcoRRAP\CopyOtherData_MasterSP\TripFiles - Teams: TripFiles	
Prepare network processing	Open Agisoft network monitor	• Connect to AIMS network host: meta-net-03.aims.gov.au *or* metashape-qmgr.aims.gov.au (same address) • Check current network queue is displayed after connecting	Internal link: 3D Modelling OneNote
	Check network preferences in Metashape	• Open Agisoft Metashape and check network preferences are correct • Go to: Tools > Preferences • Select the Network tab and ensure the following settings are selected: - 'Enable network processing' box checked - 'Host name' is 'metashape-qmgr.aims.gov.au' or 'meta-net-03.aims.gov.au' - 'Port number' is 5840 - The 'root' is set to the UNC path to PEARL: \\pearl\3d-ltmp	

Run chain	**Ref. models: 'Chain 2.1' (DSLR and GoPro)** **Subs. Models: 'Chain 2' (DSLR and GoPro)**	• Open project in Agisoft Metashape • Check previous steps have been completed by checking log and inspecting model • If first time using script: Read first lines of script to understand functionality and user input (open in script/text viewer) • Determine whether to run script on the Network (default) or Locally (on your personal computer). Routine processing should take place on the Network. • Navigate to Tools > Run Script (or press Ctrl + R) • Click the Browse button (folder icon) and navigate to and select script 'Chain 2.1' for reference models, and 'Chain 2' for subsequent model timepoints • Click 'no' to network processing regardless of the script selected • The script will automatically go through the steps described in Table 10 • Monitor progress of Chain 2 on the Network Monitor (can be > 12 hours to run)	• Note that for 'reference' models, Chain 2 is run in two sections: Chain 2.1 and 2.2 (Table 4). See more details below.
QA/QC	Check alignment and model quality	• If models do not achieve > 80 % alignment conduct troubleshooting (Appendix 5) • Visually inspect model for serious and minor mesh issues (Fig. 6) • Serious issues include if mesh shape: a) does not accurately represent reef shape; b) has a 'spliced' axis (multiple axes/planes of points colliding); c) has very large holes, or; d) has large sections missing (model does not fill bounding box) • Minor issues include if mesh has: a) small holes in corals or benthos; b) holes in branching coral thickets; c) holes at margins • If the mesh has serious issues record the problem in the Processing log and stop processing. Troubleshoot the model (see Appendix 5 for troubleshooting) • If the mesh has minor mesh issues: record information in processing log and continue processing	• Fig. 6 • Appendix 5
Reference models only: Set model orientation	**DSLR reference only:** Re-size and position bounding box	• Run script: 'ResizeRegion.py' • After script has run, the bounding box (grey oblong shape) will have changed size • Navigate to Workflow > Build Mesh, and select Sparse Cloud as the source (all other options as default) and make a mesh to check bounding box placement • Check that the bounding box is located in the centre of the plot. Refer to sphere trees as visual markers of plot location (Fig. 6a-d).	• Table 4 • Fig. 6

Reference models <u>only:</u> Set model orientation cont.	**<u>DSLR reference only</u>:** Re-size and position bounding box cont.	• If bounding box needs to be moved or rotated use the 'Move bounding box' and 'Rotate bounding box' tools (Fig. 6e,f). • Ensure to re-select the 'arrow' tool once bounding box adjustment is complete • Navigate to Workflow > Build Mesh, and select Sparse Cloud as the source (all other options as default) to re-make the mesh to check adjusted bounding box placement • Repeat process as required	**Note**: This step is best completed on a computer with good GPU capabilities due to long loading time and lag caused by large models
	DSLR & GoPro reference: Orient model to horizontal layout using 'Orient tool'	• Click the 'reset view' button (box with four arrows in central top toolbar) • Visually determine the bottom edge of the plot (picket A on the left), generally the deeper side of the plot • Open on-screen protractor app (e.g. PicPick or other application) and measure the angle between a line drawn parallel with the bottom edge of the model extent and the horizontal guide (Fig. 7a,b) • Enter this value in the input cell of the 'Orient tool' : Model_rotation_tool_JHarianto_V2.xlsx (Fig. 7c) • Ensure the value is entered as a negative or positive value depending on whether a clockwise or anti-clockwise rotation is required, respectively (Fig. 7c) • Open the reference pane of the Metashape project and identify the type of triad used by the x, y, coordinates entered (see key in Orient tool tab) and/or by visually examining the triad • To view triad: Right click a triad marker in the reference pane and select 'Sort photos by marker' and double click the photo to load • Copy the output x and y values for the left and right triad marker from the Orient tool then double click and paste these values to the respective boxes in the reference pane (Fig. 7d) • Click the 'Refresh' button then then 'Reset view' button in the reference pane to update model orientation • You should then see the model move to a new position • Repeat these steps if correct model orientation is not achieved	• Fig. 7

GoPro reference only: If all plots imaged together, split into Plots 1&2 and 3&4	• Right-click model and select 'Duplicate model' twice to generate 3 x copies • Rename models to 'WholeArea', 'P1P2', and 'P3P4' (Fig. 8a) • Select model 'P1P2' and crop the model using the rectangular selection tool and delete key to exclude all areas of the model from the start of P3 to the end of the area (Fig. 8b,c) • Select 'no' when asked if you want to remove markers • Repeat for model 'P3P4' removing all areas of the model from the end of P2 to the beginning of the area (Fig. 8d,e)	• Fig . 8 **Note**: Use the location of markers to estimate plot extents when cropping
DSLR & GoPro reference: Visually inspect plot to determine if slope ≥ 45°	• If the plot represents a section of reef that is a wall, steep slope, or does not suit top-down orientation, the model needs to be rotated to a 60° orientation	• Fig. 9 **Note**: A 60° rotation was

		• This can be determined visually for most plots by clicking the 'reset view' button and examining reef structure and whether most corals are directly visible from this orientation (Fig. 9a,b) • If unsure, use an on-screen protractor tool (PicPick) to measure the general angle of the slope relative to horizontal axis • Record selected orientation in log ('TopDown' or '60°')	selected to standardise model view for steep environments where a top-down orientation was not suitable (i.e. majority of corals obscured or not visible)
	DSLR & GoPro reference: **If slope ≥ 45°:** Duplicate chunk and rename '_60D'	• Right-click chunk and select 'Duplicate chunk' • Right-click chunk, select 'rename' add '_60D' to end of chunk name	
Reference models only: Set model orientation cont.	DSLR & GoPro reference: **If slope ≥ 45°:** Rotate model 60° using Geobit helper tool DSLR & GoPro reference: **If slope ≥ 45°:** Rotate model 60° using Geobit helper tool cont.	• Run Geobit helper tool script (Fig. 9c) • Navigate to Tools > Run Script (or press Ctrl + R) • Click the Browse button (folder icon) and navigate to and select script ' PS170_geobit_helper.py' • Click 'no' to network processing • A new tab called 'Helpers' will now be displayed beside 'Help' on the top toolbar of Metashape • Navigate to Helpers > Geobit Transform • In the 'View' tab, enter '60' into the 'Step value' box and click the arrow corresponding to the X or Y axis, depending on model orientation (generally this is the right 'X' arrow, Fig. 9d). This will not change the model rotation, so can be changed multiple times and reset by clicking the 'reset view' button • Assess whether a 60° model rotation is correct and more suitable than top-down orientation for the plot (i.e. more corals are directly visible)(Fig. 9d) • If 60° model orientation is appropriate, click the 'Reset view' button • If 60° model orientation is not appropriate, repeat this process trying alternate buttons (i.e. Y instead of X) and re-assess • If 60° orientation is less suitable than top-down, click the 'Reset view' button and continue to the export mesh step (skip next four points)	**Note**: There is no functionality to 'undo' transformations made using in the 'Object' tab of the Geobit helper tool. To avoid errors, ensure the project is saved prior to manipulation and

		• In the 'Object' tab, click 'OK' to the warning, enter a value of 60 into the 'Step Value' box and click the left or right arrows on Omega, Phi, or Kappa buttons (corresponding to X,Y or Z, generally this is the left 'Omega' arrow)(Fig. 9d). • In the 'Region' tab, click the 'Align to view' button to adjust the bounding box (Fig. 9e), the grey frame of the bounding box should now move around the model • Close the Geobit helper window and click the 'Reset view' button to check the 60^{o} orientation has been saved	exit without saving to cancel if required
Reference models <u>only:</u> Run chain	DSLR & GoPro reference: **Run Chain 2.2**	• If first time using script: Read first lines of script to understand functionality and user input (open in script/text viewer) • Determine whether to run script on the Network (default) or Locally (on your personal computer). Routine processing should take place on the Network. • Navigate to Tools > Run Script (or press Ctrl + R) • Click the Browse button (folder icon) and navigate to and select script 'Chain 2.2' • Click 'no' to network processing • The script will automatically go through the steps described in Table 10 • Monitor progress of Chain 2.2 on the Network Monitor (can be > 12 hours to run)	
All models: Export mesh	Export textured mesh (.ply)	• Once jobs are completed, re-open project and examine mesh • Record progress in processing log and make note of any mesh issues (Fig. 5) • Right click the model in the workspace pane and select 'Export model' • Navigate to the export location: //pearl/3d-ltmp/EcoRRAP/Outputs/TexturedMeshes/ • Save the mesh as a '.ply' with the same name as project file with the suffix '_ref' for 'reference' models and '_unr' for 'test' or 'unregistered' meshes (ie. REEF_SITEZONE_PLOT_YEAR_ref, or REEF_SITEZONE_PLOT_YEAR_unr) • Click 'no' to network processing • Mesh should take < 2 minutes to export	

Table 10. Metashape Professional v 1.7.6 processing steps involved in processing Chain 2 (Chain 2.1, 2.2). Note: For 'reference' models Chain 2 is run in two parts (Chain 2.1 and 2.2) with manual steps and individual scripts run between (see Table 9 for details). Jobs that are only present in Chain 2.1 and 2.2 are shown in blue text.

Chain no.	Job name	Job description	Settings used (DSLR and GoPro, **(bolded if GoPro differs)**
Chain 2.1	High quality alignment	• Resets initial camera alignment and re-aligns points at high quality	• Accuracy: High • Generic preselection: Yes • Reference preselection: Source • Key point limit: 40,000 • Tie point limit: 0 • Exclude stationary tie points: Yes • Guided image matching: No • Adaptive camera model fitting: No • Reset alignment: Yes • Minimum alignment: 80 %
	Calculate scalebar error	• Calculates and checks scale bar error as per Chain 1, step 4 • Stores results in a list that is printed at script completion	
	DSLR Chain 2.1: Resize bounding box	• Resizes bounding box to size of required 'plot' size	• DSLR plot size: 12 x 6 x 10 m (x, y, and z, respect
Chain 2.2	Duplicate chunk	• Duplicates chunk to preserve unedited point cloud (failsafe)	
Chain 2.2 cont.	***DSLR Chain 2.1:*** Crop point cloud	• Removes all sparse cloud points outside bounding box	
	Initial camera optimization	• Performs an adjustment procedure using coordinates, depths, scale bars, and corresponding accuracies, to	

	refine exterior and interior camera orientation parameters and tie-point coordinates	
Filter and re-optimize cameras	• Filters point cloud by: o Selecting points with a reconstruction uncertainty > the ‘maximum reconstruction uncertainty’ and > ‘minimum projection accuracy’ o Checking if the selected points > ‘maximum point cloud percentage’ and deletes points up to the ‘maximum point cloud percentage’ • Re-optimizes cameras • Performs 5-step loop of reprojection error improvement (repeatedly removing the worst ‘percentage point cloud removal’ of current point cloud) by: o Checking reprojection error before each iteration o Optimising after each iteration o Using the ‘target reprojection error’ o Loop stops when either the target value is reached, or point cloud size falls < ‘minimum point cloud size’ of the original size (whichever comes first) • Performs final full optimisation of cameras	• Maximum reconstruction uncertainty: 10 **(50)** • Minimum projection accuracy: 3 **(10)** • Target reprojection error: 0.5 • Maximum point cloud percentage: 50 • Percentage point cloud removal: 10 • Minimum point cloud size (%): 30
Build depth maps	• Generates multiple pair-wise ‘depth maps’ from overlapping image pairs considering their relative exterior and interior orientation parameters. These are merged into a combined depth map of the plot from which a mesh can be made.	• Filtering: Mild • Reuse depth maps: No • Maximum neighbours: 40 • Maximum group size: 100
Build mesh	• Reconstructs a polygonal mesh model based on depth maps data	• Source data: Depth map • Surface type: Arbitrary (3D) • Depth map quality: Medium **(High)** • Facecount: High

		• Custom facecount: 200,000 • Interpolation: Enabled (default) • Depth filtering: Mild • Point classes: All • Calculate vertex colours: Yes
Build texture	• Builds texture for the model	• Texture type: Diffuse map • Source data: Images • Mapping mode: Generic • Blending mode: Mosaic (default) • Texture size: 8192 • Enable hole filling: Yes • Enable ghost filter: No

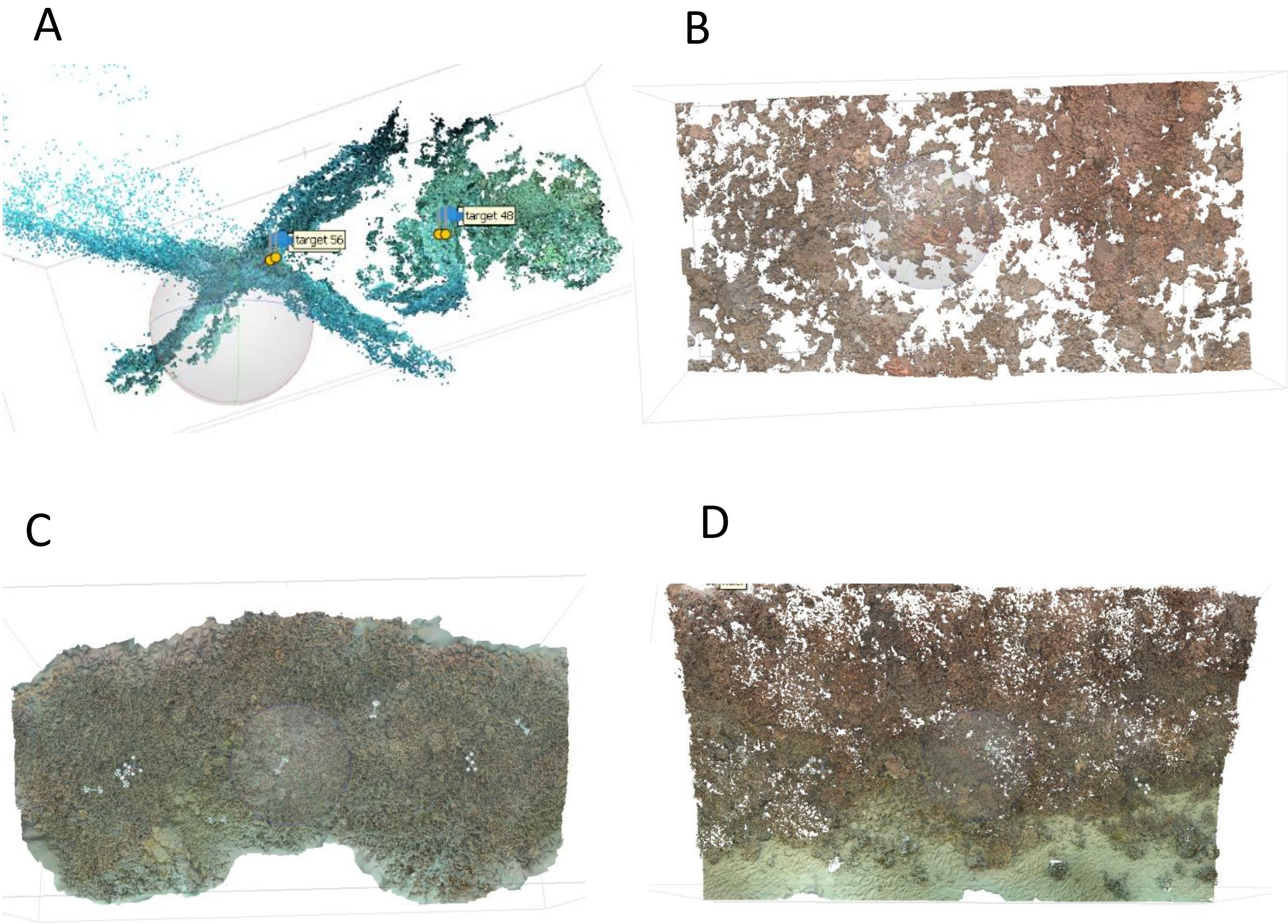


Figure 5. Examples of serious alignment and mesh (digital surface model, DSM) issues: a) an aligned point-cloud with a deformed reef structure showing multiple intersecting 'spliced' axes likely caused by errors in marker detection or image collection; b) a DSM with significant holes in mesh, potentially due to imaging in poor visibility or the presence of moving benthic cover; c) a DSM with large gaps at the edge of the area (not rectangular in shape) likely caused by the diver not swimming wide enough when imaging the plot; d) a DSM with consistent holes throughout a branching coral thicket. Depending on the cause of these issues they may/may not be able to be solved through processing, however all should be examined to determine the cause of the issue.

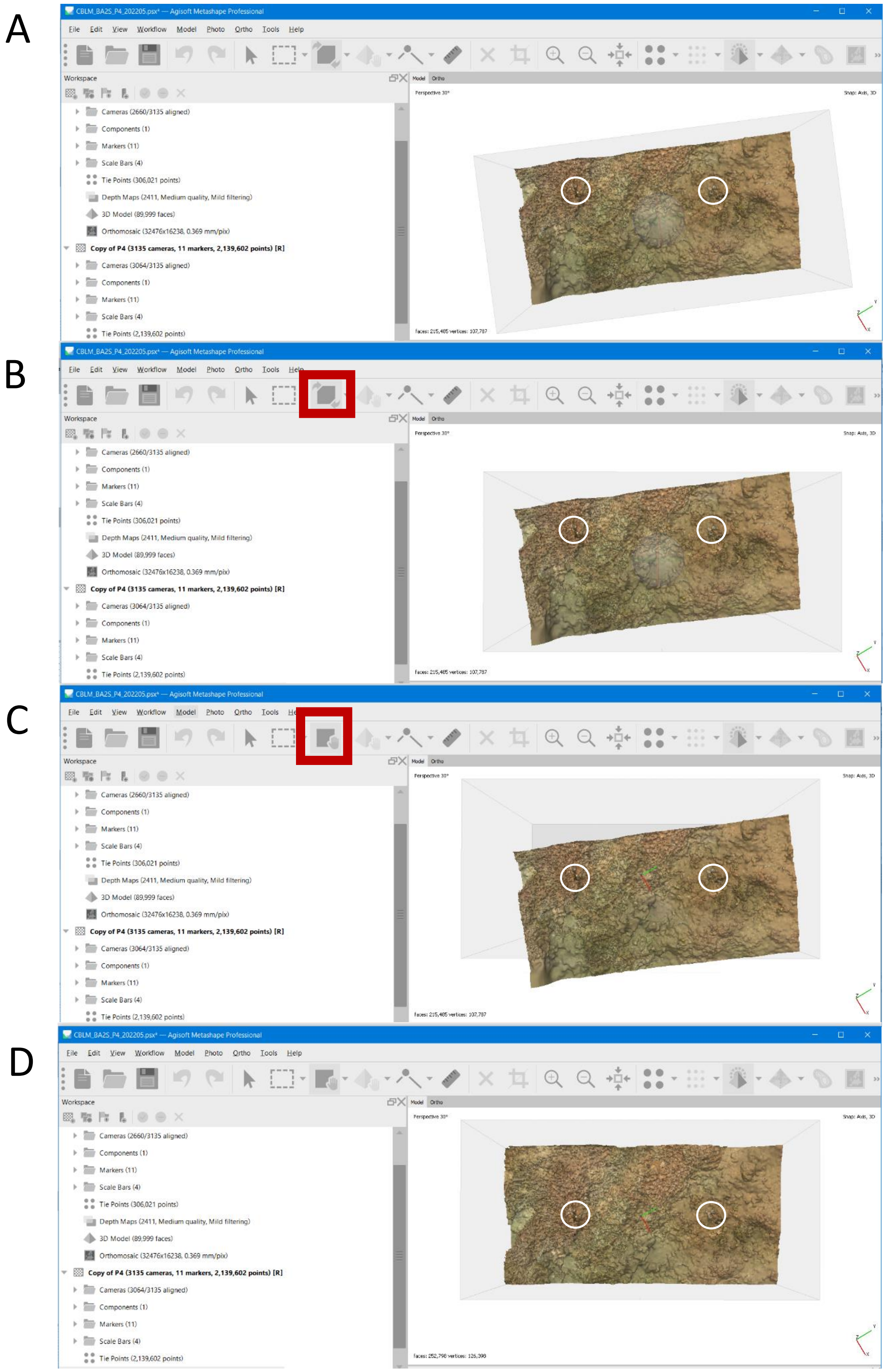

A
B
C
D
CBLM_BA2S_P4_202205.psx* — Agisoft Metashape Professional
File Edit View Workflow Model Photo Ortho Tools Help
Workspace
Model Ortho
Perspective 30°
Cameras (2660/3135 aligned)
Components (1)
Markers (11)
Scale Bars (4)
Tie Points (306,021 points)
Depth Maps (2411, Medium quality, Mild filtering)
3D Model (89,999 faces)
Orthomosaic (32476x16238, 0.369 mm/pix)
Copy of P4 (3135 cameras, 11 markers, 2,139,602 points) [R]
Cameras (3064/3135 aligned)
Components (1)
Markers (11)
Scale Bars (4)
Tie Points (2,139,602 points)

Figure 6. Visual check and adjustment of bounding box placement, note star-pickets are circled in white: a) Initial bounding box not centred on plot; b) bounding box rotated; c) bounding box moved; d) mesh re-made to new bounding box location. Note: Red square shows the location of the ‘rotate’ and ‘move’ bounding box tools.

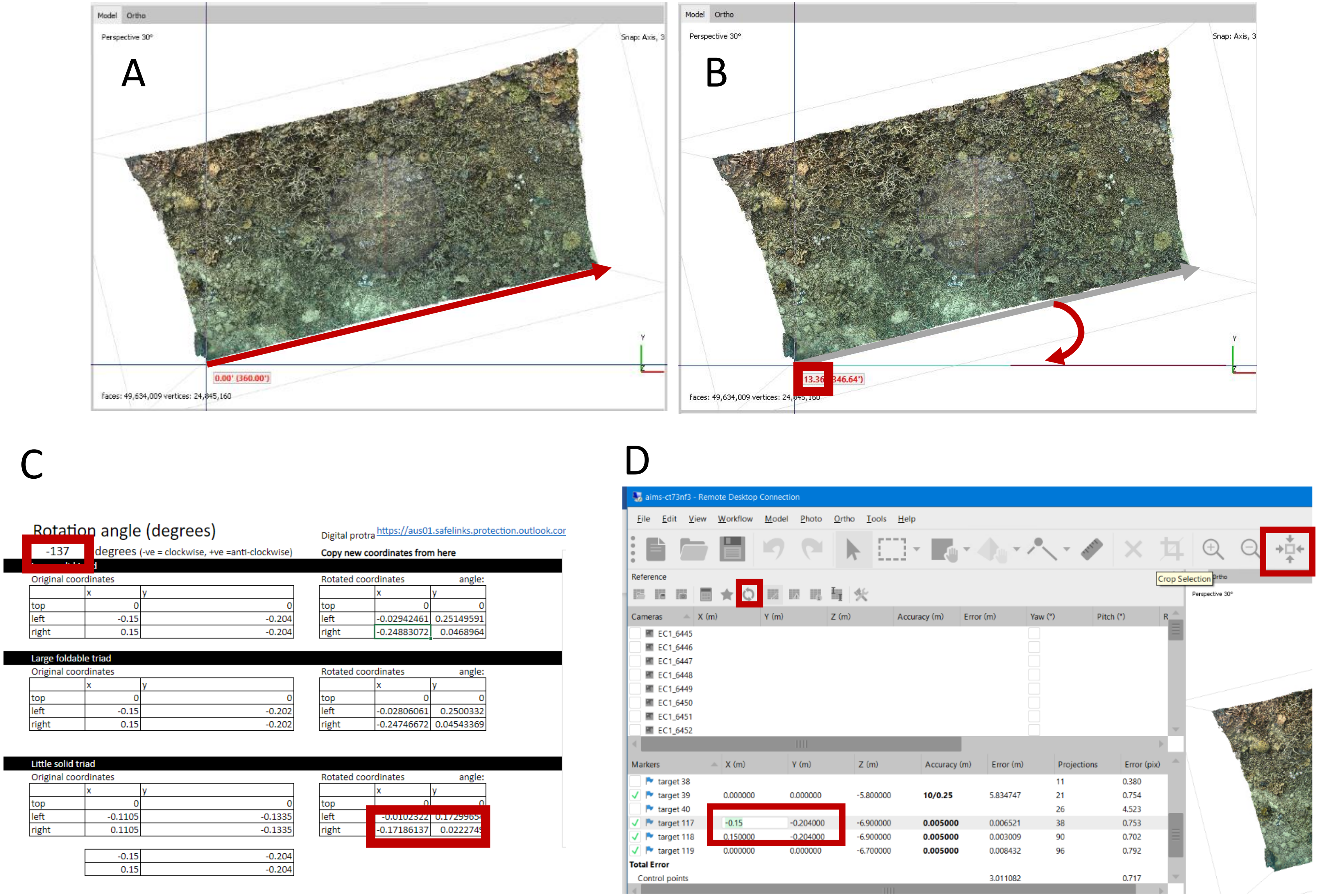


Figure 7. Measuring and adjusting model orientation using onscreen protractor (PicPick) showing: a) line drawn perpendicular to bottom model extent; b) angle measured from line to horizontal guide; c) angle entered into Orient tool (circled left) and X and Y outputs to be copied from (circled right), and; d) X and Y coordinates copied from orient tool are entered into triad marker coordinates in reference pane (cells circled) then the 'refresh' button (circled left) and 'reset view' button (circled right) are clicked to update the model.

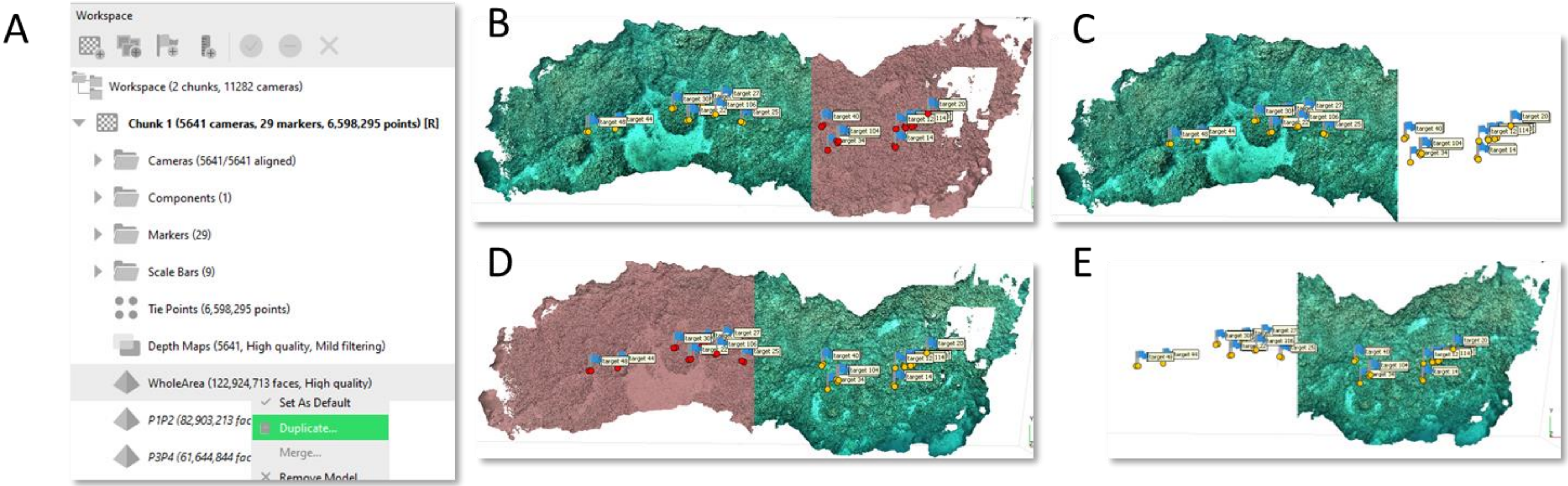


Figure 8. Steps involved in duplicating and splitting GoPro models between plots: a) right click model and select 'Duplicate,' then rename as shown to 'WholeArea', 'P1P2', and 'P3P4'; b and c) select and delete model areas of plots 1 and 2; and d) Duplicate the model locally; e) select the model that was duplicated and select the 'Undo' botton. Once the previously deleted area appears, select 'Crop Selection' to keep plots 1 and 2. Note: locations of markers and sphere trees are used as guides to indicate plot location.

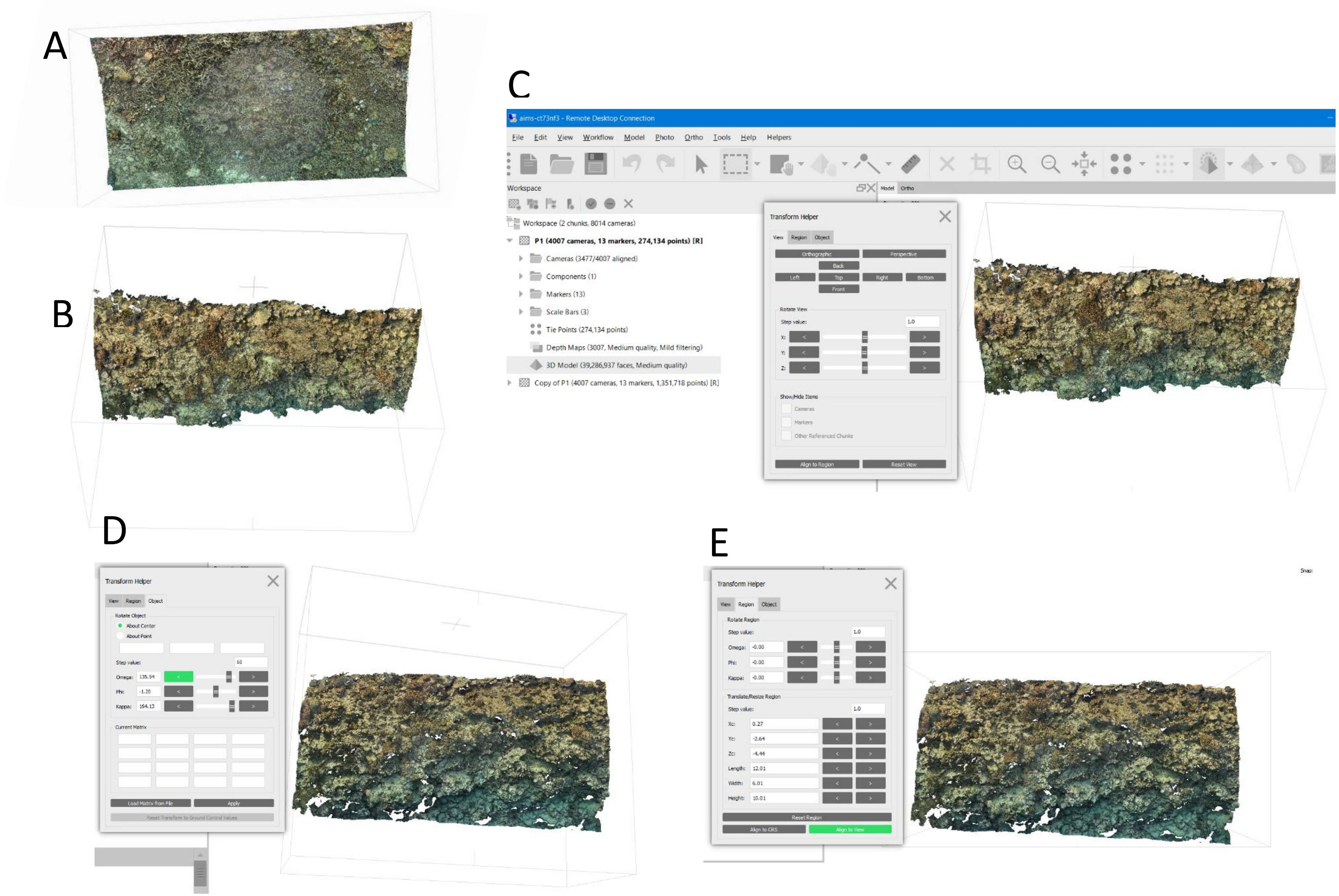


Figure 8. Assessing and adjusting model orientation: a) well-suited top-down oriented model; b) badly suited top-down oriented model; c) Geobit helper tool; d) 60 model rotation, and; e) bounding box adjustment.

Table 11. Model co-registration workflow.

Step	Part/consideration	Key tasks (DSLR and GoPro, **(bolded if GoPro differs)**	Additional info
CloudCompare	Import 'reference' and 'test' (subsequent timepoint) meshes	• Open CloudCompare • Navigate to File > Open > Select .ply models files (or drag and drop into CloudCompare) • In the 'File Open dialog' leave all the fields as default and click 'Apply' (or 'Apply all' if multiple entities are selected) • **Note**: GoPro models should be co-registered as P1P2 and P3P4. Co-registering models containing all plots (P1,2,3,4) results in unacceptably-high error	Figs. 10,11
	Rename reference mesh	• Unclick the mesh view check-box in left pane tree to speed up loading time (Fig. 10a) • Rename the 'reference' mesh by double clicking its name in the left pane • Rename the 'reference' mesh to 'ref' to avoid confusion in following steps (Fig. 10b)	
	Transform meshes into point clouds	• Select both meshes in the left pane (CTRL + click both)(Fig. 10c) • Click 'Sample points on a mesh' button • Change the point density to for meshes 100,000 **(50,000)**, click OK (Fig. 10c) • You will now see two *.sampled point clouds in the left pane (Fig. 10d)	
	Select both point clouds and click alignment by spheres	• Select the reference and the 'test' (subsequent timepoint) sampled clouds (CTRL+ click) • Click the 'Align by picking points' tool (Fig. 10e) • In the Entity Selector dialog, select the 'test' point cloud to be registered (referred to as 'aligned' or 'to align', depending on the CloudCompare version) and click OK (Fig. 11a) • In the point-pair registration dialog (right top corner by default), click the white sphere icon and set the search radius to r = 0.05 and RMS to RMS < 100 % (Fig. 11b)	
	Click the centre of the 'reference', then 'test', spheres	• Visually check that both point clouds have the same number of spheres reconstructed • Rotate the cloud so the sphere tree is clearly visible without the presence of obscuring shapes in the foreground (left-click to rotate, right-click to pan, middle-click to zoom in and out	

<table>
<tr><td>CloudCompare cont.</td><td>Click the centre of the ‘test’, then ‘reference’, spheres cont.</td><td>

Check or un-check the ‘Auto-update zoom’ box in the bottom left corner of the sphere alignment dialogue box to turn on/off automatic model centring when switching between models
Starting with the reference point cloud (uncheck show ‘to align’ entities to avoid confusion between the point clouds), click the centre of the spheres (Fig. 11c)
A new entry will appear for each sphere centre picked in the corresponding table and a colour sphere will appear (Fig. 11c)
Keep picking the centre points for the following number of spheres:
<u>- DSLR: All spheres present</u>
<u>- GoPro: 2 spheres per tree, total 8 spheres per model</u>
Repeat this process for the ‘to align’ point cloud, <u>ensure you remember the order you select the spheres, it must be the same for both models</u>
Tips:
- Delete spheres by clicking the red cross at the end of the table. To remove a single sphere, click the red cross and select ‘No’ to remove equivalent point. To remove a pair of spheres, click the red cross and select ‘Yes’ to remove equivalent point
- For GoPros, if spheres are not completely reconstructed, you can increase the default point size to make it easier to identify the spheres. Default point size options appear on the top left of the 3D view window

</td><td>Figs. 10,11</td></tr>
<tr><td></td><td>For GoPro only: Add additional 4 points manually</td><td>

Once 8 sphere-pairs have been selected click ‘align’
For GoPro co-registration, add an additional 4 x points on the reef by de-selecting the ‘sphere icon’ (Fig. 11b) and dropping points (Fig. 11e)
Drop points on clearly identifiable features present on the reef located above and below the centre of plots 1 & 2 and 3 & 4 (Fig. 11e)
The addition of these points helps improve GoPro model co-registration over large areas

</td><td></td></tr>
<tr><td>CloudCompare cont.</td><td>Check co-registration</td><td>

Once all pairs have been selected click ‘align’
CloudCompare will give a view of the registered point clouds, RMS (value in top-centre of window), and error of each point pair (in table),
Visually check the co-registration for:
- How well the two models are aligned (e.g. are corals in the same location?)

</td><td></td></tr>
</table>

CloudCompare cont.	Check co-registration cont.	- The model RMS ('root mean square,' the overall distance between clouds) - The error of each point pair ('Error' in the top right table) • If one or several pairs are not well aligned (e.g. if sphere trees have moved) variation in their position in 3D space will be visible and their Error will be higher. This will negatively influence the overall co-registration (see screenshots below) • Delete point-pairs that are not well aligned and click 'yes' to 'remove equivalent point' to remove the pair. As a general rule, the RMS and point pairs should have an error of: - **< 0.04 for DSLR model co-registration** - **< 0.07 for GoPro co-registration** • Repeat this process, adding/removing point pairs until the above requirements are met, see Appendix 5 for troubleshooting. Aim to keep a minimum of 3 sphere-pairs in total for DSLRs and 4 sphere-pairs for GoPros, and at least one pair on each tree • **If sphere trees and starpickets have moved significantly between timepoints, or co-registration error needs to be improved, additional benthic points can also be added during DSLR co-reg (as per GoPro steps) and spheres can be removed as required** • Once co-registration looks visually suitable and the above error values are achieved, click 'align' again and conduct a final check on visual model alignment, RMS, and pair error	Figs. 10,11
	Apply co-registration	• When satisfied, validate the co-registration by clicking the green tick. The current registered point cloud can be reset by clicking 'reset' • Once applied, CloudCompare will display the final RMS and transformation matrix • **Note**: this information will also appear in the Console and the matrix will also be displayed in the Properties when selecting the registered point cloud in the left pane	
	Export transformation matrix	• Copy and save the transformation matrix into a text document • Select the 'test' (aligned) model mesh in the left pane • Navigate to the left Properties pane > Scroll and click on the Transformation matrix tab > Export tab > select Clipboard (the console will show it has been 'copied to clipboard') • Open an empty text editor page (e.g. Notepad) and click 'Paste' to input the matrix • The matrix should contain 16 numbers in a 4 x 4 arrangement • Save the file under the name of the model to be applied to as a .txt file	

Metashape	Open 'test' (non-reference) Metashape project	• Open Metashape project to be co-registered • Select the chunk to be registered (double-clicked and bolded) • Ensure the chunk is duplicated and re-named as '_60D' if reference model has been rotated (if rotated, there should be chunks named '_TopDown' and '_60D')
	For GoPro only: Duplicate chunks	• Note: Transformation matrices will be ***applied to all models with in a chunk.*** Since multiple GoPro models are present within a chunk (P1P2, P3P4, WholeArea) chunks need to be duplicated to ensure there is one chunk per model before applying transformations • Right click the chunk with models to be co-registered and select 'Duplicate chunk' • Once complete, rename the chunk relative to the model to be co-registered (e.g. 'P1P2', or 'P1P2_60Deg') • Delete the duplicate model not being used from the chunk (e.g. Model P3P4 if co-registering P1P2) by right-clicking the model and selecting 'Remove model' • Note: Models of the 'WholeArea' can stay within chunks
	Run 'Chain 3'	• Navigate to Tools > Run Script (or press Ctrl + R) • Click the Browse button (folder icon) and navigate to and select script 'Chain 3' • Click 'no' to network processing • When prompted, navigate to and select the model transformation matrix where it is saved, e.g. \\pearl\3d-ltmp\EcoRRAP\outputs\TransformationMatrixes
	For DSLR only: Specify bounding box reference file	• **For DSLR only:** When prompted, navigate to, and select, the location of the current project and the reference project to specify bounding box extents • When script is running, the current and reference bounding box projects will load, before returning to the original project. • Once script is applied (instantaneous) model orientation will visibly change
	For DSLR only:	• Once script is applied model bounding box (as well as model orientation) will visibly change

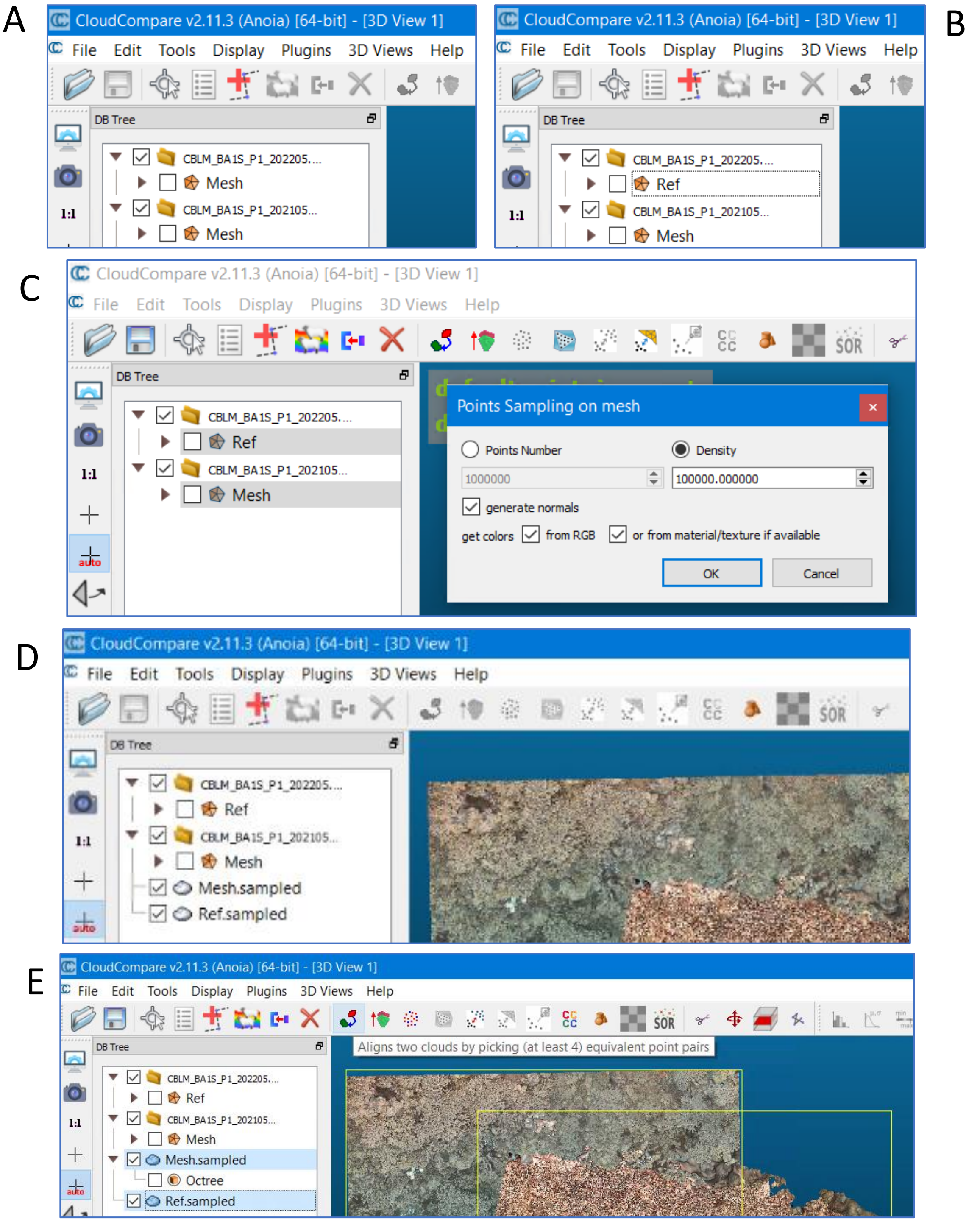


Figure 9. Steps for model co-registration in CloudCompare: a) import meshes; b) rename reference mesh, c) subsample mesh; d) subsampling completed; e) select meshes and click align tool (green and red sphere icon). Steps are continued in Fig. 11.

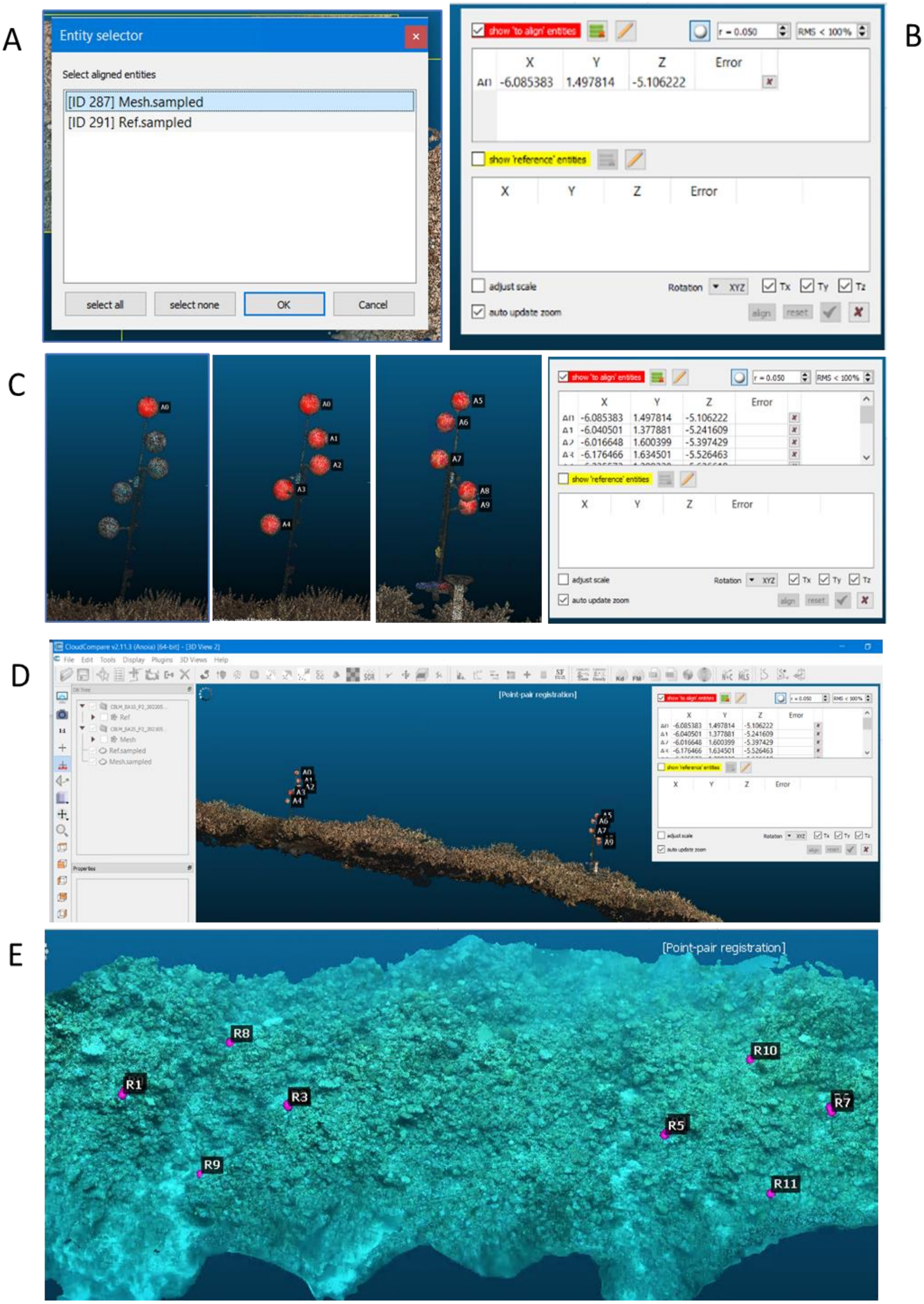


Figure 10. Steps for model co-registration in CloudCompare, continued from Fig. 9: a) select 'test' model as 'aligned entity'; b) select sphere icon and set 'r' to 0.050, and RMS to 100; c) click 'test' spheres in order from top to bottom of each tree; d) repeat for 'reference' spheres, making sure to select spheres from both meshes in the exact same order, and; e) GoPro model showing location of selected spheres (R1-7) and additional benthic points (R8-11) used for model co-registration of two plots.

4.3 Output generation and post-processing

4.3.1 Output generation

Once models have been processed, co-registered, and set to the appropriate orientation, the final 3D models can be exported 2D orthomosaics can be generated and exported. These final output generation and export steps are described in Table 12.

All EcoRRAP final model output are available via AIMS data servers in the following locations:

- 3D models
  - EcoRRAP Digital Surface Models | AIMS Data Repository | aims.gov.au
- 2D orthomosaics
  - EcoRRAP Benthic Orthomosaics | AIMS Data Repository | aims.gov.au

4.3.2 Output post-processing

Depending on the intended use of final 3D models and 2D orthomosaics some output post-processing steps may be required (see Table 12, Fig. 12, Appendices 6,7). For example, the following steps are only required if outputs are to be used for:

- **Orthomosaic annotation in Taglab**

  The current EcoRRAP workflow involves annotation of 2D orthomosaics within the software Taglab (Pavoni et al. 2021). This workflow is described in SOP 3: Annotation and metric extraction (Table 1, Fig. 1). Taglab requires that orthomosaic pixel extent is identical between orthomosaics of different timepoints. Although the current workflow produces model with identical coordinates, and for DSLRs identical bounding box extents, often this does not translate to identical orthomosaic pixel extents once generated. Accordingly, prior to use in Taglab, orthomosaics are clipped to the same pixel extent in ArcGIS using the 'Extract by mask function' (see Table 12, Fig. 12). This step is therefore not required in any application where orthomosaic pixel extent does not need to be identical between timepoints.

- **3D model upload to SketchFab**

  The current EcoRRAP workflow also involves uploading some models to the EcoRRAP SketchFab page (3D model collections by EcoRRAP (@AIMSEcoRRAP) - Sketchfab. The purpose of uploading models to SketchFab is to increase accessibility and visibility of EcoRRAP models to the public and potential collaborators. Note that models housed on SketchFab are of reduced file quality and size, therefore collaborators wanting to extract data from these models should request the full-size files be shared. Before uploading to SketchFab models require reduction in file quality/size (called 'decimation') needs to be completed, these steps are described in Appendix 6.

- **Colour correction of GoPro orthomosaics**

  While DSLR models images are currently colour-corrected using in-camera in-water white balancing techniques (see SOP 1) in the EcoRRAP workflow, in-camera white balance is not effective for GoPros. Accordingly, until improved colour correction workflows for imagery are incorporated into the EcoRRAP workflow (e.g. using SeaThru algorhythms, (Akkaynak & Treibitz 2019)) it is recommended to colour correct GoPro orthomosaics after generation. These steps can be completed using a number of platforms, however an example of this is provided for Photoshop in Appendix 7.

4.4 Metric extraction

A very wide range of ecologically informative data can be extracted from the final 2D and 3D outputs generated by the current EcoRRAP 3D processing workflow. The current workflow was primarily designed to enable the extraction of data relating to: 1) 2D benthic community data (e.g. benthic community composition and benthic cover); 2) 2D taxa demographic data (e.g. growth and mortality rates of benthic taxa); and 3) 3D benthic complexity data (e.g. surface area and rugosity)(Fig. 1). The workflow used to generate this data is detailed in 'SOP 3: Annotation and metric extraction' for all 2D metric extraction and section 3.7.1 for 3D complexity metric extraction steps.

In addition to the above data, the current 2D and 3D model outputs can also be used to generate data on 3D taxa demographic data, spatial landscape (seascape) ecology, and many other ecological metrics. As EcoRRAP techniques and data extraction workflows are developed they will be incorporated into the current document and internally within the AIMS 3D Modelling Teams page here. For more information regarding 'Next steps' see Section 4 'Next steps and additional resources'.

4.4.1 3D Complexity metric extraction

The process described below is the current technique used by EcoRRAP to extract 3D complexity metrics from models (.ply). Steps and files presented here have been developed by Mitch Bryson ('ComplexityMetrics' tool), Ryan Krensel ('MetricsCalc' tool), Renata Ferrari and Will Figueira (integrated workflow and 'Complexity bat file builder'). For full details, method explanation, and background information please see documents in the AIMS GitHub and internally in the AIMS Tool explainer and Source files folders. Any use of this technique and resultant extracted metrics should reference these authors accordingly.

A detailed workflow description for applying the above 3D complexity metric extraction tools to EcoRRAP 3D model outputs (in specified folder structures) is provided in section 3.7.1. For updated information and AIMS-specific details see internal 3D Modelling Sharepoint page here.

.

Table 12. Final 3D and 2D output generation and export steps.

Step	Part/consideration	Key tasks (DSLR and GoPro, **(bolded if GoPro differs)**	Additional info
Export final 3D model	Export textured mesh (.ply)	• Open Metashape project • Right click the Model to be exported in the workspace pane and select 'Export model' • Navigate to the export location: //pearl/3d-ltmp/EcoRRAP/Outputs/TexturedMeshes/ • **For reference models:** Save the mesh in *.ply* format under the project file name (ie. REEF_SITEZONE_PLOT_YEAR) with the suffix '_ref' within the Reference meshes subfolder • **For coregistered non-reference models**: Save the mesh in *.ply* format under the project file name (ie. REEF_SITEZONE_PLOT_YEAR) within the Co-registered meshes subfolder • Click 'no' to network processing • Mesh should take < 2 minutes to export	
Generate orthomosaic	Process orthomosaic	• Check for missing photos before orthomosaic generation • Right click any photo and select 'Check path,' and 'Entire workspace' • A dialogue box will then check file paths and either confirm no files are missing or identify missing photo files (see Appendix 5 for troubleshooting if files are missing) • Check network processing preferences are correct • Navigate to Workflow > Build Orthomosaic • In the Orthomosaic window: • Select : Planar (Type), Top XY (Project plane) • Check the refine seamlines box **(leave un-checked for GoPros)** • Keep other settings as default • Click 'Yes' to network processing (monitor progress in Network Monitor)	
	Export orthomosaic (tiff)	• Once the orthomosaic has finished processing, open the Metashape project • Double click on the orthomosaic in workspace pane to view • Right click the orthomosaic in the reference pane and select 'Export orthomosaic' • If using Orthomosaics in Taglab (EcoRRAP workflow protocol) - In the Export Orthomosaic pane > Check the 'Max. dimensions (pix)' box and enter '32000' into the dialogue box and keep all other settings as default.	

Generate orthomosaic cont.	Export orthomosaic (tiff) cont.	• Navigate to the export location: //pearl/3d-ltmp/EcoRRAP/Outputs/Orthomosaics • Save the orthomosaic as a .tiff under the project file name (ie. REEF_SITEZONE_PLOT_YEAR) within the year subfolder • Exporting will take approx. 2-5 minutes per orthomosaic, so can be completed via local processing or network if required.	
Clip test (non-reference) orthomosaics to reference extent	***Note**: This step is only required if orthomosaics are to be used in Taglab or another application that requires orthomosaics to have identical pixel extents between years (i.e. between reference and test (non-reference) orthomosaics)*		
	Launch ArcGIS Pro	• Launch ArcGIS Pro • Click 'Start without template' • Navigate to Insert > New Map	Figs. 12,13
	Import orthomosaics	• Drag and drop the reference and test (non-reference) orthomosaic from a file explorer window onto the map (Fig. 12a) • Select 'No' if asked whether to 'calculate statistics' during orthomosaic import • Right-click an orthomosaic in the contents pane and select 'Zoom to layer' to view (Fig. 12b) • Visually check that orthomosaics align well (corals in same location) by checking/un-checking the orthomosaic layer in the map pane (Fig. 12c) • If orthomosaics do not align well, troubleshoot co-registration and model generation (Appendix 5)	
	Apply reference dimensions	• Navigate to Analysis > Tools > Geoprocessing to open this pane on the screen • In the Geoprocessing pane, search for the 'Extract by Mask' tool and click to load (Fig. 12d) • Select the test (non-reference) orthomosaic layer as the 'Input raster' (Fig. 12e) • Select the reference orthomosaic layers as the 'Feature mask' • Leave the output raster name and location as default • Click Run (the process can take a few minutes) • The new orthomosaic will appear in the left map contents pane when complete (Fig. 12f)	
	Export edited orthomosaic	• Right-click the newly created orthomosaic in the contents pane and select > Data > Export Raster (Fig. 13a)	

Clip test (non-reference) orthomosaics to reference extent cont.	Export edited orthomosaic cont.	• In the Export Raster pane (Fig. 13b): - Change the Output Raster Dataset location to the required folder within \\pearl\3d-ltmp\EcoRRAP\outputs\Orthomosaics - Name the ortho 'ClusterReef_SiteZone_Plot_YearMonth_**c**.tif' - Select 'WGS 1984 Web Mercator (auxillary sphere) as the 'Coordinate system' - Select 'Same as Layer,' and select reference orthomosaic for 'Clipping Geometry' - Tick the box 'Maintain Clipping Extent' - Change the columns and rows input to match the pixel extent of the reference orthomosaic - To check pixel extent of the reference orthomosaic, right-click the orthomosaic in the contents pane and select > Properties > Source > Raster Information (Fig. 13c) - Leave the rest as default (making sure format is TIFF) - Click 'Export' • Once exported, the orthomosaic will appear as a new layer in the contents pane (Fig. 13d) • You can now close the ArcGIS project without saving (or start cropping next orthomosaic)

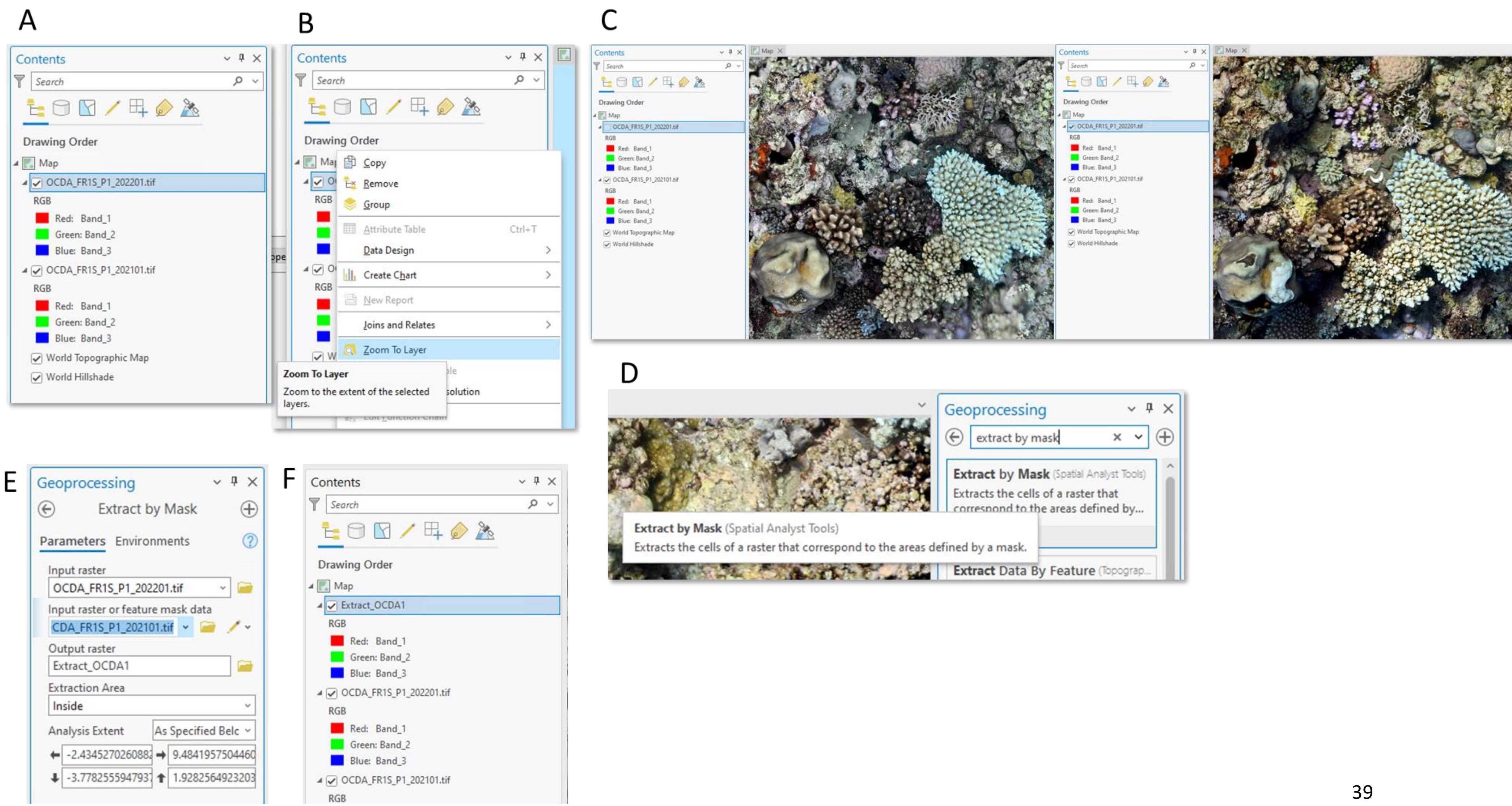


Figure 11. ArcGIS steps used to crop ‘test’ (non-reference) orthomosaics to the pixel extent of reference orthomosaics: a) Importing orthomosaics; b) viewing orthomosaics; c) checking orthomosaic features line-up between timepoints; d) loading ‘extract by mask’ Geoprocessing tool; e) setting extract by mask parameters; f) extracted layer present in contents pane. Steps continued in Fig. 13.

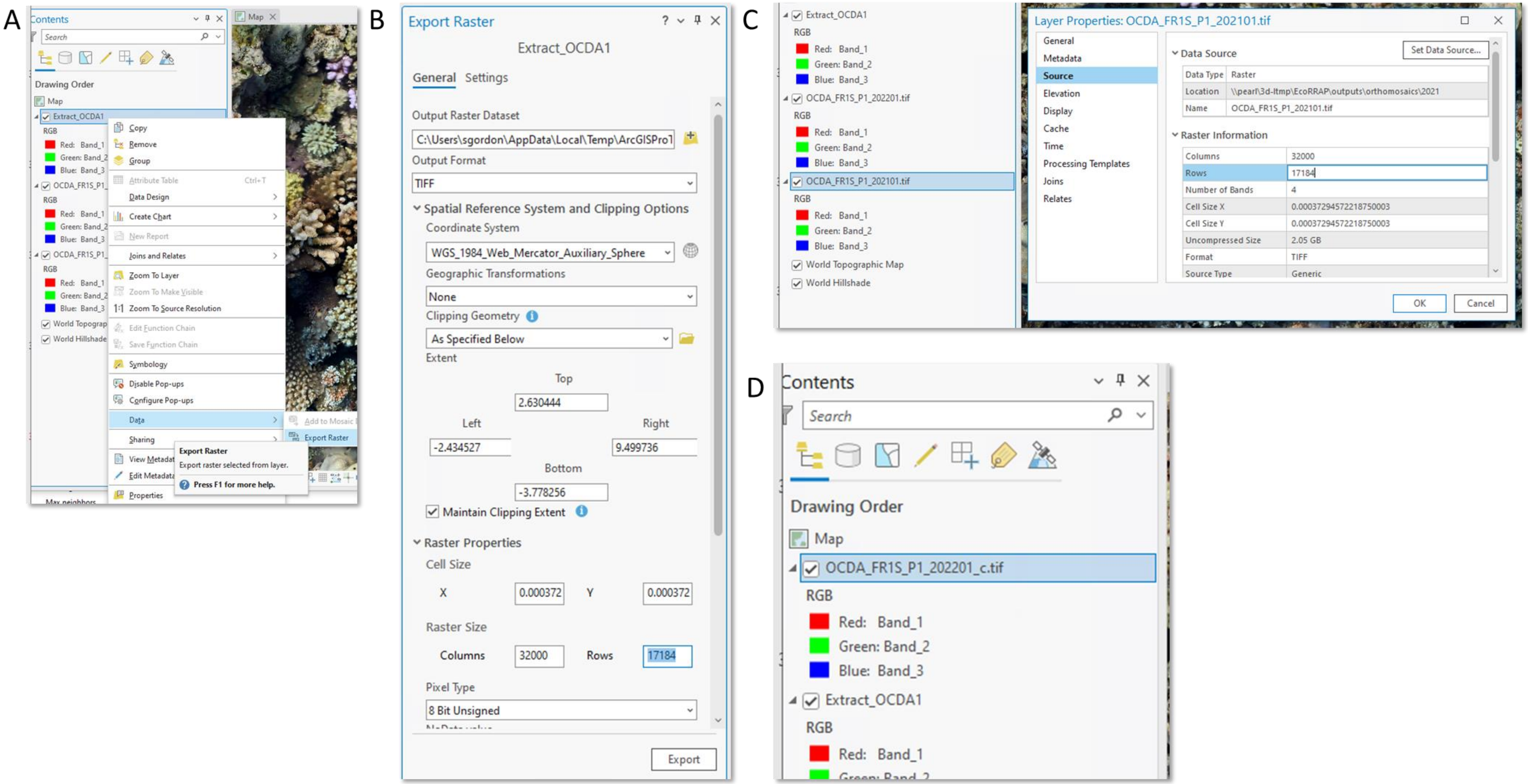


Figure 12. ArcGIS steps used to crop 'test' (non-reference) orthomosaics to the pixel extent of reference orthomosaics, continued from Figure 12: a) exporting new layer; b) specified export settings; c) viewing pixel dimensions of reference orthomosaic, and; d) final exported orthomosaic visible in contents pane.

Table 13. 3D benthic complexity metric extraction workflow adapted to EcoRRAP data and folder structure from Mitch Bryson ('ComplexityMetrics' tool), Renata Ferrari and Will Figueira (integrated workflow and 'Complexity bat file builder').

Step	Key task	Additional info for EcoRRAP users
Download files	• Download all files - Externally: AIMS GitHub - Internally: Tool download folder (3D Modelling Sharepoint) - EcoRRAP: These files are already downloaded and stored in PEARL here: \\pearl\3d-ltmp\EcoRRAP\outputs\Complexity_Metrics\ComplexityTools\USYD-EcoRRAP_Tool	• This tool can be run from the existing location in PEARL without needing to re-download files
Open the 'ComplexityBatBuilder.xlsm' file and edit inputs	• Input cells are shown in green (pale & bright) and can all be altered to suit the required application - For an in-depth description of each of these inputs see resources in the Tool explainer folder - Default settings are provided in the file to suit EcoRRAP workflow (72 sq. m plots) - Select 'No' to • This tool can be run on model files located in a single folder, or multiple folders by: - Selecting the input from the drop-down in cell B12, and entering either the: - Source folder in cell B13, for models a single folder, or - Source file paths in cells B29-onwards, for models in multiple locations - Regardless of which location format is selected, you will need to enter the model names in cells A29 onwards • **Note if running script on files stored in a network drive:**	• Create a copy of this file in the same location (to keep the example file unchanged as a template) and change the inputs in the **bright** green cells only: - **Your model locations** (see comments above re single/multiple model locations), e.g. Example model files provided in: Z:\EcoRRAP\outputs\Complexity_Metrics\ComplexityTools\USYD-EcoRRAP_Tool\Example\Models - **Location for output metrics files,** e.g. metric outputs saved in: Z:\EcoRRAP\outputs\Complexity_Metrics\ComplexityTools\USYD-EcoRRAP_Tool\Example\MetricsFiles - If running this script on the example files, ensure the 'MetricsFiles' folder is empty (delete files) prior to running. - Check outputs against files in the 'ExampleOutputs_MetricsFiles' folder

	- Use input paths in the mapped-drive form (e.g. **Z:**EcoRRAP\\….) rather than the UNC path **(\\\\pearl\\3d-ltmp**EcoRRAP\\...) - Ensure the drive letter entered is the same as mapped to your computer - If PEARL is not mapped to your computer, follow the steps in this link: Map a network drive in Windows - Microsoft Support and enter the path '\\\\pearl\\3d-ltmp'	
Click 'Run Script' button	• Click the large green 'Run Script' button in the 'ComplexityBatBuilder.xlsm' file • There will be no change within the excel file, but: • New files called **'files.txt'** and '**RunMetrics.bat**' will be generated in the scripts folder • **Note:** You can open the **'files.txt**' to see which metric files will be written by the script (therefore which models the script will be run on) listed as each row of the file	
Double click the 'RunMetrics.bat' file to run	• Open the file explorer window and double-click on the ''RunMetrics.bat' file • Once clicked: - A black Windows console screen will open - The console will show script progress (e.g. Loading data, Computing metrics, etc.) - Once complete, the console window will close automatically	Run time is approx. 5-10 minutes per EcoRRAP DSLR model (700 - 2,500 MB file size) if run locally (computer on-site at AIMS) or through PEARL
View outputs	• Once complete, the following files will be created: • Individual models: One folder per model, each with: 'metrics.csv' and 'quadrats.ply' - Outputs: '**metrics.csv':** Whole-plot info (GridX= -1, GridY= -1) and per-quadrat info (described by all other GridX and GridY	**Note**: To create a .csv file containing the whole plot complexity metrics for all models in one file: • Use script 'CombineMetricsOutputs.py' • Open script with a script editor or text viewer and enter required inputs and create required filepath .csv file (detailed instructions in script)

values) for each model. 'ComplexityMetrics' outputs only (no 'MetricsCals' outputs)
'**quadrats.ply':** Visual model file showing model quadrats

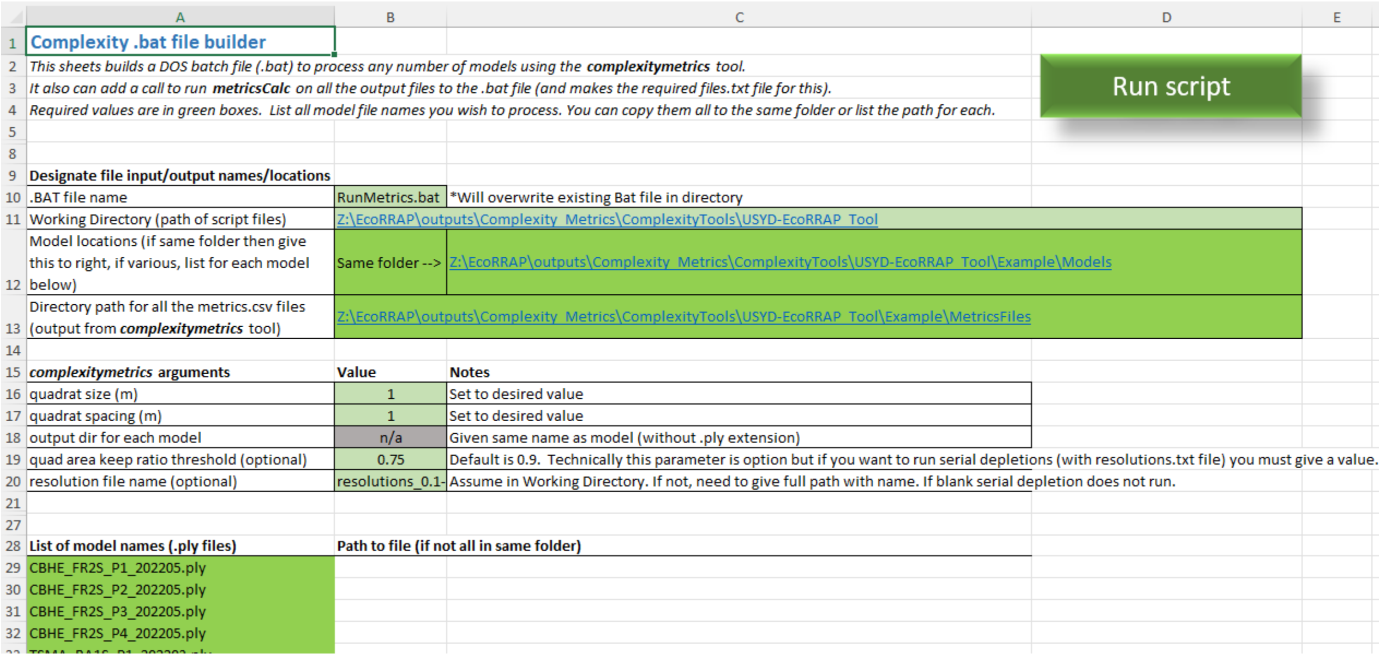
- File location: Folders are named as per model name and saved within the folder specified as the output location in the ComplexityBatBuilder.xlsm' file. Files for each model (.csv and .ply) are saved within the each model folder

- **'Quadrats.ply' f**iles can be viewed in CloudCompare (or other 3D model viewer), if viewed in CloudCompare
  - Squares represent quadrat placement used in calculations
  - Green squares represent quadrats with calculated metrics
  - Red squares represent quadrats that metrics were not calculated for (< 75 % of quadrat had model data)

- **Definitions of all complexity metrics are presented in Appendix 8, in the AIMS GitHub, and internally in the AIMS Tool explainer and Source files folders. Contact RFerrari for further discussion re interpretation of these metrics r.ferrari@aims.gov.au**

- Run script in your python environment to generate summary .csv file

A



B

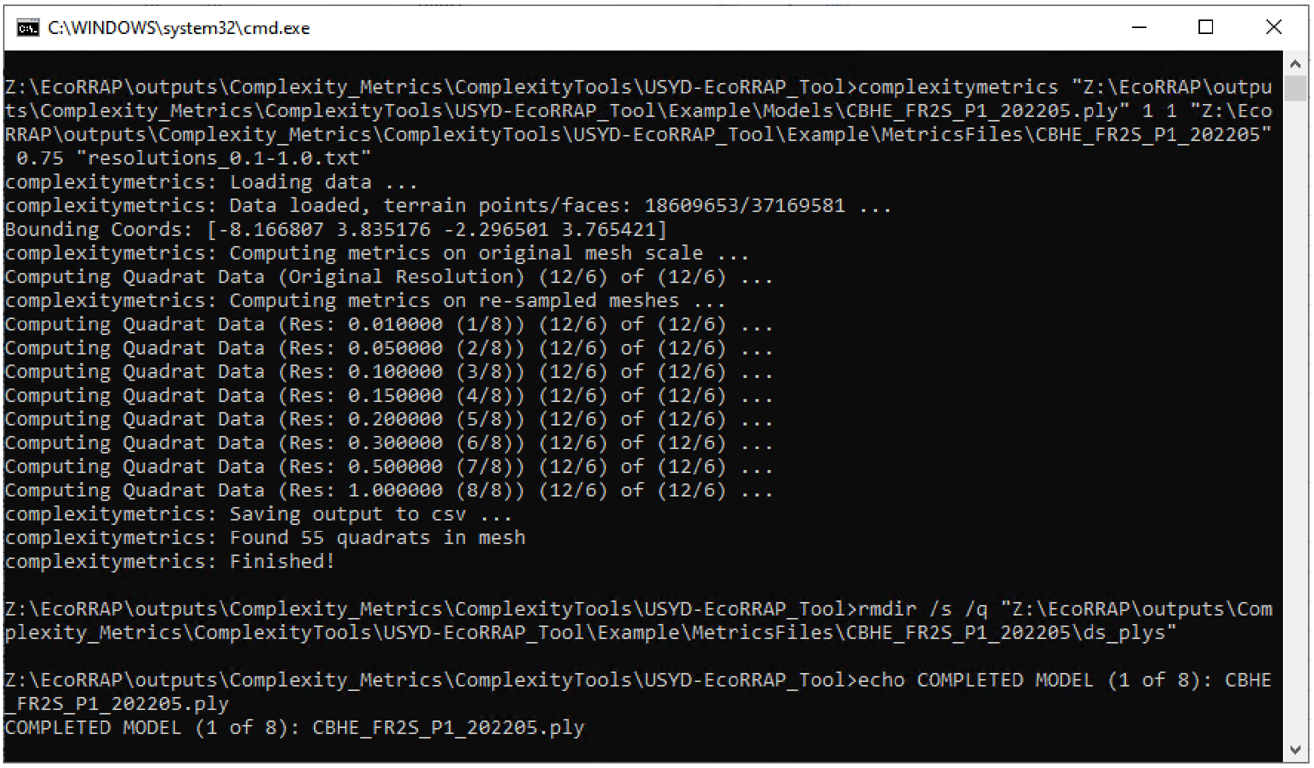


Figure 13. 3D Complexity metric export steps: a) 'ComplexityBatBuilder' file showing input cells to be changed in green with EcoRRAP default settings and large 'Run Script' button; b) screenshot of 'Run.Metrics' bat file outputs when running.

	Mesh	Grid X	Grid Y	Center X	Center Y	Center Z	Quad Size	Num Face	Num Verts	Landscap	Quad Fitte	Vertical Ar	Vertical Ar	VertAngHi	VertAngH
2	...MetricsFiles\CBHE_FR2S_P1_202205	-1	-1	-2.17	0.73	-5.94	12	37169581	18609653	18.3	18.3	51.7	28.4	0.026	0.069
3	...MetricsFiles\CBHE_FR2S_P2_202205	-1	-1	-1.58	-0.38	-4.89	12.2	46392972	23229172	13.3	13.3	50.9	28.2	0.026	0.069
4	...MetricsFiles\CBHE_FR2S_P3_202205	-1	-1	1.68	1.36	-5.63	12.2	58009496	29052284	35.5	35.5	56.5	30.9	0.02	0.057
5	...MetricsFiles\CBHE_FR2S_P4_202205	-1	-1	-0.57	-0.3	-6.1	12	45269058	22661417	23.7	23.7	55.5	30	0.019	0.052
6	...MetricsFiles\TSMA_BA1S_P1_202203	-1	-1	-0.86	-0.54	-5.46	12	35558151	17823319	11.8	11.8	58	31.3	0.022	0.049
7	...MetricsFiles\TSMA_BA1S_P2_202203	-1	-1	-1.4	0.14	-4.97	12	25239146	12649564	17.1	17.1	60.4	31.9	0.019	0.045
8	...MetricsFiles\TSMA_BA1S_P3_202203	-1	-1	2.16	0.51	-4.78	12	49739893	24930619	13.8	13.8	59.2	32	0.028	0.059
9	...MetricsFiles\TSMA_BA1S_P4_202203	-1	-1	0.15	-0.09	-5.32	12	23604391	11829118	15.6	15.6	59.3	32	0.026	0.066

	Mesh	Grid X	Grid Y	Center X	Center Y	Center Z	Quad Size	Num Face	Num Verts	Landscap	Quad Fitte	Vertical Ar	Vertical Ar	VertAngHi	VertAngHi
2	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	-1	-1	-2.17	0.73	-5.94	12	37169581	18609653	18.3	18.3	51.7	28.4	0.026	0.069
3	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	1	1	-6.17	-1.27	-6.31	2	2262204	1134601	18.3	20.5	52.5	29.1	0.028	0.075
4	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	1	2	-6.17	0.73	-5.77	2	3364262	1685932	18.3	19.1	55.7	30.3	0.023	0.064
5	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	1	3	-6.17	2.73	-5.13	2	2429847	1218433	18.3	12.3	52.1	29.6	0.026	0.07
6	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	2	1	-4.17	-1.27	-6.56	2	1322210	663799	18.3	19.7	50.6	26.4	0.021	0.058
7	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	2	2	-4.17	0.73	-5.86	2	1649063	827388	18.3	23.3	52.8	28.9	0.026	0.067
8	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	2	3	-4.17	2.73	-5.21	2	2541107	1273969	18.3	17.3	49.8	27.5	0.025	0.066
9	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	3	1	-2.17	-1.27	-6.57	2	1859386	932569	18.3	12.3	50	26.1	0.02	0.054
10	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	3	2	-2.17	0.73	-6.05	2	1963881	984769	18.3	21.6	52.2	28.3	0.024	0.067
11	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	3	3	-2.17	2.73	-5.33	2	2185182	1095456	18.3	22.2	49.6	27.4	0.03	0.078
12	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	4	1	-0.17	-1.27	-6.74	2	1806085	906356	18.3	5	52.1	28.1	0.026	0.068
13	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	4	2	-0.17	0.73	-6.25	2	3452684	1730963	18.3	23.1	50.8	27.8	0.029	0.072
14	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	4	3	-0.17	2.73	-5.57	2	1505401	755326	18.3	17.7	51.9	29	0.03	0.075
15	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	5	1	1.83	-1.27	-6.71	2	1441631	723578	18.3	17.9	50.9	28	0.031	0.081
16	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	5	2	1.83	0.73	-6.17	2	3302069	1655187	18.3	17.7	53.2	29.3	0.027	0.07
17	Z:\...\MetricsFiles\CBHE_FR2S_P1_202205	5	3	1.83	2.73	-5.58	2	1246934	625969	18.3	13.6	51.6	28.1	0.027	0.071

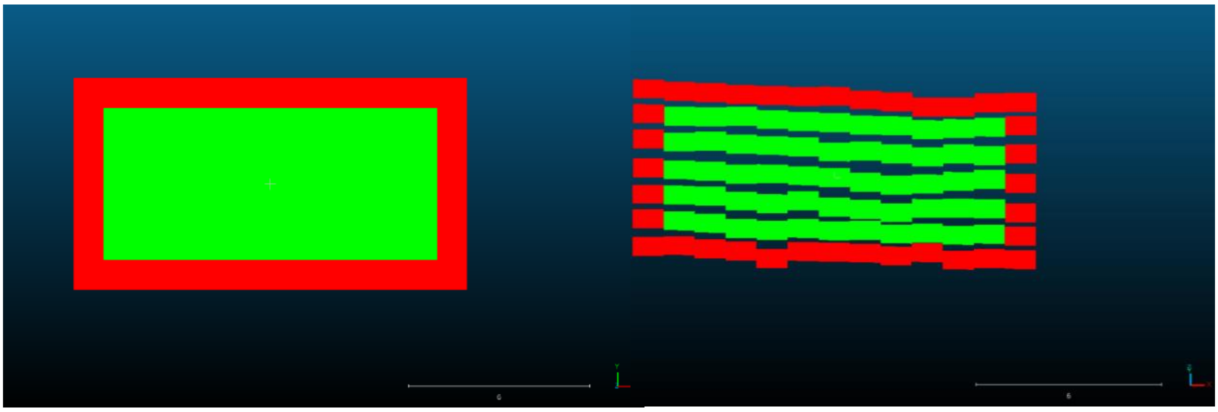


Figure 14. Example 3D Complexity metric outputs: a) ‘'AllMetrics.csv' output, showing data from multiple models for the whole model extent; b) 'metrics.csv' output, showing data from a single model, for the whole area and all quadrats; c and d) 'quadrats.ply' outputs, showing data from a single model for the whole model extrent with quadrats shown (viewed in CloudCompare at a top down, and slightly oblique view, respectively). Note that squares in 'quadrats.ply' outputs represent quadrat placement used in calculations with green squares represent quadrats with calculated metrics and red squares indicating quadrats that metrics were not calculated for (e.g. < 75 % of quadrat had model data).

5 NEXT STEPS AND ADDITIONAL RESOURCES

5.1 Workflow continued…

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

- Annotation and metric extraction (SOP 3)

5.2 Additional resources/quick links

- EcoRRAP links
  - Website: EcoRRAP (ecological intelligence for reef restoration)(gbrrestoration.org)
  - SOPs: Reef monitoring sampling methods | AIMS
  - Metadata: EcoRRAP Metadata
  - Data management templates: EcoRRAP Photogrammetry Data Management Templates
  - EcoRRAP Equipment Schematics: EcoRRAP Photogrammetry Equipment Schematics
  - GitHub: GitHub - AIMS/EcoRRAP

- 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/

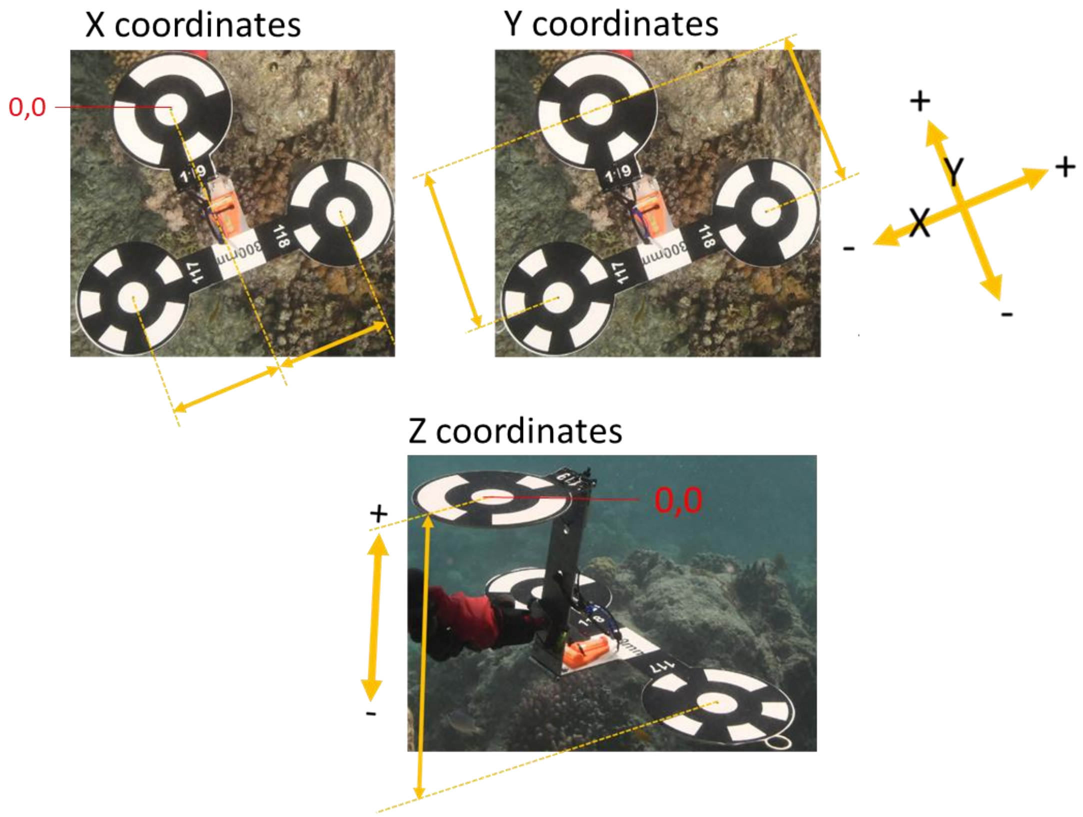
APPENDICES

Appendix 1. Overview of EcoRRAP 3D model processing workflow. All steps are described in detail in Tables 7-12, reproduced from Table 6 in text.

Step	Platform	Key tasks
Model processing (in-field)	File management	• Copy image files to computer
	Microsoft Access	• Enter metadata and marker depth data into database • Export and save 'Marker depth' CSVs from database
	Agisoft Metashape	• Create Metashape project file and import photos • Run processing script: 'Chain 1' (Local processing) • Conduct manual QA/QC checks
Model processing (in-office)	Agisoft Metashape	• Save photos and Metashape projects to AIMS network drive • Open Agisoft Network monitor and prepare network processing • Reference models (T_1) - Run Chain 2.1 (Network processing if available) - Set reference model orientation (use associated scripts) - Run Chain 2.2 (Network processing if available) • Subsequent timepoints (T_2, T_3…) - Run Chain 2 (Network processing if available) • Conduct manual QA/QC check • Export 3D models
	CloudCompare	• Load 'reference' and 'test' (non-reference) models • Rename and subsample models • Complete model co-registration and QA/QC • Export transformation matrix
	Agisoft Metashape	• Subsequent timepoints (T_2, T_3…) - Load project and run 'Chain 3' (Local processing)
Output generation	Agisoft Metashape	• Generate orthomosaic • Export orthomosaic (.tif) as 2D output (final ref. 2D output) • Export 3D model (.ply) as final 3D output (ref. and subs.)
	ArcGIS	• Clip orthomosaics from subsequent timepoints (T_2, T_3…) to reference extent in ArcGIS and save final subs. 2D output

Appendix 2. Triad coordinate values used in model scaling. Note: ‘Small’ triads are generally used for DSLR model scaling, while ‘large’ triads are used for GoPro model scaling. Each EcoRRAP site contains 3 x small triads and 1 x large triad.

Triad type	Marker	X value	Y value	Z value
Large triad	Top	0	0	Depth measured
	Left	-0.15	-0.204	Depth of top - 0.2
	Right	0.15	-0.204	Depth of top - 0.2
Small triad	Top	0	0	Depth measured
	Left	-0.1105	-0.1335	Depth of top - 0.114
	Right	0.1105	-0.1335	Depth of top - 0.114



Appendix 3. Visual representation of triad coordinate values used in model scaling.

Appendix 4. Marker accuracy values used in model scaling. See descriptions of GCP (ground control points) in SOP 1 (Table 1).

GCP	X Accuracy	Y Accuracy	Z Accuracy	Comment
Dumbbells	10	10	0.25	
Triad (enabled)	0.005	0.005	0.005	One per GoPro project
Triad (disabled)	10	10	0.25	GoPro only, all unused GoPro triads

Appendix 5. List of all current Metashape processing scripts

Chain	Script type	Camera	Reference model (Y/N/All)	Processing location	Script name	Dependencies
1	Chain	DSLR	All	Local	Chain1_Local_DSLR.py	
	Chain			Network	Chain1_Network_DSLR.py	DisableLowQPhotos_DSLR.py MarkerQCheck_DSLR.py ScalebarAddQCheck_DSLR.py
	Script			Local/Network	DisableLowQPhotos_DSLR.py	
	Script			Local/Network	MarkerQCheck_DSLR.py	
	Script			Local/Network	ScalebarAddQCheck_DSLR.py	
	Chain	GoPro	All	Local	Chain1_Local_GoPro.py	
	Chain			Network	Chain1_Network_GoPro.py	DisableLowQPhotos_GoPro.py MarkerQCheck_GoPro.py ScalebarAddQCheck_GoPro.py
	Script			Local/Network	DisableLowQPhotos_GoPro.py	
	Script			Local/Network	MarkerQCheck_GoPro.py	
	Script			Local/Network	ScalebarAddQCheck_GoPro.py	
2	Chain	DSLR	N	Network	Chain2_Network_DSLR_NonRef.py	SparseCloudClean_DSLR.py
	Chain		Y	Network	Chain2.1_Network_DSLR_Ref.py	SparseCloudClean_DSLR.py ResizeRegion.py
	Chain		Y	Network	Chain2.2_Network_DSLR_Ref.py	
	Script		All	Local/Network	SparseCloudClean_DSLR.py	
	Script		Y	Local/Network	ResizeRegion.py	
	Chain	GoPro	N	Network	Chain2_Network_GoPro.py	SparseCloudClean_GoPro.py
	Script		All	Local/Network	SparseCloudClean_GoPro.py	
3	Chain	DSLR	N	Local	Chain3_Local_DSLR_NonRef.py	
	Chain	GoPro	N	Local	Chain3_Local_GoPro_NonRef.py	

Appendix 5. EcoRRAP model processing troubleshooting steps.

Step	Issue	Solution	Additional info
Any network processing	Network processing fails due to error locating image	• Within Metashape, right-click any photo and select 'Check paths' > 'Entire workspace' • If any photos are missing or file paths are broken they will be displayed in the dialogue box • To correct the file path, right-click any photo and select 'Change path' > 'Entire workspace' and navigate to the correct location and select a file within it • Run 'Check paths' > 'Entire workspace' again to check if issue has been resolved • Note: If changing paths of renamed files (e.g. GoPro files bulked renamed in the form 'GP1 (1).JPG), ensure the file extension 'JPEG' is correct when selecting the file in its' folder location	
Image quality assessment	Not all images assessed	• If images are missing quality value (values missing in Photos pane > Details view) select images with missing values, right-click and select 'Estimate image quality' > Selected cameras • Images will then be assessed for quality (job can run locally or on the network as required)	
	Images below threshold enabled	• To manually disable cameras navigate to Photo pane > Details view > Sort by quality (click column heading) > The select (click + shift) photos to be disabled, right click and select 'Disable cameras'	

Alignment	Low alignment (< 80 %)	• Check and address any errors relating to file management and photo quality: - Errors in imported photos (time, date, and camera incorrect) - Missing files (number and timestamp of photos incorrect) - Poor photo quality (photos out of focus, incorrect camera settings, turbid water • If the above does not improve alignment, check for errors relating to model alignment: - Model shape does not reflect realistic reef shape and structure - Model has multiple axes (multiple colliding planes) - Model has large spread of floating points and no clear structure - If there is no issue with files, the above errors generally indicate an issue with dubious marker detection causing errors in model alignment (proceed to next step) • Check markers for numbers of projections and projection error - Disable and uncheck questionable markers (low projections, high error) and realign model	Bayley and Mogg (2020) Keypoint/ tiepoint limits: https://www.agisoft.com/forum/index.php?topic=3559.0 https://www.youtube.com/watch?v=AWso2m2FPkA
Alignment cont.	Low alignment (< 80 %) cont.	- If this is unsuccessful, remove all markers, realign, then re-detect markers after alignment • If all above steps do not work, realign model with the following settings: - Quality: High - Generic preselection: No (uncheck) - Keypoint limit = 0 - Tiepoint limit = 0 - Note that processing time will these settings may increase significantly	
Marker detection	Low marker detection	• Add markers manually • If one marker of a ground control point (GPC) is not detected but another is, right-clicking on an existing detected marker and select ‘Filter photos by markers’ • Select photos in which the undetected marker is visible and drop a marker on its’ centre by right-clicking the centre of the unrecognised marker and selecting ‘Add Marker’ • A new marker will now be visible in the Reference pane as ‘point 1’ • Rename the marker from ‘point 1’ to the appropriate Target number as displayed on the GPC and edit coordinate values and error as appropriate • Add an additional projection by double-clicking on another photo with the missing marker visible and right clicking on the centre of the marker and selecting ‘Place marker’ and selecting the marker required	Over et al. 2021

		• Once two projections of the new marker have been made, right click the marker in the Reference pane and select 'Filter photos by markers' • Add projections on the resultant photos by clicking on or moving the automatically detected white flags to confirm them (confirmed projections will be shown in green) • Repeat until all targets have at least 5-10 projections (DSLR and GoPro, respectively) • If marker pairs can't be used to add missing markers, click on the 'Show images' button on the toolbar to overlay the point cloud with photos from the region in focus • Navigate around the point cloud and look for images with undetected markers • Once found, right click on the marker and select 'Filter photos by point' • New markers and projections can now be added to these images as per above steps
Marker detection	Low marker projections	• Follow above steps (excluding addition of new markers) to add more projections to markers
	High marker projection error	• If there are sufficient other markers to complete scaling, disable marker and do not use • If there are not sufficient other markers to complete scaling, check projections • Within the reference pane, right-click the marker in question and select 'Show info' • Click on the 'Value' column heading and arrange in descending order of pixel error • Double-click the image containing the highest error value to display it • Check if the marker projection looks incorrect or not (i.e. placed on coral, placed at distorted edge of image) • If projection is questionable, remove the projection by right-clicking the marker and select 'Remove marker' • This should lower the error value. If still greater than 10 pixels, repeat these steps for the next image with the highest associated target error value. • These steps can also be used as troubleshooting if scaling error is high
Scalebar error too high	Control scale bar value: > 0.01 (DSLR) > 0.02 (GoPro)	• Ensure that only the markers of one triad (if more than one used in chunk) are checked in the marker pane • Uncheck all dumbbell markers and click 'Update transform' at the top of the reference pane and check the effects on the control scale bars value

		• If this drops the value < 0.01, check one dumbbell marker at a time, clicking update transform after each change. Continue checking and un-checking dumbbells and updating the transform until you check as many dumbbell markers as possible while keeping the control scale bars value < 0.01/0.02 • Scalebars of dumbbell markers unchecked in the marker pane do not need to be unchecked or removed in the scalebar pane
Co-registration	Co-registration error too high	• Click ‘Adjust scale’ check box in co-registration pane and see if error decreases • If so, open Metashape projects and check Reference pane for scaling error • Complete above scale bar error and marker projection error troubleshooting steps to improve model scaling error • Export adjusted models and repeat co-registration procedure • If clicking the ‘Adjust scale’ check box does not improve co-registration error, visually check whether sphere trees have moved (e.g. not in same position in both models) • If sphere trees have moved, delete spheres placed on moved trees and do not use for co-registration • Instead, de-select the sphere tool and use the point tool to select additional benthic points on the reef for co-registration points
Orthomosaic cropping	Orthomosaics do not line up	• Check imported orthomosaics are correct (correct file name and version), if they are complete the following checks: • Open Metashape projects of orthomosaics and check that coordinates of orthomosaics and 3D models are consistent • Check coordinates by using the ‘Ruler’ tool to click on a feature on both the orthomosaic and model • Navigate to the Console pane and check whether the coordinates of both the model and orthomosaic are consistent (indicates that issue is not due to orthomosaic generation) • If coordinates are consistent, check whether models have been correctly co-registered • Open Metashape projects and export models

- Import models into CloudCompare and examine whether they are lined up
- If not, re-coregister models and apply the transformation matrix in Metashape (as per Tables 11,12).

Appendix 6. Steps to decimate 3D models prior and upload to Sketchfab.

Metashape steps

1. Open desired Metashape project
2. Once project is opened, select (double-click) the chunk containing the model to decimate
3. Run script by pressing Ctrl-R and navigate to the script location
    - E.g. \\pearl\3d-ltmp\scripts\EcoRRAP\PythonScripts\
4. Select the Python script required based on the number of chunks requiring decimation:
    - Single chunk: 'SketchFab_Prep.py'
    - Multiple chunks: 'SketchFab_ModelPrepMultipleChunks.py'
    - Select 'no' to network processing when prompted
5. Decimating will take approx. 5-10 minutes per model
6. Once models are decimated, run script (as above) 'SketchFab_ModelUpload.py'
    - Note: This will upload only your active chunk, so ensure your decimated chunk is set as active before running script
7. Check Metashape console to ensure no error messages occur then close Metashape
8. **Note**: Do not run multiple project scripts simultaneously, scripts use the same temporary file

SketchFab steps

1. Models uploaded via above steps may take up to ten minutes to appear in SketchFab
2. When model is uploaded it will be visible as a blank, featureless thumbnail with the same name as the file name originally used (e.g., 'OCDA_FR1S_P1_202301.psx')
3. Navigate to the three dots near the bottom right of the model icon > Select properties
4. Change the title of the project by:
    - Deleting the file extension, e.g. 'OCDA_FR1S_P1_202301.psx'
    - Changing the reef code to reef name, e.g. 'Davies_FR1S_P1_202301'
5. After the title is changed, select the 'Allow AR?' toggle on the right side of the page. This allows certain devices to view our models in Augmented Reality.
6. Select 'Free' under the Download tab on the right side of the page. Ensure that the License that appears says CC Attribution to allows for use and distribution of models with fair attribution.
7. Click **'**Save' on the bottom right
8. Once properties are saved, click on the blue 'Edit 3D Settings' button near the top
9. Navigate to the first tab > General > select 'Show advanced rotation' toggle and rotate your model to be upright. Most models will start upside down.
    - Note: Use plate corals and the sphere trees to orient the model upright. Start by hitting the arrow next to X under the rotate tab twice to flip it over and work from there.
10. Rotate the camera using the mouse (click and drag) to a top-down position so you can view the entire model. It should look the same as the other thumbnails in Sketchfab. Once you have a suitable view and zoom level, click 'Save View' in the top left corner of the model viewer.
11. Navigate to the AR/VR tab in the navigation ribbon > 'World Scale' > click the 'Use 1 Unit = 1 Meter' button to set the scale for VR. You may want to use the arrows under the human figure to drag the starting view closer to the model—typically one or two grid squares away.
12. Click 'Save Settings' in the top right corner.

Appendix 7. Steps to colour-correct GoPro orthomosaics.

Photoshop steps

1. Import orthomosaic (.TIFF) to Photoshop
2. Select the 'Levels' tool in the 'Adjustment' tab (Fig. 1a)
3. Select the 'Eyedropper' tool (black, grey or white) in the 'Colours' tab, then select your sample size (Fig. 1b)
4. Using the 'Eyedropper' tool, click on the desired points in the orthomosaic used to colour correct the image (ideally these should be the black or white of dumbbells or colour charts placed in the plots (Fig. 1b)
5. Note: selecting points at different depths will improve the overall result.
6. You may save your edit settings to apply to other projects by adding the selected layers to 'Your presents (+)' adjustments (Fig. 1a)
7. Export the colour-corrected file to a final location in the format required (generally .TIFF)

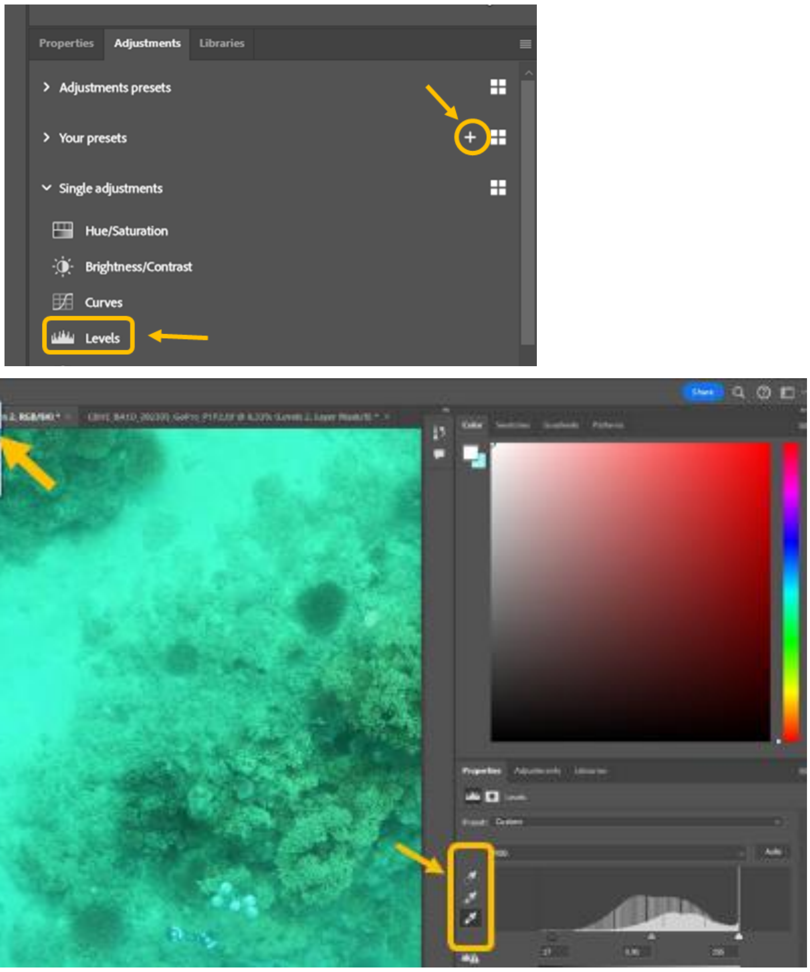


Figure A1. Screenshot of Photoshop showing: a) 'Levels' and 'Presets' tools, and; b) 'Eyedropper' tool.

Appendix 8. Complexity metrics definitions from Mitch Bryson ('ComplexityMetrics' tool) and Ryan Krensel ('MetricsCalc' tool).

complexitymetrics tool	
Values below are summarised in 'metrics.csv' file for each mesh. Each row is a sample unit (whole mesh is first row, quadrats come after this).	
Descriptor	**Explanation**
Mesh	Name of the mesh
Grid X	Quadrat position in grid - x dimension. -1 for full mesh
Grid Y	Quadrat position in grid - y dimension. -1 for full mesh
Center X	x value (in model coordinate system) of sample unit.
Center Y	y value (in model coordinate system) of sample unit.
Center Z	z value (in model coordinate system) of sample unit.
Quad Size	length of one side of square quadrat (as defined by user)
Num Faces	Number of faces found in the sample unit.
Num Verts	Number of vertices found in the sample unit.
Landscape Slope	Slope (0 is flat) of the overall mesh (will be the same for all sample units)
Quad Fitted Slope	slope (0 is flat) of the mesh in just the area of the sample unit.
Vertical Angle Mean	Mean value of all face angles (0 is flat) in the sample unit.
Vertical Angle StdDev	Standard deviation of all face angels ((0 is flat) in the sample unit.
VertAngHist xx-xxdeg	Percent of all face angles in the sample unit within the designated degree bin. 0 is flat, 90 is vertical, 180 is downward facing.
Quad Height Range	Range (max-min) of heights (z-values) of all faces in a sampling unit.
Quad Height StdDev	Standard deviation (max-min) of heights (z-values) of all faces in a sampling unit.
Quad 2D Area	The 2D area of the sample unit projected onto the overall model plane.
Quad 3D Area	The 3D area of the sample unit (sum of all faces within the unit).

Quad Rugosity	3D area divided by 2D area
Quad 2D Area (plane)	The 2D area of the sample unit projected onto the plane of best fit of all data within the sample unit.
Quad Rugosity (plane)	3D area divided by 2D area (plane)
Quad Height Range (x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.
Quad Height StdDev (x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.
Quad 2D Area (x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.
Quad 3D Area (x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.
Quad Rugosity (x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.
Quad 2D Area (plane) (x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.
Quad Rugosity (plane)(x.xx m)	As above but for model built with stated resolution (xx.x m). Present for all resolutions listed in the resolutions.txt file.

6 REFERENCES

AccuPixel. 2021. Scripts for Free – Transform Helper. AccuPixel Ltd, Forensic Photogrammetry Training, Products and Services. https://accupixel.co.uk/2021/08/26/scripts-for-free-transform-helper/.

Akkaynak D., and Treibitz T. 2019. Sea-thru: A Method For Removing Water From Underwater Images. Proceedings / CVPR, IEEE Computer Society Conference on Computer Vision and Pattern Recognition. IEEE Computer Society Conference on Computer Vision and Pattern Recognition.

Aston E., Duce S., Hoey A., Ferrari R. 2022. A protocol for extracting structural metrics from 3D reconstructions of corals. Frontiers in Marine Science. DOI:7;9:854395.

Aston E. 2023. Quantifying and assessing coral reef structural complexity and its role in ecological processes and dynamics using photogrammetry (Doctoral dissertation, James Cook University).

Bayley DT., and Mogg AO. 2020. A protocol for the large-scale analysis of reefs using Structure from Motion photogrammetry. Methods in Ecology and Evolution. 11(11):1410-20.

Gordon S., Aston E., Lechene M., Harianto J., Bray P., Figueira W., Gonzalez Rivero M., and Ferrari Legorreta R. (2023) Field photogrammetry in 4D. Reef Restoration and Adaption Program (EcoRRAP). Standard Operational Procedure Number 14 (1 of series): Overview and in-field workflow. Australian Institute of Marine Science, Townsville. (62 pp) https://doi.org/10.25845/SE7T-PS86

Lechene A., Figueira F., Murray N., Aston E., Gordon S., Ferrari R. 2024. Evaluating error sources to improve precision in the co-registration of underwater 3D models. Ecological Informatics. DOI:1;81:102632.

Over J.R., Ritchie A.C., Kranenburg C.J., Brown J.A., Buscombe D., Noble T., Sherwood C.R., Warrick J.A. and Wernette P.A. 2021. Processing coastal imagery with Agisoft Metashape Professional Edition, version 1.6— Structure from motion workflow documentation: U.S. Geological Survey Open-File Report 2021–1039, 46 p., https://doi.org/10.3133/ofr20211039

Pavoni G., Corsini M., Ponchio F., Muntoni A., Edwards C., Pedersen N., Sandin S., Cignoni P. 2022. TagLab: AI-assisted annotation for the fast and accurate semantic segmentation of coral reef orthoimages. Journal of field robotics. 39(3):246-62.