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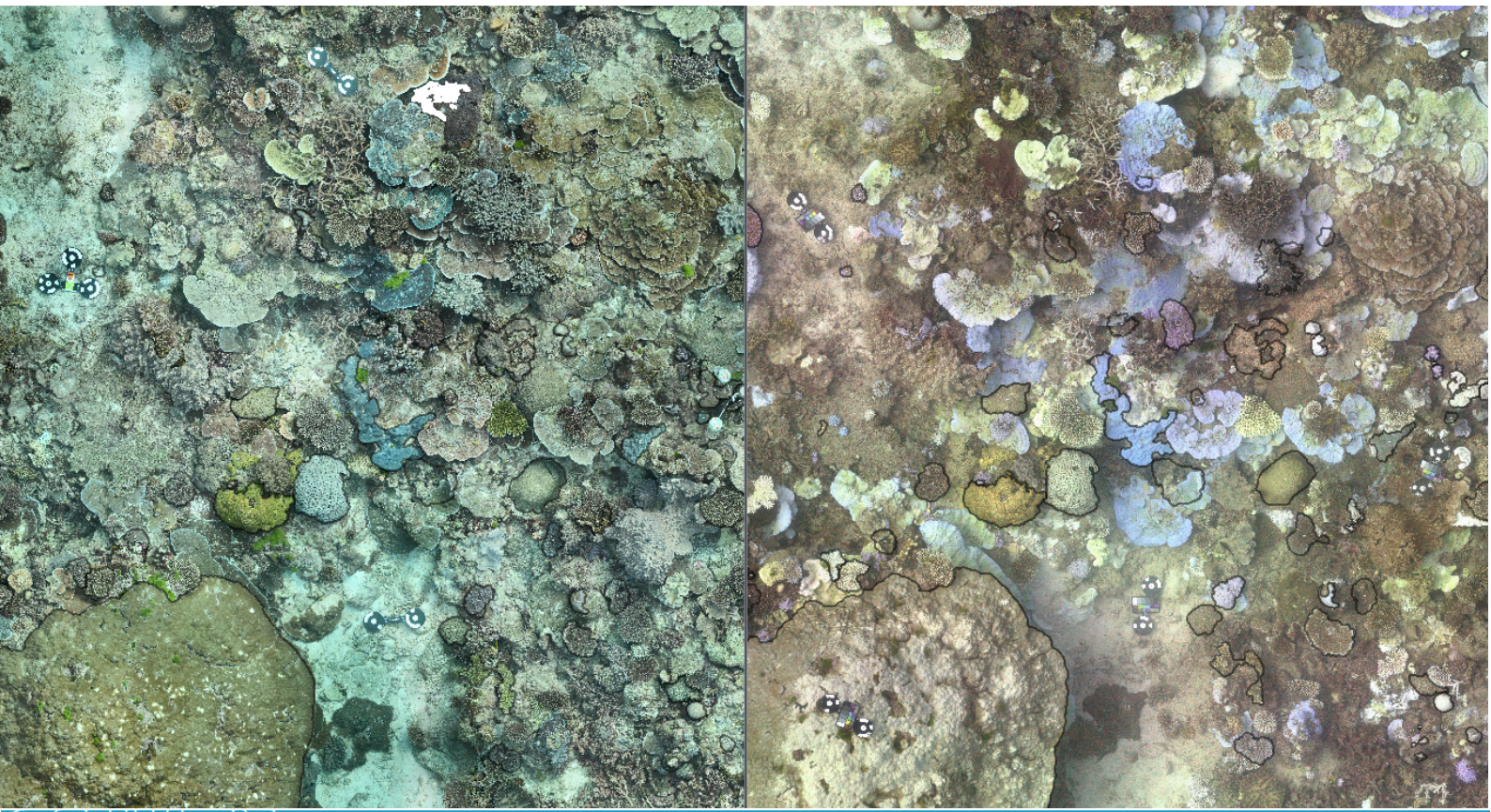
Australian Institute of Marine Science

Field photogrammetry in 4D: *Quantifying coral bleaching in orthomosaics*

Reef Restoration and Adaptation Program (EcoRRAP)

Standard Operational Procedure number 19 (No. 5 of series)

Madison Becker, Maren Toor, Deborah Burn, Marine Lechene, Mariana Álvarez-Noriega, Sophie Gordon, Grace Frank, Neal Cantin, Renata Ferrari



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Revision History	Name	Date	Comments
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Cover photo: Orthomosaics of the same survey plot (left) during a normal year, and (right) during bleaching. Orthomosaics were produced from 3D photogrammetry and coral colonies segmented in Taglab. Image credits: EcoRRAP AIMS photogrammetry team.

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on Land and in Sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections to Land and Sea Country.

We specifically acknowledge and thank the following Traditional Owners of Sea Country that this report relates to:

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

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SUMMARY

The Australian Institute of Marine Science's (AIMS) Ecological Intelligence for Reef Restoration and Adaptation Program (EcoRRAP) quantifies natural coral demographic processes (e.g., growth, survival, settlement) and coral health metrics (e.g., injuries, bleaching) to assess coral population maintenance and recovery potential in the event of disturbance. These processes are examined across a range of environmental conditions and coral taxa over multiple years to understand spatial, temporal and taxonomic variation in demographic rates and coral health which informs the Reef Restoration and Adaptation Program (RRAP). The RRAP is a collaboration across many research institutes and experts, managed by AIMS.

This document is the Standard Operational Procedure 19, produced by the EcoRRAP sub-program at AIMS. It outlines the standard procedures for collecting, generating and extracting data on the prevalence and severity of coral bleaching from two-dimensional (2D) orthomosaics produced via photogrammetry. This SOP explicitly expands on the workflows outlined in Standard Operational Procedures 14 (field photogrammetry), 16 (3D model processing) and 17 (2D coral digitisation and metric extraction) and complements SOP 18 (using AI to monitor coral seeding devices in TagLab). As such, a comprehensive understanding of the methods outlined in previous SOPs is essential to the implementation of the procedures presented in this document (SOP 19).

SOPs 14 , 16, 17 and 18 are published online at AIMS's SOP page (Reef monitoring sampling methods | AIMS). Table 1 outlines the complete list of SOPs and other supplemental resources for reproducing the methods implemented by EcoRRAP and can be found in AIMS Metadata records Reef monitoring sampling methods | AIMS), the EcoRRAP Website (EcoRRAP (gbrrestoration.org) and, for AIMS internal users, on the EcoRRAP Metadata records page (EcoRRAP Metadata).

Table 1. EcoRRAP data collection activities and associated standard operating procedures.

Activity	Associated documents
Overview and in-field workflow	SOP 14: Field photogrammetry in 4D: No. 1 of series
3D Model processing	SOP 16: Field photogrammetry in 4D: No. 2 of series
Coral digitisation and metric extraction	SOP 17: Field photogrammetry in 4D: No. 3 of series
Monitoring Coral Seeding Devices	SOP 18: Field photogrammetry in 4D: No. 4 of series
Coral bleaching assessments	SOP 19: Field photogrammetry in 4D: No. 5 of series (current doc)

Information regarding data generated by the EcoRRAP sub-program can be accessed through the EcoRRAP metadata records (EcoRRAP Metadata). Additional links to project outputs can be found here: Survey Output Products and throughout this document. The EcoRRAP Database (internal document) and data management files and folder templates are located here: EcoRRAP Data Management Templates. Processing scripts are publicly available and via the EcoRRAP GitHub.

1 INTRODUCTION

1.1 Overview

The Reef Restoration and Adaptation Program (RRAP) unites leading experts from Australia and around the world to help protect the future of the Great Barrier Reef (GBR), other Australian reefs, and coral reefs globally. Within RRAP, the 'EcoRRAP' sub-program focuses on enhancing the success of restoration efforts by identifying the optimal 'what', 'where', and 'when' of restoration interventions. It also addresses key gaps in ecological knowledge related to coral recovery processes on the GBR.

EcoRRAP uses close-range photogrammetry to quantify structural complexity, benthic communities, coral health and demographic rates across various spatial and temporal scales. This process generates two main outputs from collected imagery: 3D Digital Surface Models (DSMs), used to measure habitat structural complexity, and 2D orthomosaics, used to analyse benthic community composition and structure, and monitor coral health and demographic rates of over 18 coral morpho-taxa.

These photogrammetric outputs are generated using Structure from Motion (SfM) algorithms (Ferrari et al. 2016; Aston et al. 2022; Gordon et al. 2023; Lechene et al. 2024), which align and reconstruct overlapping images in 3D space to create accurate models of reef topography. To monitor change over time, model co-registration techniques are applied, aligning 2D and 3D outputs with a mean precision of 1.37 ± 16.55 mm. This enables detailed measurement of temporal shifts in reef structure and coral demographics (Lechene et al. 2024).

During annual EcoRRAP surveys in 2022 and 2024, widespread coral bleaching was observed across permanent monitoring plots on multiple reefs. These events provided an opportunity to use EcoRRAP's high-resolution 2D orthomosaics to detect and quantify bleaching at both the plot- and colony-level.

***Note**: A detailed overview of the EcoRRAP sub-program, sampling design, and image collection techniques used are provided in the first SOP of this series 'SOP 14: Overview and in-field workflow' (Gordon et al. 2023).*

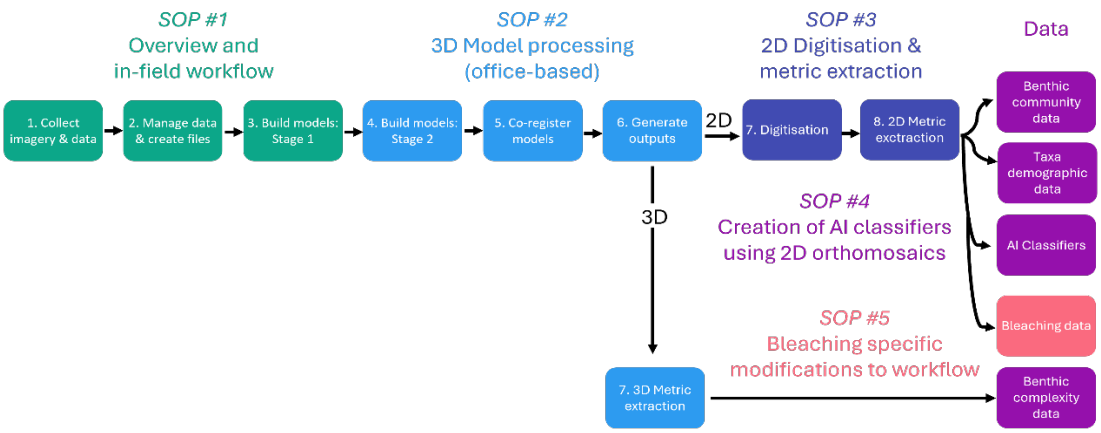


Figure 1. EcoRRAP photogrammetry workflow and key data outputs.

1.2 Applications of photogrammetry for coral bleaching

This Standard Operating Procedure (SOP) outlines methods for assessing coral bleaching prevalence (i.e., the proportion of colonies affected) and severity (i.e., the planar area affected by bleaching per colony) using annotated 2D orthomosaics. The methods integrate with established EcoRRAP workflows and are suitable for opportunistic application during bleaching events. While developed for EcoRRAP's objectives and equipment, they are broadly applicable across reef systems and taxa and can be adapted for use by other organisations and monitoring programs.

The approach begins with in-field image acquisition and processing, followed by the generation of orthomosaics. These workflows are detailed in SOPs 14, 16, and 17 but require some modification for optimal results during bleaching conditions. Orthomosaics act as spatially accurate basemaps which support colony-level digitisation and enable standardised quantification of bleaching ranging from no visible bleaching to full colony bleaching with or without recent mortality. As well as outlining methods for image-based analysis during bleaching using ArcGIS Pro (v3.2.1), Agisoft Metashape (v1.8), and the AI segmentation software TagLab (v2022.02.11–v2025.2.15; Pavoni et al., 2021), this SOP also outlines methods for complementary in-water bleaching surveys. Software-specific instructions in this SOP are intended to complement the more detailed guidance found in SOPs 14, 16, and 17.

Bleaching metrics derived from this process include plot-level prevalence and colony-level severity, attained per taxon to allow for assessment of spatial and taxonomic variation in bleaching prevalence and severity. Moreover, this method enables temporal tracking of colony condition and demographic rates associated with bleaching severity. These data will be important contributions to a broader understanding of bleaching dynamics and coral resilience.

To date, EcoRRAP has used these methods to assess bleaching of over 5,000 colonies across five reefs during the 2022 mass bleaching event (Alvarez-Noriega et al., 2025), and 9000 colonies across 9 reefs during the 2024 event.

While outside the scope of this SOP, photogrammetric data such as 2D orthomosaics may also be suitable for use in AI-based platforms (e.g., ReefCloud) to support automated bleaching assessments. Additionally, while EcoRRAP uses in-water white balancing to minimise colour distortion caused by bleached corals, the workflow presented in this SOP also allows for post-processing colour correction, which is an important step for preparing imagery for machine learning applications. These approaches represent potential extensions of this workflow and are not covered in this document.

While currently implemented at the organisational level within AIMS, this workflow provides a scalable and transferable framework for coral bleaching assessment that can be adopted by other programs seeking to leverage photogrammetry-based monitoring tools.

1.3 How to use this Standard Operational Procedure (SOP)

Note: *Prerequisite steps to this SOP are explained in "SOP 14: Overview and In-field Workflow" (Gordon et al. 2023), "SOP 16: 3D Model Processing" (Gordon et al. 2025), and "SOP 17: Digitisation and 2D metric extraction" (Toor et al. 2025). These should be understood and some of the processes*

outlined in these documents will need to be completed before proceeding with the steps presented in this document.

The EcoRRAP photogrammetry workflow consists of several stages outlined by a series SOPs (Figure 1, Table 1).

1. Field-based data collection and model building (SOP 14)
2. Office-based model building using High Performance Computer (HPC; SOP 16)
3. Data generation and metric extraction
4. Modifications to data collection, processing and outputs for bleaching assessments.

The metrics extraction stages (step 3 and 4, above) can be divided into 5 data outputs (Figure 1; far right):

1. Coral vital rates (demography) (SOP 17)
2. Benthic community composition and structure (SOP in prep.)
3. Creation of AI classifiers to monitor coral seeding devices (SOP 18)
4. Bleaching prevalence and severity (this SOP)
5. Structural complexity metrics (SOP 16)

This SOP describes the modifications to field-based data collection and model processing required to conduct bleaching assessments using the EcoRRAP workflow. It also provides a standardised framework for characterising bleaching prevalence and severity at the plot and colony-level from 2D orthomosaics. This document is intended as a practical guide to support both in-field bleaching assessments and image-based analysis using orthomosaics (single images may also be used, where appropriate).

Procedures that are regularly updated, and/or are AIMS specific, are described in AIMS 3D Modelling OneNote (internal link: AIMS 3D Modelling OneNote) to ensure this SOP remains relevant and useful. Some steps will also require an AIMS user account with the right approvals and access to the AIMS server "PEARL." If you are using a non-AIMS issued computer and want to access the AIMS computing network, you will need to establish a remote connection (described in the AIMS 3D Modelling OneNote). If you are using your own network, you will need to ensure correct setup is done before following the steps in this SOP. Users not associated with AIMS can contact the authors of this SOP to request access to internal information.

1.4 Steps for implementation

1. Image collection (full workflow in SOP 14, modifications for bleaching here in Section 2)
2. In-water bleaching assessments for validation (Section 2.2), including underwater map creation (Section 2.2.1)
3. Creation of 3D models and orthomosaics (full workflow in SOP 16, modifications for bleaching here in Section 3)
4. Site-level bleaching assessments from orthomosaics (Section 4.1)
5. Digitization and colony edge refinement in TagLab (full workflow in SOP 17)
6. Colony-level bleaching assessments from orthomosaics (Section 4.2)

2 FIELD METHODS

EcoRRAP's photogrammetry-derived products, including 3D digital surface models (DSMs) and 2D orthomosaics, serve as the foundation for the bleaching assessment methods outlined in this SOP. It is also recommended that in-water colony-level bleaching assessments be conducted alongside orthomosaic assessments to provide validation for the image-based methods. This SOP section details the field-based methodological modifications, including changes to image acquisition and processing required when working on highly bleached reefs as well as the in-water validation surveys used by the EcoRRAP team.

2.1 3D Mapping for bleaching

Full details on EcoRRAP 3D field mapping methods should be reviewed in SOP 14. Recommended modifications for 3D mapping during bleaching are described in each of the following sections.

2.1.1 Personnel and Equipment Requirements

Note: *These requirements differ to the equipment requirements outlined in SOP 14. For a recommended packing list, see Appendix A, Table 14.*

A minimum of four divers are required for plot setup, imaging, and in-water bleaching validation (Table 2). Two divers should set up the plot using equipment outlined in Table 3 as shown in Figure 2. These divers also take depth measurements of standards, as per SOP 14. An important modification to the plot set up during bleaching is the addition of the colour chart attached to the standard using a Velcro strip (Figure 2B). These charts allow for colour correction in images during post processing, although colour correction methods are outside the scope of this SOP. A minimum of one diver is required to complete imaging, and one diver is required to perform in-water bleaching surveys. All can participate in packing up the plot. Further details are found in section 2.1.3 and 2.2.

Table 2. Diver personnel required to conduct 3D mapping during coral bleaching.

Diver	Task
1	Photogrammetry - Imaging
2, 3	Photogrammetry - Setup - Pack-up - Measurements
4 (5 optional)	In-water validation - Taxonomic knowledge required

Table 3. Equipment for plot setup (bleaching-specific).

Item	Total number required	Location in plot	Comment
Standards (dumbbells and colour charts)	7 (minimum 5)	2 or 4 on corners of plot (~1.5m from picket) 3 spread along centre line of plot	Try to capture variability in depth and light across plot Dumbbells act as scalebars (30cm from center dot to center dot).
White balance slate	1	Kept with diver imaging, only used immediately prior to plot imaging	Grey slate for white balancing
Sphere trees	2	On pickets	As per SOP 14

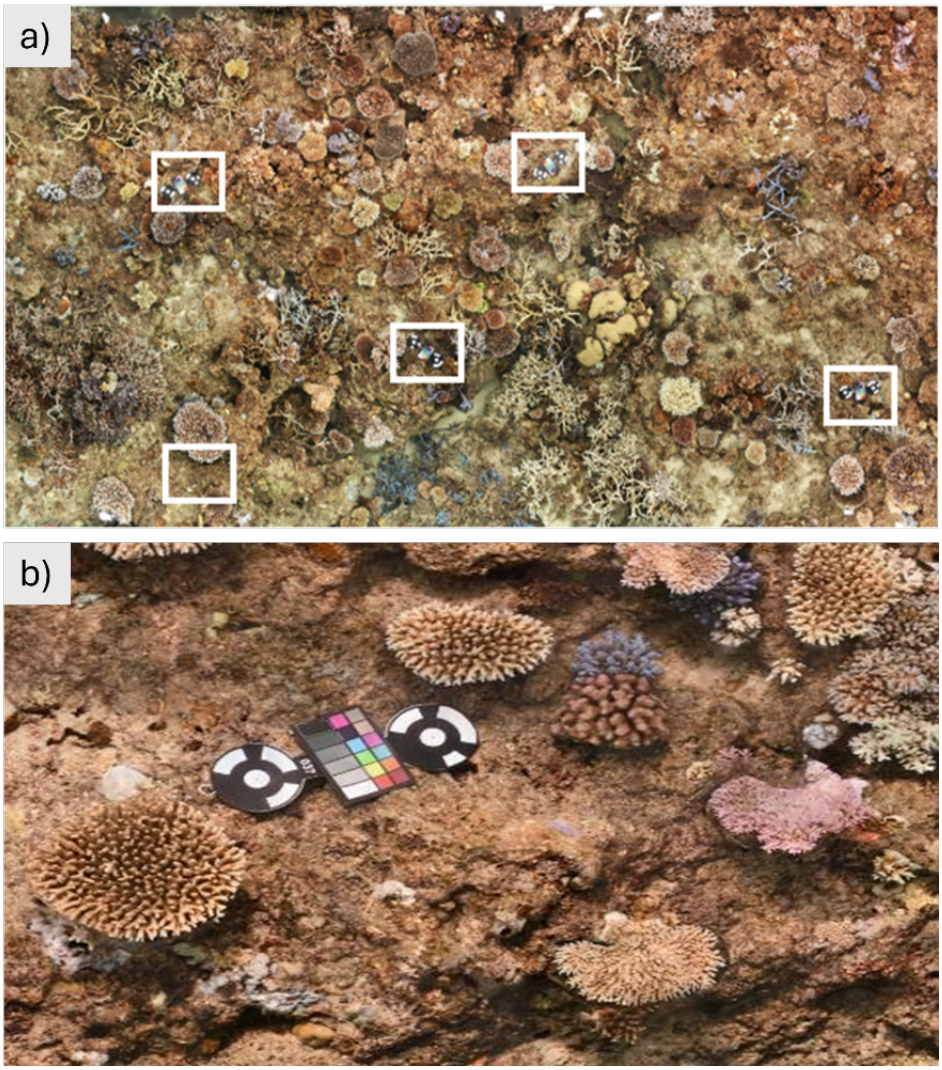


Figure 2. Examples of standard placement. (a) white rectangles highlight standards with dumbbell and attached colour chart placed throughout the plot. (b) A close-up of one standard on the reef. Ensure standard is not placed on top of coral and is not blocked from the view of the camera (e.g. obscured by a coral). Also ensure colour chart does not obscure marker patterns on either end of dumbbells.

2.1.2 Camera Settings

Recommended camera settings for imaging during a bleaching event are outlined below (Table 4). These are a guide and should be assessed by imagers at the start of each dive. See SOP 14 for further detail on settings. For bleaching, it's recommended that RAW images be collected in addition to the standard JPEG's outlined in SOP 14 for additional colour standardisation purposes. However, users should be aware that RAW files will significantly increase the data storage requirements for both memory cards and hard drives, see Appendix A, Table 15 for details.

Table 4 provides recommended camera settings for maximising data quality when collecting images. Details on specific EcoRRAP cameras (Nikon D850 and SONY A6700) can be found in Appendix A.

Table 4. Recommended settings for maximising data quality when collecting images during bleaching conditions. These settings apply to most mirrorless and DSLR cameras.

Setting	Recommendation
Imaging Mode	Aperture priority or Manual
ISO sensitivity	Auto or 1000-1600 for bright, shallow areas; 2500 for dark, deep areas. Restrict to a maximum of 3200 to avoid noise
Shutter speed	1/500s Restrict to a minimum of 1/320
Aperture	F8 – F11 Okay to go lower if needed to meet above settings for ISO and shutter speed
Image format	RAW (lossless compressed) + JPEG (small, basic)
Interval timer	0.5 - 1s Aim for ~1200-1500 for a 12 x 6 m plot
Exposure compensation	-0.3 in low light -0.7 in high light Negative exposure compensation is important to reduce overexposing light/white colonies

2.1.3 Suggested Workflow

5 describes the recommended workflow for conducting photogrammetric surveys during a bleaching event. This can be adapted to fit different capabilities, personnel, and resources. Detailed methods are outlined in Section 2.2.

Table 5. Suggested imaging workflow for between 4-6 divers.

Dive Team	Number of divers	Tasks	Equipment
Setup	2	All divers work to locate pickets Diver 1: - Clean and scrape pickets as needed - Replace picket tags if damaged or missing - Attach sphere trees to pickets with clamps Diver 2: - Place dumbbell markers and attach colour chart with Velcro - Measure marker depths	- 2 x catch bag for dumbbells - Bag of 28 x colour charts - Clamp bag with 8-12 clamps - 1 marker data sheet - Dive slate with pencil - 8x sphere trees - Cable ties (if clamps don't fit) - Replacement cattle tags - Bag of tools for scraping pickets - 4x sets of 7 dumbbells
Photogrammetry imaging	1-2 (if only 1 diver, they dive with bleaching assessment or set-up team)	Diver 1: - Image plot 1 and 2 according to method in Table 5 - If only one diver, image all four plots Diver 2 (optional): - Image plots 3 and 4 according to method in Table 5 Both divers: - If time allows after imaging, assist in dismantling sphere trees and collecting dumbbells	- 2 x camera rigs - 4 x DSLR cameras (2 per rig) - White balance slate (neutral gray)

Bleaching assessment (optional, recommended for field validation)	1-2 (if only one diver, dive with imager)	Diver 1: - Complete in-water bleaching assessment at the colony and plot level - If only one diver, complete assessment in Plot 1 and 3 (approx. 10-12 minutes per plot) Diver 2 (optional): - Complete in-water bleaching assessment at the colony and plot level in Plot 2 and 4. See section 2.2 for in-water survey methods. Both divers assist in packing up dumbbells and sphere trees once finished.	- Printed benthic map and datasheet to record categories (only possible if site has been visited previously) - Large A3 dive slate with pencil

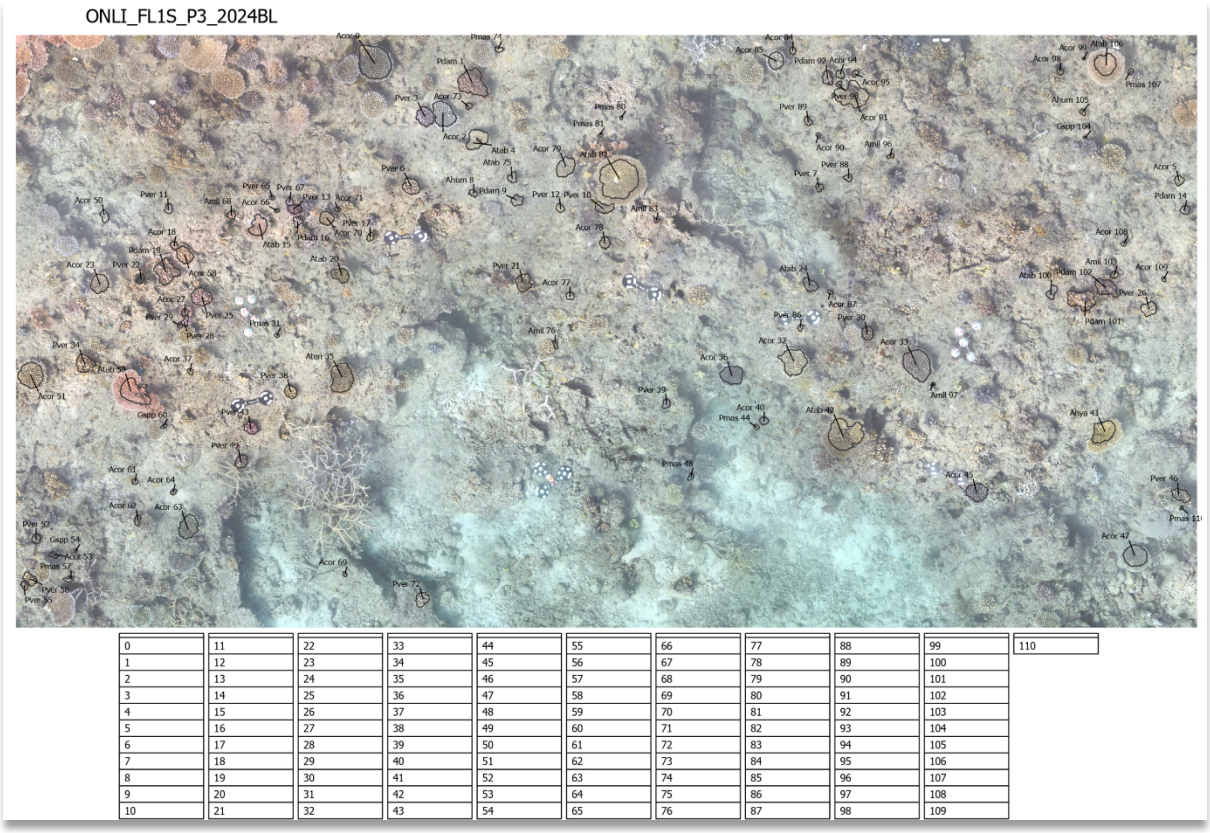
2.2 In-water survey methodology

Where practical, orthomosaic-based bleaching classifications should be validated using in-water surveys of digitised colonies. To ensure colonies are uniquely identified, categorised and consistently tracked, this in-water survey method is applicable only to plots with existing orthomosaics. The previous orthomosaic is used as a reference map to locate colonies and record their bleaching categories. To optimise data collection within a constrained dive time (approx. 20-30 minutes), two of the four plots per zone (see SOP 14 for survey design). The same two plots (e.g. plots 1 and 3) should ideally be surveyed in each zone, unless the quality of the previous orthomosaics is inadequate for reliable colony relocation (e.g. due to missing areas, poor lighting, or image blurriness). Orthomosaic quality should be assessed prior to printing plot maps.

Prior to conducting the surveys, plot maps must be created and printed (see Section 2.2.1 for map creation). For plots of approximately 100 m², maps should be printed on A3-size underwater paper (for legibility; requires an A3-size slate). Each map should clearly display the digitised colonies, with the taxon name and a unique numerical ID labelled for each colony (Figure 3; see Section 2.2.1 for details on map creation). For plots substantially larger than 100 m², consider dividing the plot into multiple maps for ease of use underwater.

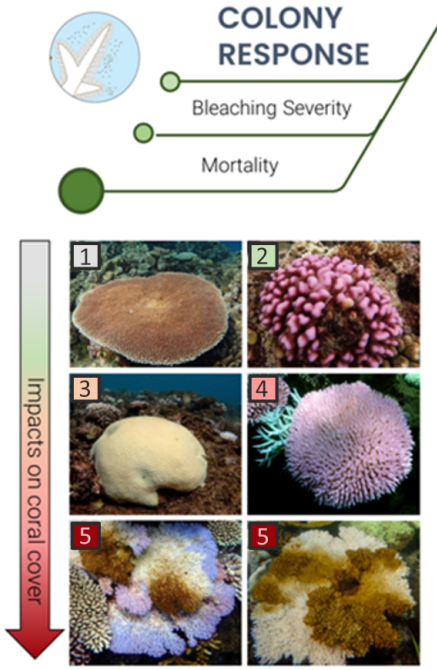
At the beginning of each survey, observers should orient themselves within the plot using sphere trees as reference points and use the printed maps to locate colonies. Observers should aim to validate as many colonies as possible across a range of bleaching categories, colony sizes, and target taxa within approximately 10–15 minutes per plot. Validating between 3 and 10 colonies per bleaching category, per taxon, and per size class (i.e. small, medium, large) is acceptable. The exact number will depend on the number of taxa selected, the difficulty of colony relocation, and the available dive time.

Once a colony is located, assign a bleaching category following the methods described in Cantin et al. (2021) (Figure 4; based on Gleason 1993; Baird & Marshall 2002). Record the assigned bleaching category next to the corresponding colony number in the table located below the map (Figure 3). Any new (non-digitised) colonies encountered during the survey can be noted in the map margins for subsequent digitisation. See Appendix B, Table 22 for the list of EcoRRAP priority taxa that were included in the 2024 in-water bleaching assessments.



0	11	22	33	44	55	66	77	88	99	110
1	12	23	34	45	56	67	78	89	100	
2	13	24	35	46	57	68	79	90	101	
3	14	25	36	47	58	69	80	91	102	
4	15	26	37	48	59	70	81	92	103	
5	16	27	38	49	60	71	82	93	104	
6	17	28	39	50	61	72	83	94	105	
7	18	29	40	51	62	73	84	95	106	
8	19	30	41	52	63	74	85	96	107	
9	20	31	42	53	64	75	86	97	108	
10	21	32	43	54	65	76	87	98	109	

Figure 3. Bleaching map datasheet example. Plots are oriented so the top is towards the reef flat (shallow side) and the bottom is towards the reef slope (deeper side). Numbers in the table below the map correspond to numbered colony. Divers use maps to locate outlined, numbered coral colonies and assign a bleaching category to the table using the corresponding colony ID number. Black and white markers denote scale (distance between 2 targets is 40 cm).



Bleaching Impacts that could decrease coral cover

Colony Response	% Colony Area Bleached	Descriptor	Potential Impact	Score
No Bleaching	0	Healthy looking coral	none	1
Partial Bleaching (MINOR)	5-50	Partial colony bleached white with 95-50% pigment remaining	low	2
Partial Bleaching (MAJOR)	50-90	Partial colony bleached white with 10-50% pigment remaining	medium	3
Fully Bleached (SEVERE)	100	Entire colony bleached white with or without fluorescence	high	4
Dead	10-100%	Full colony or partial tissue loss	high	5

Adapted from Cantin et al. 2021

Figure 4. Examples of bleaching categories used for in-water validation surveys of colonies within EcoRRAP plots. Figure adapted from Cantin et al. 2021.

2.2.1 Bleaching map creation

The following workflow (Table 6; Figure 5) describes the process for generating underwater maps (Figure 3) for use in the in-water survey method described in section 2.2. This workflow uses ArcGIS Pro (Version 3.2.0) to review, select, and prepare orthomosaic files (.tif) and annotation files (.shp) for printing on A3 size underwater paper.

It is recommended to create a Processing Log in Microsoft Excel or similar platform to track map creation progress and record the specific .tif and .shp files used to create each map. A sample processing log and EcoRRAP-specific file storage location can be found in Table 20 in Appendix A.

Note: *This workflow assumes some previous knowledge of ArcGIS Pro. Please see the ESRI website for a more detailed introduction on how to use ArcGIS Pro. Maps can also be made in other GIS software such as QGIS or R, however, these may require alternate steps to those presented below. Additionally, in the following instructions, the term 'annotation file' is used to refer to the shapefile/vector data (e.g., labelled features), and the term 'ortho' is used to refer to the underlying .tif/raster imagery associated with those shapefiles.*

2.2.1.1 Map Creation Steps in ArcGIS Pro

Table 6. Steps to create underwater maps for in-water colony-level bleaching validation assessments.

Step	Task	Details
1	Start project	Open ArcGIS Pro > New Project > Map Name project as desired and save in desired location
2	Add folder connection	In Catalog pane (right-hand side of window by default): - Right-click on **Folders** > **Add Folder Connection** (ctrl+shift+c) - Navigate to folder with ortho and annotation files and select OK - Selected folder will now appear as a subfolder under 'Folders'
3	Add layers	Load the ortho and corresponding annotation file from the most recent timepoint to the map (drag/drop or manual add) - If asked to build pyramids/stats: untick and click OK. If loading fails, re-add and accept prompts.
4	Select plots	Select ortho files for selected plots: - Review target plots to use (e.g., plots 1 and 3) and determine whether ortho quality is good enough. - If not, review other potential plots (e.g., plots 2 and 4) or use all plots if more divers are available - If no orthos from that timepoint are of sufficient quality, review and select files from the previous timepoint
5	Set transparency	Select RGB ortho layer (in Contents pane) > **Raster Layer** tab (top of window) > Set **Transparency** to **25–40%** (dependent on individual ortho)
6	Style annotations	Right-click annotation layer (in Contents pane) > **Symbology** > Click on coloured rectangle next to Symbol > Choose **unfilled polygon with bold outline**

7	Label colonies	Select **'List by Labeling'** (tag icon) in Contents pane - Tick **Class 1** and open labelling tab (top of screen) - Select **'TL_id'** and **'TL_Class'** for label - Click '**Label**' (top left of window) Customize style (font, size, color) Save for reuse
8	Create layout	Insert > **New Layout** > A3 Landscape. Rename map/layout to match plot file name (e.g. TSAU_BA1S_P1_2024BL). Record ortho name in Processing Log
9	Add map frame	Insert > **Map Frame** > draw bounds on layout. Layout tab > **Activate** to zoom/pan, then **Close Activation**
10	Clean map view	Uncheck **World Topographic** and **World Hillshade** in Contents
11	Add table	Insert > **Table Frame** for colony list - In Element Pane > Fields > tick only **'TL_id'**
12	Add title	Insert > **Text** with plot name (should match map/layout name saved in step 8).
13	Final check and export	Ensure clear layout with white space at edges Share > **Export Layout** > **Flattened PDF** > save to network (save in desired location) Open PDF, confirm appearance, and print single-sided on **A3 waterproof paper**. Mark as complete in Processing Log

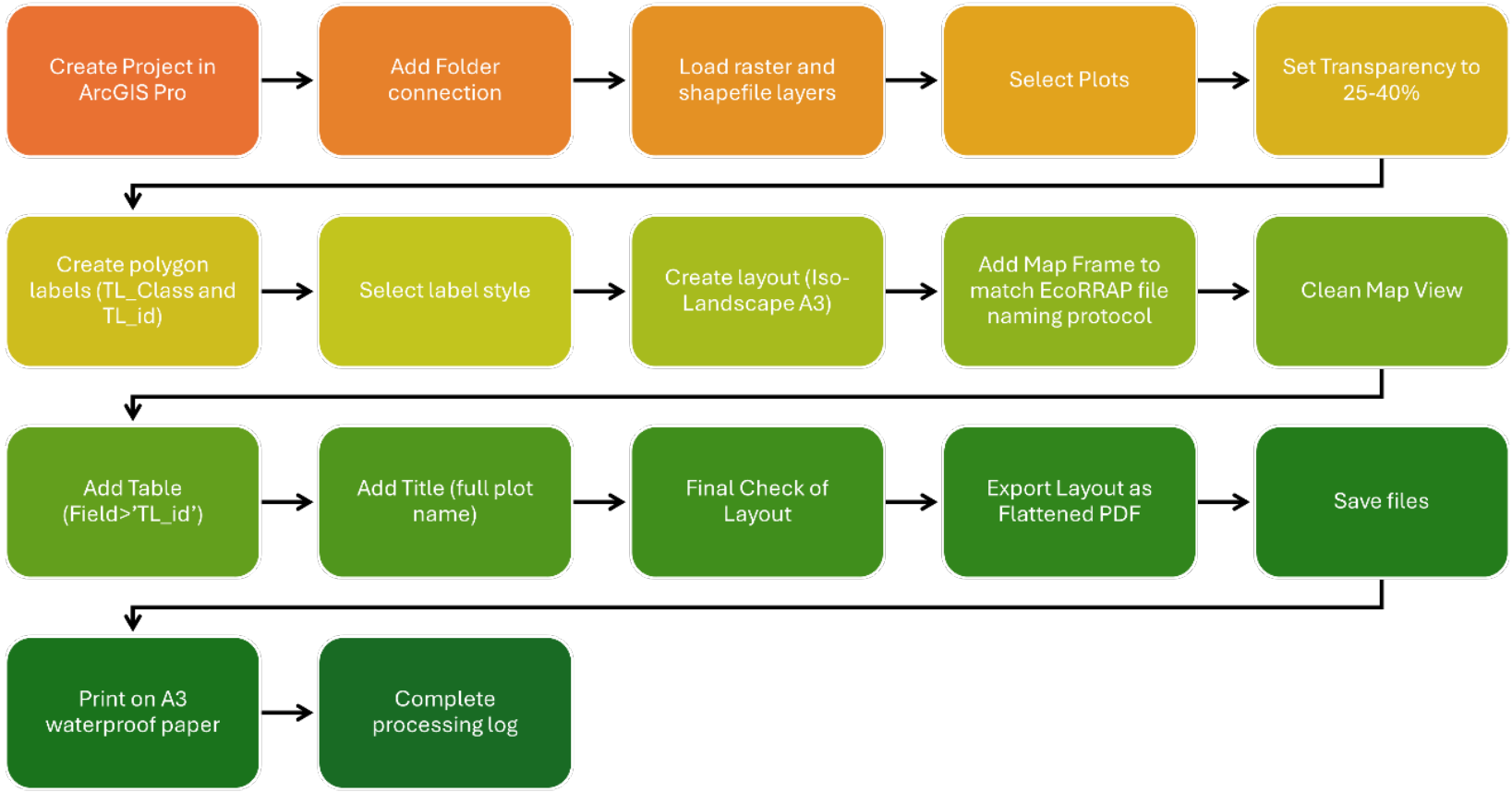


Figure 5. Flowchart representation of the steps to create a printed map for in-water validation surveys from an orthomosaic.

2.3 In-field processing

Basic in-field processing is strongly recommended to ensure that collected images are of sufficient quality for later analyses. Because photogrammetry requires substantial computing power, full processing in the field is typically impractical on standard field computers. Instead, field processing should serve as a preliminary image quality check. The results can guide real-time decisions, such as whether a site should be re-surveyed if image quality is poor and improvements are understood, or inform adjustments for upcoming surveys if image quality is acceptable but could be enhanced. While field processing is not mandatory, it is highly recommended. If time or resources do not permit in-field processing, images should at minimum be manually reviewed for quality. Table 7 outlines recommendations for quality checks at various stages of in-field processing.

Note: *Full workflow for in-field processing is described in SOP 14 Field photogrammetry in 4D: Overview & in-field workflow. The following are modifications that should be considered when applying the workflow during coral bleaching.*

Table 7. Considerations and potential modifications required for in-field Metashape processing during coral bleaching.

Consideration	Recommendation
Image file type	Use small .JPEG images only (~ 3Mb, 3104 x 2064 px) for faster processing. RAW files are used later for in-office final processing. They can be used later for colour correction in-office or simply converted to high quality JPEGs for office processing (*though colour correction is outside the scope covered by this SOP*).
Review image exposure	Scroll through the photo set and check for overall exposure consistency: 1. Are images generally too dark or too light? 2. Are bleached corals overexposed (loss of detail in white areas)? If the answer to either of the above is 'Yes', consider batch postprocessing to improve images or resurveying, also analyse how to improve images in near-future dives.
Model alignment	Align photos at medium quality using small JPEG images. Use this alignment to check image coverage and alignment accuracy. If alignment is less than 80% of enabled images see SOP 14 for potential solutions or consider resurveying that site.
Build basic mesh	Generate a mesh from the medium-quality alignment using default settings.
Build orthomosaic	Set orientation to top-down manually by eye using the rotate object tool, then build the orthomosaic using the mesh as source and the 'Current View' setting.
Orthomosaic export (optional)	Export the orthomosaic at a pixel size of 4600 or inspect directly in Metashape.

3 IN OFFICE PROCESSING

Processing 3D models from bleaching events requires specific modifications to the standard EcoRRAP workflow (SOP 14 & 16) to ensure consistent and accurate orthomosaics and 3D models. Field-based and in-office Metashape processing settings require modification when working on heavily bleached reefs due to a potential reduction in image quality, poor model alignment, or large holes in the model caused by the abundance of bright white bleached corals. This is especially problematic in areas of large monoculture thickets of staghorn *Acropora* spp. Additional differences from the standard EcoRRAP workflow may arise from using alternative camera systems (e.g., quality and quantity of images) and should be considered by individual users.

Alternative settings for working with images from bleached reefs are presented for both in-field (Table 7, Section 2.3) and office-based (Table 9) processing, including how to convert RAW image files to JPEG (Table).

3.1 In-office processing

Note: *Full workflows for the in-office processing and 3D model creation are described in SOP 16 Field photogrammetry in 4D: Model processing. The following are alterations that should be considered when applying this workflow processing models from bleaching imagery.*

3.1.1 Converting RAW files to JPEG

This section contains lines of code that can be copied and pasted as required. These lines appear in the following format: `code line`

It is recommended to capture bleaching images in RAW rather than in the standard JPEG format described in SOP 16. Since RAW files cannot be processed directly in Metashape, they must first be converted to JPEG. This section outlines the steps for converting images to JPEG specifically using the AIMS HPC and Python scripts. The RAW file types NEF and ARW refer specifically to files produced by Nikon and Sony cameras used by AIMS; therefore, the following scripts are applicable only to these file types.

Note: *It is recommended to colour-correct RAW files prior to conversion to .JPEG format, although that workflow is outside the scope of this SOP.*

The python scripts needed in Table 8, step 3 below are provided here:

- For .NEF raw: https://github.com/open-AIMS/EcoRRAP3D/blob/main/convert_nef_to_jpeg.py
- For .ARW raw: https://github.com/open-AIMS/EcoRRAP3D/blob/main/convert_arw_to_jpeg.py

Note: the python scripts to convert raw to jpeg provided here are specific to NEF and ARW raw formats. If the raw format used is different, it is recommended to edit and test the conversion scripts.

- A SLURM file (Table 8, step 4) example can be found here https://github.com/open-AIMS/EcoRRAP3D/blob/main/raw_conversion.slurm

Table 8. Steps to convert RAW images to JPEG using the AIMS HPC.

Step	Task	Notes
1	Set up HPC for processing (AIMS specific)	Requirements for use of HPC: - Windows 10: Install Windows Terminal from Microsoft Store - Windows 11: Inbuilt (no need to install Terminal), WSL2 compatible, contact AIMS Helpdesk for account/access to HPC Information on HPC use can be found here: - Introduction - AIMS HPC User Documentation
2	Create Anaconda environment and install python packages	- Open Terminal/Command Prompt - Connect to Secure Shell Frontend (SSF) by typing: o **`ssh username@hpc-l001.aims.gov.au`** - Enter password (will not be visible) and hit enter - Ensure home directory by typing: **`cd~`** - Create conda environment: o **`module load conda/anaconda3`** o **`conda create -n 'environment name' python='version`** o *`(e.g., conda create -n raw_conversion python=3.12)`* - Activate conda environment: o **`conda activate 'environment name'`** o *`(e.g., conda activate raw_conversion)`* - Install required packages 'rawpy' and 'imageio': o **`pip install rawpy`** o **`conda install -c conda-forge imageio –y`**

3	Create directory and check script is running	- Create directory: o **`mkdir 'directory name'`** o *(e.g., mkdir raw_conversion)* - Change directory to the new created directory: o **`cd 'directory name'`** o *(e.g., cd raw_conversion)* - Launch Nano text editor: o **`nano 'python script.py'`** o *(e.g., nano convert_nef_to_jpeg.py)* - Copy and paste relevant (arw or nef) python script provided earlier into Nano window (right-click to paste) - Press Crtl + X to exit, then Y to save, then Enter to exit - Confirm file has been saved: o **`cat 'python filename.py'`** o *(e.g., cat convert_nef_to_jpeg_py)* - Check input/output paths: o **`ls -l/filepath`** o *(e.g., ls -l/net/cluster1-prod-hpcnfs.aims.gov.au/3d-ltmp/pipeline/EcoRRAP_HPC/test_input)* - Run python script on a subset of data to check that it works: o *(e.g., python convert_nef_to_jpeg.py "/net/cluster1-prod-hpcnfs.aims.gov.au/3d-ltmp/pipeline/EcoRRAP_HPC/test_input" "/net/cluster1-prod-hpcnfs.aims.gov.au/3d-ltmp/pipeline/EcoRRAP_HPC/test_output")* - Check job is running on head node by opening a new Secure Shell (SSH) connection and **`htop`** to view node load

4	Create a SLURM (Simple Linux Utility for Resource Management) batch file to run script across multiple HPC nodes	- Open Nano and create SLURM file: o **`nano 'slurm filename.slurm'`** o *(e.g., nano raw_conversion.slurm)* - Write/paste in script (link to example provided earlier) and save (Ctrl + X, Y, Enter) - Check SLURM file: o **`cat 'slurm filename.slurm'`** o *(e.g., cat net_conversion.slurm)* - Run file: o **`sbatch 'slurm filename.slurm'`** o *(e.g., sbatch nef_conversion.slurm)* - If successful, output will read: o **`'Submitted batch job #####'`** - Check job queue: o **`squeue`** - *Note at this point, one SLURM is needed per input folder, to run multiple scripts on multiple folders, create multiple SLURM files to send jobs simultaneously – change the job name in each SLURM file accordingly.* - Check outputs and errors in the current directory: o **`ls –l`** - Use **`cat`** function to print and inspect above errors and outputs o *(e.g., cat nef_to_jpeg_324480.err)* - To cancel a job: o **`scancel 'job number'`** o *(e.g., scancel 324480)*

3.1.2 Metashape Processing

The following section outlines the key modifications to standard in-office processing workflows outlined in SOP 16, Table 10. These modifications are necessary for handling bleaching imagery.

Table 9. Recommended modifications to in-office Metashape processing Chain 2.

Task	Recommendation	Notes
Alignment	**Highest quality**	Used to increase the number of points (fill holes and improve alignment of bleached coral thickets). The rest remains unchanged; however the key and tie point limit can be set to 0 (Metashape will find as many tie points as possible), which can be beneficial for high-quality results but will increase processing time and resources needed significantly.
Sparse Cloud filtering	**GoPro filtering values or no filtering**	For some plots, applying the DSLR filtering values found in SOP 16 resulted in too many points being deleted. To prevent this, we recommend using the GoPro filtering values or no filtering at all. This will retain more points in low image-number projects. The GoPro filtering script is part of the 3D processing workflow published in SOP 16 and can be found here: EcoRRAP3D/Metashape_v1.7.6/GoPro/Chain2/SparseCloudClean_GoPro.py at main · open-AIMS/EcoRRAP3D
Build Dense Cloud (recommended)	**Medium quality** **Calculate point confidence**	Use as a troubleshooting step if building mesh from depth maps results in poor quality mesh. Building the mesh from the dense cloud can increase the number of points (fill holes and improve alignment of bleached coral thickets). In Metashape: Workflow > Build Dense Cloud. It is recommended to tick the 'Calculate point confidence' box to later be able to remove low confidence points and reduce the dense cloud size before building the mesh (Figure 6a).
Build mesh	**Source: Dense Cloud** **High face count**	Used to increase the number of points (fill holes and improve alignment of bleached coral thickets) and produce better (i.e., less holes) meshes than those created from depth maps. If a dense cloud was built, choose 'Dense cloud' as source data in the dialog box. In Metashape: Workflow > Build Mesh (Figure 6b)
Export mesh for co-registration	**unchanged**	Follow the steps in SOP 16, Table 11 to co-register the mesh with the reference and apply the co-registration matrix.

Build DEM	**Source: Dense Cloud**	If the mesh presents a lot of holes, building a DEM from the dense cloud will enable to build an orthomosaic from the DEM (next step) and reduce the number of holes present in the orthomosaic.
Build Orthomosaic	**Source: DEM**	Helps reducing the number of holes in the orthomosaic if there are holes in the mesh.

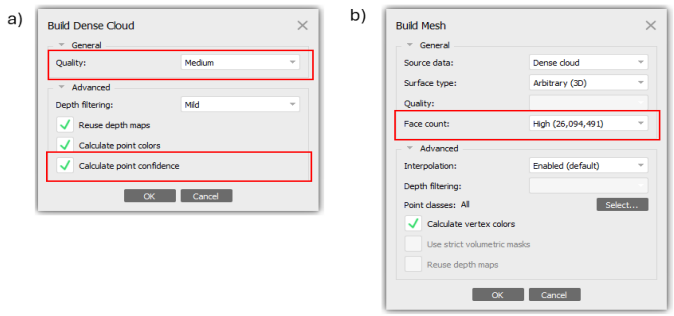


Figure 6. a) Build Dense Cloud window in Metashape, quality level set to medium, 'Calculate point confidence' option ticked, and b) Build Mesh window in Metashape, face count set to high (outlined in red).

4 OPERATIONAL WORKFLOW FOR QUANTIFYING PLOT AND COLONY LEVEL CORAL BLEACHING FROM ORTHOMOSAICS

This section describes the workflows for quantifying 1) the spatial extent of bleaching at the plot level and 2) bleaching prevalence and severity at the colony-level from 2D orthomosaics using the software TagLab (v2022.02.11-v2025.2.15). Detailed information on how to allocate the various biological manifestations of bleaching into our prescribed bleaching categories follows in Section 5. See SOP 17 in this series for details on how to use TagLab and the EcoRRAP methods for colony digitisation. The information presented below is supplemental to that provided in SOP 17 and only details the steps to assess bleaching extent, prevalence, and severity. Note that it is also possible to apply these methods using other software (e.g. ArcGIS), however, this is not explicitly covered in this document.

The workflow presented in the following sections is compatible with a range of bleaching categorisation systems. However, for consistency across studies, we recommend using the severity categories outlined in the following sections (used by EcoRRAP in the 2024 bleaching event). These categories provide a high level of detail but can be collapsed down for comparability. The EcoRRAP photogrammetry team conducted surveys during both the 2022 and 2024 bleaching events that affected the GBR. Whilst the methods and severity categories for assessing colony-level bleaching

differed slightly between events, they remain comparable, and both are described in the appendices.

4.1 Plot-level orthomosaic bleaching assessment

Note: *For detailed guidance on generating orthomosaics, refer to SOPs 14 & 16.*

It is recommended to quantify the prevalence (i.e., bleaching was present or absent within a plot) and estimated proportion (i.e., number of individuals bleached vs not bleached) of bleaching across each plot to complement in-water assessments (section 2.2) and colony-level categorisation from orthomosaics (section 4.2). Plot -level assessments provide bleaching metrics which quantify the spatial extent (geographical footprint) of bleaching, resulting in a complementary dataset that augments understanding of bleaching impacts to multiple scales. The following plot-level assessment method is based on the EcoRRAP survey design where each zone includes four replicate 12 x 6m plots, each captured in a single orthomosaic, but can be modified for use with differing survey designs.

This method can be used as either 1) a rapid assessment following in-field model processing (see SOP 14), or 2) conducted following completion of in-office model processing (see SOP 16). Table 10 describes the steps required to conduct a rapid assessment of the spatial extent of bleaching at the plot level the day following imaging using low-quality orthomosaics produced in the field.

Scoring methods are adapted from Berkelmans et al. (2022) aligning with the classification categories used by the AIMS Aerial Bleaching Assessment Team during aerial surveys. This consistency ensures that bleaching data collected from orthomosaics can be meaningfully compared with broader-scale aerial data and used for ground-truthing.

4.1.1 Bleaching assessment workflow (plot-level)

After each plot is imaged (see SOP 14 for details), steps in Table 10 can be followed to assign one of the five bleaching categories listed in Table 11. Note that with the following workflow there is the potential for observer bias, especially when there are multiple observers performing surveys. To limit this, a single observer is recommended where possible.

Table 10. Plot -level bleaching assessment workflow.

Step	Task	Notes
1	Create orthomosaic	Generate low-quality orthomosaic as per SOPs 14 & 16 and section 3 of this SOP.
2	Crop orthomosaic	Crop to typical plot extent (e.g. 12 x 6m for EcoRRAP plots) using Windows Photo Viewer. Dumbbell markers or other reference features can be used for scaling (for EcoRRAP, 30cm between center black dots on dumbbells).
3	Divide and zoom	Divide orthomosaic into 4 quarters to better assess coral cover and substrate type. Zoom in so that one quarter fills screen.
4	Estimate hard coral cover	Assign an estimate of hard coral cover (users can include estimates of other taxa that bleach, depending on the research question)
5	Assign bleaching category (quarter plot-level)	Assign an estimate of bleaching for each quarter of the orthomosaic based on the **percent of living corals bleached** (categories adapted from Berkelmans et al. 2022, see Table 11). White, pale, and fluorescent colonies are considered bleached in this method. Categories reflect the areal extent of the living coral affected, not the number of colonies.
6	Calculate plot category	Calculate overall plot category by averaging the four quarter-plot categories. Round to nearest whole number.
7	Calculate site/zone category	Only applicable if multiple plots exist within a zone. Calculate zone-level category by averaging plot-level categories (e.g. four plots per zone, and 2 zones per site for EcoRRAP).

Table 11. Plot-level bleaching categories and associated descriptions, adapted from Berkelmans et al. 2022.

Category	Corals bleached	Description
0	< 1%	No bleaching evident, all corals look normally pigmented
1	1-10%	The odd, bleached colony present (figure 7a)
2	10-30%	Some bleaching, but less bleached colonies than healthy (7b)
3	30-60%	Equal numbers of bleached and healthy colonies (7c)
4	60-90%	More bleached colonies than healthy (7d)
5	>90%	Almost all colonies bleached, with some recent heat stress mortality (7e).

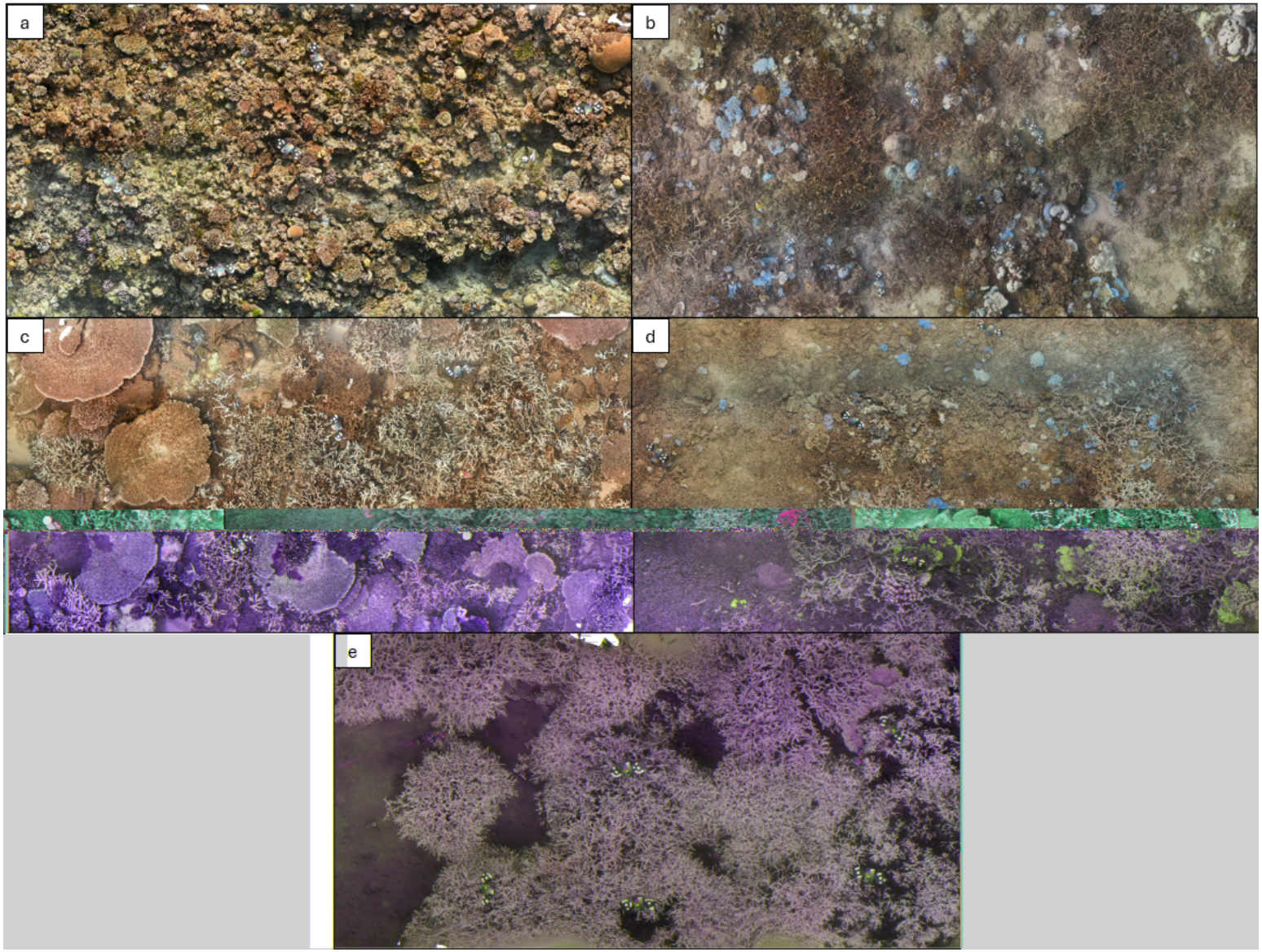


Figure 7. Low quality orthomosaic examples for plot-level bleaching categories 1-5.

a) less than 10% of colonies show signs of bleaching, resulting in category of 1; b) 10-30% of colonies show signs of bleaching, resulting in a category of 2; c) 30-60% of colonies show signs of bleaching, resulting in a category of 3; d) 60-90% of colonies show signs of bleaching, resulting in a category of 4; e) >90% of colonies show signs of bleaching, resulting in a category of 5.

4.2 Colony-level bleaching assessment from 2D orthomosaics

As well as plot level bleaching assessments, it is recommended to quantify bleaching at the colony level within 2D orthomosaics. This not only provides detailed data on differential bleaching prevalence and severity within and among priority taxa and colony sizes but also adds bleaching metrics to existing demographic data for tracked colonies. Importantly, colonies tracked through time via co-registration can be assigned a bleaching category useful for predicting changes in vital rates. The colony digitisation workflow in SOP 17 is a compulsory prerequisite to the bleaching assessment method presented here, which should be performed after (or simultaneously with) the workflow described in SOP 17. This section (Table 12; Figure 8) outlines the sequential steps to follow to assign colony-level bleaching categories to digitised corals within an orthomosaic. Steps 1 and 4 in Table 12 are specific to bleaching assessment and are additional to the standard digitisation tasks described in SOP 17. Visually quantifying bleaching is inherently subjective, but to aid standardisation, we provide detailed information on how to select a bleaching category in Section 5.

Table 12. Steps to quantify colony-level bleaching from 2D orthomosaics.

Step	Task	Notes
1	Observer comparison and standardisation	Before commencing assessments, it's recommended for observers to consult with experts, review independent bleaching categories across a subset of colonies, and cross-compare results to standardize scoring criteria. It's recommended that observers reach a 90% agreement rate on categorisation before proceeding with assessments. Based on above procedure, EcoRRAP developed a decision tree to assist with consistent categorisation (Figure 8).
2	TagLab setup	See SOP 17 for detailed steps, if required. Load orthomosaic from bleached timepoint. Transfer colony polygons from previous timepoint (or digitize new colonies).
3	Edit colony edges	If transferring from previous timepoint: edit polygon border and add any required notes before assessing bleaching (see SOP 17 for detailed steps).
4	Assign bleaching category	Assess bleaching level based on Figure 8 and Table 13. Colony-level bleaching categories from 2D orthomosaics, adapted from Cantin et al. (2021) and Gleason (1993). All EcoRRAP categories can be collapsed to broadly compare with Cantin et al. (2021) as shown in the far-right column. More detail and examples is provided in Section 5. Add numerical category in the 'Notes' section (make sure to do this after all edits to colony polygon are completed, otherwise notes may be deleted) - Add a comma followed by a space after any other notes - When bleaching level cannot be reliably assessed (poor imagery, hole in orthomosaic, etc.), use an 'X' in the Notes section to represent 'unknown' and indicate that the colony has been reviewed (i.e., not accidentally missed) - Optional: Add a 'p' (for pale) or 'f' (for fluorescent) to the numerical category, (e.g. 1p, 2f, 3f, etc., see Table 14 and section 5 for more information) o Review orthomosaic from previous timepoint to compare colony appearance. - Optional: Add an 'e' when the category assigned may be an overestimate. Due to colony orientation, the category may be higher than if the colony were to be viewed in the water. E.g., a massive colony may appear fully bleached when viewed from a top-down orientation, but the sides of the colony may still retain symbionts. - If a colony is split into multiple remnant colonies by fission, digitize and categorise each segment separately
5	Export data	Export .shp and .csv files as outlined in SOP 17.

6	Compile data into dataset	See SOP 17 for how to merge files into final dataset or link colonies across timepoints (if dataset contains multiple timepoints).

There are many different methods for categorising bleaching at the colony level, but it is important to ensure methods are comparable (Khen et al. 2022). Therefore, to aid standardisation, we outline the bleaching categories recommended and used by EcoRRAP (Figure 8; Table 13). These methods are adapted from Gleason (1993), are highly detailed, but can be collapsed down for comparability across other studies.

To select a category, observers must 1) determine if a colony can be reliably categorised; 2) determine if there is recent mortality present; 3) if yes, determine if mortality is caused by bleaching; 4) determine the areal extent of the colony impacted by either bleaching or mortality; and 5) assess if there is fluorescence. Table 16 presents the recommended categories and their descriptions, whilst Figure 8 provides a decision tree showing the sequence of questions used to determine the appropriate category for each colony. Additional guidance on applying these categories is provided in Section 5.

Table 13. Colony-level bleaching categories from 2D orthomosaics, adapted from Cantin et al. (2021) and Gleason (1993). All EcoRRAP categories can be collapsed to broadly compare with Cantin et al. (2021) as shown in the far-right column. More detail and examples is provided in Section 5.

Colony response	EcoRRAP category	% colony affected	Description	Cantin et al. 2021 category equivalent
Healthy	**1**	<5%	Healthy looking coral (inclusive of pale branch tips or table edges)	1
Pale	**1p**	<5%	Colony appears paler than usual, but no parts of the colony are completely bleached (i.e., have lost all symbionts from a specific region of tissue). Usually classified where: i. colony is pale but not bleached enough to warrant a 2; and/or ii. colony appears paler than last year but would have been classed as healthy without the ability to look back at last year	1 Note: Cantin et al. (2021) have collapsed pale into healthy category due to inability to look back in time to know if paleness is bleaching or natural variation
Partial bleaching (MINOR)	**2** **2f**	5-50%	5-50% symbiont pigment lost Either: i. <50% is bright white or fluorescing, or ii. <50% of the pigment is lost from the entire colony If fluorescing, add f.	2
Partial bleaching (MAJOR)	**3** **3f**	51-90%	51-90% symbiont pigment lost Either i. >50% is bright white or fluorescing, or ii. >50% of the pigment is lost. If fluorescing, add f	3
Full bleaching (SEVERE)	**4** **4f**	91-100%	Entire colony white or fluorescing. If fluorescing, add f.	4
Recent mortality (MINOR)	**5** **5f**	5-50%	5-50% tissue loss due to bleaching, with bleached tissue. If remaining tissue is fluorescing, add f.	5 Note: Cantin et al. (2021) include colonies with any signs of mortality to be a category of 5.

Recent Mortality (MAJOR)	**6** **6f**	51-90%	51-90% recent tissue loss due to bleaching, with bleached tissue. If remaining tissue is fluorescing, add f.	5
Whole colony mortality (SEVERE)	**7**	>90%	Colony is recently dead, and bleaching is the assumed and likely cause.	5

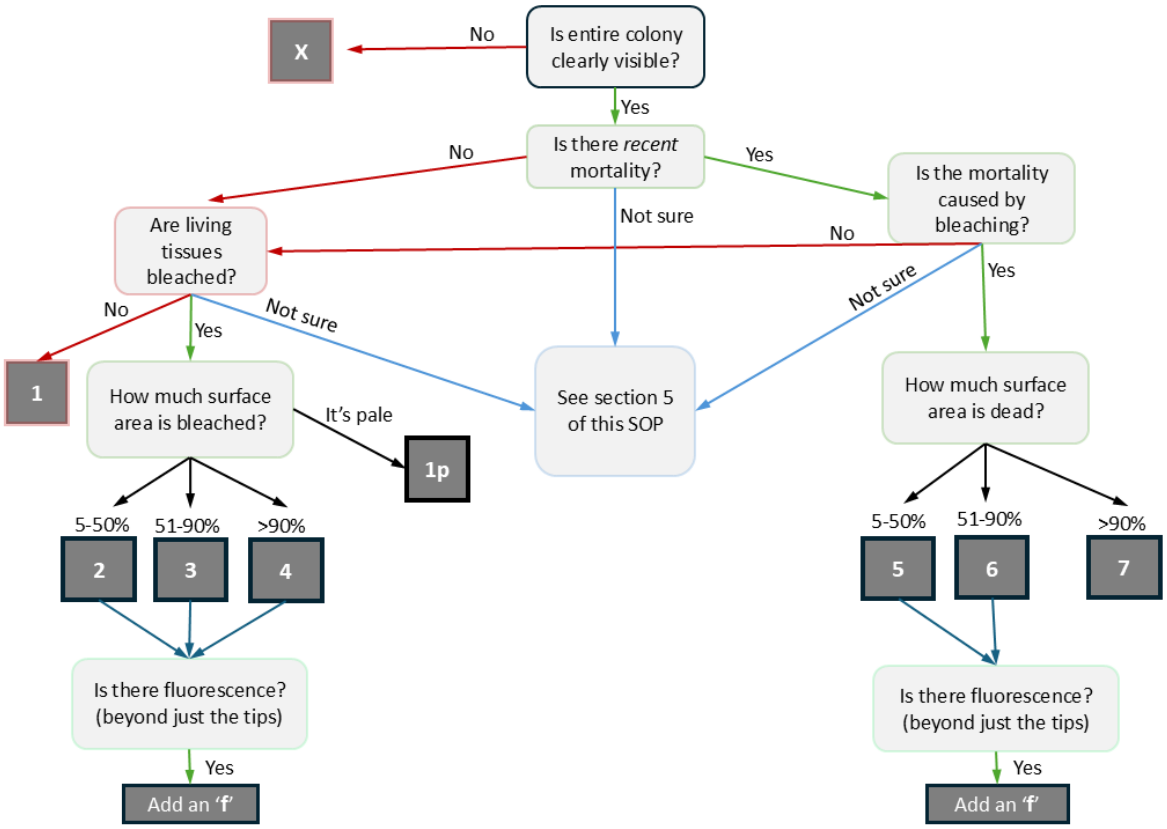


Figure 8. Decision tree to aid consistency in colony-level bleaching category assessment in orthomosaics. Next section in this SOP discusses and offers specific examples for each category.

5 GUIDELINES FOR IDENTIFYING AND CATEGORISING COLONY-LEVEL CORAL BLEACHING RESPONSES FROM ORTHOMOSAICS

5.1 Bleaching category overview

Classifying coral bleaching into discrete categories can be challenging owing to the variety of responses elicited from bleaching coral colonies, from pale and partial bleaching to white and colourful bleaching, as well as varying degrees of mortality. This section provides additional detail on recognising bleaching, and how to assign the recommended bleaching categories (1-7) to colonies from orthomosaics in TagLab.

The following sections are structured in an order which reflects the thought process implemented by observers when assessing bleaching and provides visual examples specific to orthomosaics. The process is ordered as follows: 1) determine if assigning a bleaching category is possible based on the image quality; 2) assess the areal extent of bleaching-induced mortality (none, partial or whole colony) to determine if a colony falls into categories 1-4 (no observed bleaching-related mortality) or categories 5-7 (partial to whole colony bleaching-related mortality); 3) assess the areal extent of bleaching or bleaching-induced mortality to arrive at the final category; and 4) determine if a colony is fluorescent (optional).

Note: *Not all mortality and tissue damage observed will be the result of bleaching. This section includes examples of other agents of colony mortality and provides guidelines on assigning a cause.*

5.2 Determining if a bleaching category is possible

Sometimes sections of the 2D orthomosaic may be obscured, blurred, or certain areas omitted. If confronted with a colony where a bleaching category cannot be confidently ascribed, it is recommended to assign an 'unknown' note instead of a numerical bleaching category (1-7). This is important to clarify in the output that this colony was not missed. If following EcoRRAPs recommended annotation structure (SOP 17), we recommend an 'X' (unsure). Notes of 'X' might be assigned to colonies that are excessively blurry, those that fall within an 'hole' in the orthomosaic, or where only part of the colony is visible (Figure 9).

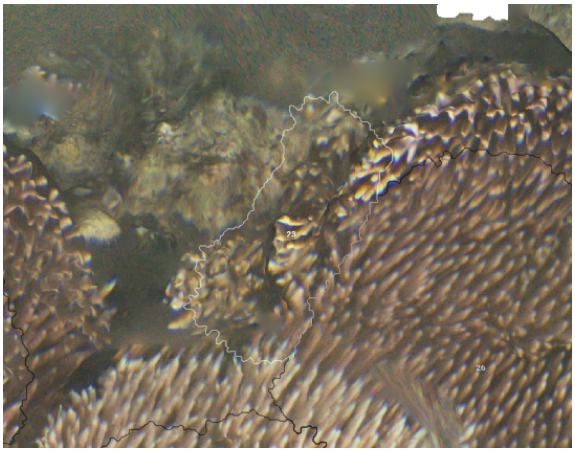


Figure 9. Example of when a bleaching category should not be assigned and instead given an 'X'.

5.3 Determining bleaching-induced mortality (Categories 5-7)

Once it is determined that a colony can be assigned a bleaching category (based on Section 5.2), the next step is to determine if there is any mortality (partial or whole). If there is mortality, it should be determined whether the mortality is recent or old, and then if that mortality was likely caused by bleaching or not. If the mortality was recent and caused by bleaching, a bleaching category (5-7) should be selected based on the areal extent of the mortality as seen in the orthomosaic. The following sub-sections detail the process of recognising recent, bleaching-induced mortality and selecting a category from 5-7.

5.3.1 Recognising mortality

Here, mortality is considered to occur when any portion—or the entirety—of a coral colony's tissue has died. This may accompany skeletal damage (e.g., breakage), but often the tissue sloughs off leaving intact skeleton behind. When assessing a colony for mortality, confidence in the visual differences between living and non-living coral is essential. Colour and texture are key indicators to consider when determining mortality from an orthomosaic. These features vary depending on the age of the injury, whereby recent injuries appear starkly different from older injuries. However, even for injuries of the same age, colour and texture can fluctuate spatially and temporally (i.e., with temperature and nutrient content). Therefore, determining mortality from images will require training and practice. See Section 5.3.2 for more detail on estimating the age of mortality.

5.3.2 Recognising recent vs old mortality

If surveys are competed within a month of peak heat stress (which is our recommendation, where possible), mortality resulting from bleaching will be relatively recent. As such, it is necessary to visually differentiate between old and recent mortality.

Very old mortality will likely be covered in late successional algal turf communities and/or have little to no skeletal detail remaining (Figure 10a). Generally, colour is the easiest distinguishing feature from orthomosaics, where algal turfs appear dark brown or green, and in more scoured environments, the skeleton may appear grey with less details visible, especially at colony edges. If mortality is old, then it is not possible to reliably determine if bleaching is the cause, thus eliminating the bleaching category options of 5, 6, and 7. In this case, only the remaining living tissue is to be

considered for a bleaching category of 1-4. See Section 5.4 for more information about categorising living tissue.

Note: *Partial mortality, old or new, should be noted in the notes section of TagLab as 'pm' as per Table 26 if following the EcoRRAP general annotation structure.*

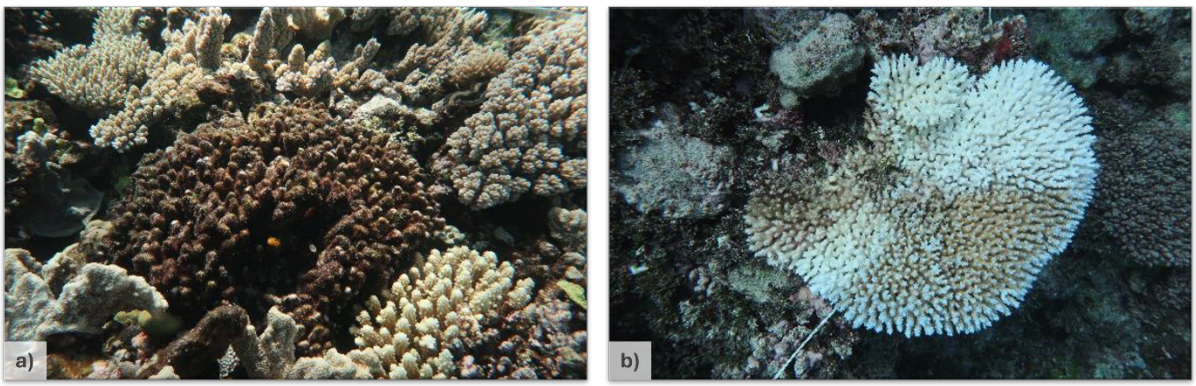


Figure 10. Examples of old and recent morality, including a) Old mortality appearing dark brown and fuzzy from turf algae overgrowth, and b) very recent mortality appearing white with skeletal details still visible.

Very recent mortality (within days) will be bright white with fine-scale skeletal details intact. Slightly older mortality (within weeks) should still be considered, where the skeleton has a fine covering of filamentous algae or turf, often appearing yellow or light brown/green, but retains fine-scale skeletal details (Figure 11). These recent injuries should provide such skeletal detail as to provide the observer with confidence in identifying to genus and/or species (Figure 10b). There will always be a degree of subjectivity in determining the cut-off between when mortality is deemed 'recent enough' to be included, and this should be discussed amongst observers initially. We recommend an independent scoring process followed by QAQC amongst team members. For more information on estimating the age of mortality, see Chandler et al. (2025).

Importantly, recent mortality may or may not be caused by bleaching and more investigation is required before assigning a bleaching category. See the following section, 5.3.3, for how to determine if mortality is bleaching-induced.

5.3.3 Recognising bleaching as an agent of mortality

Depending on survey timing, mortality caused by bleaching is likely to have occurred several days or weeks prior. Therefore, it is expected that bleaching-induced mortality would range from bright white skeleton to a yellow-green hue (Figure 11), but no older. Note that recent mortality will always have relatively fine-scale skeletal structure visible. We recommend observers discuss a cut-off point based on their image-set, as reef conditions will affect the appearance of recent mortality.

Note*: Our recommendations are based on mid-shelf reefs on the GBR during the 2024 austral summer, and may not be directly relevant to every location, or bleaching event.*

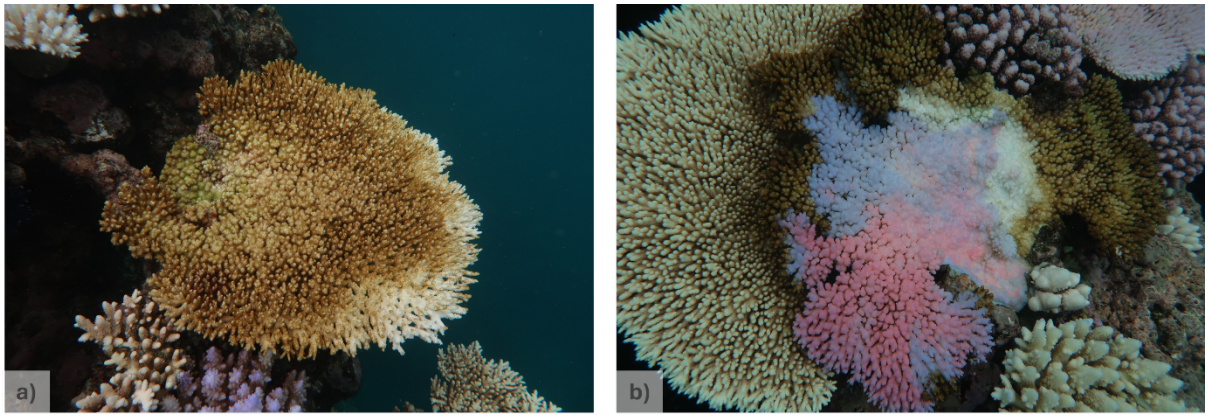


Figure 11. Examples of recent mortality due to bleaching, including a) near full colony mortality caused by bleaching, and b) recent mortality caused by bleaching alongside fluorescing, bleached tissue. Note the yellow-green hue and fine-scale skeletal structure on both examples, indicating that mortality occurred within the few weeks prior to image collection.

However, not all recent mortality will be the result of bleaching (see Burn et al. 2022) and observers should attempt to assign cause, where possible, before assigning a bleaching category of 5-7. Figure 12 shows various examples of recent mortality caused by different agents. Common patterns to look for when recognising bleaching-induced mortality are:

1. Bleaching-induced mortality can be uniform in colour or on a gradient of colour depending on the rate of mortality (i.e., if instantaneous mortality or mortality occurring over several days-weeks).
2. Bleaching-induced partial mortality will generally be accompanied by bleached living tissue close to the site of mortality (Figures 11b, 12a).
3. Often the colony top or branch tips will die first owing to their exposure to photic stress (Figure 12a).

Other common agents of mortality which can be confused with bleaching-induced mortality include predation (Figure 12b, c), disease (Figure 12e). Recognising different agents of mortality is not always possible and requires practise. Here we recommend some patterns associated with non-bleaching agents of mortality to look out for which can help aid decision making:

1. *Drupella* snails consume coral tissue in patches, which can result in a patchwork or gradient or mortality, not dissimilar from bleaching (Figure 12b). Snails are often encrusted in pink CCA so look for their presence to rule them out (circled in yellow, Figure 12b). Snails often (but not always) feed in cryptic interstitial spaces, which usually differs from bleaching-induced mortality, which typically affects colony extremities.
2. Crown-of-thorns starfish (CoTS) usually feed in patches. A CoTS scar often has rounded edges to match the shape of their everted stomach, but may feed multiple times on one colony, obscuring this pattern (Figure 12c). Where CoTS feed on the same colony on different days, patches may differ in colour (Figure 12c). Look for the presence of CoTS (Figure 12c), to rule them out, however often CoTS are cryptic in nature and may be impossible to locate from an orthomosaic. As such, we recommend noting the presence of

CoTS in or nearby plots during image collection in the field and referring to these notes during bleaching categorisation.

3. Coral diseases typically progress across the colony surface over time and are often associated with a distinct coloured band or lesion (Figure 12e). The coloured band demarcates the boundary between live (apparently healthy) tissue and dead coral skeleton. White syndromes present as white bands or patches that can be mistaken for bleaching. Unlike bleaching, which generally affects the colony more uniformly, disease progression is spatially and temporally uneven, creating a visible gradient of colour change that indicates recent mortality (Figure 12e).

Ultimately, if predators are not present, the pattern of mortality is consistent with that caused by bleaching, and adjacent tissue/colonies are bleaching, then it is recommended a bleaching category be assigned from 5-7.

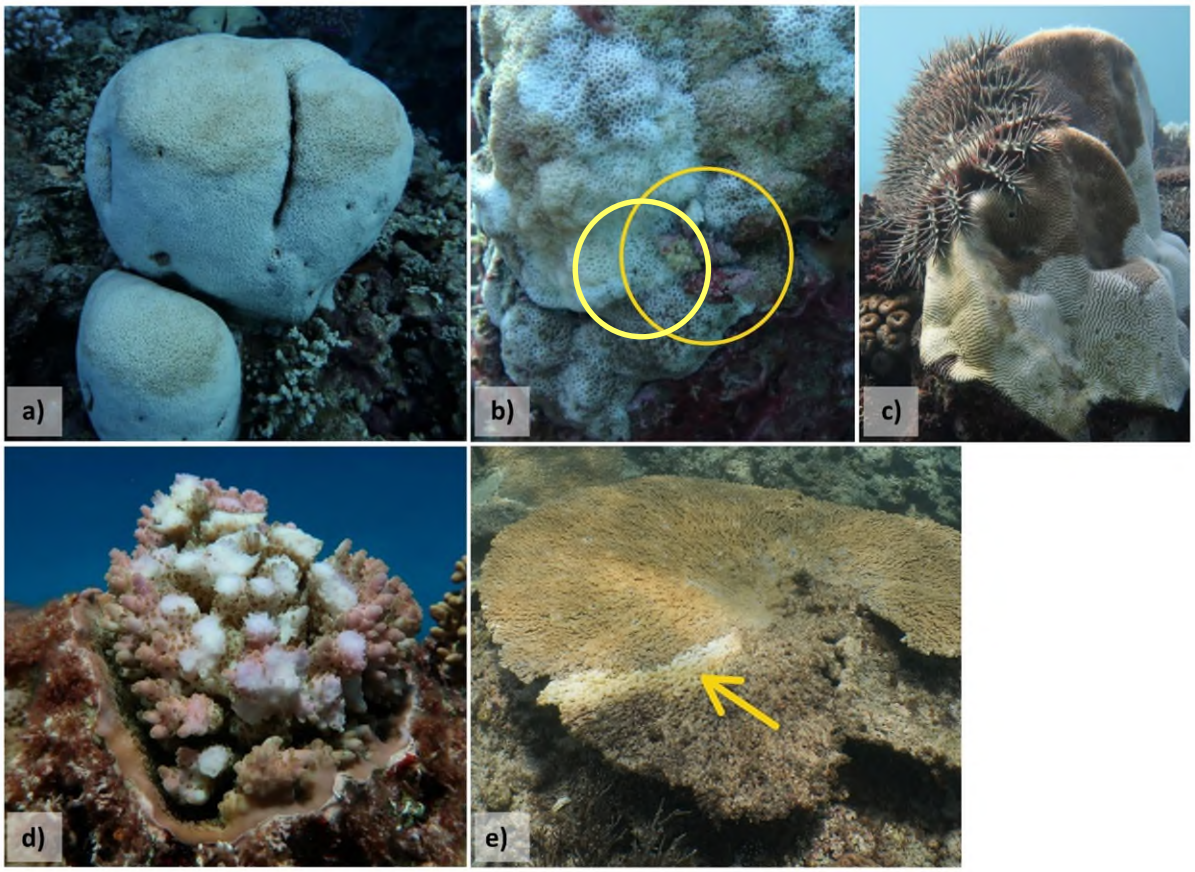


Figure 12. Different causes of mortality. a) Bleaching induced mortality affecting the top of a *Goniastrea* colony; b) *Drupella* snails consume coral tissue in patches. Snails are often encrusted in pink CCA (circled in yellow); c) Two CoTS feeding on a *Leptoria* colony. Note the rounded edges of the scars which differ in colour; d) Mechanical damage leading to breakage and thus mortality; e) White syndrome demarcated by a white band (yellow arrow) progressively causing mortality across a tabular *Acropora*. Applying categories based on extent of mortality

Once it is determined that observed mortality was caused by bleaching, the appropriate bleaching category (5-7) should be assigned based on the areal extent of the bleaching-induced mortality. Determining if whole colony mortality (category 7) was caused by bleaching can be difficult in the

absence of any bleached living tissue. Therefore, to assign a bleaching category of 7, which indicates >90% bleaching-induced mortality (Figure 11a), several criteria must be considered.

These criteria include:

1. Checking for bleaching at the plot level (the absence of bleaching elsewhere in the plot suggests that bleaching may not be the cause of mortality)
2. Confirming whether the mortality is recent
3. Assessing whether the skeletal colour is uniform or forms a gradient across the colony (rather than being patchy). ***Please note*** *that this method has the potential to slightly overestimate bleaching induced whole colony mortality but is more accurate than ascribing all mortality to bleaching.*

For partial mortality (categories 5 & 6), where part of the colony remains alive, the same steps should be applied with the added assistance of looking for evidence of adjacent bleached living tissue (Figure 11b; 12a). Healthy tissue adjacent to mortality suggests another cause (e.g., Figure 12b & c). Colonies exhibiting <50% bleaching-induced mortality receive a category 5, and colonies exhibiting 51-90% bleaching-induced mortality receive a category 6. These categories are assigned regardless of the areal extent of bleaching on remaining tissue, and percentages are determined based on the extent of the colony visible in the orthomosaic. For examples, see Figure 13.

Determining mortality and potential causes can be challenging *in situ*, and may be even more so from orthomosaics, particularly if image quality is sub-optimal (Figure 13). Useful tools include zoom functionality, and the ability to compare images of the same colony across time, especially from years without bleaching events. When uncertain about which category to assign, use these tools to assist with decision making.

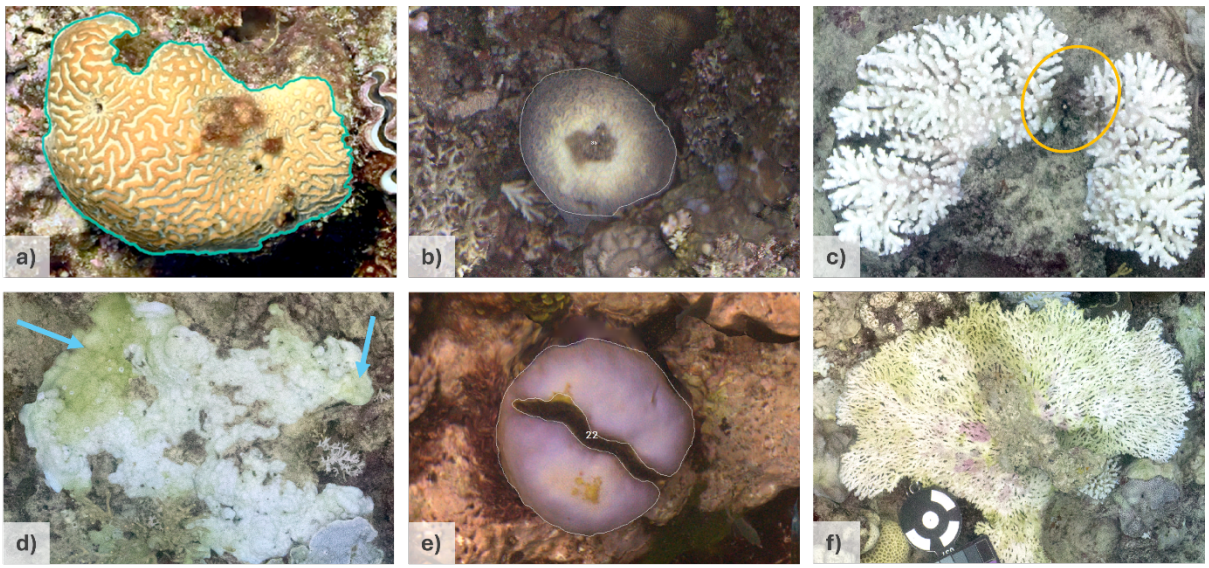


Figure 13. Examples of mortality on colonies in orthomosaics. a) <50% recent mortality evident on *Platygyra*. Adjacent living tissue is not bleached, resulting in a bleaching category of 1 (not bleached); b) Old mortality on a *Platygyra* colony not considered for bleaching, resulting in a bleaching category of 2 (<50% of colony bleached); c) Old mortality that split colony into two remnant sections (circled in yellow) is not the result of bleaching. Each section is assessed separately, each receiving a bleaching category of 4 (100% bleached with no bleaching related mortality); d) Some recent, bleaching-related mortality on a *Montipora* colony (green sections with turf algae overgrowth, blue arrows). Adjacent bleached tissue indicated mortality caused by

bleaching resulting in a bleaching category of 5 (5-50% bleaching-related mortality); e) Full colony bleaching with small patches of early mortality resulting in a bleaching category of 5 (5-50% bleaching-related mortality); f) Old mortality in centre of colony not considered for bleaching categories but recent mortality in green is considered, resulting in a category of 5 (5-50% bleaching-related mortality).

5.4 Determining bleaching extent (categories 1-4)

As discussed in the previous sections, the bleaching categories are initially determined by assessing the presence of bleaching-induced mortality. If there is no mortality is present, or mortality is not deemed to be caused by bleaching, the observer must then assess the areal extent of bleaching on coral tissue. This section provides a detailed explanation of categorising bleaching on live tissue (categories 1-4). It is important to note that the distinction between categories 5-7 and 1-4 lies in the extent of accompanying mortality, whereby colonies with bleaching categories of 1-4 will not display any bleaching-related mortality.

5.4.1 Applying bleaching categories based on extent of bleached tissue

If a colony 1) does not have mortality, 2) has old partial mortality, or 3) has recent mortality not caused by bleaching, then it is recommended to assess the areal extent of the living tissue that is showing signs of bleaching, and assign a category of 1 (not bleached), 2 (5-50% bleaching) , 3 (51-90% bleaching) or 4 (>90% bleaching). Note that the colour of a colony comes from two sources – the symbionts and the host pigments (the latter are usually fluorescent). Only the loss of symbiont pigment should be used to determine the bleaching category from 1-4. As such, bleached tissues are not necessarily white, and can manifest in a multitude of colours (termed colourful bleaching). This is discussed later in Section 5.5. The following sub-sections describe when to assign categories 1-4.

5.4.1.1 Not Bleached (category 1)

A category of '1' relates to a colony with no signs of bleaching (Figure 14). Note that non-bleaching colonies can have some white tissue, often on growing edges (Figure 14b; branch tips, table edges, base edges).

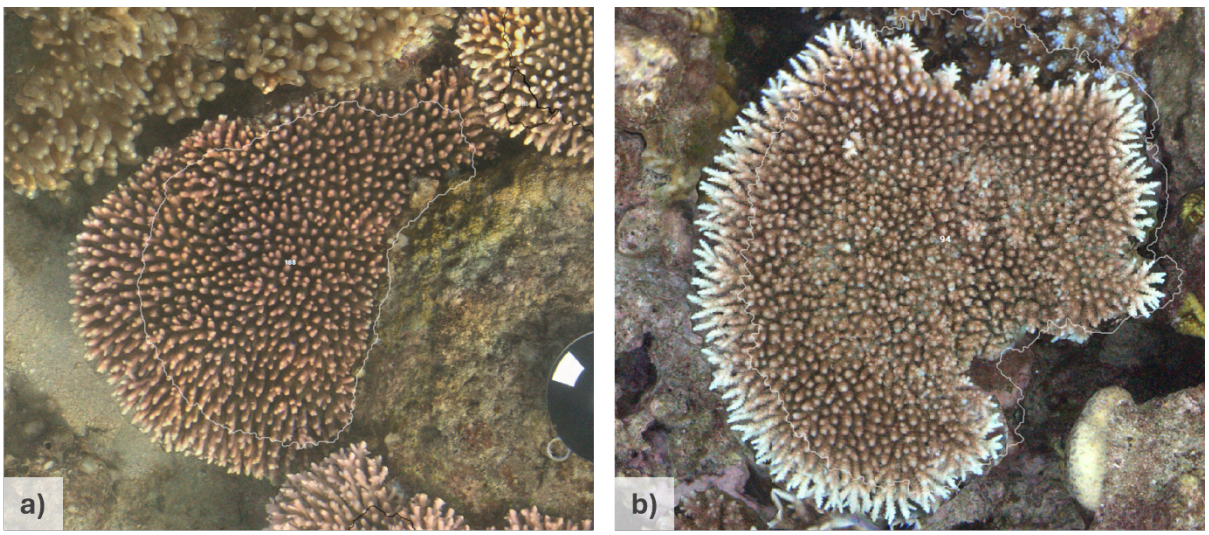


Figure 14. Examples of colonies not bleaching from orthomosaics, including a) healthy, pigmented colony, and b) healthy colony with white branch tips on growing edges (not considered bleaching).

5.4.1.2 Pale and partial bleaching (Categories 1p, 2, 3)

Categorising pale and partially bleached colonies (categories 1p, 2 & 3) can be challenging and is inherently subjective. Pale colonies (category 1p) are especially difficult to categorise owing in part to the natural occurrence of pale colonies during non-bleaching conditions. As such, some bleaching studies do not take paleness into account (e.g., Cantin et al. 2021), whereas others do (e.g., Hughes et al. 2018). The rationale behind the categories recommended here is to ensure data is comparable across studies and teams, where categories and definitions follow the majority of the literature (Gleason 1993; Hughes et al. 2018; Cantin et al. 2021) but can also be condensed down where required into a variety of broader categories (e.g., binary 'bleached', and 'not bleached', where 'pale' colonies could be placed into either bin to match other studies). Importantly, using temporally tracked imagery provides the unique opportunity to compare colony health through time, allowing a more accurate assessment of 'paleness'. In this section, we clearly define the recommended bleaching categories and provide written and visual examples for each.

Colonies falling within categories 1p, 2, 3 & 4 tend to take on two predominant forms:

1. A portion of the colony will be entirely bleached, leaving the remainder of the live tissue pigmented (Figure 15c & d).
2. The entire colony may appear pale; branch tips or colony edges may appear progressively lighter (Figure 15a & b)

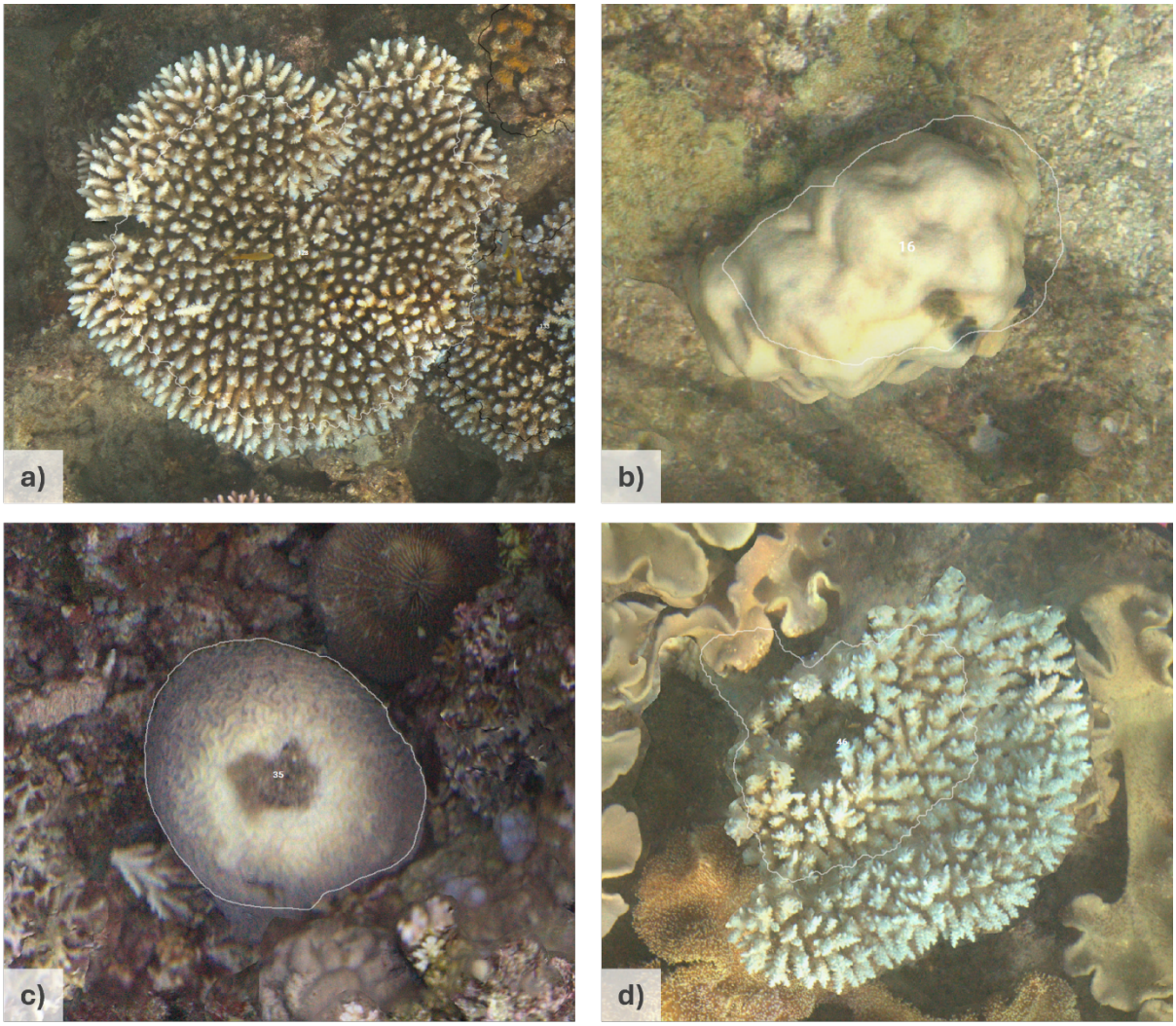


Figure 15. Examples of paleness and partial bleaching from orthomosaics. a & b) Colonies that could be categorised as not bleached (1) or pale (1p) depending on what the colony looked like in the previous timepoint; c) colony <50% partial bleaching (2); d) colony with >50% partial bleaching (3).

Colonies falling under option 1, with clear portions of bleached tissue, are generally easy to categorise: When 5-50% of the tissue is bleached, category 2 is assigned; when 51-90% of the tissue is bleached, category 3 is assigned; and when >90% of the tissue is bleached, category 4 is assigned. These categories should be applied based on the percentage of bleached vs healthy tissue visible in the orthomosaic.

For colonies under option 2, where colonies are pale and may be progressing toward partial bleaching, decision making can become highly subjective so the following stepwise considerations are recommended:

1. Assess if the colony is pale in the previous timepoints.
    a. Check the orthomosaic from the previous timepoints (where available) to determine if the colony is naturally pale (Figure 16).
    b. If the colony appears the same in both years, categorise the colony as 1 (not bleached). If the colony is definitively paler, move on to step 2.
2. Look at colony edges/top/branch tips.

a. Assess whether there is a high degree of whiteness extending down the branches or from the extremities. Some whiteness at branch tips is a normal feature of healthy, growing corals, and there is no fixed threshold for what constitutes "normal." This distinction often relies on familiarity with the species' usual appearance and growth patterns. Assess if there a high degree of whiteness extending down the branches/ from the extremities.
    i. If not, categorise the colony as category 1p (not bleached but pale); b). *The reason for this category is to provide as much detail as possible while maintaining comparability with widely used scoring categories.*
    ii. If colony edges/branch tips appear whiter than normal, consider step 3.

3. Determine the percentage of tissue bleached based on the degree of whiteness extending along colony edges/branches, or the percentage of symbionts lost uniformly across the colony surface area. In such cases, categories 2 (<50% bleached), 3 (51-90% bleached) and 4 (>90% bleached) may be considered.

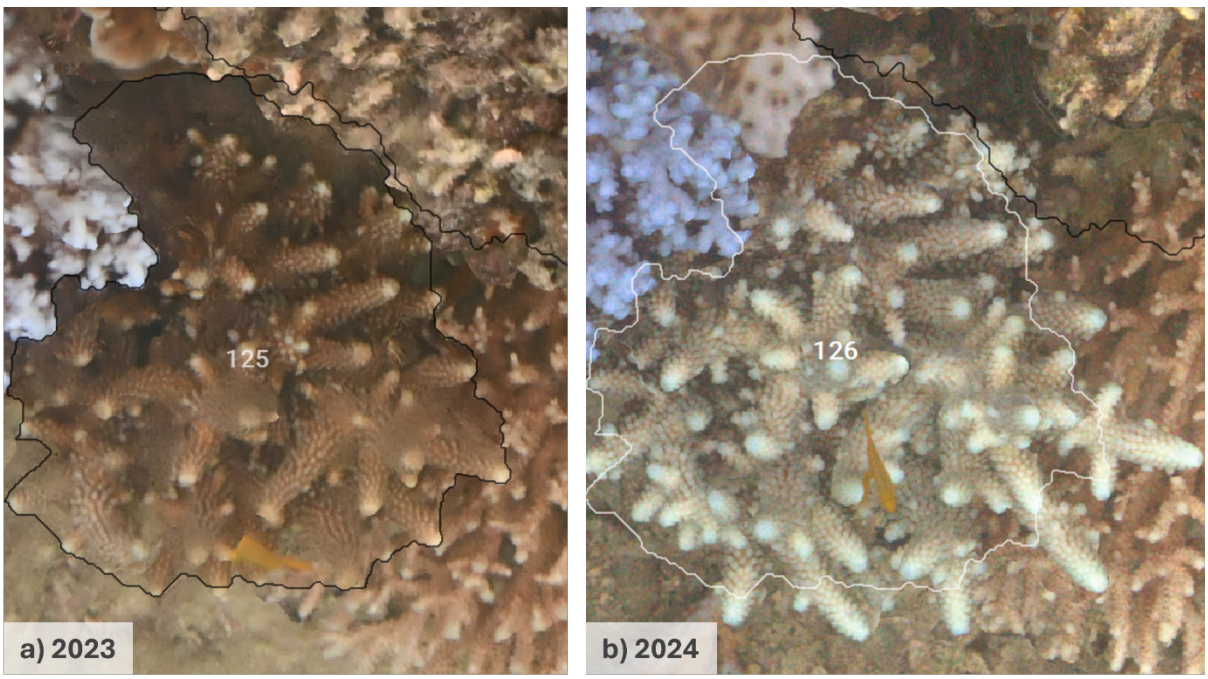


Figure 16. The same *Acropora* aff. *humilis* colony in a) 2023 and b) 2024 orthomosaics. The colony may not be considered bleaching in 2024 alone, although comparison with 2023 reveals noticeable paling relative to non-bleaching years. The whiteness does not extend far down branch tips, resulting in a category of 1p.

5.4.1.3 Whole colony bleaching (Category 4)

A bleaching category of 4 relates to colonies where >90% of the tissue is bleached. Colonies may be entirely white, entirely fluorescent (see Section 5.4), or mostly white/fluorescent with some symbionts still visible (usually in the interstitial spaces or shaded parts of the colony). It can be difficult to tell apart recently dead colonies and bleached white colonies from orthomosaics. To assist in determining the category, (i) look for subtle differences in colour, as bleached colonies may display some fluorescence (Figure 17), and (ii) use the zoom functionality to look for demarcations in colour that suggest partial mortality (e.g., Figure 13a). It can also be difficult to tell apart very pale

(for example, category 3) and pink-red fluorescent colonies (e.g., Figure 17a). If in doubt, discuss among observers for consensus.

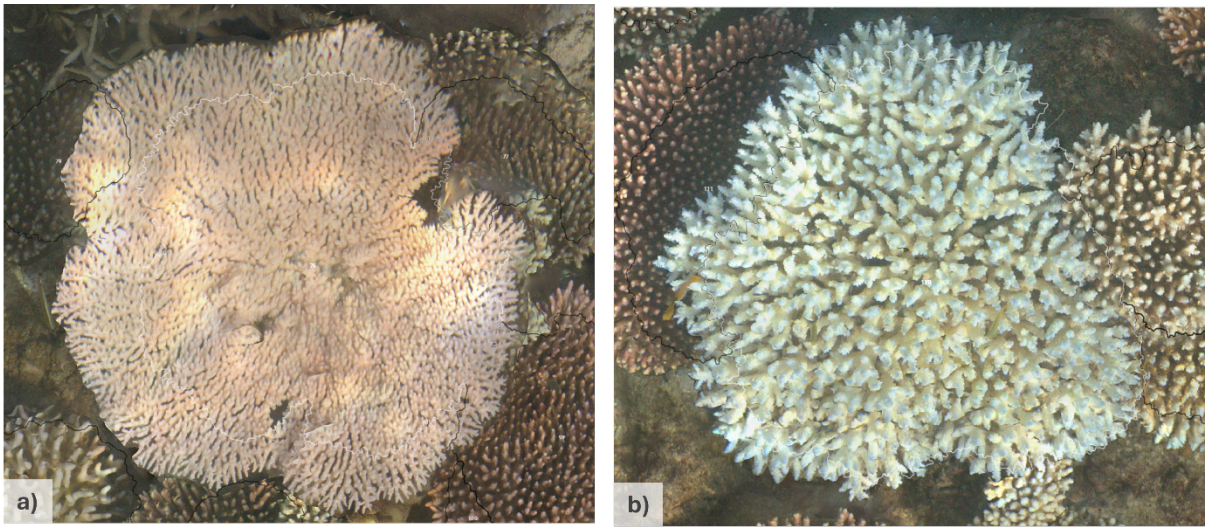


Figure 17. Examples of whole colony bleaching (>90% loss of symbionts). a) Colony exhibiting pink-red fluorescence, resulting in a category of 4f; b) Colony is fully white and is fluorescing at the branch tips so receives a category of 4f.

5.5 Fluorescence (optional)

Many colonies express fluorescence derived from green fluorescent protein (GFP)-like pigments produced by the coral host. During bleaching, fluorescence can therefore be retained and may be more prominently expressed (Figure 18, 19), with some evidence suggesting fluorescence confers resilience (Bollati et al. 2020). Fluorescent pigment can be expressed in many colours with the most common being blue, purple, pink (appearing almost red or brown in some cases), and yellow. Multiple fluorescent colours may occur on a single colony (Figure 18). To denote fluorescence, 'f' can be added to any bleaching category from 2 - 6. Noting fluorescence is optional, but may be of interest to those studying the causes or consequences of colourful bleaching.

***Note**: Even if not explicitly quantifying fluorescence, observers should familiarise themselves with fluorescent pigments and must take care not to confuse fluorescence with symbiont pigmentation. Fluorescing colonies are bleached colonies.*

5.5.1 Recognising and noting fluorescence

If taking fluorescence into account, we recommend assigning the usual bleaching category followed by 'f' to denote any level of fluorescence. This yields a binary result - 'fluorescing' or 'not fluorescing' - though levels of extent or severity of fluorescence could be quantified with a sub-category, which is beyond the scope of this SOP.

Some colonies can express strong fluorescence even when healthy, which can increase difficulty in discerning bleaching extent (e.g., Figure 18a). In such cases, we recommend observers either (i) search for tissue in a shaded area of the same colony and compare the colour to the section with suspected bleaching, or (ii) compare with an image of the same colony from a previous non-

bleaching timepoint. For example, Figure 18a shows the edges of a *Montipora* colony (indicated by orange arrows) are bleached and are a brighter pink, whilst the shaded central portions (indicated by green arrows) are a darker purple-brown, suggesting they are healthy with retained symbionts.

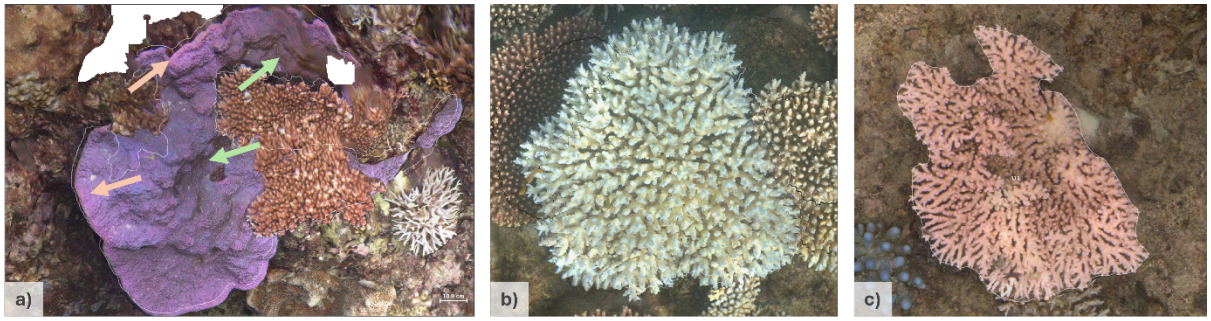


Figure 18. Examples of fluorescing colonies in orthomosaics. a) *Montipora* spp. colony exhibiting bleaching related fluorescence (orange arrows) and healthy fluorescent tissue (green arrows); b) Bleached *Acropora* spp. colony exhibiting blue and yellow fluorescence; c) *Acropora* spp. colony exhibiting nearly full-colony fluorescence.

Figure 19. Additional examples of fluorescence in *Acropora* colonies, taken *in-situ*.

5.6 Additional considerations specific to 2D bleaching assessments from orthomosaics

5.6.1 Viewing colonies as 2D or 3D objects when assessing bleaching from orthomosaics

Orthomosaics intrinsically allow for only a 2D top-down view of a given colony. Consider the *Platygyra* example previously provided in Figure 15c, where roughly 40% of living tissue appears bleached from the top-down perspective. Whilst only the top of the colony might be visible, observers know the colony in nature is 3-dimensional. Observers may also know that bleaching is often most prominent on the top of a colony while the sides can remain healthy. If observers were to extrapolate an estimate of bleached tissue based on knowledge of coral morphology and ecology, it might seem that much less than 40% of the living tissue is bleached, it is just not visible.
Even though it may seem intuitive to assign bleaching categories based on this, we recommend for consistency, not to infer a bleaching category for tissue that is not directly visible. The way we recommend approaching this is to consider how AI would categorise the colony from only a top-down perspective. While this method may potentially inflate bleaching categories, it is important to note that growth and mortality data will be estimated in the same 2D plane from orthomosaics. To retain consistency across plots, taxa and demographic outcomes, we recommend providing a category based only the visible 2D plane, ensuring this is considered prior to interpretation of results.

5.6.2 Recognising glare when ascribing partially bleached and pale categories

Another intrinsic limitation to working with 2D orthomosaics is the potential for glare on the underlying images used for reconstruction. Orthomosaics are derived from images collected from coral reefs in nature. In nature, glare and shadows in the water, caused by the sun's orientation and intensity, are sometimes captured in photos.

This may be especially prevalent for colonies at a particular aspect or depth, where overexposure of the image might look like bleaching. If observers suspect glare, we recommend colonies be compared with the entire plot, where it is often possible to ascertain a degree of glare across the plot to differentiate between glare and partial bleaching. Consider the *Acropora* example in Figure 15a, where some lighter and darker patches are visible due to glare, not bleaching. If observers are unsure, an 'X' denoting 'unsure' should ascribed for the bleaching category.

APPENDIX A

Packing list for field-based bleaching assessments

This is a recommendation only; exact items and quantity should be determined by the user(s).

Table 14. Recommended packing list for field-based bleaching workflow. Adapted from SOP 14.

Category	Item	Quantity	Comments
Bleaching photos	Coral health chart	23	
	Colour chart	30	
	Cannon G7 + housing + accessories	2	
Photogrammetry – cameras (DSLR)	Nikon D850	5	
	Nikon 20mm lens/Sony lens	4	
	Lens bag and caps	5	
	Nauticam dome port/Wet wide angle conversion port	5	
	Dome bag, caps and covers		
	Nauticam 17222 NA-D850 housing	5	
	Housing accessories	5	
	XQD card	5	
	512 GB micro SD	5	
	256 GB SD	4	
	Nikon batteries	8	Works fine to capture RAW at 0.5 sec interval
	Nikon battery charger	10	
	Acrylic polish kit & cloths	5	
	Nikon manual	1	
		1	

Photogrammetry – cameras (SONY)	Sony α6700 Sony 16-50mm lens (E PZ 16-50mm F3.5-5.6 OSS) Nauticam housing with WWL-C Lens bags, caps and covers Housing accessories XQD card 512 GB micro SD 256 GB SD Sony batteries Sony battery charger Acrylic polish kit & cloths Sony manual	See Above (same number as for DSLR)	Sony will only capture RAW at 1 sec intervals so workflow/speed must be adapted accordingly to ensure 80% overlap of images.
Photogrammetry – camera rig	Camera bar Foam mat Bar mount Camera mount Dive computer Camera rig stand	3 1-2 3 3 1 2	
Photogrammetry – ref. markers	Standards Sphere trees Sphere tree clamps Stakes/star pickets Clip/carabiner Dumbbell weights and holders Marker datsheets Spare dumbbell stickers	30 10 20 20 6 20 16	Figure 2 (includes 2 spare) Minimum 8, take spare Include both types Trip/manpower dependent If available

Photogrammetry - Computer	Field computer	1	Minimum 1
	Monitor, keyboard, mouse	1	
	External harddrive	3	Minimum 2
	Agisoft Metashape licence	1	Minimum 1, per computer
	Access database/excel	1	
Photogrammetry – maintenance	Kim wipe, paper towel, alcohol wipe	1	
	Tool kit (allen keys, screw driver, etc.)		
	Cotton tips	1	
	Elastic bands, cable ties		
	Maintenance/batter briefcase	1	
	Other misc. field gear	1	
		1	
		1	
Juvenile quadrats	Cattle tags	1 bag	
	Quadrat	2	
	Olympus camera, housing, accessories	1	
Diving	BCDs	TBD	
	Regulators	TBD	
	All other dive gear	TBD	
	Transect tape	2	
Instruments	Marotte	10	
	AA batteries	24	
	Tracer wire	1	
	Field laptop computer	1	
Spotter Buoy	GPS + waterproof bag	3	
	Depth sounder	1	
	Grippy gloves	1	
	General purpose gloves	7	

Other	Sunscreen	3
	Cable ties (various sizes)	
	Aquaear	3
	Pens, pencils, scissors, etc.	

File size considerations

The following calculations and considerations are for the Nikon D850 camera. Write speeds of 200 mb/s are too slow for Nikon D850 to write RAW and JPEG @ 0.5 second intervals. Write speeds of 300 mb/s can achieve this (speeds between 200-300 mb/s not tested).
SD card used: Lexar Professional GOLD 256 GB 300mb/s.

Table 15. Estimates of file storage needs based on image file type.

File type	Approx. size per photo (KB)	File size per 'plot', per camera* (RAW+JPEG @ 0.5 sec interval for 5-7 min.)	No. plots per 256 GB SD card
RAW: Large, lossless compression	60,000	62,000 KB x 600-820 photos = 38-51 GB	5-6
JPEG: Small, basic	2000	See above	See above

Table 16.File size estimate examples. Note: numbers provided are 'per-plot' based on 5 nadiral passes per plot.

Camera		No. photos (per plot)			File size			
		Total no. captured (RAW & JPEG)	Total RAW captured	RAW per camera	Large RAW (NEF/ARW) per image (KB)	Small JPEG per image (KB)	Total per plot (RAW & JPEG) (GB)	Total per camera per plot (RAW & JPEG) (GB)
Nikon D850	Mean	2800	1400	700	59,000	1,800	85	43
	Range	2000-3800	1000-1900	500-950	54,000 – 65,000	900-2,300	77 – 115	39 – 58
Sony AS6700	Mean	1370	685	343	38,000	3,200	28	14
	Range	800 - 2000	400-1000	200-500	33,000 – 42,000	1400-3,700	16 – 42	8 – 21

APPENDIX B: ECORRAP SPECIFIC INFORMATION

2022 bleaching assessments

During the 2022 mass bleaching event, the EcoRRAP photogrammetry team conducted surveys on 26 Central GBR sites (>7400 square meters; DHW ranged from 4.1 to 5.2 across EcoRRAP sites; see Álvarez-Noriega et al. 2025). Resulting orthomosaics were used to digitise >5000 coral colonies across 13 taxa with a bleaching severity category attributed to each (20). All taxa that significantly bleached were digitised and annotated (see Table 25 in Appendix A for a full list). Criteria used to determine which colonies are selected for digitisation are described in detail in SOP 17.

Bleaching categories were assigned by a single observer in 2022 (Mariana Álvarez-Noriega) by overlaying colony shapefiles (exported from TagLab) onto orthomosaics in ArcGIS Pro (v 3.2.1). Each segmented colony in the orthomosaic was assessed and a single bleaching category of 1 to 8 (20) was added and saved directly into attributes table in ArcGIS Pro. Further detail and results can be found in Álvarez-Noriega et al. 2025.

Table 17. Colony-level bleaching categories used on orthomosaics imaged during the 2022 bleaching event.

Response	Colony area bleached	Label
No bleaching	0%	1
Minor	0 < x < 50%	2
Major	50 < x < 95%	3
Fully	> 95%	4
Recently dead	Partial mortality	5
Recently dead	Whole colony mortality	6
Unclear		7
Not Found		8

2024 bleaching assessments

During the 2024 mass bleaching event (~12 DHW), AIMS visited EcoRRAP reefs in the Southern, Central, and Northern GBR clusters. Teams were deployed to the various clusters and conducted 3D mapping on as many EcoRRAP sites as possible, prioritising bleached sites over non-bleached sites. If no visual signs of bleaching could be observed by snorkelers, plots in the Central cluster (which had already been surveyed in 2024 prior to the bleaching event) and Northern cluster were not imaged (Table 21). No bleaching was observed in the Torres Strait.

Table 18. Number of plots imaged at EcoRRAP reefs in each cluster (Torres Strait not included). Sites on Little Broadhurst and some sites on Heron not surveyed due to poor weather but bleaching was present.

Cluster	Reef	No. plots imaged
Southern Offshore	Heron Island	24
	Lady Musgrave	15
Southern Inshore	Keppel Islands	20
Central Offshore	Chicken Reef	12
	Davies Reef	12
	Little Broadhurst Reef	0
Central Inshore	Orpheus Island	8
	Pelorus Island	19
Northern Offshore	Lizard Island	24
	Moore Reef	16

Table 19. Information specific to field- and office-based bleaching monitoring work conducted by EcoRRAP during 2022 and 2024 bleaching events.

Method section	Notes	
2022 bleaching assessment		
2024 in-water validation surveys	-	The target taxa for the in-water bleaching assessments in 2024 are outlined in Table 25. This includes Priority 1 taxa (See SOP 17 for full list of taxa and associated priorities) as well as those listed in bold. If time allowed, other taxa in the table were categorised along with taxa not identified in Table 25 that presented significant bleaching.
Underwater maps for in-water validation	-	The 2024 in-water bleaching surveys used printed maps with orthos from 2023, except where 2023 orthos were unavailable or unsuitable (e.g. due to missing tiles, distortion, poor clarity, or scale mismatch with the shapefile; see SOP 16 for more), in which case orthos and/or annotations from 2022 or 2021 were used (whichever year provided a better quality file). These cases were recorded in the Processing Log.

2024 bleaching	- Plot-level bleaching assessment was carried out in the field for Southern sites as part of the in-water validation surveys based on low quality field-processed orthomosaics, as per Table 16 (1-5 bleaching scale). - Processing settings were modified from the standard workflow to accommodate Southern GBR 2024 bleached imagery. Adjustments were necessary due to poor model alignment and large gaps in areas with heavily bleached *Acropora spp*. thickets. Additional differences were applied for Heron Island, Lady Musgrave Island, and the Keppel Islands, reflecting variations in image quantity and quality. Fewer images were collected in the Southern GBR due to different camera systems and a lower capture rate (1 image per second vs. 0.5 images per second). - Surveys conducted during the bleaching in the Southern cluster, Lizard Island, and Moore Reef are used as the standard transitional timepoint for EcoRRAP data (e.g. growth and survival come from the bleaching orthomosaics), noting that not all sites were surveyed during these trips. The Central Cluster was surveyed as per usual EcoRRAP fieldtrip schedule prior to the bleaching in January 2024 as well as during peak bleaching in February 2024 (subset of plots) – the non-bleaching orthomosaics were used for standard EcoRRAP demographic data collection (survival and growth) and the bleaching orthomosaics were referenced separately to assess the colony-level bleaching (i.e. the orthomosaic in the TagLab project is from January 2024 but the category assigned to colonies is from the February 2024 orthomosaic that is not within the TagLab project). - Due to model processing issues, numerous plots from heavily bleached reefs (Southern GBR) could not be reconstructed well enough for reliable growth metrics. In these cases, all colonies in the plot have a 'bad' note but survival and bleaching data can still be used for analyses.

EcoRRAP file naming and storage

Table 20. EcoRRAP file naming structure and storage location (internal only).

File	File type	File naming	File location
2022 DSLR data (images)	.NEF, .JPG	NA	\\pearl \ 3d-ltmp \ EcoRRAP \ data \ 202204 \ REEF \ SITE \ ZONE \ DSLR

2022 GoPro data (images)	.JPEG	NA	\\pearl \ 3d-ltmp \ EcoRRAP \ data \ 202204 \ REEF \ SITE \ ZONE \ GoPro
2024 DSLR data (images)	.NEF, .JPG .ARW, .JPG	NA	\\pearl \ 3d-ltmp \ EcoRRAP \ data \ 202402 \ REEF \ SITE \ ZONE \ PLOT \\pearl \ 3d-ltmp \ EcoRRAP \ data \ 202403 \ REEF \ SITE \ ZONE \ PLOT
2022 DSLR Metashape projects	.psx	REEF_SITEZONE_DATE_BL (OCDA_BA1D_202204_BL)	\\pearl \ 3d-ltmp \ EcoRRAP \ projects \ REEF \ SITE \ ZONE \ DATE
2022 GoPro Metashape projects	.psx	REEF_SITEZONE_DATE_BL_GoPro (OCDA_BA1D_202204_BL_GoPro)	\\pearl \ 3d-ltmp \ EcoRRAP \ projects \ REEF \ SITE \ ZONE \ DATE
2024 DSLR Metashape projects	.psx	REEF_SITEZONE_PLOT_DATE (OCDA_FL1S_P1_202402)	\\pearl \ 3d-ltmp \ EcoRRAP \ projects \ REEF \ SITE \ ZONE \ DATE
2022 orthomosaics	.TIF	REEF_SITEZONE_PLOT_DATE (OCDA_BA1D_P1_202204)	\\pearl \ 3d-ltmp \ EcoRRAP \ outputs \ orthomosaics \ 2022_Bleaching
2024 orthomosaics (cropped)	.TIF	REEF_SITEZONE_PLOT_DATE_c (OCDA_BA1D_P1_202402_c)	\\pearl \ 3d-ltmp \ EcoRRAP \ outputs \ orthomosaics \ 2024_Bleaching_c
TagLab projects (includes all years of EcoRRAP monitoring)	.json	REEF_SITEZONE_PLOT (OCDA_BA1D_P1)	\\pearl \ 3d-ltmp \ EcoRRAP \ outputs \ TagLab \ Projects \ REEF
2024 underwater maps	.PDF	REEF_SITEZONE_PLOT_YEARBL (OCDA_BA1D_P1_2024BL)	\\pearl \ 3d-ltmp \ EcoRRAP \ outputs \ ArcGIS \ Bleaching2024_plotMaps \ Maps_forPrinting
Underwater map creation template	.aprx	NA	\\pearl \ 3d-ltmp \ EcoRRAP \ outputs \ ArcGIS \ Bleaching2024_plotMaps \ updatedTempBleaching_March2024

Bleaching map processing log template

Table 21. Recommended processing log template for bleaching map creation for field-based validation surveys.

Orthomosaic file name	Shapefile name	Bleaching Reference Map created (YorN)	Map exported (YorN)	Map PDF visually checked (YorN)	Printed on Waterproof paper (YorN)	Comments

EcoRRAP taxa list

Table 22. EcoRRAP priority taxa, see SOP 17 for further information on digitisation of priority taxa in EcoRRAP orthomosaics. All taxa in priority level 1 have been assessed for bleaching level in EcoRRAP orthomosaics from the 2024 bleaching event. Taxa in bold have been assessed for bleaching in EcoRRAP orthomosaics from the 2022 bleaching event (Central Cluster only).

Taxon	Morph	Digitisation priority
Porites massive	Massive (large)	1
***Acropora* corymbose**	Corymbose	1
***Acropora* digitate**	Digitate	1
Acropora millepora	Corymbose	1
Acropora tenuis	Corymbose	1
***Acropora* table**	Tabular	1
Acropora humilis	Digitate	1
Pocillopora damicornis	Branching (small)	1
Stylophora pistillata	Branching (small)	1
Pocillopora verrucosa	Branching (small)	1
***Goniastrea* spp.**	Massive	1
Platygyra	Massive	1
Seriatopora hystrix	Branching (small-fine)	2
Montipora plating/tiers	Foliose	2
Diploastrea heliopora	Massive (large)	2

***Acropora* staghorn**	Branching (large)	2
Porites cylindrica	Branching (massive)	2
Pachyseris speciosa	Foliose	3
Acropora divaricata	Corymbose	3
***Lobophyllia* spp.**	Massive	3
Leptoria phrygia	Massive	3
Lobophyllia hemprichii	Massive	3
Astreopora myriophthalma	Massive	3
Acropora latistella	Corymbose	3
Favites spp.	Massive	4
Dipsastraea spp.	Massive	4
Echinopora	Foliose	4
Acropora spathulata	Corymbose	4
***Montipora* encrusting**	Encrusting	4

All possible colony notes in Taglab (Modified from SOP 17)

Table 23. EcoRRAP colony notes attributed during the digitisation and temporal colony transfer process.

Option	Key task	Notes

1	Partial mortality ('pm')	• If a colony shows any observable partial mortality (up to 99%)
		• If morality occurs along the border of a colony:
		  - Edit the polygon so that only areas of live tissue are included (polygon edge should be on the border between live tissue and dead skeleton)
		• If partial mortality occurs centrally on the colony:
		  - Leave it included in the polygon (i.e. do not cut out)
		• Type "pm" in the notes section (under Attributes) for any partial mortality (central or along the border of colony)
		• Type "pm base" for staghorn Acropora where the base section has died but branch tips remain alive
		• See option 10 if partial mortality has split a colony into separate remnant sections

2	Obscured colonies ('o')	• A colony is considered obscured if it is overtopped or partially blocked by another substrate or piece of equipment (e.g. sphere tree, dumbbell) but is still visibly alive • Type an "o" in the notes section
3	Unobscured colonies ('unobscured')	• A colony is considered 'unobscured' if it was previously overtopped or obscured by another substrate, which is no longer there so that the entire colony can now be seen. • Type "unobscured" in the notes section
4	Bleached colonies ('bleached')	• Type "bleached" in the notes section if a colony is displaying any level of bleaching, including partial or full bleaching • Confirm with EcoRRAP team member if unsure
5	Dead colonies ('d')	• A colony is considered dead when there is 100% mortality and the structure is still visible • Type a "d" in the notes section

6	Missing colonies (‘m’)	• A colony is considered missing when it cannot be visually located within the orthomosaic but the location where the colony previously was can be identified (i.e. not obscured by other substrate). • Type an “m” in the notes section • Note: if an orthomosaic has shifted even slightly between time points, colonies may not align perfectly. Search within the nearby area for the colony, using the previous time point as a reference
7	Detached (‘detached’)	• A colony is considered detached when it can be visually located within the orthomosaic and is visibly alive but is no longer attached to the reef in its previous location - Observer must be 100% sure that it is the same colony • If the colony is both detached and dead, both notes can be entered • Type “detached” in the notes section
8	Bad colonies (‘b’)	• A colony is considered bad if it meets any of the following criteria: - Falls partially outside of the orthomosaic bounds and the visible area is still alive - Falls partially within a hole in the orthomosaic and the visible area is still alive - The colony appears blurry or distorted - The quality of the orthomosaic is too poor to determine the colony border but it is still visibly alive • Type a “b” in the notes section - Note that “Bad” has also been used previously and is the equivalent of “b”
9	Unknown colonies (‘unknown’)	• A colony is considered unknown if it: - Falls fully outside of the orthomosaic bounds - Falls fully within a hole in the orthomosaic - Is fully obscured by another substrate - Falls partially outside of orthomosaic bounds or partially within a hole in the orthomosaic and the visible area is dead - Orthomosaic quality is too poor to determine if the colony is alive or dead • Type “unknown” in the notes section
10	Merged colonies (‘merged’)	• When two or more digitised colonies merge so that a distinct edge cannot be detected (e.g. staghorn Acropora) • Combine polygons using the merge tool or remove one polygon and edit the border of the other to encompass the entire merged area • When a digitised colony merges with another non-digitised colony, refine the polygon to include the newly merged section • Type “merged” in the notes section of the polygon

11	Remnant/split colonies ('remnant')	• If mortality splits a colony in two or more separate sections: - Use the cut tool to split the original polygon into multiple polygons and digitise the living sections of the colony separately - Alternatively, refine the border of the original polygon around the largest remaining section and generate new polygons around remnant sections of the colony (if a new polygon is generated be sure to annotate it with the same class) • Type "remnant" in the notes section for all polygons of the colony as well as "pm" to indicate partial mortality • NB: this step was only applied from the 2022-2023 transfer onwards - In the 2021-2022 transfer, only the largest living section of the colony was retained in the polygon, smaller remnant sections were not digitised
12	New colonies ('new')	• Any new colony added after T_0 (2021 for EcoRRAP) should be noted as such to differentiate it during the joining process • Type "new" in the notes section • Note: Due to improvements in EcoRRAP orthomosaic quality between the T_0 and T_1 (2022) timepoints, new colonies were added to the T_1 orthomosaics - No new colonies have been added to future timepoints after T_1 (current as of December 2024)
13	Genetics colonies ('ng####')	• See section for details on genetics colonies within EcoRRAP plots • Any genetically sampled colonies in the EcoRRAP plots contain a note with "ng" for 'new genetics' and a unique identification number from the genomics database, e.g. ng1234 • Note: the "ng" note will appear in the previous timepoint from when it was collected in the field. For example, a colony nubbin collected in 2022 will have the note in the 2021 orthomosaic because the 2022 orthomosaic will not have been generated at the time of collection.
14	ID validated colonies ('v', 'validated')	• A colony whose species identification was validated *in-situ* by a coral taxonomist • See section for more information on the ID validation process
15	Acropora staghorn thicket ('thicket')	• A staghorn Acropora cluster where individual colonies are indistinguishable • Type "thicket" in notes section • This note has only been used from 2024 onwards due to the addition of staghorn Acropora thickets for bleaching purposes. Any staghorn Acropora in previous years will have been digitised as an individual colony.

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