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AUSTRALIAN INSTITUTE OF MARINE SCIENCE

Aerial surveys of coral bleaching

Standard Operating Procedure Number 11

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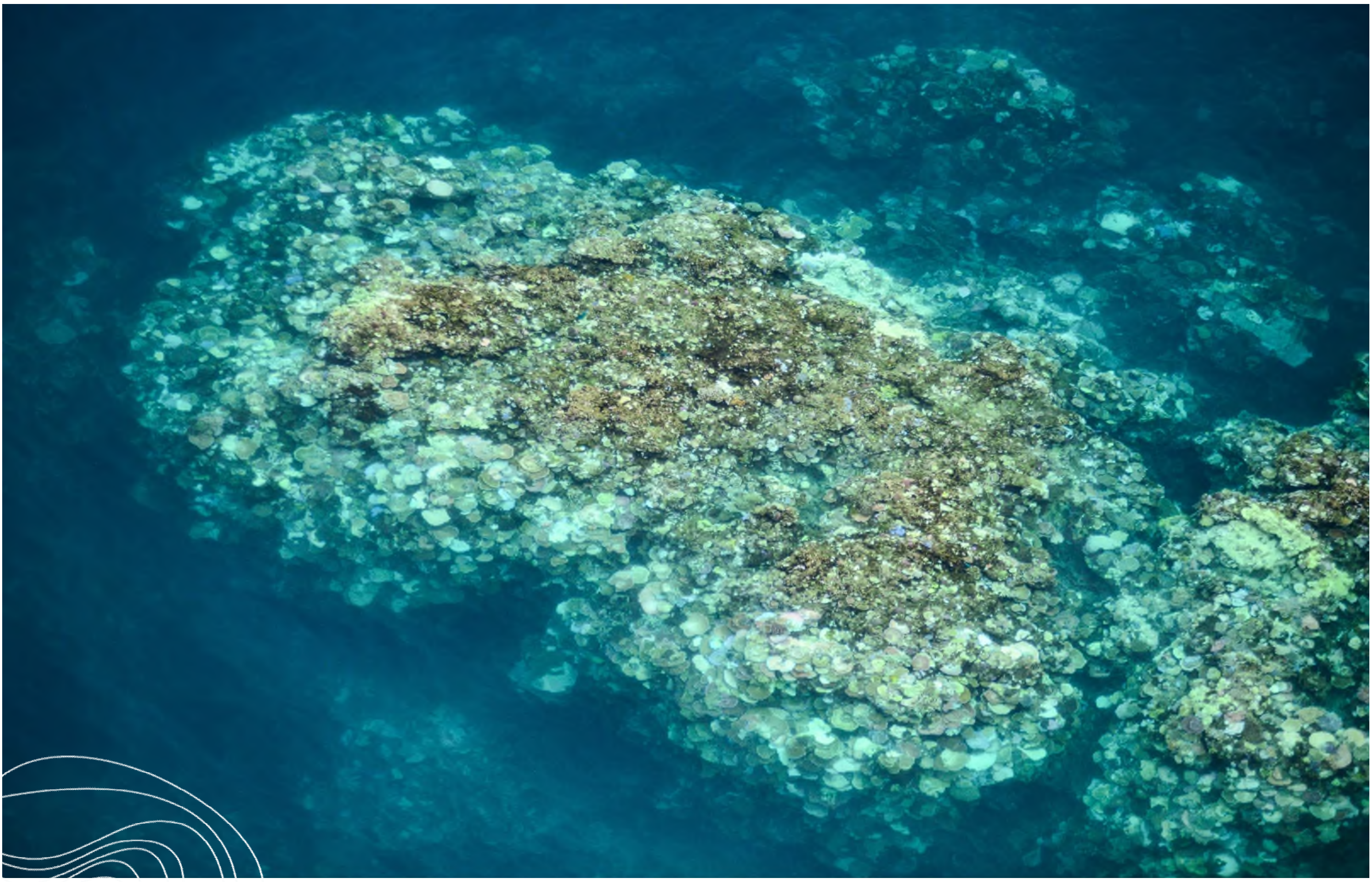

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Cover photo:
Extreme bleaching (>90% of live coral cover affected) at Nathan Reef near Innisfail, QLD on 9 March 2017.
Photo: Sam Noonan, AIMS

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1 PREFACE

The environmental and ecological monitoring programs of the Australian Institute of Marine Science (AIMS) contribute to the sustainable use and development of the tropical marine environment by setting baselines and by advising managers at the Great Barrier Reef Marine Park Authority (the Reef Authority) of changes in ecosystems and the environment[1].

This Standard Operational Procedure (SOP) is Volume 11 (v3) within the series of AIMS SOPs. Produced in collaboration with the Reef Authority through joint monitoring response efforts, it details a standard procedure to conduct aerial surveys of coral bleaching extent and severity (the proportion of shallow-water coral cover exhibiting bleaching). Aerial surveys only record the percentage of visible living coral cover (both hard and soft corals) that are bleached or not bleached. Aerial surveys do not categorize coral bleaching across the full range of individual colony intensity. This aerial survey method has been in use since the first documented mass bleaching event on the Great Barrier Reef (GBR) in 1998. Details on data management, training, and quality control are also provided.

2 INTRODUCTION

Mass coral bleaching (widespread and spatially extensive coral bleaching) occurs in response to large-scale environmental stressors, typically prolonged periods of higher-than-average sea surface temperatures. Mass coral-bleaching events within the Great Barrier Reef Marine Park (GBRMP) are evident when bleached corals become common across many individual reefs in more than two distinct regions of a coral reef ecosystem, depending on the spatial pattern of environmental stress.

Coral bleaching is a striking, visual stress response and manifests as paling or whitening of coral tissues as symbiotic zooxanthellae are expelled. As part of this stress response, any fluorescent or other animal pigments sometimes produced by the coral host tissues become more pronounced, often giving the coral a vivid (“fluoro”) glowing colouration of blue, pink, purple or yellow. Fully bleached white and fluorescent corals (severely bleached individuals) are easily seen from aerial surveys.

Coral bleaching is rarely uniform and during a bleaching episode, whether a local or mass bleaching event, it is common to observe a high level of variation in both bleaching severity (the proportion of coral cover bleached) and bleaching intensity (between different reefs and even between different sites within the same reef. This is mainly due to differences in coral community composition, the relative abundances of hard and soft corals, and reef habitat topography that influences reef hydrodynamics and the intensities of thermal stress, solar radiation, and light. Bleaching also usually attenuates with depth, when thermal gradients occur.

Variation in coral bleaching within a reef is best quanitifed with fine-scale, in-water surveys at multiple sites and depths on a representative number of reefs across the full extent of the reef ecosystem. However, extensive in-water surveys can take weeks to months to complete, will rarely be able to capture hundreds of reef locations. In comparison, aerial surveys provide a rapid and synoptic overview of bleaching events across large spatial scales (100s – 1000s km).

[1] For more information visit https://www.aims.gov.au/measuring-change

The Great Barrier Reef Marine Park (GBRMP) stretches 2300km along the Queensland coastline, covering an area of 344,400km^2 and is composed of more than 3000 individual reefs. Documenting the full extent of coral bleaching events in a marine region of this scale requires an aerial approach in combination with in-water surveys. Aerial surveys provide a broad-scale overview that qualitatively estimates the proportion of bleached and non-bleached coral cover (both hard and soft corals) within communities throughout reef flat, back reef (<3m) and upper reef slope (0-6m) habitats. This information helps reef scientists and managers at the the Reef Authority determine if a mass bleaching event has developed in response to anomalous marine heat waves.

To complement aerial surveys, in-water surveys conducted on a subset of reefs and sites are crucial in providing more detailed information on community type, living coral cover, variation in colony level bleaching severity across different coral growth forms, species and taxa, and most importantly an assessment of how bleaching severity extends into deeper reef habitats that are not visible from the air. This information is particularly critical to understanding the severity of a mass-bleaching event.

Given the extensive size of the GBR ecosystem, aerial surveys are a practical and timely way to document the spatial extent and severity of reef-wide community bleaching responses. The benefits of employing broad-scale aerial surveys include:

1. rapid and important information on the current status of reefs.
2. an historical context of ecosystem change by allowing comparisons with past events.
3. possible assessment of cumulative effects.
4. objective communication of the event in a timely manner.
5. a valuable dataset for assessing the ultimate impact of marine heatwave events on a spatially extensive marine region.
6. a valuable dataset for research into spatial and temporal patterns of coral bleaching and analyses of correlations with environmental drivers to assess adaptation potential.
7. a growing catalogue of reference data which can be used to improve our understanding of bleaching and refine reef management where appropriate.

Aerial surveys are conducted using fixed, high-wing aeroplanes or helicopters at low altitude (approximately 150m/500ft). They are generally carried out in partnership with the Reef Authority and possibly other research agencies[2]. They are one component of the Reef Authority's Coral Bleaching Risk and Impact Assessment Plan which provides a framework for decisions, actions and responses to bleaching events (GBRMPA 2013). According to the plan, when response levels 2 or 3 (Fig 1) have been reached, a two-tiered reef assessment is triggered.

[2] Note: the Australian Institute of Marine Science does not presently conduct aerial coral bleaching surveys as part of its routine Long-Term Monitoring Program

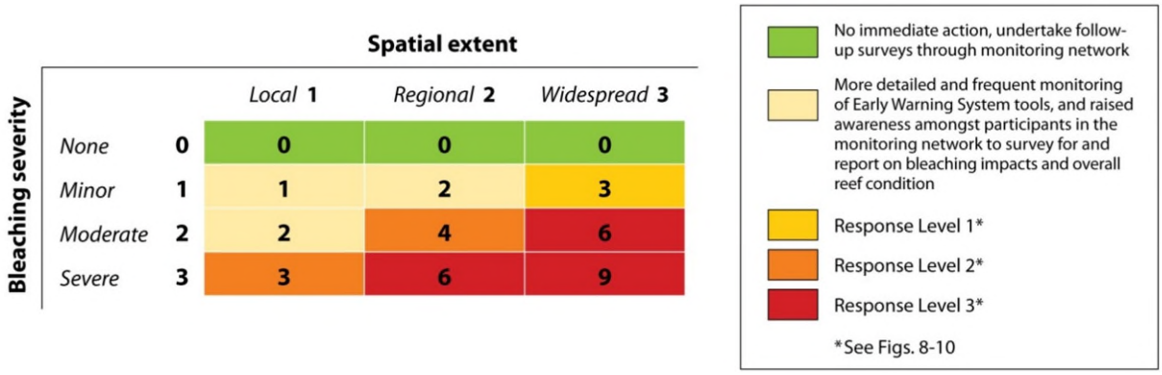

Figure 1. The classification matrix used in the Reef Authority's Coral Bleaching Risk and Impact Assessment Plan used to inform the final decision as to which response level needs to be triggered. From: Coral Bleaching Risk and Impact Assessment Plan (GBRMPA 2013).

3 DETAILED PLANNING

The Reef Authority coordinates and initiates the use of aerial surveys as the agency responsible for implementing the Coral Bleaching Risk and Impact Assessment plan, generally in consultation with science agencies such as AIMS and other stakeholders.

Detailed planning takes into consideration:

1) Specific objectives of the survey, e.g.
   a) Regional overview of bleaching, severity and extent.
   b) Training of personnel
   c) Inter-observer comparison
   d) Historical comparisons to bleaching
   e) Photographic and video surveys to document community bleaching observations

2) Geographic scope of the survey taking into consideration supporting information (eg. Spatial distribution of thermal stress, in-water reports of coral bleaching) on the unfolding bleaching event to date, time, budget and logistics. Full coverage of the GBRMP is required but should focus on regions that are most likely impacted by SST anomalies.

3) Identification of observers and their roles. Depending on the specific objectives of the survey, these should include as a minimum two observers per flight, one sitting on each side of the plane. Depending on seats available and weight restrictions, the addition of a navigator is very useful and additional observers for training purposes can be included.

   An example of roles in order of necessity could be:

   a) Observer 1 – Recording data into tablet and the Reef Authority paper zoning maps, left. Photographs and recording observations and narrating flight path.
   b) Observer 2 – Recording data into tablet and the Reef Authority paper zoning maps, right. GoPro video.

c) Navigator/photographer – Flight path planning and adherence during flight, liaison between observers and pilot, verbal cues on location to observers, noting flight time over each reef, monitoring flight time, fuel and reef priorities.
d) Observer 3 – Recording data into hardcopy maps and narrating observations, left.
e) Observer 4 – Dedicated Photography, right.

4) Drawing up a flight plan. For consistency and comparison with past aerial surveys, the flight plan should replicate previous flight paths as much as possible. A "priority list" of reefs should be created based on past aerial bleaching surveys using GIS tools and GPX files that can guide real-time flight decisions (See Appendix 2). Priority reefs for aerial surveys should includes in-water survey sites (AIMS long-term monitoring sites, sites with recent bleaching observations and bleaching severity data), reefs with in-situ temperature loggers, reefs included in previous aerial survey flight plans and/or reefs of particular interest for other justified reasons. If any of these reefs are not on the flight path, they may be added subject to flight constraints. Flight constraints usually relate to maximizing the flying time with highest number of priority reefs and total reefs covered by the survey.

5) Timing of surveys. This takes into consideration the need to conduct the surveys when bleaching is at its peak (most intense), but before major mortality sets in. This will be informed by early warning systems (e.g. satellite-derived temperature/bleaching products, real-time temperature monitoring, bleaching thresholds, etc.), in-water surveys from research teams, tourism and industry partners, anecdotal reports from the general public and scientists actively accessing the local coral reefs. In the past, the GBR surveys have generally been undertaken in March, but could be required earlier depending on the timing and intensity of marine heatwaves in January or February.

   Early warning systems include:

   Satellite SST

   NOAA Coral Reef Watch: https://coralreefwatch.noaa.gov/satellite/index.php (Global)

   Bureau of Meteorology Reef Temp Next Generation- Sea Surface Temperatures Anomalies and Degree Heating Days (14-day IMOS climatology): http://www.bom.gov.au/environment/activities/reeftemp/reeftemp.shtml (Great Barrier Reef)

6) Weather. Bleaching observations can be severely affected by weather. Wind can cause sediment resuspension which can dramatically reduce visibility of bleached coral below the surface. This is more of an issue inshore than offshore. However, even offshore breaking waves over reefs and bommies can severely affect bleaching observations and photographic documentation of the observations. For this reason, it is advised to conduct aerial surveys when wind forecasts are <15kn. Consideration also needs to be given to whether inshore reefs should be surveyed in the morning or afternoon given wind forecast, cloud cover and tide.

7) Rain often has only a modest impact on surveys. Pilots generally don't take small planes through rain showers if they can avoid them, preferring instead to go around the showers. Due to the localized nature of showers, often this precludes only a limited area from being covered in the survey. Rain radar information can inform on conditions shortly prior to the flight and provides an opportunity to make minor adjustments to the flight path if required.

8) Time of day and tides are generally also of secondary importance. Surveying at a low or medium tide height is certainly preferable but high tide observations can also be made provided water clarity is good and tide is not too high (<3.5m). Sun glint / reflection on surface can be a problem, particularly in late afternoon but this can be ameliorated by changing the direction of approach to the reef. Low sun angle in the late afternoon (>5pm) however can severely limit observations.

   The optimal time to document, assess and photograph the reef from the air is between 9am and 3pm and during mid-day low tides.

4 EQUIPMENT

Equipment required for aerial surveys consists of:

- GPS's for navigation and flight path (track) recording
- Tablets for real-time visualization of location/position
- Tablets and paper maps for data entry
- Intercom system and audio recorder
- Cameras (still and video)
- Power banks for tablets/phones and spare batteries for cameras and audio recorders
- Personal gear

It is highly recommended that all equipment is prepared and tested prior to being packed for a survey flight.

Details for each piece of equipment are discussed in more detail below.

4.1 GPS Recorders

Prior to the survey a GPS is used to as a time reference to synchronize cameras and audio recorders to. This is an important step because it allows all images and audio tracks to be geo-referenced later (see Section 2.5).

During the survey, they are used mainly to provide a detailed track of the flight path. Care should be taken to ensure the GPS's are setup to record at pre-determined 5 second intervals. Place a few around the cabin, preferably near windows, but avoid the GPS's from overheating and turning off!

If you are using a tablet without a built-in GPS, it may be necessary to either tether a GPS or set up a WIFI/Bluetooth GPS transponder to get your electronic maps to show your position. Using tablets with built-in GPS is preferable. Make sure you have tested your equipment and understand how it works (ideally before packing it for the flight). Crucial time can be wasted on the ground dealing with equipment issues. Pre-flight preparation is crucial to ensure the flight time is used to its full potential.

One set of fresh AA batteries will last a Garmin GPSMAP78 a whole day. It has sufficient storage capacity for 10,000 track points. Be aware that smaller, cheaper units may be more power hungry and less generous on track point storage. Adjust settings to capture the highest track point resolution as possible. There is always time to change batteries during re-fuelling stops.

It is advisable to check the battery status of each GPS after each flying leg. It can be useful to turn the GPS's off between flights provided you don't forget to turn them back on again for the next flight.

IMPORTANT DOs AND DON'Ts

1. DON'T use any automatic track log features your GPS may have! Usually this feature seeks to minimize the number of points recorded by only recording a point when the direction has changed. ALWAYS choose to record at fixed 5-second (or more frequent) intervals.
2. DON'T hit the save button at the end of the trip. That is right – DO NOT SAVE! Modern GPS's can be too smart for our good! A common feature is that they remove waypoints with the same (or close) coordinates upon Save. Some even change the time stamp format from UTC time to some other time format when saving to save space. This can play havoc with geo-referencing your images. Track logs are normally written to flash memory which means they are automatically saved when data is written to it and are not erased when the GPS is turned off.
3. DO test your GPS to ensure that the track is saved automatically when the GPS is turned off.
4. DON'T leave your GPS under the front windscreen of the plane. GPS's have built-in temperature sensors and turn off when they get too hot. Use multiple GPS's to be sure! Check them from time to time if possible.
5. DO make sure you put fresh batteries in the GPS before the survey.
6. Do make sure your GPS's have enough memory to store your track points for a day's flying. Some smaller, cheaper models don't! Check their specifications!
7. DO download your GPS tracks every day!

4.2 Tablets for real-time navigation

If you are recording onto paper maps, some form of real-time visual position information can be a lifesaver. This is particularly important if you are not in the front seat and have a restricted wide view. A laptop computer or tablet with a real-time geo-reference and appropriate spatial GIS map layers can provide this navigational information and simplify the survey assessment with current location and approaching reefs. If your laptop or tablet has a built-in GPS, so much the better (highly recommended!). If not, you will need to either tether a GPS or find a wireless GPS solution.

A good choice of software to run on the computer or tablet is Memory Maps which have the Reef Authority Marine Park zoning maps as one of the map options that can be purchased. This software is available in your App Store for Windows PC, Android, or iPhone/iPad operating systems. These maps are preferable because they contain all the relevant reef-related information such as reef name, reef sub id, indicative reef outlines and zoning. As a bonus, this app also provides flight path logging, aircraft speed, altitude and other potentially useful information. Other map systems may also be suitable if they provide an equivalent level of information.

One tablet per observer/navigator would be ideal. Tablets in 8" (200mm) configuration take up very little space and can be easily handled next to, or on the observers' lap. Cradles and mounts designed to cradle and clamp your tablet inside the aircraft are widely available and free up space for hands-free data entry (RAM Mounts Tablet Mounts :: Express Post Delivery (hurtlegear.com.au)).

Figure 2. As used in 2017 and 2022, real-time navigational information is provided by an Android Lenovo tablet. Surveys are aided by running Memory Maps mapping software, and the AIMS coral bleaching app that operates within the ArcGIS Field Maps App, which includes GBR and Torres Straits reef features to guide flight path. The digital apps used in conjunction with hardcopies of the Reef Authority zoning maps to record bleaching observations, capture GPS locations of each data point and provide complete data records ready for analysis at the end of each flight through ArcGIS.

4.3 GIS based data collectors and paper maps for data entry

Until (and including) the 2016 bleaching event, all data entry was onto hardcopy the Reef Authority zoning maps (Figure 3). This is a tried and proven, low-tech method of data entry with very little that can go wrong. However, there are down-sides to this method of data entry. These include cumbersome folding of large paper sheets, changing and stowing maps with each change in map coverage and, most significantly, considerably more time and effort in digitizing hand-written scores and notes with associated potential for error. Daily review of data from hard copy maps makes reporting of survey observations a slower process.

In 2017, a digital data entry system was trialed by one of the four observers involved in the survey in addition to the traditional paper data record. This involved an 8” (200mm) Android tablet (the same used for navigation) running the “ArcGIS collector” app, developed by AIMS and available in both Android and iPad operating systems from your App Store. This app enables the collection of geo-referenced bleaching observations and images from aerial and on-ground surveys. Some major advantages of this system are that all entries are automatically geo-referenced. It is also quick and easy to use, and the results from each survey can be instantly viewed during and after the survey. Once back in mobile/wireless range, your data are automatically uploaded to a server. No manual data entry is required. The 2017 trial was largely successful and was used again in 2022 by all observers to collect data and navigate the reef as updated GIS layers provide all location information required within the AIMS ArcGIS data .

Figure 3. The essential GBRMPA hard copy zoning maps which are used to record each bleaching observation during flight.

INSTRUCTIONS FOR INSTALLING THE AIMS CORAL BLEACHING AERIAL SURVEY APP

This app allows the collection of bleaching observations and geo-referenced images from aerial and in-water surveys. Your device should be set up while in mobile/wireless range. Afterwards, the app uses GPS only to record the points and will upload your data once you are back in mobile/wireless range.

For questions or problems, contact Ben Radford (b.radford@aims.gov.au); James Gilmour (j.gilmour@aims.gov.au) or Neal Cantin (n.cantin@aims.gov.au).

Downloading & installing the app

Search your preferred app store for ‘ArcGIS Field Maps’ in your store and load onto tablet.

- Contact Ben Radford to register as a user and to receive login credentials
- Click on “Field Maps Icon” to open app, choose Sign in with ArcGIS Online
- Click “Continue” at next screen, which will bring you to sign in page
- Sign in (first time use only, or if you sign out)
- Click on the “AIMS Coral Bleaching Aerial Survey App v2”
- You need to download maps to use in offline mode while in the air for the surveys. Click on 3 dots within the AIMS Coral Bleaching Aerial Survey App v2 icon and select “Add offline area”. Choose your work area (by zooming into include the GBR Full Area or you can do by region). Edit Level of Detail: County or State to reduce download size and click “Download Area” (this downloads the base map for offline use – 300-600Mb). Rename the area once downloaded.
- After entering ArcGIS Field Maps you will need to adjust the Collection Settings: Click on user profile icon in top right corner; select collection settings; Change Accuracy to 100m to enable some delay between tablet GPS and ensure data can be entered as required if GPS signal weakens. During 2022 surveys, GPS accuracy was usually 2-3m.

A complete set of instructions for this app can be found here.

4.4 Intercom and audio recording system

The 2016 and 2017 aerial surveys were the first to use an audio recording system with dedicated intercom between observers. It consisted of:

Audio recorders – 4-channel "Zoom Handy Recorder H4n" (Figure 4). The kit included a primary recorder and a spare. This unit records to an SD card. A full day of recording resulted in an 8 Mb audio file. The audio recording has a timestamp which needs to be set to the GPS time (refer Section 2.5) so that recordings can be geo-referenced. At the time of writing the audio recording was used as a back-up in case there were discrepancies in digitizing data from paper maps.In future, even if all data recording is done digitally via tablets, the audio recording may be a useful backup in case of equipment failure, or if an observer misses entries for other reasons. The data record is also useful to include additional observations related to coral cover or bleaching patterns, that aren't captured by the Aerial Bleaching category alone. It is therefore important that each observer calls out their scores as they make them. It is also useful if the navigator calls out location information on a regular basis, e.g. "approaching Noggin Reef from the SE, …traversing Noggin Reef south to north, … leaving Noggin Reef on the NW side…"

Figure 4. A four-channel Zoom Handy recorder H4n. The plug at the bottom right connects directly to the intercom box. Two intercom boxes can be plugged into the recorder at once. The stereo microphones on top of the recorder are only used when in autonomous mode

1) Intercom boxes – "Pilot Communications PA400S-ASC" (Figure 5). The kit included two boxes which can each accommodate up to four headsets. The two boxes can be daisy chained to expand the system to seven headsets (the eighth socket-pair being taken up by the daisy-chain plugs). Each box runs off 2 x 9V batteries. Batteries were exchanged after each flying leg.

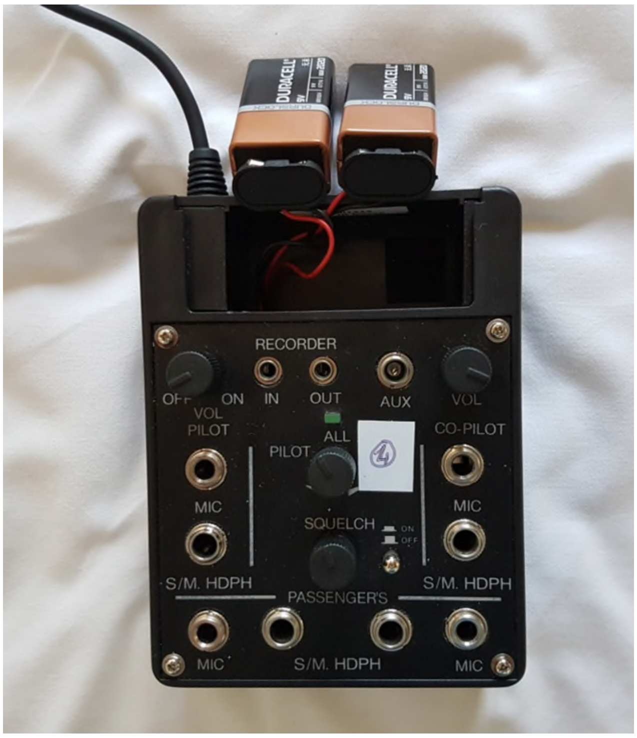

Figure 5. A 4-channel PA400S-ASC intercom box by Pilot Communications. There are 4 pairs of sockets to take headsets – designated as "pilot", "co-pilot", and two "passengers". The audio recorder plugs into the "Out" socket

2) Aviation headsets – "David Clark Company". The kit included seven headsets. Each set terminates into two plugs, one for the L and R speakers and one for the microphone. The microphone and speaker plugs are different diameters so there can be no confusion about what plugs go where. Any plug-pair can go into any socket-pair.

   With a single intercom box, a four-headset configuration is shown below (Figure 6).

Figure 6. Four headsets plugged into a single intercom box with an audio recorder. To use it so that all four persons can talk to each other, the selector switch must be in the CENTRE position. Note that the daisy-chain plug-pair (top left of the intercom box) is left unplugged in this configuration.

With two intercom boxes and four headsets, the configuration looks like the set-up in Figure 7. If required (e.g. for inter-observer comparison), the top two headsets can be isolated from the bottom two by unplugging the daisy-chain leads while the recorder still records both sets of communication.

Headset extension leads may be required to provide enough reach from the intercom box to observers and navigator sitting in different rows and/or different sides of the plane, particularly if the plane is “large” (e.g. a 12-seater).

Figure 7. Four headsets plugged into two intercom boxes with a single audio recorder plugged into each intercom box. The two boxes are daisy chained via a set of connector leads which can plug into any socket-pair. The top intercom box can accommodate one more headset while the bottom intercom box can accommodate another two headsets. To use it so that all four (or seven) persons can talk to each other, the selector switch must be in the LEFT position.

4.5 Cameras

Photos provide an invaluable means of permanently capturing small-scale views of the bleaching state of reefs. Since observers only get a very short dwell-time over each reef (seconds – 10’s of seconds) and >100 reefs may be flown in a day, repeated over multiple days, it can be highly taxing on the brain (image overload). Committing this wealth of visual imagery to memory is near impossible. Reviewing the aerial images provides an opportunity for more of this information to “sink in” and regain perspective.

It is often also the case that new things are seen in photos which were missed during the flight (e.g. presence and extent of recent coral mortality, community types, deep bommies etc).

Photos and video are also very important to document the severity scores recorded for each reef and for communication and training.

The rule of thumb is: “take lots”, even when you see little or no bleaching! For scientific and training purposes, the best images are ones that are zoomed-in (e.g. Figure 8). For communication purposes, the best images are ones which provide a wide view and have easily recognizable features in them (e.g. an island, boat, tourist pontoon etc). However, for the latter images to “work” (i.e. illustrate bleaching, bleaching must be intense and coral cover high (e.g. Figure 9, Front cover).

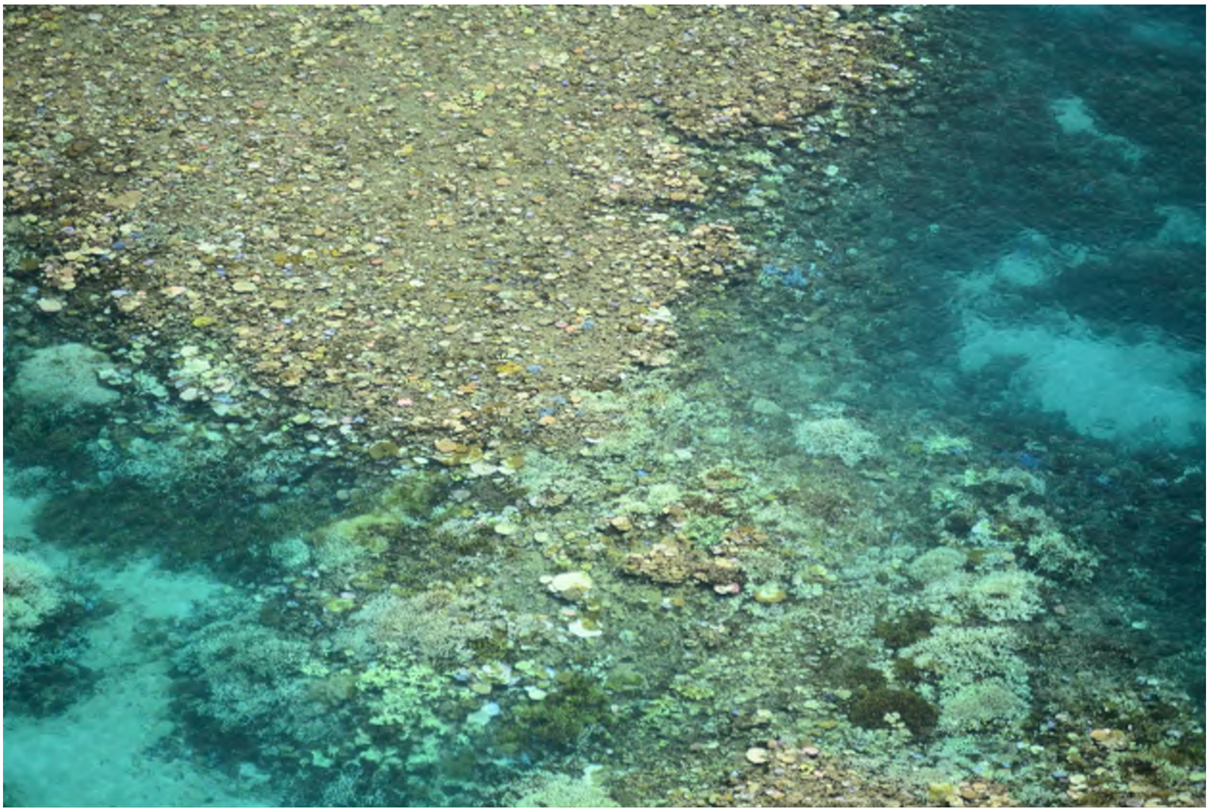

Figure 8. An example of a zoomed-in image for scientific purposes. It shows extreme community bleaching (> 90% of corals bleached (fully bleached white, pale and/or “fluoro”), recent mortality of staghorn/branching and plate corals (green patches in the foreground) and that the community is dominated by plate corals on the reef flat and branching corals in deeper lagoon areas.

Figure 9. An example of a wide-view image suitable for communication showing extreme bleaching on Lorne Reef, an inshore patch reef, with Rattlesnake Island in the background. (Image taken March 1998).

For best results, use a good quality digital SLR camera fitted with either a 24-70mm or a 70 – 300mm zoom lens. A circular polarising filter is essential for reducing glare and improving the clarity of underwater features and corals beneath the surface. Since the images "move" fast, use the fastest shutter speed your camera will allow in the light conditions. Shutter speeds of <1/1000th second are recommended. To achieve this, it may be necessary to reduce the F-stop (open the aperture, e.g. F1.8 - F5.6) and use a moderately high ISO number for increased light sensitivity (e.g. 800-1800 depending on the light conditions, modern full frame mirrorless cameras can use even higher ISO settings without losing pixel clarity up to 4000 or higher, but by rule use the lowest ISO settings to give less "grainy" images). Turn the automatic image stabilization feature on your camera to "ON" and try not to support the camera (or arm, shoulder, elbow) on the side of the plane to minimize image blurring due to vibration. It is important to review photos as you go (when practical!) and adjust the settings as required throughout the flight as light conditions will change dramatically through the day.

Video imagery of the flight may be recorded using one or more Go-Pro video cameras (or equivalent) and a suction-cup mount through one of the back windows. Choose a window towards the back of the plane to avoid the landing gear and wings disrupting the field of view. Battery life on the Go-Pro was not sufficient for a single camera throughout the entire day. Four cameras were used in 6 hours of flight. Cameras were changed when possible by the closest observer and angled down to minimize the reflection and glare from the window. In future flight planning, aircraft with a vertical downward facing port would be ideal to equip the aerial survey with high-resolution video cameras and hyperspectral imaging cameras to obtain richer and more quantitative data of bleaching.

IMPORTANT:

1. To geo-reference your photos, you need to set the camera clock to the time shown on a GPS. Ensure that the GPS has a clear view of the sky and a good fix (i.e. not indoors). Set it to the nearest second and check. Repeat until you get it spot on. This can save work later!
2. Take a photo of the GPS time with your camera so that the camera clock time can be verified and, if necessary, minor changes can be made.

4.6 Personal gear

On small planes, weight and room are at a premium. Therefore, it is important to keep personal gear to an absolute minimum. Take enough water with you to last the day, food, a towel to sit on and not much more. There is enough clutter in the plane with your scientific equipment!

5 AIRCRAFT CHARTER

The choice of what type of aeroplane to charter for the surveys can be a challenge. At a minimum, it should have high wings so that the view is not obstructed. Everything else (apart from safety!) is of secondary importance. Small single-engine planes such as the Cessna 172 (3 seats, plus pilot, Figure 10) are the cheapest to charter and most manoeuvrable (handy around islands and bays) and can fly quite slow (<100kn, also a plus). On the other hand, they only take a maximum of 3 observers and are somewhat cramped, especially with our equipment.

Larger-single engine planes such as the Cessna Grand Caravan (Figure 10) can seat up to 12 people (plus pilot and co-pilot), but for weight, manoeuvrability and comfort, no more than five people is recommended. It is considerably less manoeuvrable and more expensive than the Cessna 172. A Cessna 210 (Figure 10) with 5 seats (plus pilot) may be a good compromise, if you can find one.

Cessna 172	
Cessna Grand Caravan	

Cessna 210	

Figure 10. Single-engine fixed-wing planes

Twin-engine, high-wing planes are intrinsically safer, and for remote offshore surveys, this could be required, but have been very hard to access or not available at all from Queensland charter companies during the 2022 survey planning. They are generally more expensive to charter than their single-engine equivalent but for increased safety and size, they may be a wise choice. The smaller Cessna 337 Skymaster (5 seats, plus pilot, Figure 11) with its distinctive front and rear engines is excellent for aerial survey work and the pick of the bunch, but rare. The Vulcanair P68 (5 seats, plus pilot, Figure 11), is more common and also excellent.

Larger twin-engine planes such as the Aero Commander 500 (Figure 11) are also good, but expensive and hard to find.

Cessna 337 Skymaster	
Partenavia P68 (Vulcanair P68)	
Aero Commander	

Figure 11. Twin-engine fixed-wing planes

Helicopters can provide a very flexible and capable option for aerial surveys, as flight path and hovering with open windows can improve aerial image quality. Cost of helicopters is higher but worth the additional expense for flight and survey flexibility in distant offshore locations. Helicopters were used for 10 of the 11 flying days during the 2022 aerial surveys.

Figure 12. Airbus AS350 B3 Squirrel Helicopter

Figure 13. Bell 407 Helicopter

Health and safety standards will require extra equipment to be carried on board the plane while flying over the ocean, including a mandatory life raft, a personal EPIRB/radio beacon and life jackets for each passenger. For the 2017 survey, each passenger was equipped with a Nautilus LifeLine VHF-GPS Radio, in 2022 the life jackets used were equipped with a personal EPIRB. The requirement for a life raft should be communicated to the charter company early to allow them to find and fit it as they are not a normal aviation requirement over water.

Corporate safety standards, the availability of suitable aircraft and requirement of low altitude qualified pilots will severely limit the choice of aircrafts available for the survey and the scheduling of each flight.

TIPS:

1. For the right aircraft and the right price, it may be worth relocating a plane from another airport, especially if the survey is for multiple days.
2. An aircraft broker who knows the industry and the availability of charter planes may save you a lot of time and effort!
3. Vertical ports for camera equipment would be an excellent feature when shopping for the survey plane.

6 SURVEY TECHNIQUE

6.1 Basic protocol

The survey technique is simple. The aircraft flies along a pre-determined flight path (refer Section 2) at an altitude of approximately 150m (500ft) and, upon entering visible reef area, each observer looks for live coral and scores the percentage of live coral that appears bleached. “Bleached” in this instance can be any coral colony that appears pale, white or “fluorescent” (“fluoro”).

At this point the observer checks their position within the reef and writes their score on a paper map in the appropriate place. If an electronic data entry method is used, this step is taken care of in the software as all entries are automatically geo-referenced. The timing of data entry is important in order to capture the location within each reef the observation represents. The ArcGIS Field Maps data entry tool stores the GPS location as soon as the data point is entered, there is time to then enter the bleaching category and any additional field related to coral cover that are required.

Using the AIMS Aerial survey bleaching app, the observer hits the (+) to add a new observation and then selects the bleaching category from the available radio buttons. If the plane traverses multiple reef habitats (Fig 16) observers score as many of these habitats as they can. Try to take a moment within each habitat before making your score and record only 1 or 2 observations for each habitat within each reef. If the reef is very large, it will require additional scores for within habitat variation. Try to score consistently the same number of observations depending upon the size of the reef. A general guide: Small reefs will generally have up to 3 observations and larger reefs can have 5-10 observations.

Reefs are classified into six bleaching categories (Appendix 1) based on the proportion of coral cover that appeared white in a zone covering the reef crest and upper reef slope (Berkelmans et al. 2004; Hughes et al. 2017):

Aerial Category 0 = <1% of live coral is bleached (No Bleaching)

Aerial Category 1 = 1 – 10% of live coral is bleached (Minor)

Aerial Category 2 = 11 – 30% of live coral is bleached (Moderate)

Aerial Category 3 = 31 – 60% of live coral is bleached (Major)

Aerial Category 4 = 61 – 90% of live coral is bleached (Severe)

Aerial Category 5 = >90% of live coral is bleached (Extreme)

Mortality if clearly visible (see Figure 20) also recorded as and “M” with Bleaching Category

It is recommended that each observer keep a laminated copy of these categories and their ranges in front of them for ready referral (Figure 16, Appendix 1).

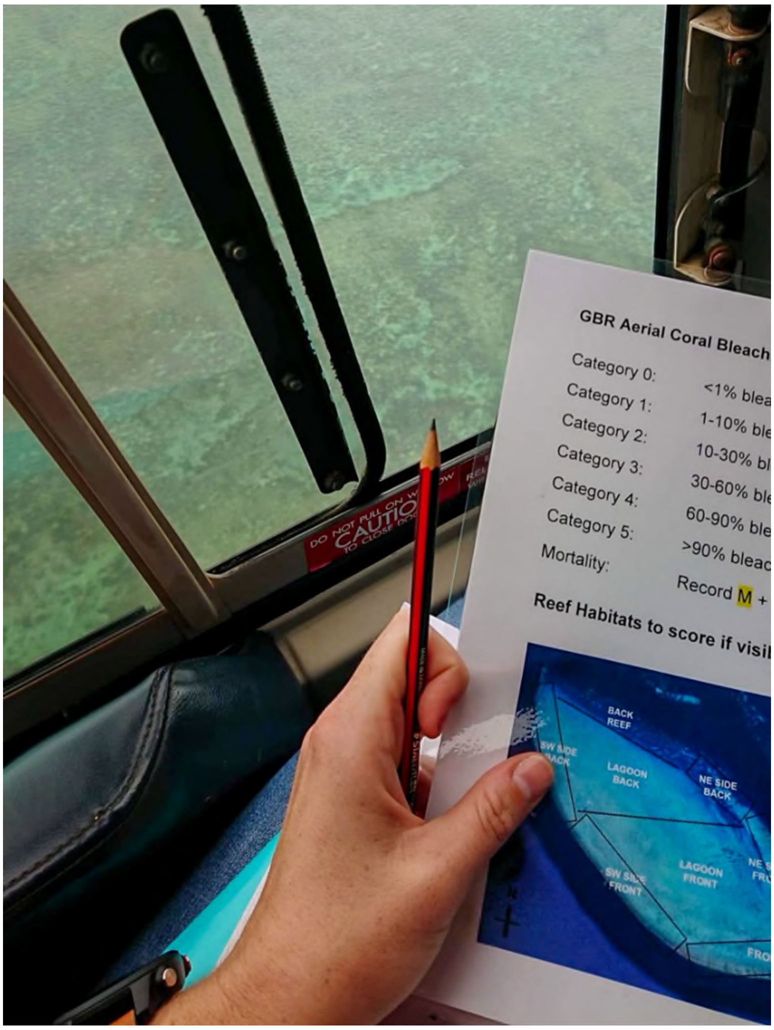

Figure 12. A laminated copy of the bleaching categories and a diagram of reef zones is kept in the seat pocket in front of the observer.

6.2 Discerning between categories

Scoring the bleaching state of a reef is by nature a subjective process. To maintain a high-quality dataset that is consistent between observers and with in-water observations, it is important that all observers be experienced in coral reef field ecology. It is also highly advisable that they have undergone a process of training and standardisation in the office/lab and in the air prior to each aerial survey campaign.

The technique requires observers to the know where on a reef to look for live coral, recognize what type of coral community is present and to know the difference between normally pigmented coral and bleached (or partially bleached) coral. In addition, observers also must discern living coral from dead coral, recently dead coral and bare substratum.

It is ultimately about very subtle differences in colour, shape and texture which only someone intimately familiar with how living corals underwater appear and how they respond during a bleaching event are likely to be able to do well. Observers with experience conducting transect based coral bleaching surveys underwater are well suited to be trained for aerial surveys. At the peak of a bleaching event, as community bleaching severity increases, the differences between non bleached living coral and fully bleached white and/or fluorescent colonies becomes more obvious.

The mental process of deciding on a bleaching category for an observed patch of reef can be difficult even for trained observers, but the decision process can be thought of along these lines:

1) The two extremes: Category 0 (no bleaching evident, all corals look normally pigmented) and Category 4 and Category 5 (60-90% and >90% bleached, most if not all corals are white, pale, fluoro or a combination) are normally easy to recognize. Seeing a category 4 is often a "wow, look at that, every coral is glowing!" moment.
2) Category 1 (1-10% bleaching) is when you see only a few colonies standing out from the reef as bleached white or fluoro, nothing major in the overall scene of typical reef substrate (brown green) but definitely present.
3) If your observation doesn't fall into the above categories, that only leaves two categories to decide between: Category 2 (10-30% bleached) and 3 (31-60% bleached).
    i. Category 2 (10-30% bleached) can be thought of as "low-level" bleaching. Bleached white corals are plentiful, although most corals look normal.
    ii. Category 3 (31-60% bleached) can be thought of as "moderate to high" bleaching. Bleached corals are very abundant, but by no means is everything bleached. Look between bleached colonies and get a perspective of the proportion of bleached vs healthy corals. This will also help differentiate Category 3 from 4 bleaching.

Prospective observers should review photo examples of each category and talk through the differences before the survey. At the beginning of the first flight especially, it is important to communicate observations among all observers to standardise scores as much as possible. It may be helpful to start with reefs close to home that observers are all familiar with. Do a few passes over a handful of reefs until observers have their "eye in". A training flight as in-water reports of bleaching become increasingly common is always useful to develop a sufficient team of observers that are scoring the reef with a common agreed perception of bleaching severity from the air.

During the 2022 aerial survey a large number of reefs throughout the GBR and the Torres Straits displayed very low coral cover visible in the shallow reef habitats visible from the air (Figure 21). During these situations, the coral cover present can begin to influence the aerial bleaching scores and make it a lot harder for the observers to differentiate living coral from other reef benthos and assess coral bleaching. As fast growing, diverse coral communities become impacted by past disturbance events (eg. Cyclones, Coral bleaching, Crown of Thorns starfish), reefs with low living coral cover will influence the relationship between thermal heat stress and bleaching severity (Hughes et al. 2018).

As a result for the 2022 Aerial surveys additional categories were created in order to capture reefs with very low coral cover visible from the air, reefs dominated by massive porites and reefs with diverse coral cover displaying a true, no bleaching response.

Within the ArcGIS Field Maps aerial bleaching survey app, in addition to recording the Aerial bleaching category, if use the drop down menu No Bleaching Category to record a descriptive category related to coral cover visible from the air. Only record these descriptors at reefs when the categories become applicable, living coral cover is very low (ie. Your are seeing mostly hard consolidated reef pavement and/or only 1 coral growth form (Porites or sub-massives) and it becomes challenging to determine a bleaching score because there are very few corals available and visible to bleach. The objective with this descriptive data observation record, is not to estimate coral cover from aerial surveys, but to differentiate a reef score that is influenced by very low coral cover, so that we can document a No Bleaching reef score at reefs with and without typical hard and soft coral cover.

No Bleaching descriptive Coral Cover Categories included:

- **Low Coral Cover**: majority of reef tops look like either hard consolidated reef rock (flat pavement) or long dead coral skeletons with very low living coral cover
- **Low Cover Porites dominant**: Coral cover is low (<5%) and the most common growth form visible is massive Porites
- **Porites dominant**: Coral cover appears to be normal but the most common growth form is massive Porites or sub-massive corals. No visible diverse branching corals
- **No Live Coral**: no living coral (hard or soft corals) visible
- **No View Deep**: Aircraft has travelled over a reef on the Zoning map, but does not see coral in shallow depths.
- **No View**: if observer is on the opposite side of the aircraft and doesn't see a reef along flight path
- **Sediment / No Vis:** water clarity is too dirty to determine coral cover or bleaching state, can be common on inshore locations.

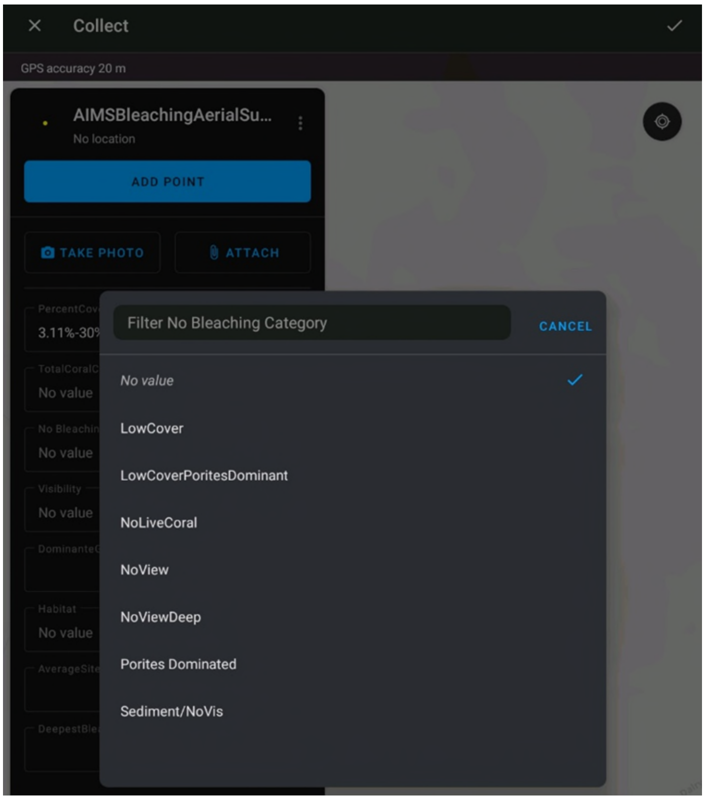

Figure 13: AIMS Coral Bleaching app data point collect options to select a No Bleaching Category despcriptor

7 EXAMPLE AERIAL BLEACHING CATEGORY PHOTOS

Examples of visual aerial bleaching and scores are presented below. We have been building a more extensive database of photos, for the benefit of training observers and maintaining consistency.

Figure 14. Examples of the no bleaching Category 0 (<1% bleaching). Individual coral colonies may be hard to see, however the reef zone where you would expect to find living coral on the reef slope and edge suggests well pigmented corals.

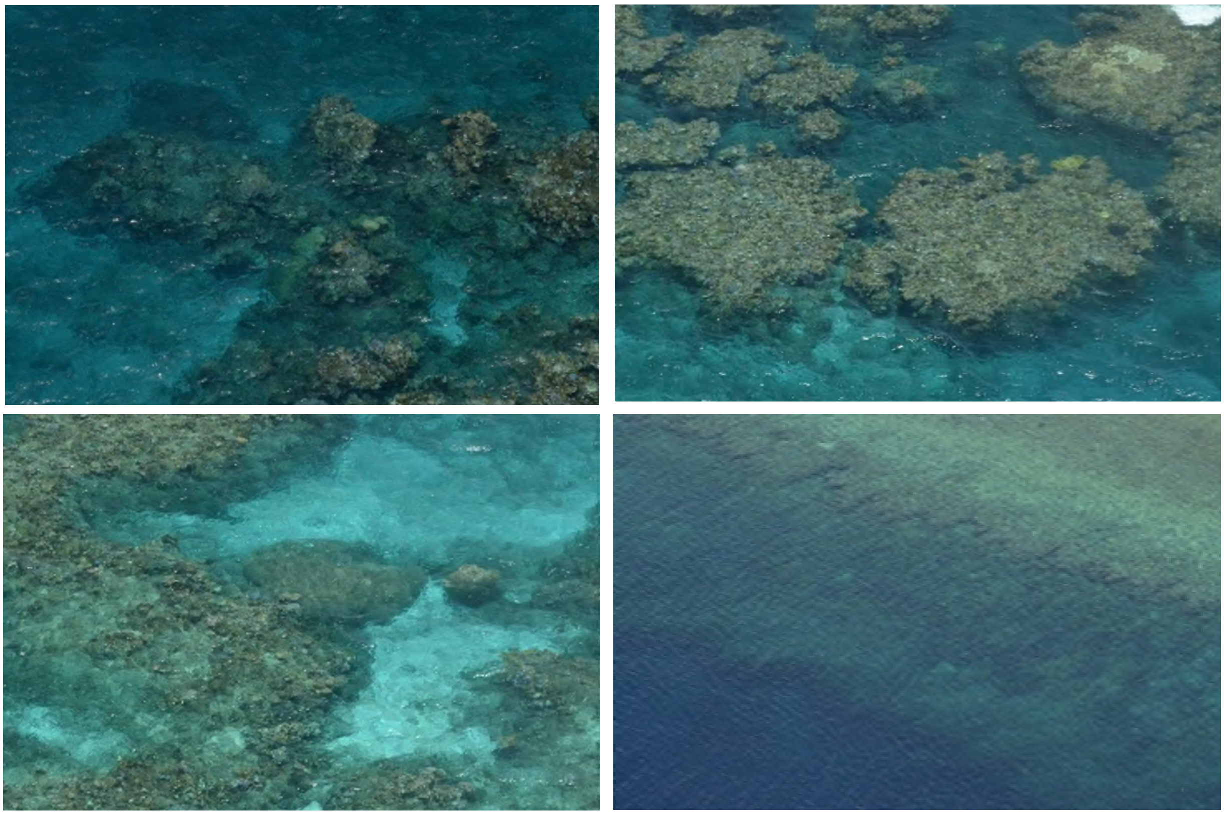

Figure 15. Examples of the minor bleaching Category 1 (1-10% bleaching). It is challenging to portray this category from a photo but to the discerning eye once exposed to higher levels of bleaching, this category is characterized by a low % of pale corals among a reef scene that otherwise looks normal.

Figure 17. Examples of moderate bleaching Category 2 (10-30% bleaching). A close look at the reef crest shows quite a few pale colonies, but most are still normally pigmented, especially down the reef slope.

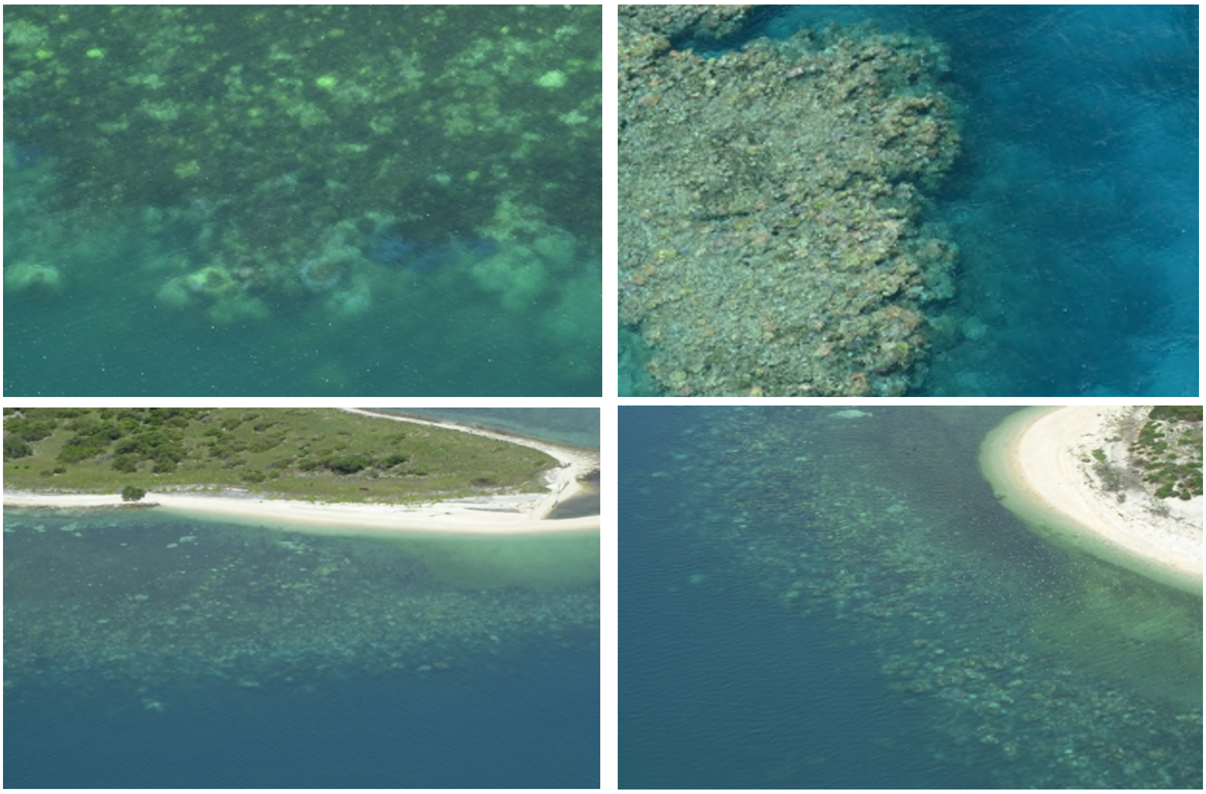

Figure 16. Examples of major bleaching Category 3 (30-60% bleaching). About half the corals in these photos have started to bleach. In between bleached corals you can see an equivalent number with normal pigment, especially down the reef slope.

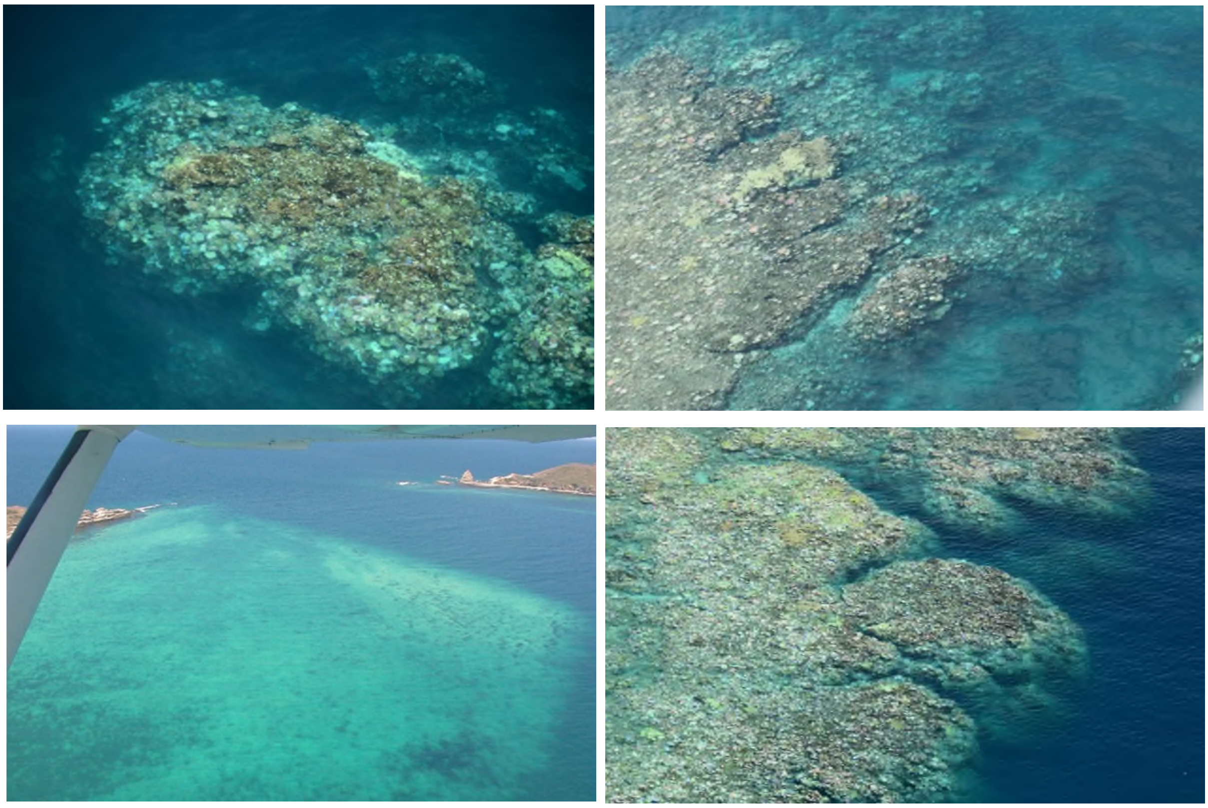

Figure 19. Examples of severe bleaching Category 4 and 5 (60-90% bleaching right side and >90% left side). Virtually every coral colony is white or “fluoro” in these photos. Where coral cover is high the reef appears to “glow”.

Figure 17. Examples of the Extreme Category 5 (>90% bleaching) with moderate to high recent mortality, which is evident as green turf algae overgrowing the coral skeleton.

Figure 18. Examples of reefs with low living coral cover, long-dead skeletons (top image; category 5 bleaching as all living coral remaining is low in abundance and bleached), low cover porites dominated communities (middle image; Category 2 bleaching) and low living coral cover that is mostly hard consiladated reef rock (bottom image).

8 AERIAL BLEACHING SCORES COMPARED TO IN WATER SURVEYS

Reef community coral bleaching scores collected during the aerial surveys are a visual estimate of the amount of living coral that is bleached (% of living coral cover bleached), in the shallow reef areas visible from the air. On a reef community scale, when more than 60% of the coral cover is bleached, this is considered a severe community response.

Since the aerial bleaching estimates are based on the proportion of living coral bleached vs not bleached, in-water observations of colony level bleaching severity can be directly compared to the aerial estimates of coral reef community bleaching by comparing the estimates of per cent bleached coral from the air to the measured per cent bleached living coral cover (Hard and soft coral types; Figure 26 B-E) in-water. During the 2016 bleaching event on the GBR, the Australian National Coral Bleaching Taskforce combined the use of in-water quantitative, transect based surveys from 259 sites at 104 reefs that overlapped with aerial survey scores to ground truth the community estimates of coral reef bleaching collected using the aerial survey method. Median in-water measured bleaching proportions align within each aerial category range confirming the aerial estimates accurately estimate proportion of bleached coral communities.

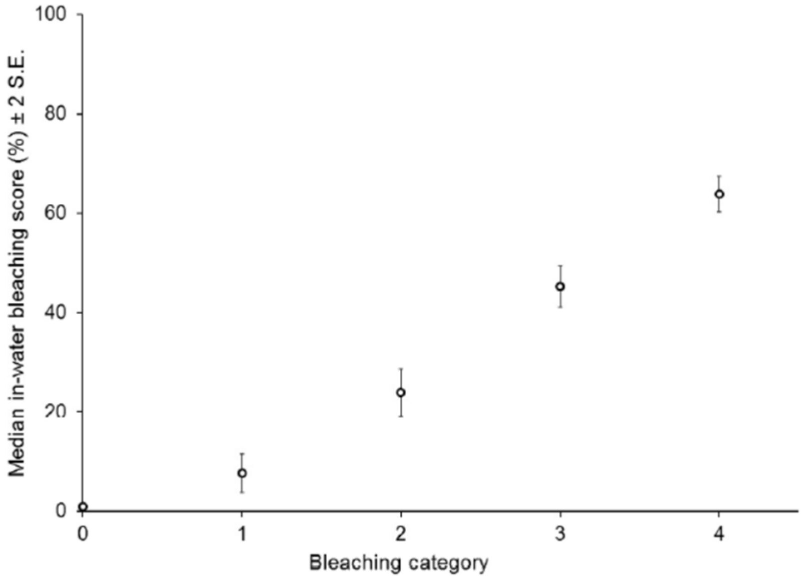

Figure 19. Ground-truthing comparisons of aerial and underwater bleaching proportion of living coral reef communities. Aerial community bleaching categories are: 0 (No bleaching; <1%), 1 (Minor; 1-10%), 2 (Moderate; 10-30%), 3 (Major; 30-60%) and 4 (Severe; >60%) on the Great Barrier Reef in 2016. Continuous (0-100%) measured bleached living coral cover from *in situ* underwater observations within 1x10m belt transects (5 replicates per habitat) from 259 sites (104 reefs). Data published in: Hughes et al. 2017.

In-water surveys certainly provide supportive evidence alongside the broad scale assessment of bleaching from aerial surveys. It is important to document at as many reefs as possible the proportion of reef corals that are severely bleached, fully white and/or fluorescent (Figure 27 D-E) and at risk of not surviving the coral bleaching event. In-water surveys also provide context for how deep severe colony bleaching extends which can not be captured by aerial surveys alone.

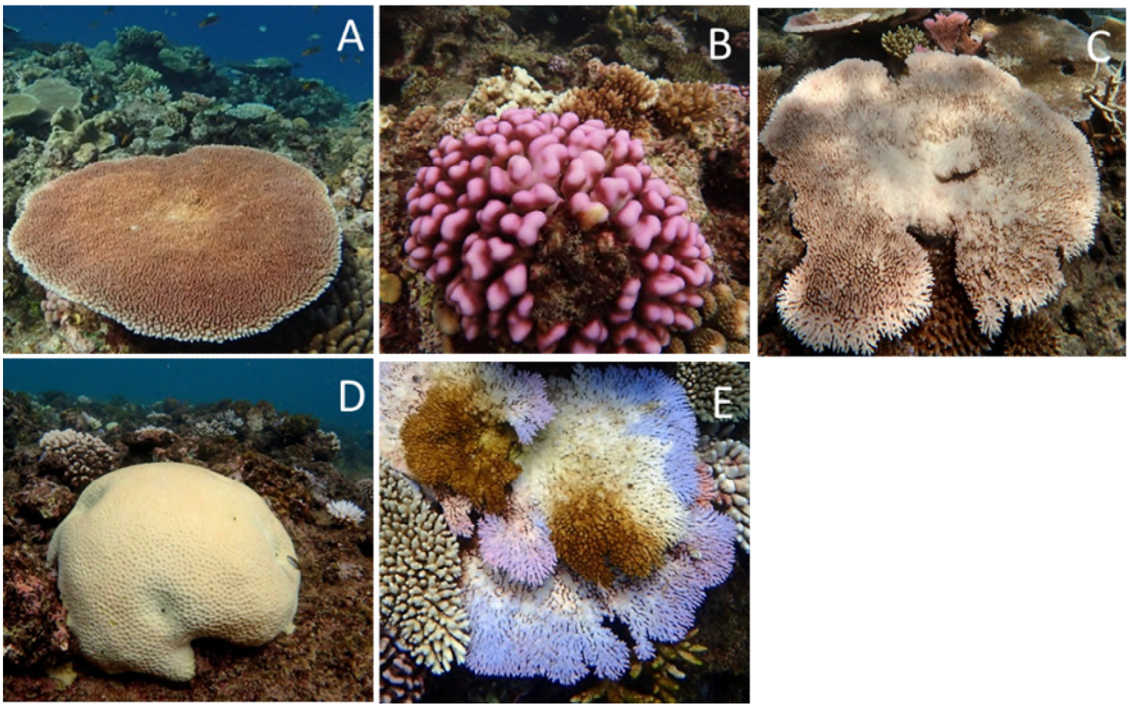

Figure 20. In-water coral colony level bleaching severity scores for in water bleaching surveys which range from: **(A)** No Bleaching (Colony bleaching category 0); **(B and C)** Partial bleaching with dark algal symbionts (*Symbiodiaceae)* clearly visible within the coral tissue (Colony bleaching category 3 (10-50% colony bleached) and 4 (50-90% colony bleached)); **(D)** Fully bleached completely white, with no algal symbionts visible in the coral tissue (Colony bleaching category 5: 100% bleached) and **(E)** Severely bleached and fluorescent coral colony with bleaching related recent mortality (Colony bleaching category 6; partial mortality)**.**

9 INTER-OBSERVER COMPARISON

To assess the variation in bleaching scores between observers, a comparison was made between two pairs of observers during an aerial survey of reefs between Townsville and Cairns on 9 March 2017. These inter-observer comparisons can provide valuable training and data quality control at the start of each aerial survey, particularly when new or different observers are used. For the comparison, two observers were seated on the left side of the plane, the other two on the right, however only one observer on the left could communicate with one on the right and vice versa (Figure 23). Thus, the two left observers (Pair 1) scored reefs independently of each other, as did the observer pair on the right (Pair 2). Observers 1 and 4 communicated freely and were isolated in communication from Observers 2 and 3, except for the first six reefs at the start of the survey.

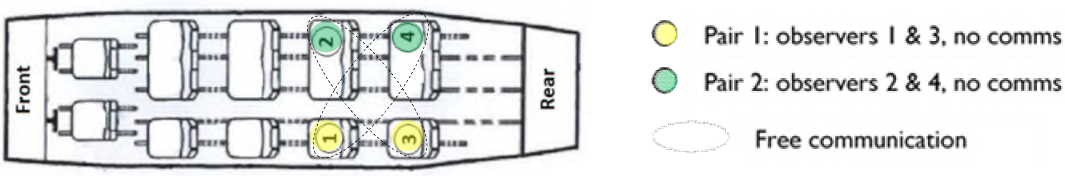

Figure 21. Seating arrangement of observers in the Cessna Grand Caravan used for the inter-observer comparison. Observers 1 and 4 were in communication as were observers 2 and 3. Observations by observer 1 and 3 were therefore independent of each other, as were those between observers 2 and 4.

During the first 6 reefs, observers in Pairs 1 and 2 made hand signals to calibrate observations which then ceased for the rest of the survey.

On most reefs, observers scored a number of different reef habitats. For each observer, scores were averaged for each reef and rounded to the nearest integer to retain the original bleaching categories (0 – 4). Scores within each pair were then subtracted from each other (Pair 1: observer 1 – observer 3; Pair 2: observer 2 – observer 4). Pair 1 scored a total of 46 reefs while Pair 2 scored a total of 52 reefs in the abbreviated dataset (not all reefs are available on both sides of the plane, particularly around island fringing reefs).

On a reef-by-reef basis, the results show that for both observer-pairs the median and modal scores were 0 (i.e., no difference, Table 1). Where there were differences in scores, these differences were few and not consistent in one direction or the other (i.e. no bias, Figure 24). Kurtosis, an indicator of the “tallness” or “narrowness” of the distribution of score differences, was high in both pairs (5.3 and 12.4). A normal distribution has a Kurtosis of 3 (3 standard deviations), so the values found here indicate that the distributions are highly concentrated around the means. Skewness was slightly higher in observer Pair 2 than Pair 1 (1.70 vs 0.93 respectively). This was entirely due to two outliers in the Pair 2 data: one point with a value of 3 and another of 2. A difference in observer scores of 3 is large and a close inspection of the data shows that this observation was from a small section of coastline along Cape Grafton near Cairns. Observer 2 saw bleached coral through the highly turbid water whereas Observer 4 did not. Live coral was very difficult to see hence both scores may be wrong and in opposite directions.

The only other large difference (2 categories) was at Needle Rf. One observer (Observer 2) scored this reef category 1 whereas the other three observers scored it category 3. This difference could not be further resolved with the assistance of the available photos. Aside from these two outliers, only 11 out of 98 reefs in the combined dataset of the two pairs had a difference of one category. All other differences were zero indicating a very high overall level of agreement among observers.

Table 1. Summary statistics on a reef-by-reef basis: comparison of observer pairs

	Pair 1 (Obs1 vs Obs3)	*Pair 2 (Obs2 vs Obs4)*
Mean	0.05	-0.07
Median	0	0
Mode	0	0
Standard Deviation	0.36	.62
Kurtosis	5.31	12.39
Skewness	0.93	1.7
Range	2.38	5
Minimum	-1.38	-2
Maximum	1	3
Count	46	52
Confidence Level (95.0%)	0.11	0.17

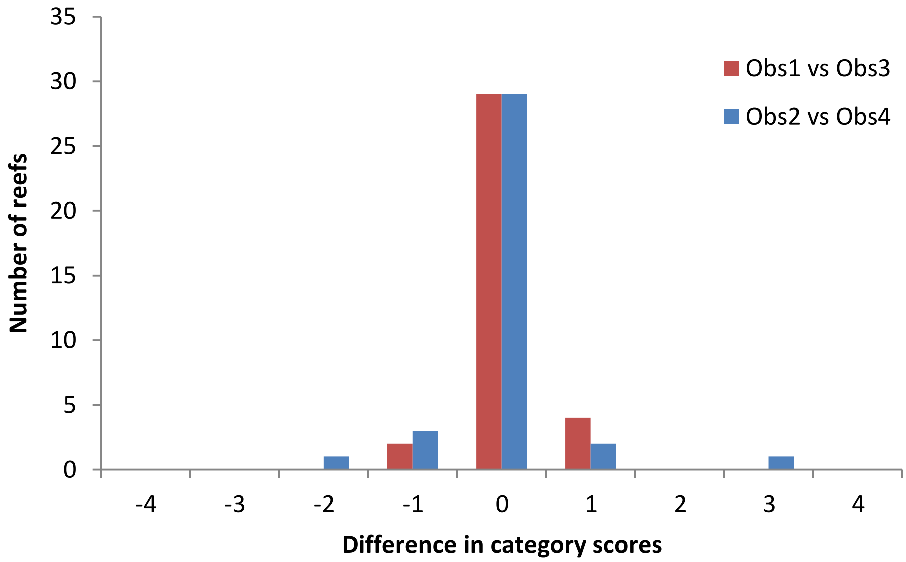

Figure 222. Distribution of differences in scores between observers in each pair (Pair 1, left, observer 1 – observer 3; Pair 2: right, observer 2 – observer 4).

Table 2. Summary statistics by bleaching category: individual observers

	Observer 1		Observer 2		Observer 3		Observer 4	
	# Reefs	%	# Reefs	%	# Reefs	%	# Reefs	%
Observations as 0	0	0	0	0	0	0	0	0
Observations as 1	2	2.99	4	6.45	1	1.49	3	4.76
Observations as 2	10	14.93	10	16.13	10	14.93	7	11.11
Observations as 3	14	20.90	11	17.74	14	20.90	11	17.46
Observations as 4	41	61.19	37	59.68	42	62.69*	42	66.67

Table 3. Summary statistics by bleaching category: front row and back row observers

	Av of Obs1 & Obs2		Av of Obs3 & Obs4	
	Avg %	SE	Avg %	SE
Observations as 0	0	0	0	0
Observations as 1	4.72	1.73	3.13	1.63
Observations as 2	15.53	0.60	13.02	1.91
Observations as 3	19.32	1.58	19.18	1.72
Observations as 4	60.44	0.76	64.68	1.99

Based on summary data, there were relatively small differences in the overall number and proportion of reefs in each category as scored by the individual observers (Table 2). Around 63% of reefs were scored as bleaching category 4 (range 59 – 67%) while ~19% of reefs were scored as category 3 (range 17 – 21%) and ~14% as category 3 (range 11 – 16%).

When the front row observers (observers 1 and 2) are averaged to account for “availability bias” (left and right side of the plane) and compared to the average of the back-row observers (observers 3 and 4) the difference in numbers and proportion of reefs is even smaller in each bleaching category (Table 3). Averaging across observers clearly provides a very robust summary of bleaching observations.

Overall, these data clearly show that inter-observer variation is small, and that the method is robust. However, it should be noted that there were relatively few reefs in categories 0 to 2 (11 out of 76 unique reefs, all observers combined). A higher number of reefs with low or no bleaching may increase the spread of scores as some of the middle categories are more difficult to score, especially if coral cover is low and water is turbid. Under these conditions, interpreting the data on a reef-by-reef basis is not advisable. However, as a regional overview of bleaching, aerial survey data are highly robust with respect to observer bias.

10 REFERENCES

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GBRMPA 2013. Coral Bleaching Risk and Impact Assessment Plan. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2810

Hughes, T.P., Kerry, J.T., Baird A.H. et al. 2018. Global warming transforms coral reef assemblages. Nature 556: 492-556.

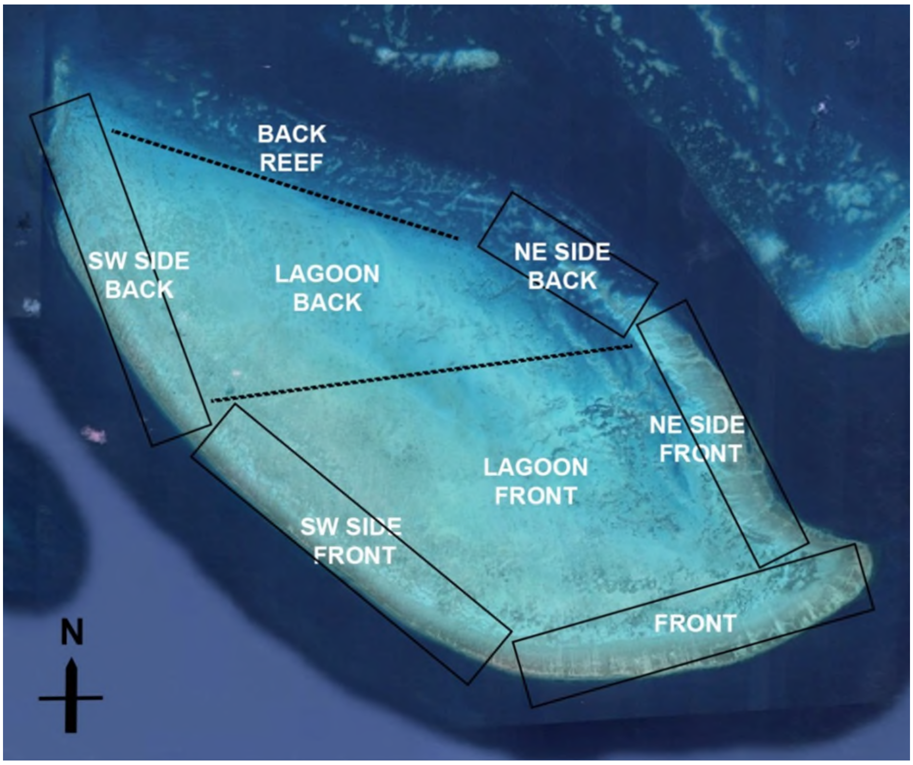
11 APPENDICES

11.1 Appendix 1 – Reference Sheet of Bleaching Categories and Reef Habitat Diagram. Record 1-3 scores per reef habitat depending on size of reef.

CORAL BLEACHING AERIAL SURVEYS

Category 0 :	<1% bleached	NO BLEACHING
Category 1 :	1-10% bleached	MINOR
Category 2:	11-30% bleached	MODERATE
Category 3:	31-60% bleached	MAJOR
Category 4:	61-90% bleached	SEVERE
Category 5:	>90% bleached	EXTREME
Mortality:	Record “**M**” **+ Bleaching Category**	

Reef Habitats to score if visible up to 3 scores per reef / habitat depending on Size of the reef.



11.2 Appendix 2: QGIS map of within reef aerial bleaching scores and flight path which can help flight planning and priority reef locations for future aerial surveys.

Key Attributes of priority reefs for aerial surveys include AIMS Long-term monitoring reefs (LTMP and inshore MMP), in-situ temperature logger locations, reefs included in past aerial survey data sets (1998, 2002, 2016, 2017, 2020 and 2022).