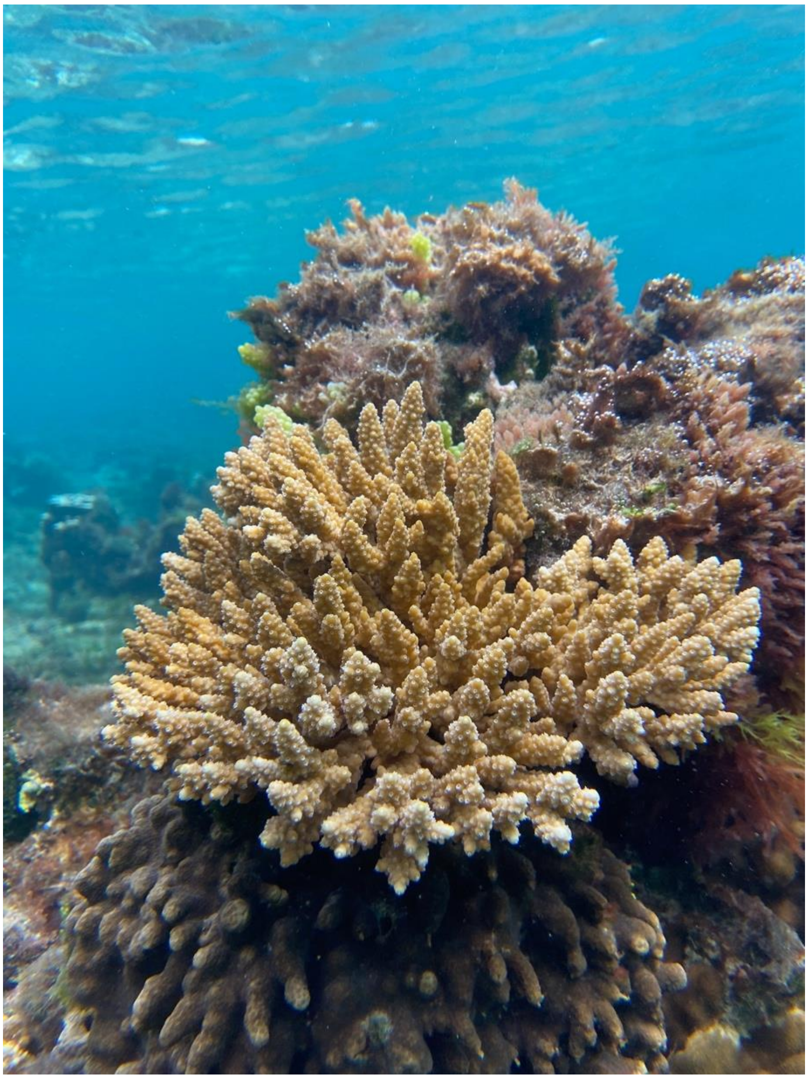
Reef Health Survey Report for Emily and Slaughter Bay, Norfolk Island (January 2022- April 2023)



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Executive Summary

Emily Bay, Slaughter Bay, and the adjacent Cemetery Bay form the inshore coral reef lagoons on the southern and south-eastern sides of Norfolk Island within the Norfolk Marine Park and are adjacent to the UN World Heritage listed Kingston and Arthur Vales Historic Area (KAVHA). The protected lagoonal reefs host a diverse and abundant coral reef ecosystem with many undescribed and likely endemic organisms, which in addition to the unique biodiversity of the coral reef is an essential recreational area for Norfolk Island residents and vital tourist site supporting the regional economy.

Since March 2020 Parks Australia has commissioned an ongoing monitoring program for Emily and Slaughter Bays due to the high socio-economic and natural value of the ecosystem to Norfolk Island. Since reef health monitoring commenced the coral reefs of Emily and Slaughter Bay have been continually impacted by ongoing stressors (including thermal stress events, sedimentation and land-based runoff, severe storms and cyclones) resulting in significant changes in the benthic community composition cover and health of these ecosystems.

Documented impacts to the ecosystem during this time include:

- *February-April 2020*: The first officially recorded **coral bleaching** event in Emily and Slaughter Bay. Coral bleaching is caused by increased sea surface temperatures above those normally experienced at a particular location. Increased sea surface temperatures (SST) are driven primarily by climate change and result in wide-spread mortality of corals and/or significant reduction in health of corals leading to slower growth rates, reduced reproduction and increased susceptibility to disease and competition from other organisms, in particular algae. Coral bleaching was no longer seen in December 2020. These effects were recorded in the region throughout 2020.

- *August 2020-present:* **Extended periods of above average rainfall events and high nutrient inputs** resulting in repeated sedimentation of Emily and Slaughter Bay, flushing of the land-based contaminants from adjacent catchment into the Bays, reduced water quality and nutrient enrichment of the marine ecosystem. Flooding events also resulted in official closures of the Bays due to high bacterial counts that pose both a human health risk and increased risk of zoonotic disease (~disease spread between animals to humans and vice versa). Water from the wetland also enters Emily and Slaughter Bay through ground water discharge. The level of nutrient inputs was likely exacerbated by the extended dry period prior to 2020 (when the plug was in place). Nutrient levels in the Bays and surrounding catchment exceeded the Australian and New Zealand Environment and Conservation Council (ANZECC) water quality guidelines on numerous occasions.

Tracing of Fluorescent Whitening Compounds (FWC**)** (products found only within laundry detergents and cleaning agents for the purpose of brightening fabrics/surfaces) conducted throughout the catchments identified FWC contaminants within creek systems leading to and within the KAVHA catchment, within the wetland, and within the inshore lagoonal reef during flood events. Land-based nutrient inputs may include cattle grazing in the catchment, other animal inputs, fertilizer use, onsite wastewater disposal (septic systems and grey water used on gardens) within the catchment or surrounding areas and septic/sewage inputs into the waterways, including groundwater, leading to the lagoonal reef.

Coral reefs are associated with oligotrophic (i.e., low nutrient) waters, addition of excessive nutrients (in particular nitrogen and phosphate) often leads to reduced ecosystem health in coral reef systems. These reductions in ecosystem health can be characterised by reductions in coral cover, increases in coral disease and increases or changes in algal cover or type (algae are one of the major competitors for corals).

The coral health monitoring program conducted since March 2020 has consistently identified <u>several indicators consistent with declining ecosystem health</u> in Emily, Slaughter and Cemetery Bays, these observations include (but are not limited to):

- *March 2021 - present*: Significant changes in the **type and abundance of algae** seen in Emily and Slaughter Bay, including declines in algal types associated with healthy coral reef ecosystems and subsequent increases in algal types that are associated with excessive nutrient inputs and declining water quality. This includes a red cyanobacteria found to cover up to 30% of the benthos in April 2022, with alga recorded overgrowing and covering live corals and other algal types. Red cyanobacterial overgrowth is associated with elevated nutrient inputs, indicative of a reef under stress from land-based runoff (Ford et al. 2018). Red cyanobacterial growth was subsequently removed by a large storm surge event in June 2022, but was then replaced by macroalgae also growing to ~30% benthic cover.

Prior to the high rainfall events in August 2020 these algae contributed to less than 8% of the benthic cover. Increases in macroalgae cover are linked to phase shifts from coral dominated to algal dominated reefs attributed to the presence of increased nutrients from excessive stormwater runoff. These conditions resulted in algal competitive advantage over live coral and inhibition of juvenile coral recruitment. In addition, *Lyngbya*-like cyanobacteria has been identified in increased abundance on the reef for the first time since December 2022. *Lyngbya* is a genus of blue-green algae, some species of which produce a toxin that can cause skin, eye and respiratory issues in a range of species including humans. Growth of this algae is also linked to elevated nutrient inputs in other systems where it is found, in particular iron, phosphate and nitrogen (Ahern et al. 2007).

- *April 2021 – present*: **Significant coral diseases outbreaks** in all of the dominant coral taxa in Emily and Slaughter Bay, including *Montipora* and *Acropora* corals which contribute to over 60% of the coral assemblage in the bays. A healthy coral reef maintains less than 5% of individuals exhibiting signs of disease. Coral disease rates exceeding 5% are considered a disease outbreak and disease outbreaks greater than 20% of the population are substantial outbreak events which have been rare globally and are usually associated with reefs in decline (Burke et al. 2023; Walton et al. 2018). In Emily Bay ***Montipora*** **White Syndrome** rates have been consistently above 38% of the population since December 2020, with at times, up to 78% of colonies showing disease signs. ***Acropora*** **White Syndrome** disease rates have exceeded 22% since April 2021 while rates in Slaughter Bay have been greater than 28% since April 2022. Coral disease outbreaks are associated with degraded ecosystem health. In addition to leading to coral mortality, diseased corals have reduced capacity for competition with other organisms (such as algae) and have reduced reproductive output.

Taken together these biological responses are indicative of a reef system under significant stress from anthropogenic stressors. Increased algal type and abundance are early signs of potential phase shift from a coral dominated to algal dominated system. Phase shifts are characterised by a rapid loss of coral that is replaced by alga, once a phase shift has occurred recovery back to a coral ecosystem is slow and reliant on coral recruitment and regrowth in addition to conditions returning to those that support coral growth. Loss of the coral ecosystems in Emily and Slaughter Bay may significantly impact many cultural aspects of the local community and directly impact on the island economy.

Management recommendations. There are several management actions that should be considered to minimise the risks of a phase shift from a coral to algal dominated ecosystem, these include:

- Priority should be given to rapidly **reducing the nutrient inputs** into the Bays and minimise other activities that may place additional stressors on the corals. Until anthropogenic inputs are reduced the ecosystem health will continue to decline. Parks Australia's action to introduce a no-take zone in Emily and Slaughter Bay is particularly important to eliminate harvesting of sea urchins and sea cucumbers which play an important ecosystem service role in maintaining ecosystem health. Ecosystem decline is already evident in the bays with altered algal communities and coral disease outbreaks.
- **Visitor education and outreach** to ensure awareness of minimising additional stressors such as coral breakage, handling corals and walking on corals is important for end-users accessing the reef.
- Additional protection of high and or healthy coral cover areas (such as western Slaughter Bay, Cemetery Bay) and rare corals (such as the elkhorn growth Acropora and coral bommies) is recommended.
- Implementation of an **ongoing monitoring program** of the benthic communities and coral disease rates in the Bays. This information is vital for informed management decision making and to detect changes in community structure that would indicate further phase shifts and to better understand the risks of coral disease spread within and between bays.
- Implementation of an on-going nutrient and **water quality monitoring program** for a range of measurable analytes (ammonium, nitrate, phosphate) in the surrounding catchment, wetland and bays. This would help demonstrate the extent to which the KAVHA wetland provides control over water clarity and minimisation of sedimentation during water flows through the wetland, reducing likelihood of sedimentation of corals within Emily Bay and near-by Slaughter Bay. Monitoring of water quality will also inform opportunities and protective measures to be implemented to protect from land-based contaminant, nutrient inputs, and disease causing organisms.

- Implement an ongoing **monitoring program of other potential terrestrial inputs**, such as sulphur, nutrients, herbicides and pesticides. This would recognise other possible anthropogenic stressors that have not yet been identified.
- Ongoing **assessment of coral recruitment** within and between bays and reefs in Norfolk Marine Park and identification of source shallow/inshore reefs for coral re-introduction to inshore lagoons and understanding of connectivity between reefs.

Background

Norfolk Island is a high island located in the South Pacific Ocean approximately 1400 km east of Brisbane Australia. The island is approximately 34 km^2 with a population of 2188 in the 2021 Australian census. On the southern side of the Island there are two sheltered lagoons (Emily Bay and Slaughter Bay; Figure 1) that are used extensively by the local residents for recreation and are a major visitation site for tourists, the bays are also used by a local glass bottom boat operation. Together the area of the Bays is approximately 0.18 km^2 and contain significant amounts of coral on the benthos. On the eastern side of Emily Bay is Cemetery Bay, a more exposed bay which is likely to have fewer terrestrial inputs. These Bays are adjacent to the World Heritage listed Kingston and Arthur Vales Historic Area (KAVHA) and contain a variety of constructions from the Australia's convict era.

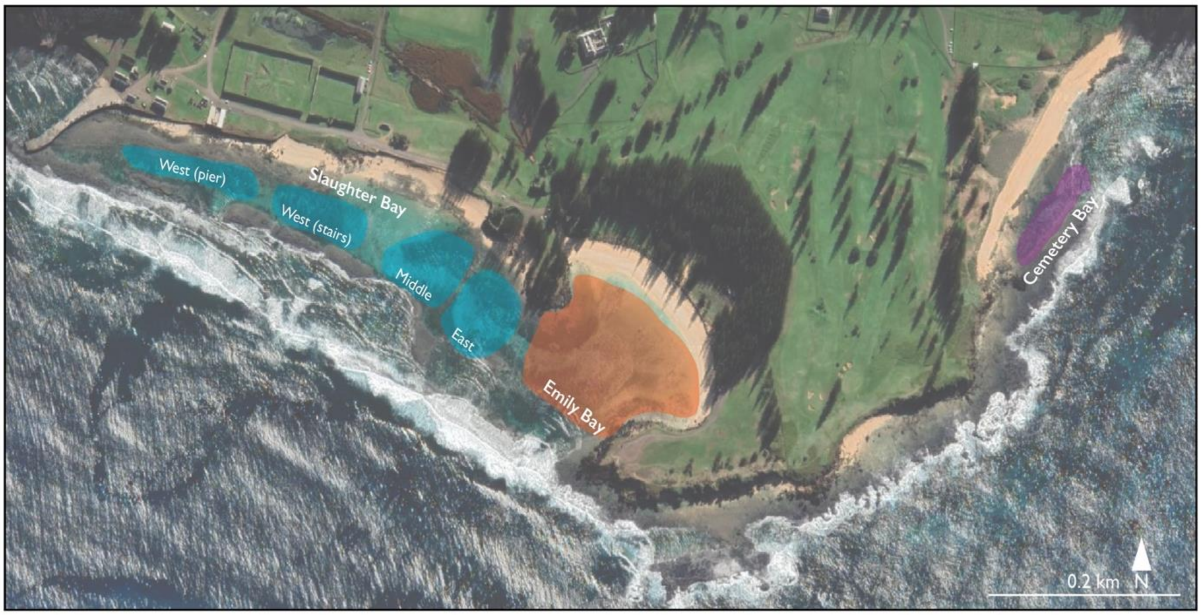


Figure 1. *Image of Emily, Slaughter and Cemetery Bay. Part of the KAVHA convict constructions can be seen at the top (north) of the image.*

Known pressures on Emily and Slaughter Bay

Emily and Slaughter Bays face a variety of anthropogenic stressors that are found in other coral reefs adjacent to a developed land mass, including both global scale threats, such as increased sea surface temperature leading to coral bleaching, and local scale threats such as eutrophication of the bays from adjacent terrestrial inputs. These inputs in isolation or in combination can result in the loss of coral cover and/or decreased ecosystem health. Previous research in Emily and Slaughter Bay has observed the first documented mass coral bleaching event in the Bays (February-April 2020) and significant nutrient inputs from terrestrial sources associated with large rainfall events (Ainsworth et al. 2021). The Norfolk Island Water Resource Assessment (NIWRA), being undertaken by CSIRO for the Department of Infrastructure, Transport, Regional Development, Communication and the Arts, includes water quality investigations to assess water quality in the bays and develop marine water quality targets for Norfolk Island. NIWRA water quality investigations include assessment of nutrient sources, which is believed to include onsite wastewater disposal (septic systems) and animals. Documenting benthic cover of the ecosystem and monitoring the health of corals is one effective way to determine if ecosystem state is changing. There is also the potential of other terrestrial inputs that have not been previously examined such as pesticides, herbicides, or chemicals related to the acid sulphate soils found on Norfolk Island.

Coral reef lagoon ecosystems are generally classified as oligotrophic (nutrient poor) due to the relatively low concentrations of dissolved inorganic nutrients in the water column (< 1 µM NH_4^+ and NO_x) or organic matter deposited within the sediment (< 2% nitrogen; Koop et al. (2001)). The surrounding surface oceans of tropical and sub-tropical latitudes are some of the most nutrient-depleted areas on the planet (referred to as ocean deserts; Atkinson, 2011) and any nutrients produced within the reef itself are quickly recycled by the nutrient-starved benthic community. Eutrophic (nutrient rich) conditions on coral reefs (5 – 20 µM NH_4^+ and NO_x; Fabricius, 2005) are generally caused by land-based nutrient introduction (e.g., runoff of organic matter or nutrients). Analysis of dissolved inorganic nutrients in coral reef seawater can therefore indicate if runoff is elevating the nutrient concentrations within a reef lagoon on relatively short time scales (hours to days) as pollution occurs, while the analysis of sediment organic matter composition helps determine the relatively longer, accumulated effect of nutrient runoff (months to years) (Yamamoto et al., 2001). Taken together these analyses can provide information for management agencies to identify and alleviate the impacts of pollution prior to the emergence of impacts at biological and ecological scales.

The impact of water quality and runoff on the health of corals and coral reefs has been widely documented within the scientific literature. Studies have shown effects including high coral disease prevalence, increased sensitivity to coral bleaching, lower coral cover and higher competition with algae occurring on reefs that are impacted by pollution, runoff, land-based pollution, sedimentation and nutrient influxes. For example, on Australia's Great Barrier Reef the GBRMPA (Great Barrier Reef Marine Park Authority) Sewerage Discharge Policy (2005) provides regulations governing maximum nitrogen and total phosphorus loads discharged in the park. Monitoring guidelines within the GBR marine park include regulations on daily and monthly water quality monitoring, visual inspections for evidence of water contamination, including turbidity and slick formation adjacent to outfall and discharge sites. Coral disease, bleaching and poor health outcomes associated with pollution have been correlated to freshwater runoff carrying increased nutrients, pathogenic and opportunistic microbes and toxins, as well as the additive and synergistic impacts of these factors on impacted reef systems

Previous Studies of Emily and Slaughter Bay

One of the first studies of the coral reefs of the Bays was conducted in 1988 by the Australian National Parks and Wildlife Service (Ivanovici 1988) that examined the benthic community of the Bays noting high coral cover in some areas up to 64 % with few to no observations of dead or algae covered corals. In this report the author noted that there were concerns from some island residents regarding the health of the ecosystem. Subsequent reports over the intervening 30 years also characterise coral species assemblages (Veron 1997, unpublished species list), benthic algal species (Millar 1999), fish species (Francis 1993), fish connectivity (van der Meer et al. 2013) and the general species occurrence (Heather et al. 2022; Stuart-Smith et al. 2017). Norfolk Island's catchment usage and water movement has also been investigated with early descriptions of the islands' hydrology in 1976 and a number of studies since (Abell 1976; Abell and Falkland 1991; Petheram et al. 2020). Prior to 2020 there were no comprehensive monitoring programs on the reefs of Emily and Slaughter Bay.

Coral Health Monitoring Program

Aims and management goals

In response to the prediction of a possible marine heatwave in the region Parks Australia commissioned a rapid assessment of the health of Emily and Slaughter bays in 2020 prior to any bleaching event. (Ainsworth et al. 2021). Subsequently ongoing assessment of the benthic community structure of the bays was commissioned in response to concerns that the overall health of the ecosystem was declining. From March 2020 – March 2023 six benthic surveys have been undertaken with the goals of:

1. Determining if coral cover in the Bays was changing over time. Coral cover is an important indicator of ecosystem health.

2. Determining if algal cover in the Bays was changing over time. Algae are one of the main coral competitors for space in reef assemblages. Healthy coral reefs have an equilibrium between algal and coral cover, which may vary between seasons (Brown et al. 2020) but is generally stable over longer time periods. Large changes in the composition or abundance of algal communities is often an early indication of deterioration of ecosystem health and a shift from a coral dominated to an algal dominated ecosystem.
3. Determining rates of coral disease in the Bays. Increases in prevalence or ongoing severity of disease rates are often an early sign of ecosystem health decline.
4. Conduct ad-hoc sampling of water quality parameters during periods of high rainfall.
5. Develop a citizen science web site containing information on Emily and Slaughter and provide a portal for citizen science data submission.

Results and discussion

Benthic surveys

The latest period of benthic health monitoring involved surveys in September and December 2022 and March 2023. The December 2022 and March 2023 surveys consisted of 24 x 10 metre belt transects in Emily Bay and 27 x 10 metre belt transects Slaughter Bay (Figure 2). These transects were analysed and added to the available data from March 2020 and April 2022 surveys (Figure 3). For each transect (10 m), 10 photos were taken with a TG-6 Olympus underwater camera at 1m increments using a 0.5 m^2 photo quadrat to standardize the area (n = 10 photos $transect^{-1}$). The resulting photos were analysed using the online platform *CoralNet* (https://coralnet.ucsd.edu) with a grid of 100 points per photo. A standardised label set was uploaded to *CoralNet* and the data were used to describe overall benthic cover (i.e. % cover of corals, algae and sand). Corals were classified as *Acropora* sp. (branch or non-branch), *Pocillopora* or *Stylophora* sp. (hybrids impossible to differentiate), *Montipora* sp. (encrusting or plating), *Acanthastrea* sp., *Porites* sp., *Goniopora* sp. and *Platygyra* sp.. Resulting cover was summed across each transect so that each category is described as the % cover $transect^{-1}$.

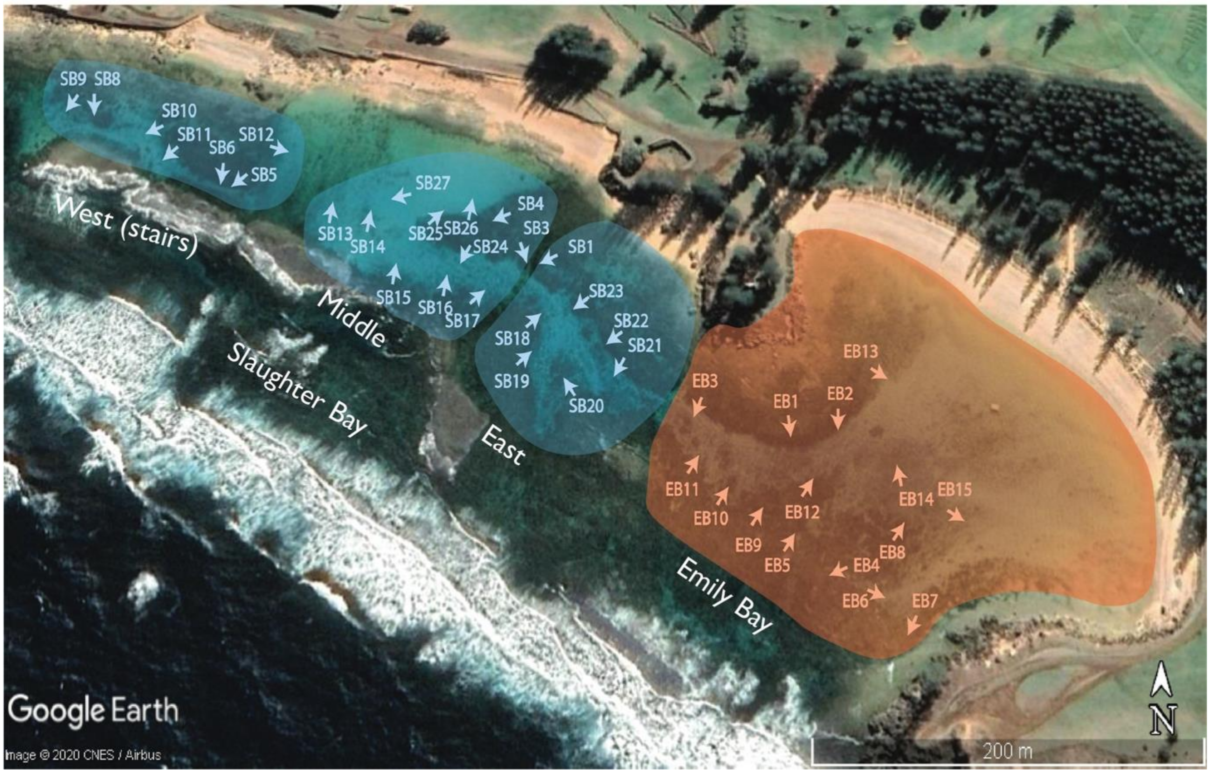


Figure 2. *Transect locations for December 2022 and March 2023 benthic surveys. Broad areas of Emily and Slaughter Bay are also shaded.*

In general, over the survey period coral cover has remained relatively stable in both Emily and Slaughter Bay, ranging from 17 ± 2% to 35 ± 4% (Figure 3). The average and median recorded coral cover has increased slightly in Emily Bay (average, from 26% to 36%, median 28% from 41%). However it must be stated that the increases in cover seen in September/December 2022 and March 2023 is likely as a result of an increase in the number of transects in Emily Bay (from 15 to 24; Table 1) as opposed to an actual increase in coral cover. There has also been an increase in the variance around the median in Emily Bay (Figure 3a) indicating that while in some areas within Emily Bay coral cover is increasing, in others it is decreasing. During this period, average cover in Slaughter Bay as a whole has remained relatively stable (average 26% (December 2020) to 28% (March 2023). Breakdown of Slaughter Bay into three distinct areas (East, Middle and West (stairs); Figures 6-9) illustrates that there is significant variability across the bay. Highest coral cover is seen in the Western Slaughter Bay (stairs) with coral cover exceeding 25% over all survey periods (Figure 9), while coral cover is lowest the middle of Slaughter Bay (<12.5% over all periods, Figure 8). In all areas of both Emily and Slaughter Bay the dominant coral types are from the genus *Acropora* and *Montipora* (Figures 6-9).

While coral cover has not changed significantly, there have been significant changes in other benthic community types with a succession of different algal types dominating the bays. A red turfing algae began to dominate both Emily and Slaughter Bay, increasing from a low amount in 2020 (<10%) to a coverage greater than 30% in 2022 (Figure 3). The red alga was removed in a large 6 m ocean swell in June 2022, however has again been identified in the March 2023 survey period (between 7 and 9% cover; Figure 3). When the red algae was removed in 2022 it was replaced in the September 2022 survey period by a macroalgae (Figure 4B, 4E,F), this algal type has then established in over 35% of the benthic community by December 2022 and has since slightly declined as the red algae returned. In comparison, macroalgae made up only between 6-8% of the benthos in the initial March 2020 survey before significant anthropogenic inputs occurred with the breaking of an extended dry period and reopening of the Emily Bay creek into the bay (Ainsworth et al. 2021) . Finally, in the December 2022 and March 2023 survey periods a *Lyngbya*-like algae was identified for the first time with up to 3% abundance and was detected in approximately 50% of transects. *Lyngbya* is a genus of blue-green algae, which was recently reclassified as the genus *Moorea*, some species of which have been linked to human health impacts in other systems (Osborne et al. 2007; Werner et al. 2012). It is unknown if this algal type is a toxin producer, this can only be determined by DNA sequencing to determine if toxin genes are present.

Increases in macroalgae can lead to phase shifts from coral dominated to algal dominated reefs under the presence of increased nutrient loading, particularly on reefs with low herbivory (McCook 1999), such as Emily and Slaughter Bay. While it is known that macroalgal abundance varies seasonally, long-term residents indicated they had not previously seen the high macroalgal densities observed in September 2022.

The large increases in red, macro and *Moorea* algae have led to a decline in green turfing algal abundance, a natural part of a coral reef, from approximately 37% of the benthic cover in March 2020 to less than 1.5% in the April, September and December 2022 and March 2023 survey periods. The changes seen in algal cover in the Bays are indicative of increased nutrients entering the system, leading to a competitive advantage for some algal types.

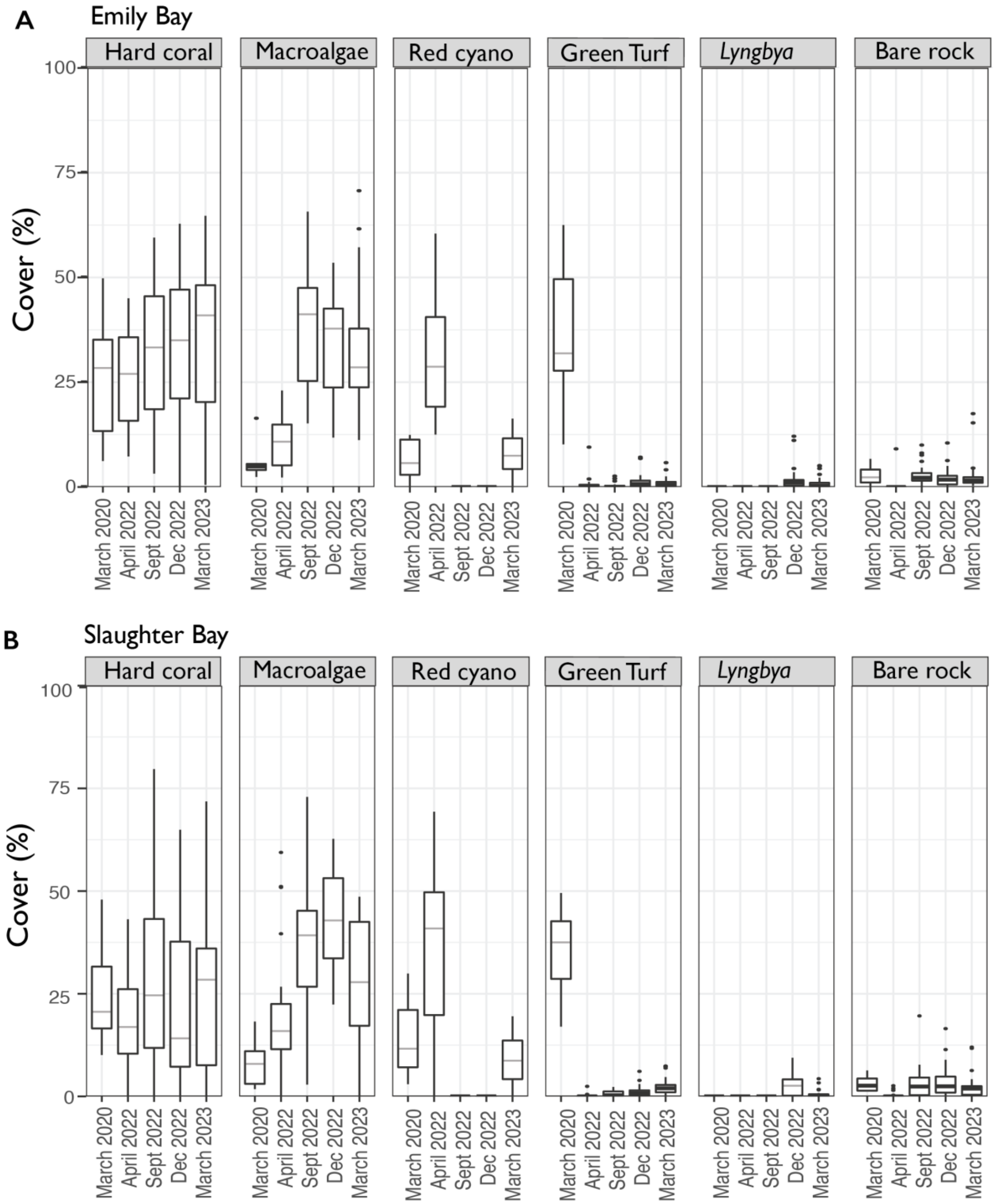


Figure 3. *Benthic cover at Emily and Slaughter Bays measured during surveys conducted in 2020 – 2023.*

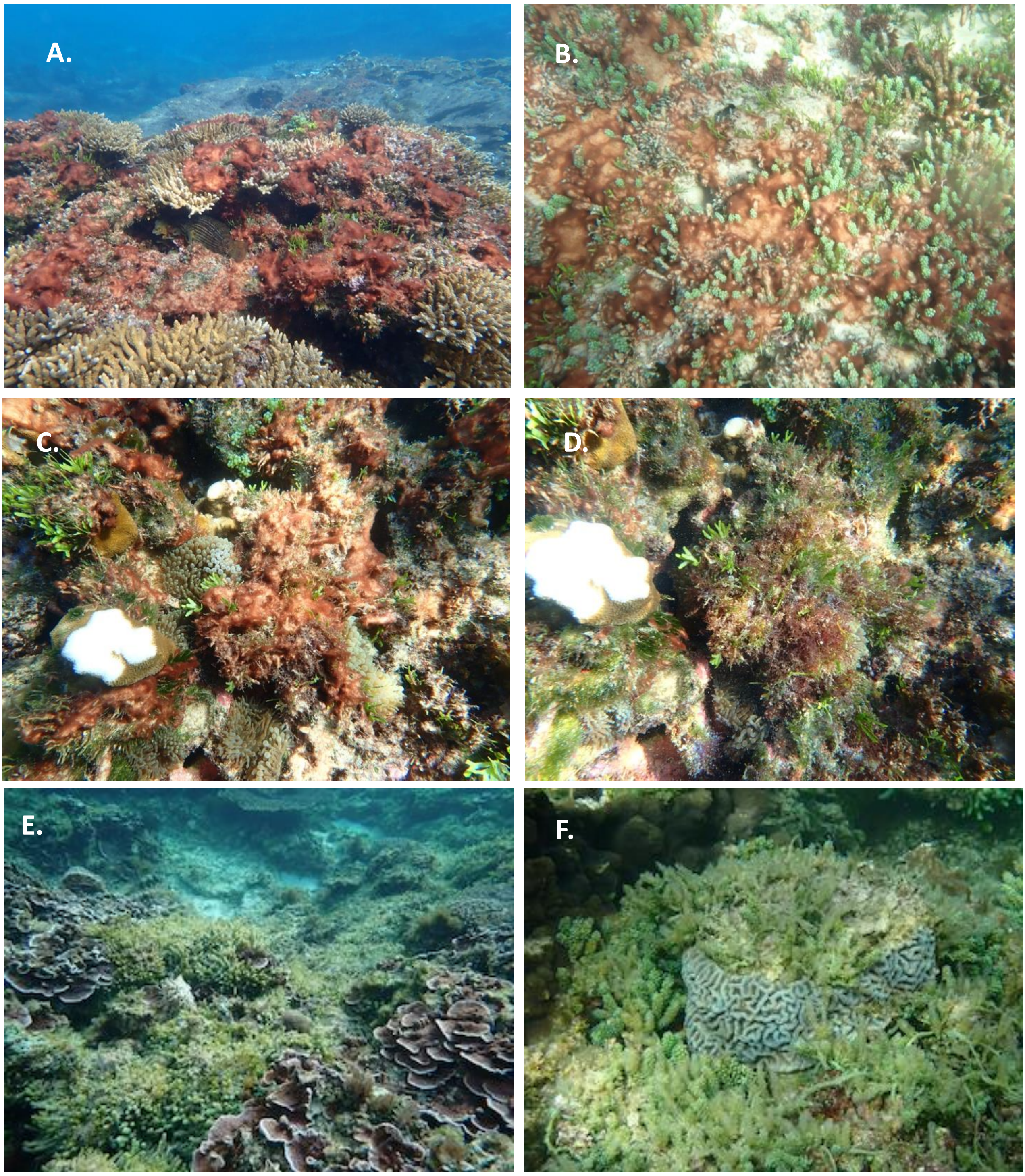


Figure 4. *Examples of red cyanobacterial mats (A-D) and macroalgae (E,F) seen in Emily and Slaughter Bay in April 2022 and September 2022 respectively. Examples of the red cyanobacteria associated with (A) corals and (B) green algae. The red cyanobacteria mat covers the existing benthos (C) which can be seen when the cyanobacteria is removed (D), note position of the white coral for orientation. Representative images of macroalgae competition with coral in September 2022 (E,F).*

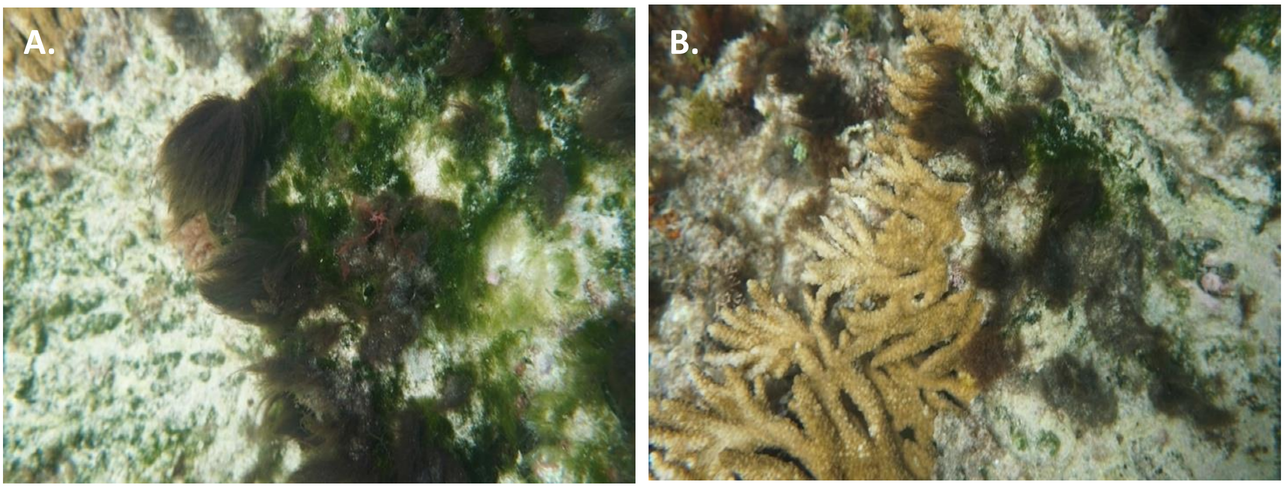


Figure 5. *Lyngbya-like turfing algae seen in the December 2022 and March 2023 surveys.*

Table 1. *Sampling effort of benthic health surveys (number of transects performed).*

	Emily Bay	Slaughter Bay	Cemetery Bay	Western Slaughter Bay
March 2020	7	9		
April 2022	15	27		
September 2022	24	27	3	
December 2022	24	27		
April 2023	24	27	9	22

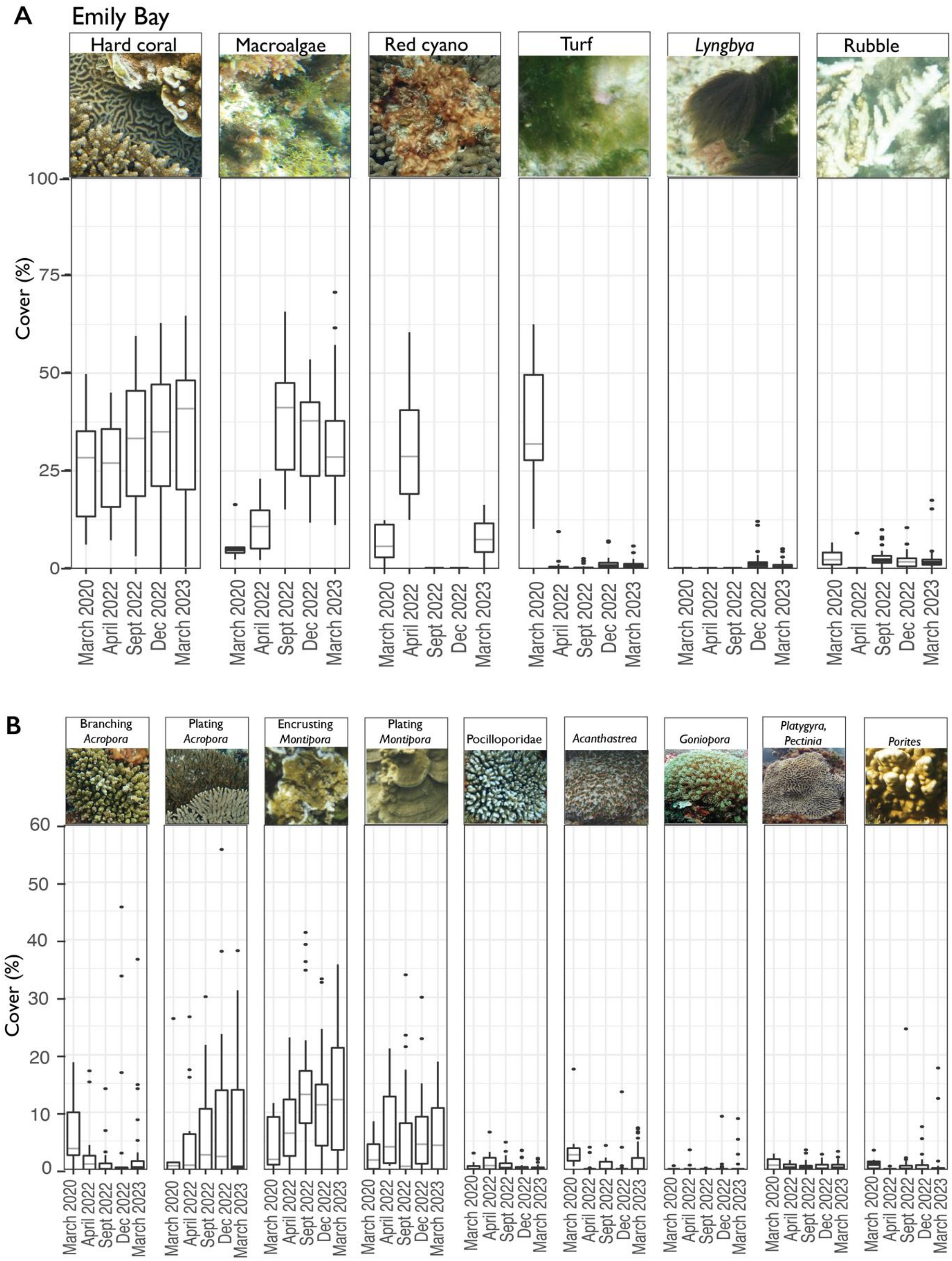


Figure 6. Benthic cover at Emily Bay during surveys conducted in 2020 – 2023, including coral type.

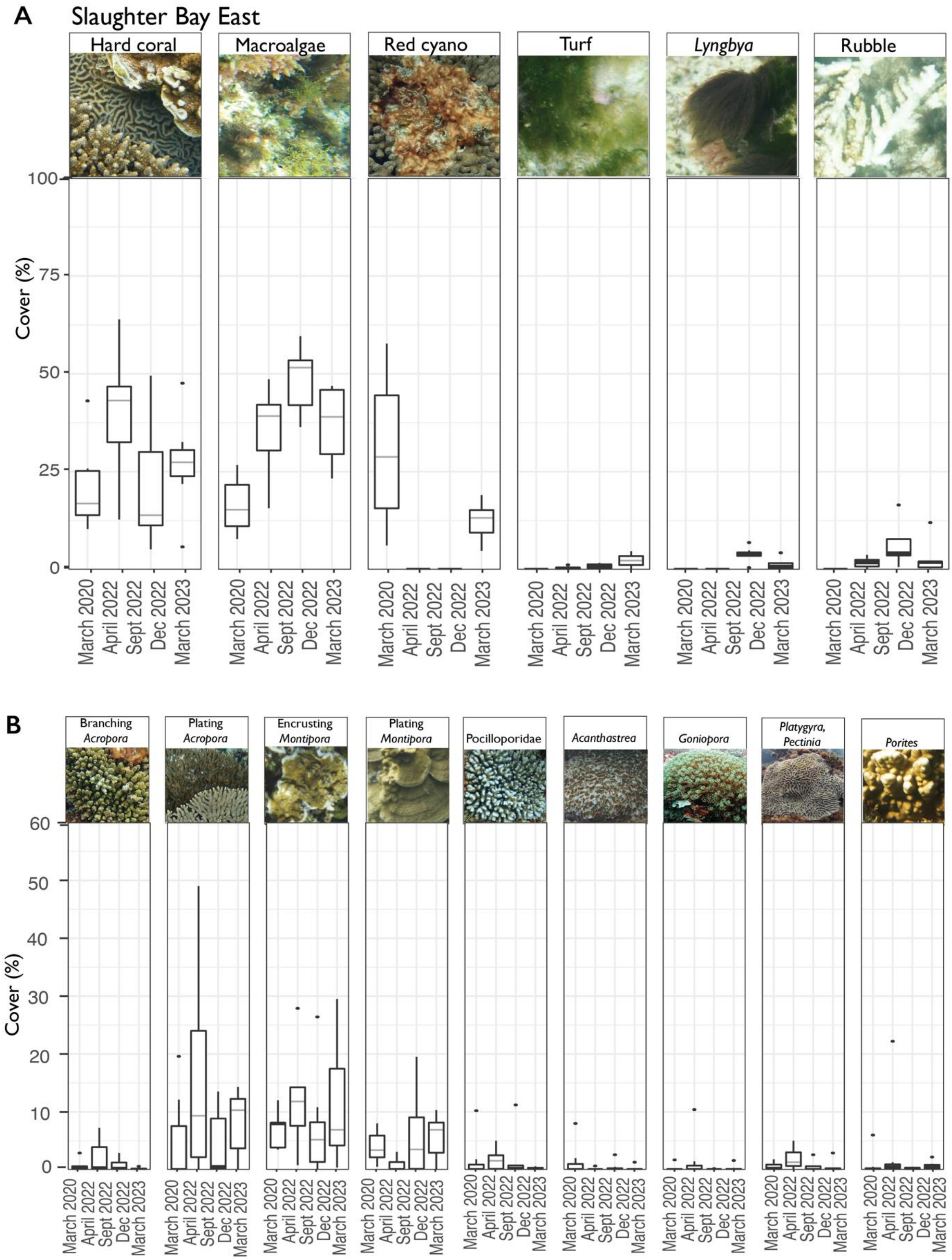


Figure 7. *Benthic cover Slaughter Bay east during surveys conducted in 2020 – 2023, including coral type.*

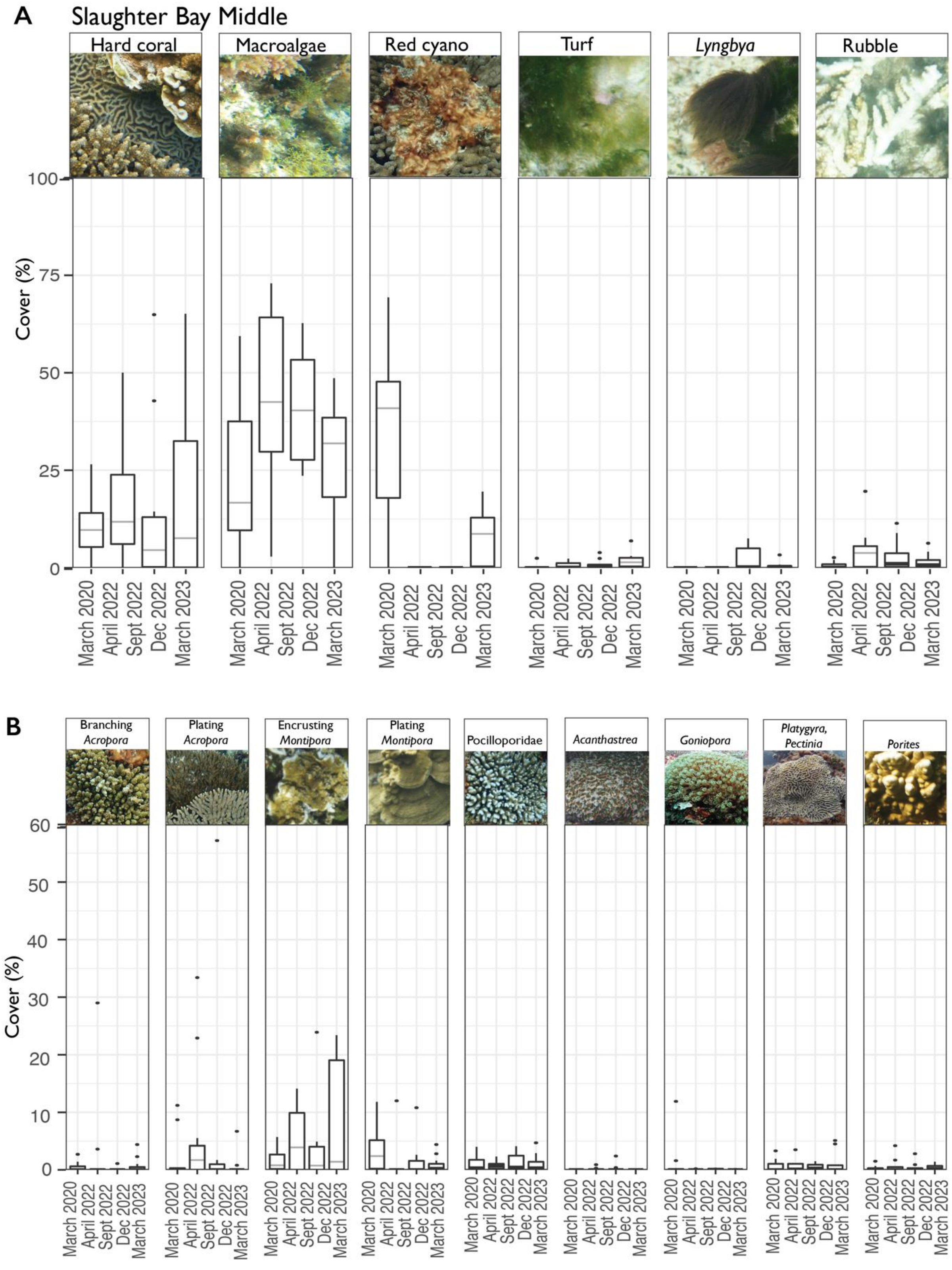


Figure 8. *Benthic cover Slaughter Bay middle during surveys conducted in 2020 – 2023, including coral type.*

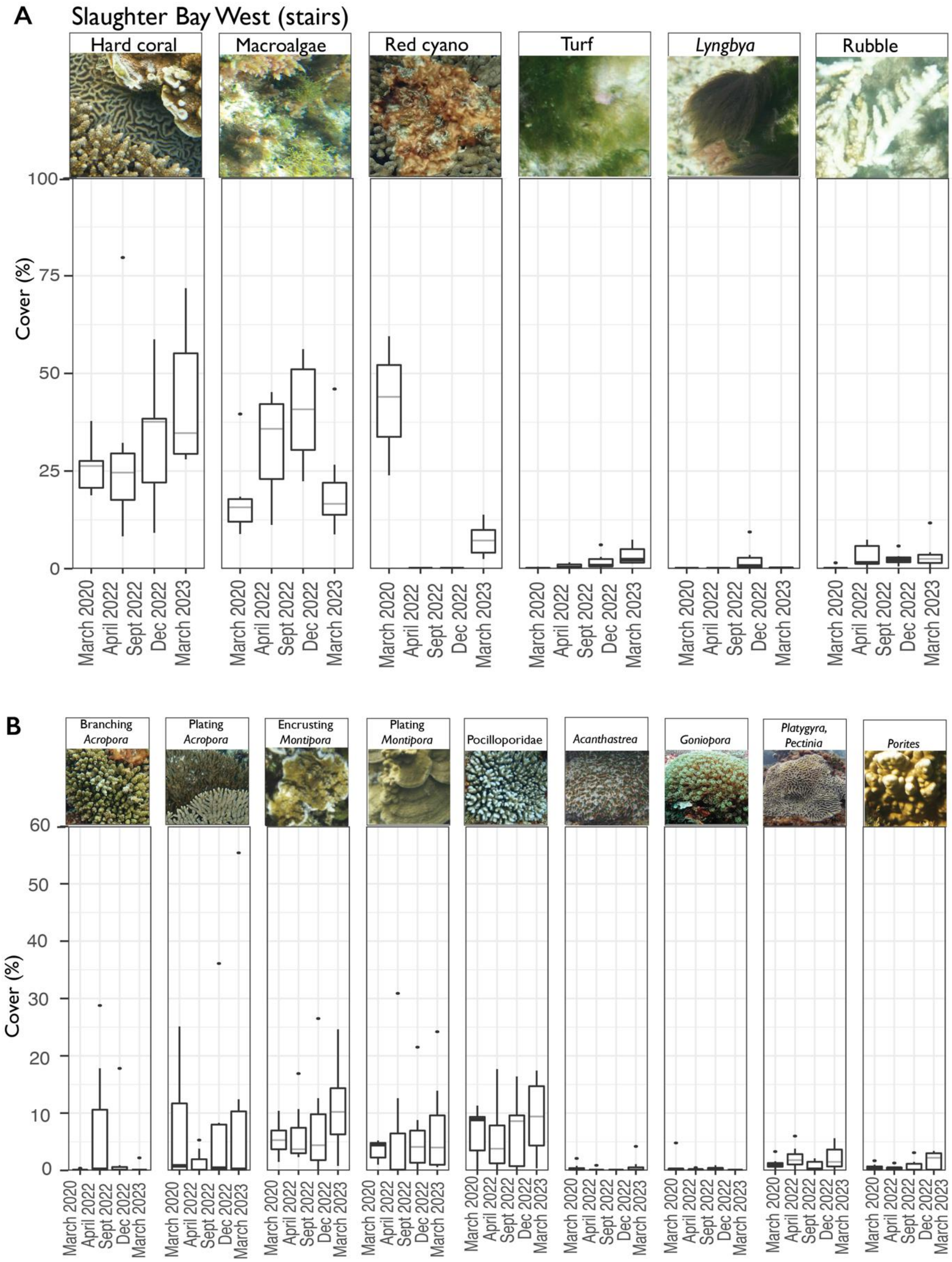


Figure 9. *Benthic cover Slaughter Bay west (stairs) during surveys conducted in 2020 – 2023, including coral type.*

In the March 2023 survey period additional transects were undertaken in Western Slaughter Bay adjacent to the Kingston Pier (See Figure 2). This area is characterised by a series of pools surrounded by shallow rock outcroppings. Twenty-five transects were undertaken by snorkel (15 m^2 in total, Figure 10) along with additional observations made from the shore. Some parts of this area were unable to be surveyed due to risks associated with waves on the exposed crest. While coral cover was only 20% in this area (Figure 10), coral colonies were generally healthier with less signs of disease or partial mortality (Figure 11). It has previously been shown that eutrophication (Tomascik and Sander 1987) and disease (Borger and Colley 2010; Weil et al. 2009) negatively impact coral reproductive output, and as such, the healthy corals that are further away from eutrophication inputs in Emily and Slaughter Bay may provide a significant contribution to coral recruitment in the bays. A source of coral recruits beyond the terrestrial inputs seen in the rest of the bays may be of particular importance if the health in other areas of the bays continue to decline. In this area branching *Acropora* was the most abundant growth type (Figure 10), in contrast the rest of Emily and Slaughter Bay are dominated by plating *Acropora* and encrusting *Montipora.* There are also a variety of other coral species found in the extreme shallows of Western Slaughter and not seen elsewhere throughout Emily and Slaughter Bay (Figures 12-14).

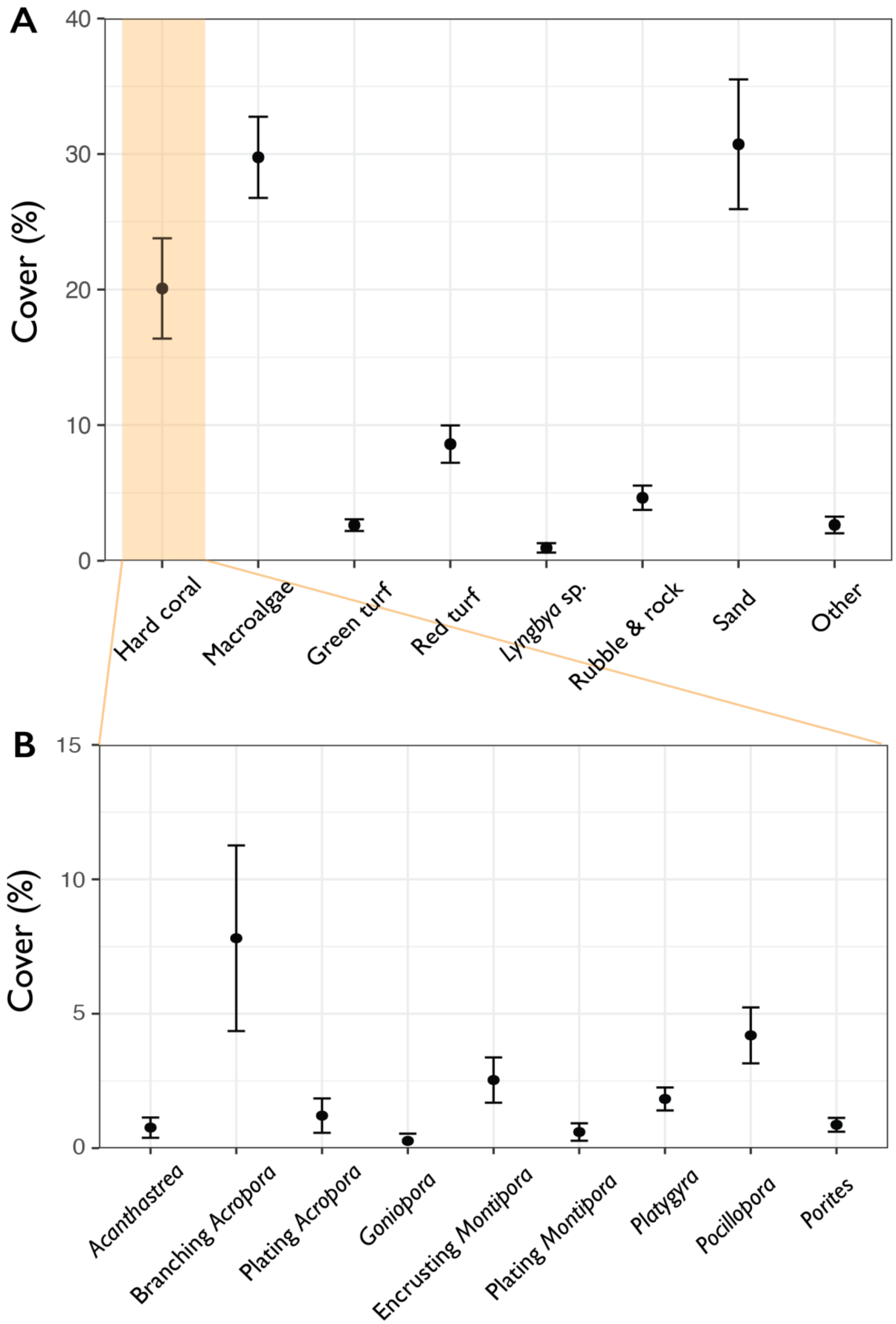
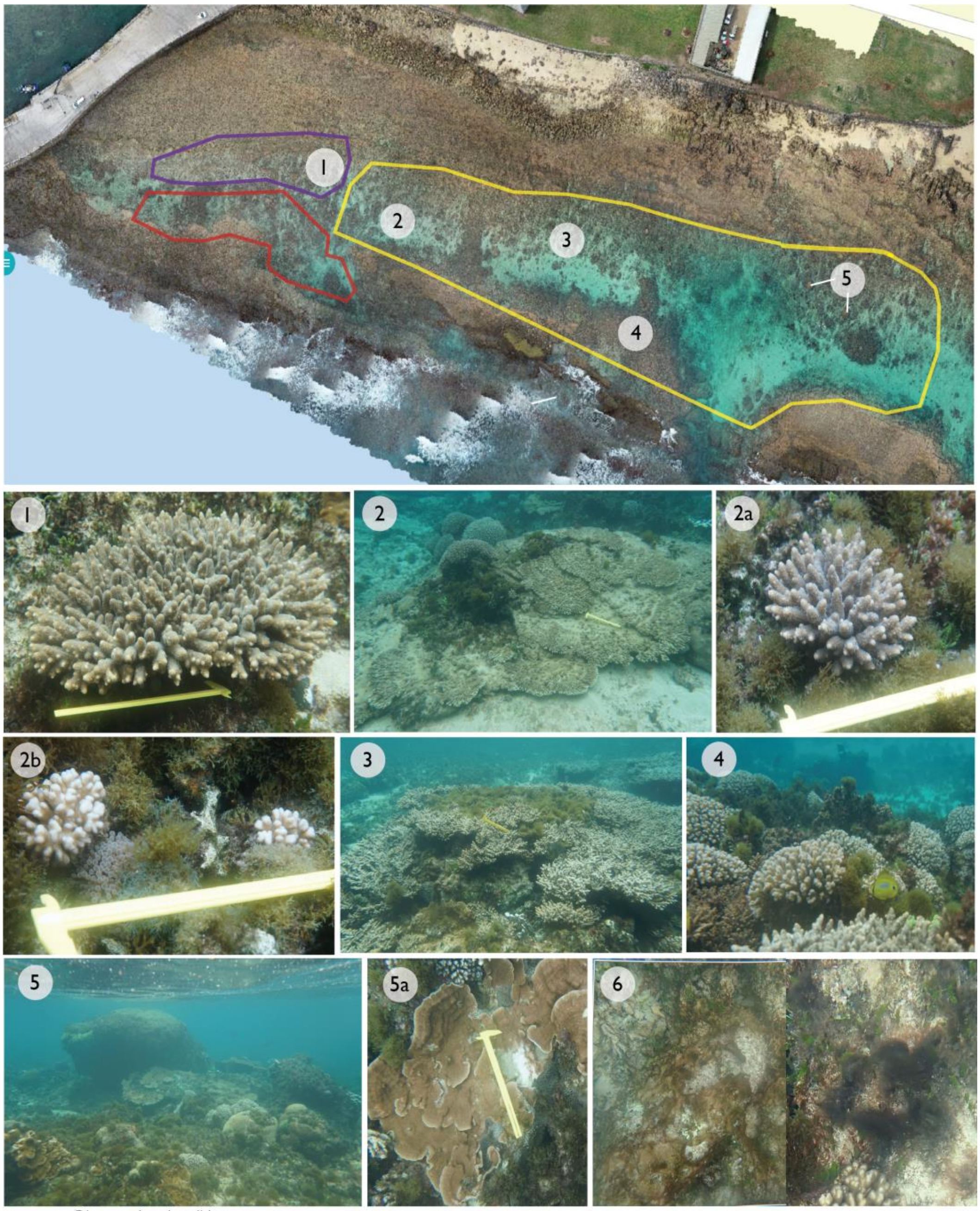


Figure 10. *Benthic cover Slaughter Bay west (Pier) during surveys conducted in 2023, including coral type.*



- Observational walking surveys
- Unsurveyed area, shallow pools
- Benthic and coral health survey area. 23 benthic surveys, total reef area assessed115 m^{-2}

1. Undescribed branching *Acropora* species noted. Several small and medium colonies observed throughout survey area.
2. Bommies of mixed coral assemblages, including plating *Acropora*, *Montipora* and *Pocillopora* and juvenile *Acropora* (2a) and (2b) *Pocillopora*
3. Mid-reef area populated by large branching colonies of *Acropora*. Surrounding colonies are often other coral colonies including juvenile *Acropora* (2a) and (2b) *Pocillopora*. Also note foliose algal assemblage commonly observed in this reef area.
4. Backreef area populated by a large number of *Pocillopora* colonies. Colonies often interspersed by fleshy algae and small *Acropora* colonies.
5. Large rock bommies exposed at low tide that support numerous coral colonies. This area is further characterised by numerous encrusting and foliose *Montipora* colonies, some of which show signs of tissue loss and possible disease (5a).
6. Throughout Western Slaughter microalgal communities consisted of *Lyngbya*, red cyanobacteria in addition to diverse turf assemblages.

Figure 11. *Survey areas and representative images of Western Slaughter (Pier), March 2023*

Slaughter Bay hosts an array of rock pools, reef flat and shallow water reef channel habitats which extend along the reef towards the Kingston Pier.

The shallow reef flat ecosystem includes coral-lined sandy bottom reef channel, shallow water coral bommies and intertidal rock pools which provide an abundance of benthic habitats supporting diverse, cryptic and likely endemic coral, invertebrate, fish and algal assemblages, cryptic species.

Shallow reefs and rock pools are important habitats on reefs, with observations of juvenile organisms in the area suggesting the area supports nursery habitats and in addition to the site specific biodiversity.

Figure 12. *Representative images of the rock pools of Western Slaughter Bay and large colonies found there.*

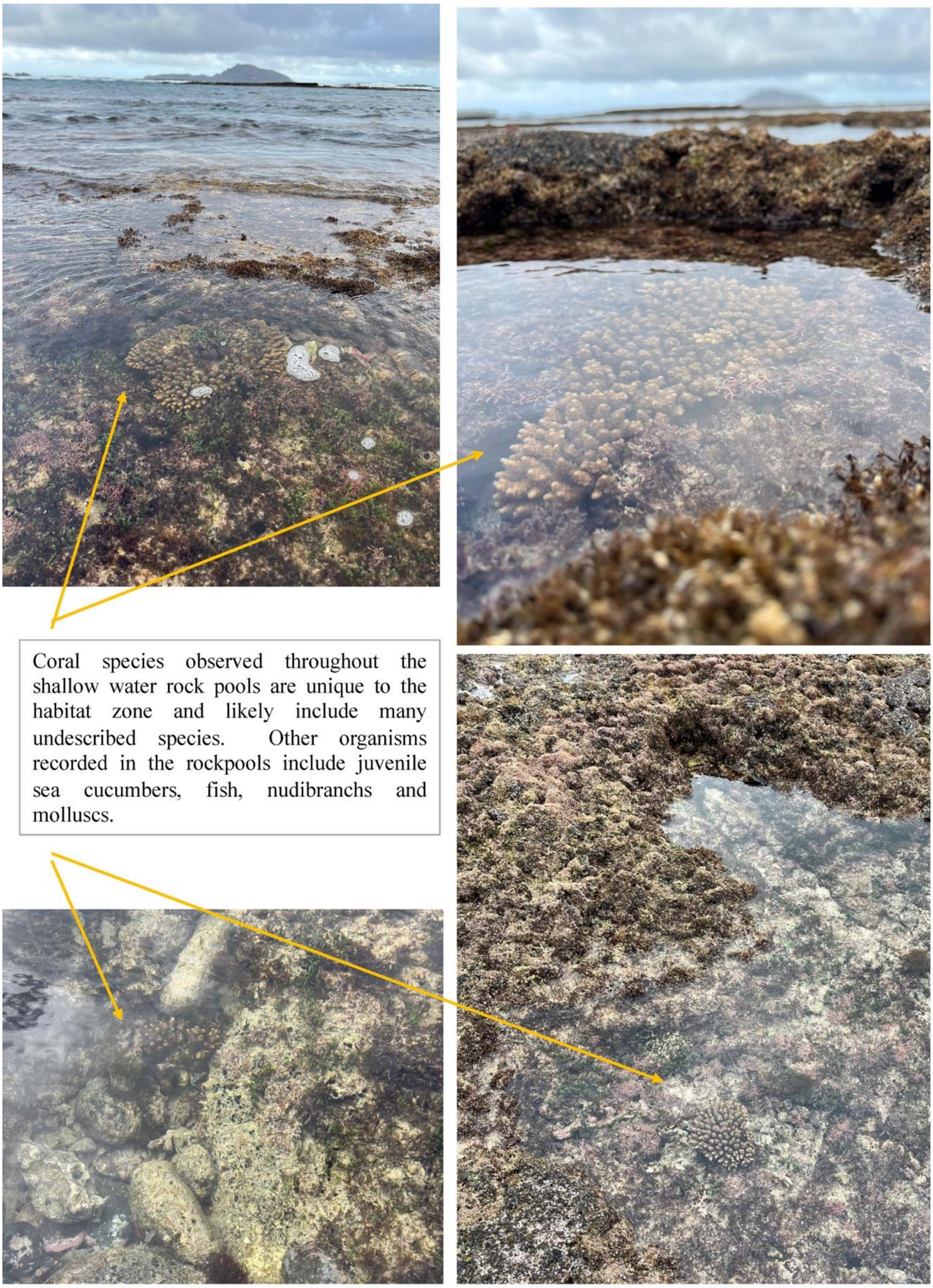


Figure 13. *Images showing coral colonies seen in the extreme shallow rockpools of Western Slaughter Bay*

Figure 14. *Some of the corals seen only in Western Slaughter and not elsewhere in Emily and Slaughter Bay.*

Coral Disease Surveys

Corals under stress are particularly susceptible to disease and in other systems increases in disease have been used as an indicator of a stressed ecosystem. Disease rates on the two dominant coral types in the bays have been measured since 2020.

To quantify prevalence (i.e. the proportion of community infected) of *Montipora* White Syndrome and *Acropora* White Syndrome ecological surveys were conducted within the lagoon. For *Montipora* taxa, disease was assessed in December 2020, April 2021, April 2022, September 2022, December 2022 and April 2023. For *Acropora* taxa disease was assessed in April 2021, April 2022, September 2022, December 2022 and April 2023. At each time point a total of 12-replicate belt-transects were conducted within the lagoon. Six transects at each time point were laid in both Emily Bay and Slaughter Bay respectively. Survey methods involved placing a 10 m transect line along the benthos parallel to the depth contours of the reef structure at approximately 1-2 m depth. All transects were placed at least 10 m apart. Transect sites were semi-fixed (i.e., a permanent reef marker was not used, but the same reef area was re-visited at the repeat time point). All colonies of *Montipora* and plating *Acropora* over 10 cm in diameter and within a 1 m belt on either side of the transect were monitored for signs of disease, representing a total of 20 m^{-2} of reef area surveyed per transect. Disease prevalence was calculated for each belt-transect by dividing the number of colonies showing signs of disease by the total number of colonies present within a transect. When a colony showed signs of disease, disease severity was estimated as the approximate area of a colony covered by the disease lesion (i.e. disease lesion size). All colonies were also size-classed as small (0.1 – 0.5 m), medium (0.51 – 1 m) and large (>1 m). Signs of disease were also assessed in Cemetery Bay for *Acropora* in April 2022, September 2022, December 2022 and April 2023 and for *Montipora* in September 2022, December 2022 and April 2023. Here a random survey of colonies was conducted, where the nearest colony after two fin kicks were examined for disease. This same method was applied in Western Slaughter Bay in April 2023. Disease prevalence for each taxa was calculated as the proportion of total colonies surveyed that showed signs of disease.

Generally, disease rates of corals are less than 3-5% on healthy coral reefs. The September and December 2022 data along with the April 2023 data for both Emily and Slaughter Bay indicate that both the *Acropora* and *Montipora* populations are undergoing an on-going disease outbreak with disease prevalence of over 28% in both bays (Figures 15 and 16, Table 2).

Plating Acropora White Syndrome dynamics: Since the initial disease surveys in April 2021 the prevalence of White Syndrome (WS) Disease of plating *Acropora* has been over 22% in Emily Bay (Figure 15A). In contrast WS was not found in Slaughter Bay until the April 2022 survey period. This pattern suggests that the WS disease originated from Emily Bay and has moved to Slaughter Bay. This interpretation is also supported by the pattern seen with disease severity (i.e. the proportion of the coral colony affected by disease). In April 2021 severity in Emily Bay was less than 10%, this then increased over the following survey periods (Figure 15B), suggesting that while WS was widespread in April 2021 in Emily Bay it had not as yet significantly impacted coral colonies. This pattern of severity increasing over time is also seen in Slaughter Bay after the detection of the disease in April 2022. WS disease was also found in Cemetery Bay (although it should be noted that surveys only began in April 2022) which is considered more pristine than Emily and Slaughter most likely due to its more open exposure to ocean flushing. Disease prevalence in Cemetery Bay is generally less than Emily and Slaughter Bay, less than 20% at all survey periods and prevalence has now declined to levels that would not be considered outbreak levels (5% in April 2023) with a concomitant decline in severity (Figure 15).

Montipora White Syndrome dynamics: Since surveying began in December 2020 *Montipora* White Syndrome (WS) has been at what would be considered outbreak levels in Emily, Slaughter and Cemetery Bays (Figure 16). Rates of prevalence was highest in Emily Bay in 2020 (75%) and then decreased to between 35% and 58% over the remaining surveys. Prevalence of WS in Slaughter Bay have been consistent across the survey period (between 38% and 64%). In both Emily and Slaughter Bay there been no significant decline in severity across the survey periods (Figure 16A), while levels in Cemetery Bay are showing a decline over the survey periods September 2022 – April 2023 (45% to 23%). Importantly a study on WS has indicated that large colonies are more likely to be affected by the disease (Page et al. 2023b), given that in most populations large corals are the most fecund and the highest contributor to restocking (Álvarez-Noriega et al. 2016) this elevated disease susceptibility in the large size cohort has the potential to negatively impact recruitment stocks and recovery of coral populations from anthropogenic impacts in Emily and Slaughter Bay.

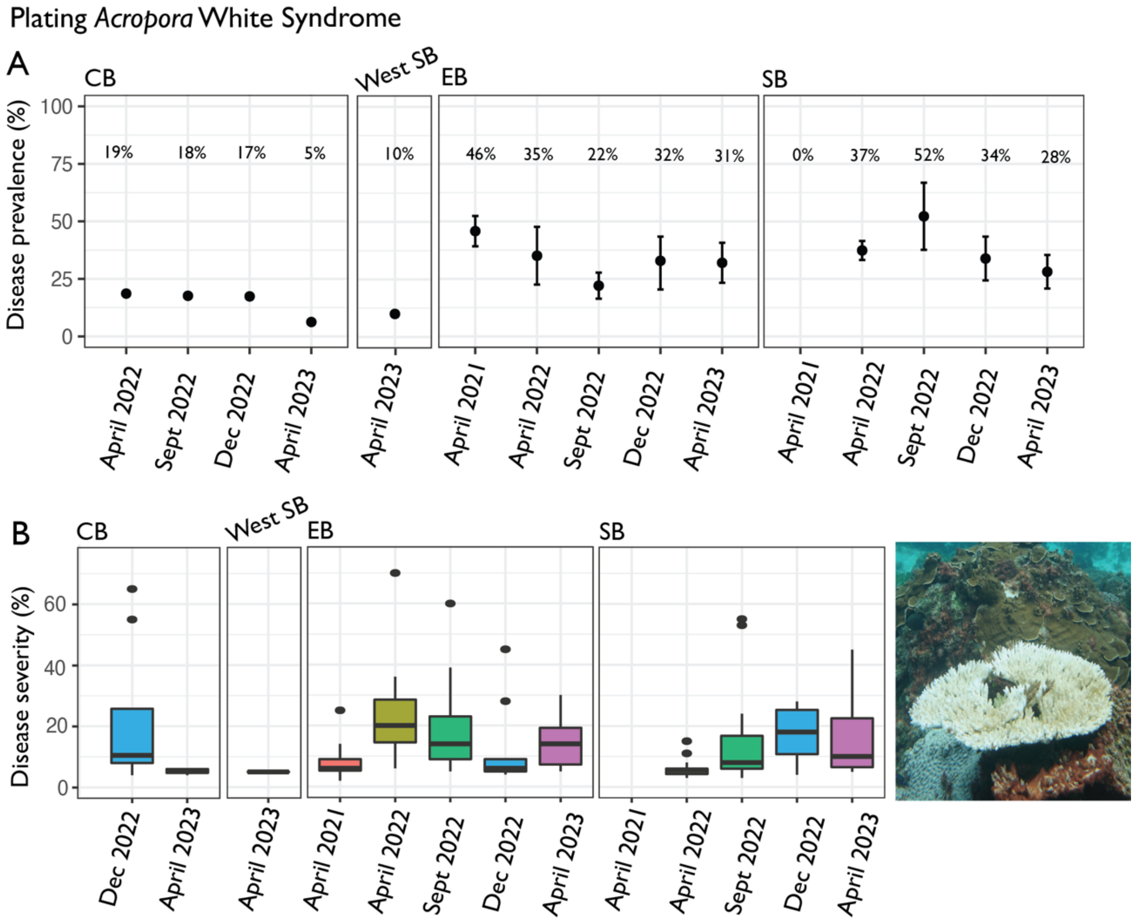


Figure 15. A. *Disease prevalence levels recorded over time for plating Acropora White Syndrome (A) Plotted values are mean ± se. Written values are mean prevalence.* ***B.*** *Boxplots of disease severity (i.e. average colony area of disease lesion) for plating Acropora White Syndrome. The middle line represents the median value, the box represents the interquartile range, whiskers are the maximum and minimum values and points represent outliers. The latest April 2023 values indicate an ongoing severe coral disease outbreak.*

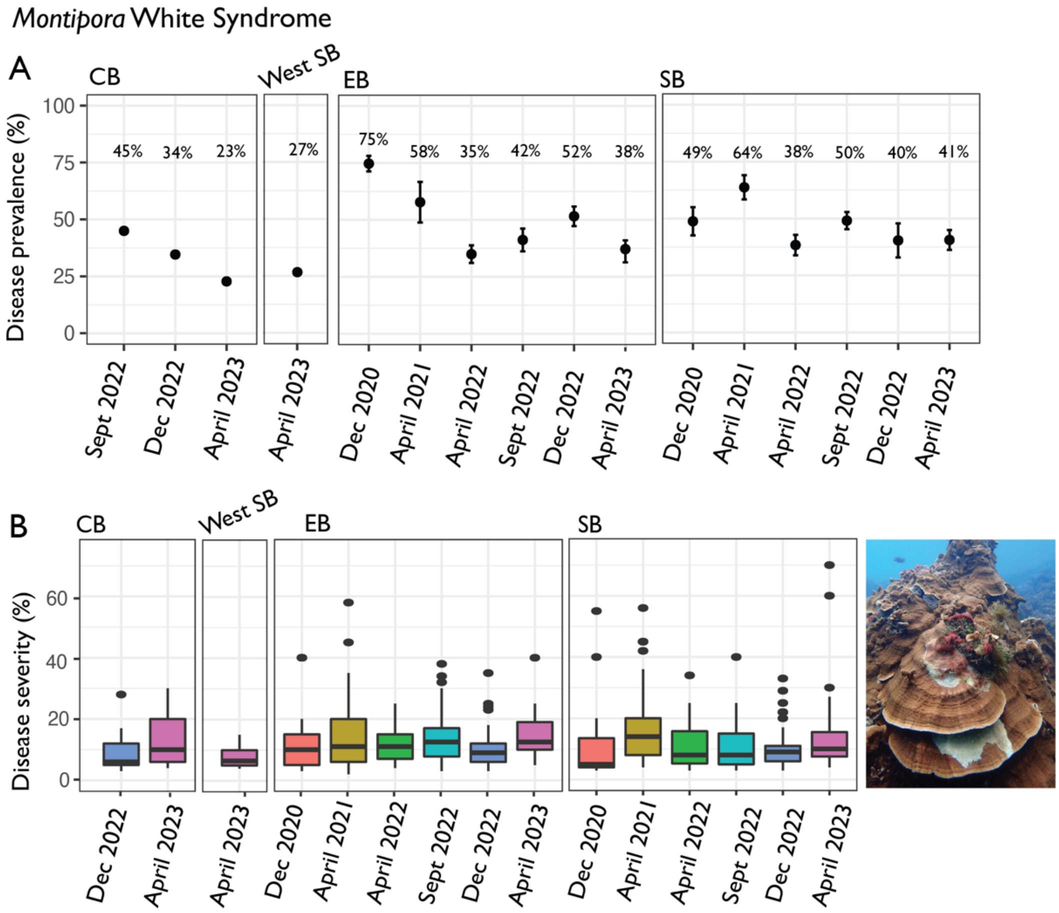


Figure 16. A. *Disease prevalence levels recorded over time for Montipora White Syndrome (A) Plotted values are mean ± se. Written values are mean prevalence.* ***B.*** *Boxplots of disease severity (i.e. average colony area of disease lesion) for Montipora White Syndrome. The middle line represents the median value, the box represents the interquartile range, whiskers are the maximum and minimum values and points represent outliers. The latest April 2023 values indicate an ongoing severe coral disease outbreak.*

Table 2. *Total disease prevalence of White Syndrome within the lagoon over time. Plus or minus represent the standard error range. The latest April 2023 values indicate an ongoing severe coral disease outbreak.*

Time point	Taxa	Mean lagoon prevalence
December 2020	***Montipora***	61.7% ± 5
April 2021		60.7% ± 5
April 2022		37% ± 2.9
September 2022		45% ± 3
December 2022		46% ± 5
April 2023		38% ± 3
April 2021	***Acropora***	46% ± 7 (n.b only in EB)
April 2022		36% ± 6
September 2022		37% ± 9
December 2022		33% ± 6
April 2023		28% ± 6

Possible occurrence of the ascidian Diplosoma virens

An initial survey by Dr Ashley Coutts (Biofouling Solutions (2022)) in April 2022 putatively identified a species of ascidian (commonly called a sea squirt) *Diplosoma virens* (Figure 17), that may smother other benthic organisms (Figure 17) and recommended that they should be included in monitoring efforts. Other species of ascidians have been observed to overgrow corals in locations with elevated nutrients as they gain a competitive advantage in these conditions (Shenkar et al. 2008). Given this, a subset of the coral disease benthic survey images from December 2020 to April 2023 were reanalyzed to determine if this species could be identified in Emily, Slaughter and Cemetery Bay. Ascidians were not observed in survey photos from December 2020 and April 2021, however analysis of images from April 2022 identified them in Emily, Slaughter and Cemetery Bays (note this was the first time point for Cemetery Bay which images were available for; Table 3). Following April 2022 ascidians were further identified in the September and December 2022 and April 2023 survey period in Cemetery Bay, indicating a sustained population. Given in the original survey analysis ascidians were classified in the other category these data points can be further re-analysed.

Anecdotal observations by the Reef Health team also identified the ascidian in Emily and Slaughter Bay after April 2022. Given that this species may pose a threat by smothering other benthic organisms and it is possible to reliably identify them in the benthic survey images it is recommended that the entire photo library be reanalyzed to identify the presence of this ascidian and that it is included in the list of organismal and abundance observations for the citizen science program.

Table 3. *Presence, absence, percent cover, and frequency of occurrence (FOC) of ascidians in each transect taken at the 3 sites Cemetery Bay, Emily Bay, and Slaughter Bay over 6 time points. No surveys were conducted in Cemetery Bay in December 2020 and April 2021.*

Time point	Site	No. of transects	Presence/absence	Cover (%)	FOC
December 2020	Emily Bay	6	absent	0	0
	Slaughter Bay	6	absent	0	0
April 2021	Emily Bay	6	absent	0	0
	Slaughter Bay	6	absent	0	0
April 2022	Cemetery Bay	3	present	0.1	0.33
	Emily Bay	6	present	0.18	0.17
	Slaughter Bay	6	present	0.17	0.17
September 2022	Cemetery Bay	3	present	0.23	0.33
	Emily Bay	6	absent	0	0
	Slaughter Bay	6	absent	0	0
December 2022	Cemetery Bay	3	present	0.1	0.67
	Emily Bay	6	absent	0	0
	Slaughter Bay	6	absent	0	0
April 2023	Cemetery Bay	3	present	2.3	0.67
	Emily Bay	6	absent	0	0
	Slaughter Bay	6	absent	0	0

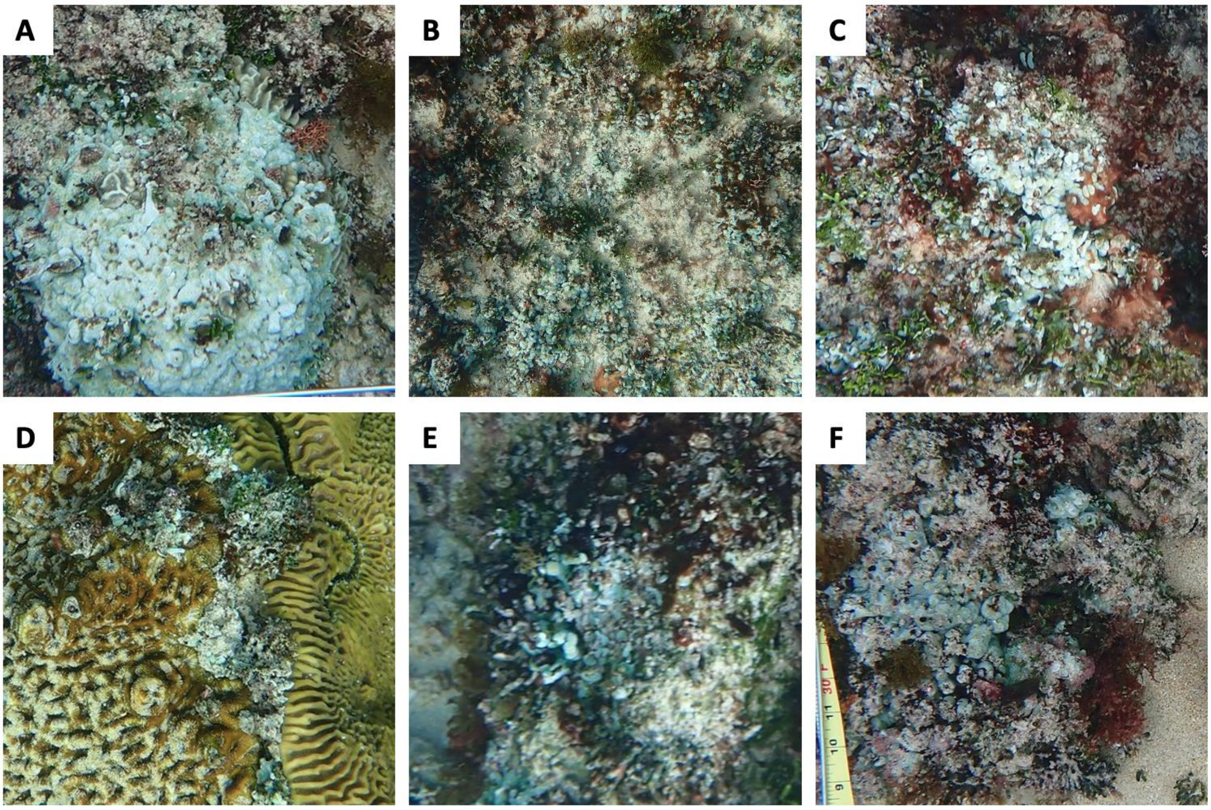


Figure 17. *Images of ascidians taken in Cemetery Bay in April 2023 growing on (A) live coral, (B) sand next to fleshy algae and red cyanobacteria, (C) turf-sediment matrix, in between red cyanobacteria and fleshy algae (Caulerpa), (D) on sediment on the boundary between two corals, (E) on sediment next to fleshy algae and red cyanobacteria, (F) on a turf-sediment matrix next to patches of fleshy algae.*

Water Quality Monitoring

Nutrient water quality monitoring

As part of the ongoing reef health monitoring program the reef health team have been conducting ad-hoc analysis of both nutrients and fluorescent whitening compounds in the bay to determine if nutrients are entering the bay and possible location sources. The major anthropogenic influences on Emily and Slaughter Bay are associated with terrestrial nutrient inputs into the bay. Rainfall data were obtained from the Australian Bureau of Meteorology for the station number 200288 (29.0389° S, 167.9408° E) located at Norfolk Island airport. The lagoonal system of Norfolk Island is affected by freshwater incursion which brings sedimentation and flooding that influence the benthic community structure and health. Prolonged abnormal rainfall events are associated with shifts in the benthic community and decrease in ecosystem health. The environmental data reported below show that high rainfall events occurred in the summers of 2020 and 2022 (Figure 18). To determine the impact of these events 17 water samples were taken along the shoreline of Emily and Slaughter Bay on the 15th April 2022 (Figure 19) while the Emily Bay drain was flowing to determine ammonium and nitrate/nitrite (NOx) concentrations. Water samples were collected and immediately frozen, samples were defrosted prior to analysis, filtered and analysed by the UNSW Mark Wainwright facility. Ammonium concentrations were highest at the Emily Bay creek (111 µg/L) and decreased as distance increased from the source indicating that this drain is the major source of nutrients entering into the bay during rainfall events (Figure 19). Ammonium levels in all samples throughout Emily and Slaughter Bay, in addition to one site to the west of the Slaughter Bay pier were above the default ANZECC guideline levels (20 µg/L). NOx concentrations were also higher than the default ANZECC guidelines (25 µg/L) across all samples although did not demonstrate the same spatial decrease as seen for ammonium (Figure 19). This is likely because ammonium is more readily assimilated by photosynthetic organisms. This evidence that nutrients are entering from the Emily Bay drain are supported by a study examining stable isotopes (Page et al. 2023a) that found nutrient inputs were primarily from the Emily Bay drain but also from a secondary source in Slaughter Bay.

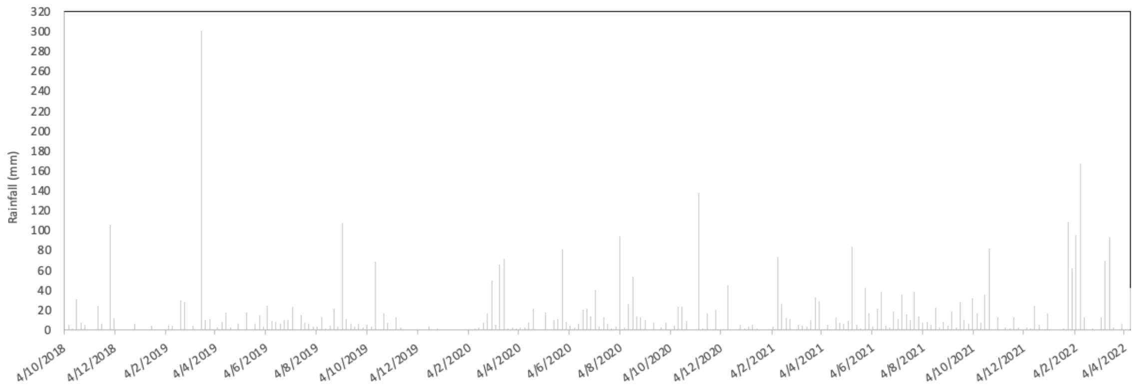


Figure 18. *Rainfall was recorded at Norfolk Island meteorological station from the 4th of October 2018 to the 4th of April 2022.*

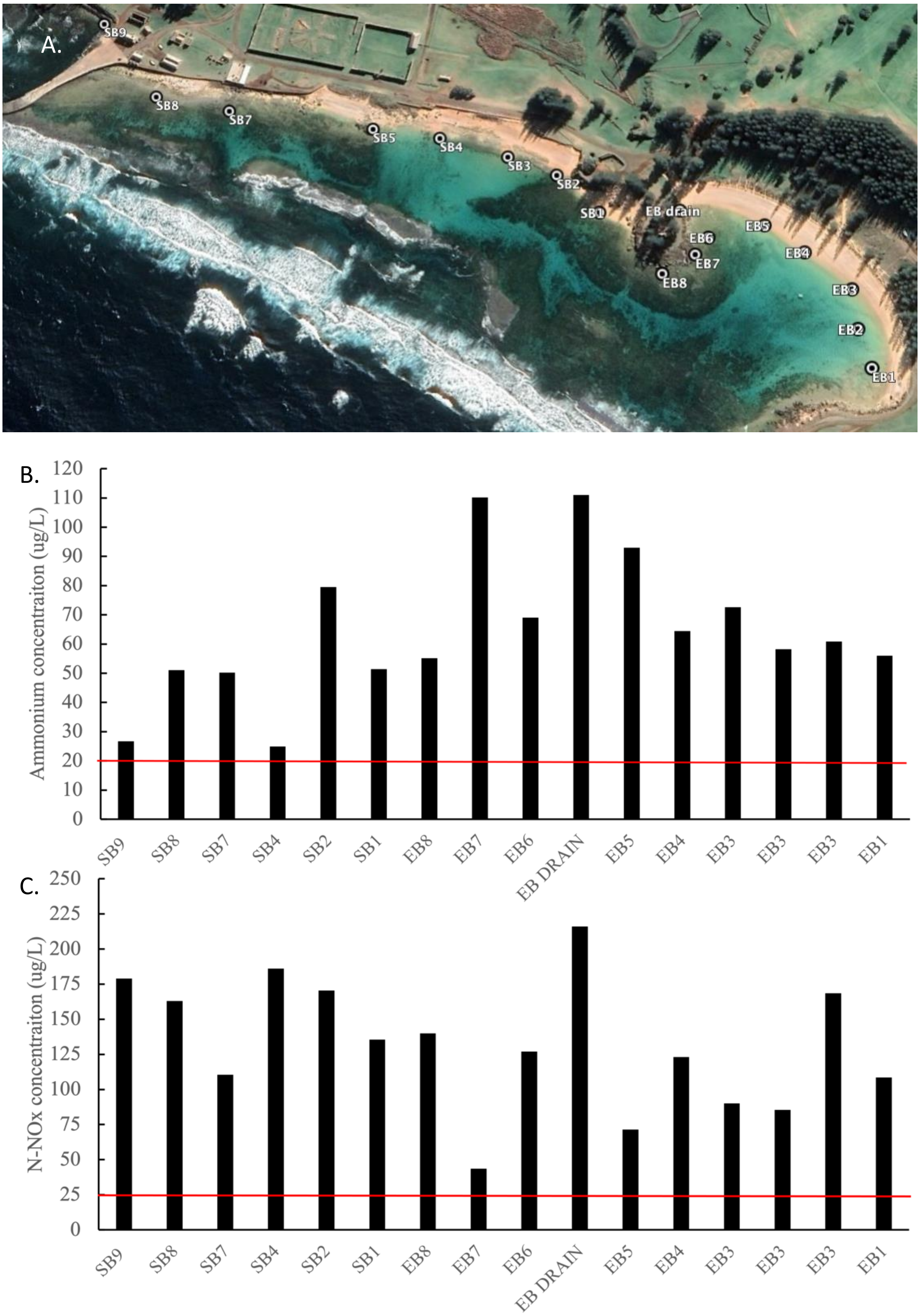


Figure 19. *Nutrient concentrations across Emily and Slaughter Bay while the Emily Bay creek was open (15th April 2022). (A) locations of sampling, (B) ammonium concentrations, (C) nitrate/nitrite (NOx) concentrations. Red lines indicate ANZECC default guideline thresholds.*

The ANZECC guidelines described above come from the 2000 default trigger guidelines and are designed to provide a generic starting point for water quality assessment. ANZECC now recommends that trigger levels are developed for specific locations based upon the identification of community values and management goals for the area (https://www.waterquality.gov.au/anz-guidelines).

Fluorescent whitening compound monitoring

Fluorescent whitening compounds (FWC), or optical brighteners, are primarily added to laundry detergents and cleaning agents for the purpose of brightening fabrics/surfaces. Laundry wastewater ('grey water') is the largest contributor of FWC's to wastewater systems because it retains a large proportion of dissolved whitening compounds. Toilet papers also contain FWC's and as toilet paper breaks down, fluorescent whitening agents are released into the water. Since whitening compounds decompose relatively slowly, except through photo-decay (exposure to sunlight), they serve as ideal indicators of discharge from wastewater treatment systems and/or failing septic systems.

Using FWC's as indicators of detecting wastewater has several advantages including: detection is nearly instantaneous, the equipment used is relatively inexpensive and large numbers of samples can be analysed in a short period of time. The detection of FWC's is undertaken using fluorometric analysis of samples that have been exposed to UV radiation (6W, 15sm distance, $\lambda = 365$nm) for 1 minute and then again at 9 minutes. The fluorescence intensity typically reduces with each UV exposure, and the ratio of signal reduction is used to determine if FWC's are present (fluorescence decreases more rapidly due to FWC than organic matter). This method is described by Cao et al. (2009).

Sampling was conducted over two time periods (9th-10th September 2022 and 1st-5th April 2023) in a variety of locations within the Emily Bay catchment and Emily and Slaughter Bay (Figure 20). The September 2022 sampling occurred after a period of heavy rain while the April 2023 survey was conducted after a period of little rain (inset Figure 20-23). In the September 2022 sample FWCs were detected throughout the catchment and in Emily Bay at the Emily Bay drain inlet (Figure 20, 21, Table 4). In contrast, sampling in April 2023 detected FWC only at one site (the creek under Country Road, Table 4, Figures 22, 23) at one sampling time point.

The presence of FWC in the catchment confirms the presence of wastewater entering the catchment system, in particular during periods of heavy rainfall when FWC could be identified throughout the entire catchment and also at the drain entering Emily Bay. The inability to identify FWC in other locations in the bays is not surprising given dilution effects from the volume of water in these. This data provides clear evidence that wastewater is a source of nutrients entering Emily and Slaughter Bay.

Table 4. *Fluorescent whitening compound (FWC) presence/absence at sites on Norfolk Island. Red = present, nd = not detected, grey – not sampled. * for Watermill Ck, see figures showing sites where FWC's were detected.*

Site	9 Sep 2022	10 Sep 2022	1 Apr 2023	5 Apr 2023
Laundry discharge				
Septic				
WAS				
Watermill Ck*			nd	nd
EB1 (Emily Bay – near outlet)			nd	nd
EB2 (Emily Bay)	nd	nd	nd	nd
EB3 (Emily Bay)	nd	nd	nd	nd
SB1 (Slaughter Bay)	nd	nd	nd	nd
SB3 (Slaughter Bay)	nd	nd	nd	nd
SB5 (Slaughter Bay)	nd	nd	nd	nd
Officers Bath			nd	nd
Cemetery Bay	nd	nd		nd
Cascades Wharf		nd		nd
Cascades Ck		nd		nd
Bomboras		nd		nd
Bomboras Ck				nd
Country Rd (creek under road)				nd

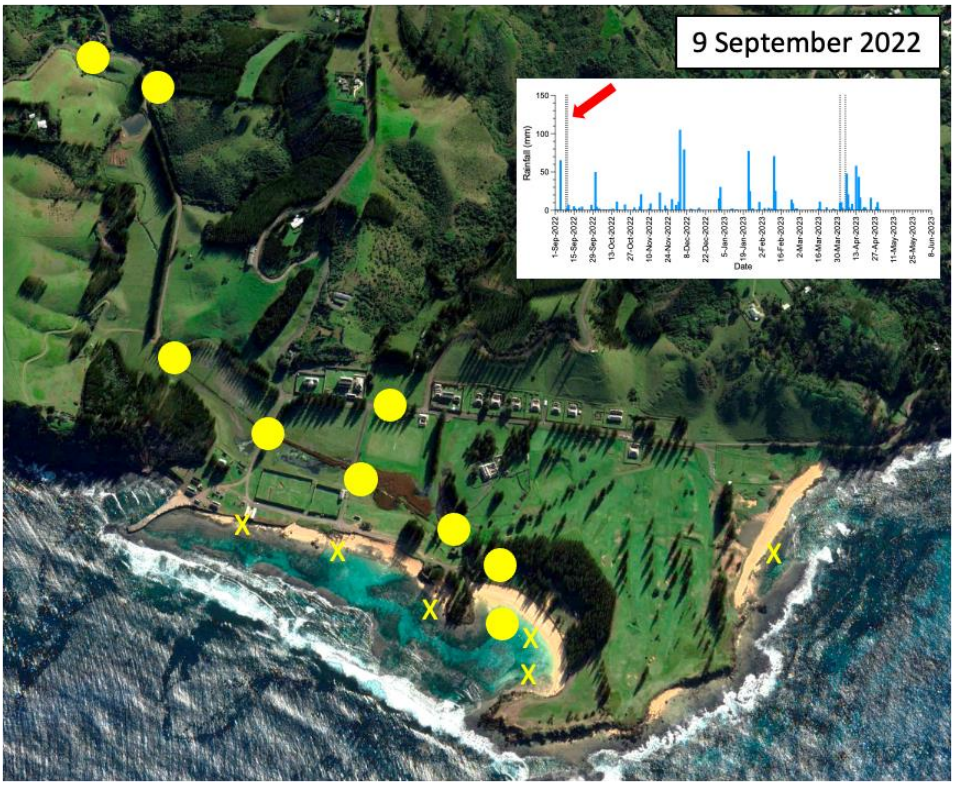


Figure 20. *Sampling sites showing presence (large yellow circle) or absence (small yellow* cross*) of FWC's for 9 September 2022 following rainfall.*

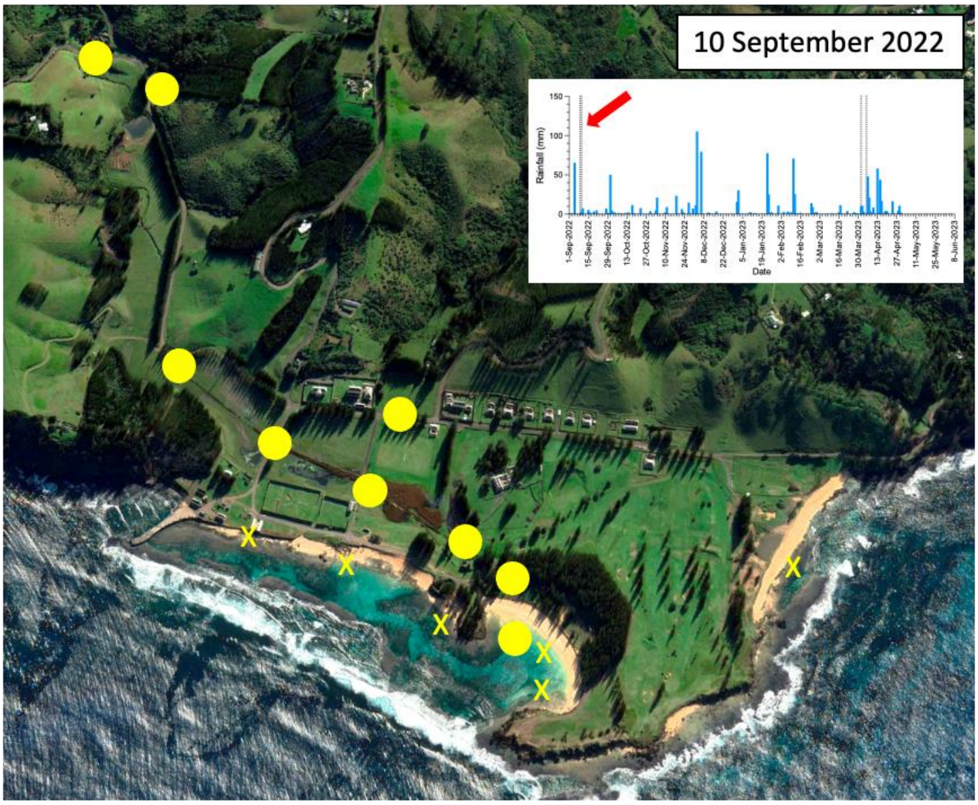


Figure 21. *Sampling sites showing presence (large yellow circle) or absence (small yellow* cross*) of FWC's for 10 September 2022 following rainfall*

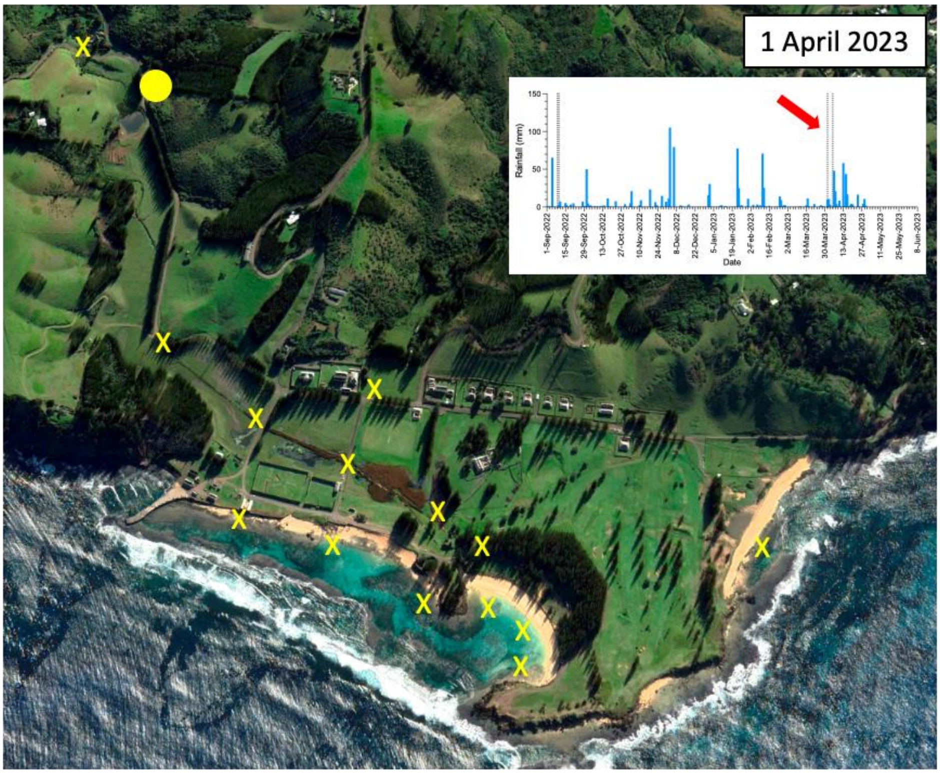


Figure 22. *Sampling sites showing presence (large yellow circle) or absence (small yellow* cross*) of FWC's for 1 April 2023.*

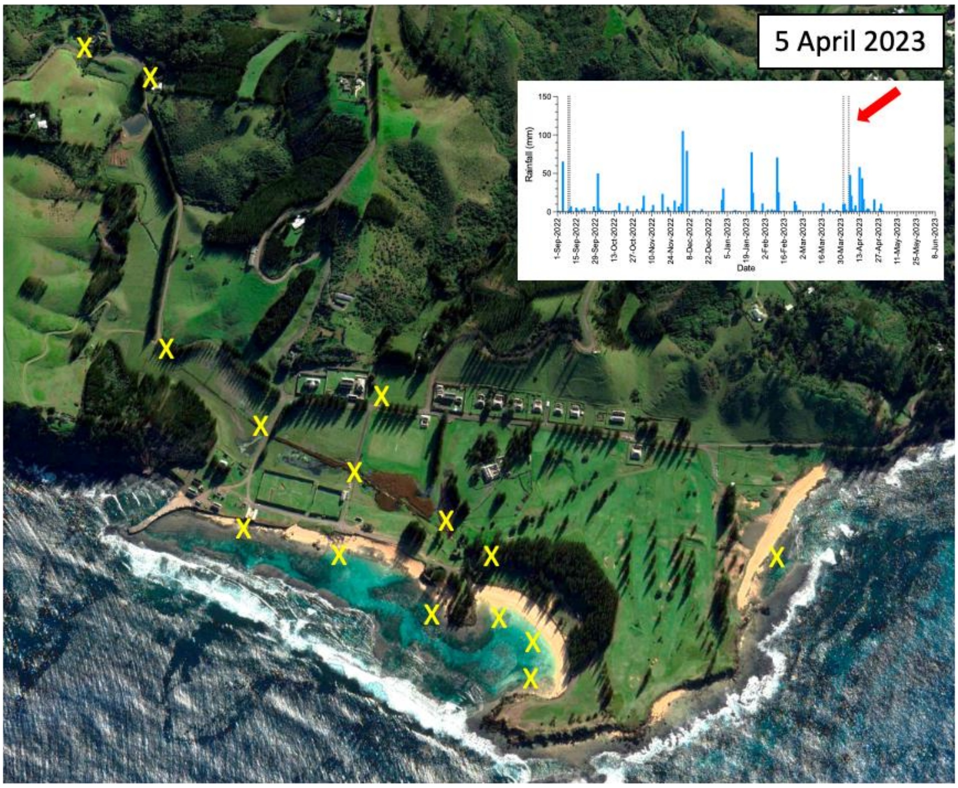


Figure 23. *Sampling sites showing presence (large yellow circle) or absence (small yellow* cross*) of FWC's for 5 April 2023.*

Nature-based solutions for catchment-derived water quality issues

Anthropogenic effects of wastewater overflows, failing septic systems and stormwater runoff can be a source of continued water quality issues for receiving waters (McMinn et al. 2019). Additionally, human illness can be attributed to contaminated recreational waterways from these anthropogenic effects. To minimise the impacts of pollution events, catchment-based approaches are increasingly being considered, fostering the development of innovative solutions for water quality management (McMinn et al. 2019). Wetlands act as natural biofilters and have demonstrated effectiveness in removal of physical, chemical, biological and microbial contaminants (Matamoros and Rodríguez 2017; Stottmeister et al. 2003). As such, the flow of catchment-derived water through a wetland can allow for the reduction of contaminants, improving downstream water quality upon discharge from the wetland. Furthermore, the protection and enhancement of natural wetlands provides additional benefits to both humans and wildlife such as habitat restoration and biodiversity gains.

Community outreach and engagement and citizen science initiatives

Engagement with the local Norfolk Island Community is key to address the issues impacting Emily and Slaughter Bays. With this in the mind the Reef Health team has undertaken a variety of outreach events on Island (see Table 5). Generally, most residents were concerned about the state of Emily and Slaughter Bay, in particular those that regularly swim in the bay, and accepted that catchment management was needed in addition to management of the bays to prevent further ecosystem decline. There were several questions raised about other possible reasons for ecosystem decline including changes to the hydrodynamics in the bay and sedimentation caused by planting of Norfolk pines in Emily Bay, inputs from the golf course, inputs from the historic garbage dump that was located on the Emily Bay headland and acid sulphate soils. In addition to the events listed in Table 5 members of the reef health team were regularly engaged by local community members while on the island.

__Table 5.__ List of community events and outreach.

Activity	Date
Article in the Norfolk Islander	April 2022, August 2022, December 2022
Community presentation at Emily Bay	April 2022
Fauna and Fauna Society presentation	December 2022
Presentation of on-going results to local community – Castaways Resort	December 2022
Community discussion/consultation	March 2023
Launch of citizen science website	March 2023

As part of engagement with the community the Reef Health team has developed an information portal for members of the public to report their observations (https://coralreefhealth.com; Figure 24, 25). The site contains representative photos of a variety of coral disease, information on coral bleaching, maps of the Bays to identify location of observation and instructions on reporting observations.

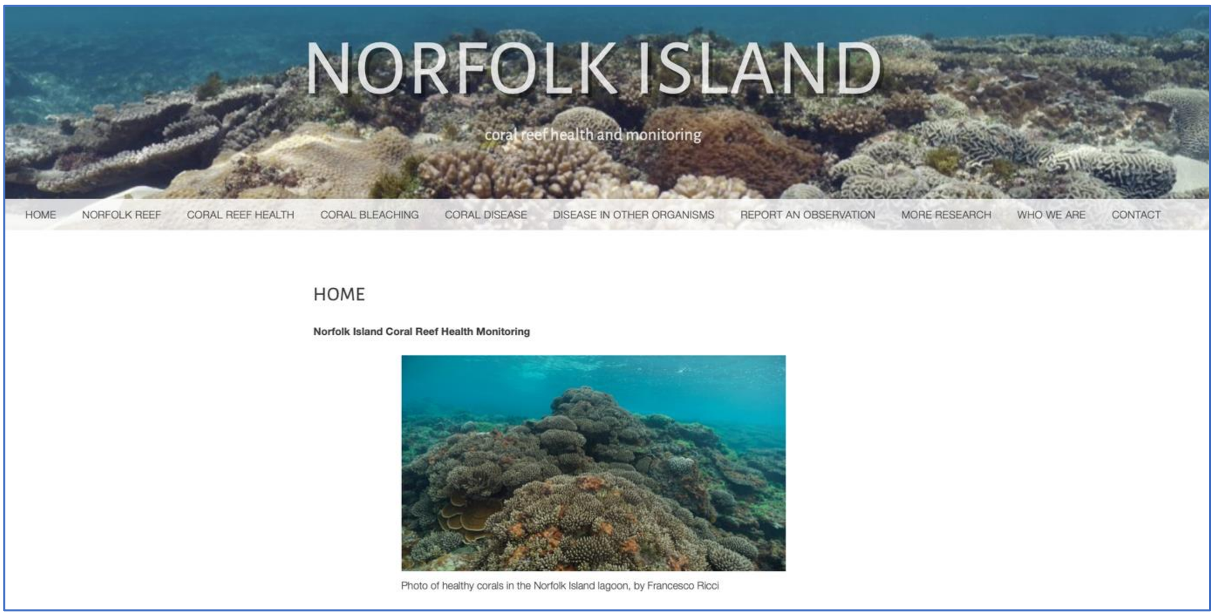


***Figure 24.** Home page of the Norfolk Island citizen science portal (https://coralreefhealth.com).*

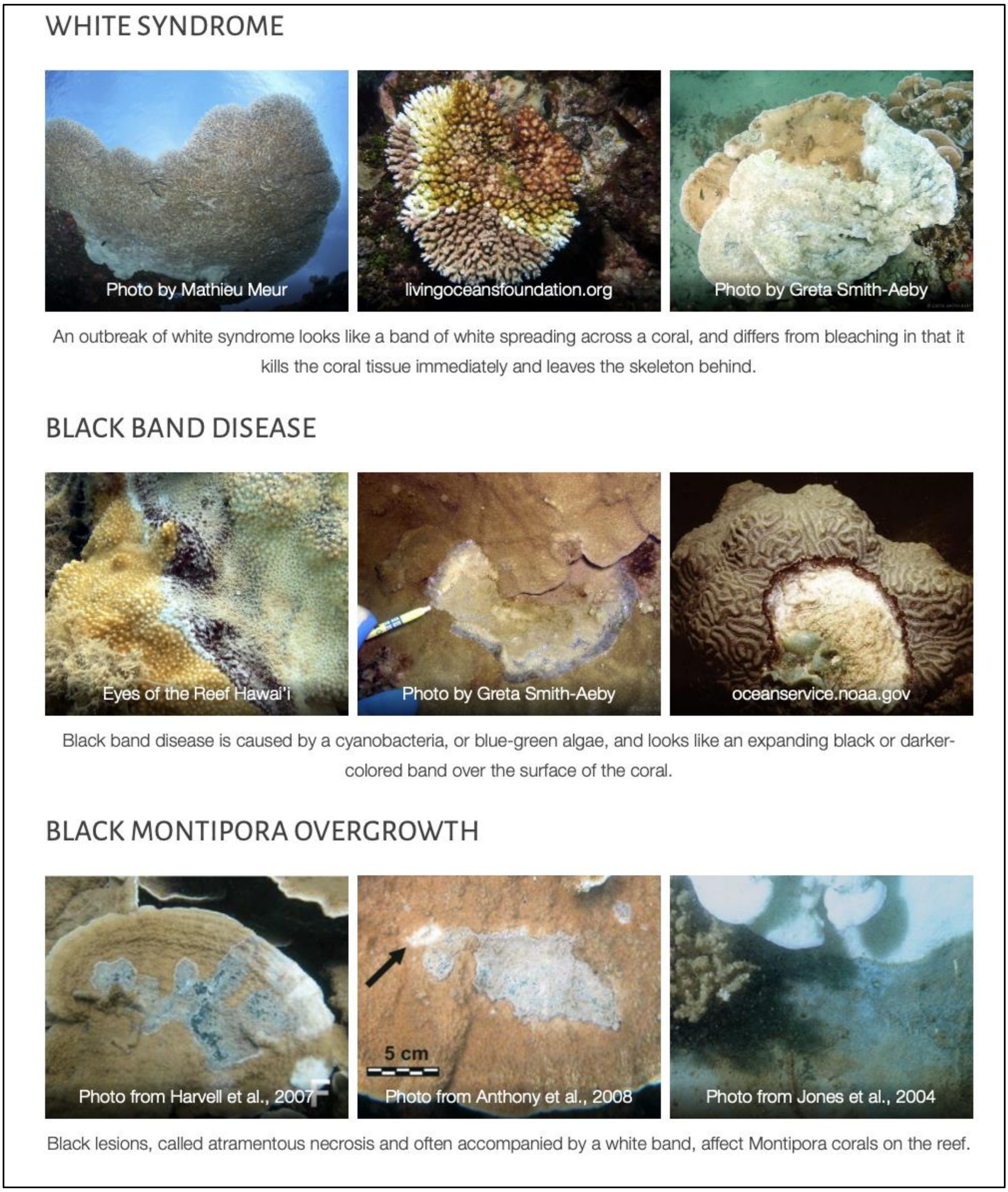


Figure 25. *Example of coral disease images from the Norfolk citizen science web portal to assist in disease identification and reporting.*

Through the website citizen scientists are directed to either a Google form or Facebook form where they report their observations by answering the following questions

1. What animal has been sighted?
2. What is the health status – diseased, bleached, healthy, or other?

3. At what approximate depth was the animal sighted?
4. When was the animal sighted (date) ?
5. Where was the animal sighted? Use the Norfolk Island grid map below to find the corresponding grid location (A1, A2, etc)
6. Any other observations?

Summary of outcomes and management recommendations

Since reef health monitoring commenced in 2020 the coral reefs of Emily and Slaughter Bay have been repeatedly impacted by a variety of stressors resulting in changes to benthic cover and ecosystem health. These impacts and changes include:

- *2012-2020:* An extended period of below average rainfall from 2012-2020, resulted in a build-up of anthropogenic inputs (especially nutrients) in the Emily and Slaughter Bay catchment. During this time the Emily Bay drain was only infrequently open to the ocean.
- *February-April 2020*: The first recorded coral bleaching event in Emily and Slaughter Bay.
- *March 2020*: Cyclone Gretel passing close to Norfolk Island, with an associated high rainfall event.
- *August 2020-present:* Extended periods of high rainfall events resulting in repeated opening of the Emily Bay drain plug, flushing of the stored nutrient materials from the catchment into the Bays and repeated closures of the Bays for human use due to high bacterial counts.
- *September 2020- present*: High levels of anthropogenic linked nutrient inputs into the bays from the Emily Bay drain and other sources in Slaughter Bay. The level of nutrient inputs was exacerbated by the extended dry period prior to 2020. Nutrient levels in the Bays and surrounding catchment have exceeded ANZECC guidelines on numerous occasions.
- *March 2021*: Significant decline in green turfing algae (<5%) seen in the Bays since previous survey period (>30%). Green turfing algae are a major algal cover in healthy reef systems.
- *March 2021 – April 2022:* Significant increase in red cyanobacterial cover in Emily and Slaughter Bay, from less than 5% in March 2020 to over 30% in April 2022. Red cyanobacterial overgrowth of reefs is associated with

elevated nutrient inputs and are indicative of a reef area under stress (Ford et al. 2018). This alga was removed by a large storm event in June 2022 however can again be detected in the latest March 2023 survey data (8% benthic cover).

- *December 2020 – present*: Outbreak levels (considered to be above 15% of the population displaying signs of disease) of *Montipora* White Syndrome recorded in Emily (up to 75% prevalence) and Slaughter Bay (up to 49% prevalence) from the initial surveys in December 2020 through to the latest survey period (March 2023).
- *April 2021 – present*: Initial outbreak level of *Acropora* White Syndrome recorded in Emily Bay (46% prevalence, low severity). Outbreak levels of *Acropora* White Syndrome recorded in all surveys through to the latest survey period (March 2023).
- *April 2022 - present*: Initial outbreak level of *Acropora* White Syndrome recorded in Slaughter Bay (37% prevalence, low severity). Outbreak levels of *Acropora* White Syndrome recorded in all surveys through to the latest survey period (March 2023).
- *April 2022 - present*: Initial outbreak level of *Acropora* White Syndrome recorded in Cemetery Bay (19% prevalence). Outbreak levels of *Acropora* White Syndrome recorded in all surveys, however declined in the last survey in March 2023 to below outbreak levels (5% prevalence, low severity)
- *September 2022:* Survey of Cemetery Bay found outbreak levels *Montipora* White Syndrome (45%), prevalence declines until last survey in March 2023 (23%).
- *September 2022 – present:* Increases in macroalgal cover, from initial levels of 6-8% in March 2020 to over 29% of the benthos. Increases in macroalgae cover can lead to phase shifts from coral dominated to algal dominated reefs under the presence of increased nutrient loading, particularly on reefs with low herbivory (McCook 1999), such as Emily and Slaughter Bay. While it is known that macroalgal abundance varies seasonally, long-term residents indicated they had not previously seen the high macroalgal densities observed since September 2022.

- *September 2022 – present:* The presence of FWC in the stream system leading to Emily Bays, this indicates that wastewater is entering the catchment.
- *December 2022 - present*: *Lyngbya*-like algae identified in benthic surveys for the first time (average abundance 1-3%). *Lyngbya* is a genus of blue-green algae, some species of which have been linked to human health impacts in other systems (Osborne et al. 2007; Werner et al. 2012) and growth of which is linked to elevated nutrient levels.

Taken together these anthropogenic inputs and biological responses are indicative of a reef system with declining ecosystem health. While as yet there have not been overall declines in coral cover, the changes in algal type and abundance are early signs of a phase shift from a coral dominated to algal dominated system. There are a number of management actions that should be considered, these include:

- Identifying and developing solutions to reduce nutrients entering the bays supported by;
    - Ongoing monitoring of nutrient (ammonium, nitrate, phosphate) sources in the surrounding catchment and bays.
    - Trialling of a comprehensive monitoring program of other potential terrestrial inputs, such as sulphur, herbicides and pesticides.
- Ongoing benthic monitoring of the Bays to identify changes in coral disease prevalence, benthic cover and algal type and cover. It is recommended that the current photo transect method is utilised to ensure that existing dataset can be continued. This survey also allows for identification and characterisation of coral disease outbreaks and changes in algal community types.
- Additional protection of high and or healthy coral cover areas (such as western Slaughter Bay, Cemetery Bay) and rare corals (such as the elkhorn growth *Acropora* and coral bommies) is recommended.
- Reanalysis of the benthic reef health image library to identify presence/absence of *Diplosoma virens.* This should be coupled with a positive taxonomic identification of this species.

- **Visitor education and outreach** to ensure awareness of minimising additional stressors such as coral breakage, handling corals and walking on corals is important for end-users accessing the reef.

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APPENDIX

Table A1. Total number of colonies surveyed at each site over time for disease. Colonies in SB and EB assessed through health transects, colonies in CB and Western SB assessed through random swims.

Month	**Site**	**Plating *Acropora***	***Montipora***
Dec-20	EB	NA	61
	SB	NA	69
Apr-21	EB	24	86
	SB	27	112
Apr-22	Cem	43	NA
	EB	50	74
	SB	57	80
Sep-22	Cem	51	40
	EB	67	105
	SB	52	118
Dec-22	Cem	46	52
	EB	39	129
	SB	47	110
Mar-23	Cem	64	57
	EB	64	107
	SB	55	117
	West SB	37	60