Norfolk Island Lagoonal Reef Ecosystem Health Assessment 2023-2024

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Executive Summary

In late 2023, increasing sea surface temperatures across the South Pacific and Eastern Australian reef systems underpinned predictions of widespread coral bleaching for the Great Barrier Reef Marine Park, Coral Sea Marine Park and Temperate East Marine Park network, including the Norfolk Marine Park. Anomalously high sea surface temperature consistent with the accumulation of coral bleaching conditions were evident in the Norfolk Marine Park from December 27th 2023. Observations of coral bleaching were recorded in March 2024 with bleaching rates on inshore reefs peaking during March to April 2024. The most severe bleaching conditions for Norfolk Marine Park on record to date occurred in the summer of 2023/24 with a peak of 13 degree heating weeks (0-20 scale for bleaching severity, over 8 indicates high risk for coral mortality). Coral bleaching events with degree heating weeks above 8 are linked to coral mortality and reductions in coral cover on reef ecosystems. Subsequent surveys of the inshore reefs of Norfolk Marine Park in May 2024 indicated rapid coral recovery across the reef and limited evidence for coral mortality, as a result of the 2024 bleaching event.

Parks Australia contracted long-term monitoring program of the Norfolk Marine Park inshore lagoonal coral reefs ecosystems from March 2020 to May 2024 provides records of coral and coral reef health and assessment of indicators of ecosystem change within the marine park (including rates of coral disease, coral cover, algal populations and cover and indicators organisms including urchins, crustose coralline algae and ascidians). Coral disease rates have remained high within the inshore reefs and at levels consistent with severe outbreak rates. Diseases, including white syndromes, tissue loss and coral tumours remain at the highest rates on record for coral reefs in Australian Marine Parks. The inshore marine park also continues to record seasonally high rates of algal populations linked to reef decline and inshore pollution, including red cyanobacteria and *Lyngbya*, alongside multi-year trends of increasing algal cover on the reefs. Urchin populations have been found to increase in 2024 following previous years of low populations, and coral recruitment remains active into the inshore reefs indicating capacity for recovery of the populations where drivers of ecosystem decline, particularly inshore runoff, sedimentation and herbivore harvesting, are removed.

Coral Reef Management Recommendations

Water Quality Improvements for Inshore Reef Ecosystems. The connectivity between land and inshore coral reefs is known to influence the resilience of coral reef ecosystems. As such, connecting catchment and reef management practices is increasingly a focus of inshore marine management. Knowledge-sharing between communities, stakeholders, management agencies and scientists is key to driving the catchment to reef connectivity for better ecosystem outcomes. High disease rates in corals are widely linked to poor water quality. Ongoing severe disease outbreaks in the Norfolk Island lagoonal coral populations indicate the need for continued water quality and benthic health monitoring for Emily Bay and Slaughter Bay. The prevalence, severity and evidence for disease spread in these lagoons suggests that movement and retention of water impacted by land-based sources is likely to be maintaining ongoing disease outbreaks in the primary habitat for corals of the bays.

Ongoing Monitoring of Reef Health Metrics and Ecosystem Structure. Assessment of coral health and benthic structure outside the lagoon is needed to provide comparison of health metrics at sites with less land-based connectivity. Ongoing monitoring of coral health and algal cover of inshore lagoons is also needed to determine coral disease rates, the impact of disease and bleaching to inshore coral populations, and coral recruitment into areas currently impacted by high algal cover occurs. Coral recruitment demonstrates that connectivity within the reefs remains with the potential for recruitment of corals to the bays as water quality improves and benthic competition with fast growing algae reduces. The trend of increasing turf algae cover across the bays indicates an ongoing shift to higher algal cover across the reef, which will limit future coral recruitment and survival of recruits.

Continued Lagoonal No Take Zones. Evidence of increasing urchin populations in Cemetery Bay suggests that maintaining a no-take zone for the inshore reefs of Cemetery Bay, Emily Bay and Slaughter Bay can aid restoring high populations of herbivores to the inshore bays, particularly where and when, terrestrial anthropogenic inputs are minimized.

Community Outreach and Engagement. Engagement with local communities is now recognised as an effective way to make effective and long-term positive outcomes for environmental management. Throughout the 4 years of the current monitoring program there has been a dedicated effort to engage with local stakeholders on island, through public presentations, school outreach and presentations to specific organisations such as the Norfolk Island Flora and Fauna Society. It is recommended that this, or a similar program continue, to inform the local community on on-going issues and management responses for Emily and Slaughter Bay. In addition, it is recommended that education and outreach signage for safe reef practices at, or near, Emily and Slaughter Bay is considered targeting tourist who currently are not targeted by outreach material.

Norfolk Island Coral Reeth Health Project Background

Parks Australia contracted the 2023/2024 lagoonal coral reef ecosystem health project as part of the long-term monitoring program of the Norfolk Marine Park in response to predictions of coral bleaching during the summer period. Climate model predictions indicated sea surface temperatures (SST) would reach conditions consistent with wide scale coral bleaching across Australia's east coast coral reef areas, including Lord Howe Island, the Solitary Islands, Norfolk Marine Park, the Great Barrier Reef and Coral Sea. Surveys continued those used for the long-term monitoring program (LTMP) (see LTMP reports 2020/21, 2021/22, 22/23), in addition to undertaking Rapid Health Surveys and coral disease surveys (as per LTMP reports 202/21, 2021/22, 22/23). Reef wide surveys were conducted prior to the onset of anomalous sea surface conditions in December 2023 (referred to as pre-bleaching baseline), again in March 2024 to coincide with predicted peak sea surface temperatures (referred to as bleaching record) and again in May 2024 following reduction in heat stress and prior to onset of winter conditions (referred to as post-bleaching mortality record). Benthic surveys were conducted to characterise the extent of coral bleaching and any coral mortality in Emily, Slaughter and Cemetery Bays.

Coral bleaching occurs when SST exceed the long-term summer maxima by only 1-2 ºC. This elevated temperature leads to a dysfunction between the coral host and the intracellular symbiotic algae, referred to as coral bleaching. Under elevated temperatures symbiotic algae are expelled from the coral host tissues as a stress response of the coral animal, as the algae provide much of the colour to the coral, the coral colony then appears to pale and whiten as the underlying coral skeleton becomes visible and increasing proportions of algae are lost. The symbiotic algae provide the host corals with much of the nutrient supply and a significant loss of this algae population (coral bleaching) is associated with starvation of the coral host which can result in mortality of the coral colony. Where sea surface temperatures are extremely high the coral animal can also begin to die due to extreme heat exposure (Leggat et al., 2019). The mortality of corals on reefs is then associated with a weed-like increase in growth of turfing and macro-algae which overgrow the coral colonies, which can result in the reef ecosystem losing coral cover for extended periods of time (Adam et al., 2022). A high proportion of weed-like algal growth on a reef dominates the benthic space and can prevent coral recruitment to the area (Ilsa et al., 2006). Where coral cover has reduced, and large weed-like algae have established, the capacity for the ecosystem to return to habitats dominated by corals is therefore substantially reduced.

Sea surface temperature conditions are used by NOAA for regionally explicit (~5 km^2) bleaching predictions, the extent (time period) and severity (temperature above long term summer average) are used together as a metric of bleaching severity. Referred to as degree heating weeks (DHWs), this metric provides a scale from 0, no stress, when 4 DHWs are reached coral bleaching is normally seen, while at 8 DHW mortality often begins to occur. Much like scale severity of cyclones and storms, a scale of bleaching severity provides a basis from which bleaching events can be predicted, assessed, and later compared (Hughes et al., 2018; Kayanne, 2017). On the Great Barrier Reef DHW reached a peak of 15.5 during the bleaching event of 2024 (NOAA Coral Reef Watch). The Norfolk Island Regional Station (https://coralreefwatch.noaa.gov/product/vs/gauges/norfolk_island.php) provides regularly updated coral bleaching predictions for the Norfolk Marine Park, in 2020 a DHW of 10.7 was associated with lagoon wide coral bleaching (Ainsworth et al., 2021) while in the 2024 event a DHW of 13.7 was reached.

Parks Australia commissioned long-term monitoring program (LTMP) of the lagoonal coral reef ecosystem of Norfolk Marine Park that began in March 2020, providing 6 monthly assessments and annual State of the Reef Reports for the lagoonal reefs of Norfolk Island, Norfolk Marine Park. LTMP assessments cover the period of the previous 2020 bleaching event and inshore flooding events of 2020 and 2021, resulting in a detailed baseline assessment of the reefs' coral diversity, coral cover, macro-algal diversity, macro-algal cover, crustose coralline algae, invertebrate associations (ascidians, urchins, anemones) and coral disease (prevalence and severity).

Coral Reef Health Assessment

Assessment of ecosystem condition of the inshore lagoonal reefs of Norfolk Island was conducted via long-term monitoring of coral cover and algal cover (including *Lyngbya* and red cyanobacteria (Red CB)) and ecological indicators of responses to changing environmental drivers including rapid algal growth, coral disease, coral recruitment, crustose coralline algal (CCA) cover, urchin abundance, and ascidian cover from 2020 to 2024. Assessing coral bleaching responses during anomalous sea surface temperature was also undertaken in both 2020 and 2024. Environmental drivers and organismal/ecosystem responses can be linked in an ecological framework that summaries these interactions (Figure 1.).

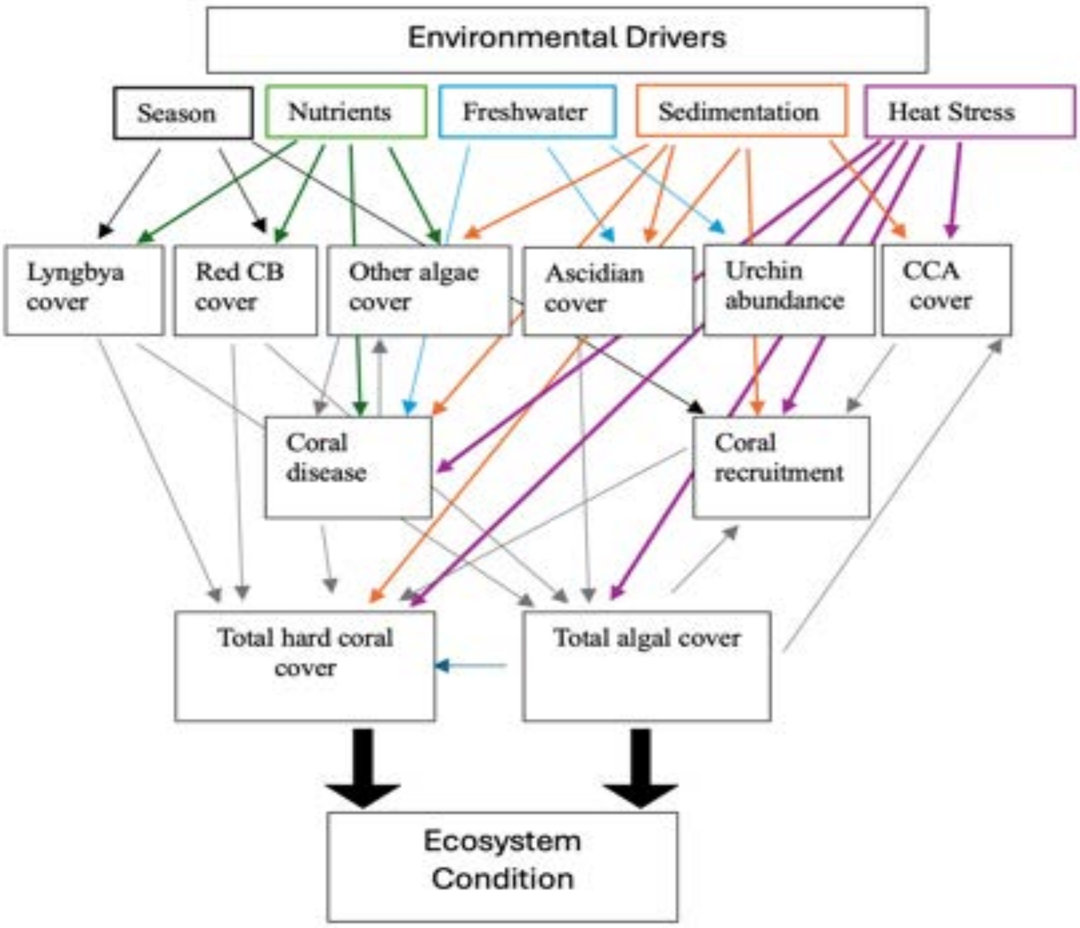
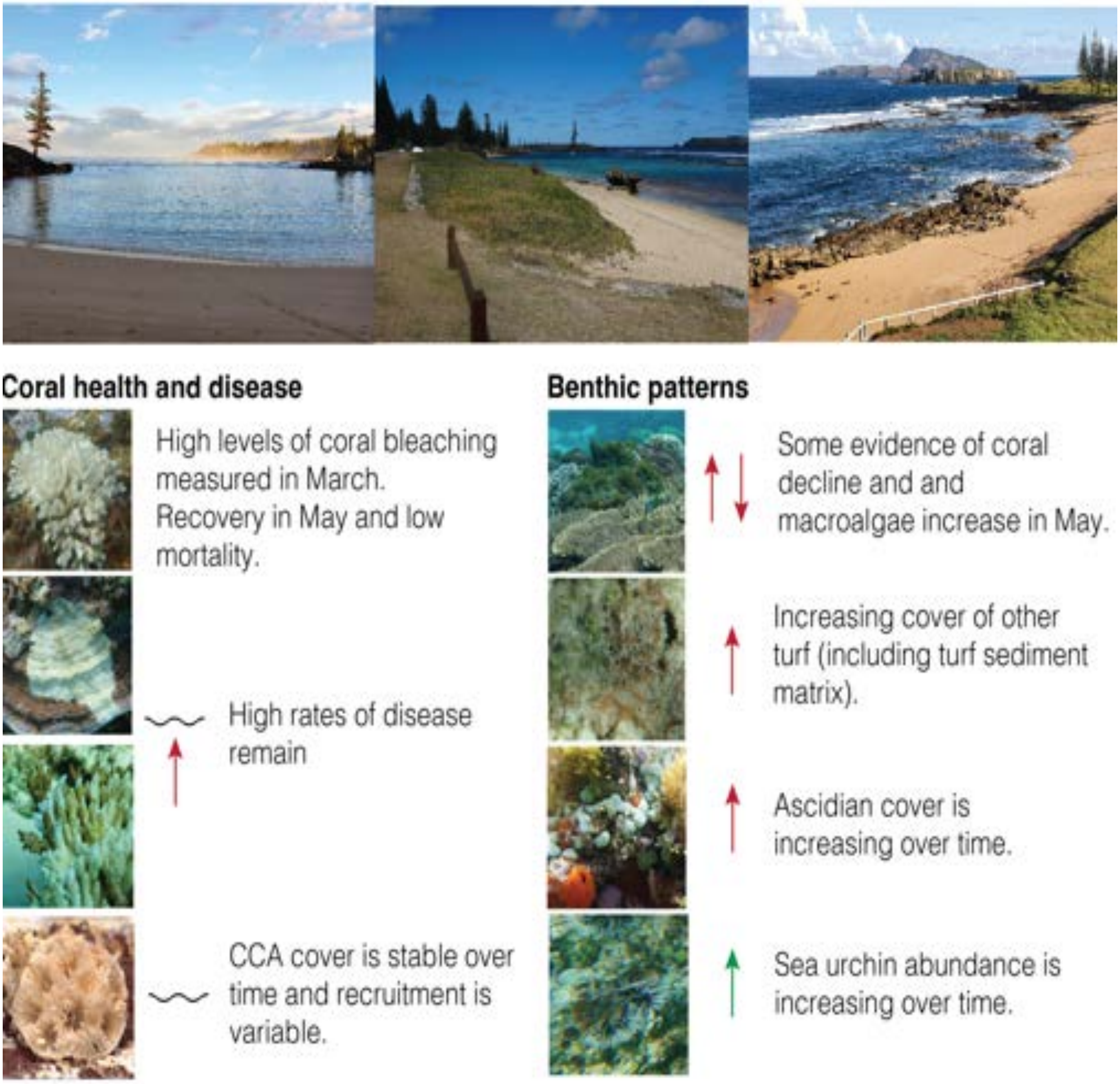


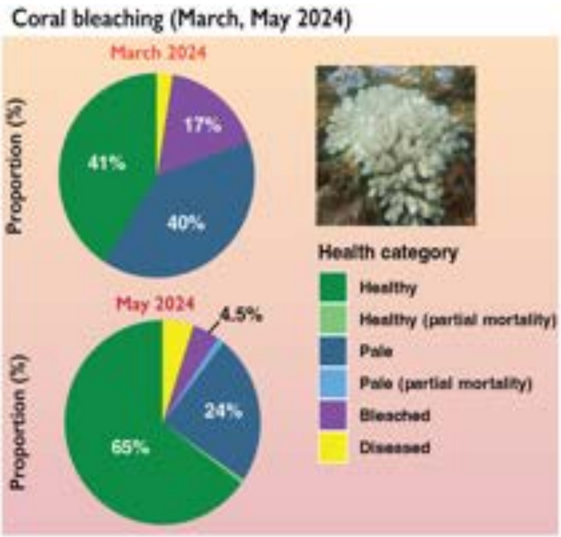
Figure 1. Ecosystem framework indicating environmental drivers of change.

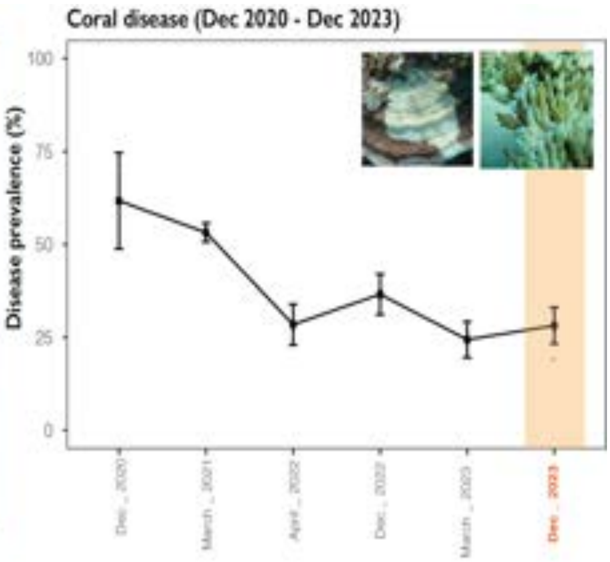
Norfolk Marine Park Inshore Reefs

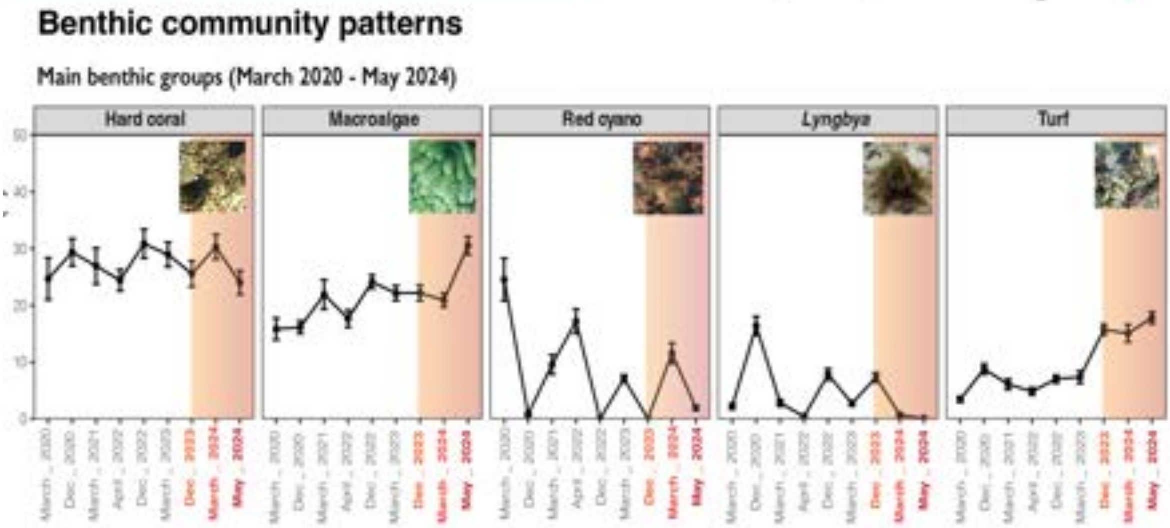
Report Card May 2024

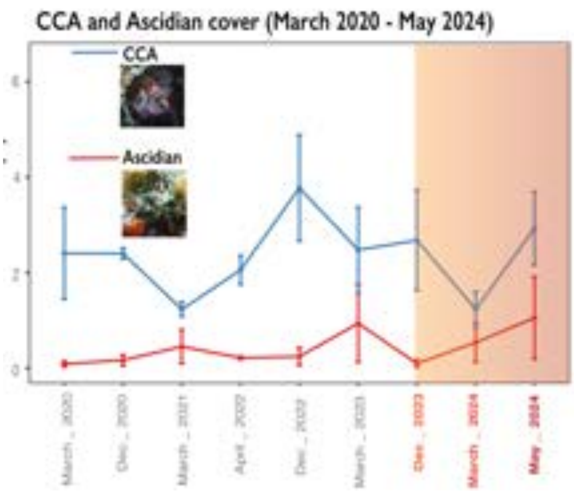


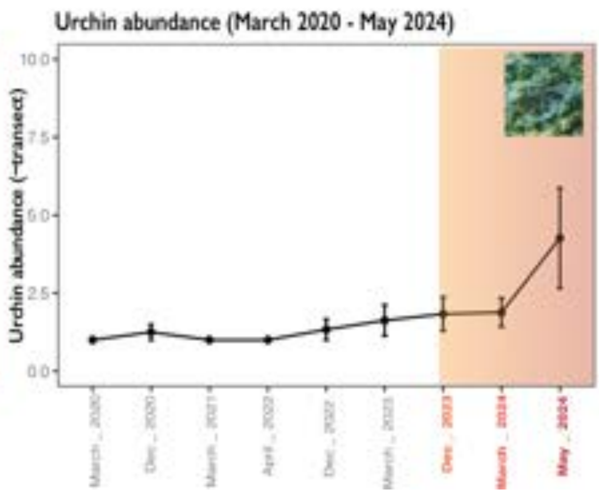
Trends in Reef Health Metrics for Norfolk Marine Park 2020-24



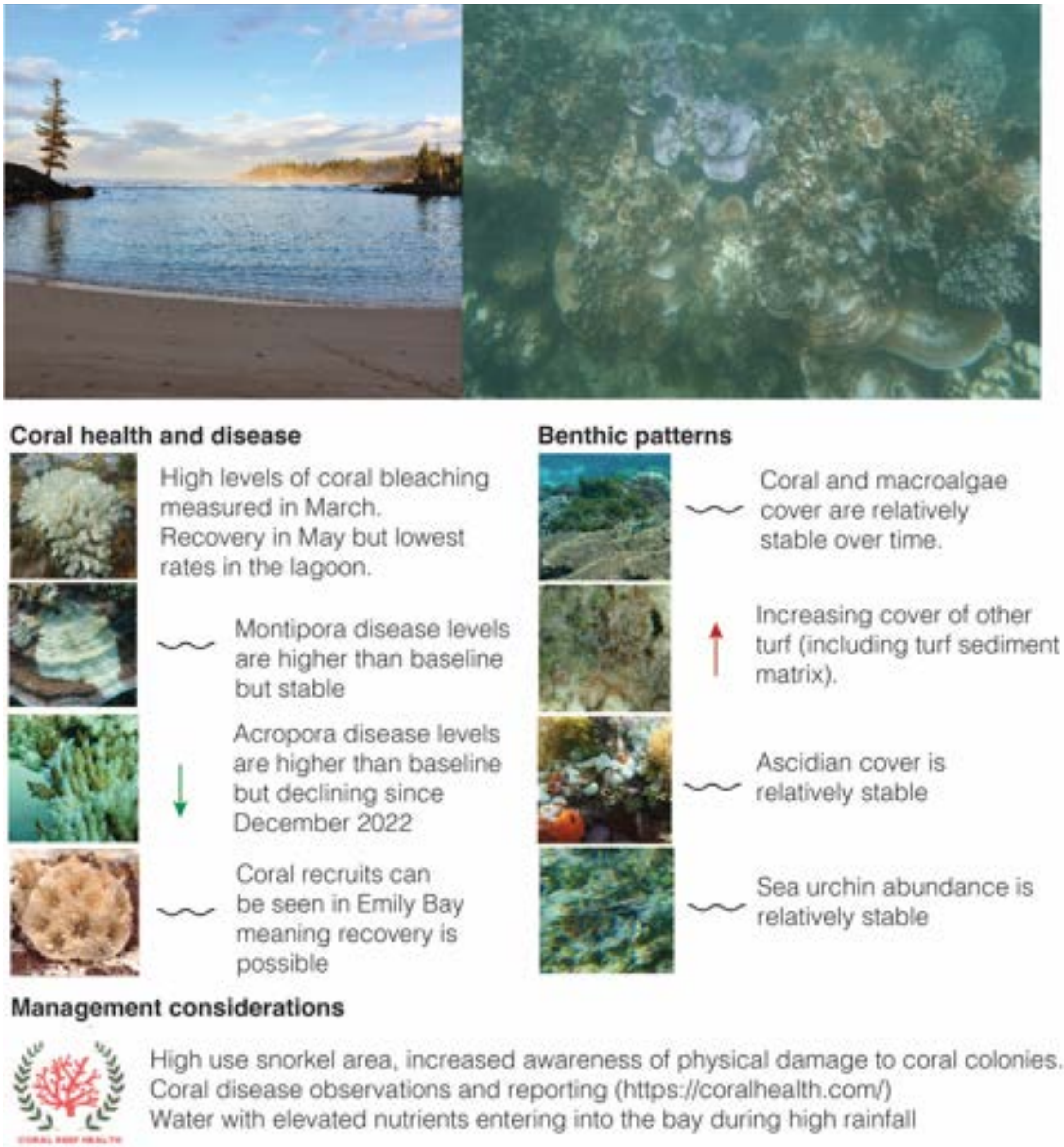




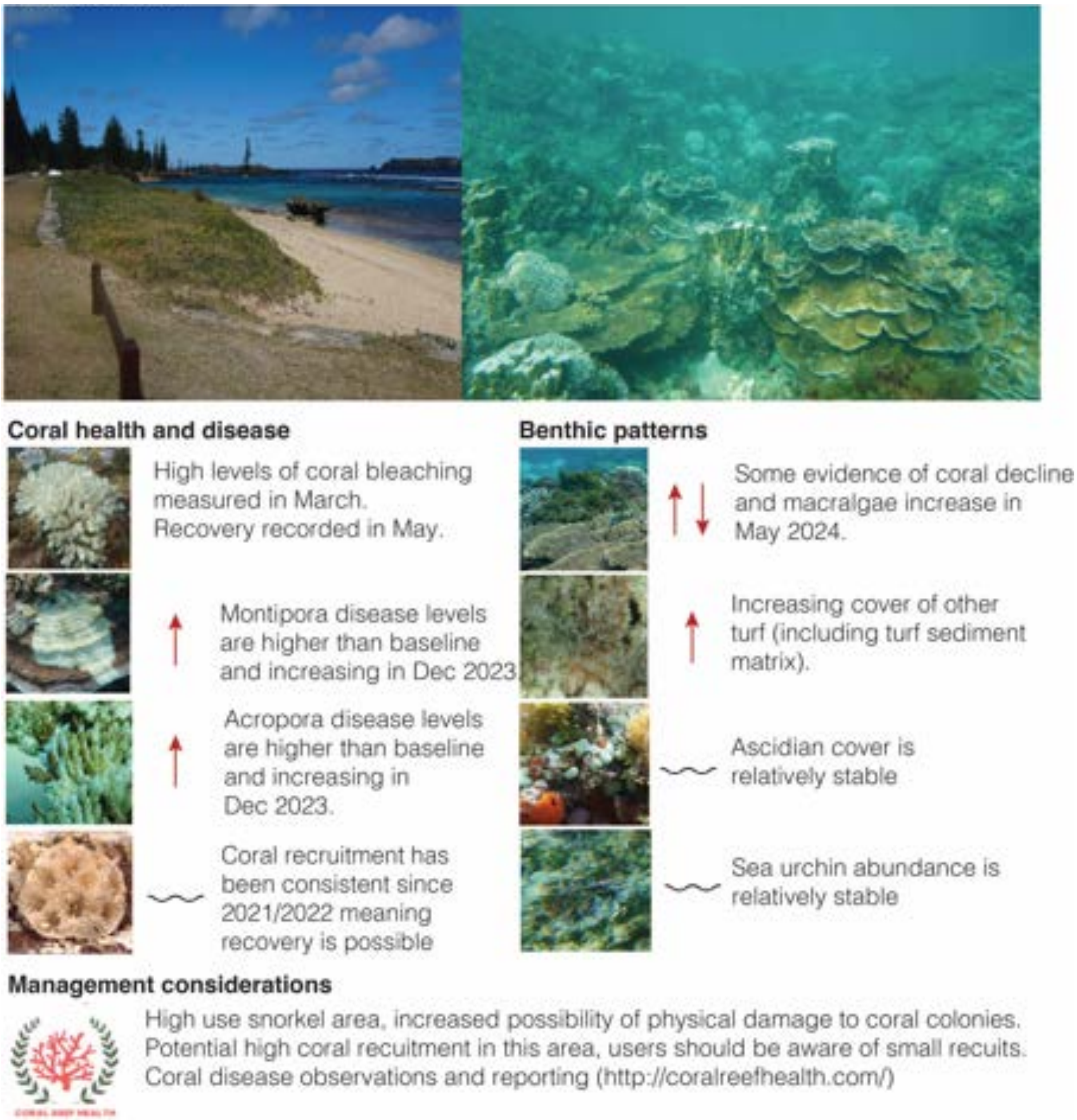




Reef Heath Status Report Card Emily Bay May 2024

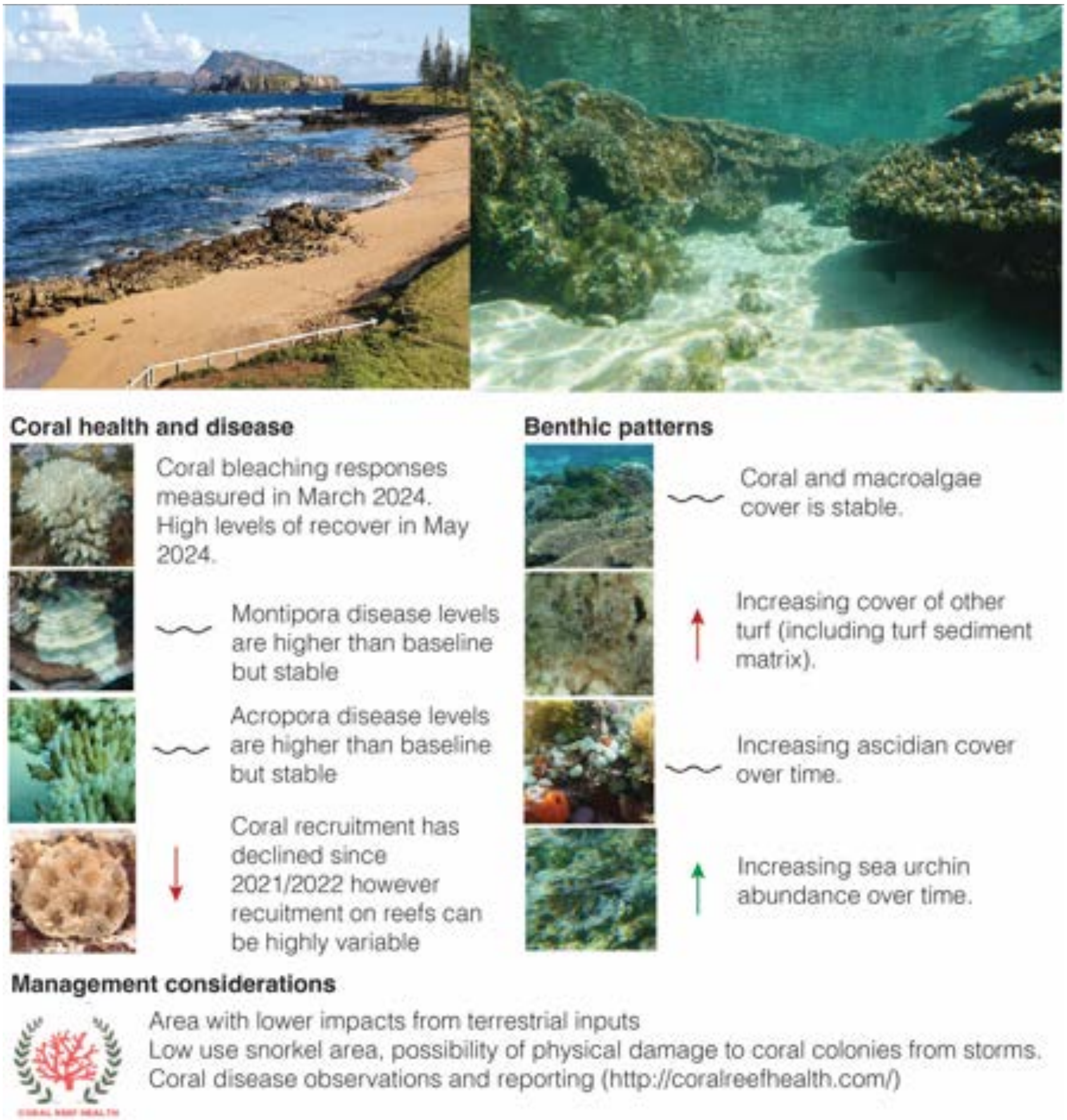


Reef Health Status Report Card Slaughter Bay May 2024



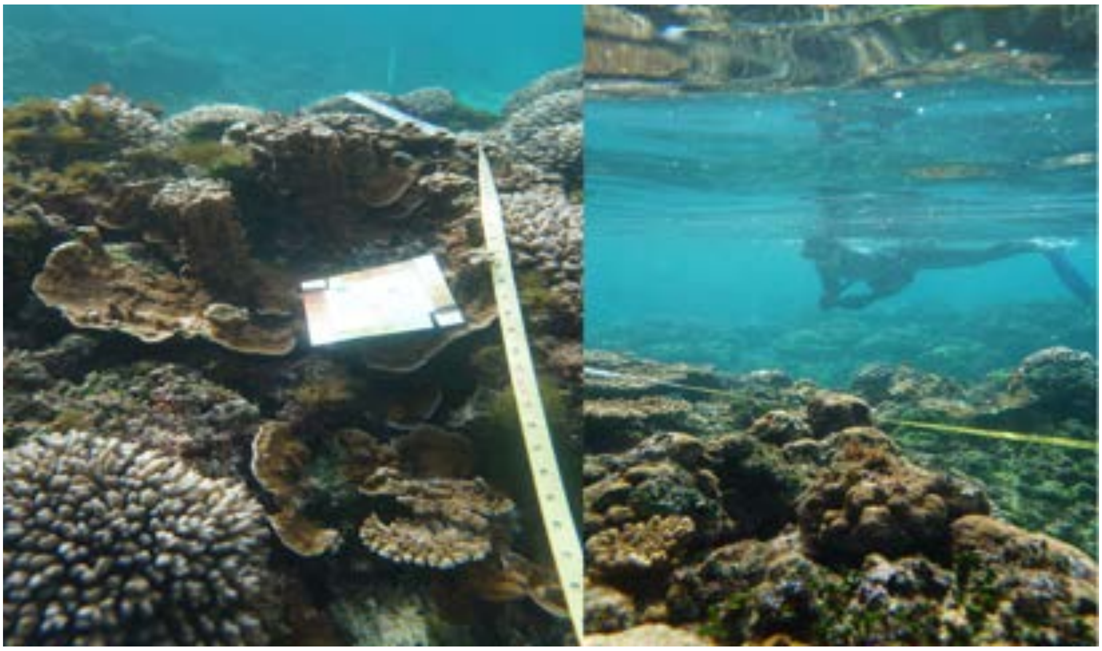
Reef Health Status Report Card Slaughter Bay (West) May 2024

Reef Health Status Report Card Cemetery Bay May 2024



Coral Health Monitoring Program Aims 2024

1. Undertake baseline coral and reef health assessment, prior to onset of predicted heat stress and coral bleaching responses, within the lagoonal coral reefs of the Norfolk Marine Park, including Emily Bay, Slaughter Bay, Cemetery Bay.
2. Identify the environmental conditions, in particular sea surface temperature range, that occur over the summer period and influence the extent and impact of coral bleaching within Emily, Slaughter and Cemetery Bay.
3. Undertake Rapid Health Surveys for real-time monitoring of coral health and bleaching during extreme events within lagoonal coral reef ecosystem.
4. Monitor coral taxa specific and within reef specific coral bleaching responses of the inshore lagoonal coral reefs of Norfolk Island, Norfolk Marine Park, including Emily Bay, Slaughter Bay, Cemetery Bay.
5. Assess within reef coral reproductive potential prior to coral spawning and coral recruitment following coral spawning.
6. Undertake benthic community composition surveys of lagoonal coral reef ecosystems of Norfolk Marine Park, including Emily Bay, Slaughter Bay, Cemetery Bay.
7. Undertake outreach and engagement activities associated with each monitoring period to inform Norfolk community of research practices and findings, including providing News articles, student education programs, public presentations with researchers.



Long Term Monitoring Program 2020-24 Aims

1. Assess coral cover, coral composition, algal cover, algal composition of the lagoonal coral reef ecosystems on Norfolk Marine Park, including Emily Bay, Slaughter Bay, Cemetery Bay.
2. Assess environmental conditions associated with occurrence and severity of extreme weather events occurring within the Norfolk Marine Park.
3. Assess occurrence and distribution of indicator invertebrate species including ascidians populations (increasing populations linked to potential pest species and associated within poor water quality conditions) and urchin species (decreasing populations linked to poor water quality and overfishing/harvesting).
4. Assess coral disease occurrence and prevalence within Norfolk Marine Park lagoonal coral reef including Emily Bay, Slaughter Bay, Cemetery Bay.
5. Assess prevalence and distribution of crustose coralline algal within Norfolk Marine Park Inshore coral reefs, linked to coral recruitment potential.
6. Implement and undertake Rapid Health Surveys for real-time monitoring of coral health and bleaching during extreme events within lagoonal coral reef ecosystem

Coral Health Monitoring Program Reef Surveys

Benthic health assessment was undertaken using a variety of different methods, these included Rapid Health Assessment across the bays for coral bleaching (Figure 2), continuation of the LTMP (

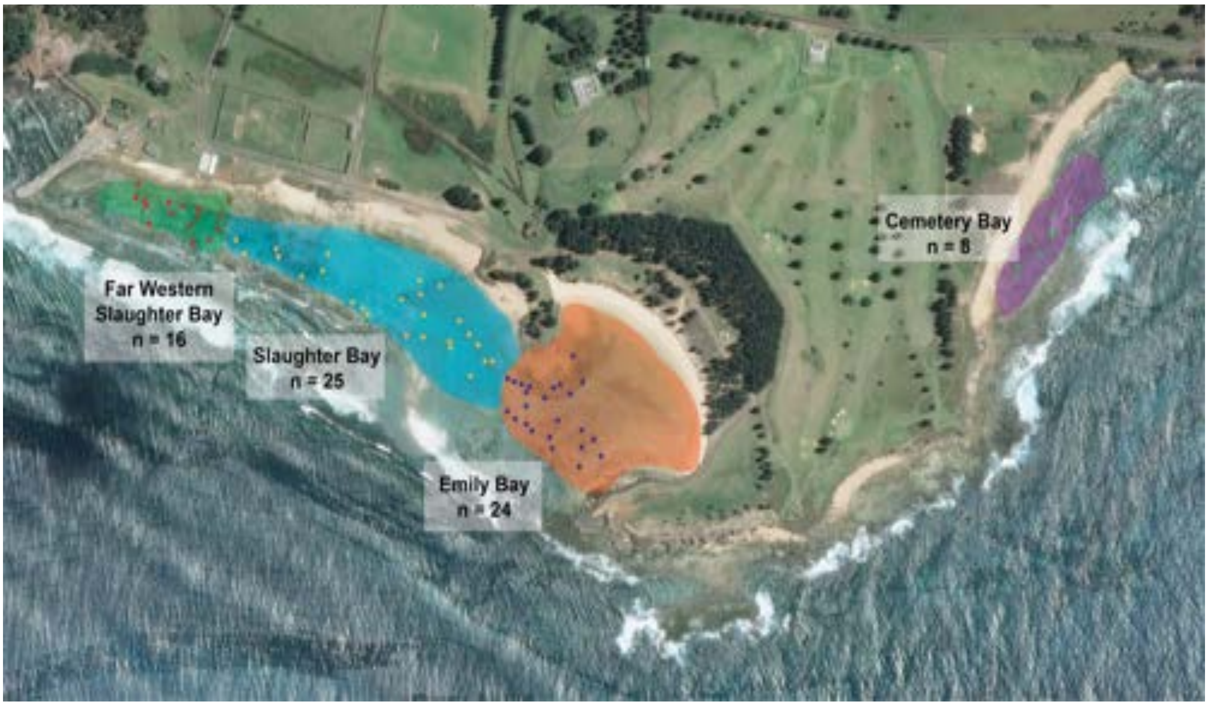


Figure 3), coral disease survey (Figure 4) and coral recruitment survey (Figure 5).

Rapid Health Survey Locations

Figure 2. Rapid Health Survey (RHS) site locations Emily Bay, Slaughter Bay, Far Western Slaughter Bay), and Cemetery Bay. Dots indicate location of surveys.

Benthic Health and Community Composition Survey Locations

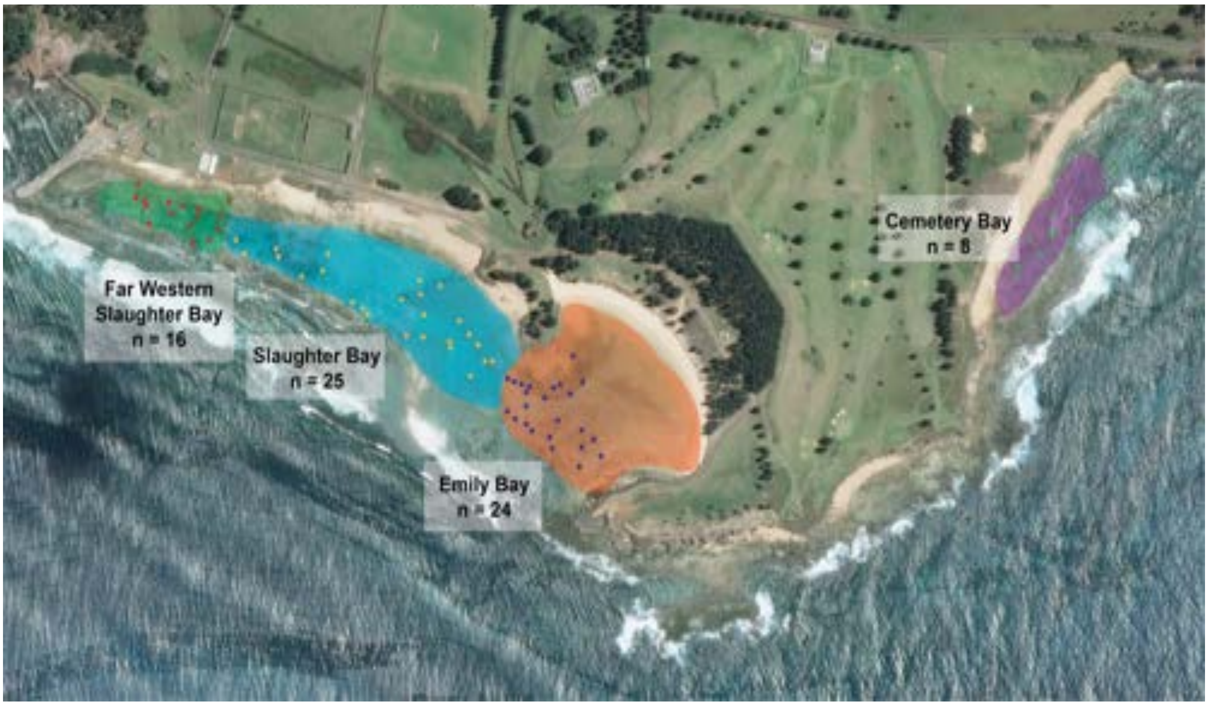


Figure 3. Benthic Health and Community Assessment Survey site locates Emily Bay, Slaughter Bay, Far Western Slaughter Bay and Cemetery Bay. Dots indicate location of surveys.

Coral disease survey locations

Figure 4. Coral Disease Survey site locations Emily Bay, Slaughter Bay, Far Western Slaughter Bay and Cemetery Bay. Dots indicate location of surveys**.**

Coral recruitment 2023 – 2024 Recruitment Tile Placement

Figure 5. Areas coral recruitment tiles were deployed within Emily Bay, Slaughter Bay, Cemetery Bay.

Assessment of Environmental Conditions Summer 23/24

Sea surface temperatures are derived from nighttime satellite records provided regionally through the NOAA website (https://coralreefwatch.noaa.gov/index.php). The Norfolk Island regional station established in 2020 provides SST temperature records from 1980 to current day (https://coralreefwatch.noaa.gov/product/vs/gauges/norfolk_island.php) and predictions for bleaching risk within the Norfolk Marine Park. Predictions of coral bleaching risks in the Norfolk Marine Park during the Austral 23/24 summer period were released from September 2023. SST records from the summer period (Figure 6.) indicates that heat stress began to accumulate on the 30th of December 2023, (reported as DHWs, indicating temperatures one degree above the historic maximum mean temperatures) and where the maximum night-time sea surface temperate in the region of the Norfolk Marine Park temperature recorded was 24.9 °C (

Figure 7. , Figure 8.). In situ temperature loggers have been placed in the lagoonal coral reefs of Norfolk Marine Park since 2020 to provide records of temperature conditions within the lagoon and adjacent to the coral growth (1-3 m depth). In situ temperature records from summer 2023/24 within the Norfolk lagoonal coral reef ecosystems showed that temperatures consistent with heat stress accumulation began 5-days earlier, with anomalous temperatures consistent with accumulation of DHWs recorded from the 25th December 2023 within the lagoon (Figure 8.). These records demonstrate that, consistent with predictions of bleaching risk in the Norfolk Marine Park, anomalously high temperature conditions occurred both across the sea surface and within the water column surrounding the inshore lagoonal coral reef.

SST records of the Norfolk Marine Park over the summer period show that a peak in thermal stress was reached across the region on the 16th of March 2024 at which time DHWs where recorded at 13.7 °C- weeks (Figure 8.). Maximum SST measured across the Norfolk Marine Park on the 16th of March 2024 was a recording of 25.6 °C. *In situ* temperature data from the lagoonal reef however shows that thermal stress within the lagoon reached a peak of 12.6 °C-weeks, an approximate 1 °C-week less than sea surface temperature DHW. This calculation is reflective of slightly lower temperatures at reef depth to sea surface (Figure 8.). The maximum temperature recorded in the lagoon was 25.3 °C, compared to the 25.6 ° C peak of sea surface temperature (Figure 8.). Based on SST records DHWs peaked in March and remained at 13.7 for 7 days before declining to below DHW 8 on 29th April 2024 and below DHW 4 on 20th May 2024. Using *in situ* temperature data from the lagoon DHWs remained above 12 °C-weeks from the 11th of March until the 14th of April 2024 (Figure 8.). The reef wide monitoring period was completed on the 26th of May at which time DHWs had declined to 2 °C-weeks based on SST temperature, however based on lagoonal temperatures DHWs had declined to 5.4 °C-weeks on 21st of May (Figure 8.) indicating a slower reduction in temperature conditions within the lagoon. In general, there was reasonable agreement between satellite derived measures of thermal stress and those recorded from data loggers within the lagoons indicating that satellite derived SST provide a reasonable estimate of in-situ water temperatures at this location. Temperature records across the lagoon indicate within lagoon variation in temperature of up to 0.5 °C which is likely reflecting within reef variation in water flow and mixing (Ainsworth et al., 2021).

A reduction in water temperature from late March 2024 within the Norfolk lagoonal reef was co-incident with a reduction in minimum (overnight) air temperatures within the region (Figure 9.). A peak of both maximum and minimum air and water temperatures between late December and late March was also evident in the bleaching period of 2020 within the Norfolk Marine Park region, however the 2020 cooling conditions were influenced by cloud cover, water mixing and wind associated with Cyclone Gretel. The onset of summertime cooler temperatures in the region, and unique climate conditions of the Norfolk Island region, as compared to regions such as the Great Barrier Reef Marine Park, warrants further investigation to better understand long-term severity of climate induced coral reef degradation to determine regional potential for protections from severe bleaching conditions.

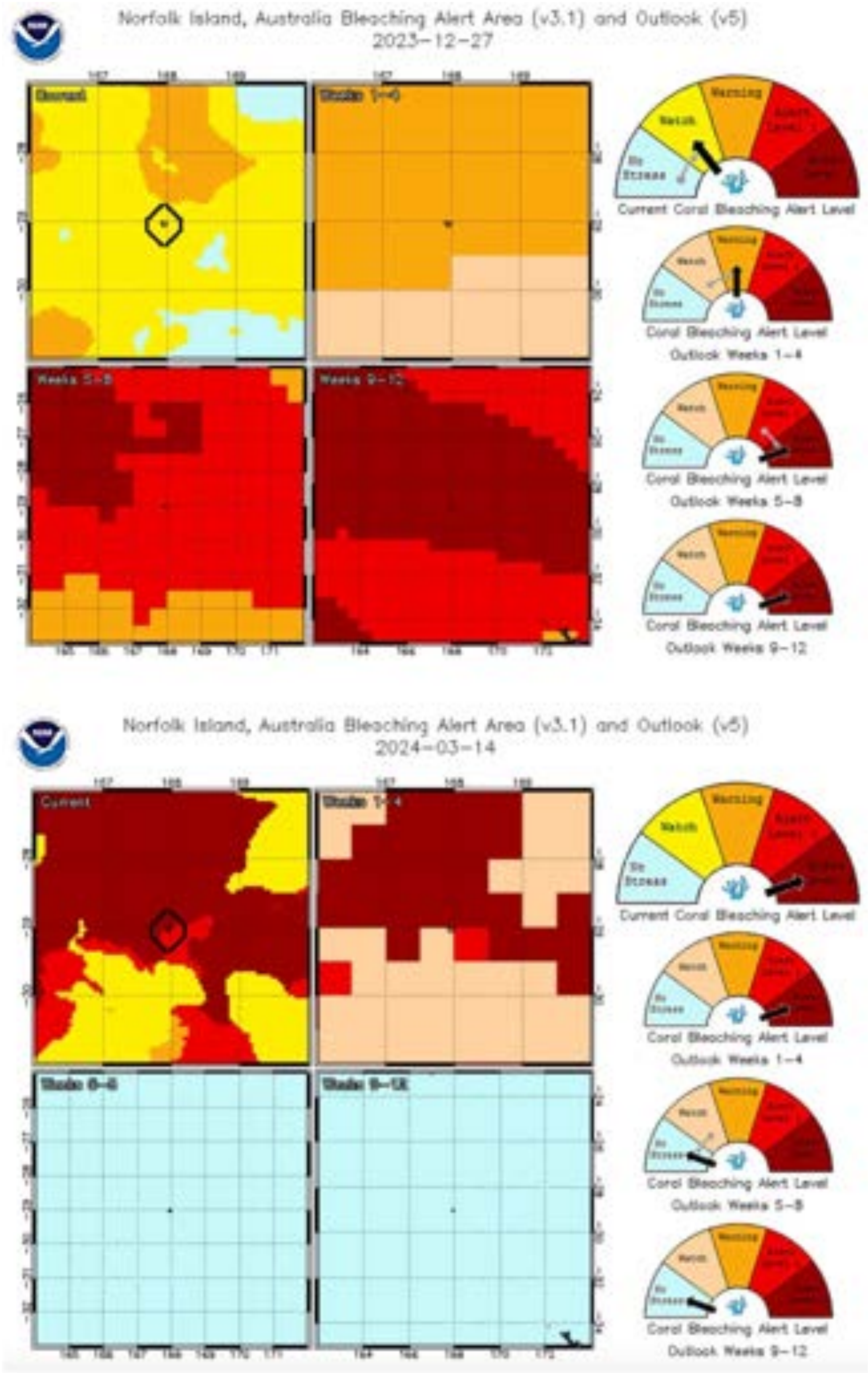


Figure 6. Coral bleaching conditions (top left box) and predictions (1-4 weeks top right, 6-8 weeks bottom left and 9-12 weeks bottom right) based upon climate models for the Norfolk Island Virtual station for (top) 27th December 2023 and (bottom) 14th March 2024.

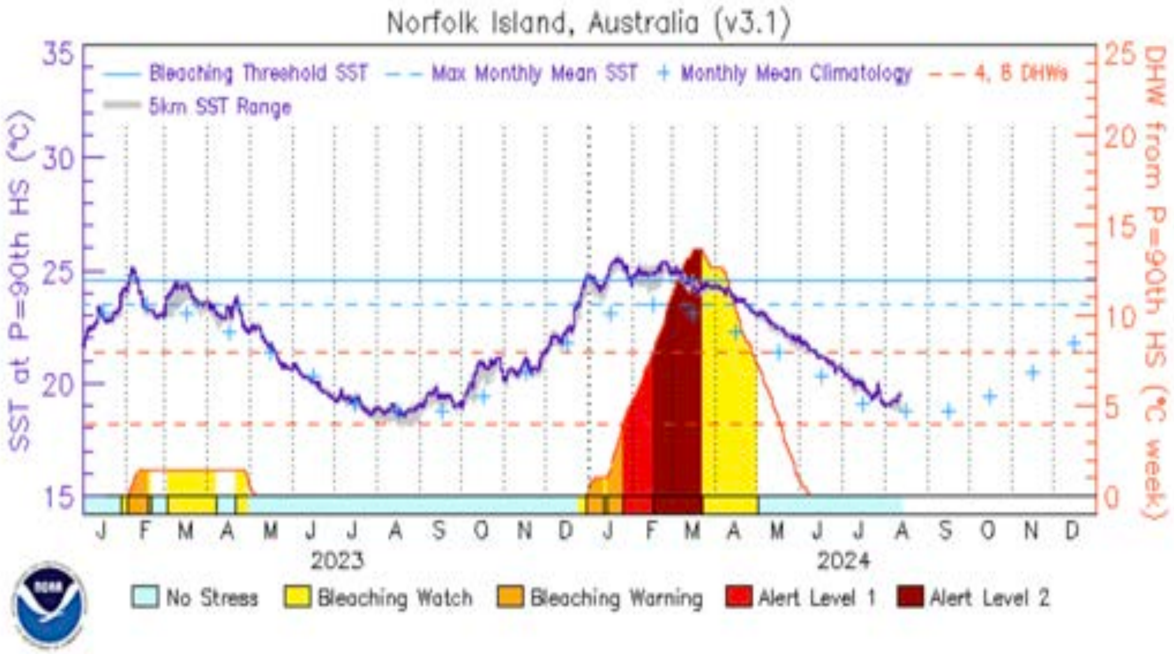


Figure 7. Satellite derived sea surface temperatures (blue line) and accumulated thermal stress (Degree Heating Weeks, DHW) for Norfolk Island from January 2023 - April 2024. Shading represents bleaching alerts. Image and data from NOAA Coral Reef Watch.

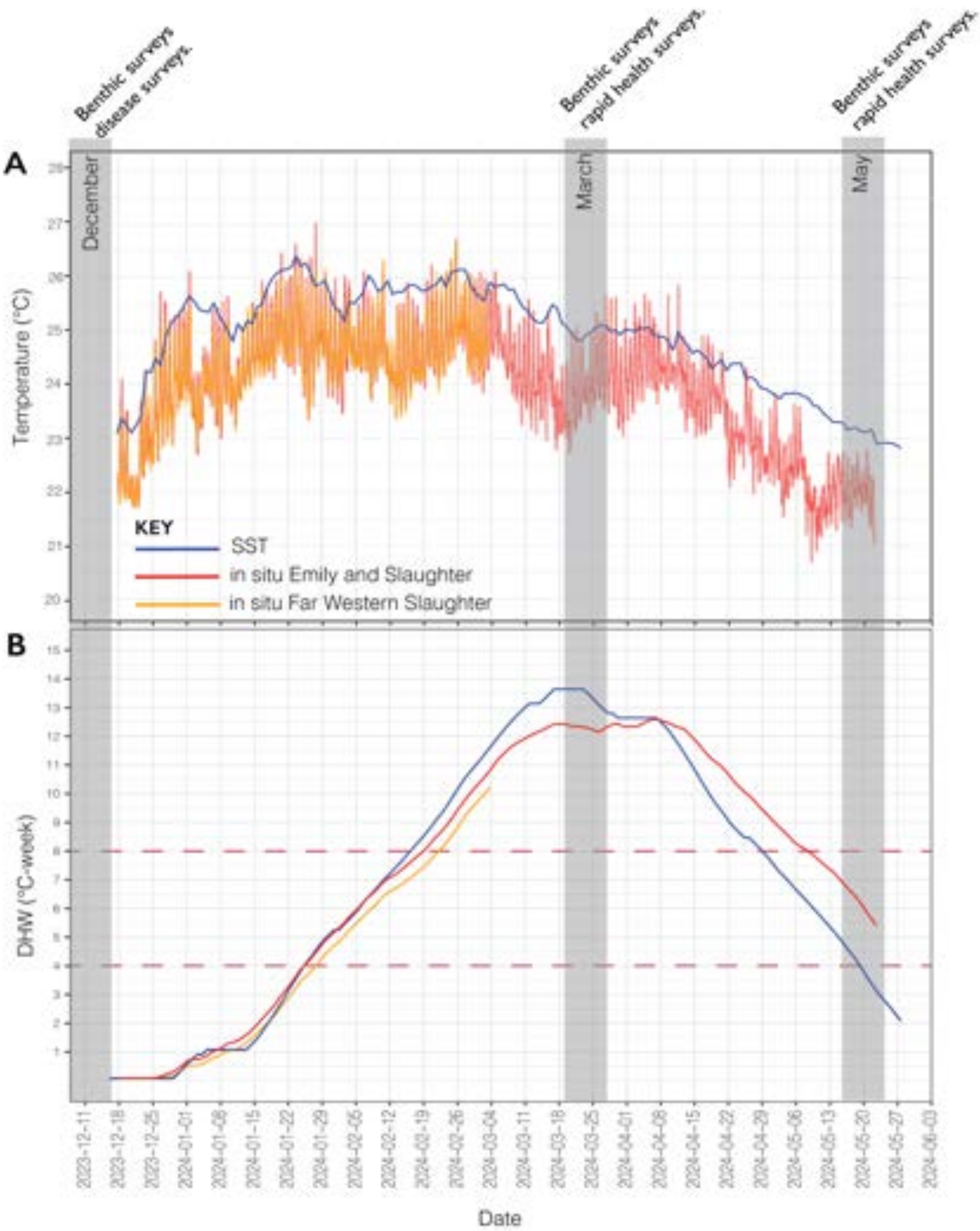


Figure 8. Satellite sea surface temperature (SST, blue line) and in situ temperature data from Emily and Slaughter Bay (red line), and far Western Slaughter Bay (orange line). December 2023 – May 2024 (Top). Heat stress accumulation as Degree Heating Weeks (DHW) calculated using satellite sea surface temperature (blue line) and in situ data from Emily and Slaughter Bay (red line) and far Western Slaughter Bay (orange line). Dotted red lines represent DHW levels over which we expected to see bleaching (DHW = 4) and mortality (DHW = 8) (bottom).

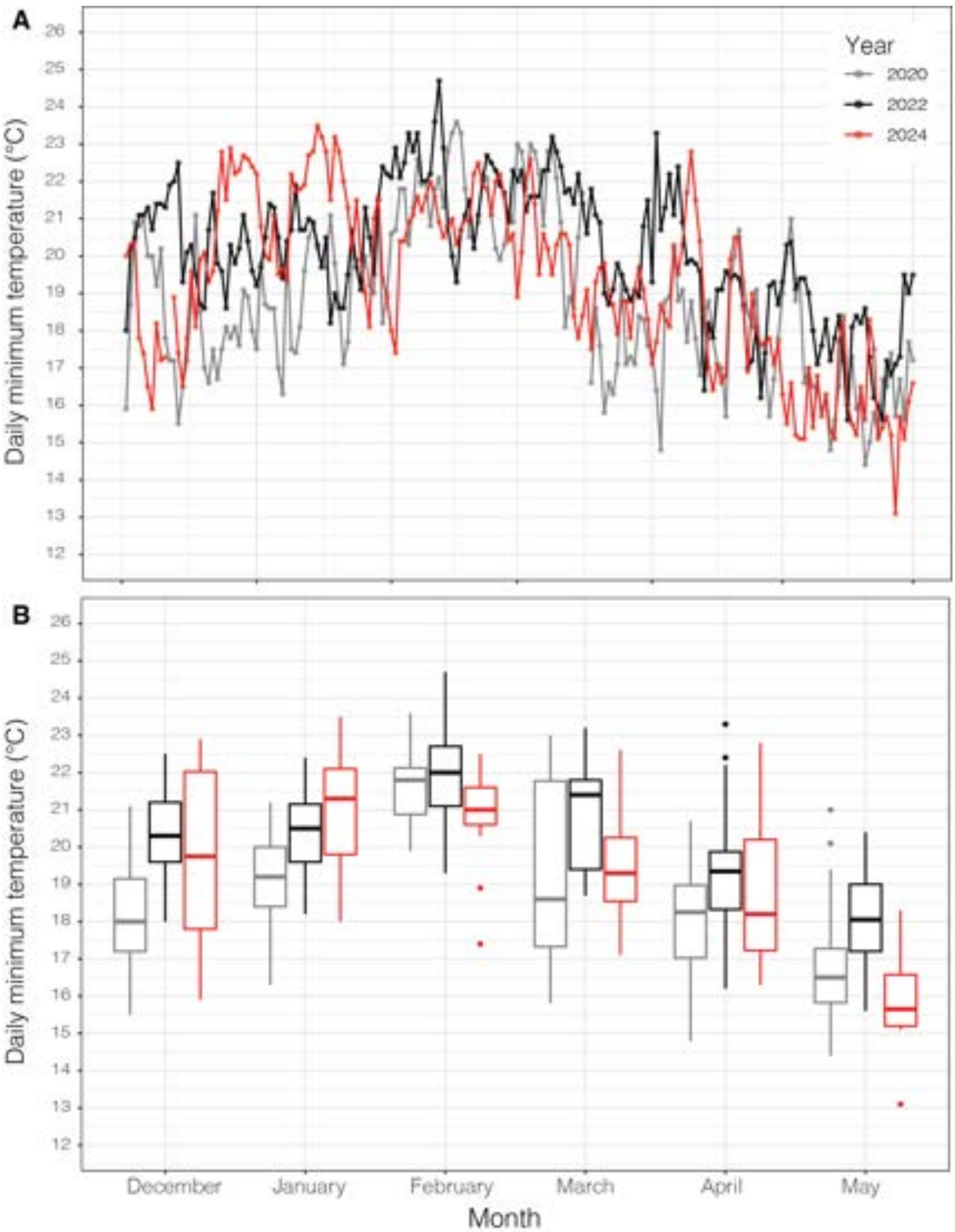


Figure 9. Nighttime minimum air temperatures from Norfolk Island, recorded at the Norfolk Island airport weather station. (A) Daily minima and (B) monthly average.

Fluorescent Whitening Compound Analysis.

Fluorescent whitening compounds (FWC), or optical brighteners, are mainly added to laundry detergents and cleaning agents for brightening fabrics/surfaces. Laundry wastewater is the largest contributor of FWC's to wastewater systems because it retains dissolved whitening compounds. Toilet paper also contains 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 wastewater has several advantages including: detection is nearly instantaneous, the equipment used is relatively inexpensive and large numbers of samples can be analyzed 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, l = 365nm) for 1 minute and then again at 9 minutes, as FWC fluorescent decreases with UV exposure more than natural fluorescence, the difference between the two readings can be used as an indicator of FWC presence . This method is described by Cao et al. (2009).

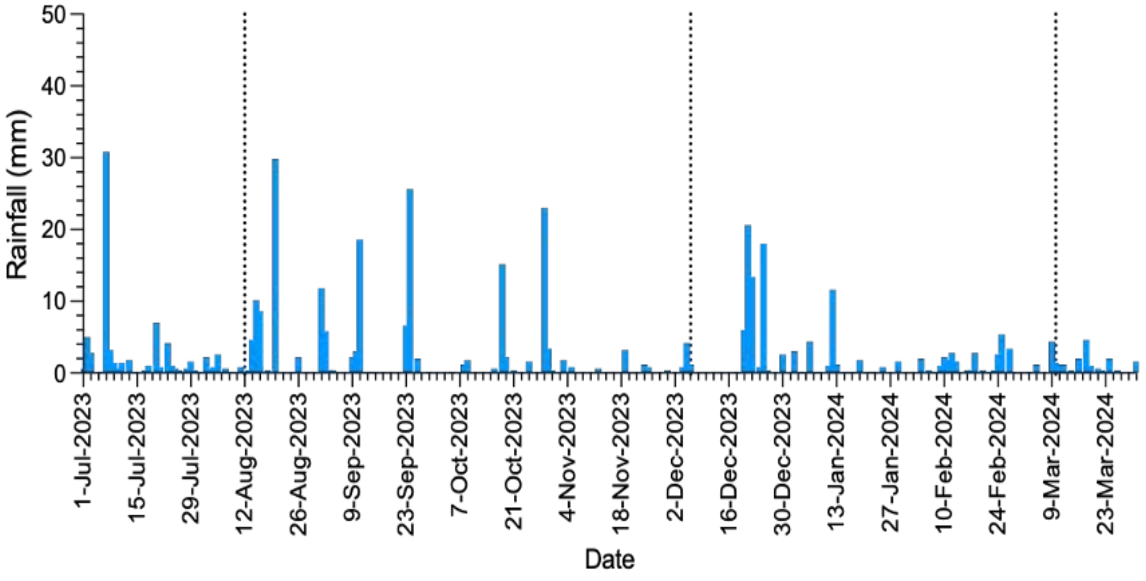


Figure 6. Rainfall recorded at the Norfolk Island Airport Bureau of Meteorology weather station. Dotted lines indicated sampling dates. Data source: http://www.bom.gov.au/climate/data/index.shtml.

Fieldwork was undertaken on 12 August 2023, 6 December 2023 and 10 March 2024 (**Error! Reference source not found.**; **Error! Reference source not found.**). Laundry discharge was sampled on each occasion to provide a baseline for the presence/absence of FWCs. Fieldwork did not occur after major rainfall events yet FWC's were reported at sites in Watermill Ck in August (

Figure 11.) and December 2023 (Figure 12.), however not in March 2024 (Figure 13.) when there had been an extended period of low rainfall (Figure 10). FWC have previously been detected after periods of heavy rainfall on Norfolk Island using this approach (Leggat et al., 2023).Creeks at Cascades and Bomboras also reported FWC presence in the absence of rainfall. Furthermore, the creek that flows under Country Rd (near the Taylors Rd intersection) tested positive for FWC's on each sampling occasion.

Table 1. Fluorescent whitening compound (FWC) presence/absence at sites on Norfolk Island. Red = present, clear = not present, grey – not sampled. * for Watermill Ck, see figures showing sites where FWC's were detected.

Site	12 Aug 2023	6 Dec 2023	10 Mar 2024
Laundry discharge	Red	Red	Red
Septic	Grey	Grey	Grey
WAS	Grey	Grey	Grey
Watermill Ck*	Red	Red	
EB1 (Emily Bay – near outlet)			
EB2 (Emily Bay)			
EB3 (Emily Bay)			
SB1 (Slaughter Bay)			
SB3 (Slaughter Bay)			
SB5 (Slaughter Bay)			
Officers Bath			
Cemetery Bay			
Cascades Wharf			
Cascades Ck	Red	Red	
Bomboras			
Bomboras Ck	Red		Red
Country Rd (creek under road)	Red	Red	Red
Headstone (creek under road)	Red		

Figure 11. Sampling sites showing presence (large yellow circle) or absence (yellow crosses) of FWC’s for 12 August 2023.

Figure 12. Sampling sites showing presence (large yellow circle) or absence (yellow crosses) of FWC’s for 5 December 2023.

Figure 13. Sampling sites showing presence (large yellow circle) or absence (yellow crosses) of FWC's for 10 March 2024.

Assessment of Coral Bleaching Responses 2024.

Assessments for coral bleaching were conducted in March and May 2024 applying a **rapid health survey (RHS)** method to provide real-time assessment of reef health (see Figure 2). Rapid health assessments consisted of 20 m line intercept transects (3 x in each of EB salt house, EB back reef, SB East, SB West, SB far West and Cemetery Bay) with a 20m x 1m belt surveyed by counting and classifying all coral colonies according to the morphotype and health categories listed below. RHS provides a proportion (%) of health categories overall and per morphotype and site and is useful for management as it provides a rapid assessment of reef health.

Assessment of coral colour and health category was conducted following the Coral Watch coral health chart (wherein each colour square provides an estimate of the concentration of symbiotic algae within the coral tissue). The Coral Watch chart was developed for coral colours across tropical reef locations and is applied cautiously to the subtropical corals of Norfolk Marine Park where the chart provides benchmarking for paling and bleaching in coral colonies within and between sites. Photo quadrats from benthic surveys were also analysed for coral health using the Coral Health Chart. Analysis of these images gives % cover of health categories for each morphotype.

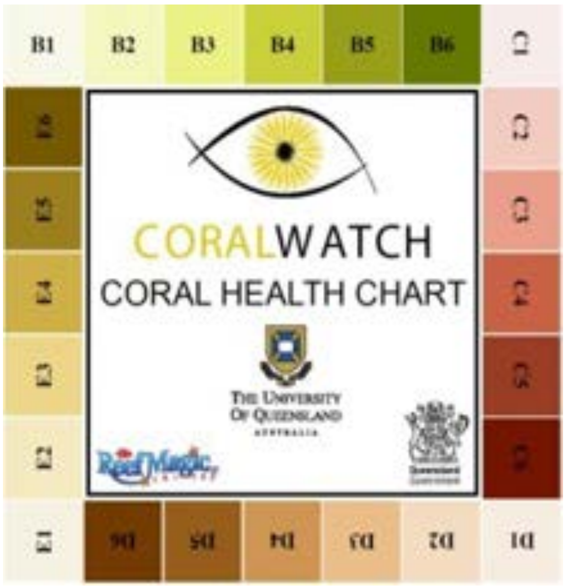
Coral Watch coral health charts were used to record severity of paling and bleaching. Colour is coral genera and morphotype specific with coral colors ranging from browns, greens, reds. The Coral Watch coral health chart is not suitable for use with purple and blue coloration corals, where recording colors in purple and blue Montiporid corals of the Norfolk lagoon coral colours were recorded as dark purple or light/pale or white.

SCORE

1 - indicates complete bleaching,

2 and 3 - indicates paling,

4, 5 and 6 - indicates healthy coral colour



Coral health and Colour Categories

Healthy = tissues look visibly healthy with normal pigmentation (brown)

Pale = pale or light fluorescent pigmentation compared with normal (healthy) colour

Diseased/unhealthy = non-uniform pigmentation changes (i.e. white band, black band, white spots or patches with distinct margins)

Patchy bleaching or paling = Coral colony will begin to pale and bleach in gradients of colour across a coral colony (i.e. not all uniform white). The colony shows a patchy response (including health/pale patchy tissue and pale/bleached patchy tissue).

Recently dead partial mortality = white skeleton still visible with signs of green algal colonization or pale brown biofilm, oxygen bubbles on surface of the colony indicating a biofilm formation (see Figure 7)

Dead = skeleton visible but grey/dark and colonized by slow growing benthic organisms including large macro-algae, ascidians, crustose coralline algae, sponges etc.

Across all reef sites rapid health survey indicated that morphotypes most impacted at peak bleaching temperatures (March 2024) were:

- Pocilloporidae (30.6% bleached and 55.6% pale),
- *Porites* (32.3% bleached and 44.3% pale) and
- primary reef building *Montipora* (6.5% bleached and 41.3% pale).

Primary reef building Acroporids were found to be tolerant to heat stress within the lagoonal reef, with no signs of bleaching observed and only 11 % of branching growth forms showing signs of paling. A similar result was found in surveys of bleaching at Norfolk Island in 2020 (Ainsworth et al., 2021).

In May 2024 the patterns of bleaching tolerance between morphotypes were sustained, with overall the total proportion of colonies pale or bleached declining, indicating coral recovery. For example, there was a 66 % decrease in bleached Pocilloporidae colonies in May compared to March 2024, whilst the proportion of healthy colonies increases by 178%. We observed similar recovery patterns in *Porites* and *Montipora*. Results of the rapid health survey also indicate variation in bleaching responses across the lagoonal reef sites. The region of Emily Bay Salt House was found to have the highest proportion of bleached (18.5 %) and pale (35 % colonies) in March 2024, followed by eastern Slaughter Bay (18.5 % bleached and 27 % pale colonies) and far western Slaughter Bay (14.5 % bleached and 41.5% pale colonies) (Figure 8). Bleaching and paling rates between 12% and 41.5% was found at all surveyed reef sites, including Cemetery Bay.

In May the proportion of healthy colonies increased at all reef sites indicative of a rapid recovery from bleaching across the lagoon sites and also Cemetery Bay (Figure 8). The highest rate of increase in healthy colonies was recorded in far Western Slaughter Bay, where the total proportion of healthy colonies increased by 92.8%, from 42% of the community being healthy in March to 81% in May 2024 (Figure 8). The lowest recovery rate of 22.7% was measured at the salt house region of Emily Bay, where 57.7% of colonies were measured as being healthy in March and 70.8% in May 2024 (Figure 8). Full mortality of coral colonies measured in May 2024 was very low (< 5%) and only noted at one site, back reef Emily Bay in *Platygyra* taxa. However, bleaching responses in *Platygyra* were low (3.2% pale in March 2024 and 7.3% in May 2024, Figure xA) indicating that this mortality is unlikely related to bleaching. Low levels of partial mortality (< 5.5%) were observed in pale colonies in May 2024 at Emily Bay Salt house, Slaughter Bay middle and Slaughter Bay west (Figure 8, Figure 9 Figure 10).

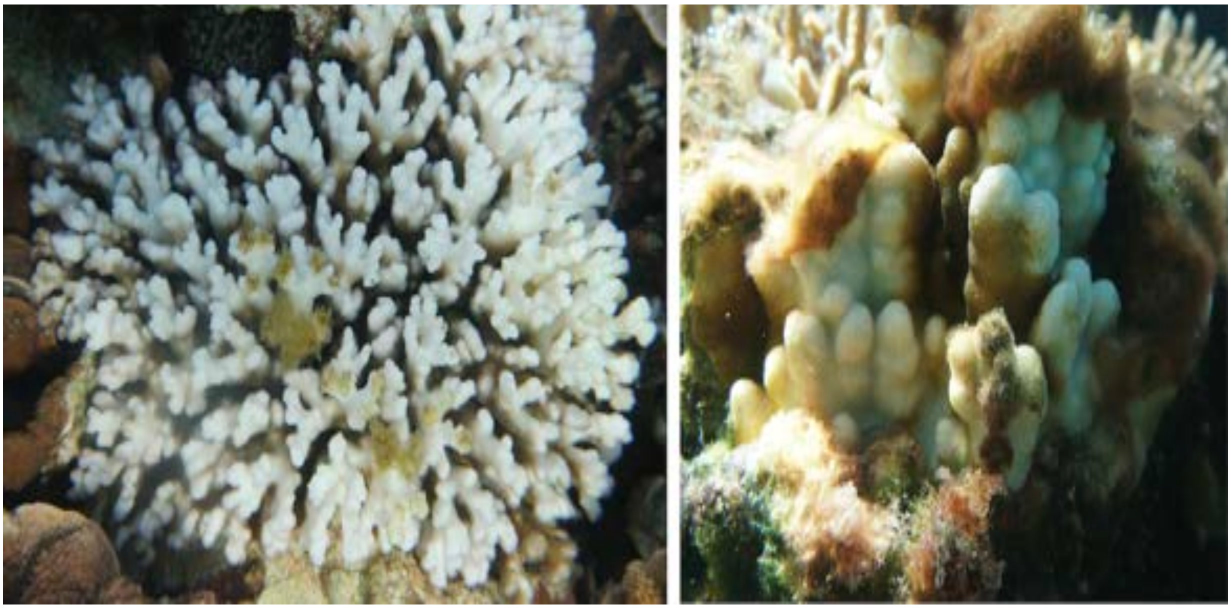


Figure 7. Photographs of partial mortality indicated by overgrowth of coral skeleton by microalgae (i.e. turf algae) evident in (Left) a bleached *Pocillopora* colony, and (right) partially bleached *Porites* colony.

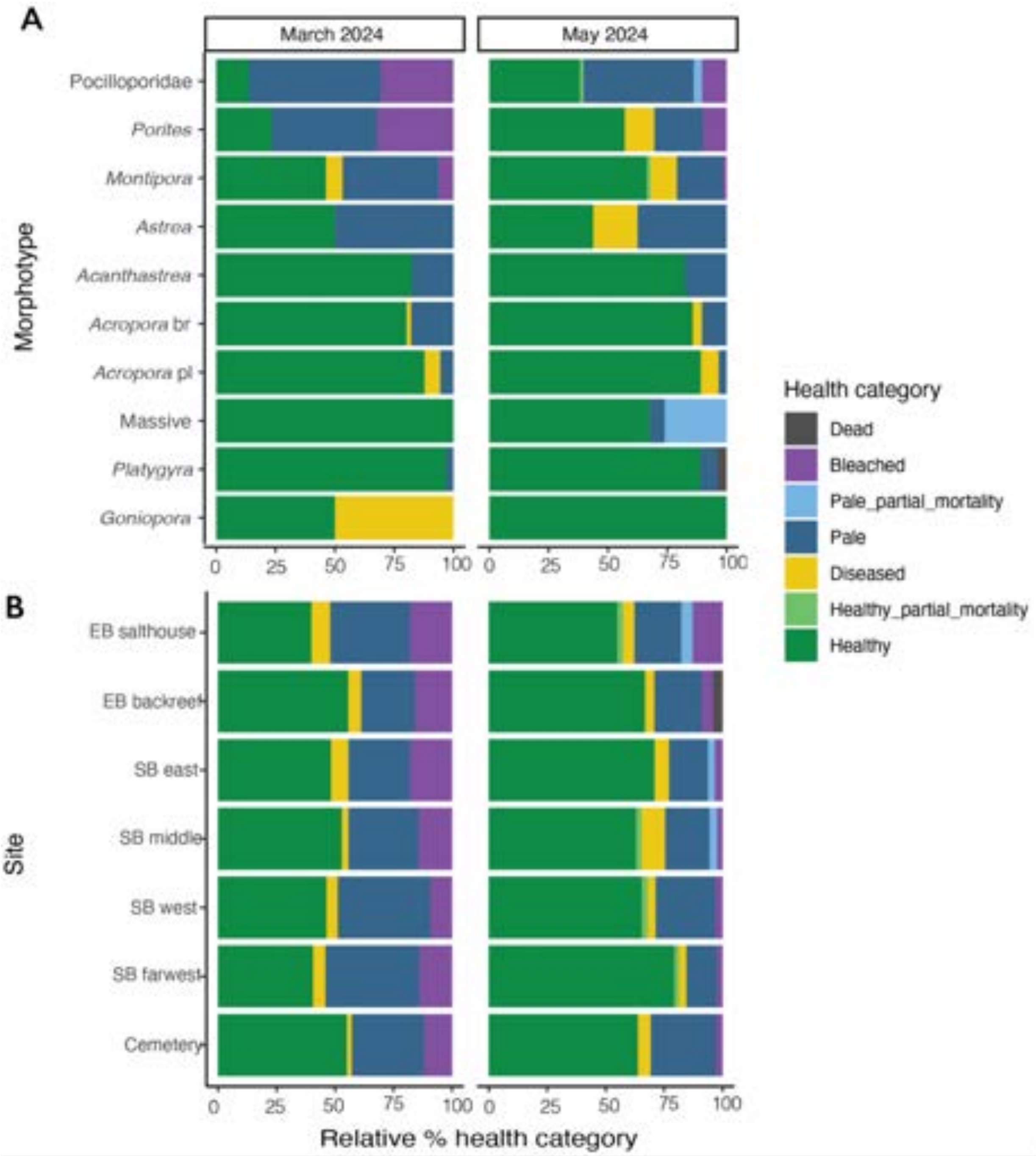


Figure 8. Coral health categories from rapid health survey undertaken at reef sites in March and May 2024. Stacked box plots show the relative proportion of health categories across (A) Morphotype at all sites and (B) across site.

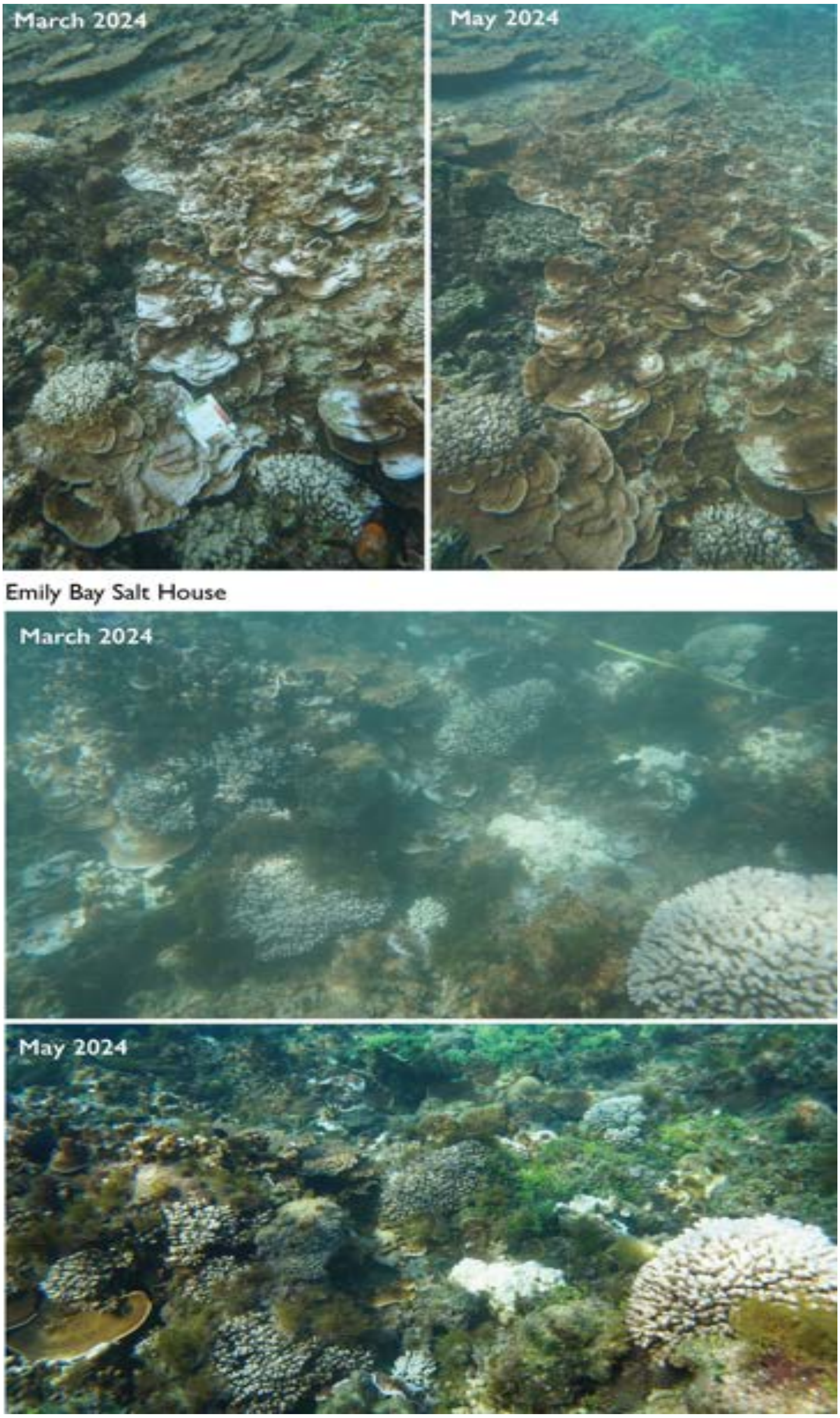


Figure 9. Photographs of the same reef area in March and May 2024. Bleaching recovery can be seen in some colonies (darker colour) while other remain bleached (e.g., bottom right corner). An increase in algal growth in May 2024 can also be seen.

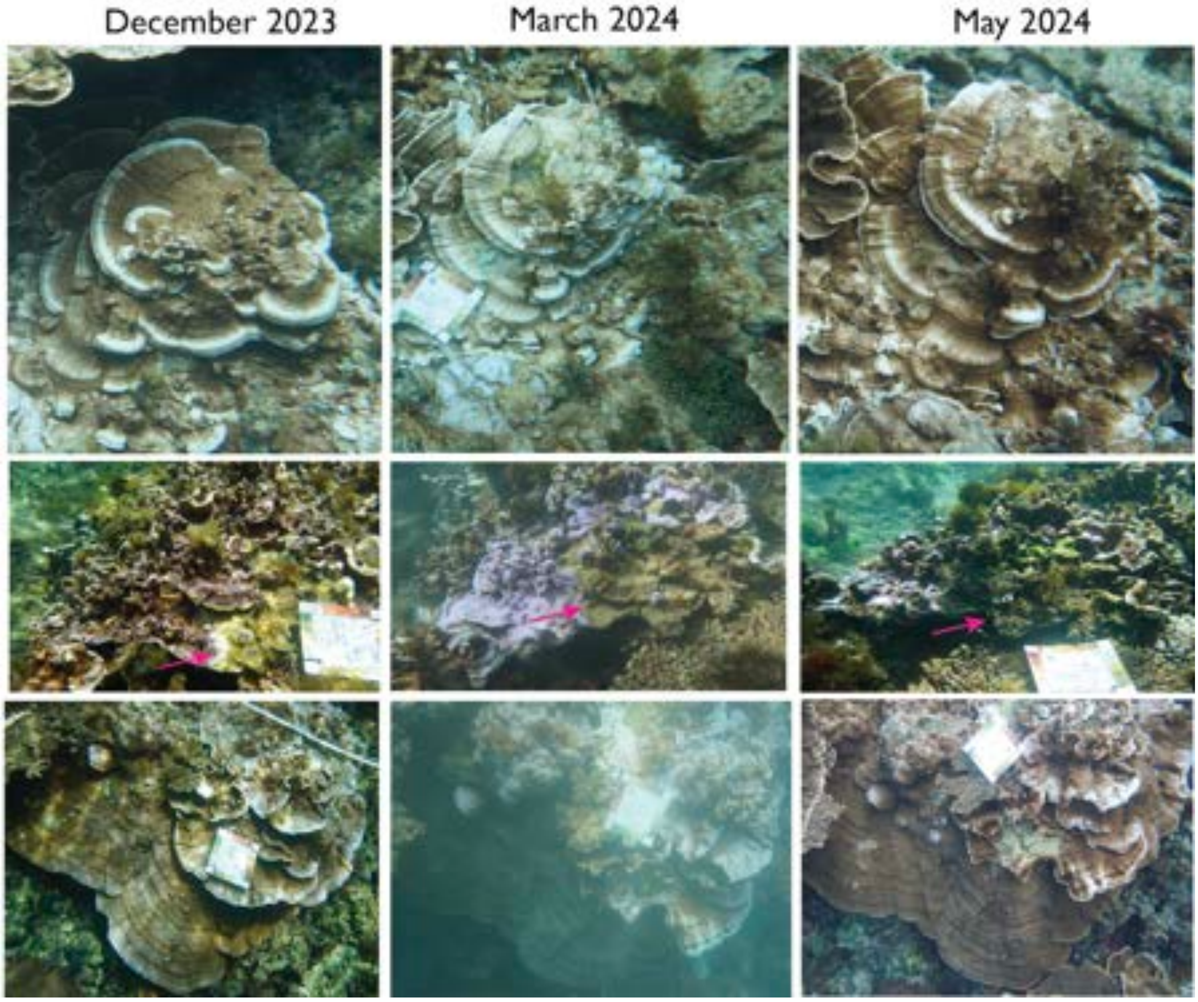


Figure 10. Photographs of the same *Montipora* colonies (in each row) over time from December 2023 – May 2024. Varying responses are evident, from recovery of brown colour after bleaching in March 2024 as shown by the top and last row. The colony in the middle row is shown to suffer from disease in December 2023 (see red arrow). This colony then suffers severe bleaching in March 2024 and diseased tissue transitions to mortality (red arrow). This colony is still pale and tissue mortality has been overgrown by macroalgae in May 2024.

Assessment of Benthic Community Composition Health Categories.

Following the established **LTMP program design** benthic surveys were conducted in March 2024 and May 2024 to provide taxa and site-specific assessment of coral bleaching responses and potential coral mortality. This approach provides a more comprehensive analysis of coral bleaching rates and changes in the benthic community structure than the rapid health assessments. Benthic surveys consisted of 24 x 10 metre belt transects in Emily Bay and 27 x 10 metre belt transects Slaughter Bay (

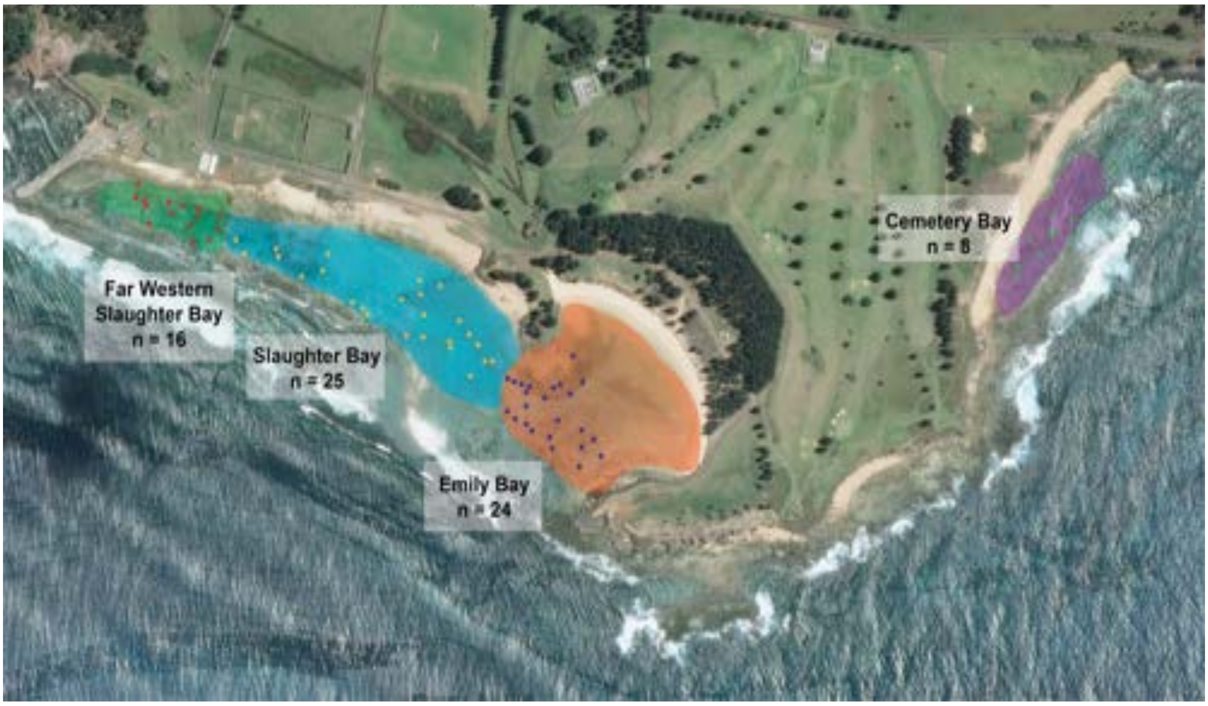


Figure 3), within each transect (10 m), 10 photographs were taken (TG-6 Olympus underwater camera) at 1 m increments using a 0.5 m^2 photo quadrat to standardize the area (n = 10 photos $transect^{-1}$). The resulting photos were analysed using the online platform *CoralNet* (https://coralnet.ucsd.edu) applying a grid of 100 points per photo for annotation. A standardised label set was used as per LTMP 2020-24 with data generated for benthic community cover and composition. Labelset includes; *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., with each taxa recorded for health categories. Resulting cover was summed across each transect so that each category is described as the % cover $transect^{-1}$. Undertaking coral health assessment of

LTMP survey provides a more robust and detailed record of coral bleaching impacts than the RHS which is designed as a management tool for near real-time indications of bleaching impacts and to inform the implementation of detailed coral health assessment.
There was significant variation in coral paling, bleaching and recovery patterns between sites. In March 2024, analysis of photo quadrats showed that all sites had bleached or paling corals (Figure 11, Figure 12) however bleaching was not severe as bleached coral cover was only above 1% of the total benthic community at Emily Bay Salt House (Figure 12). All sites also had cover of pale coral colonies, with the highest total benthic cover of pale coral cover recorded at 15.21% in Slaughter Bay West (Figure 12F). Cemetery Bay had the second highest rate of pale corals (5.8 %). At all sites in March 2024 there was also coral cover recorded as partially pale or partially bleached (Figure 12A).

In the subsequent surveys in May 2024 coral recovery was evident across all sites. Total cover of healthy coral increased in Emily Bay Salt House, Emily Bay back reef and Far Western Slaughter Bay. The greatest increase in healthy coral cover was observed in Far Western Slaughter Bay (53.2 % increase, from 9.4% of total cover in March to 14.4% in May) (Figure 12G). At Emily Bay Salt House, the percent cover of bleached and partially bleached colonies declined by 74% and 100%, whilst the percent cover of pale increased by 36% from 1.7% cover to 2.4%. This represents a transition from bleached tissue to pale, and from partially pale tissue to healthy (Figure 12). At several sites, the cover of healthy coral cover remained stable in March and May 2024 (see Slaughter Bay East, Slaughter Bay Middle and Slaughter Bay West) (Figure 12). At these sites recovery can be observed through declines in the total amount of bleached, pale and partially bleached and pale colonies. At Cemetery Bay total cover of healthy coral was observed as declining from 26% to 20% (Figure 12). Notably, the percent cover of dead coral cover also increases at Cemetery Bay in May compared to March 2024, the reason for these changes is unclear.

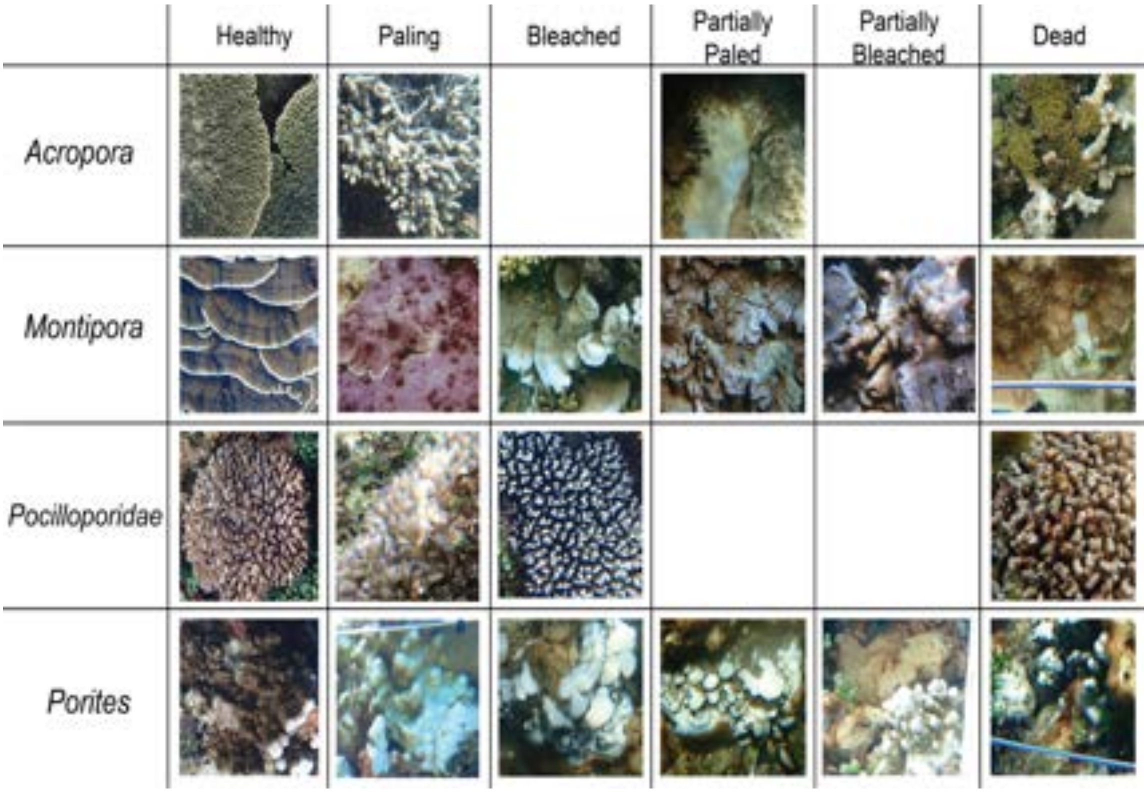


Figure 11. Coral health categories applied to the main genera in CoralNet. Labels in plots below for partially pale is Pale/Healthy and for partially bleached is Pale/Bleached.

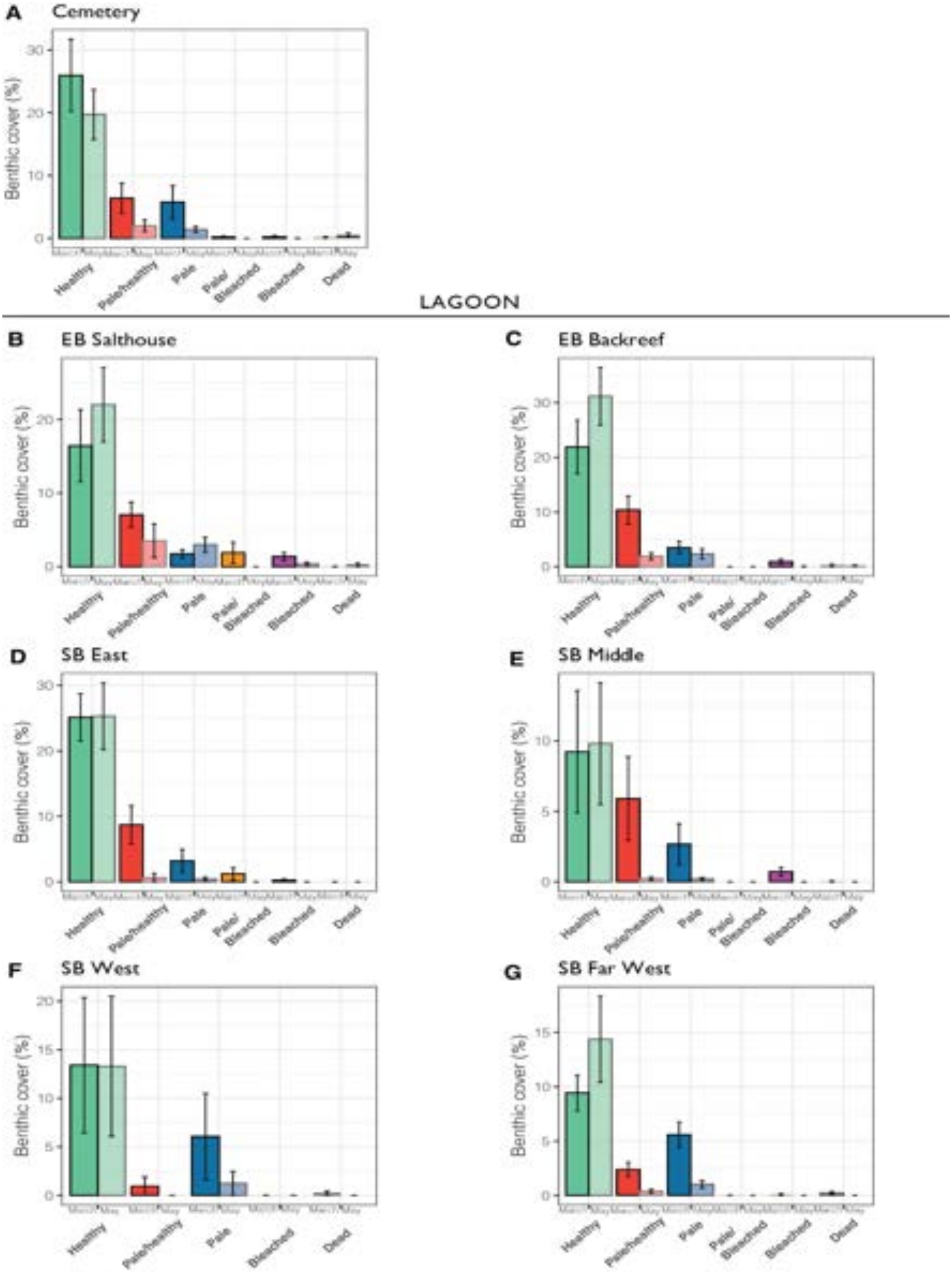


Figure 12. Total benthic cover of coral health categories across all genera at sites. Bars represent mean values and lines are +- standard error. The March time point is indicated by a dark coloured bar, and the May time point is indicated by a light-coloured bar.

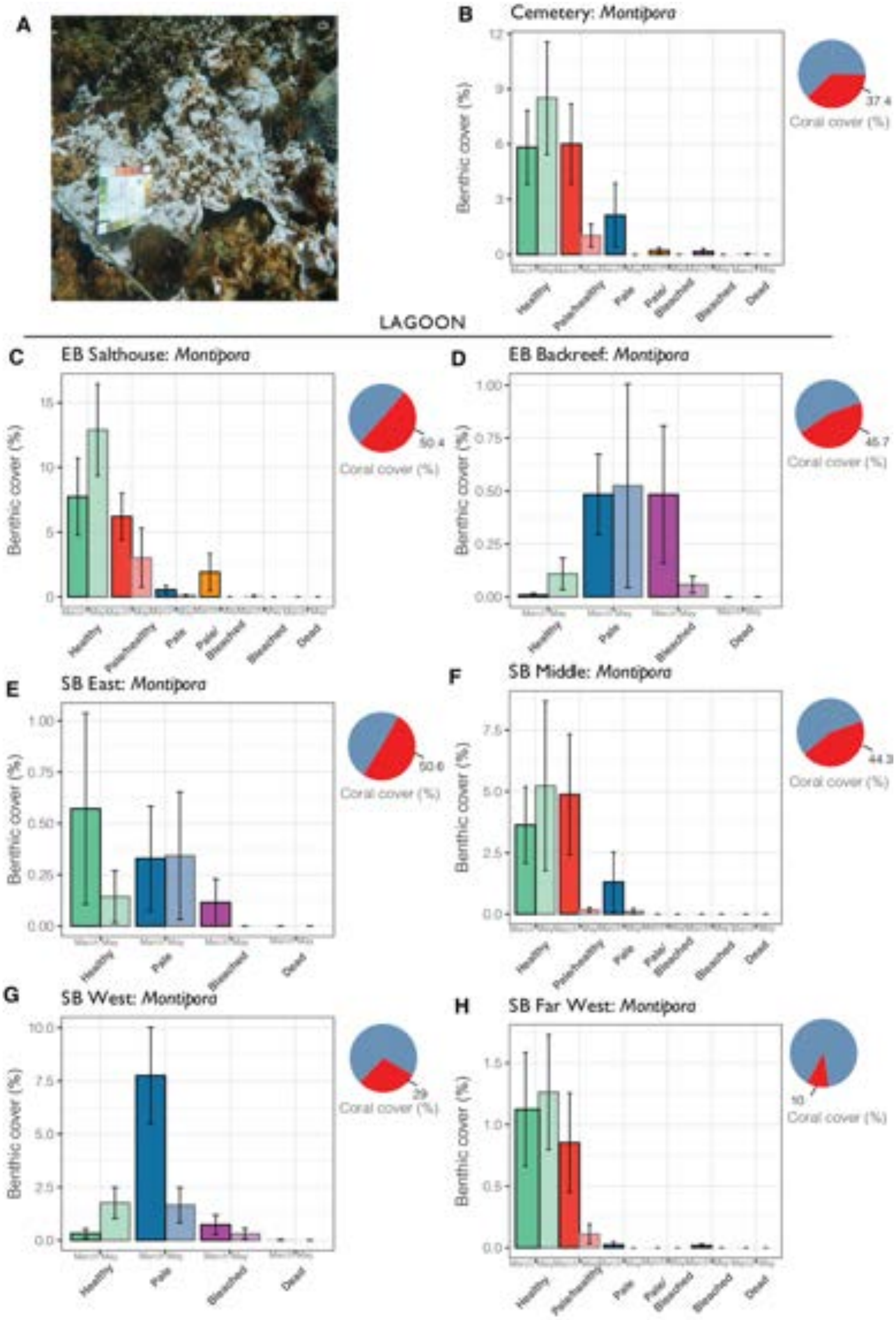


Figure 13. Total benthic cover of coral health categories for *Montipora* taxa at reef sites. Bars represent mean values and lines are +- standard error. Red area in pie chart indicates the cover of *Montipora* taxa relative to all the coral cover at each reef site. The March time point is indicated by a dark coloured bar, and the May time point is indicated by a light-coloured bar.

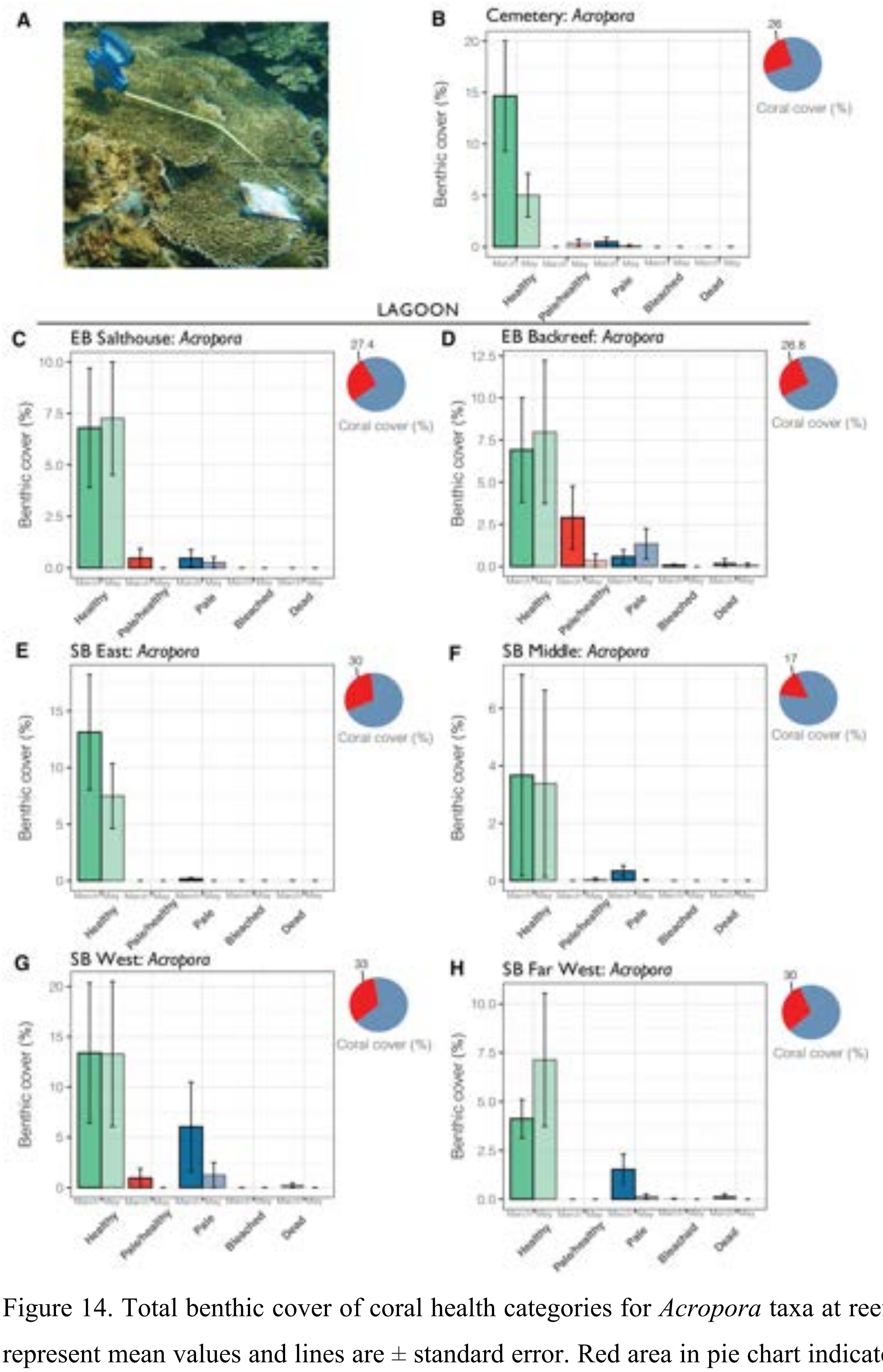


Figure 14. Total benthic cover of coral health categories for *Acropora* taxa at reef sites. Bars represent mean values and lines are ± standard error. Red area in pie chart indicates the cover of *Acropora* taxa relative to all the coral cover at each reef site. The March time point is indicated by a dark coloured bar, and the May time point is indicated by a light-coloured bar.

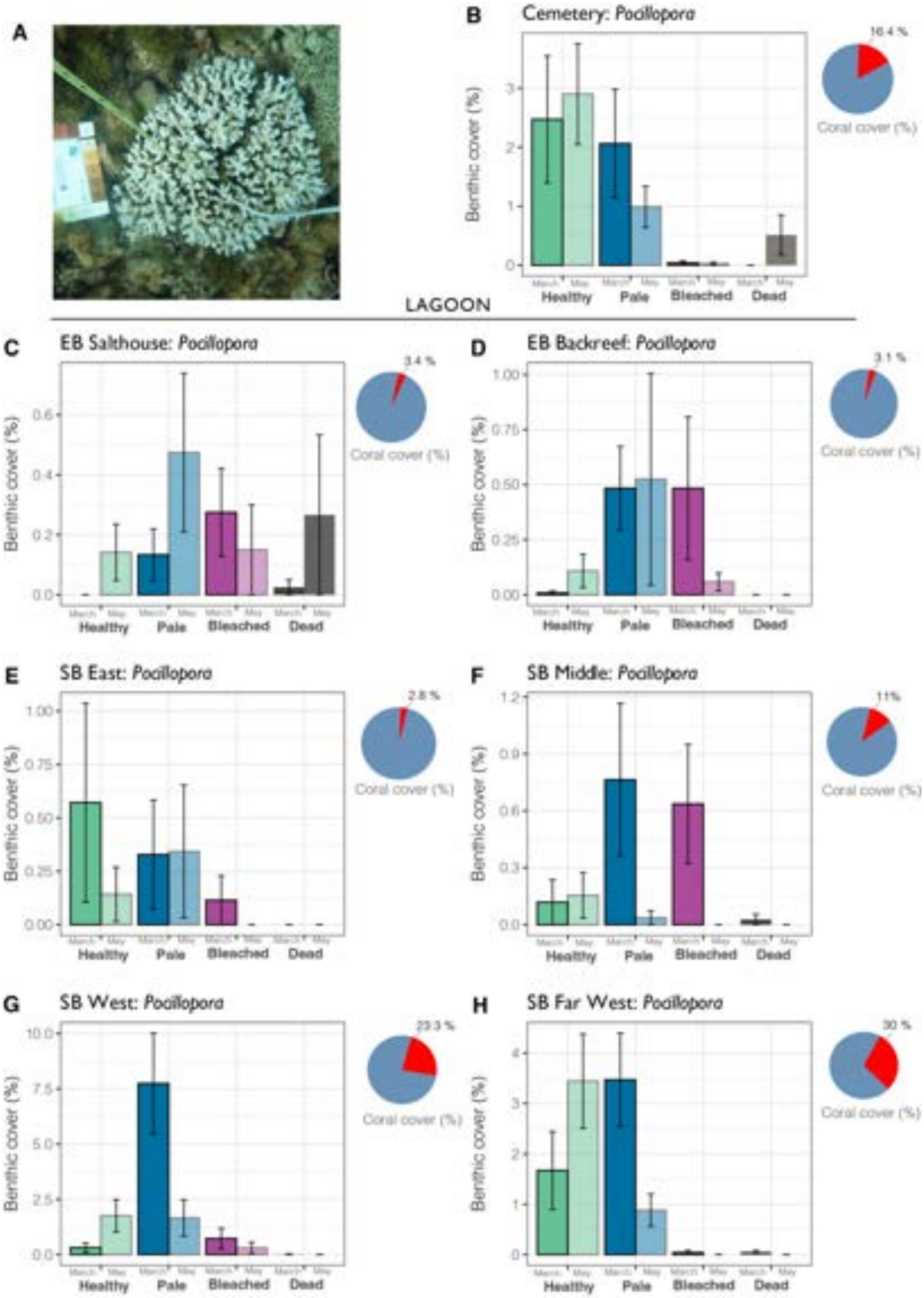


Figure *15*. Total benthic cover of coral health categories for *Pocillopora* taxa at reef sites. Bars represent mean values and lines are ± standard error. Red area in pie chart indicates the cover of *Pocillopora* taxa relative to all the coral cover at each reef site. The March time point is indicated by a dark coloured bar, and the May time point is indicated by a light-coloured bar.

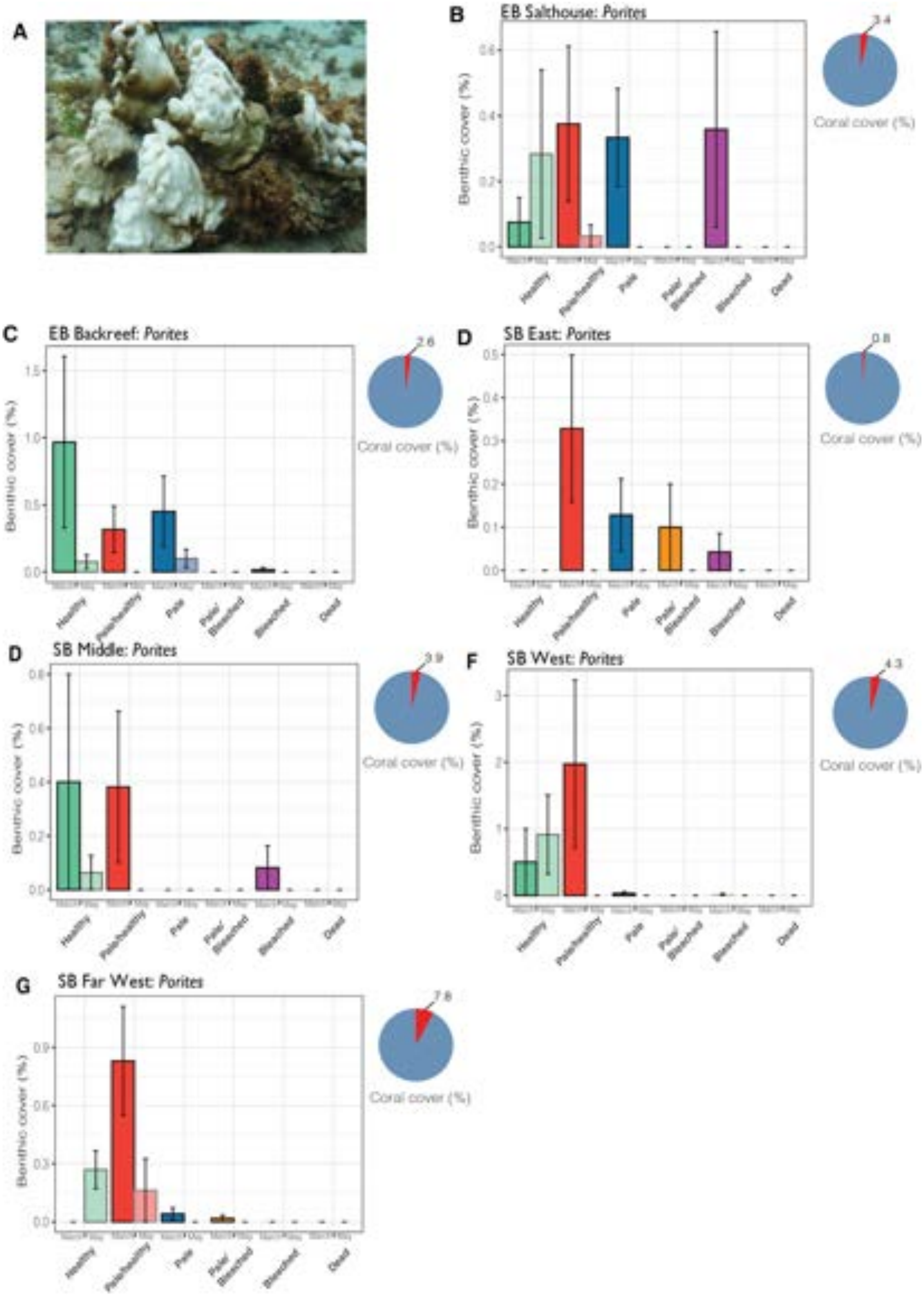


Figure *16*. Total benthic cover of coral health categories for *Porites* taxa at reef sites. Bars represent mean values and lines are ± standard error. Red area in pie chart indicates the cover of *Porites* taxa relative to all the coral cover at each reef site. The March time point is indicated by a dark coloured bar, and the May time point is indicated by a light-coloured bar.

Assessment of Benthic Community Composition 2020-24

Following the established **LTMP program design** benthic surveys were conducted in December 2023, March 2024 and May 2024. Benthic surveys consisted of 24 x 10 metre belt transects in Emily Bay and 27 x 10 metre belt transects Slaughter Bay (

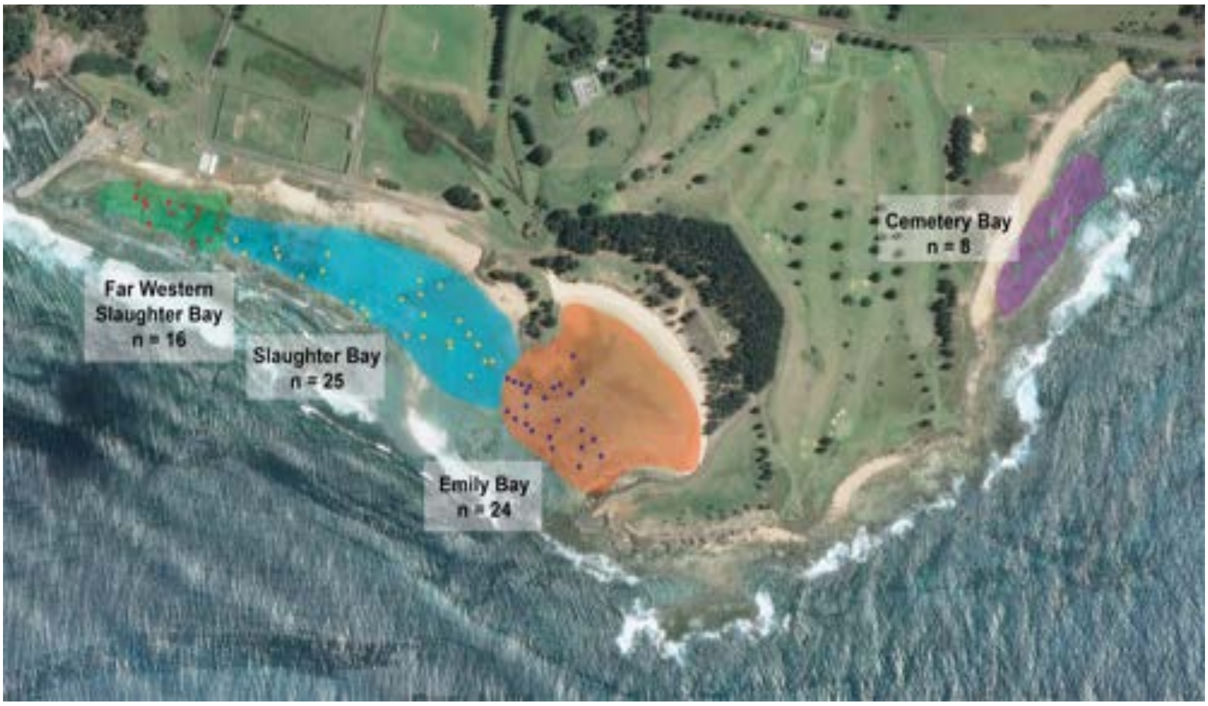


Figure 3), within each transect (10 m), 10 photos (TG-6 Olympus underwater camera) at 1m increments using a 0.5 m2 photo quadrat to standardize the area (n = 10 photos transect-1). The resulting photos were analysed using the online platform CoralNet (https://coralnet.ucsd.edu) applying a grid of 100 points per photo for annotation. A standardised label set was used as per LTMP 2020-24 with data generated for benthic community cover and composition. Labelset includes; coral taxa (as per previous), algal categories, and invertebrate categories as listed below. Resulting cover was summed across each transect so that each category is described as the % cover transect^{-1} (Table 2; Table 3).

Total hard coral cover has remained relatively stable since 2020 in Emily Bay (Figure 17), Slaughter Bay (Figure 18), Slaughter Bay far west (Figure 19) Cemetery Bay (Figure 20). It should be noted that sampling effort significantly increased after April 2021 (Table 4). The most consistent pattern has been an increase in macroalgae and other turfing algal abundance in Emily Bay, Slaughter Bay and Cemetery Bays. There are also clear seasonal pattens to the abundance of red turfing algae (high abundance present in March/April surveys) and black turf

(*Lyngbya*, high abundance present in December surveys) (Figure 17; Figure 18; Figure 19; Figure 20; Figure 21)

Table 2. Mean and median cover values per year per site for hard coral, macroalgae and other turf. TP = survey time points in the year. EB = Emily Bay, SB = Slaughter Bay, CB = Cemetery Bay and WS = Far Western Slaughter Bay.

Year	Site	Group	Mean cover (%)	Median cover (%)	Group	Mean cover (%)	Median cover (%)	Group	Mean cover (%)	Median cover (%)	Number of TPs
2020	EB	Hard coral	30.4	30.4	Macroalgae	16.0	16.0	Other turf	5.9	5.9	2
	SB		24.3	24.3		16.2	16.2		6.3	6.3	2
2021	CB		51.7	51.7		6.7	6.7		6.7	6.7	1
	EB		24.5	24.5		18.5	18.5		3.4	3.4	1
	SB		23.5	23.5		27.0	27.0		7.7	7.7	1
2022	CB		40.9	37.8		21.2	23.6		4.0	5.2	3
	EB		31.5	31.4		22.3	23.9		5.5	6.0	3
	SB		24.1	23.0		27.9	24.6		5.0	6.0	3
2023	CB		28.2	28.8		22.6	24.9		7.5	7.0	3
	EB		33.1	33.5		22.5	23.2		14.8	14.0	3
	SB		28.1	28.6		22.4	22.3		11.6	10.0	3
	WS		17.0	19.7		22.2	19.4		9.2	12.7	3
2024	CB		31.7	31.7		17.9	17.9		15.5	15.5	2
	EB		33.4	33.4		23.8	23.8		12.2	12.2	2
	SB		26.3	26.3		27.1	27.1		14.1	14.1	2
	WS		16.9	16.9		30.4	30.4		26.6	26.6	2

Table 3. Table showing the mean and median cover values per from December 2023 – May 2024 per site for hard coral, macroalgae and other turf. EB = Emily Bay, SB = Slaughter Bay, CB = Cemetery Bay and WS = Far Western Slaughter Bay.

Month	Year	Site	Group	Mean cover (%)	Median cover (%)	Group	Mean cover (%)	Median cover (%)	Group	Mean cover (%)	Median cover (%)	Number of transects
Dec	2023	CB	Hard coral	29.9	23.2	Macroalgae	26.8	21.6	Other Turf	9.4	9.5	10
		EB		33.5	35.2		23.2	22.2		18.6	18.4	19
		SB		26.7	28.5		22.3	23.0		16.7	16.4	24
		WS		9.8	4.8		17.4	14.8		14.9	13.4	14
March	2024	CB		38.5	47.4		17.0	15.2		10.3	8.9	10
		EB		33.6	31.0		19.7	17.1		6.0	4.7	24
		SB		32.2	33.9		21.9	21.2		11.9	11.1	25
		WS		18.0	20.1		23.4	20.6		35.5	32.4	17
May	2024	CB		24.8	22.2		18.9	16.2		20.8	20.8	8
		EB		33.1	31.1		27.9	30.0		18.5	16.6	24
		SB		20.3	13.1		32.3	35.2		16.3	16.2	25
		WS		15.8	11.3		37.4	39.8		17.8	17.1	16

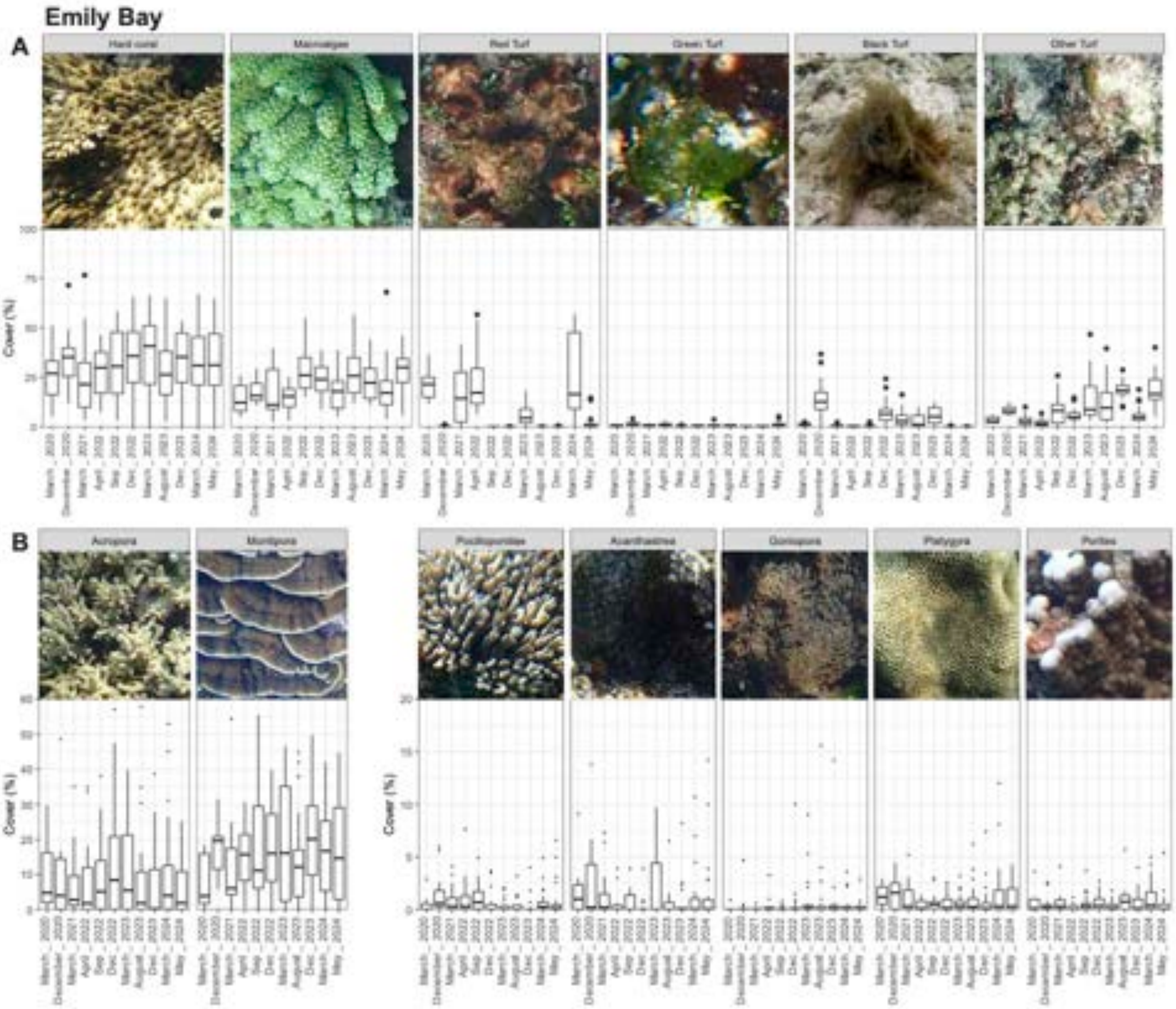


Figure 17. Community cover patterns from 2020 – 2024 recorded at Emily Bay for the main benthic groups (A) and main hard coral taxa (B). Dark line represents the medium value, boxes upper and lower values represent the interquartile range (25th and 75th percentile) and line represent the maximum and minimum values. Points represent outliers (i.e. transects placed on anonymously high areas of cover for the group being plotted).

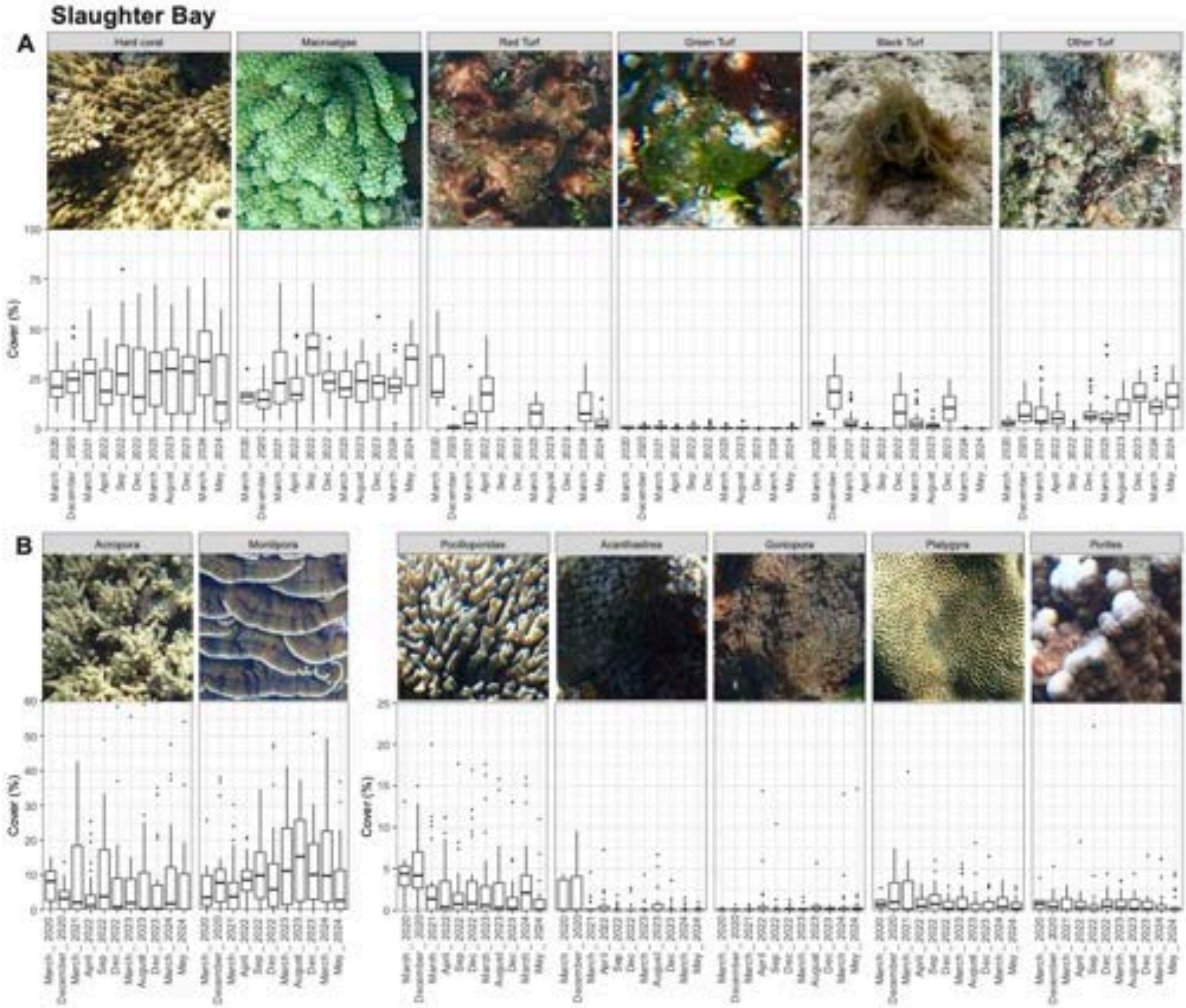


Figure 18. Community cover patterns from 2020 – 2024 recorded at Slaughter Bay for the main benthic groups (A) and main hard coral taxa (B). Dark line represents the medium value, boxes upper and lower values represent the interquartile range (25th and 75th percentile) and line represent the maximum and minimum values. Points represent outliers (i.e. transects placed on anonymously high areas of cover for the group being plotted).

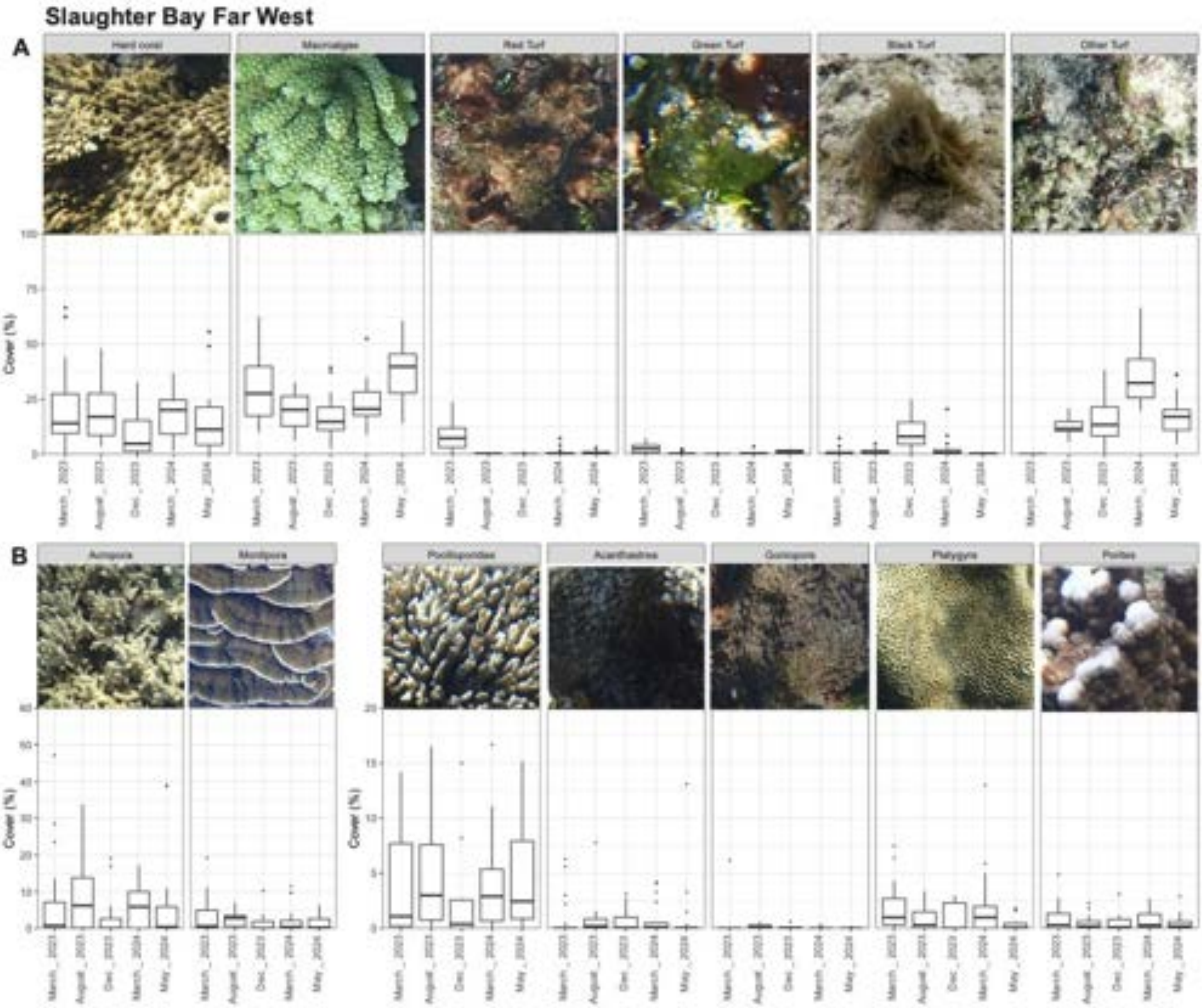


Figure 19. Community cover patterns from 2020 – 2024 recorded at Far Western Slaughter Bay for the main benthic groups (A) and main hard coral taxa (B). Dark line represents the medium value, boxes upper and lower values represent the interquartile range (25th and 75th percentile) and line represent the maximum and minimum values. Points represent outliers (i.e. transects placed on anonymously high areas of cover for the group being plotted).

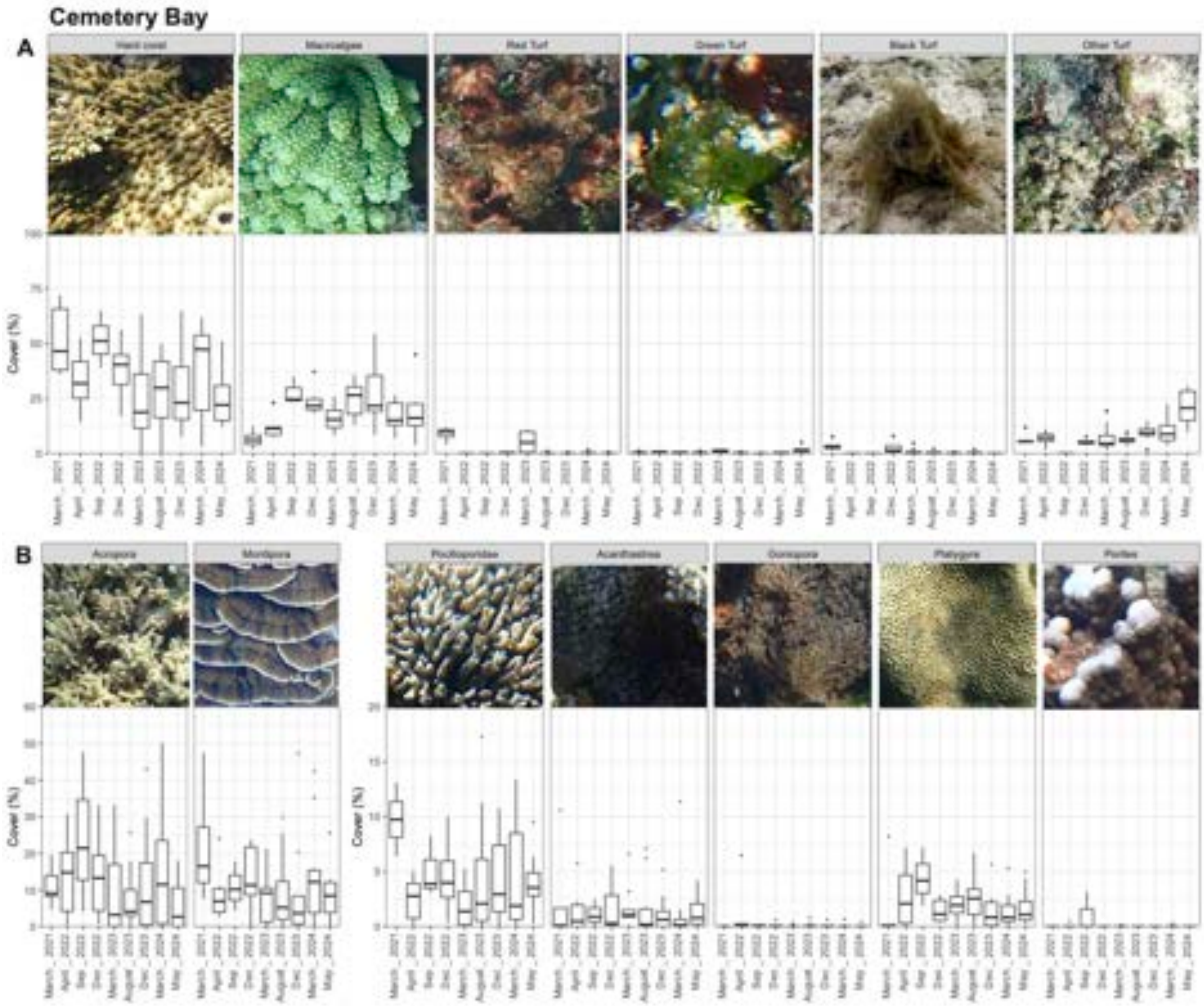


Figure 20. Community cover patterns from 2020 – 2024 recorded at Cemetery Bay for the main benthic groups (A) and main hard coral taxa (B). Dark line represents the medium value, boxes upper and lower values represent the interquartile range (25th and 75th percentile) and line represent the maximum and minimum values. Points represent outliers (i.e. transects placed on anonymously high areas of cover for the group being plotted).

Table 4. Table showing the number of transects competed per time point per site.

Year	TP	Site	Number of transects
2020	March	EB	7
		SB	7
	December	EB	15
		SB	20
2021	March	EB	15
		SB	25
		CB	5
2022	April	EB	15
		SB	25
		CB	6
	September	EB	24
		SB	26
		CB	3
	December	EB	24
		SB	24
		CB	8
2023	March	EB	24
		SB	25
		WS	23
		CB	10
	August	EB	24
		SB	25
		WS	15
		CB	10
	Dec	EB	19
		SB	24
		WS	14
		CB	10
2024	March	EB	24
		SB	25
		WS	17
		CB	10
	May	EB	24
		SB	25

		WS	16
		CB	8

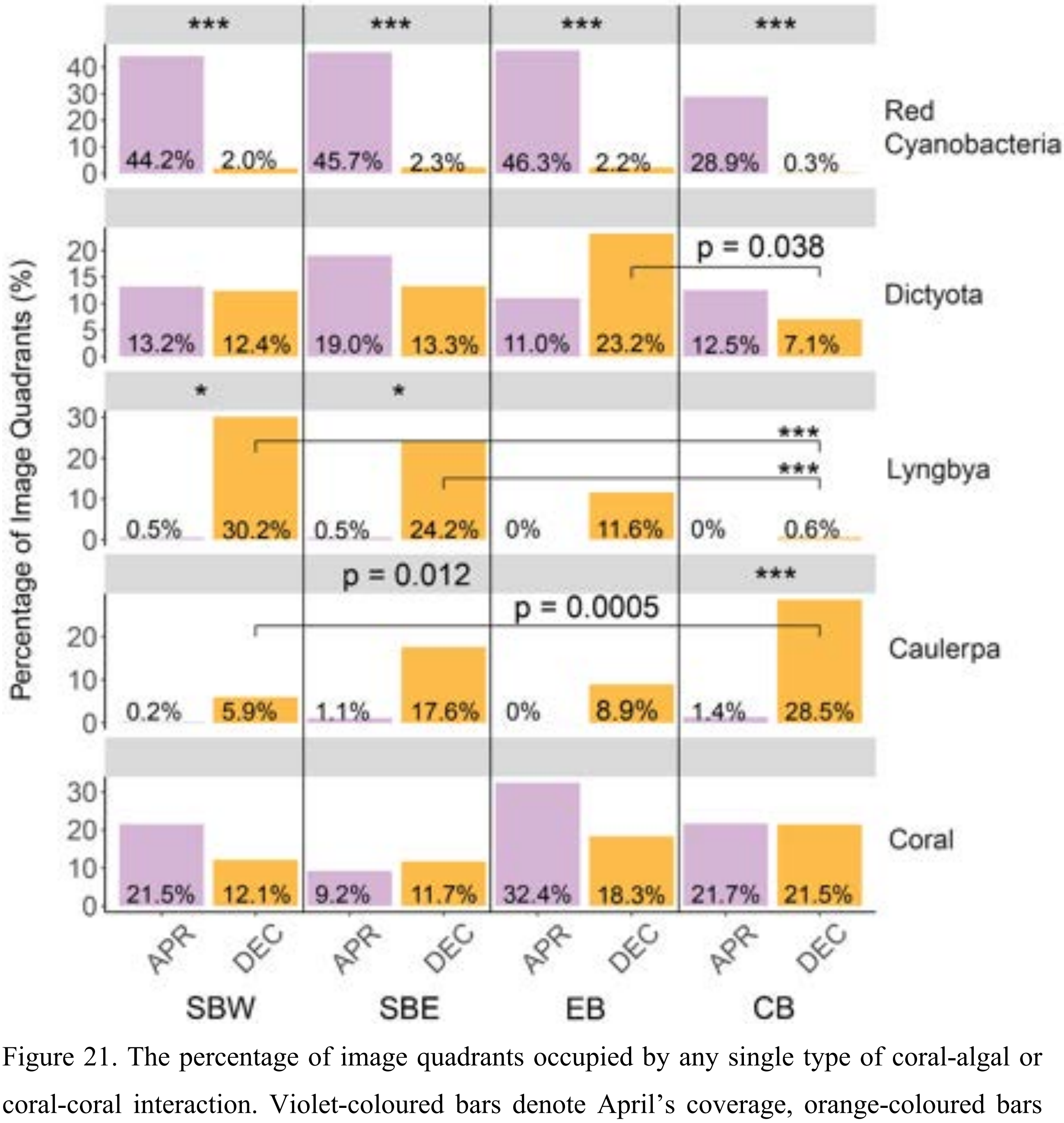


Figure 21. The percentage of image quadrants occupied by any single type of coral-algal or coral-coral interaction. Violet-coloured bars denote April's coverage, orange-coloured bars denote December's coverage.

Pocilloporid and Acroporid corals observed were categorized by size, size estimated by metal quadrats with colour card side in the region of western laughter bay. Size categories included large (> 50 cm), Mid 10 cm - 50 cm, Small 5 cm – 10 cm and Juvenile < 5 cm.

Given the small size and shallow depth, large colonies were rare within the area (<10 % of coral colonies). The upper extent of coral growth is likely limited by depth and available space in this region of the reef with reef depth measuring less than 1m during mid to low tides in the area. Unlike other regions of the EB/SB reef with higher cover of macro-algae and disease rates, juvenile and small coral colonies of the Pocilloporid and Acroporid corals were evident throughout the western slaughter coral reef. Corals measuring 0 -10 cm accounted for 45% (Pocilloporid) and 54% (Acroporid) of colonies on the western Slaughter region of the reef, the presence of corals across the small (<5 cm; age estimates 1-2 years) small. (5-10 cm 1-5 years), medium size (10-50 cm 5+ years) and large (50 cm >20 years) classes suggests ongoing recruitment and survival of juvenile corals on the western Slaughter Bay reef. Small and juvenile corals are very rarely observed within the Slaughter and Emily Bay reefs suggesting limited recruitment or survival of recruiting corals into the EB and SB reef areas.

Pocilloporid corals: Total coral colonies counted = 210

Large >50 cm	Mid 10-50 cm	Small 5-10 cm	Juvenile <5 cm
15 (7%)	98 (48%)	63 (31%)	28 (14%)

Acroporid corals: Total colonies counted = 279

Large >50 cm	Mid 10-50 cm	Small 5-10 cm	Juvenile <5 cm
26 (9%)	104 (37%)	100 (36%)	49 (18%)

.

Figure 22. Examples of small (A, B) and large (C, D) Acroporid (A, C) and Pocilloporid (B, D) colonies found in far western Slaughter Bay.

Assessment of indicator organism reef associations 2020-2024

Following the established **LTMP program design**, benthic surveys were conducted 2020 to May 2024 and from which populations of key indicator organisms were assessed including urchins, ascidians and crustose coralline algae. Benthic surveys consisted of 24 x 10 metre belt transects in Emily Bay and 27 x 10 metre belt transects in Slaughter Bay (Figure 23). Within each transect (10 m), 10 photos (TG-6 Olympus underwater camera) at 1m increments were captured using a 0.5 m^2 photo quadrat to standardize the area (n = 10 photos $transect^{-1}$). The resulting photos were analysed for recorded invertebrates (including urchins and ascidians as reported here) using the online platform CoralNet (https://coralnet.ucsd.edu) applying a grid of 100 points per photo, for annotations of urchins. Individual urchins present were confirmed by counts within each photo quadrat allowing urchins to be reported as counts. Ascidians are reported as ascidian cover, calcifying algae is reported as CCA cover.

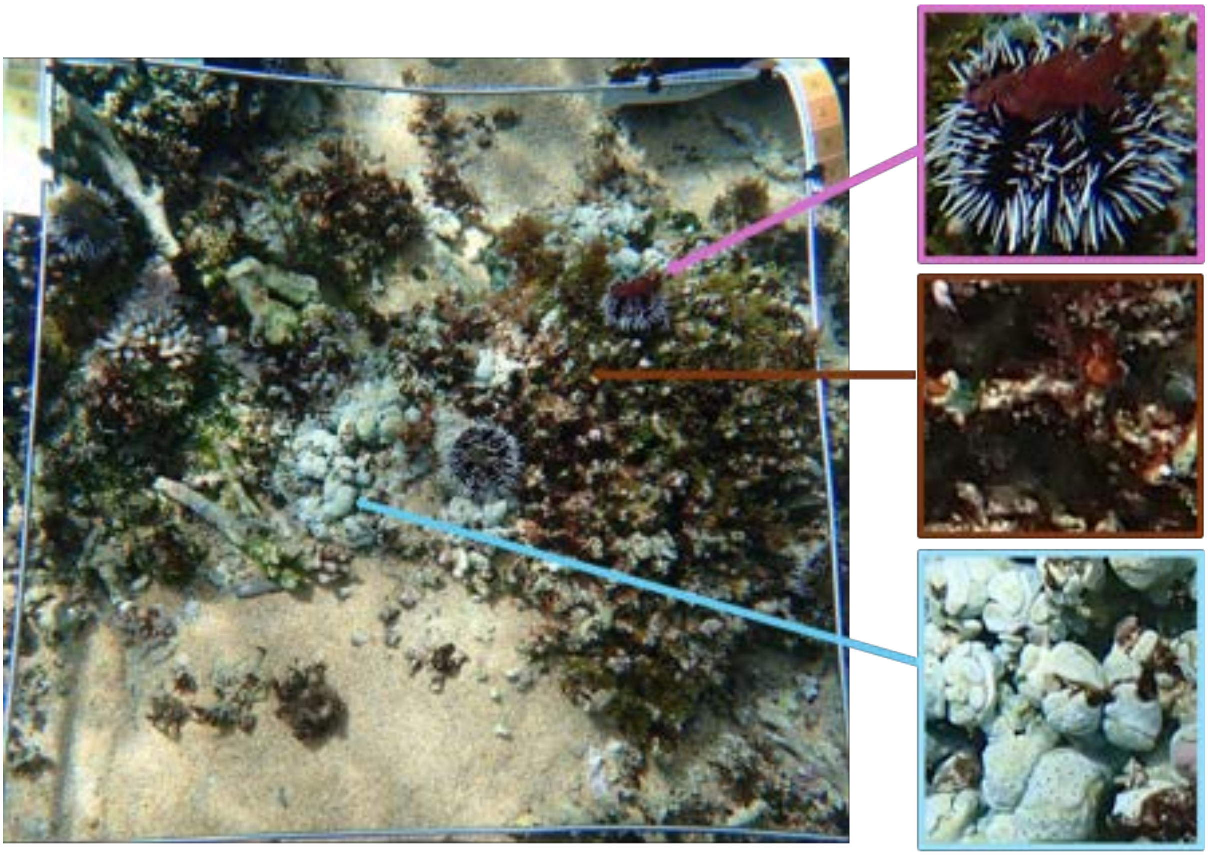


Figure 23. Photoquadrat showing urchin (pink arrow), Ascidians (blue arrow) and calcifying algae (brown arrow).

Urchin abundance within the lagoonal reef system averages 1 individual per transect (measured within LTMP at every survey timepoint). In March 2024 marginally higher sea urchin abundance are recorded in Slaughter Bay, with 1.3 individuals observed per transect and Far Western Slaughter, with 1.6 individuals per transect (Figure 24, Figure 25). Emily Bay also has peaks in sea urchin abundance of 1.5 per transect in September 2022 (Figure 25). Highest sea urchin abundance is recorded in Cemetery Bay. Levels increase over time from 1 individual per transect in April 2022, to a mean of 9.2 individuals per transect recorded in May 2025 (Figure 25). This result is consistent with observations of a large population of juvenile sea urchins in Cemetery Bay (Figure 25) and indicates a recent recruitment of herbivorous urchin populations into the inshore lagoonal coral reef ecosystem.

Figure 24. Photograph of reef area in Cemetery Bay taken in May 2025. Red arrows point to juvenile sea urchin *Tripneustes kermadecensis.*

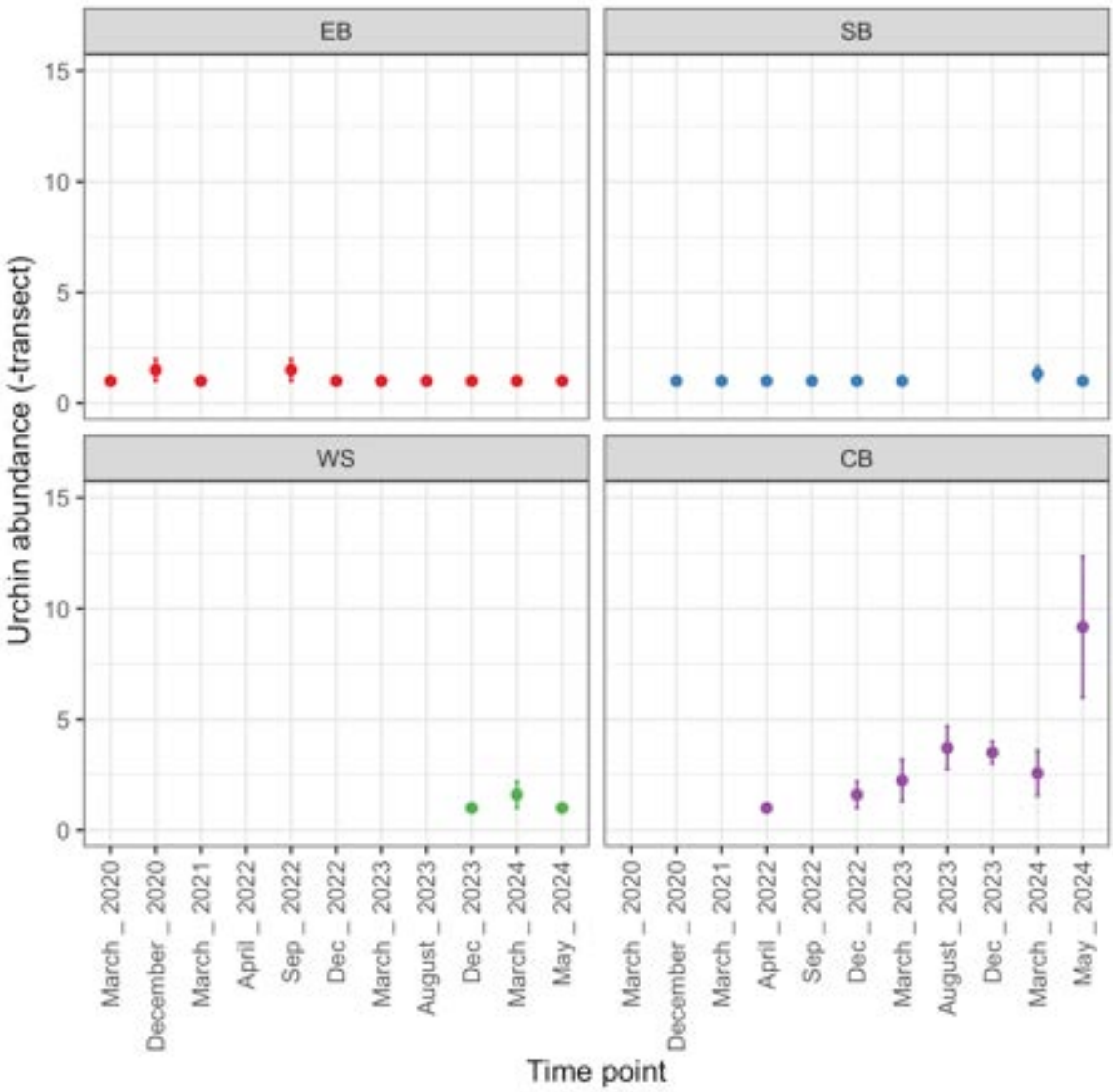


Figure 25. Urchin abundance per transect (10 x 0.5 m^{-2}). Plotted values are mean +- se. EB = Emily Bay. SB = Slaughter Bay. WS = Far Western Slaughter and CB = Cemetery Bay.

Ascidians (*syn. Diplosoma virens)* have previously been identified as occurring in a number of locations around Norfolk Island by Biofouling Solutions (Biofouling_Solutions, 2022). Biofouling Solutions identified two different growth forms, with a green morph associated to photosynthetic algae *Prochloron* sp, outside of Emily and Slaughter Bay while a flat white growth form was seen within the bays (Figure 26). It was hypothesised that this difference in growth form may be related to elevated nutrient levels within the bays leading to increased growth rates, as such it was recommended that this species be including in ongoing monitoring given the potential of this species to smother other species. In a recent study (Eckhardt et al., 2024) ascidians at Norfolk Island were found to be associated primarily with sand and sediment substrates at all reef locations. Ascidians were observed as growing on hard coral in EB and CB and ascidians at every site underwent interactions with hard coral (2.2% in SB, 5.6% in EB, 6.5% in CB) (Eckhardt et al., 2024). On average ascidian cover within the lagoon is below 0.5 %. Some variability in cover over time is evident but overall ascidian populations remain stable over the 2020 – 2024 period in the lagoon (Figure 27). The highest cover of ascidians is recorded in Cemetery Bay in May 2025 at 3.6 % of the benthos. Ascidian cover at Cemetery was between 2.5 and 3.5 % cover from March 2023 – August 2023 but then declined in December 2023 to 0.3 %. We then record an increase from December 2023, where cover increased by 487% to 1.76 % in March 2023, and then by 105% to 3.6 % in May 2024. Patterns indicate that ascidian populations are variable over time in Cemetery Bay, the Ascidian population is Cemetery Bay is higher than that observed of other lagoons.

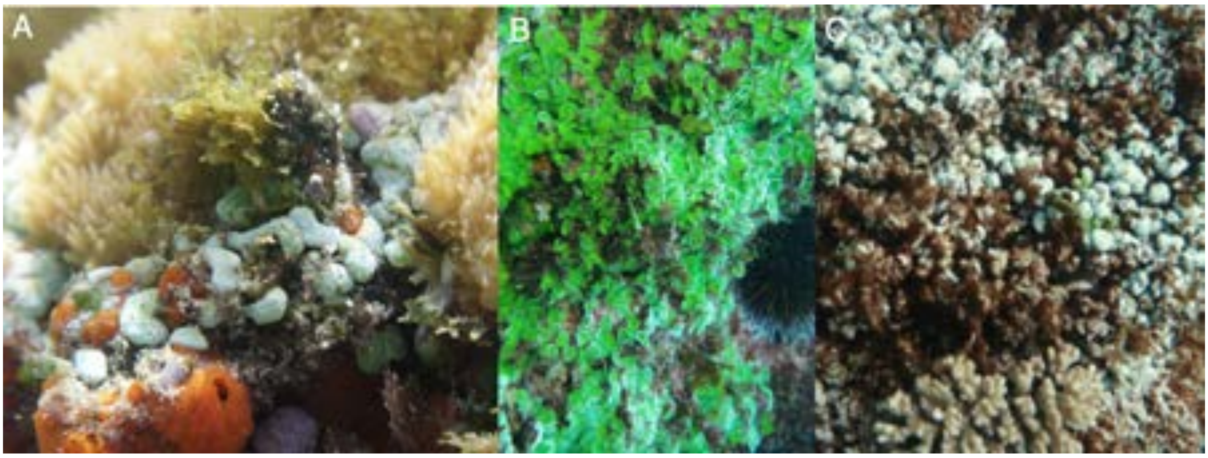


Figure 26. Photograph of grey (A) and green (B) morphotype of *Diplosoma* sp. (C) Ascidian growth on top of dead coral (from Eckhardt et al., 2024).

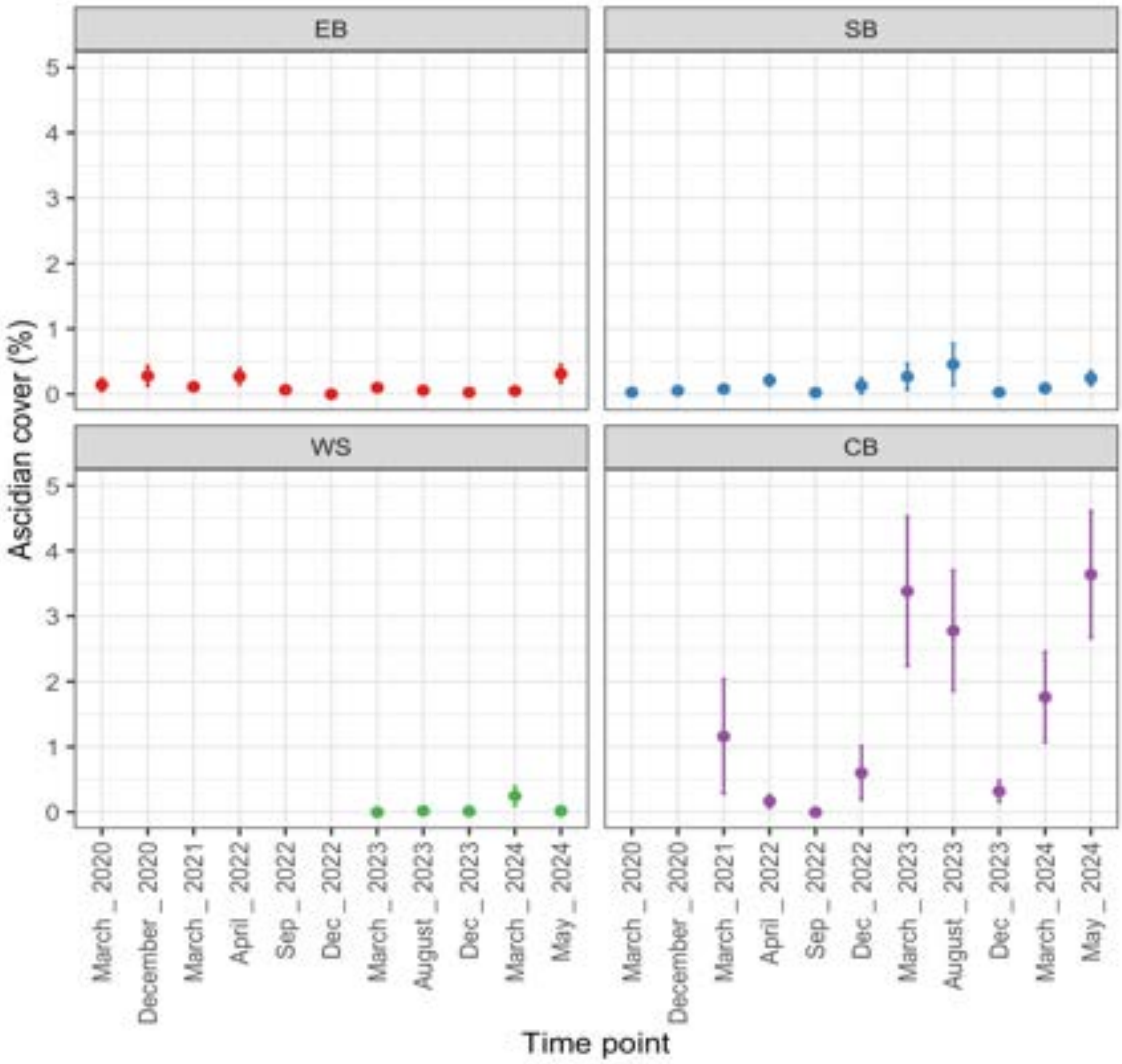


Figure 27. Ascidian cover over time at sites. Plotted values are mean +- se. EB = Emily Bay. SB = Slaughter Bay. WS = Far Western Slaughter and CB = Cemetery Bay.

Calcifying algae, also referred to as crustose coralline algae (***CCA***) on coral reef ecosystems, is an important member of the benthic reef ecosystem (See recent review Nash et al 2019; Cornwall et al 2023). CCA provide habitat for many micro invertebrates, bind loose materials on the benthos, contribute substantially to a reef's carbonate budget and importantly provide settlement cues and a benthic structure that supports coral and invertebrate larval recruitment (Figure 28). Certain coral species, such as the primary reef habitat coral *Acropora* preferentially recruit to regions of a coral reef where particular CCAs are found, for example red crustose coralline (Deinhart et al., 2022), The occurrence, type and distribution of CCA within the subtropical coral reefs on Norfolk Marine Park has yet to be investigated. Understanding the dynamics of CCA populations on rocky structure and within the complex benthic algal assemblages on the inshore lagoonal reefs can provide an insight into the potential for recruitment within the reef habitats and the role of specific CCA communities in facilitating phase shifts from algae dominated to coral dominated systems. Within the Emily, Slaughter and western Slaughter Bays CCA contributes between 1 to 2.5% of the cover. Interestingly within the Cemetery Bay lagoon CCA peaks at 5% of the benthic cover, with a potentially increasing trend of CCA cover occurring over time. On reefs of the Great Barrier Reef CCA cover has been recorded as low as <1% on inshore reefs and up to 30% on offshore coral reefs (Dean et al., 2015; Fabricius & De'ath, 2001). Dean et al. highlight that their findings could indicate CCA populations are influenced by anthropogenic activities, particularly in inshore regions impacted land-based runoff. CCA is also lower in all reef locations in March 2024 compared to prior and later survey dates suggesting the potential of heat stress impacts on identifying CCA, or directly on CCA cover, on the reefs. Further investigation into the species, distribution and thermal tolerance of CCA occurring within the bays and on reef habitats will aid in understanding their role in coral recruitment in the Norfolk Marine Park and their potential as indicators of reef condition particularly in response to heat stress events co-incident with coral recruitment. CCA was predominantly observed as a red/orange CCA across all reef sites recorded and abundance was consistent across the years at Emily and Slaughter Bays (Figure 29) while CCA abundance has increase at Cemetery Bay and Western Slaughter (Figure 29).

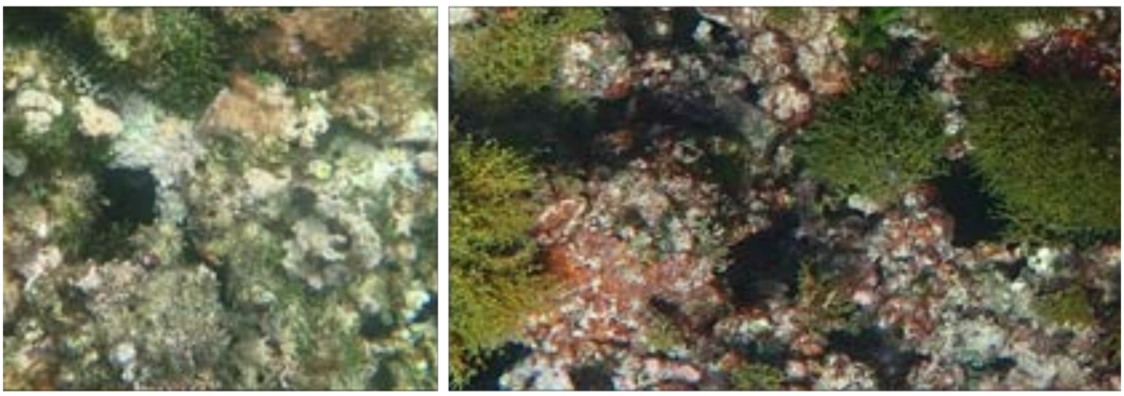


Figure 28. Pink and red/orange CCA found across all reef locations.

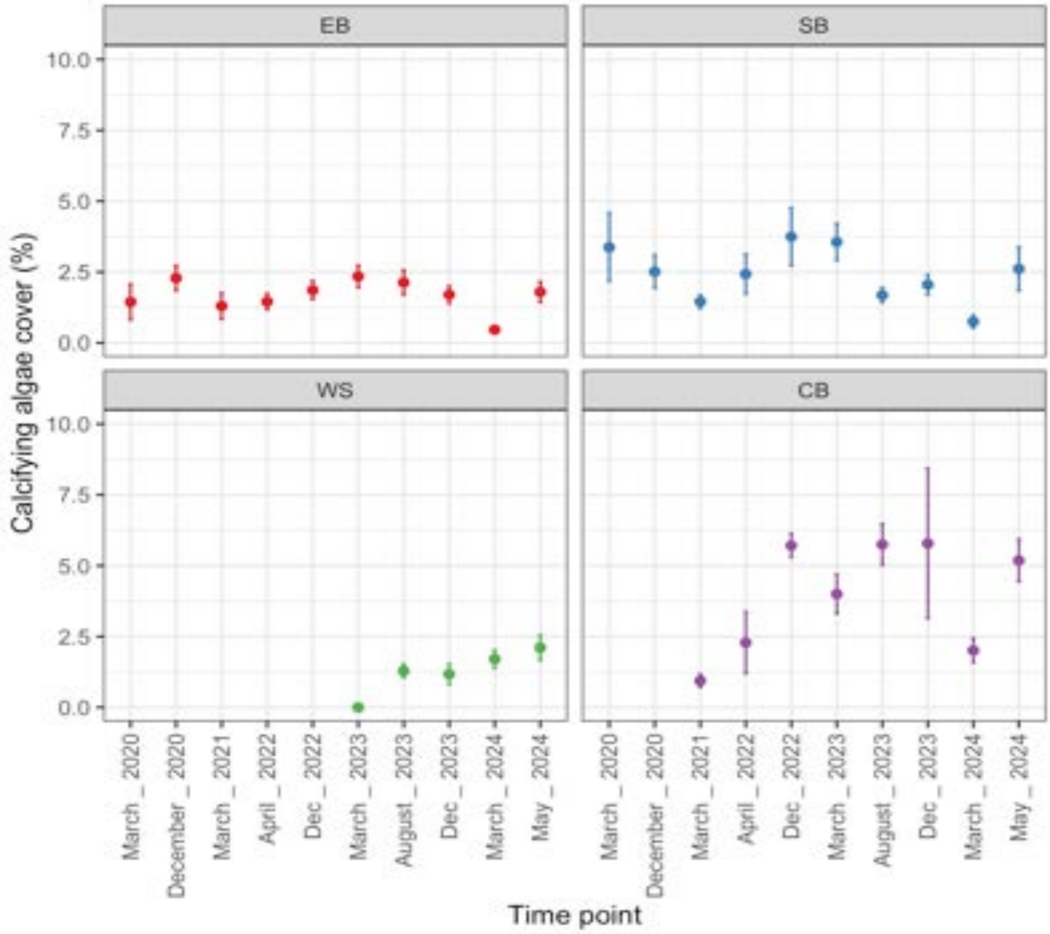


Figure 29. CCA cover over time at sites. Plotted values are mean +- se. EB = Emily Bay. SB = Slaughter Bay. WS = Far Western Slaughter and CB = Cemetery Bay.

Methodology and Assessment of Coral Disease 2020-2024

Coral disease monitoring for the populations of the two primary reef builders, plating *Acropora* spp. and *Montipora* spp. (**Error! Reference source not found.**), has been ongoing since December 2020 within the LTMP commissioned by Parks Australia. Coral disease monitoring was undertaken as per the LTMP in December 2023 with additional disease observations recorded in March and May 2024 with the rapid health survey.

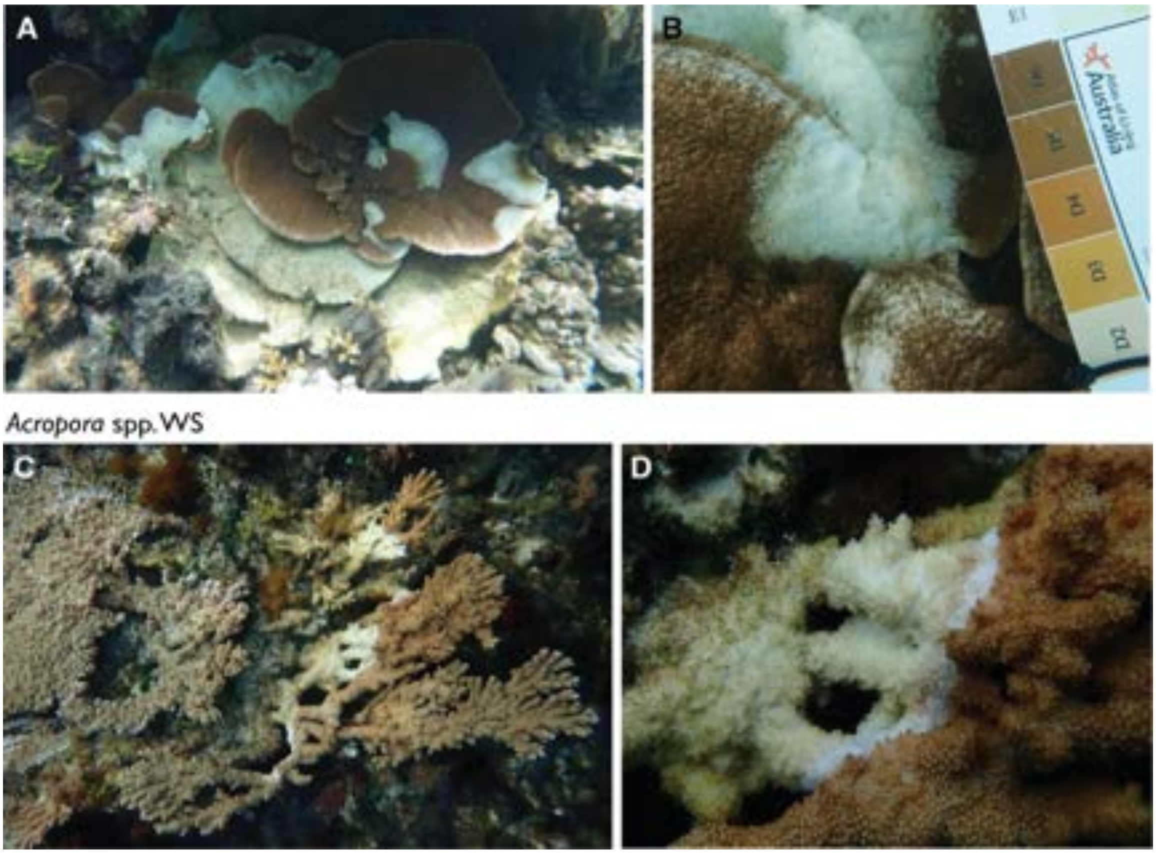


Figure 37. Examples of colonies impacted by Montipora white syndrome (MWS) (A,B) and Acropora white syndrome (AWS) (C,D) in December 2023.

Disease prevalence (the proportion of community infected) of *Montipora* white syndrome and *Acropora* white syndrome was reported within *Montipora* taxa, from December 2020, April 2021, April 2022, September 2022, December 2022, April 2023 and December 2023; and *Acropora* taxa for April 2021, April 2022, September 2022, December 2022, April 2023 and December 2023. Data was collated at each time point from a total of 12-replicate belt-transects, six transects at each time point were laid in both Emily Bay and Slaughter Bay respectively, with a 10 m transect line 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. Where a coral 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). Signs of disease were also assessed in Cemetery Bay for *Acropora* in April 2022, September 2022, December 2022, April 2023 and December 2023 and for *Montipora* in December 2023, April 2023 and December 2023. Within the Cemetery Bay reef 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 and December 2023. Disease prevalence for each taxa was calculated as the proportion of total colonies surveyed that showed signs of disease.

An on-going disease outbreak within both Emily and Slaughter Bay was evident in December 2023, with disease rates above background in both *Acropora* and *Montipora* populations (Figure 30). The most severe disease outbreak on record on the Norfolk reef was the *Montipora* white syndrome disease outbreak in 2020, and for December 2023 prevalence and severity remain at similarly high rates of above 30% of the population affected (Figure 30). *Acropora* white syndrome prevalence was lower in Emily Bay in December 2023 compared to previous, but higher in Slaughter Bay (Figure 30). *Acropora* white syndrome disease severity was found to be lower in both Emily and Slaughter Bay compared to previous records. Both diseases have been observed in Cemetery and Western Slaughter Bay and remain at the same prevalence as previous records (Figure 30).

Montipora White Syndrome (MWS) (Figure 30) was previously recorded as highly prevalent within the lagoon since December 2020. The disease has been observed at outbreak levels in Emily Bay, Slaughter Bay, Far Western Slaughter and Cemetery Bay throughout 2020-2024. Disease prevalence was highest in Emily Bay in 2020 (75%), and between 35% and 58% over the remaining surveys. In December 2023 disease prevalence remained similar to that of April 2023, at 41% and 38% respectively. In Slaughter Bay, following a peak in prevalence of 64% in April 2022, disease levels remained consistent across the following survey period, between 38% and 52%. Since December 2020, disease severity has remained between 8 – 16% across Emily and Slaughter Bays. MWS disease was recorded in both Cemetery Bay and far Western Slaughter Bay in December 2023. Both sites are considered more pristine than Emily and Slaughter most likely due to their more open exposure to ocean flushing.

Over the April 2021 – April 2023 period prevalence of *Acropora* white syndrome (AWS) disease of plating *Acropora* remained over 22% in Emily Bay (Figure 30). In December 2023, 14% AWS disease was recorded in Emily Bay, the lowest levels of disease recorded in Emily Bay to date. AWS was first recorded in Slaughter Bay in April 2022, suggesting that the WS disease originated from Emily Bay spreading to Slaughter Bay. After reaching peak disease levels of 52% in September 2022, disease in Slaughter Bay in December 2023 was 34%, representing a decline from the April 2023 period, but still considered to be at disease outbreak levels (outbreak is a disease recorded at >20%). AWS disease was also observed in Cemetery Bay and far Western Slaughter Bay in December 2023. Disease prevalence in Cemetery Bay was 11% which is higher than background disease rates that are seen in healthy coral reef (5% in a normal population) and severity of disease is low (Figure 30). Disease prevalence at far Western Slaughter Bay is also above what is generally seen in healthy coral reefs, measured at 10 and 12% in April and December 2023 respectively, indicating slightly elevated disease rates

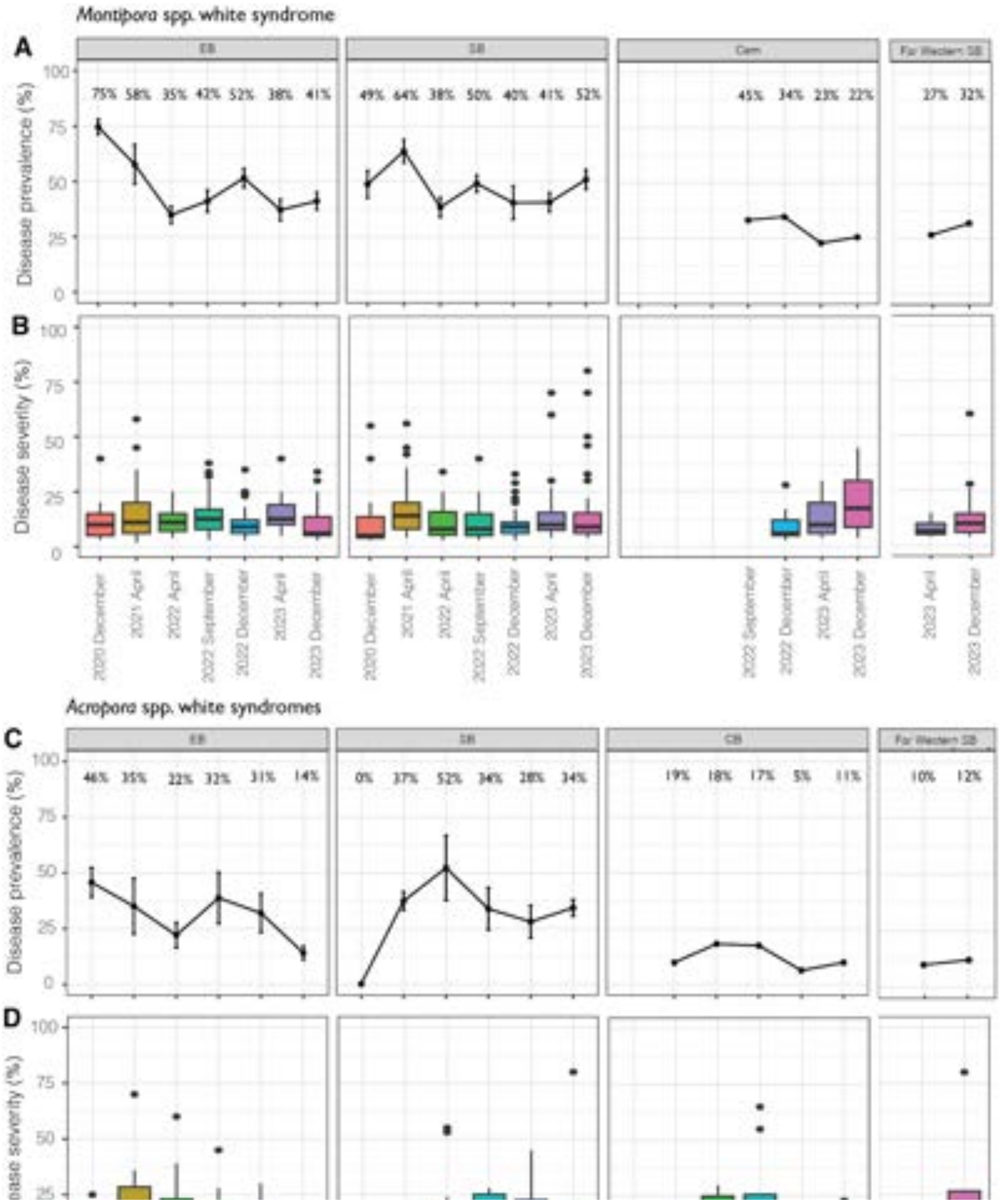


Figure 30. Disease prevalence levels for *Montipora* white syndrome. Plotted values, mean +- se. Written values are mean prevalence. **B.** Boxplots of disease severity (i.e. disease lesion average area) for *Montipora* white syndrome. The middle line represents the median value; box represents the interquartile range; whiskers are maximum and minimum values and points represent outliers. **C.** Disease prevalence levels for plating *Acropora* White Syndrome. Plotted values are mean +- se. Written values are mean prevalence. **D.** 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 maximum and minimum values and points represent outliers.

Table 5. The total number of coral colonies surveyed at each time point.

Month	Site	*Acropora* colony count	*Montipora* colony count
2020 December	EB	No data	61
	SB	No data	69
2021 April	EB	24	86
	SB	27	112
2022 April	EB	50	74
	SB	57	80
	Cem	43	No data
2022 September	EB	67	105
	SB	52	118
	Cem	51	40
2022 December	EB	39	129
	SB	47	110
	Cem	46	52
2023 April	EB	64	107
	SB	55	117
	FarWestSB	37	60
	Cem	64	57
2023 December	EB	60	110
	SB	57	125
	FarWestSB	33	47
	Cem	51	51

Monitoring of an undisturbed site

To understand the coral disease dynamics of an reefs with little to no anthropogenic inputs surveys were undertaken at Crystal Pool (-29.0343,167.5611). This site includes two shallow rock pools separated by a semi-submerged rocky ledge (Figure 31) which is highly flushed during a tidal cycle and can be considered to be unimpacted by terrestrial inputs. Each pool is flushed by the ocean and is sloping in depth from approximately ~0.5 m (shallowest) to ~5 m. Inclusion of this site contextualises the on-going disease events that have been observed in Emily, Slaughter and Cemetery Bays. Coral colonies are found in the shallow depths and along the steep boulders forming the walls of the pools (Figure 2,3). Coral cover in pool one is approximated at around ~30 % of the pool area and cover in pool two is approximated as ~20 %. In both pools Montiporid coral colonies were the dominant taxa present. Of the *Montipora* colonies, only brown colour morphs were present and predominant growth form was encrusting (Figure 31). Along the walls of the pools all coral colonies are encrusting growth forms. In the shallows several colonies of branching *Stylophora*, *Pocillopora* and *Acropora* were also observed, including small colonies of each taxa (Figure 31). The following taxa were recorded within the pools: *Acropora, Montipora, Pocillopora, Stylophora, Astrea, Platygyra/Paragoniastrea, Acanthastrea.*

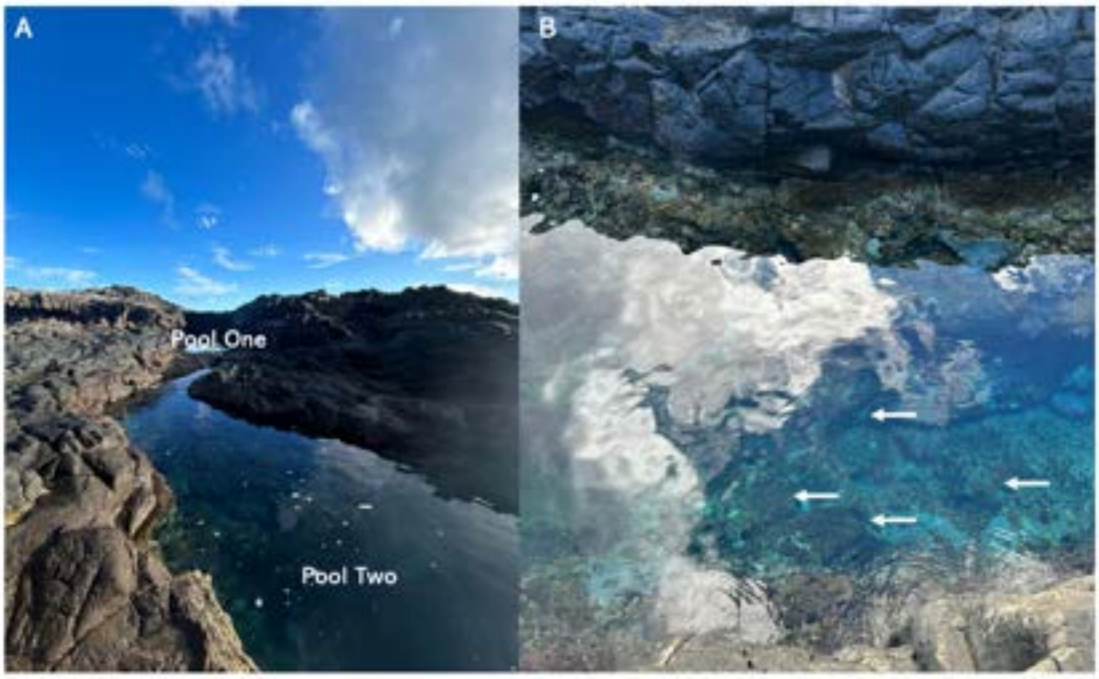


Figure 31. A. View of crystal pools showing the upper pool (Pool One) and the lower pool (Pool Two). Pools are connected through flow of water over rock barrier from pool one to pool

two. B. Picture looking down into Pool One showing abundant healthy encrusting *Montipora* colonies on pool floor.

Signs of damage or disease (lesions) in pool one was found to be 9.3 % (Figure 32, Figure 33) of Montiporid corals, wherein pool one *Montipora* abundance was estimated as 43 individuals, with four of these individuals found to have lesions (which could include both signs of white disease (MWS) or physical damage resulting in exposure of the coral skeleton) (Figure 32). One colony was observed as having a larger lesion (~20 % of the colony impacted, see Figure 6A), whilst other colonies had small lesions (< 10 % of the colony impacted, Figure 33). Colonies with lesions were found in the shallow portion of the pool close to the entry/exit point, indicating lesions in the area could be associated with physical damage. Multiple medium (0.5 – 1 m) and large (~1 m) colonies were observed within the pool in good condition. Prevalence lesions in pool two was also found to be 10 % (Figure 33), where in pool two, *Montipora* abundance was recorded as 50 individuals with five of these individuals were found to have lesions. Severity of lesions (proportion of colony impacted) was small in pool two. A single coral colony was also found to be affected by a Growth Anomaly (prevalence 2%) (Figure 34). Multiple medium (0.5 – 1 m) and large (~1 m) colonies were observed within the pool in good condition. Given the location of diseased individuals within the pools, white lesions are likely associated with physical abrasion. Encrusting *Montipora* colonies dominate the hard coral assemblage in both pools which coral cover estimated at <30 % of total available substrate. Coral diversity present within the pools is high, covering a majority of primary reef building taxa found at other reef sites at Norfolk Island. No further indictors of poor coral health were observed within the pools demonstrating that the on-going disease events in Emily, Slaughter and Cemetery Bays are not found in unimpacted sites.

Figure 32. Coral colonies at crystal pools sites showing growth of encrusting coral colonies over boulders forming the pools.

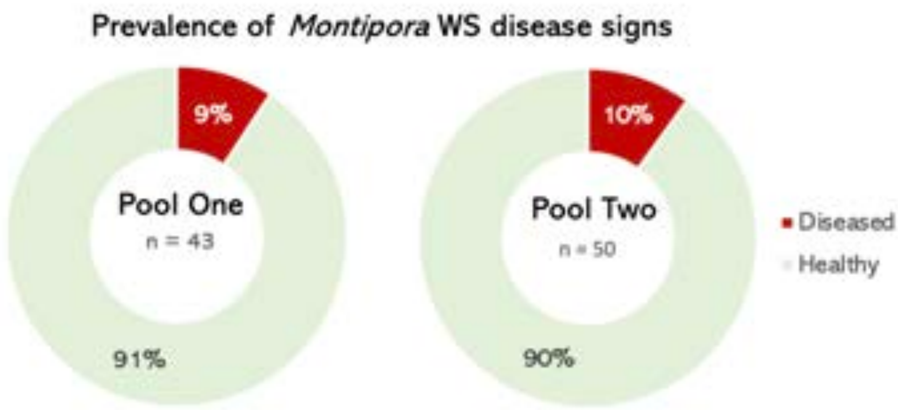


Figure 33. Plots showing the prevalence (proportion of community affected) of colonies with observed lesions.

Figure 34. Coral lesions observed in pool one. A. Single colony showing a larger lesion of white disease signs (~20 % of colony). B. Colony showing a small area of colony tissue impacted by disease signs (< 10 %).

Assessment of Coral Reproduction and Recruitment

The reproductive state of 5 different coral species was determined by removing replicate branches from a colony and examining them for the presence of oocytes (eggs) between December 7th – 10th 2023 (Figure 35) prior to the late December spawning. Each fragment was classified as either no oocytes, white oocytes or pink oocytes and the dominant reproductive state assigned to that colony (Table 6). In all species the majority of colonies examined were found to be reproductively active with either pink or white oocytes present (Figure 35, Figure 36, Table 6). Following these surveys possible coral spawning slicks were observed on the 27th December by Susan Prior, spawning was also reported at a similar time at Lord Howe Island, while there have been no other reports of spawning at later times additional spawning periods cannot be ruled out. Coral settlement blocks were also deployed (Figure 37) across the inshore reefs of Norfolk Marine Park in December 2023, including Slaughter Bay Far West, Slaughter Bay (Salt House) and Cemetery Bay (Table 7). Tiles were recovered in May 2024 and the type, and number, of coral recruits visible using dissecting microscopy were assessed on each tile. Settlement tiles deployed from December 21 to April 2022 were also assessed for recruitment.

Table 6. Abundance of colonies in reproductive state. Replicate colony fragments were taken to determine reproductive state, counts represent dominant reproductive state of colony fragments (7th-10th December 2023).

	No oocytes	White oocytes	Pink oocytes
Acropora branching	1 (10%)	8 (80%)	1 (10%)
Acropora Plating Growth Anomaly	3 (38%)	5 (62%)	
Acropora Plating Healthy		9 (90%)	1 (10%)
Acropora elkhorn		20 (100%)	
Platygyra (see Figure x)		3 (30%)	7 (70%)

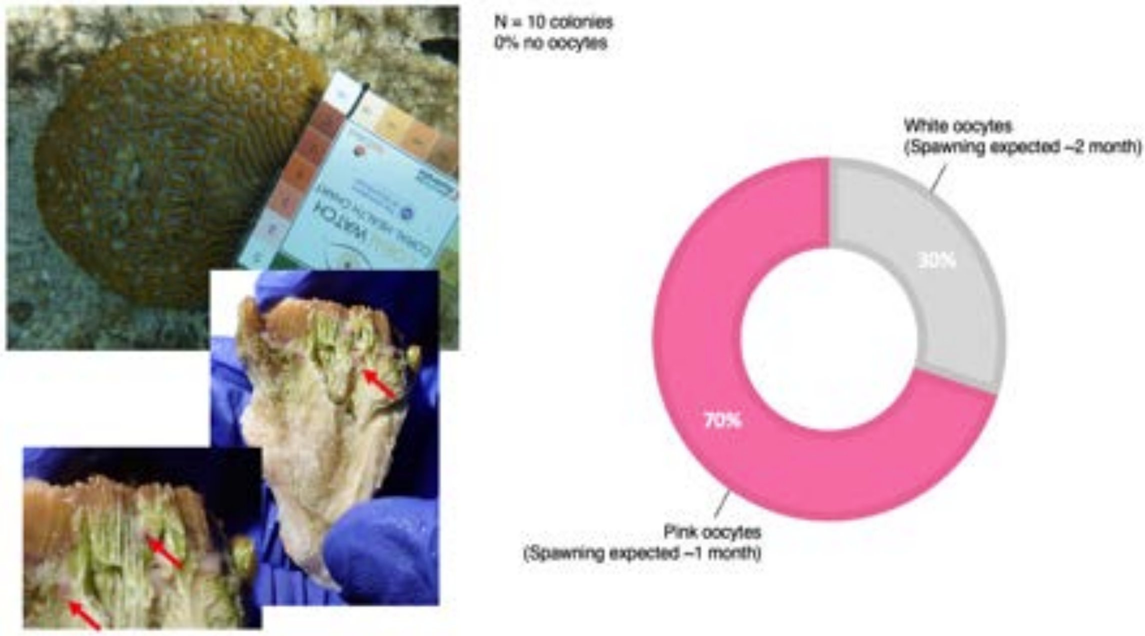


Figure 35. Plot showing the proportion of *Platygyra* colonies sampled with white and pink oocytes. Photographs from top to bottom show a *Platygyra* colony and example of coral sample with pink oocytes visible.

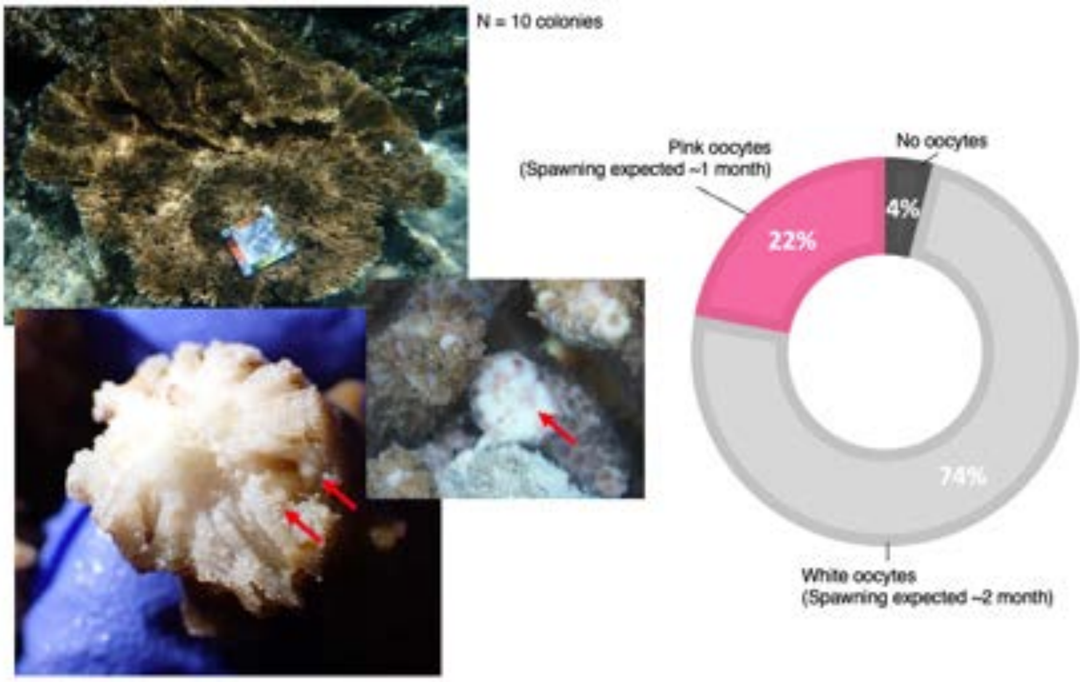


Figure 36. Plot showing the proportion of plating healthy Acropora colonies sampled with no, white and pink oocytes. Photographs from top to bottom show a Acropora colony and example of coral sample with white oocytes visible.

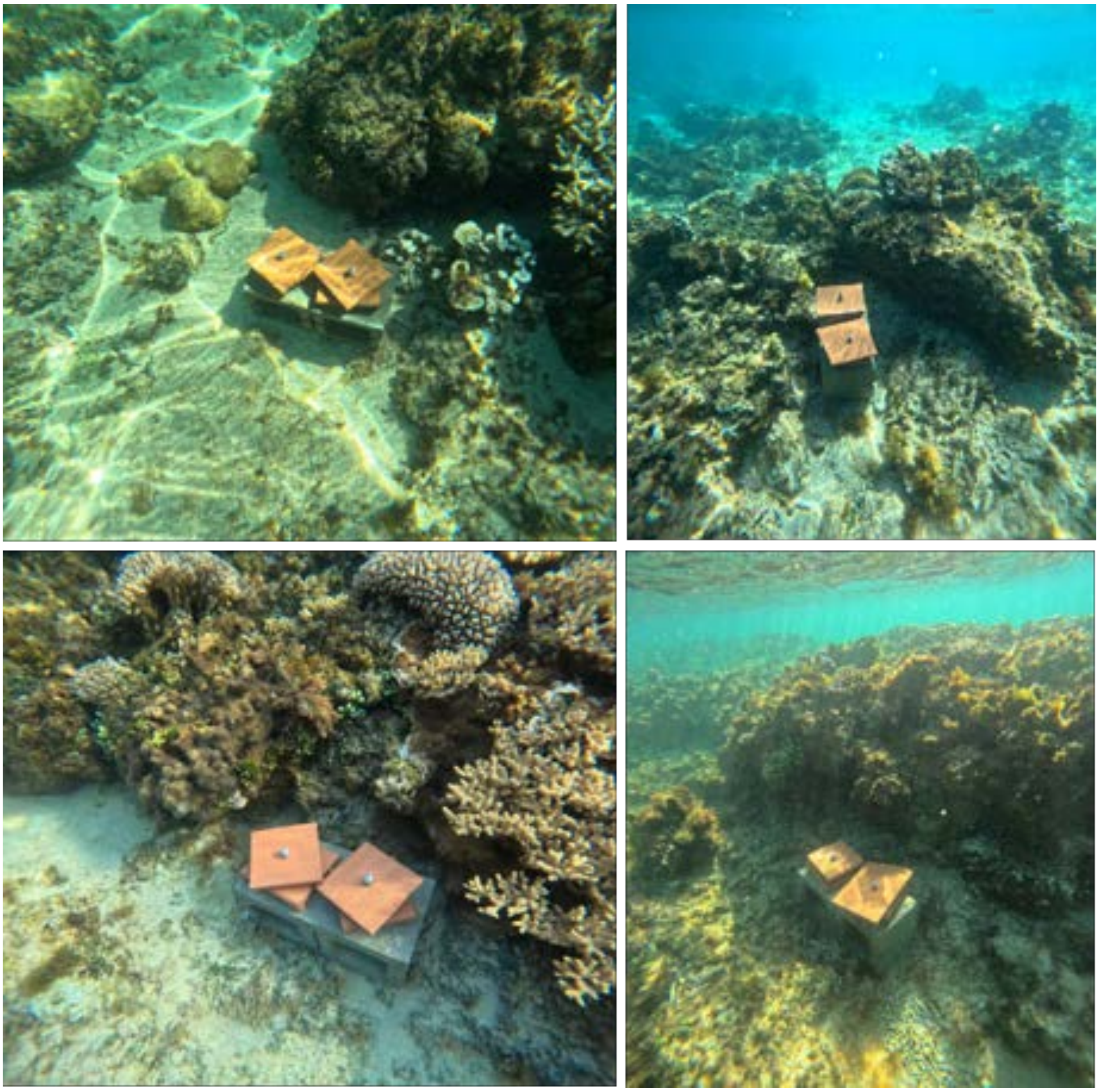


Figure 37. Deployed coral settlement tiles.

Table 7. Location of deployed settlement tiles (deployed December 2023).

Location	Latitude	Longitude
Cemetery Bay	29º 03.5554' S	167 º 58.0884' E
	29º 03.5583' S	167 º 58.0876' E
	29º 03.5625' S	167 º 58.0797' E
Slaughter Bay	29º 03.5717' S	167 º 57.5745' E
	29º 03.5787' S	167 º 57.5732' E
	29º 03.5754' S	167 º 57.5695' E
	29º 03.5691' S	167 º 57.5785' E
Slaughter Bay (Pier)	29º 03.5195' S	167 º 57.3371' E
	29º 03.5248' S	167 º 57.3251' E
	29º 03.5236' S	167 º 57.3285' E
	29º 03.5244' S	167 º 57.3352' E

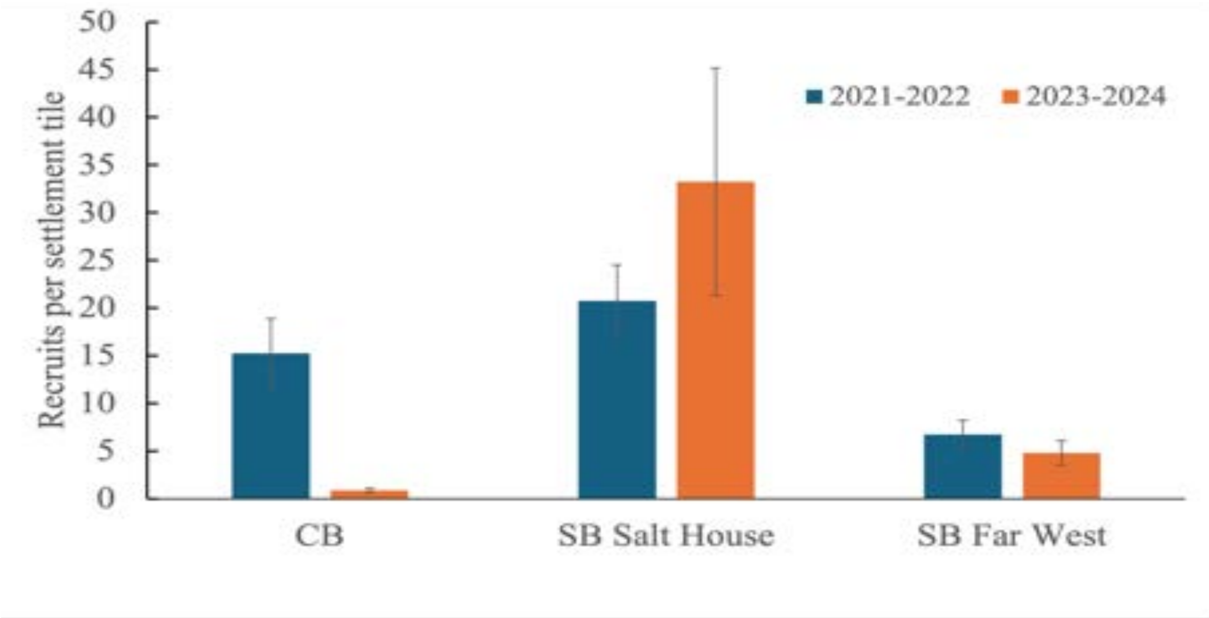


Figure 38. Coral recruitment patterns across the bays for the 2021-2022 and 2023-2024 spawning periods.

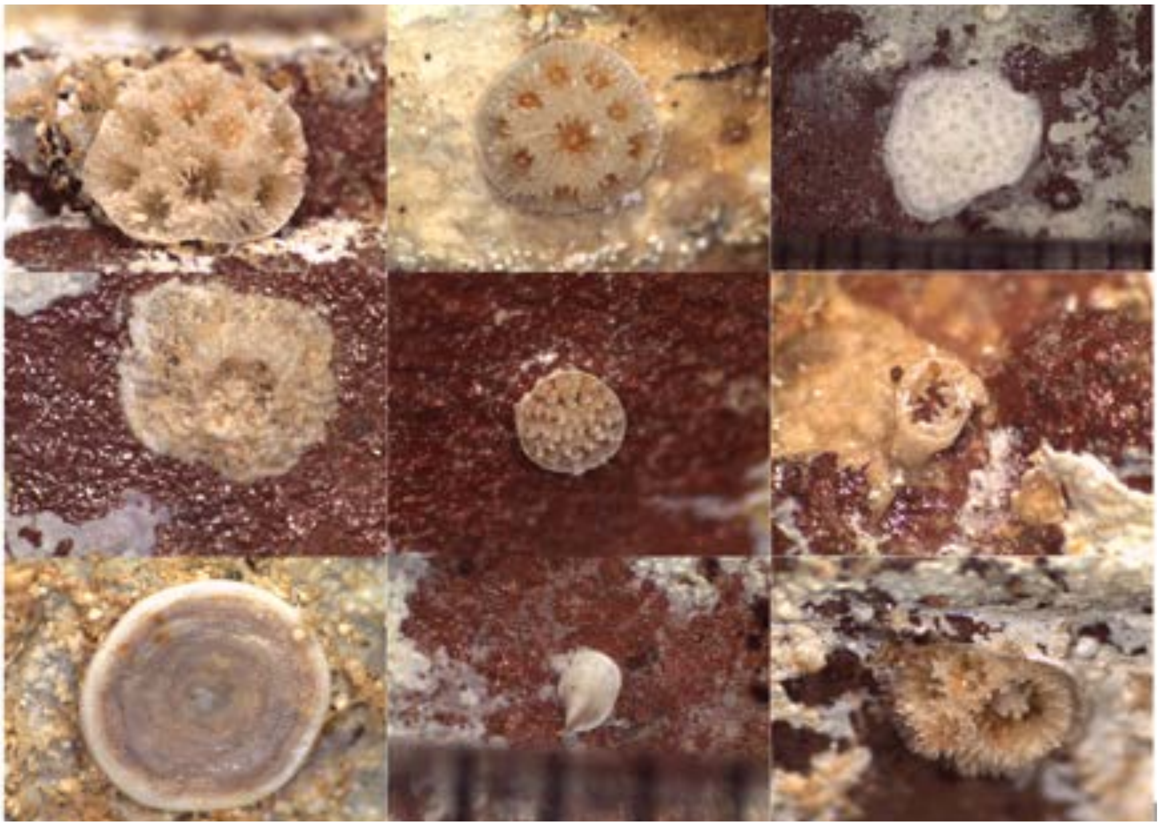


Figure 39. Recruits observed on settlement tiles following 4-month deployment in lagoonal reefs.

Coral recruitment is evident across the Norfolk Marine Park lagoonal reefs in both the summers of 2021-22 and 2023-24 (Figure 38, 39). The number of recruits per tile was higher in Cemetery Bay in 2021/22 but not statistically different at the Slaughter Bay Salt House and Far Western Slaughter Bay between the 2 years. Coral recruitment is often highly variable year to year and is influenced by a variety of factors including currents and weather, as coral larvae generally stay in the water column for 9-12 days post fertilisation, in addition to the fecundity of the source population. Given this, high interannual variability comparison between locations must be considered carefully. Recruit abundance recorded at Norfolk reef is similar to that previously recorded in studies on the GBR (Dunstan & Johnson, 1998). However, coral reproduction and subsequent coral recruitment are well documented to be reduced when both corals and coral larvae are exposed to heat stress conditions. The timing of coral spawning and recruitment on Norfolk Marine Park reefs in December to February, coinciding with the accumulation of heat stress in the Norfolk Marine Park, indicates that these reefs may have higher susceptibility to the negative impacts of heat stress on coral recruitment in the region which requires ongoing investigation.

Community Outreach and Engagement Activities 2020-24

Associate Professor Troy Gaston and Dr Charlotte Page (University of Newcastle) delivered outreach activities for approximately 50 year 7, 8 and 9 students from the Norfolk Island Central School on the 5th December (images below). Associate Professor Gaston and Associate Professor Ainsworth delivered outreach activities for approximately 15 year 10 students in March.

Associate Professor Tracy Ainsworth (University of New South Wales), Associate Professor Bill Leggat (University of Newcastle) and Professor Jane Williamson (Macquarie University) gave a public presentation at the Norfolk Discovery Centre on the 13th December 2023. This included an outline of the Citizen Science web page (https://coralreefhealth.com) where they answered questions on the use of the website. In addition, Dr Page and PhD candidates Sophie Vuleta (UNSW) and James Wong (UoN) gave presentations at Castaways Resort in March 2024.

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