CORAL SEA MARINE PARK

CORAL REEF HEALTH SURVEY 2022

Report on reef surveys // February - March 2022

Produced for Parks Australia, June 2022
by James Cook University

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In responding to a tender from Parks Australia, a team of researchers representing the ARC Centre of Excellence for Coral Reef Studies at James Cook University (JCU) completed surveys of fifteen reefs in the Coral Sea Marine Park.

On the cover – A school of fusiliers over a coral bommie at Flinders Reef, central Coral Sea Marine Park, 24th February 2022. Photograph taken by Victor Huertas

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We acknowledge the Traditional Owners of the
sea country in which this research and monitoring
was conducted and pay our respects to their
elders, past present, and emerging.

Two traditional owners of the Meriam people joined our team during previous surveys of Ashmore and Boot Reefs in October 2018, and can be seen here snorkelling over Ashmore Reef.
Image credit: Martin Russell

Acknowledgements

This *Coral Reef Health in the Coral Sea Marine Park* research project was jointly funded by the Director of National Parks, Australia and the ARC Centre of Excellence for Coral Reef Studies. The surveys were conducted by Andrew Hoey, Eva McClure, Victor Huertas, Morgan Pratchett, Deborah Burn, and Josie Chandler. The report was prepared by Andrew Hoey, Eva McClure, and Deborah Burn, with important contributions by Josie Chandler, Ben Cresswell, Gemma Galbraith, Victor Huertas and Morgan Pratchett. Hugo Harrison provided the R scripts and analytical pipelines used to summarise data and produce figures.

The authors wish to thank the relevant staff at Parks Australia for managing this project, with particular mention given to Mitchell Baskys (Senior Marine Parks Officer, Coral Sea Marine Park), Martin Russell (Manager, Coral Sea Marine Park) and Russell Gueho (Director, East Region). We also thank Mitchell Baskys for his assistance in deploying, collecting and processing the coral settlement tiles during the October-November 2021 and February-March 2022 voyages.

Additional funding was provided through an Our Marine Parks Round Two Grant from the Department of the Environment and Energy to support the surveys of deeper reef habitats (Ref No 4-FISTKU, Diving into the Deep: The unique habitats of the Coral Sea).

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We are indebted to Rob Benn (owner/skipper) and the entire crew and staff of MV Iron Joy for enabling this work, despite sometimes trying conditions.

1. Executive Summary

The Coral Sea is a critically important and significant ecosystem, which (like coral reefs globally) is increasingly threatened by changing environmental conditions, particularly ocean warming. Previous surveys conducted in 2020 and 2021 showed shallow reef habitats across the Coral Sea Marine Park (CSMP) experienced severe and widespread bleaching in early 2020, with almost two-thirds of all corals surveyed across the CSMP being bleached, and leading to a substantial (39%) decline in coral cover across the CSMP in 2021.

James Cook University was commissioned by Parks Australia to assess:

(i) the latest condition of benthic, fish and invertebrate communities,

(ii) any ongoing impacts of the 2020 bleaching event on benthic, fish and invertebrate communities, and

(iii) gain some understanding of the potential resilience and recovery of corals following the 2020 bleaching event.

The project undertook detailed surveys of coral, fish and macro-invertebrate communities and associated reef health at fifteen CSMP reefs over two voyages in November 2021, and February-March 2022. Surveys were conducted to provide rigorous quantitative information on temporal (i.e., 2020, 2021, and 2022) and spatial (i.e., among reefs and regions) patterns in (i) cover and composition of corals and macroalgae; (ii) regional patterns of biodiversity; (iii) coral health, injury, and recruitment; and (iv) abundance and

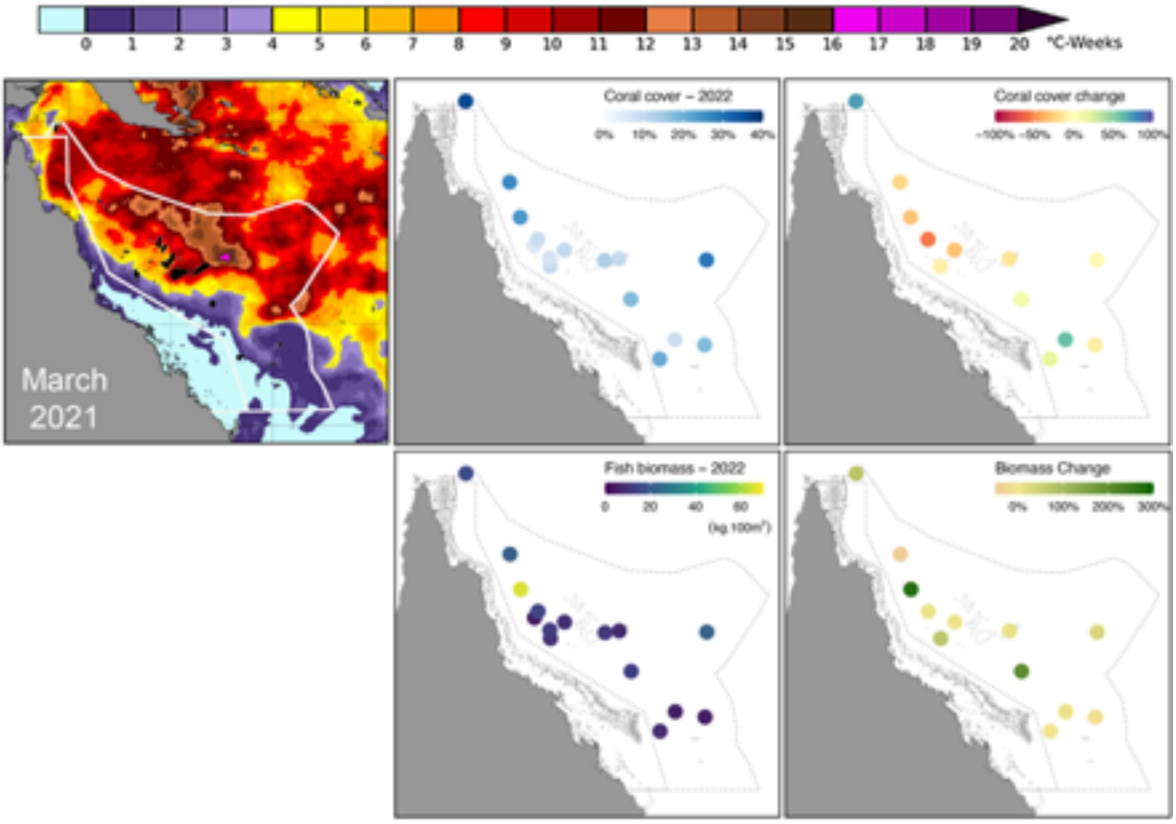

Figure 1. Summary of spatial variation in the heat stress experienced across the Coral Sea Marine Park in March 2021, and the effects on shallow water reef communities: the cover of live corals and biomass of reef fishes ~1 year after the 2021 heat stress event, and relative decline in coral cover and fish biomass on 12 reefs between the most recent surveys. Values are averaged across habitats and sites on each reef, and based on surveys conducted during 2021 and 2022. The only exceptions are two ‘bright spot’ reefs, Ashmore Reef in the far north and Mellish Reef in the far east, that were surveyed in 2018 and 2022.

composition of reef fishes, sea snakes, and ecologically or economically important invertebrates.

The project surveyed 68 sites across 15 reefs in the CSMP, spanning 12.5 degrees of latitude (~1,600 km) from Ashmore Reef in the north (10.3°S) to Saumarez Reef in the south (22.8°S). The surveys revealed that CSMP wide shallow water coral cover decreased by 18% from 2021 to 2022, compounding on the 39% reduction in coral cover recorded from 2020 to 2021. This system-wide decline was driven by 26% and 28% declines in coral cover in the central and northern CSMP, respectively. In contrast, there was a small (4%) increase in total shallow water coral cover in the southern CSMP in 2022. Although only low levels of bleaching (Pale - Recently Dead) were recorded across CSMP reefs in February 2021 (6.8% of colonies surveyed), a large area of the central and northern CSMP was exposed to significant heat stress in March 2021 (Figure 1). The geographic footprint of this heat stress event coincides with the recorded declines in coral cover from our surveys. In the absence of other major disturbances, the recorded declines in coral cover are almost certainly attributable to the elevated ocean temperatures experienced in March 2021, and occurred against a shifted baseline of coral communities, with the abundance of bleaching sensitive coral taxa being reduced due to previous (i.e., 2016, 2017, and 2020) bleaching events.

Together with the variation in the decline in coral cover among regions, there were substantial differences in the change in coral cover among reefs within regions (e.g., ranging from an 8.7% increase at Marion Reef, to a 56% decline at Holmes Reef in the central CSMP, and 23% decline at Osprey Reef, to a 30% decline at Bougainville Reef in the northern CSMP), and sites within reefs (e.g., 18% decline at Herald 1 vs a 45% decline at Herald 4). Similar variation in coral loss was reported across relatively small spatial scales following the 2020 bleaching event and could reflect differences in the composition of coral communities (due to previous disturbances or natural variation), local environmental conditions, resilience to heat stress, and/or other identified factors and warrants further investigation.

The combined effects of the back-to-back 2020 and 2021 bleaching events in the CSMP have resulted in mean coral cover decreasing from 28% in 2020 to 16% in 2022 across all reefs surveyed, and decreasing from 27% in 2020 to 13% in 2022 across the eleven reefs surveyed in 2020, 2021 and 2022, a mean decline of 52%. Despite these declines in coral cover over the past 2 years, current coral cover in the CSMP (16%) is broadly comparable to estimates for the Great Barrier Reef following the 2016 and 2017 bleaching events (19%), and greater than the level seen as critical to avoid ecosystem collapse (>10%) in other reef systems. Moreover, while mean coral cover on central CSMP reefs (13.9%) is higher than historical estimates of 1-6% coral cover on some central CSMP reefs (i.e., Herald Cays, Chilcott Islet and Lihou Reef), four central CSMP reefs had coral cover < 10% (Flinders: 9.3%; Holmes: 9.2%; Heralds Surprise: 6.8%; Flora: 5.8%). In some reef systems, such low levels of coral cover have been shown to disrupt key processes and have lasting consequences for the diversity and functioning of these reefs, however it is unknown if low coral cover will have the same consequences in systems such as the CSMP where coral cover has been historically low. Further, the majority of coral colonies surveyed across the CSMP in 2021 were healthy, with only low levels of bleaching recorded (1–17% of colonies surveyed) among reefs. Continued monitoring over the next 5-10 years will be critical to assess whether coral populations and coral cover on these reefs recovers, or collapses, and any associated changes in reef fish and invertebrate communities.

The density of juvenile corals (an indicator of the recovery potential of coral populations) recorded across CSMP reefs in 2022 was low (23 juveniles per 10m^2), although represented a 41% increase on densities recorded in 2021 (16 juveniles per 10m^2). While the increase in the densities of juvenile corals will aid in the recovery of the coral populations across CSMP reefs, the majority of these juvenile corals likely settled onto these reefs prior to the 2020 bleaching event, and as such the full impacts of the 2020 (and 2021) bleaching event on the supply and settlement of coral larvae are yet to be realised. Indeed, the settlement of coral larvae to four CSMP reefs (Flinders, Holmes, Bougainville, and Osprey Reefs) over the 2021-22 summer was extremely low (0.6 coral recruits per tile), and 1-2 orders of magnitude lower than that of reefs in the northern GBRMP (6.9 - 46.2 recruits per tile). In the absence of any previous data on coral settlement for the CSMP it is difficult to determine if rates of coral settlement are naturally low (i.e., due the isolation of CSMP reefs) and/or if the low settlement is a consequence of the 2020 and/or 2021 bleaching events. Irrespective of the cause such low rates of coral settlement will delay or limit the recovery of coral populations. Continued monitoring of coral settlement is essential to determine if rates of coral settlement are naturally low on CSMP reefs, and to detect any early signs of the replenishment and recovery of coral populations.

Large-scale coral mortality commonly leads to declines in reef-associated taxa that rely on corals for food and/or shelter. While there were no substantive changes in the abundances of macro-invertebrates (i.e., sea urchins, sea cucumbers, *Trochus*, *Tridacna* clams) on CSMP reefs in 2022, the abundance of sea snakes increased on southern CSMP reefs, and the abundance and biomass of reef fishes declined on southern and central, but not northern, CSMP reefs. These declines in the abundance and biomass of reef fish coincided with previous reductions in coral cover (i.e., from 2020 to 2021), and was largely driven by declines in small bodied planktivorous fishes (e.g., damselfishes), and corallivorous butterflyfishes that are reliant on live coral for shelter and/or food. Despite these declines, the biomass of reef fishes (a key indicator of reef health, together with coral cover) recorded across all reefs in the CSMP remained high (mean = 1,424 kg per hectare) and likely reflects the isolation and relatively low fishing pressure on CSMP reefs.

While the immediate, or short-term, impacts of the 2020 and 2021 bleaching events on CSMP reefs are already apparent, continued monitoring will be critical to assess any longer-term impacts on the structural complexity of habitats and reef associated fishes and invertebrates, and the potential recovery of shallow water coral assemblages across the CSMP.

The latest (2022) surveys revealed:

- Total shallow water coral cover decreased from 16% in 2021 to 13% in 2022 across the eleven reefs that were surveyed in each year, a mean decline of 18%. The change in coral cover varied among regions ranging from 28% decline in the northern CSMP, 26% decline in the central CSMP, to a 4% increase in the southern CSMP (24-73% among reefs). There was also considerable variation in the change in coral cover among reefs (e.g., 59% decline at Holmes Reef vs a 22% increase at Saumarez Reef), and among sites within individual reefs (e.g., 18% vs 45% decline at two sites on Herald Cays).
- Although only low levels of bleaching (6.8% of colonies) were recorded across CSMP reefs in

High coral cover on the sheltered slope of Ashmore Reef with abundant branching *Acropora* colonies. Image credit: Victor Huertas

February 2021, large areas of the northern and central CSMP were exposed to seawater temperatures well above those expected to cause bleaching-induced mortality in March 2021. In the absence of any other major disturbance, the observed declines in coral cover in 2022 are most likely attributable to elevated temperatures experienced in February-March 2021, and represents the fourth major bleaching event, and the second back-to-back bleaching event, in the CSMP in the past six years.

- Low to moderate levels of bleaching (pale – recently dead) were recorded across CSMP reefs in February 2022, ranging from 10.8% at Holmes Reef to 37.8% at Marion Reef. It is important to note, however, that the heat stress within the CSMP did not reach its peak until March 2022, several weeks after our surveys. Future monitoring is essential to determine the impacts of this event.

- The reduction in coral cover in 2022 (18% decline) while lower than the 39% decline recorded following the 2020 bleaching event, occurred against an increasing shifted baseline of coral communities, with the cover of bleaching-susceptible coral taxa being reduced following the 2016, 2017 and 2020 bleaching events. This suggests the 2021 bleaching was a major bleaching event, being both significant and widespread across much of the central and northern CSMP.

- Despite the considerable loss of live corals over the past two years, there were no substantial increases in macroalgae across the CSMP. The remaining coral cover on CSMP reefs (16% across all 15 reefs) is broadly comparable to recent estimates for the Great Barrier Reef (19%), and considerably higher than that of some central CSMP reefs (i.e., Herald Cays, Chilcott Islet and Lihou Reef) from the early 2000's.

- Four reefs in the central CSMP reefs had very low (< 10%) coral cover (Flinders: 9.3%; Holmes: 9.2%; Heralds Surprise: 6.8%; Flora: 5.8%), that are approaching levels that can disrupt key processes and have lasting consequences for the diversity and functioning of these reefs. Continued monitoring over the next 5-10 years will be critical to assess whether coral populations on these reefs recover, or collapse, and any associated changes in reef fish and invertebrate communities.

- Despite a 41% increase in the density of juvenile corals, the settlement of coral larvae and the density of juvenile corals was low across CSMP reefs. The lower densities of settling and juvenile corals within the CSMP likely reflects the isolated nature of these reefs, and will likely prolong the recovery of coral populations following disturbances, such as the 2020 and 2021 bleaching events.

- There was a small increase in the abundance of sea snakes on southern CSMP reefs, however there no substantial or consistent changes in the abundance of sea snakes or macro-invertebrates (i.e., sea urchins, sea cucumbers, *Trochus*, *Tridacna* clams) on CSMP reefs in 2022.

- Twelve fish species that had not been recorded during surveys or observations on the previous voyages (2018-2021) were recorded during the 2022 surveys, taking the total fish species recorded in the CSMP during the past five years of surveys to 640 species. All of these twelve species are common on the GBR. No new species of coral were observed.

- There were declines in the species richness (4-15%) and abundance (14-27%) of reef fish communities within the southern and central CSMP from 2021 to 2022. These declines were driven by declines in corallivorous, and planktivorous fishes, and coincided with reductions in coral cover following the 2020 bleaching event. In contrast, there was a large increase in the biomass (240%) of fishes in the northern CSMP, driven by an increase in excavating parrotfishes at Bougainville Reef.

- Ashmore, Mellish and Bougainville Reefs, previously identified as 'bright spots' in terms of coral cover, richness and/or fish biomass, were again standouts. All three reefs appear to have been less adversely affected by the recent bleaching events than other CSMP reefs, with coral cover on Ashmore Reef increasing by 35% over the past 4 years (2018: 26.5%; 2022: 35.9%), and remaining largely unchanged (*ca.* 30%) on Mellish Reef over the same period. The other two bright spot reefs, Boot and Moore Reefs, were not surveyed in 2022 .

- In addition to the monitoring undertaken, several additional projects were leveraged from this collaboration between James Cook University and Parks Australia and capitalised on available space during the voyages. These leveraged projects involved 10 researchers from 3 institutions and represent a significant in-kind contribution. Collectively, these projects will increase our understanding of the ecology of deep reef habitats, the movement and connectivity of sharks and large reef fishes, island-reef connectivity and taxonomy of coralline algae within the CSMP.

In conclusion, the 2020 and 2021 bleaching events have had a significant impact on coral and reef fish communities across most CSMP reefs surveyed, the only exceptions being the Ashmore and Mellish Reefs. The 2021 bleaching event was both significant and widespread, indicating it was a major event, and the fourth such major bleaching event in the CSMP in the last 6 years (2016, 2017, 2020, and 2021). These recent bleaching events in the CSMP are reflective of the increasing frequency and intensity of marine heatwaves that are affecting coral reefs globally. Continued surveys of CSMP reefs will be critical to assess the longer-term and ongoing impacts of these bleaching events on reef fishes and invertebrates, and the potential recovery and resilience of these isolated reef systems in the absence of other stressors.

Recommendations for future research and monitoring:

- Continued annual monitoring of the sites surveyed in 2020, 2021 and 2022 is critically important to determine any longer-term effects of the 2020 and 2021 bleaching events on reef fish and other reef associated species, the potential recovery of coral assemblages, and future disturbances that may push coral cover toward critical thresholds of collapse.
- Given the increasing incidence of major disturbances impacting CSMP reefs in recent years, coupled with predicted increases in the frequency and intensity of disturbances affecting reefs globally, and the logistical constraints of working in the CSMP (i.e., isolation and exposure) regular (annual or biennial) surveys are critical. In the absence of regular monitoring, the causes of any changes in reef communities would be largely unknown, severely limiting the capacity of managers to understand the health status of these reefs and make informed decisions.
- Annual monitoring of coral, fish, sea snake and invertebrate communities on 9-12 reefs (2-5 reefs in each CSMP region), with all 22 CSMP reefs to be surveyed once every 3-5 years.
- Future regular surveys of CSMP reefs should include, and prioritise, surveys of the five ‘bright spot’ reefs (i.e., Ashmore, Boot, Bougainville, Moore and Mellish Reefs). There are no suitable anchorages at Boot or Moore Reefs, and as such these reefs can only be surveyed when weather conditions allow. Contingencies should be incorporated into voyages schedules to survey alternate reefs and/or sites should weather conditions preclude access to Boot or Moore Reefs.
- Continue dedicated sampling to directly quantify the settlement of coral larvae at a subset of accessible innermost reefs (e.g., Flinders, Holmes, Bougainville and Osprey Reefs). This would require an additional voyage in Oct/Nov to deploy settlement tiles, and may be achieved through increased communication and collaboration among government and non-government organisations (e.g., dive tourism and fishing charter operators).
- At least 2 days should be spent at each of the representative reefs to allow for surveys of additional habitats and targeted research and monitoring, and 5-7 days at a select reef each year to facilitate a more comprehensive understanding of the habitat composition and health, and to increase our understanding of links between island, shallow reef, and deep reef ecosystems.
- Repeat the 3-dimensional habitat mapping of sites mapped during the 2019-2020 voyages in the next 3-4 years. Matching the sites previously mapped will allow the relative contribution of live corals versus the underlying reef matrix and coralline algae in providing habitat structure to be assessed.
- Quantify rates of settlement and growth of coralline algae to provide important insights into the creation and persistence of 3-dimensional structures on these reefs.
- Deploy temperature and/or current loggers at key locations to investigate the potential causes (e.g., water temperature, upwelling, water flow) of the observed variation in coral cover, coral mortality, and coral recruitment within individual reefs.
- Comparable research and monitoring in all regions within and bordering the CSMP (i.e., GBRMP, Temperate East Marine Parks Network, New Caledonia, Vanuatu, Solomon Islands and Papua New Guinea) to establish the biogeographical significance and connectivity of the CSMP.

A turtle-headed sea snake (*Emydocephalus annulatus*) swims near one of the survey transects at Diamond Reef, in the Central Coral Sea Marine Park.

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2. Background

The Coral Sea is situated off Australia's north-east coast, bounded by Papua New Guinea to the north, the Solomon Islands, Vanuatu and New Caledonia to the east, and the Tasman Sea to the south. The Coral Sea is a critically important and environmentally significant ecosystem owing to i) the extent and diversity of habitats (including many unique habitats), ii) the unique fauna these habitats support, iii) the provision of habitats for species of conservation significance and, iv) connectivity with Australia's Great Barrier Reef (GBR) and other western Pacific provinces (Ceccarelli et al. 2013; Hoey et al. 2020). Australia's marine estate within the Coral Sea is managed through the Coral Sea Marine Park (CSMP) that extends from the eastward margin of the Great Barrier Reef Marine Park (GBRMP) to the outer extent of Australia's Exclusive Economic Zone, some 1,200km offshore (Figure 2.1). The CSMP is among the world's largest and most isolated marine parks, encompassing an area of 989,836km^2, and is managed by the Australian Government, Director of National Parks. Within the CSMP there are approximately 56 islets and cays and 20 widely separated shallow reef systems, ranging from Ashmore and Boot reefs adjacent to the Torres Strait in the north, to Cato Reef in the south, and Mellish Reef (>1,000 km east of Cairns) in the far east. These shallow reefs systems, including Lihou Reef one of the world's largest atolls (~2,500km^2) have a combined reef area of 15,024 km^2; equating to 1.5% of the total CSMP (DNP 2018). In contrast, the GBRMP is approximately one-third the size (334,400km^2) and contains over 100-fold more reefs (~3,000 reefs) than the CSMP.

The reefs of the CSMP are fundamentally different to the more inter-connected reefs of the GBRMP, and are largely shaped by the geomorphic, oceanographic and environmental conditions of the region. Reefs within the CSMP rise from seamounts on four major deep-water plateaus; the Eastern Plateau in the north, the Queensland Plateau in the central region, and the Marion and Kenn Plateaus in the south, such that individual reefs are separated by oceanic waters up to 4,000 m deep (Davies et al.1989, Collot et al. 2011). Given the isolation of these reefs, potential connectivity among them is likely facilitated by major ocean currents. The major oceanographic features affecting the Coral Sea are west-flowing jets of the Southern Equatorial Current (SEC), which strengthen during the summer months and bifurcate on the Australian continental shelf to form the south-flowing East Australian Current (EAC)

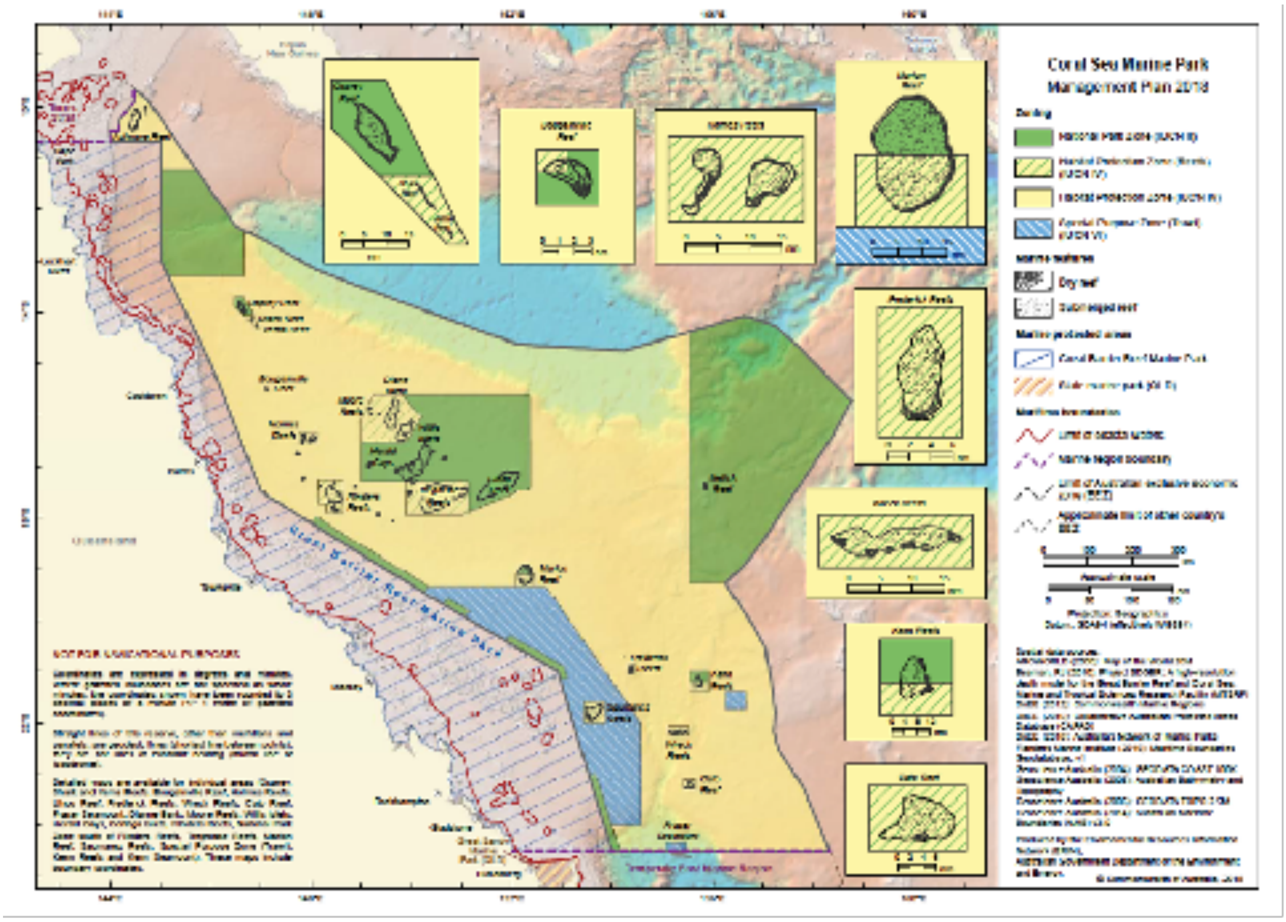


Figure 2.1. Map of the Coral Sea Marine Park, showing management zones implemented in July 2018. (Source: parksaustralia.gov.au)

and its eddies, and the Hiri Gyre in the Gulf of Papua to the north (Ridgway et al. 2018, Rousselet et al. 2016).

The CSMP is one of the most isolated coral reef environments in Australian waters, with limited exposure to direct human pressures (e.g., fishing, run-off) relative to more accessible coastal reefs. Despite this isolation, coral cover on many reefs within the CSMP has historically been relatively low (ca. 1-6% cover; Ayling and Ayling 1985, Oxley et al. 2003, Ceccarelli et al. 2008, Hoey et al. 2020, 2021). In particular, estimates of coral cover on reefs in the central CSMP indicate coral cover has been relatively low for at least the past 30+ years, with this low coral cover linked to repeated exposure to severe tropical cyclones and more recently climate-induced coral bleaching (Ceccarelli et al. 2013, Harrison et al. 2019; Hoey et al. 2020, 2021). These disturbances, coupled with limited recovery potential due to poor connectivity and supply of coral larvae from other sources, most likely account for sustained low coral cover on these reefs (Oxley et al. 2003, 2004, Ceccarelli et al. 2008).

The shallow water reef habitats of the CSMP support unique coral and reef fish communities that are distinct from those of the adjacent GBRMP, and share many species with reefs in the Tasman Sea to the south (i.e., Elizabeth and Middleton Reefs and Lord Howe Island), and nations to the east (New Caledonia, Vanuatu and the Solomon Islands; Hoey et al. 2020). While there is some differentiation of fish and coral communities among the northern, central, and southern regions of the Coral Sea, a striking feature of these reefs is the diversity of reef fish (>600 species) and the high abundance and biomass of sharks (mainly the grey reef shark, *Carcharhinus amblyrhynchos*, and the silvertip shark, *C. albimarginatus*) and other large predatory fishes (Ceccarelli et al. 2013, Stuart-Smith et al. 2013, Hoey et al. 2020, 2021). The high biomass of large predatory fishes is comparable to the other isolated reef systems, such as the Chagos Archipelago in the central Indian Ocean (Graham and McClanahan 2013), and likely reflects the limited fishing that occurs on these reefs.

Despite the isolated nature and hence limited direct human pressures on CSMP reefs, they are increasingly being exposed to the effects of climate change. Indeed, five major coral bleaching events have been recorded in the CSMP in the past two decades (2002, 2004, 2016, 2017 and 2020), with three of these occurring in the past six years, and the most recent event being the most severe and widespread (Oxley et al. 2004, Harrison et al. 2018, 2019, Hoey et al. 2020, 2021). Other bleaching events may have also affected CSMP reefs but went undetected due to its isolation and infrequent scientific surveys. These bleaching events reflect the increasing frequency and intensity of marine heatwaves that are affecting coral reefs globally (van Hooidonk et al. 2016; Hughes et al. 2018; Figure 2.2), and are becoming a major driver of the cover and composition of coral communities on contemporary reefs, and the assemblages of reef fish and other reef-associated taxa they support (e.g., Bellwood et al. 2006, 2012; Richardson et al. 2018). The effects of these bleaching events, and other major disturbances, may be particularly pronounced on isolated reefs such as those in the CSMP due to the reliance on self-recruitment of coral larvae (i.e., larvae spawned from adult corals on the same reef rather than those nearby) to replenish coral populations (Gilmour et al. 2013).

The 2020 bleaching event in the CSMP was severe and widespread, with 63% of all corals surveyed across 16 reefs exhibiting heat stress (from paling to recently dead) from high ocean temperatures in February 2020 (Hoey et al. 2020), which led to a 39% reduction in total shallow water coral cover across 13 CSMP reefs in February 2021 (2020: 28% coral cover; 2021: 17% coral cover; Hoey et al. 2021). It is also important to consider that the 2020 bleaching occurred against a shifted baseline of coral communities, with the abundance of bleaching sensitive coral taxa being reduced due to the 2016 and 2017 bleaching events (Harrison et al. 2019). There was, however, considerable variation in the decline in coral cover among regions (17% and 43% declines in the northern and central CSMP, respectively), among reefs (13% - 73% declines), and

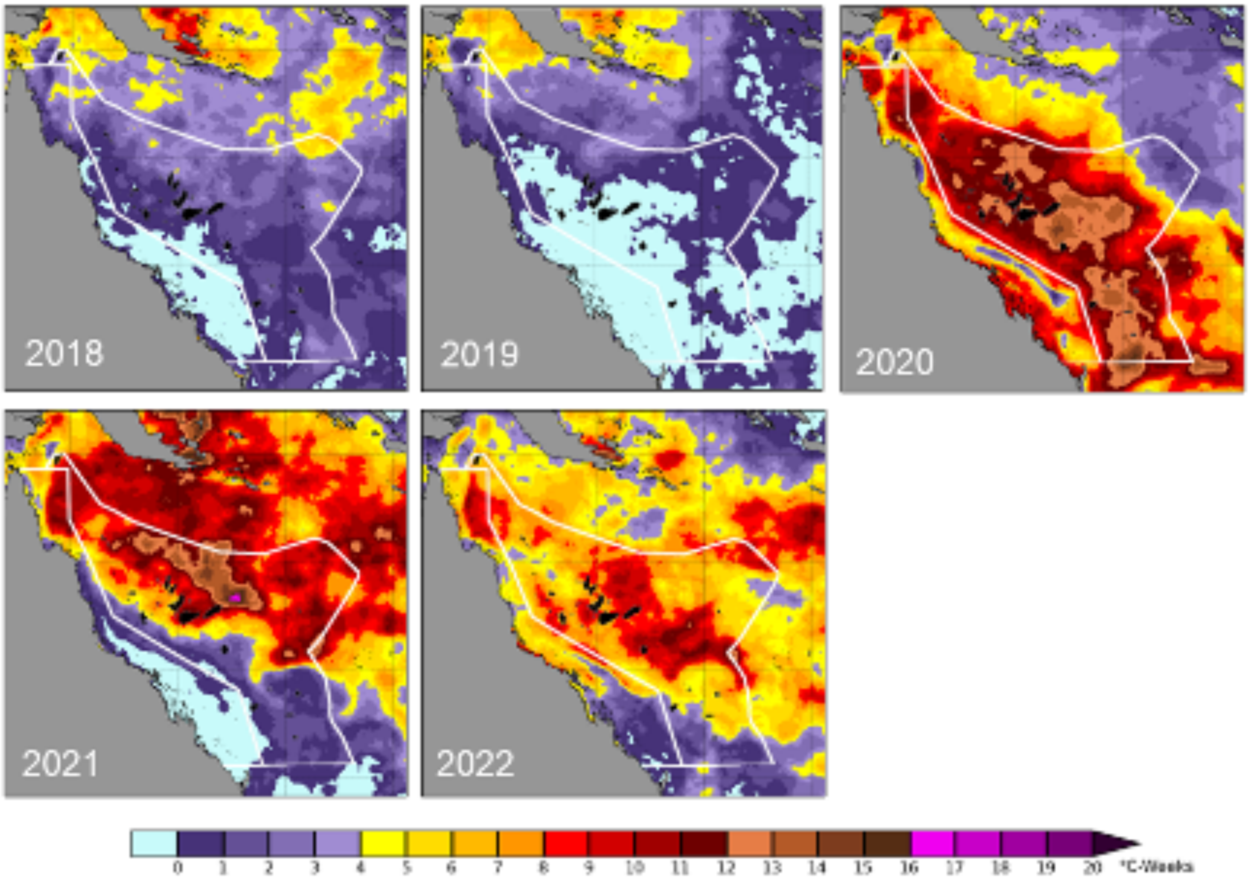


Figure 2.2 Comparison of the maximum Degree Heating Weeks (DHW) experienced throughout the Coral Sea Marine Park during 2018, 2019, 2020, 2021, and 2022. Note the maximum DHW in 2021 and 2022 occurred in March of each year. Images produced using the NOAA CRW 5km product v3.1

sites within reefs (19 - 59% declines; Hoey et al. 2021). This variation in coral loss across relatively small spatial scales could reflect differences in the composition of coral communities, local environmental conditions, resilience to heat stress, and/or other identified factors. Equally, these factors could affect the potential recovery of coral populations, as well as the associated assemblages of reef fish and invertebrates. Further, while the mortality of corals due to bleaching are typically realised in the first few months following the heat stress, although some corals can take up to 10 months to die (Baird and Marshall 2002), protracted declines are often observed for other taxa that don't rely directly on corals for food or shelter (e.g., Graham et al. 2007). Future surveys are critical to assess the potential recovery of shallow water coral assemblages following the 2020 bleaching event, and any ongoing effects of coral loss on associated fish and invertebrate communities.

2.1 Objectives and scope

The purpose of this study was to provide comprehensive assessments of the current condition of benthic and fish communities within the CSMP, assess the impacts of the 2020 bleaching event on benthic, fish and invertebrate communities throughout the CSMP, and gain a better understanding of the potential resilience and recovery of corals.

Surveys were conducted at fifteen reefs throughout the CSMP following the methods of Hoey et al. (2020, 2021). At each site, surveys were conducted along three replicate transects within each of two habitats (reef crest: 1-3m depth; reef slope: 7-10m depth) to provide rigorous quantitative information on spatial (i.e., among reefs and regions) and temporal patterns in:

i) benthic cover and composition, including the percentage cover for hard (Scleractinian) and soft (Alcyonarian) corals, macroalgae, and other sessile organisms,

ii) structural complexity of reef habitats,

iii) regional patterns of biodiversity, based on species lists for scleractinian corals and reef fishes,

iv) coral health and injuries caused by coral bleaching, disease, or coral predators (e.g., *Acanthaster* spp. and *Drupella* spp.),

v) coral recruitment (using settlement tiles) and abundance of small/ juvenile corals (<5cm diameter), as a proxy of coral recruitment and population replenishment,

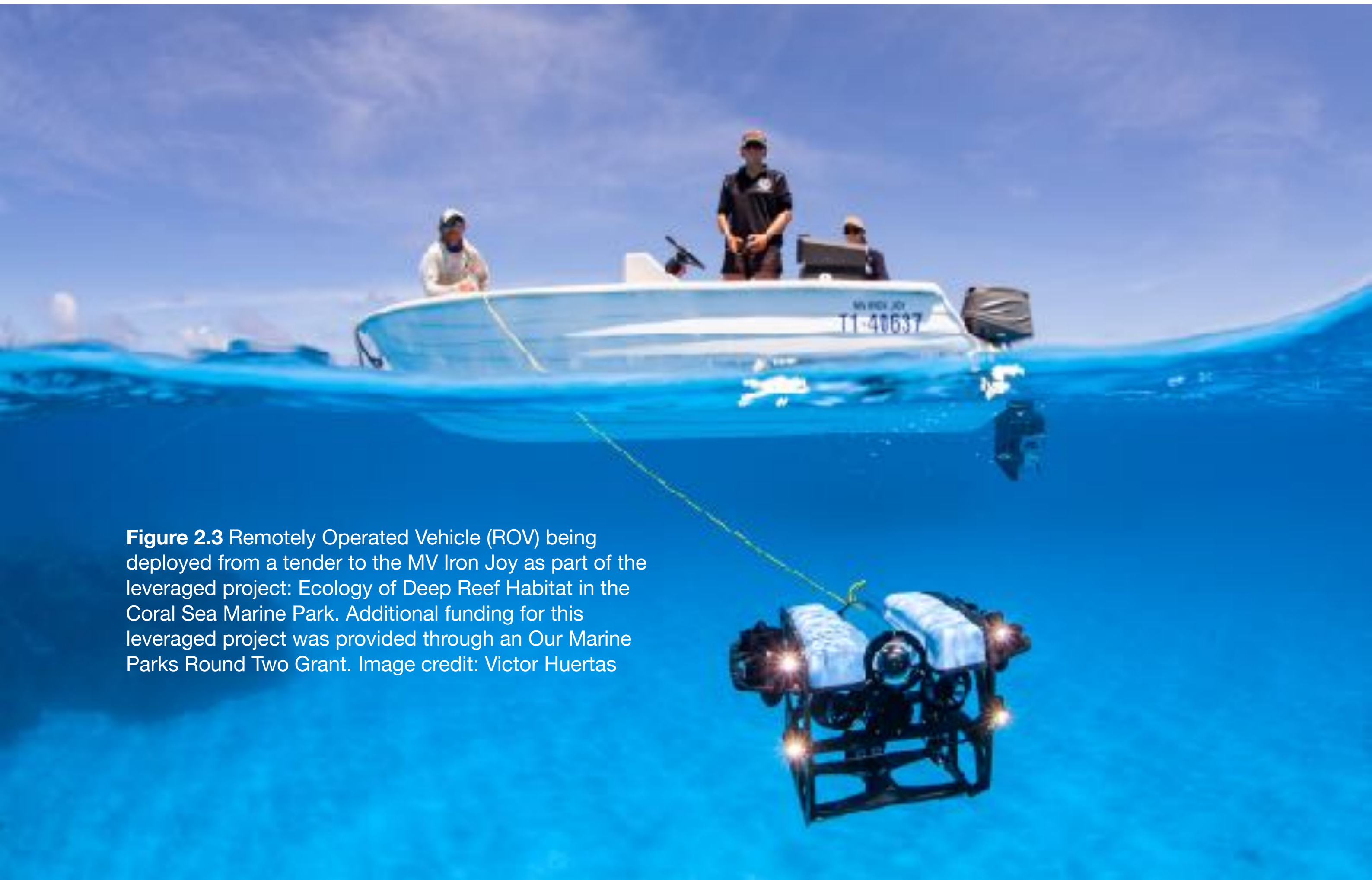


Figure 2.3 Remotely Operated Vehicle (ROV) being deployed from a tender to the MV Iron Joy as part of the leveraged project: Ecology of Deep Reef Habitat in the Coral Sea Marine Park. Additional funding for this leveraged project was provided through an Our Marine Parks Round Two Grant. Image credit: Victor Huertas

vi) size, abundance and composition of reef fish assemblages,

vii) abundance of holothurians, urchins and other ecologically or economically important reef-associated invertebrates, and

viii) the abundance and size of sea snakes

As well as the objectives listed above, several projects were leveraged from this collaboration between James Cook University and Parks Australia and capitalised on available vessel space during the voyage. These leveraged projects include:

i) Movement and population structure of sharks and large fishes within the CSMP;

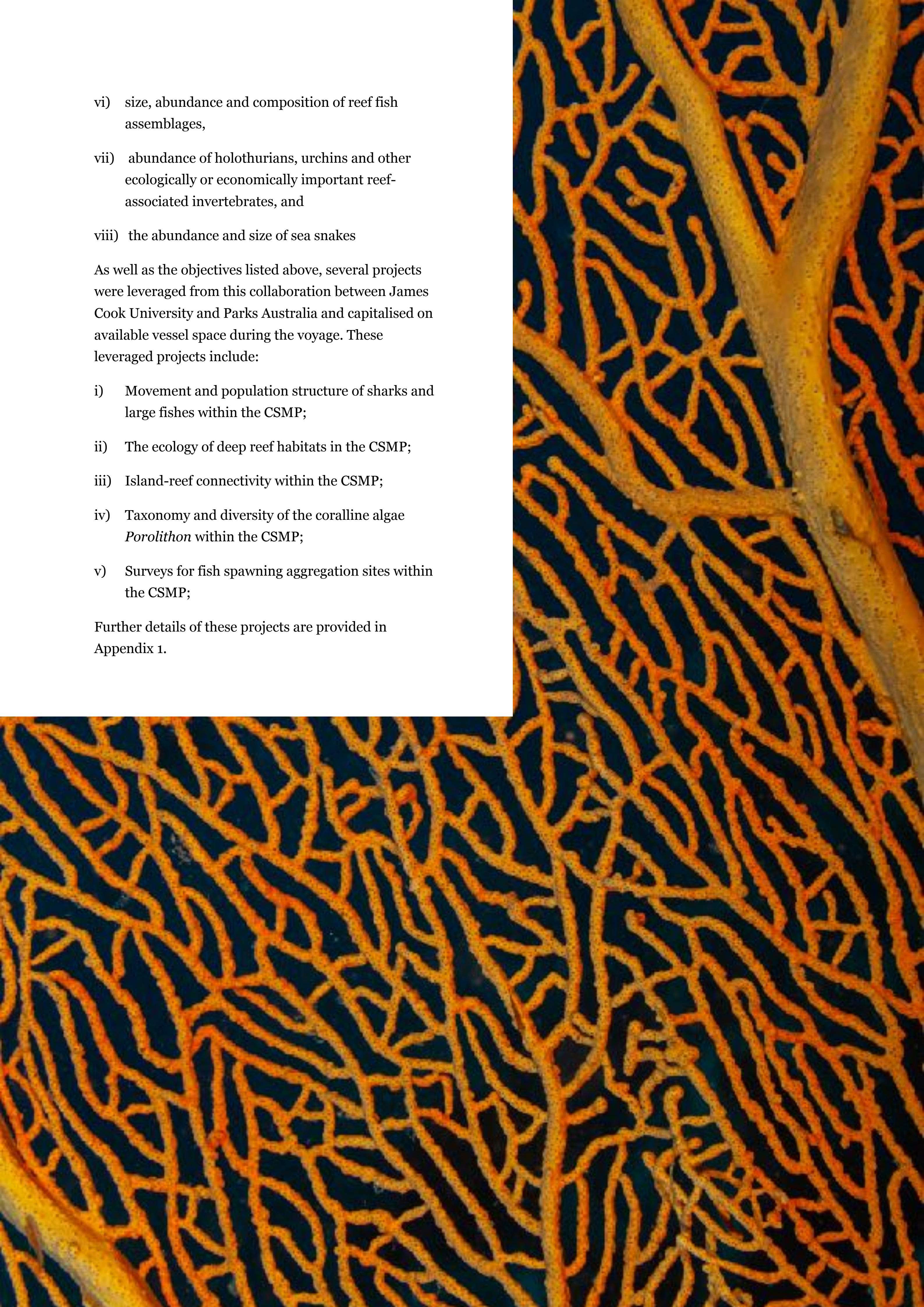
ii) The ecology of deep reef habitats in the CSMP;

iii) Island-reef connectivity within the CSMP;

iv) Taxonomy and diversity of the coralline algae *Porolithon* within the CSMP;

v) Surveys for fish spawning aggregation sites within the CSMP;

Further details of these projects are provided in Appendix 1.



3. Methods

29 days

15 reefs - 68 sites

20 km of UVC surveys

>450 diver hours

Surveys were undertaken at 63 sites across 14 reef systems within the CSMP during a 29-day voyage, 8th February – 8th March 2022 (Figure 3.1). The 14 reefs surveyed were southern CSMP: Saumarez, Kenn, Frederick Reefs; central CSMP: Flinders (north and south), Flora, Heralds Surprise, Holmes (east and west), Lihou, Marion and Mellish Reefs, Herald Cays, and Diamond Islets; northern CSMP: Bougainville and Osprey Reefs (Appendix 2). We were unable to survey Moore Reef in the central CSMP as planned due to unfavorable weather conditions at the time of the surveys (a tropical cyclone was predicted to form to the north of Moore Reef). An additional five sites were surveyed during a separate voyage to Ashmore Reef in the far north of the CSMP during November 2021. To facilitate direct comparisons in coral health and reef condition among years we re-visited the sites that were surveyed during the 2020 bleaching event (Hoey et al. 2020), or if the reef wasn't surveyed in 2020 (i.e., Mellish and Ashmore Reefs) we revisited sites that had been surveyed prior to 2020. Sites were relocated using GPS waypoints and a bearing of the direction of the transects from that waypoint. Additional sites were established on two reefs in the central CSMP (Flora and Heralds Surprise Reefs) that had not previously been surveyed by our team.

3.1 Sampling design

At each site, surveys were generally conducted within each of two different habitats, i) the reef crest (approximately 1-3m depth) and ii) the reef slope (9-10m depth, where possible). The only exceptions to this were some sites at Mellish and Holmes Reefs where the reef crest could not be safely accessed due to excessive surge and wave action. In shallow reef environments (mainly inside lagoons or in back reef

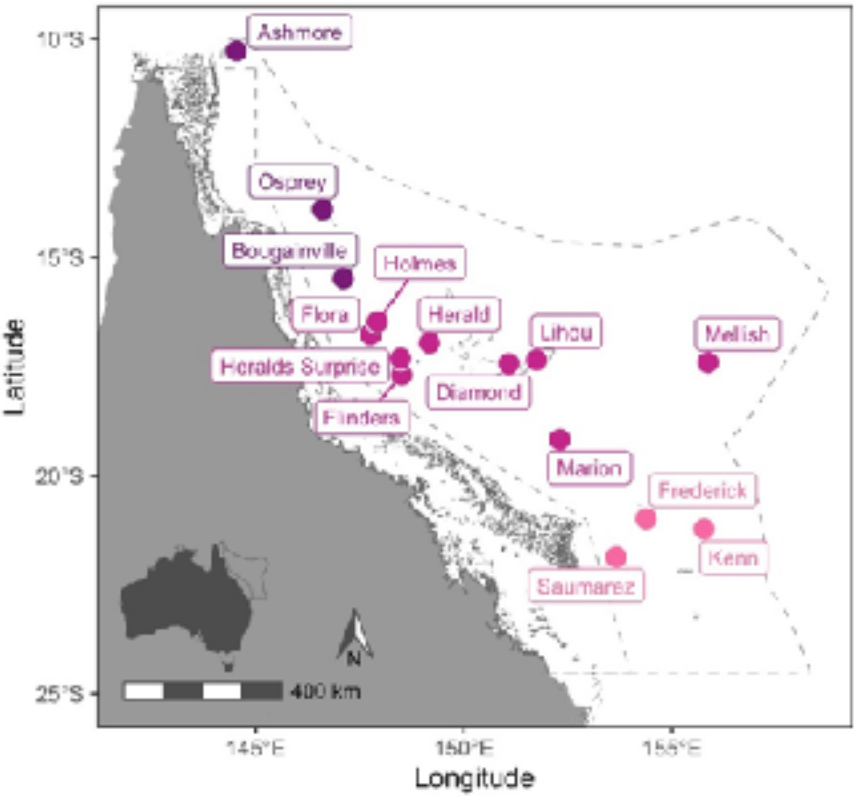


Figure 3.1 Map of the surveyed reefs in the Coral Sea Marine Park in February and March 2022, and November 2021 (Ashmore Reef). Colours relate to the regional allocation of reefs in the southern (pink), central (magenta), and northern (purple) Coral Sea Marine Park which are used throughout the report. Regional allocation is based on our current understanding of coral and fish communities.

environments), where maximum depths were less than 9m, the reef slope transects were run along the deepest margin of contiguous reef habitats, avoiding extensive areas of sand or rubble. Similarly, it was not always possible to survey the reef crest, due to low tides, limited water depth, and/ or large swells, and in those cases the reef crest transects were often run just below the outermost edge of the reef crest (2-4m).

In each depth zone at each site, three replicate 50m transects were run parallel to the depth contour, with up to 10m between successive transects. Surveys were conducted by a 4-person dive team, whereby the lead diver deployed the transect tape while simultaneously recording the size and identity of all larger (>10 cm total length, TL) or motile fish species, within a 5m wide belt (following Hoey et al. 2020, 2021). Deploying the transect while simultaneously recording fishes minimises disturbance prior to censusing, thereby minimising any bias due to mobile fishes avoiding (or in some cases being attracted to) divers. The second diver along the transect recorded the size and identity of smaller, site-attached fish species within a 2m wide belt (e.g., Pomacentridae), while species with larger home ranges were recorded within a 4m wide belt (e.g., Chaetodontidae; Appendix 3). The third diver conducted a point intercept survey, providing important information on coral cover and benthic composition, by recording the sessile organisms or substratum underlying evenly spaced (50cm apart) points along the entire length of the transect. The final (fourth) diver assessed coral health, estimated colony size, and counted abundance of juvenile corals (as a proxy of recruitment) within a 10m x 1m belt, using a 1m bar to accurately determine the boundaries of the survey area. On the return swim along the transects, one diver quantified the abundance of non-coral invertebrates (e.g., sea cucumbers, giant clams, sea urchins, *Tectus* (formerly *Trochus*), and crown-of-thorns starfish) within a 2m wide belt along the full length of each transect.

3.2 Coral and reef habitats

Benthic cover and composition – Point-intercept transects (PIT) were used to quantify benthic composition, recording the specific organisms or substratum types underlying each of 100 uniformly spaced points (50cm apart) along each transect (following Hoey et al. 2020, 2021). Corals were mostly identified to genus (using contemporary, molecular-based classifications for scleractinian corals), though some of the less common genera were pooled to 'other' for analyses. We also distinguished major growth forms for *Acropora* (tabular, staghorn, and other) and *Porites* (massive versus columnar or branching). Macroalgae were identified to genus. For survey points that did not intersect corals or macroalgae, the underlying substratum was categorised as either sponge, sand/ rubble, carbonate pavement, or other (including gorgonians, hydroids, anemones). Further, the proportional cover of crustose coralline algae (CCA) versus turf algae across all consolidated carbonate substrates (pavement and rubble) was recorded.

Topographic complexity – Topographic complexity was estimated visually at the start of each transect, using the six-point scale formalised by Wilson et al. (2007), where 0 = no vertical relief (essentially flat homogenous habitat), 1 = low and sparse relief, 2 = low but widespread relief, 3 = moderately complex, 4 = very complex with numerous fissures and caves, 5 = exceptionally complex with numerous caves and overhangs.

Coral health – The health of all coral colonies was recorded within a 10m x 1m belt on each transect (n = 3 per depth zone per site), following protocols developed by the Australian Coral Bleaching Taskforce (Hughes et al. 2017). The 10 x 1 m belt transects were generally run at the start of each 50m transect, but were relocated as required to avoid areas of sand or rubble substrata. For each colony contained wholly or mostly (>50%) within the transect area, we recorded the taxonomic identity, colony size and health. Corals were classified to genus and growth form (as described for PIT above), and then assigned to one of five size classes based on their maximum diameter (≤ 5cm, 6-20cm, 21-40cm, 41-60cm and >60cm). The health of each coral colony was then assigned to one of 8 categories (Figure 3.2), to document the extent and severity of bleaching, as well as any other recent injuries, such as evidence of recent predation. Where possible, the cause of conspicuous injury was also recorded, be it due to coral predators (e.g., *Drupella* spp., crown-of-thorns starfish or parrotfish) observed within or nearby the injured colony, or coral disease.

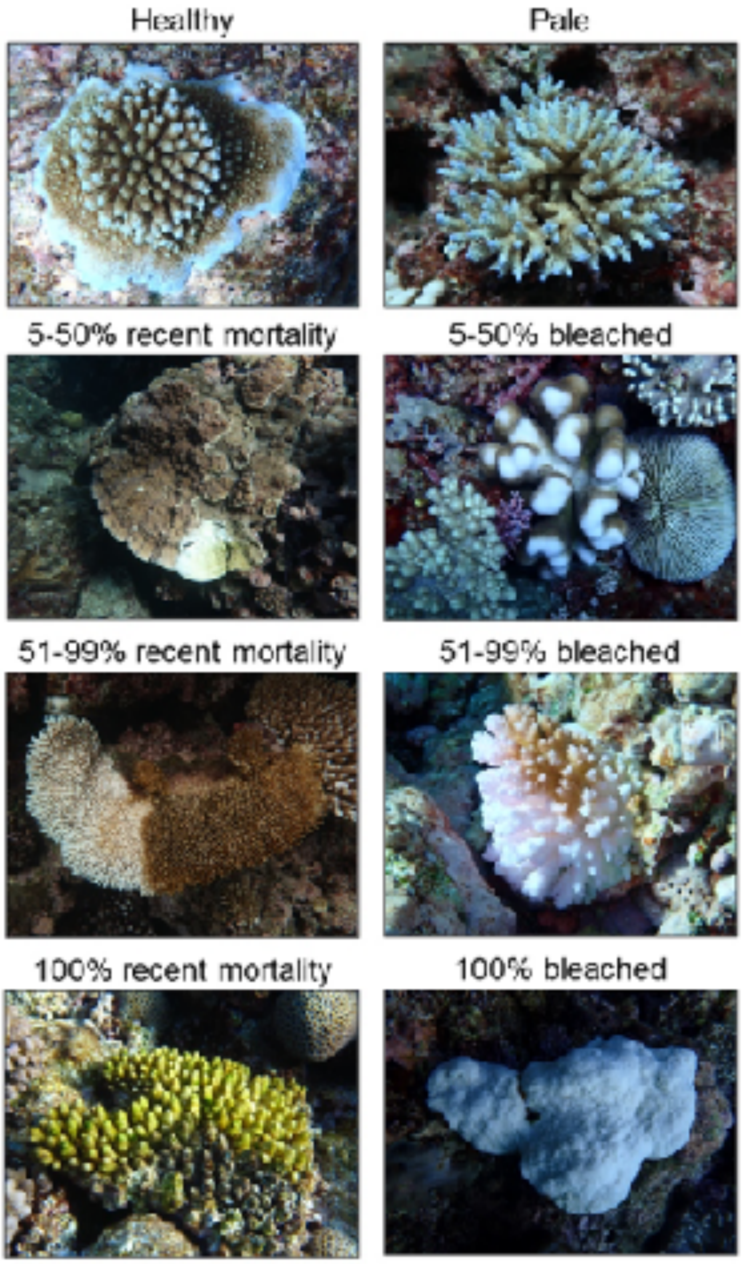


Figure 3.2 Coral health categories used for the in-water coral health assessments. Images on the left provide samples of the four injury categories, whilst images on the right are examples of the coral bleaching categories. Image credits: Deborah Burn; Morgan Pratchett

Juvenile corals – Densities of juvenile corals (≤5 cm maximum diameter, following Rylaarsdam 1983) are increasingly used as a proxy for recovery potential of coral assemblages as opposed to quantifying the number of coral larvae that settle on experimental settlement substrata (e.g., tiles). Counting juvenile corals accounts somewhat for the high mortality rates of newly settled corals, and logistically only requires a single visit to the study site. Therefore, comprehensive counts of all juvenile colonies, including the smallest colonies that are detectable with the naked eye (approximately 1 cm diameter), enable effective comparisons of potential coral recovery among habitats, sites and reefs across the CSMP. All juvenile corals within the 10 x 1m coral health transect were recorded to genus (Figure 3.3).

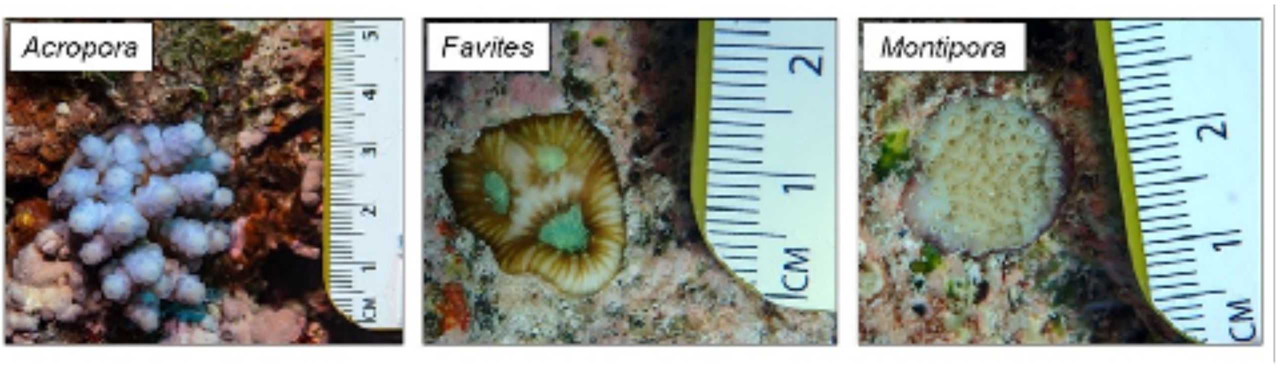


Figure 3.3 Photographs of juvenile (≤5cm diameter) corals recorded within 10m^2 belt transects within the Coral Sea Marine Park. Each juvenile coral within the 10m^2 belt transects were identified to genus and recorded. Image credits: Deborah Burn

Coral settlement – To directly quantify the supply and settlement of coral larvae among reefs and habitats in the CSMP, we deployed coral settlement tiles at ten sites across four reefs. Ten terracotta tiles (11 x 11 x 1cm) were deployed in each of two habitats (reef crest and reef slope) at each of the ten sites (Holmes Reef: 3 sites; Flinders Reef: 3 sites; Bougainville Reef: 2 sites; Osprey Reef: 2 sites) in late October 2021, approximately 6-weeks prior to the predicted coral spawning. Individual tiles were secured to the reef using a stainless steel baseplate with a bolt that passed through the centre of the tile (following Mundy 2000). The baseplates were secured to the reef using masonry push mounts into two 8mm diameter holes. Tiles were held 1-1.5 cm above the reef substratum using stainless steel nuts, and secured with a wingnut. Tiles were haphazardly placed within each site and positioned over reef substrata that was free of live coral. Adjacent tiles were separated by a minimum of 50cm.

Tiles were collected from each site in late February-early March. Tiles from each habitat at each site were placed onto a threaded bar (or skewers) immediately upon collection, with plastic spacers between each tile to prevent damage to any settled corals. Each skewer with tiles was then submerged in a dilute bleach solution for 12-24 h to remove organic material, and then rinsed with freshwater, dried and stored for later analysis. All surfaces of each tile (top, bottom and four edges) were thoroughly and sequentially searched under a dissecting microscope (40x magnification), and all coral spat present were identified to genus (*Acropora*, *Pocillopora*, *Porites*, 'other') and recorded. It is not possible to reliably identify other genera at this early stage of development (Babcock et al. 2003).

Additional tiles were deployed at three reef crest sites on each of six reefs in the northern Great Barrier Reef Marine Park (GBRMP) using identical methods in October 2021. Tiles were not deployed on the reef slope on these GBRMP reefs. These reefs included two inner-shelf (Turtle Group north, Turtle Group south), two mid-shelf (Lizard Island and MacGillivray Reef), and two outer-shelf reefs (Day and Hicks Reef). The settlement tiles deployed on GBRMP reefs were part of, and funded by, other projects but included here for comparative purposes.

3.3 Coral reef fishes

Size (body length) and abundance of reef-associated fishes (e.g., Acanthuridae, Chaetodontidae, Labridae, Lethrinidae, Scarinae, Serranidae, and Pomacentridae) was quantified using standard underwater visual census (UVC) along replicate 50m transects (n = 3 per depth zone) at all sites. Various transect dimensions were used to account for differences in the body size, mobility, and detectability of different fishes, as well as making data more comparable to other surveys conducted within the GBRMP (e.g., Emslie et al. 2010) and other Australian Marine Parks (e.g., Hoey et al. 2018). Smaller site-attached species (Pomacentridae) were counted in a 2m wide belt (100m^2 per transect). Slightly larger bodied, site-attached species (e.g., Chaetodontidae, Labridae) were surveyed in a 4m wide belt (200m^2 per transect), while all larger and more mobile species were counted in a 5m wide belt (250m^2 per transect). Body size (total length) was recorded for each individual fish, and converted to biomass using published length-weight relationships for each species. Data were standardised as abundance and biomass per 100m^2. See Appendix 3 for a comprehensive list of species surveyed.

Mixed schools of planktivorous reef fishes are common on the crest and slopes of the Coral Sea Marine Park. This photo was taken at Osprey Reef during our October field trip to survey the reefs of the Northern CSMP.

3.4 Other reef taxa

Sea snakes – The abundance and size of sea snakes (including the Olive sea snake, *Aipysurus laevis*; Dubois' sea snake, *Aipysurus duboisii*; Spiny headed or Horned sea snake, *Hydrophis peronii*; Turtle-headed sea snake, *Emydocephalus annulatus*; Figure 3.4) were quantified within the same 50 x 5m belt transects used to survey large, mobile reef fishes. All sea snakes observed within the transect area were identified to species and their length estimated.

Non-coral invertebrates – Non-coral invertebrates, including potential coral predators (e.g., crown-of-thorns starfish *Acanthaster* cf. *solaris*, pin-cushion starfish *Culcita novaeguineae*, and coral snails *Drupella* spp.) as well as ecologically and economically important species, namely long-spined sea urchins (*Diadema* spp.) sea cucumbers (holothurians); Figure 3.5), giant clams (*Tridacna* spp.) and trochus (*Tectus* spp., formerly *Trochus* spp.), were surveyed in a 2m wide belt along each transect, giving a sample area of 100m². For all crown-of-thorns starfish (*Acanthaster* cf. *solaris*) and giant clams (*Tridacna* spp.) observed, the size (diameter and length, respectively) was also recorded (to the nearest 10cm).

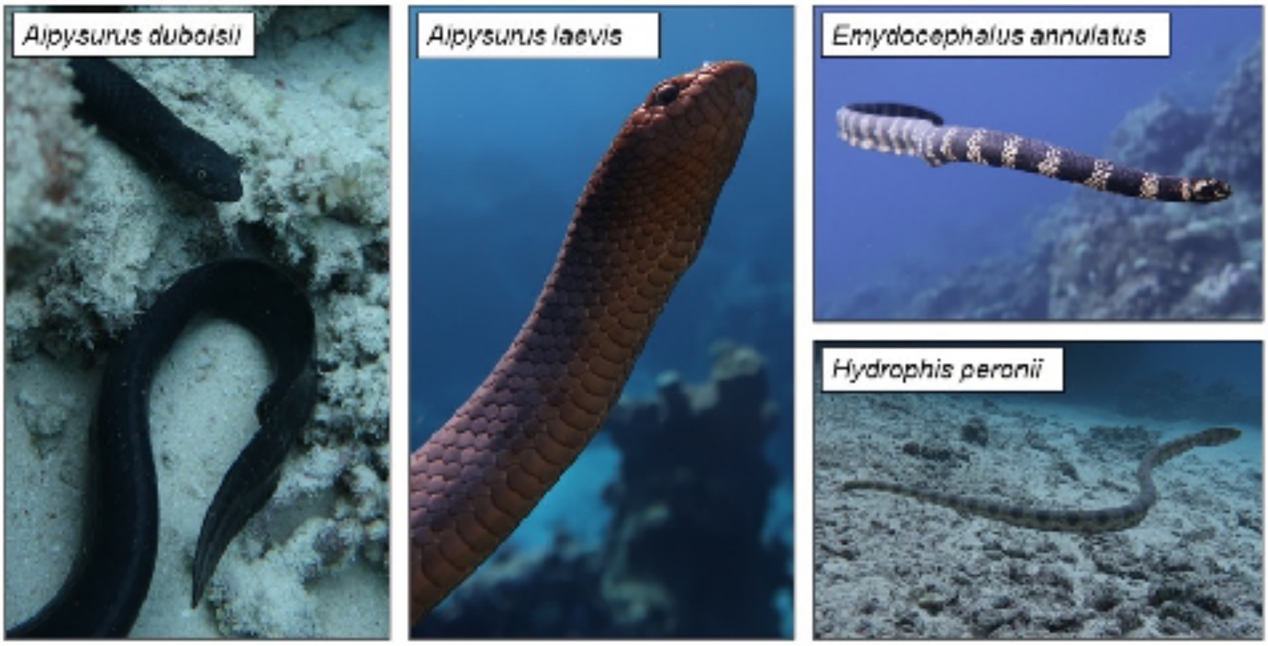


Figure 3.4 Photographs of the four species of sea snake that are commonly observed within the Coral Sea Marine Park; Dubois' sea snake, *Aipysurus duboisii*; Olive sea snake, *Aipysurus laevis*; Turtle-headed sea snake, *Emydocephalus annulatus;* Spiny headed or Horned sea snake, *Hydrophis peronii*. Image credits: Deborah Burn

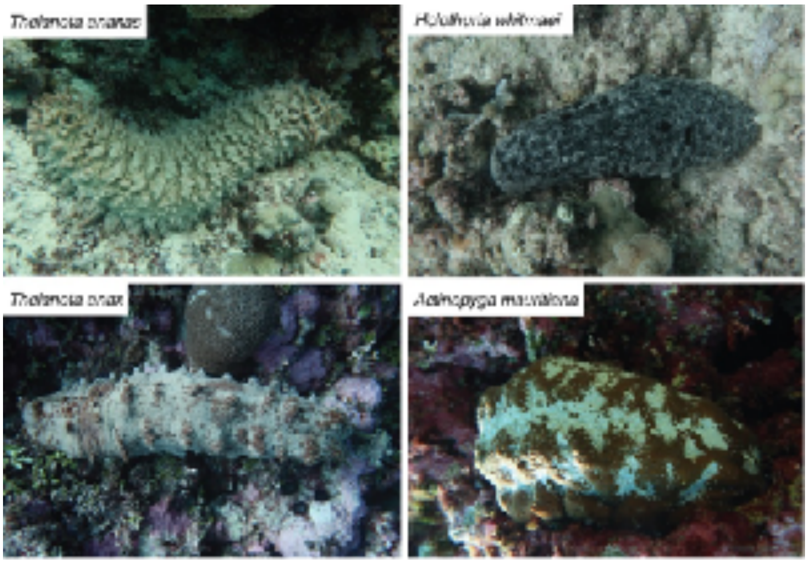


Figure 3.5 Photographs of four species of sea cucumber that are commonly observed within the Coral Sea Marine Park; Prickly redfish, *Thelanota ananas*; Black teatfish, *Holothuria whitmaei*; Amber fish, *Thelanota anax*; and Surf redfish, *Actinopyga mauritiana*. Image credits: Deborah Burn

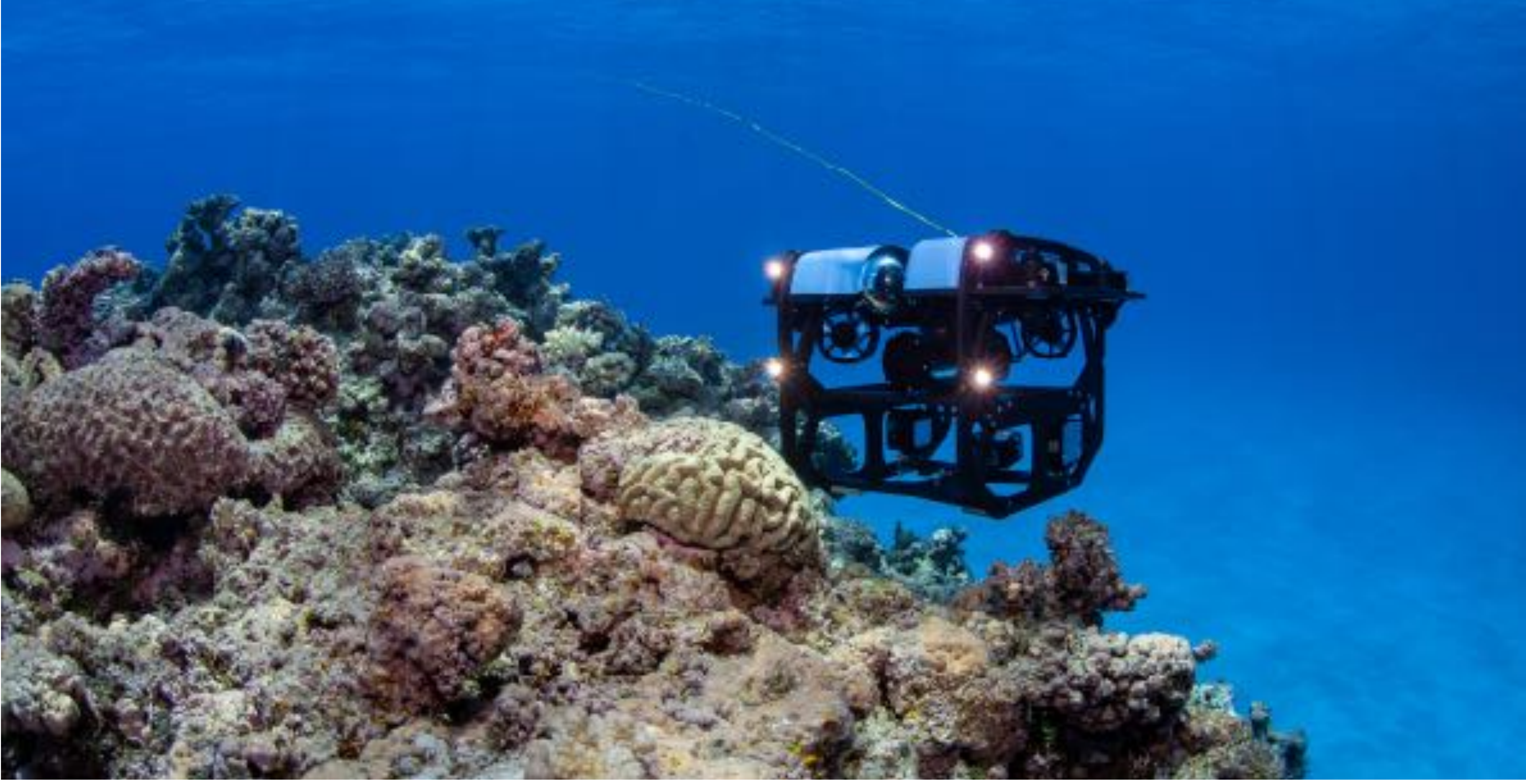
Coral predators are potentially important contributors to coral reef health and habitat structure, especially during periods of elevated densities (Pratchett et al. 2014). Population irruptions of crown-of-thorns starfish (*Acanthaster* cf. *solaris*) are a major contributor to coral loss on the Great Barrier Reef (De'ath et al. 2012) and are thought to have caused considerable coral loss on Elizabeth and Middleton Reefs in the 1980's (Hoey et al. 2018), though it is not known whether there have been population irruptions in the CSMP. Sea urchins, especially long-spined sea urchins of the genus *Diadema*, can also have a major influence on the habitat structure of coral reef environments (e.g., McClanahan and Shafir 1990; Eakin 1996). Like herbivorous fishes, larger urchin species such as *Diadema* spp. may be important in removing algae that would otherwise inhibit coral growth and/or settlement (Edmunds and Carpenter 2001). At high densities, however, intensive grazing by sea urchins may have negative effects on reef habitats, causing significant mortality of juvenile corals and loss of coral cover, thereby reducing topographic complexity of reef habitats (McClanahan and Shafir 1990), and ultimately can lead to a net erosion of the reef carbonates (Glynn et al. 1979; Eakin 1996).

3.5 Data handling and analysis

Data from the 2022 surveys (including the surveys of Ashmore Reef in Nov 2021) were combined with those of the previous voyages (2018-2021) into a single database and analysed using R version 4.1.1 (R Core Team 2021). Data were wrangled using the tidyverse environment (Wickham 2017) and visualised using the ggplot2 package (Wickham 2016). Colour palettes for figures were chosen in RColorBrewer (Neuwirth 2014) and viridis (Garnier 2018), with visualisations aided by ggrepel (Slowikowski 2018) and ggpubr (Kassambara 2018). Maps of the GBRMP and marine park boundaries were reproduced from shape files contained in gisaimsr (Barneche and Logan 2021) and dataaimsr (AIMS Datacentre 2021), data courtesy of the Great Barrier Reef Marine Park Authority. Maps of CSMP reefs and boundaries were reproduced from shapefiles generated by Project 3DGBR (Beaman 2012). All maps were produced in R using the package sf (Pebesma 2018) and ggspatial (Dunnington 2021) using the WGS84 coordinate system.

All survey data were averaged across independent transects to obtain a site, or where appropriate a zone (i.e., crest, slope), average prior to summarising data at the level of reefs or regions. For calculations of taxonomic richness, the number of species/taxa were calculated at the level of site (i.e., pooled among transects and reef zone) to give the total number of species/taxa observed at a site, prior to being summarised to the level of reefs or regions. Data are generally presented using box and whisker plots (i.e., box plots). The box plots represent the distribution of the data based on the minimum, first quartile, median, third quartile and maximum values. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the inter-quartile range, or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers (i.e., outliers) are plotted individually.

Non-metric multi-dimensional scaling (nMDS) was used to identify similarities in coral and fish assemblages among reefs in a priori defined regions (i.e., southern, central, and northern CSMP) and between years. The objective of nMDS is to summarise all available information on the presence and abundance of species, or taxa, into a simple dissimilarity matrix. In the visual representations that follow, objects (i.e., sites or reefs) that are closer to one another are likely to be more similar than those further apart. Data were square-root transformed to reduce the relative influence of the most frequent and variable taxa, which otherwise will tend to dominate the dissimilarity matrix. For the analysis of coral composition rare taxa were grouped as 'other Scleractinia' to reduce the influence of these rare taxa in the dissimilarity matrix. The data were then standardised following a Wisconsin scaling, which removes the effect of absolute species abundance and also abundance between sites, so the comparison between sites becomes relative. Distances between points were determined with the metaMDS function using the Bray-Curtis dissimilarity matrix. All data were analysed in the vegan package (Oksanen et al. 2020) using the statistical software package R version 4.1.1.



4. Findings

4.1 Impacts of the 2020 bleaching event on coral communities

The 2020 coral bleaching event in the CSMP was severe and widespread, with 63% of all corals surveyed across 16 reefs in February-March 2020 showing signs of heat stress (from pale to recently dead) from elevated ocean temperatures (Hoey et al. 2020), and resulted in a decrease in shallow water coral cover from 28% in 2020 to 17% in 2021, a mean decline of 39% (Hoey et al. 2021). There was, however, considerable variation in the decline in coral cover among regions (39%, 43% and 17% decline in the southern, central, and northern CSMP, respectively), among reefs (ranging from 13.1% decline at Bougainville Reef to a 73.5% decline at Frederick Reef), and among sites within each reef (e.g., 19% at Holmes 2 vs 59% at Holmes 6). Understanding the ongoing impacts of, and the potential recovery from, the 2020 bleaching event on the cover and composition of coral assemblages is critical in assessing the current health of reefs in the CSMP.

4.1.1. Coral cover and richness

The average cover of hard (Scleractinian) corals recorded across the 68 CSMP sites surveyed in 2022 was 16.12% (±0.68 SE), ranging from 5.75% (±1.08 SE) at Flora Reef in the central CSMP up to 35.87% (±4.55 SE) at Ashmore Reef in the northern CSMP (Figure 4.1a). Average coral cover was approximately two-fold greater on reefs in the northern CSMP (averaging 28.65%), compared to the central (13.92%) and southern CSMP (15.65%).

The average taxonomic richness of corals across the CSMP, based on the number of hard (Scleractinian) coral taxa (mostly genera) recorded using the 50m point-intercept transects at each survey site, was 15.6 taxa per site and ranged from 8.5 taxa per site (± 0.5 SE) at Flora Reef in the central CSMP to 22.0 taxa per site (± 2.8 SE) at Ashmore Reef in the northern CSMP (Figure 4.1b). Coral richness displayed a similar pattern to coral cover among CSMP regions, with coral richness being generally greater in the northern CSMP (19.6 taxa per site), compared to the central (14.1 taxa per site) and southern CSMP (16.3 taxa per site; Figure 4.1b).

There was considerable variation in both coral cover and richness among reefs within each of the CSMP regions, with Saumarez (cover: 20.50%; richness: 20.0 taxa per site), Mellish (cover: 31.90%; richness: 18.3 taxa per site), and Ashmore Reef (cover: 35.87%; richness: 22.0 taxa per site) having both higher coral cover and higher richness than other reefs in the southern, central, and northern CSMP, respectively (Figure 4.1).

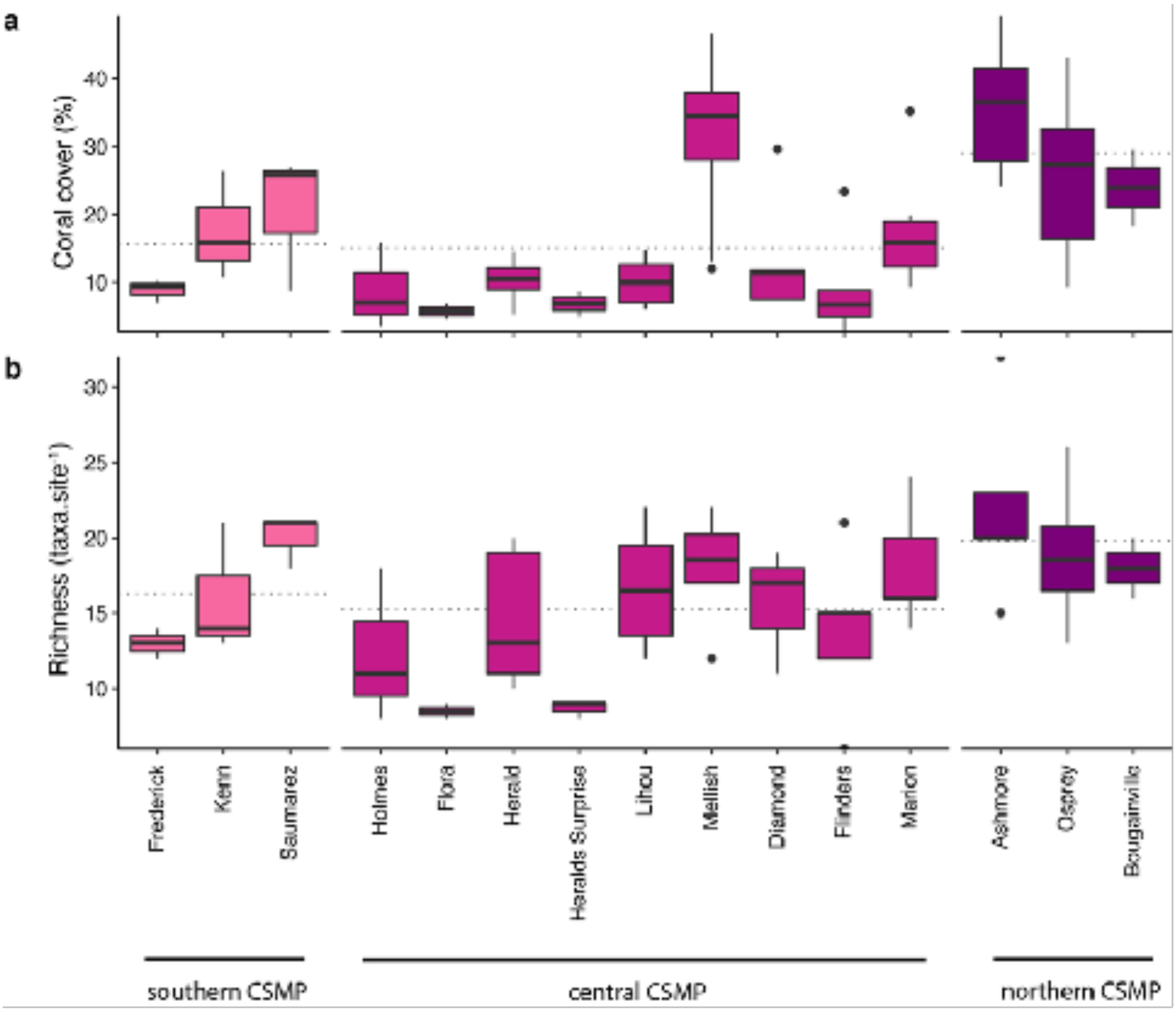


Figure 4.1 Variation in coral cover and coral richness among 15 reefs in the Coral Sea Marine Park (CSMP) in 2022. Data are based on the 50m point-intercept transects, with data for richness based on the number of coral taxa recorded at each of the 68 sites (i.e., pooled across transects and slope and crest habitats). Reefs are arranged into the southern, central, and northern CSMP and coloured by *a priori* regional assignments (following Figure 3.1). Dotted lines represent regional averages.

4.1.2 Temporal changes in coral cover and richness

Coral cover - Comparisons of coral cover in shallow reef habitats across the eleven reefs that were surveyed in 2020, 2021 and 2022 revealed marked differences in the temporal patterns in coral cover among the three CSMP regions (Figure 4.2). While a decline in coral cover was recorded in all three regions in 2021 (i.e., following the 2020 coral bleaching event; Hoey et al. 2021), coral cover remained relatively stable in the southern CSMP between 2021 (15.00%) and 2022 (15.65%), whereas 26.3% and 27.9% declines in coral cover of were recorded in the central (2021: 14.13%; 2022: 10.41%) and northern CSMP (2021: 25.38%; 2022: 18.29%), respectively (Figure 4.2). These declines in coral cover from 2021 to 2022 were relatively consistent between the reef crest (1-3m depth) and reef slope (7-10m) in both the central and northern CSMP (Figure 4.3). Overall, CSMP wide shallow water coral cover declined by 18.4% from 2021 to 2022 (2021: 15.73%; 2022: 12.83%), and compounded on the 39% reduction in coral cover recorded from 2020 to 2021 (Hoey et al. 2021).

Declines in coral cover from 2021 to 2022 were relatively consistent (22.8 – 30.3% decline) among reefs (Osprey and Bougainville Reefs) and sites within the northern CSMP, however there was considerable variation in the direction and magnitude of the change in coral cover among individual reefs, and among sites within each reef within the southern and central CSMP (Figure 4.4, 4.5). Within the central CSMP changes in coral cover from 2021 to 2022 ranged from a 57.0% decline in coral cover at Holmes Reef, to an 8.7% increase in coral cover at Marion Reef (Figure 4.5a). Notably, coral cover at Diamond Islets, that wasn't surveyed in 2021, decreased from 31.2% in 2020 to 13.6% in 2022, a decline of 56.4%. Similarly, in the southern CSMP, changes in coral cover ranged from a 12.4% decline at Kenn Reef to a 21.8% increase at Saumarez Reef (Figure 4.5a). In the absence of any known major disturbance the cause/s of these declines in coral cover are difficult to determine, however the relatively widespread nature of the declines suggest that they are unlikely to be related to localised disturbances. Low levels of bleaching (Pale - Recently Dead) were recorded across ten of these CSMP reefs (excluding Diamond Islets) in February 2021, ranging from 1.6% of colonies surveyed at Marion Reef to 21.5% at Lihou Reef, with mean of 6.8% across the CSMP (Hoey et al. 2021). However, water temperatures experienced with the CSMP were again higher than average in 2021, with the greatest heat stress occurring in March 2021 (i.e., after the 2021 surveys had been completed; Figure 4.6). Importantly, a large area of the central and northern CSMP had been exposed to >12 Degree Heating Weeks (DHW) in March 2021 (Figure 4.6), coinciding with the recorded declines in coral cover from our surveys. Such temperatures are well above those expected to cause bleaching-induced coral mortality (>6 DHW), with exposure to 10 DHW during the 2016 bleaching event on the GBR leading to a ~90% decline in coral cover (Hughes et al. 2018). While three tropical cyclones were recorded in the CSMP in the period between our 2021 and 2022 surveys (TC Niran: 1st – 6th Mar 2021; TC Seth: 31st Dec 2021-1st Jan 2022; TC Tiffany: 9th -10th Jan 2022), we didn't observe areas of broken and dislodged corals that would be consistent with physical damage from severe storms (e.g., Fabricius et al. 2008). Further the combined spatial footprint of these storms does not coincide with the recorded declines in coral cover from our surveys. Therefore, it appears most likely that the observed declines in coral cover on northern and central CSMP reefs in 2022 were related to the heat stress experienced in March 2021.

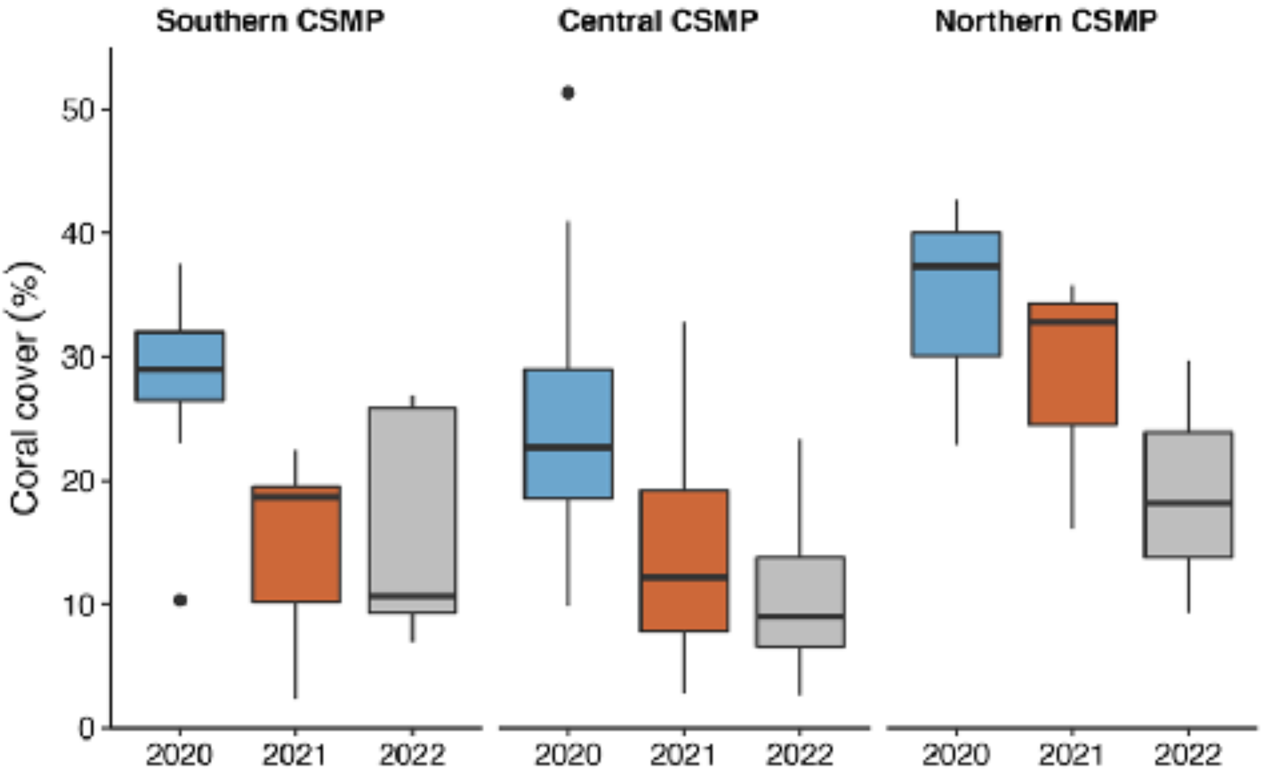


Figure 4.2 Temporal change in average coral cover (+/- SE) within the three regions of the Coral Sea Marine Park. Data are based on surveys of matching sites in 2020, 2021 and 2022 across 10 reefs (southern CSMP: Saumarez, Kenn, Frederick Reefs; central CSMP: Marion, Flinders, Holmes, and Lihou Reefs, and Herald Cays; northern CSMP: Bougainville and Osprey Reefs).

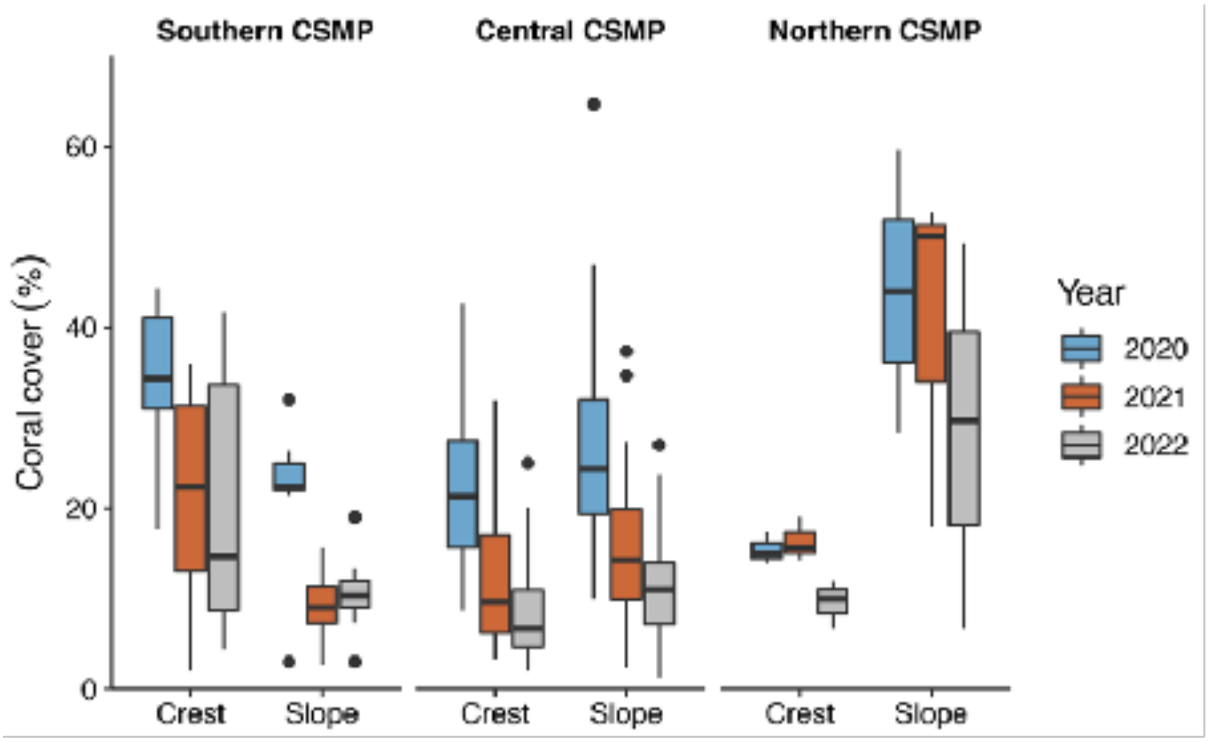


Figure 4.3 Temporal variation in coral cover between shallow reef habitats (reef crest and reef slope) within the three regions of the Coral Sea Marine Park. Data are based on surveys of matching sites in 2020, 2021 and 2022 across 10 reefs (southern CSMP: Saumarez, Kenn, Frederick Reefs; central CSMP: Marion, Flinders, Holmes, and Lihou Reefs, and Herald Cays; northern CSMP: Bougainville and Osprey Reefs).

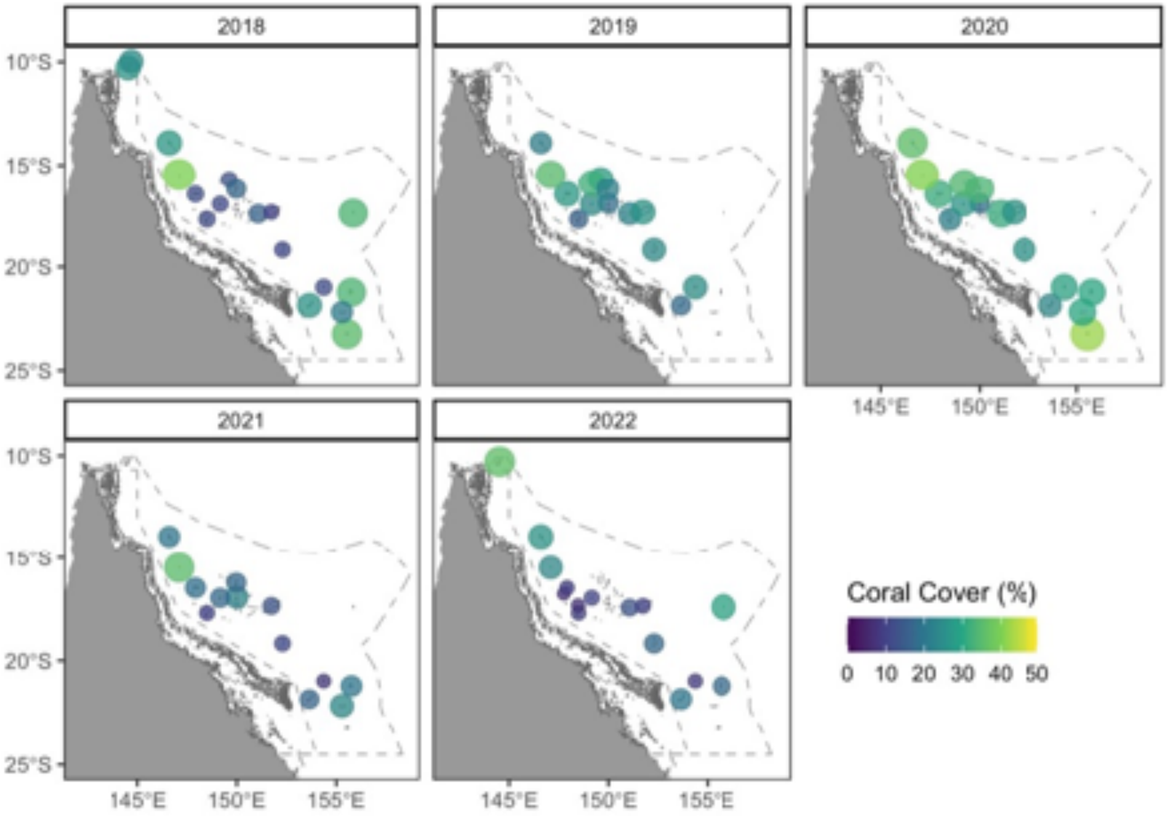


Figure 4.4 Spatial and temporal variation in coral cover on shallow reef habitats (reef crest and reef slope) across 22 reef systems in the Coral Sea Marine Park. The size of individual points is proportional to the cover of live coral at each reef.

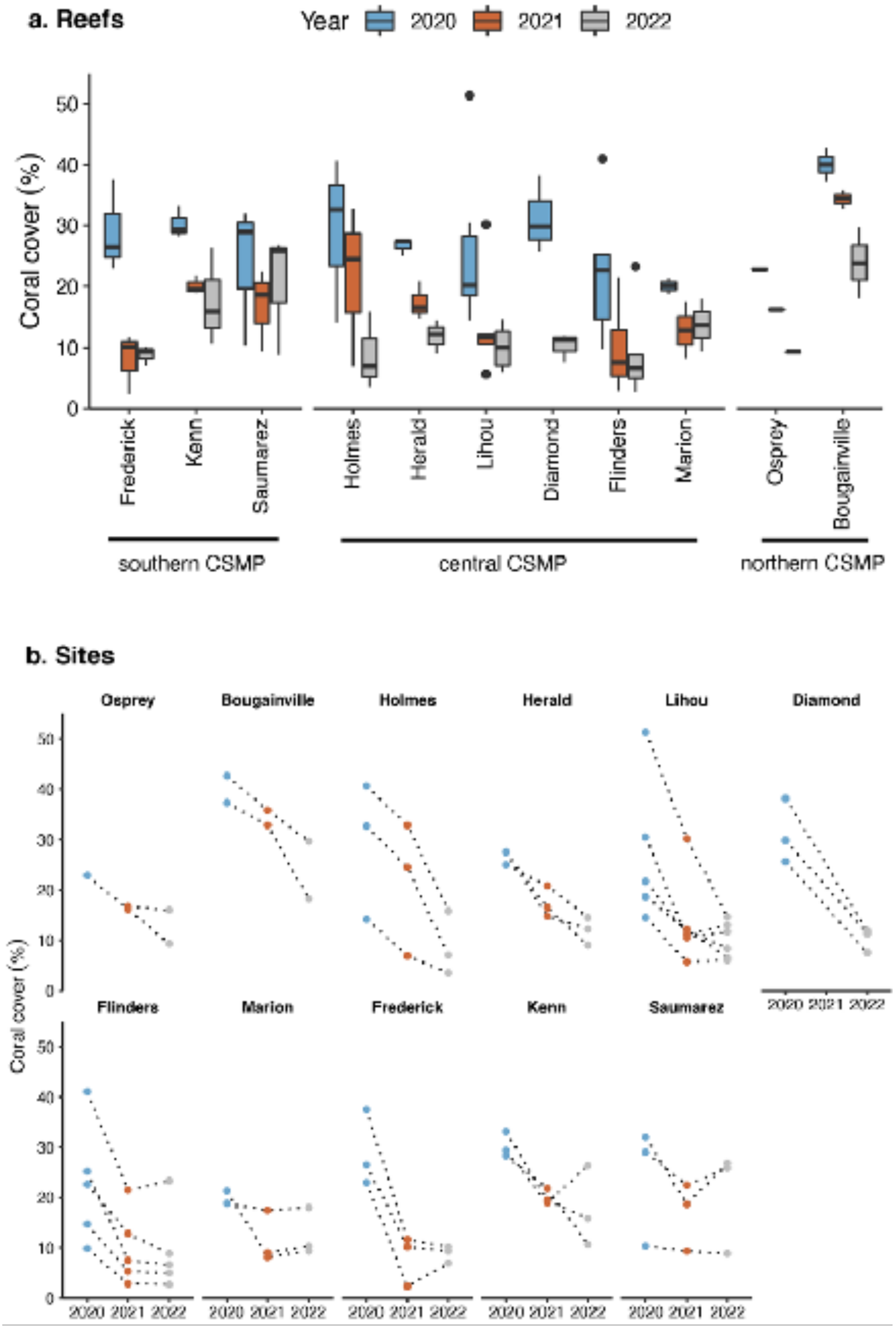


Figure 4.5 Temporal variation in coral cover among **(a)** eleven reefs, and **(b)** 36 sites in the Coral Sea Marine Park that were surveyed in 2020, 2021, and 2022. Data are based on surveys of matching sites in each year and pooled between habitats (reef slope and reef crest) within each site.

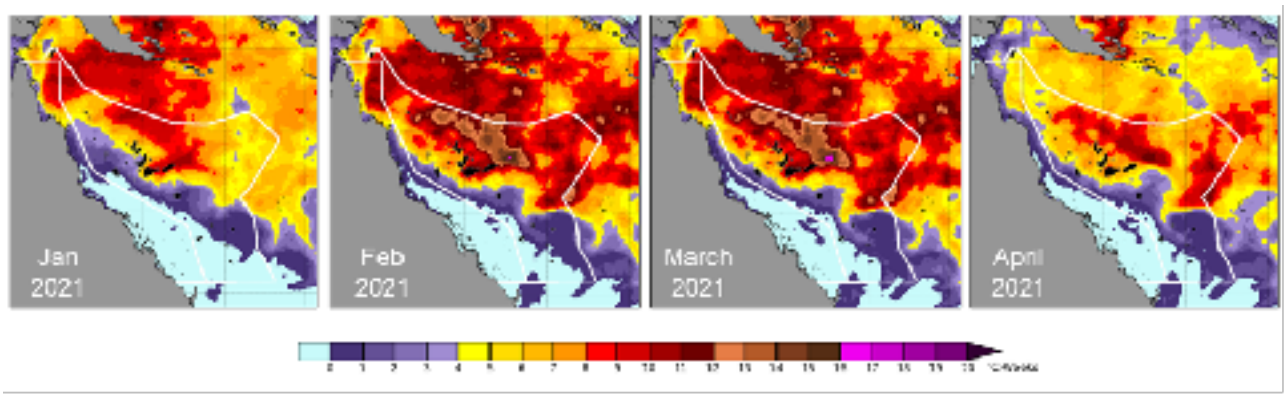


Figure 4.6 Progression of heat stress experienced throughout the Coral Sea Marine Park from January to April 2021. Colours represent the maximum Degree Heating Weeks (DHW).

Coral richness - There was a noticeable decline in the mean coral richness on reefs in the northern CSMP from 2020 to 2022, with the number of coral taxa recorded per site decreasing from ca. 21 to 17 taxa (Figures 4.7, 4.8). Mean coral richness per site was relatively consistent between 2021 and 2022 on central (2021: 15.5 taxa; 2022: 15.2 taxa) and southern (2021: 15.8 taxa; 2022: 16.3 taxa) CSMP reefs. This is in contrast to the findings of the previous year in which declines in coral richness were recorded for the southern and central CSMP, but not the northern CSMP, from 2020 to 2021 (Hoey et al. 2021). In general, the greatest declines in coral richness were on those reefs that also experienced the greatest declines in coral cover (i.e., Holmes, Osprey and Bougainville Reefs; Figures 4.5a, 4.8).

Coral diversity at Ashmore Reef, in the northern Coral Sea Marine Park. Image credits: Victor Huertas

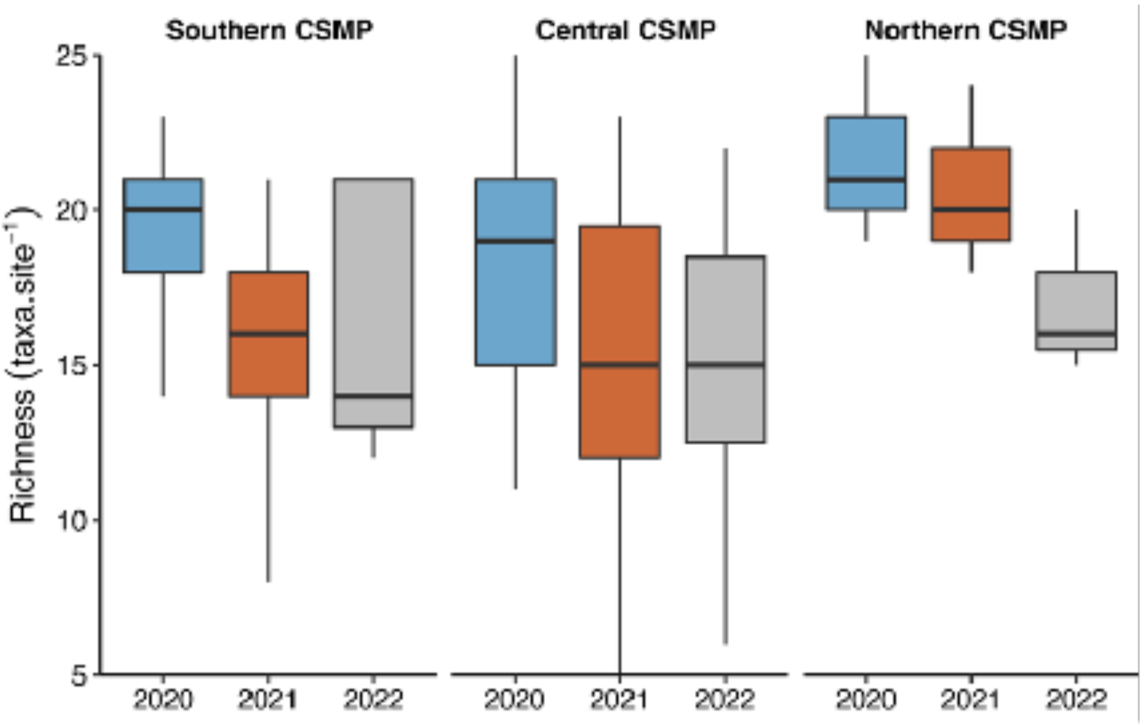


Figure 4.7 Temporal change in coral richness among the three regions in the Coral Sea Marine Park from 2020 to 2022. Data are based on the number of coral taxa recorded at each of 31 sites (i.e., pooled across slope and crest habitats).

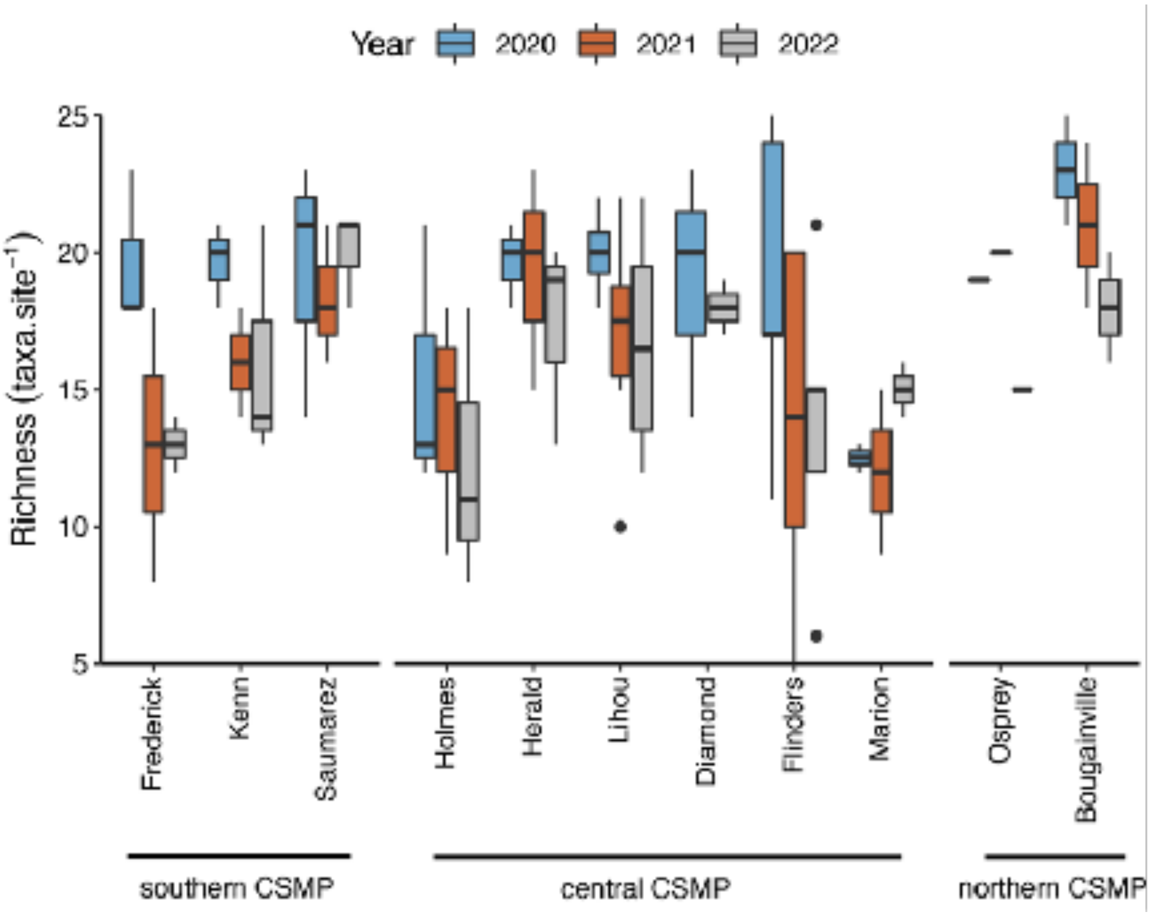


Figure 4.8 Temporal change in coral richness among eleven reefs in the Coral Sea Marine Park from 2020 to 2022. Data are based on the number of coral taxa recorded at each of 34 sites (i.e., pooled across slope and crest habitats). One to six sites were surveyed at each reef.

4.1.3 Coral composition

The greatest variation in the composition of coral assemblages was among the three CSMP regions, that were largely separated along the the first dimension of the nMDS plot (Figure 4.9). In general, reefs in the southern CSMP were characterised by a relatively higher cover of *Seriatopora* and tabular and staghorn *Acropora*, while reefs in the northern CSMP were characterised by a higher cover of *Pocillopora* and *Coeloseris* (Figure 4.9a,b). The composition of coral communities on reefs in the central CSMP was generally more variable, and was positioned in the middle of the ordination space.

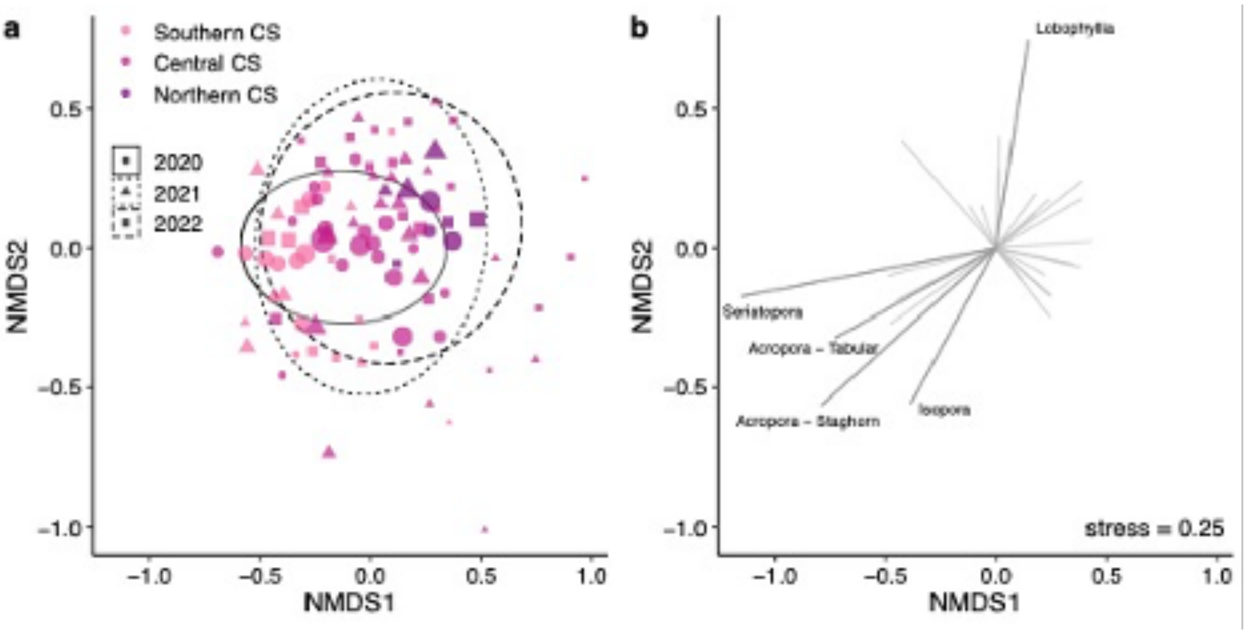


Figure 4.9 Regional and temporal (2020, 2021, and 2022) variation in the composition of coral assemblages within the Coral Sea Marine Park. Non-metric multidimensional scaling (nMDS) plot showing the variation in coral composition among years for the three regions of the Coral Sea Marine Park. Analyses are based on data from 31 sites that were surveyed in each year. The size of individual points is proportional to the cover of live coral at each site. Vectors in the right-hand side plot indicate key taxa that account for the variation in coral composition displayed in the corresponding left-hand side plot.

There was also evidence of shifts in the composition of coral assemblages among years, with the composition of coral assemblages within a region being more similar in 2020 (i.e., more clustered in the nMDS space), than in 2021 or 2022 (Figure 4.9, 4.10). There was a distinct change in the composition of coral assemblages in the central CSMP, where coral assemblages shifted from being dominated by bleaching sensitive coral taxa, such as *Seriatopora*, and staghorn and tabular *Acropora* in 2020, to a mix of largely bleaching resistant taxa (including branching *Porites* and *Coeloceris*) in 2021 and 2022 (Figure 4.10c,d). The composition of coral assemblages on central CSMP reefs was broadly similar between 2021 and 2022. In the southern CSMP the composition of coral assemblages showed a greater degree of similarity among sites in 2020 (i.e., more clustered in the nMDS space) than 2021 and 2022, likely reflecting the differential exposure to, and impacts of, the 2020 bleaching event on individual reefs (Figure 4.10e,f; Hoey et al. 2021). While on average the relative cover of largely bleaching resistant coral taxa (e.g., *Acanthastrea*, *Leptastrea*, *Lobophyllia* and branching *Porites*) increased on reefs in the southern CSMP in 2021 and 2022, there was considerable variation in the cover of these coral taxa among individual sites (Figure 4.10e,f). There was also some evidence of a reduction in the relative abundance of staghorn *Acropora*, *Coscinarea*, and *Coeloseris* in the northern CSMP from 2021 to 2022 (Figure 4.10a,b), however these changes should be treated with some caution given the limited number of sites surveyed in both years (i.e., 3 sites).

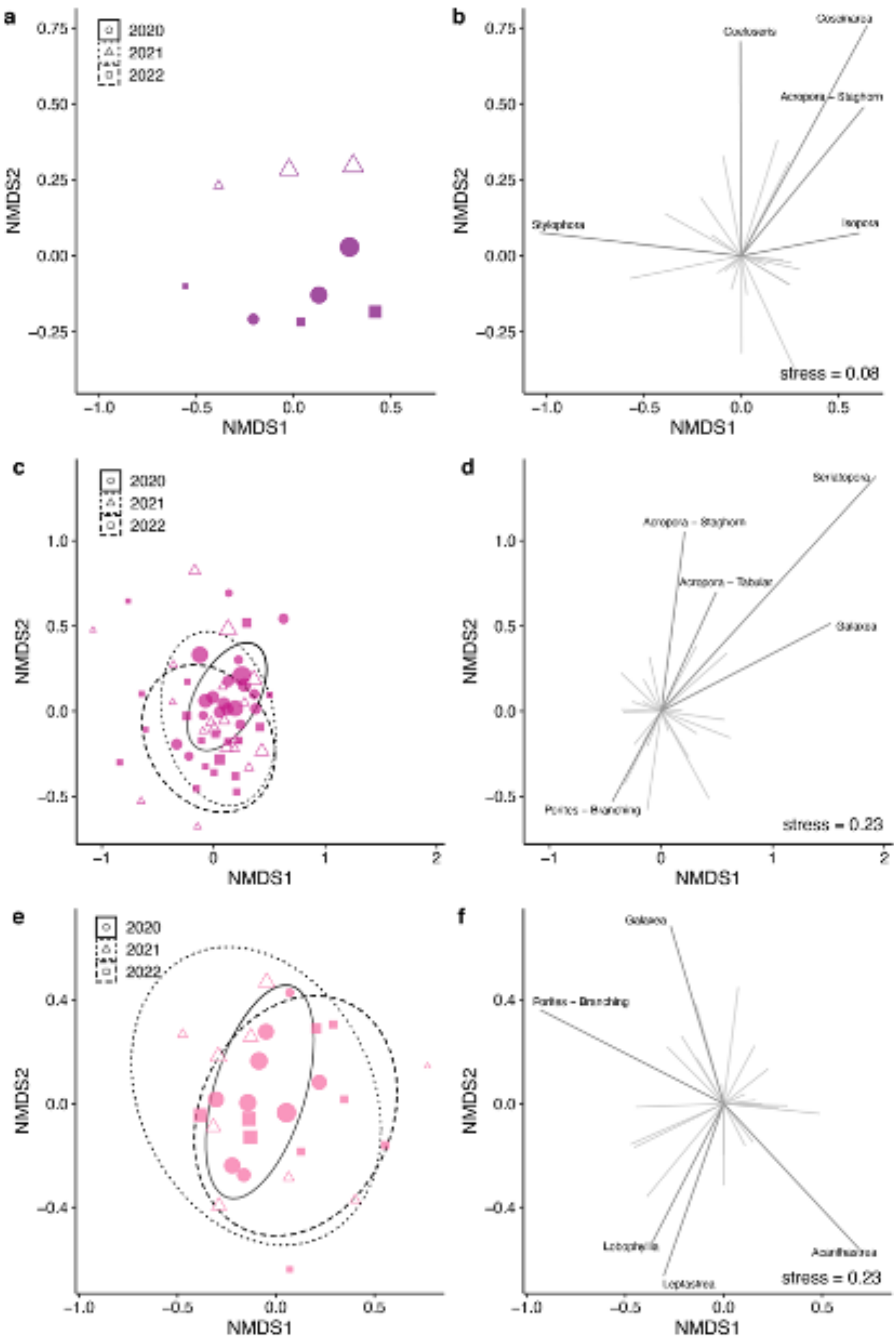


Figure 4.10 Non-metric multidimensional scaling (nMDS) plots showing the temporal variation (2020, 2021 and 2022) in coral composition among reefs in the (a) northern, (c) central, and (e) southern Coral Sea Marine Park. Analyses are based on data from 31 sites that were surveyed in each year (northern: 3 sites; central: 19 sites; southern: 9 sites). The size of individual points is proportional to the cover of live coral at each site. Vectors in the right-hand side plot indicate key taxa that account for variation in coral composition displayed in the corresponding left-hand side plot.

Figure 4.11 Photographs of shallow water coral assemblages at Frederick Reef (top; February 2022), Saumarez Reef (middle; February 2022) and Osprey Reef (bottom; October 2021) showing the variability of coral cover among sites within the Coral Sea Marine Park. Image credits: Victor Huertas

4.2. Macroalgal assemblages

High abundances of fleshy macroalgae on coral reefs are often viewed as a sign of reef degradation (e.g., McCook 1999). This view is supported by several examples of reefs shifting from coral- to macroalgal-dominance following large-scale coral mortality (e.g., Hughes 1994; Graham et al. 2015). Once established, macroalgal-dominated areas tend to persist due to a series of positive, or reinforcing, feedbacks that limit the recovery of coral populations (e.g., Hoey and Bellwood 2011; Van de Leemput et al. 2016; Johns et al. 2018). There is growing concern that the increasing frequency and intensity of temperature-induced bleaching events and subsequent declines in coral cover of reefs globally will lead to an increasing number of reefs becoming dominated by macroalgae (Hughes et al. 2017, 2018; Souter et al. 2021).

The cover of macroalgae across the fifteen CSMP reefs surveyed in 2022 was generally low, with total macroalgal cover averaging 3.4%. Macroalgal cover ranged from 0.0% on Bougainville Reef in the northern CSMP to 10.3% on Saumarez Reef in the southern CSMP, with only four reefs having macroalgal cover >3.5% (Herald Cays: 7.6%; Holmes Reef: 8.2%; Flinders Reef: 10.1%; Saumarez 10.3%; Figure 4.12). The dominant macroalga in shallow habitats of the CSMP was the green calcified alga *Halimeda* spp., accounting for 81% of all macroalgae recorded across the 68 sites in 2022. *Halimeda* is a common feature of oceanic reefs where it often forms thick curtains on steep slopes and overhangs and is an important contributor to calcification and production of reef sediments (Drew 1983). Unlike many large canopy-forming algae, such as *Sargassum*, that predominate on coastal reefs of the GBRMP and elsewhere (e.g., Wismer et al. 2009; Hoey and Bellwood 2010; Rasher et al 2013), high abundances of *Halimeda* is not considered to be symptomatic of reef degradation. The cover of other macroalgae was extremely low (<1.5%) across the fifteen CSMP reefs in 2022 (Figure 4.12). The only exception was the sheltered back-reef sites at Saumarez Reef, where the cover of the green alga *Caulerpa* was 9.1%.

There was no evidence of regional increases in macroalgal cover across shallow reef habitats in the CSMP following the 2020 bleaching event, with total macroalgal cover on the eleven reefs surveyed in each year declining from 6.3% in 2020, to 6.2% in 2021, and 3.8% in 2022 (Figure 4.13). There was some spatial variation in the cover of macroalgae, and in particular *Halimeda*, with this variation being most pronounced within the central CSMP (Figure 4.13a,b). For example, there were small increases in the cover of *Halimeda* at Holmes and Flinders Reef from 2021 to 2022, and small decreases in cover at Lihou and Marion Reefs (Figure 4.13a). Interestingly, the cover of *Caulerpa* at Saumarez remained relatively unchanged from 2021 to 2022 (ca. 9 %), after increasing from 4.1% cover in 2020 (Figure 4.13b). *Caulerpa* has a creeping habit and can quickly grow to occupy areas free of other benthic taxa (i.e., hard corals, soft corals, sponges). The cause of the higher abundance of *Caulerpa* at these sheltered reef sites on Saumarez Reef is unknown and may be related to numerous factors, such as local variation in nutrient availability (e.g., through upwelling) and/or reduced herbivory, or may reflect differential recruitment and growth of *Caulerpa* among locations. Overall, the cover of fleshy macroalgae was low throughout the CSMP (3.4%), and considerably lower than other oceanic reefs, such as Elizabeth and Middleton Reefs, and Lord Howe Island to the south (Hoey et al. 2011, 2018).

Photograph of *Caulerpa*, one of the most common macroalga in the Coral Sea Marine Park. Image credit: Victor Huertas

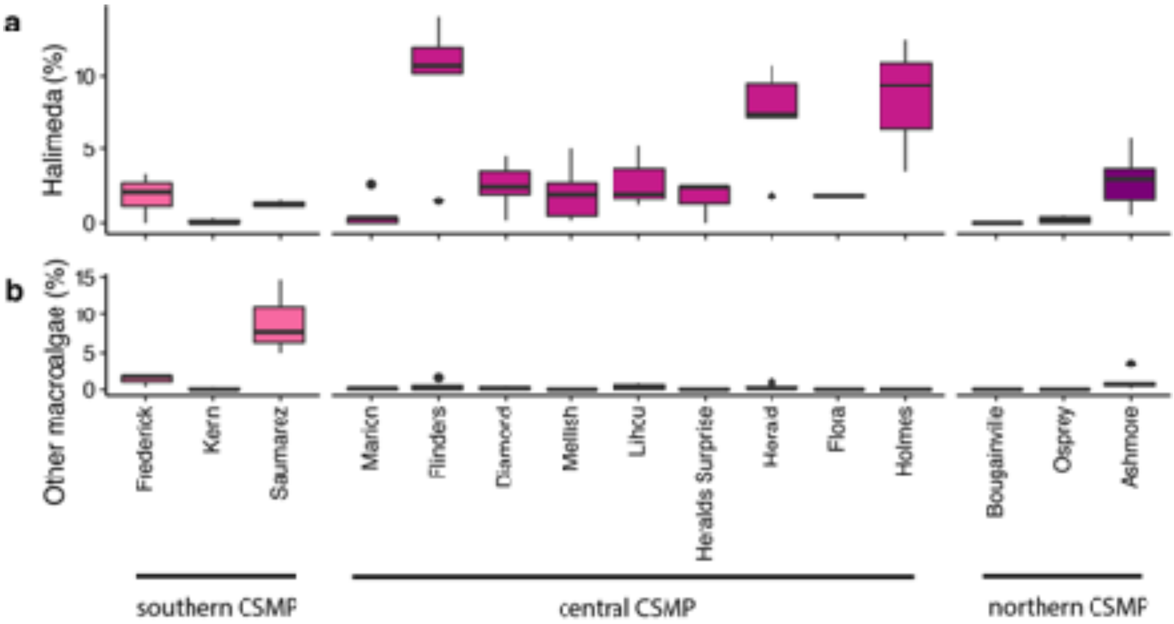


Figure 4.12 Variation in the cover of (a) *Halimeda* spp. and (b) 'other' macroalgae among 15 reefs in the Coral Sea Marine Park (CSMP) in 2022. Data are based on the 50m point-intercept transects at each of the 68 sites. Reefs are arranged into the southern, central, and northern CSMP and coloured by a priori regional assignments (following Figure 3.1).

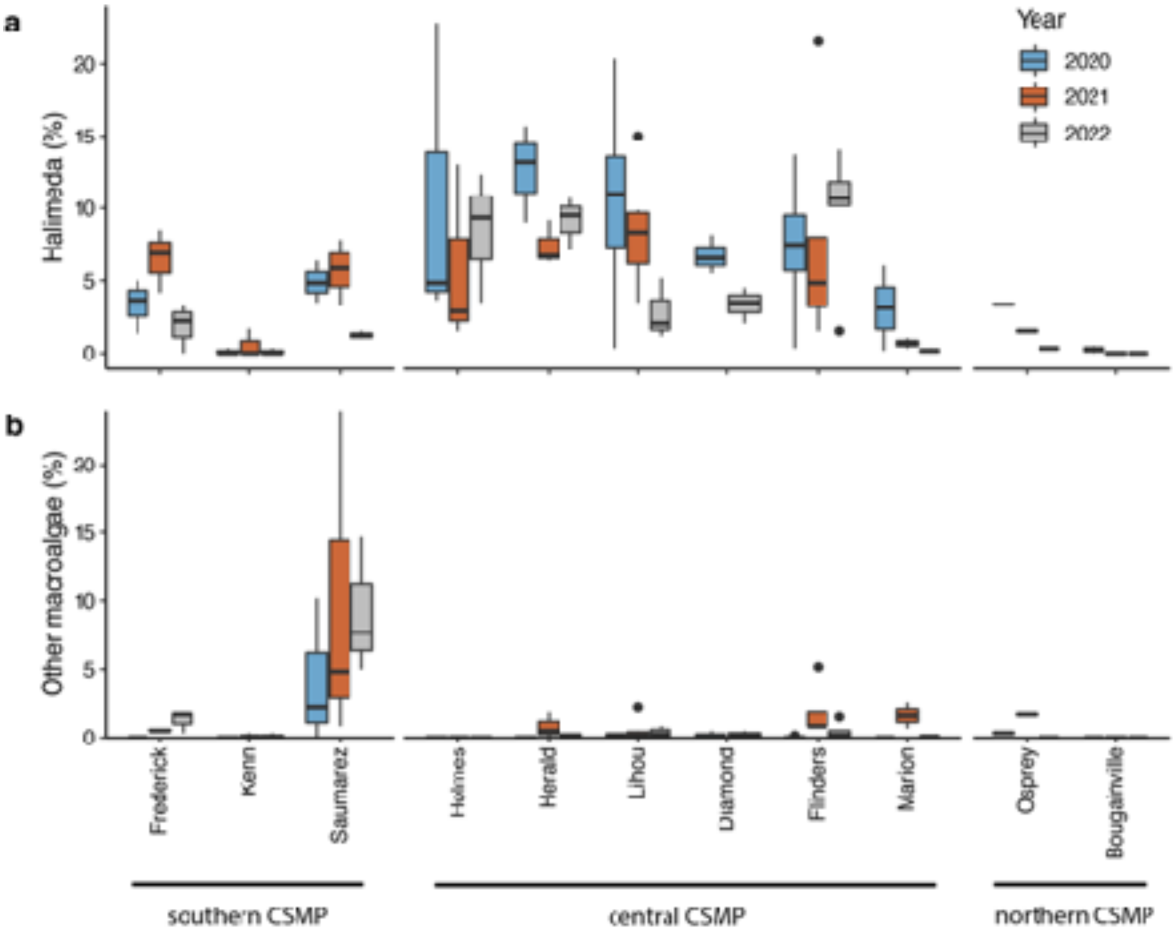


Figure 4.13 Temporal variation in the cover of **(a)** *Halimeda* spp. and **(b)** 'other' macroalgae among ten reefs in the Coral Sea Marine Park that were surveyed in 2020, 2021, and 2022. Data are based on surveys of matching sites in each year and pooled between habitats (reef slope and reef crest) within each site.

4.3. Coral Reef Fishes

The loss of coral cover, shifts in the composition of coral assemblages, and ultimately the associated loss of structural complexity of reefs following bleaching events has been shown to effect associated reef fish communities (e.g., Wilson et al. 2006; Pratchett et al. 2008, 2011b; Robinson et al. 2019). The greatest and most immediate effects on bleaching-induced coral mortality are on fishes that rely on these corals for food (i.e., corallivores) or shelter (e.g., Pratchett et al. 2008, 2011b), and have been shown to lead to shifts in the composition of fish assemblages from coral specialists to habitat and/or diet generalists (e.g., Bellwood et al. 2006, 2012; Richardson et al. 2018). In particular, the loss of fast-growing tabular and staghorn *Acropora* have been shown to reduce the three-dimensional structure and functionality of reef habitats (Hughes et al. 2018; McWilliam et al. 2020). While reductions in live coral cover may have immediate effects on populations of coral specialist or dependent species, the effects on other fish species (e.g., that use live coral as a settlement or juvenile habitat) may take several years to be realised (e.g., Graham, et al. 2007).

4.3.1 Richness, density and biomass of reef fishes

A total of 79,785 fishes were recorded across the 68 sites surveyed across 15 reefs in 2022. Twelve fish species that had not been recorded during surveys or observations on the previous voyages (2018-2021) were recorded during the 2022 surveys, taking the total fish species recorded in the CSMP during the past five years of surveys to 640 species (Appendix 4). Six of these species were recorded from Ashmore Reef in the far north of the CSMP. The richness, density, and biomass of reef fishes and sharks were generally lowest on reefs in the southern CSMP and increased with decreasing latitude (Figure 4.14). Regional species richness of reef fishes ranged from an average of 58 species per site in the southern CSMP to 69 and 96 species per site in the central and northern CSMP, respectively (Figure 4.14a). There was also considerable variation in fish species richness among individual reefs. Overall, the most species rich fish communities were recorded at Ashmore Reef in the far northern CSMP with an average of 112 species per site, over double that of Kenn Reef (52 species per site) in the southern CSMP. In the southern CSMP, mean fish species richness ranged from 52 species per site at Kenn Reef to 66 species per sites at Frederick Reef, in the central CSMP from 56 species per site at Flora Reef to 83 species per site at Holmes Reef, and in the northern CSMP from 87 species per site at Osprey Reef to 112 per site at Ashmore Reef (Figure 4.14a). The higher species richness of reef fishes in the northern CSMP is consistent with well-known latitudinal gradients in the diversity of marine species (Hillebrand 2004) and reef fishes (Bellwood and Hughes 2001).

In 2022 regional averages in fish densities were 2- to 5-fold higher in the northern CSMP (261.2 individuals per 100 m^2) compared to the central (112.9 individuals per 100 m^2) and southern CSMP (53.9 individuals per 100 m^2), respectively (Figure 4.14b). Like fish species richness there was considerable variation in the density of reef fish recorded among reefs within each region of

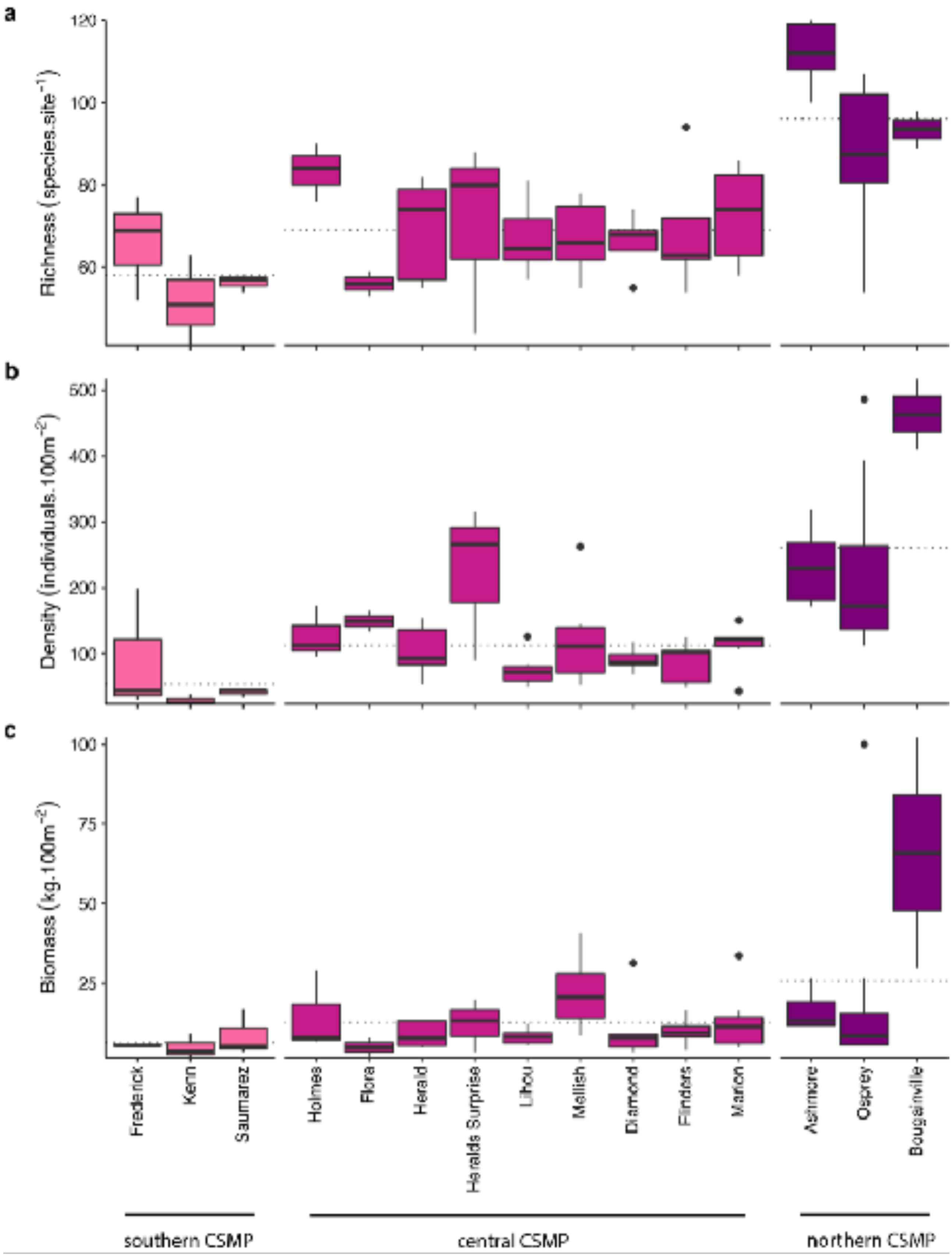


Figure 4.14 Spatial variation in the **(a)** species richness, **(b)** abundance, and **(c)** biomass of coral reef fishes and sharks among the 15 reefs surveyed in the Coral Sea Marine Park during 2022. Data are based on the 50m belt transects, with data for richness based on the number of fish species recorded at each of the 68 sites (i.e., pooled across transects and slope and crest habitats). Reefs are arranged into the southern, central, and northern CSMP and coloured by *a priori* regional assignments (following Fig 3.1). Dotted lines represent regional averages.

the CSMP. In the southern CSMP, the mean density of reef fish (including sharks) varied 3-fold among reefs, from 29.1 individuals per 100 m^2 at Kenn Reef to 91.0 individuals per 100 m^2 at Frederick Reef (Figure 4.14b). Similarly, the mean density of reef fish ranged from 76.4 individuals at Lihou Reef to 224.0 individuals per 100 m^2 at Herald Surprise Reef in the central CSMP, and from 227.5 individuals at Osprey Reef to 463.5 individuals per 100 m^2 at Bougainville Reef in the northern CSMP (Figure 4.14b).

Regional patterns in reef fish biomass were similar to those of fish species richness and density, with the mean reef fish biomass recorded on reefs in the northern CSMP (25.8 kg per 100m^2) being 2- to 4-fold greater than the biomass recorded on reefs in central and southern CSMP (12.7 and 6.3 kg per 100m^2, respectively; Figure 4.14c). Reef fish biomass varied widely among reefs, ranging from approximately 4.8 kg per 100 m^2 at Kenn Reef in the southern CSMP to 66 kg per 100 m^2 at Bougainville in the northern CSMP (Figure 4.14c). Together with Bougainville Reef (65.9 kg per 100 m^2), reefs with a high reef fish biomass were Mellish Reef (22.2 kg per 100 m^2), Osprey Reef (21.5 kg per 100 m^2), and Ashmore Reef (16.5 kg per 100 m^2). It is important to note that, with the exception of Bougainville Reef, the density and biomass of reef fishes was poorly correlated, and reflects differences in the size structure of fish assemblages among reefs, with some reefs likely supporting high densities of relatively small fishes (e.g., Frederick and Heralds Surprise Reefs), while other reefs may support a lower density of larger fishes (e.g., Saumarez and Mellish Reefs).

4.3.2 *Temporal changes in reef fish richness, density and biomass*

Richness – Twelve fish species that had not been recorded during surveys or observations on the previous voyages (2018-2021) were recorded during the 2022 surveys, taking the total fish species recorded in the CSMP during the past five years of surveys to 640 species (Appendix 3). All of these twelve species are common on the GBR. On the reefs that were surveyed in 2020, 2021 and 2022, the number of fish species recorded per site was relatively stable within the central (2021: 74 species; 2022: 71 species) and northern CSMP (2021: 94 species; 2022: 93 species) from 2021 to 2022, however there was a 15% decline in fish species richness on the southern CSMP reefs (2021: 68 species; 2022: 58 species per site; Figure 4.15a). This decline in mean fish species richness in the southern CSMP was largely driven by declines at Saumarez Reef (2021: 76 species; 2022: 56 species, and Kenn Reef (2021: 60 species; 2022: 52 species). Fish species richness was relatively consistent among reefs and years in the northern CSMP, although there was some variation among reefs in the central CSMP, with average species richness declining at Holmes and Flinders Reefs, while small increases were recorded at Herald, Lihou and Marion Reefs (Figure 4.16a).

Density – There was a small increase in the density of reef fish recorded on reefs in the northern CSMP from 2021 to 2022 (2021: 285.4 individuals per 100m^2; 2022: 311.0 individuals per 100m^2), yet density declined by 14% on central (2021: 106.0 individuals per 100m^2; 2022: 91.3 individuals per 100m^2) and 27% on southern CSMP reefs (2021: 74.1 individuals per 100m^2; 2022: 53.9 individuals per 100m^2) over the same period (Figure 4.15b). These changes in density were primarily driven by changes in abundance of planktivorous fusiliers, anthias and damselfishes (see Section 4.3.3 below). Declines in mean density were relatively consistent among the six central CSMP reefs, however there was considerable variation among reefs within the southern CSMP with the abundance of reef fish declining at Kenn (2021: 78.8 individuals per 100m^2; 2022: 29.2 individuals per 100m^2) and Saumarez Reefs (2021: 64.6 individuals per 100m^2; 2022: 41.5 individuals per 100m^2), but increasing at Frederick Reef (2021: 78.8 individuals per 100m^2; 2022: 91.0 individuals per 100m^2; Figure 4.16b).

Biomass – In contrast to density, the biomass of reef fish and sharks was relatively stable on southern (2021: 6.5 kg per 100m^2; 2022: 6.3 kg per 100m^2) and central CSMP reefs (2021: 9.2 kg per 100m^2; 2022: 10.4 kg per 100m^2) from 2021 to 2022, but increased substantially in the northern CSMP (2021: 14.9 kg per 100m^2; 2022: 35.8 kg per 100m^2; Figure 4.15c). This increase in biomass in the northern CSMP was driven by a 3-fold increase in biomass at Bougainville Reef (2021: 21.4 kg per 100m^2; 2022: 65.9 kg per 100m^2; Figure 4.16c, 4.17).

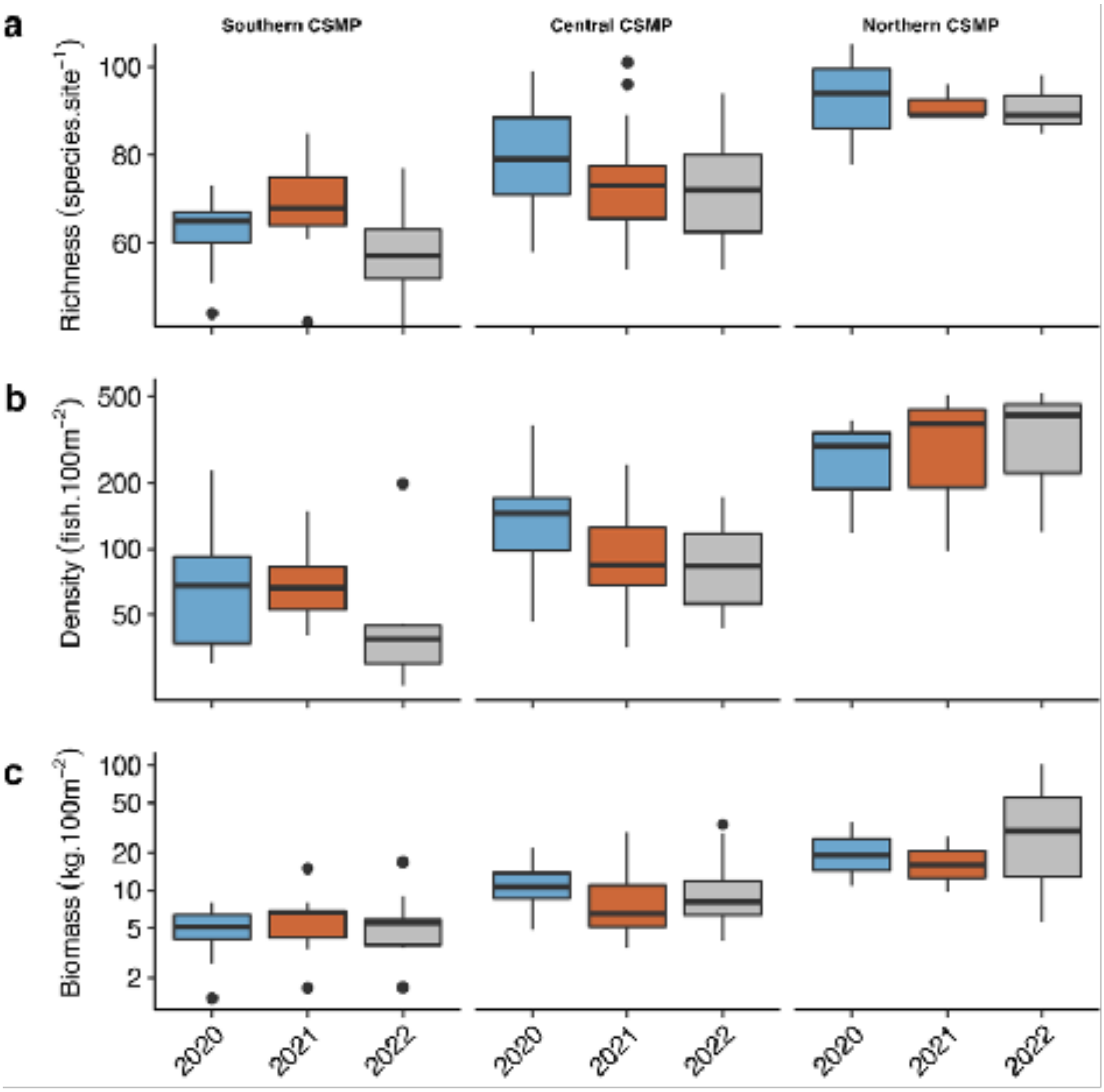


Figure 4.15 Temporal variation in the **(a)** species richness, **(b)** density, and **(c)** biomass of reef fish and shark assemblages among the three regions of the Coral Sea Marine Park. Data are based on surveys of matching sites in 2020, 2021 and 2022 across 10 reefs (southern CSMP: Saumarez, Kenn, Frederick Reefs; central CSMP: Marion, Flinders, Holmes, and Lihou Reefs, and Herald Cays; northern CSMP: Bougainville and Osprey Reefs). Note: the data for **(b)** density, and **(c)** biomass are presented on a $\log_{10}$-scale.

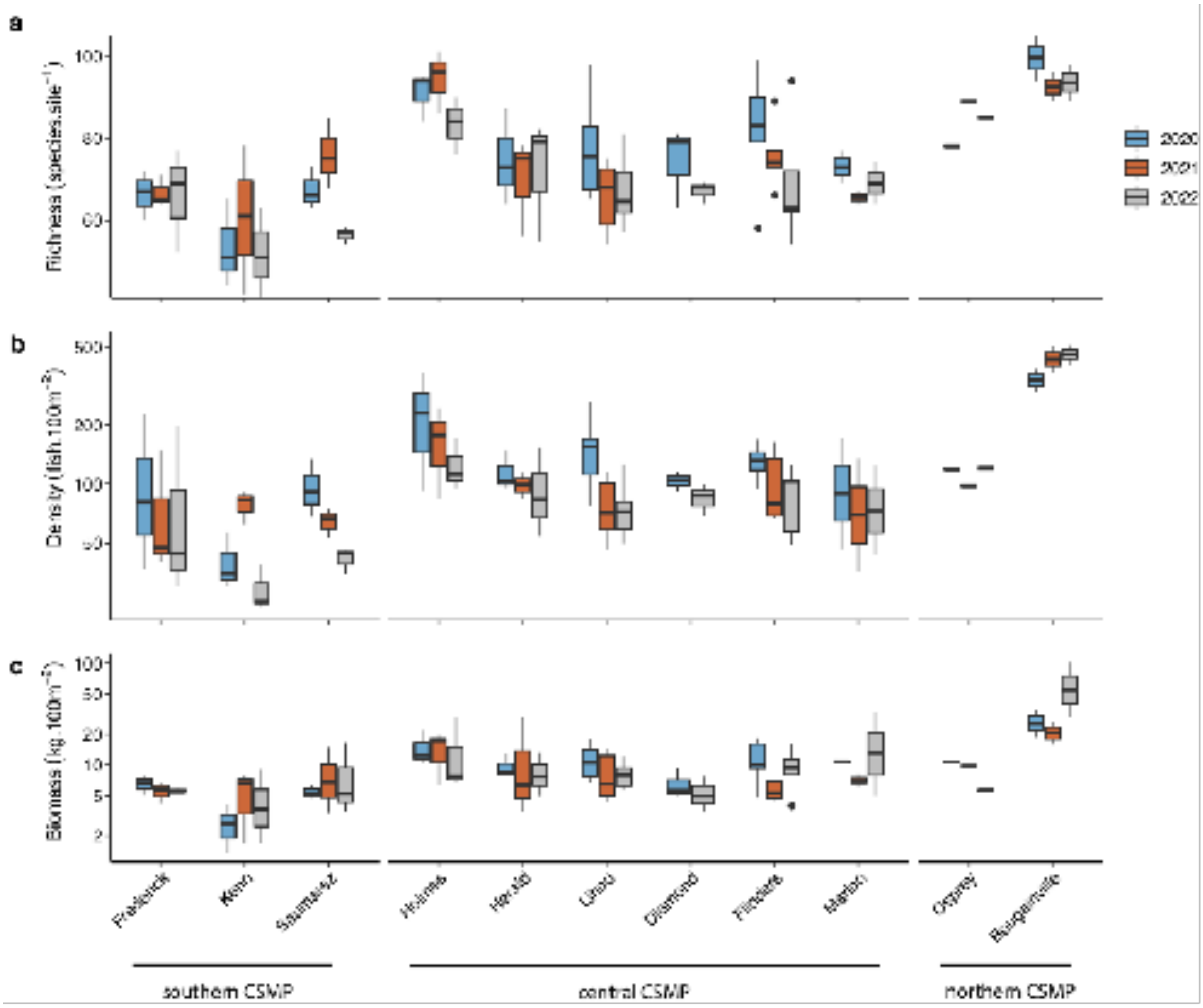


Figure 4.16 Temporal variation in the **(a)** species richness, **(b)** density, and **(c)** biomass of reef fish and shark assemblages among reefs in the Coral Sea Marine Park. Data are based on surveys of matching sites in 2020, 2021 and 2022 across 11 reefs (southern CSMP: Saumarez, Kenn, Frederick Reefs; central CSMP: Marion, Flinders, Holmes, and Lihou Reefs, Herald Cays, and Diamond Islets; northern CSMP: Bougainville and Osprey Reefs). Note: Diamond Islets were not surveyed in 2021. Note: data for **(b)** density, and **(c)** biomass are presented on a $\log_{10}$-scale.

These temporal changes in fish richness, biomass and abundance were relatively consistent among sites within each reef (Figure 4.18). The only exceptions being one site at Bougainville Reef (Bougainville 5) where the biomass of reef fishes increased markedly due to two schools (100 individuals in total) of the bumphead parrotfish, *Bolbometopon muricatum* (each 80-100cm in total length) being recorded along the reef crest, and a marked decline in the density of reef fishes at one site on Holmes Reef (Holmes 5). *Bolbometopon muricatum* have been estimated to move up to 10km along a reef (Hamilton 2005; Green et al. 2015), but are unlikely to move between isolated reefs separated by areas of deep water, such as those within the CSMP. They typically occur in schools (up to 200 individuals) and their aggregated distributions can lead to high variability in estimates of abundance and biomass among transects and sites within a single reef (e.g., Hoey and Bellwood 2008).

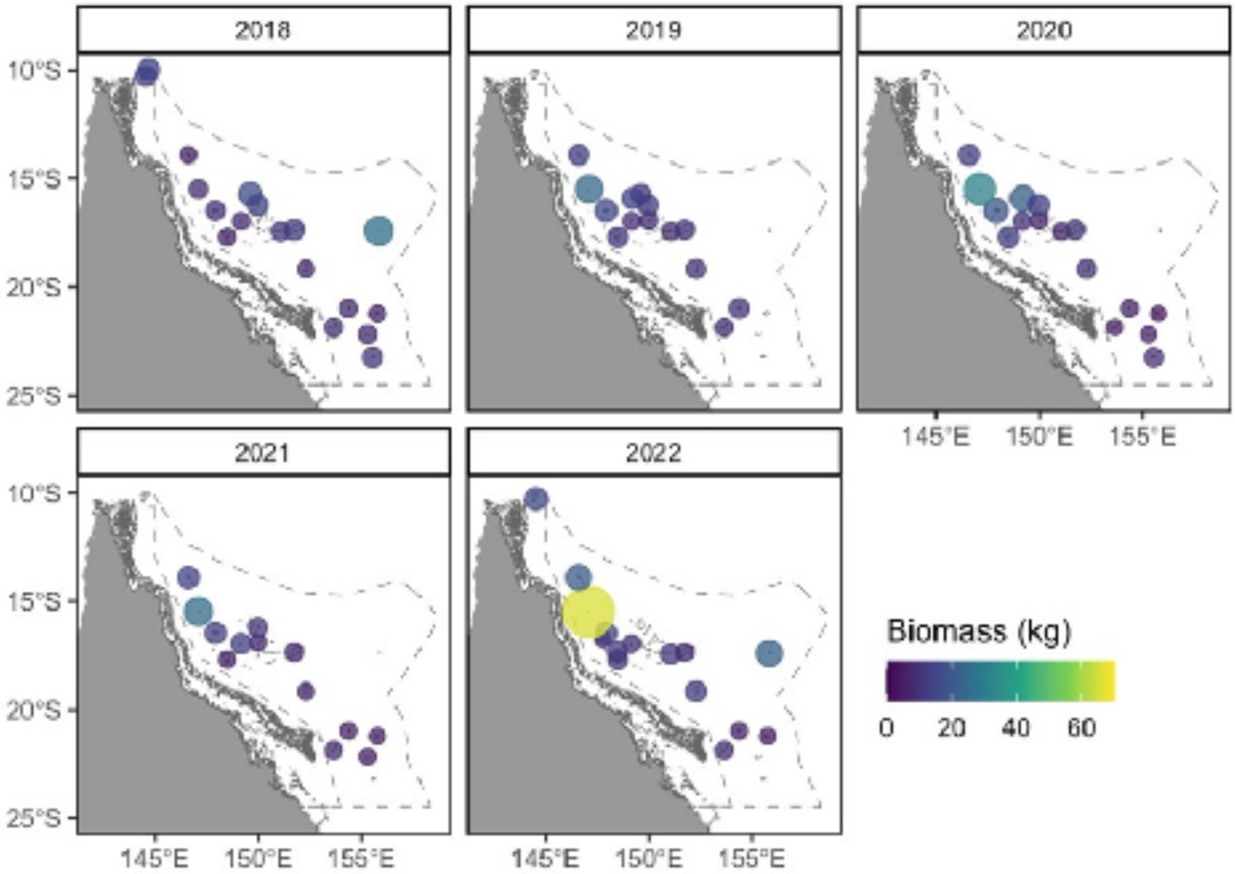


Figure 4.17 Spatial and temporal variation in the biomass of reef fish and sharks on shallow reef habitats (reef crest and reef slope) across 22 reef systems in the Coral Sea Marine Park. The size of individual points is proportional to the total fish biomass at each reef.

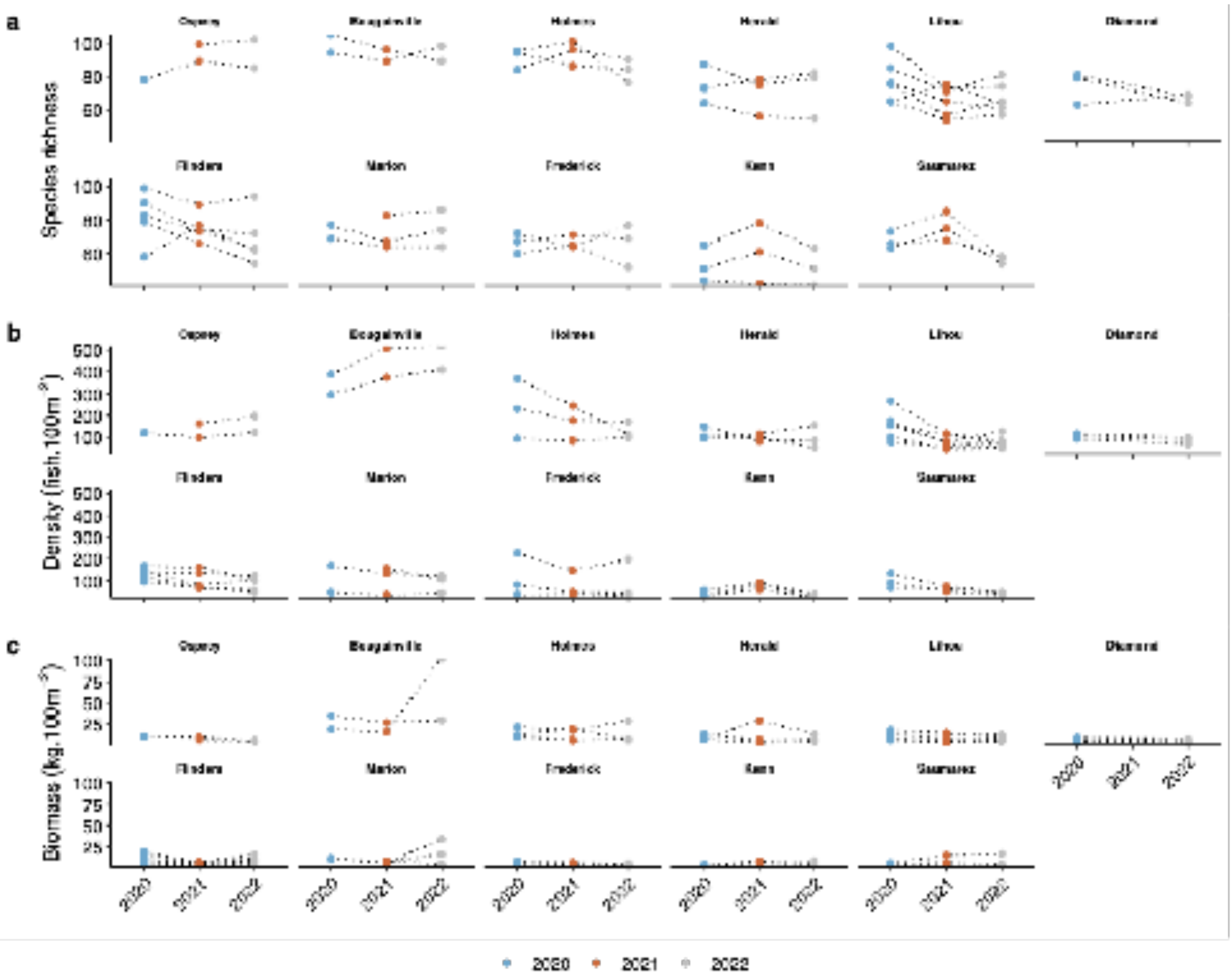


Figure 4.18 Temporal variation in the (a) species richness, (b) density, and (c) biomass of reef fish and shark assemblages among individual sites in the Coral Sea Marine Park. Data are based on surveys of 36 matching sites in 2020, 2021 and 2022 across 11 reefs (southern CSMP: Saumarez, Kenn, Frederick Reefs; central CSMP: Marion, Flinders, Holmes, and Lihou Reefs, Herald Cays, and Diamond Islets; northern CSMP: Bougainville and Osprey Reefs). Note: Diamond Islets were not surveyed in 2021.

4.3.3 Functional composition of fish assemblages

Fishes were categorised into eleven functional groups (piscivore, mixed carnivore, benthic invertivore, planktivore, omnivore, corallivore, excavator, scraper, browser, grazer, and farmer) based on their diet, morphology and feeding behaviour. Planktivorous fishes (e.g., fusiliers, anthias and some damselfishes) were the most abundant functional group on reefs in the CSMP accounting for approximately 80% of all fish recorded across 2020, 2021 and 2022 (Figure 4.19a). The abundance of planktivorous fishes decreased in the southern (2021: 38.3 individuals per 100m^2; 27.1 individuals per 100m^2) and central CSMP (2021: 64.5 individuals per 100m^2; 51.2 individuals per 100m^2) between 2021 and 2022, compounding on declines in each region from 2020 to 2021 (Figure 4.20b). In contrast, the abundance of planktivorous fishes remained relatively unchanged in northern CSMP. The next most abundant groups were grazing herbivorous fishes (primarily surgeonfishes and rabbitfishes) that typically feed on reef substrata covered by an epilithic algal matrix (i.e., short algal turfs and associated detritus, sediment and microbes, EAM; Wilson et al. 2003), and corallivores (primarily butterflyfishes; Figure 4.19a). The density of corallivores decreased on reefs in the southern and central CSMP immediately following the 2020 bleaching (i.e., between 2020 and 2021) and continued to decline between 2021 and 2022 (southern CSMP 2021: 1.64 individuals per 100m^2; 1.41 individuals per 100m^2; central CSMP 2021: 1.62

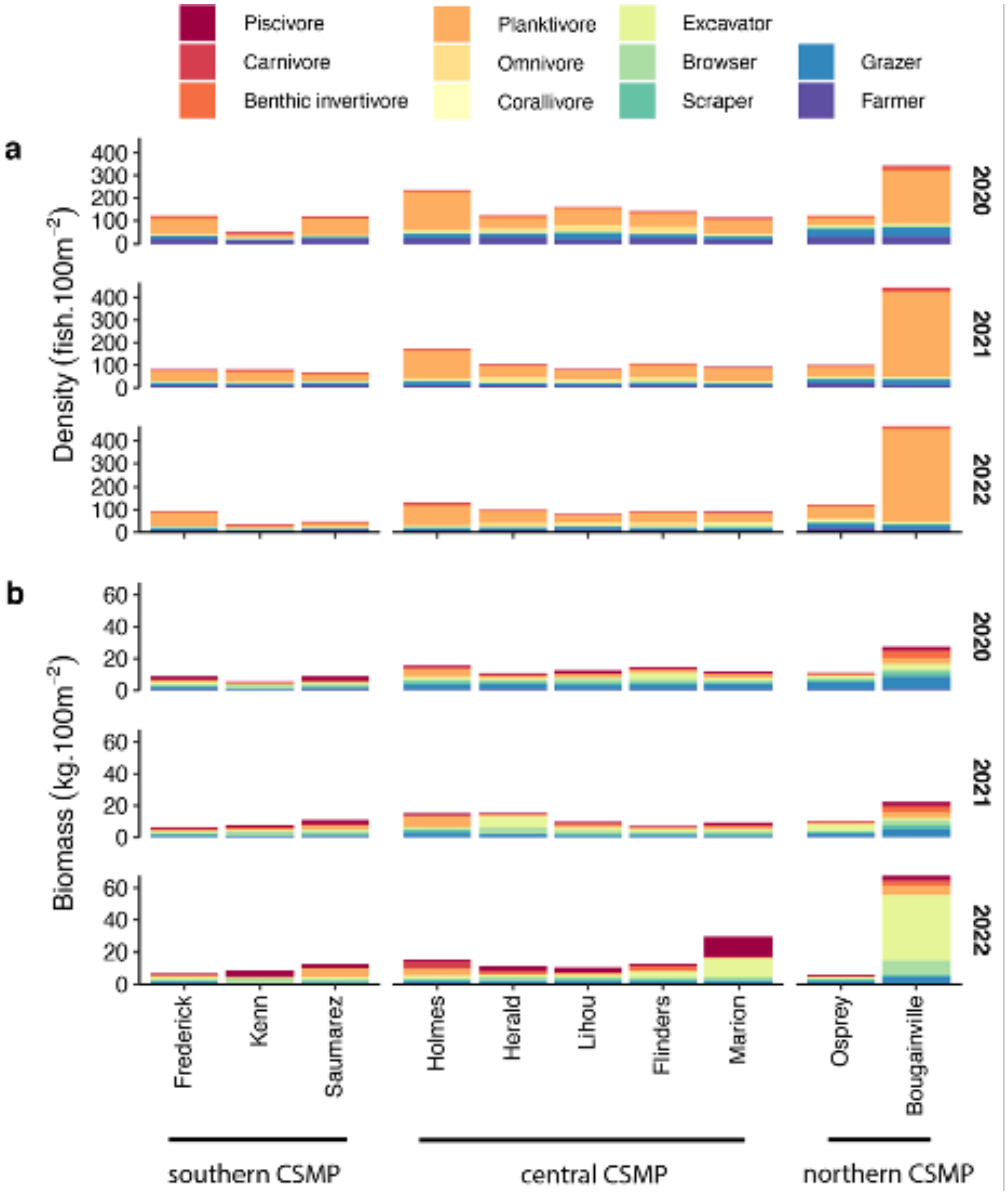


Figure 4.19 Temporal variation (2020, 2021, 2022) in the functional composition of reef fish assemblages across 10 reefs in the Coral Sea Marine Park based on **(a)** abundance, and **(b)** biomass. Values for each reef are averaged across habitats and sites.

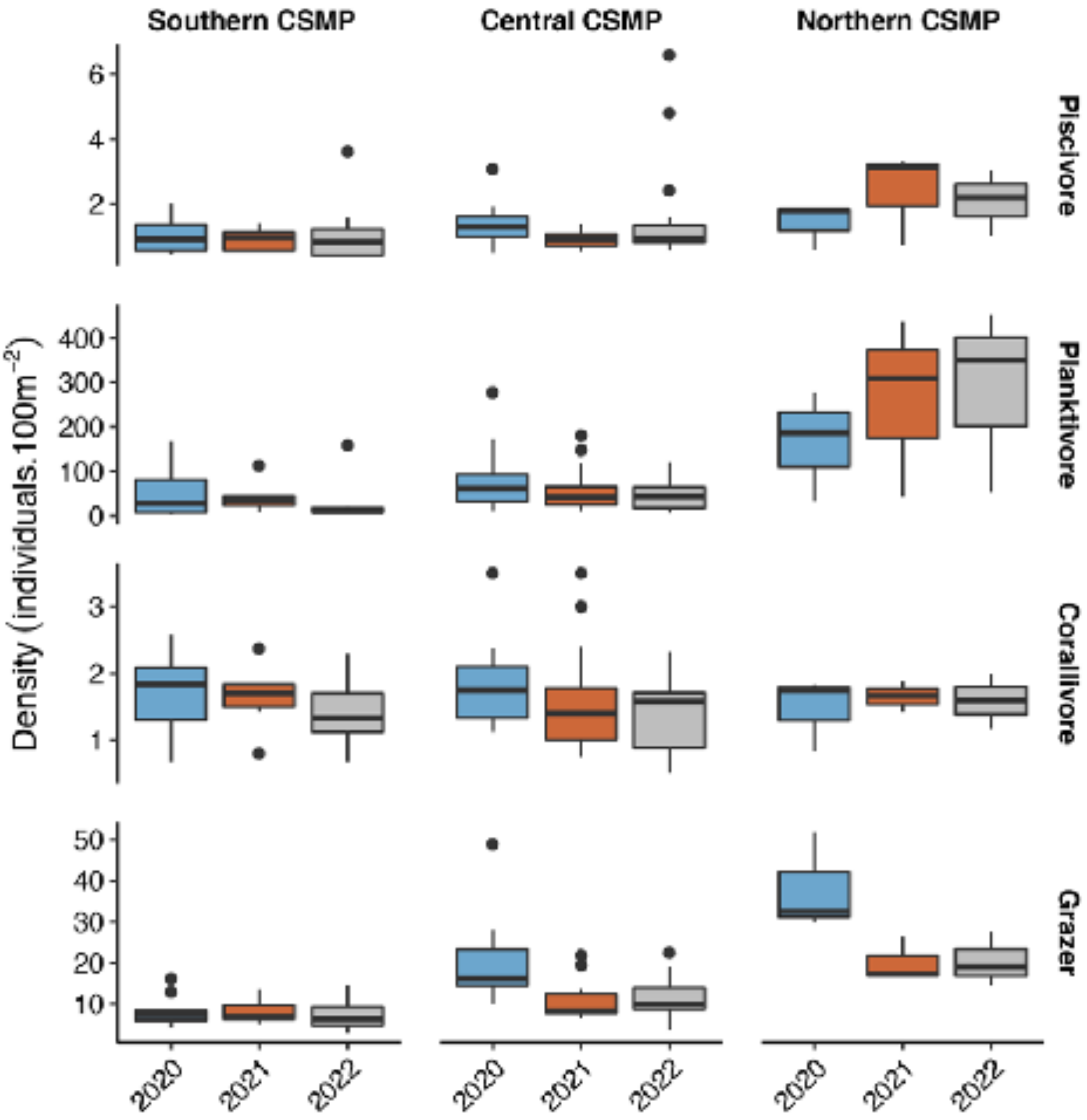


Figure 4.20 Spatial and temporal variation in the density of **(a)** piscivorous, **(b)** planktivorous, **(c)** corallivorous, and **(d)** grazing fishes among the three regions of the Coral Sea Marine Park during 2020, 2021 and 2022. Data are based on replicate 50m transects at each of 31 sites across 10 reefs that were surveyed in each year.

individuals per 100m²; 1.48 individuals per 100m²; Figure 4.20c). The density of corallivores was relatively stable on northern CSMP from 2020 to 2022 (Figure 4.20c). The majority of planktivorous and corallivorous fishes are small-bodied and hence are not major contributors to reef fish biomass.

The reported declines in the density and biomass of grazing fishes on central and northern CSMP reefs between 2020 and 2021 (Hoey et al. 2021) were maintained in 2022 with little change in abundance or biomass between 2021 and 2022 (Figure 4.20d, 4.21d). The initial declines were primarily driven by reductions in the density of grazing surgeonfishes (in particular *Acanthurus lineatus* and *Acanthurus nigrofuscus*), with no evidence of recovery of these populations in 2022. These observed and sustained declines in the density and biomass of grazing surgeonfishes is difficult to reconcile as several studies have reported substantial increases in the abundance and/or biomass of herbivorous fishes following large-scale bleaching-induced coral mortality (e.g., Adam et al 2011; Gilmour et al. 2013). Such increases have generally been related to an increase in the availability of EAM-covered substrata and subsequent increases in the growth rates of individual fishes (e.g., parrotfishes: Taylor et al. 2020). The immediate and sustained decline of grazing fishes following the 2020 bleaching event suggests that these changes may be related to the physiological response of these fishes to heat stress, rather than changes in the availability of food and/or habitat (Stuart-Smith et al. 2018). Further research is required to identify the likely mechanism/s for these declines.

There were also several changes in the biomass of excavating fishes at individual reefs between 2021 and 2022. The decline in the biomass of excavating fishes at Herald Cays in the central CSMP was attributable to a school of the giant bumphead parrotfish *Bolbometopon muricatum* being recorded at Herald 1 in 2021 but not 2022 (Figure 4.19b). Conversely, the increase in biomass of excavating fishes at Bougainville Reef was attributable to two schools of *B. muricatum* being recorded at Bougainville 5 in 2022, while the increase in biomass of excavating fishes at Marion Reef was related to a large school (>300 individuals) of the Pacific slopehead parrotfish *Chlorurus frontalis* that were observed spawning at Marion 6 (Figure 4.22).

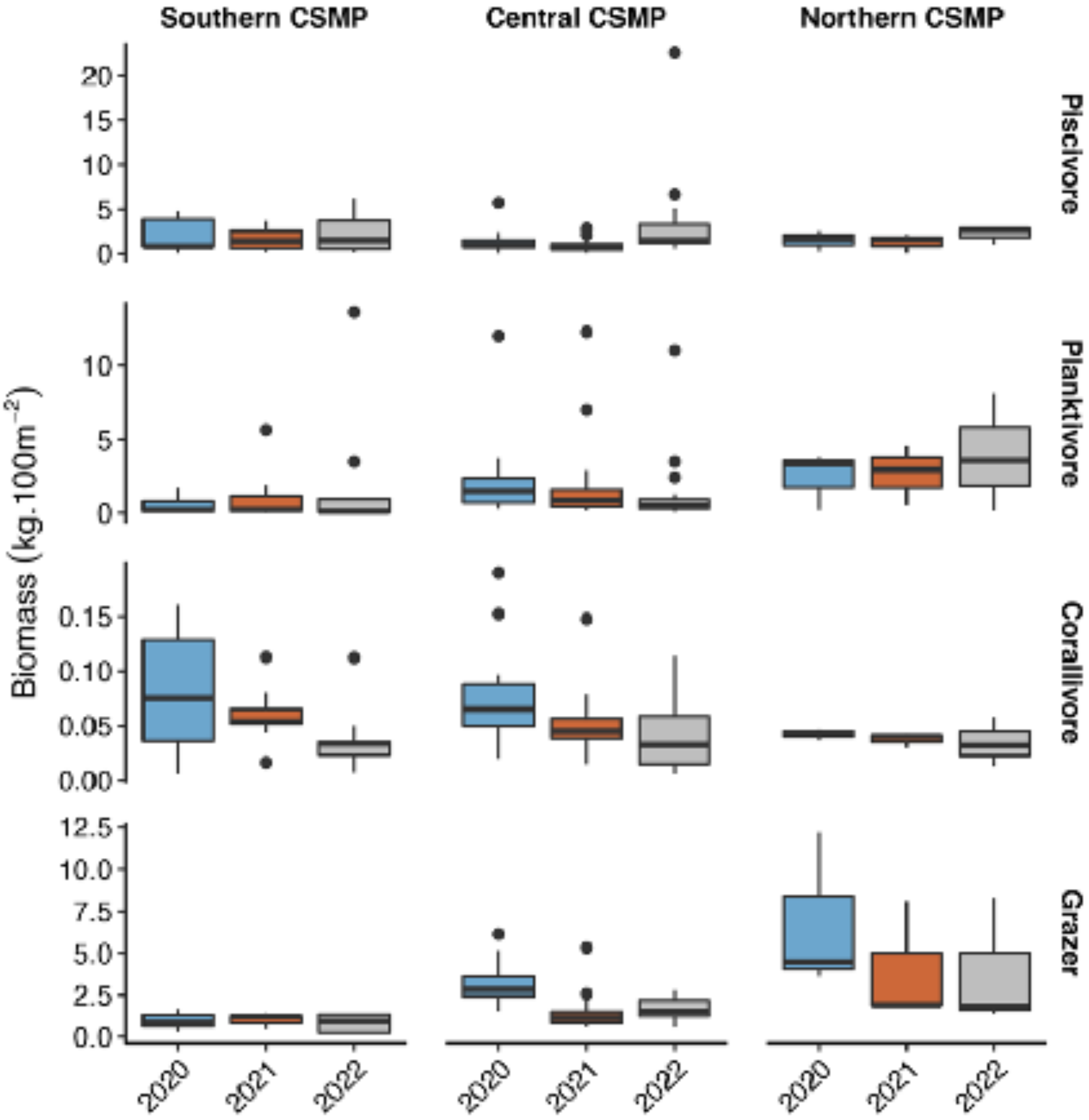


Figure 4.21 Spatial and temporal variation in the biomass of (a) piscivorous, (b) planktivorous, (c) corallivorous, and (d) grazing fishes among the three regions of the Coral Sea Marine Park during 2020, 2021 and 2022. Data are based on replicate 50m transects at each of 31 sites across 10 reefs that were surveyed in each year.

Figure 4.22 Photographs of a large spawning aggregation of the Pacific slopehead parrotfish at Marion 6 in the central Coral Sea Marine Park on the 19th February 2022. More than 300 individuals were observed. Image credits: Andrew Hoey.

4.3.4 *Fish community composition*

The greatest variation in the composition of reef fish assemblages, like coral assemblages (see Section 4.1.3 above), was among the three CSMP regions with the southern CSMP reefs occupying the lower left-hand and the northern CSMP reefs occupying the upper right hand of the nMDS space (Figure 4.23). Despite changes in the species richness, abundance and biomass of different functional groups of reef fishes on CSMP reefs from 2020 to 2022, the species composition of fish communities remained relatively stable over the same period, with almost complete overlap between years (Figure 4.23). Similarly, there was no evidence of a shift in the taxonomic composition of reef fish and shark assemblages within the central or southern CSMP from 2020 to 2022 (Figure 4.24). The nMDS failed to converge for the northern CSMP sites, likely due to the limited number of sites surveyed in each year (n=4 sites).

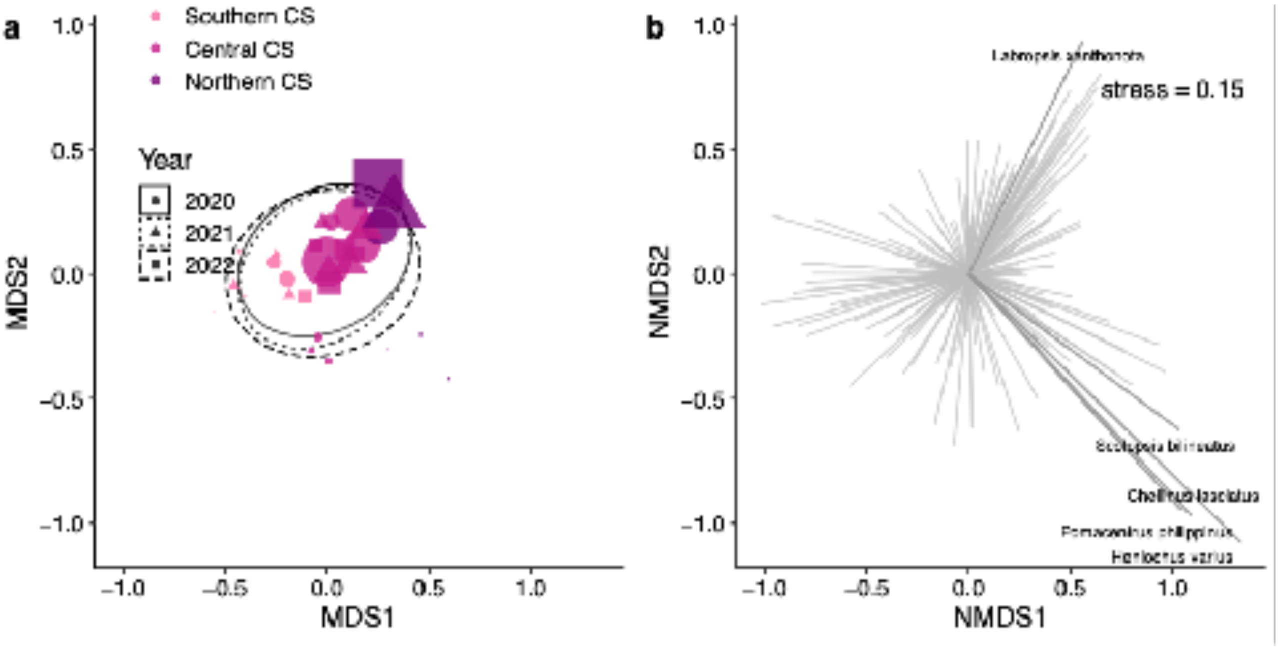
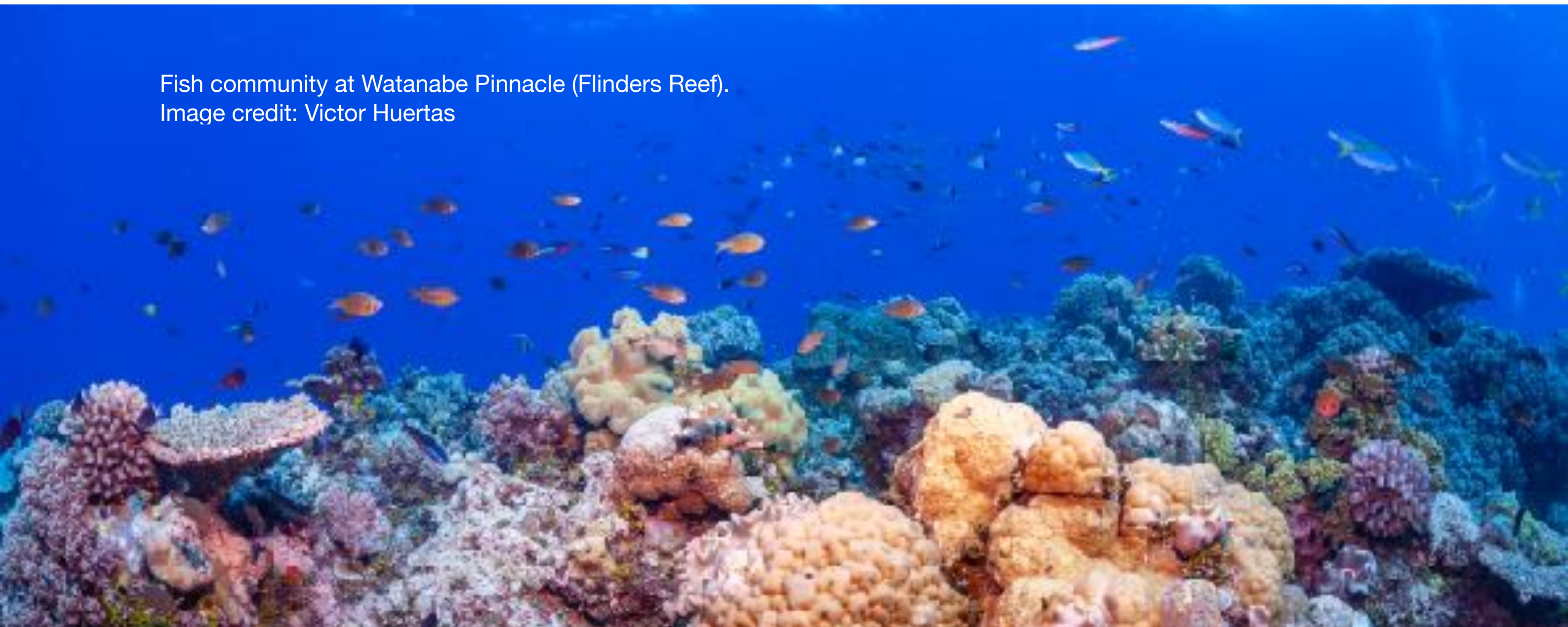


Figure 4.23 Regional and temporal (2020, 2021, and 2022) variation in the composition of reef fish and shark assemblages within the Coral Sea Marine Park. Non-metric multidimensional scaling (nMDS) plot showing the variation in reef fish composition among years for the three regions of the Coral Sea Marine Park. Analyses are based on data from 31 sites that were surveyed in each year. The size of individual points is proportional to the total fish abundance on each reef. Vectors in the right-hand side plot indicate key taxa that account for the variation in fish composition displayed in the corresponding left-hand side plot.



Fish community at Watanabe Pinnacle (Flinders Reef).
Image credit: Victor Huertas

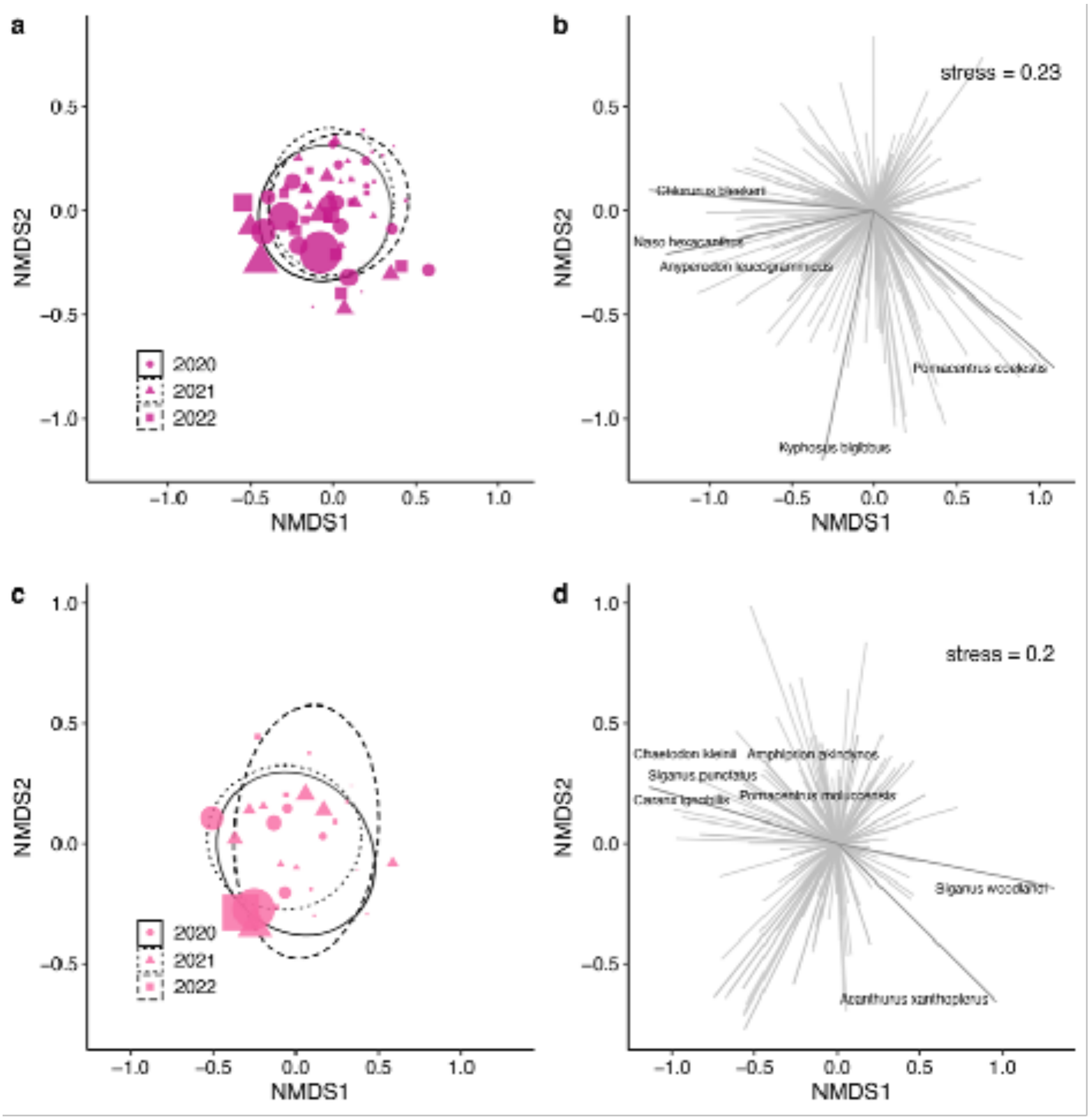


Figure 4.24 Non-metric multidimensional scaling (nMDS) plots showing the temporal variation (2020, 2021 and 2022) in the composition of reef fish and shark assemblages among reefs in the (a) central, and (c) southern Coral Sea Marine Park. Analyses are based on data from 28 sites that were surveyed in both years (central: 19 sites; southern: 9 sites). The size of individual points is proportional to the total fish abundance at each site. Vectors in the right-hand side plot indicate key taxa that account for variation in fish composition displayed in the corresponding left-hand side plot. Note the model for the northern CSMP sites failed to converge.

4.3.5 *Impact of 2020 bleaching on CSMP 'bright spot' reefs*

The 2020 bleaching event has been shown to have severe and widespread effects across the 13 reefs surveyed in 2021, with average coral cover declining by 39% (Hoey et al. 2021). The 2021 surveys, however, only included one of the five reefs previously identified as 'bright spots' (i.e., Bougainville, Ashmore, Boot, Moore and Mellish Reefs; Hoey et al. 2020). Importantly, Bougainville Reef (the only bright spot reef surveyed in 2021) had the highest coral cover and lowest recorded coral mortality of the 13 reefs surveyed. Given the geographic footprint of the heat stress across the CSMP in 2020 (Figure 2.2), it is likely that Mellish and Moore Reefs in the central CSMP, and to a lesser extent Boot and Ashmore Reefs in the far northern CSMP, experienced significant coral bleaching in 2020. Due to unfavourable weather at the time of the planned surveys we were unable to re-survey sites at Boot Reef (>30 knot winds) in November 2021, or sites at Moore Reef (predicted tropical cyclone) in February 2022. Results from surveys of five sites at Ashmore Reef (November 2021) and eight sites at Mellish Reef (February 2022) are presented below.

In contrast to most other reefs in the central and northern CSMP that experienced considerable declines in coral cover and coral richness following the 2020 bleaching event, there was no evidence of a decline in coral cover or richness at either Ashmore or Mellish Reefs (Figure 4.26). On Ashmore Reef, average coral cover increased from 26.5% in 2018 to 35.9% in 2022 (an overall increase of 35.4%, and an annual rate of increase of 7.9%), and coral richness increased from ca. 20 taxa to 22 taxa per site over the same time period (Figure 4.26). It should be noted that Ashmore Reef wasn't exposed to the same levels of heat stress as other reefs in the central or northern CSMP during 2020 or 2021 (Figure 2.2). It may be that localised upwelling of cooler water around Ashmore Reef is contributing to its higher coral cover. Coral cover and coral richness on Mellish Reef remained relatively stable between 2018 and 2022 (coral cover 2018: 33.3%, 2022: 29.0%; coral richness 2018: 20 taxa per site, 2022: 19 taxa per site; Figure 4.26). While coral cover on reefs that have not been impacted by disturbance may be expected to increase over a 4-year period, the lack of a significant decline in coral cover suggests that Mellish Reef fared much better than other reefs in the central CSMP over this period (i.e., 2018-2022). This is all the more surprising given that Mellish reef was exposed to significant heat stress (>10 DHW) in 2020, and likely again in March 2021 (Figure 4.5). As stated above, exposure to >6 DHW is predicted to cause bleaching-induced coral mortality, with exposure to 10 DHW during the 2016 bleaching event on the GBR leading to a ca. 90% decline in coral cover (Hughes et al. 2018). Although there was evidence of coral mortality at some sites around Mellish Reef (e.g., dead tabular *Acropora*), the lack of decline in coral cover is interesting and may reflect acclimation of local coral assemblages to variations in water temperatures at these sites, and/or localised upwelling providing relief from heat stress. Future research is needed to identify the mechanism/s for the apparent resilience of coral assemblages on these 'bright spot' reefs.

Declines in both the cover and richness of corals were evident at Bougainville Reef in the period 2018 - 2022, with the greatest declines being experienced from 2021 to 2022 (Figure 4.26). Coral cover at Bougainville Reef was initially high and relatively stable from 2018-2021 (ca. 35-40% cover), however declined to 23.9% in 2022. Similarly, coral richness has declined from an average of ca. 22 taxa per site in 2018, to 18 taxa per site in 2022 (Figure 4.26). Despite these declines the cover and richness of corals at Bougainville Reef are still above that of the average coral cover and richness for the CSMP.

Corresponding with the increases in coral cover and richness at Ashmore Reef, there were increases in the richness, density, and biomass of reef fishes recorded at Ashmore Reef between 2018 and 2022 (Figure 4.27). On Ashmore Reef, average fish species richness increased by 22.9% from 91 species per site in 2018 to 112 species per site in 2022, reef fish density increased by 70% (2018: 137.7 individuals per 100m^2; 2022: 234.1 individuals per 100m^2), and reef fish biomass increased by 27.5% (2018: 12.9 kg per 100m^2; 2022: 16.5 kg per 100m^2; Figure 4.27). Similar increases in richness (16.4%) and density (87.6%) of reef fishes were recorded on Bougainville Reef over the same period, along with a much more substantial increase (637.5%) in reef fish biomass from 2018 to 2022 (Figure 4.27). While much of the increase in reef fish biomass was due to schools of the bumphead parrotfish *B. muricatum* at one site in 2022 (see Sections 4.3.2 and 4.3.3 above) the reef fish biomass had been steadily increasing at Bougainville Reef prior to the 2022 surveys.

In contrast to the increases in fish richness, density and biomass at Ashmore and Bougainville Reefs in the

Figure 4.25 Photographs of diverse coral assemblage at Ashmore Reef (top: November 2021), ‘Big Mel’ a large *Porites* bommie in the lagoon at Mellish Reef (middle: February 2022), and the recovery of areas where coral cores were taken from ‘Big Mel’ during previous voyages (bottom: February 2022). Image credits: Victor Huertas (top and middle), Andrew Hoey (bottom).

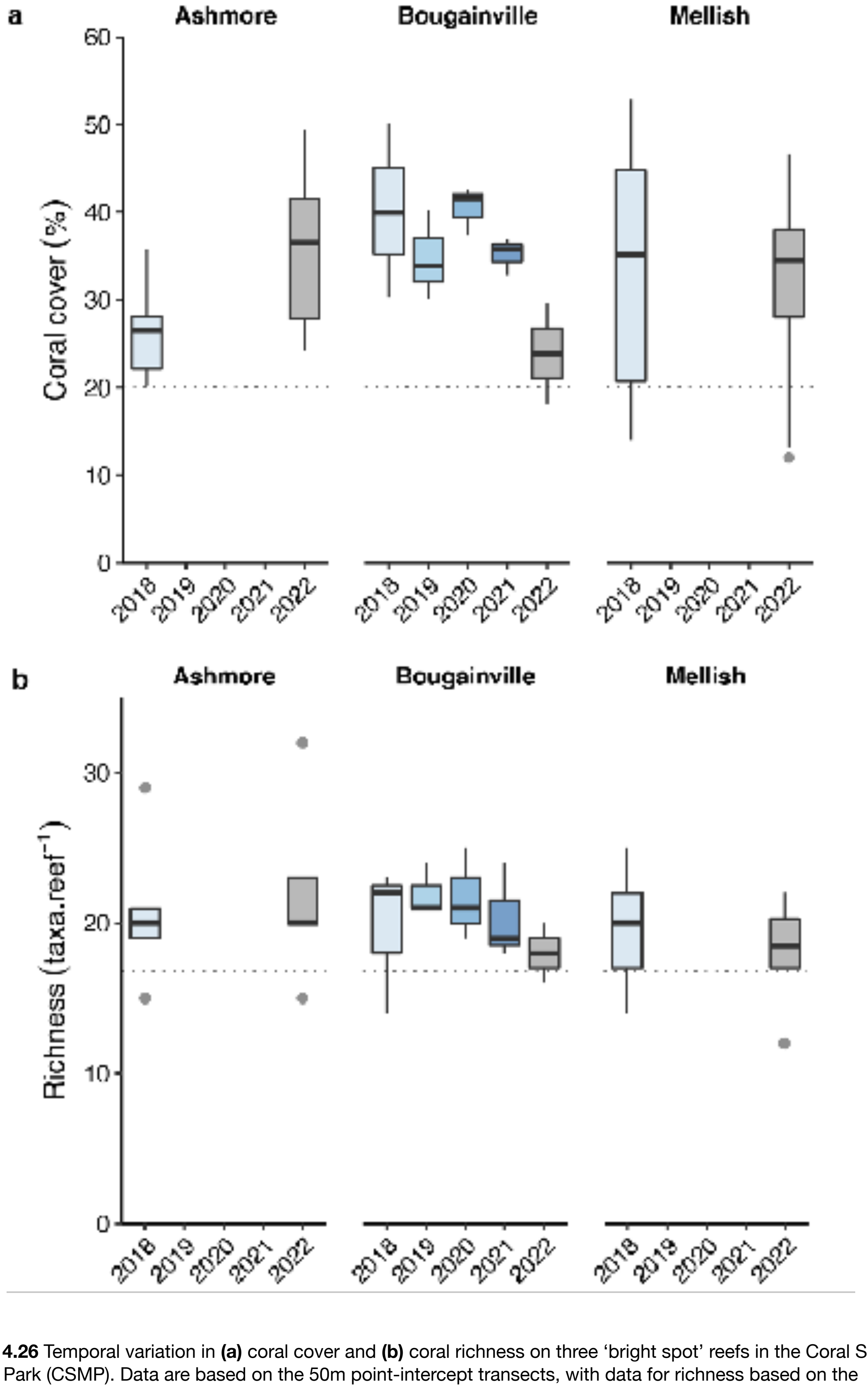


Figure 4.26 Temporal variation in **(a)** coral cover and **(b)** coral richness on three ‘bright spot’ reefs in the Coral Sea Marine Park (CSMP). Data are based on the 50m point-intercept transects, with data for richness based on the number of coral taxa recorded at each site (i.e., pooled across transects and slope and crest habitats). Dotted lines represent CSMP average.

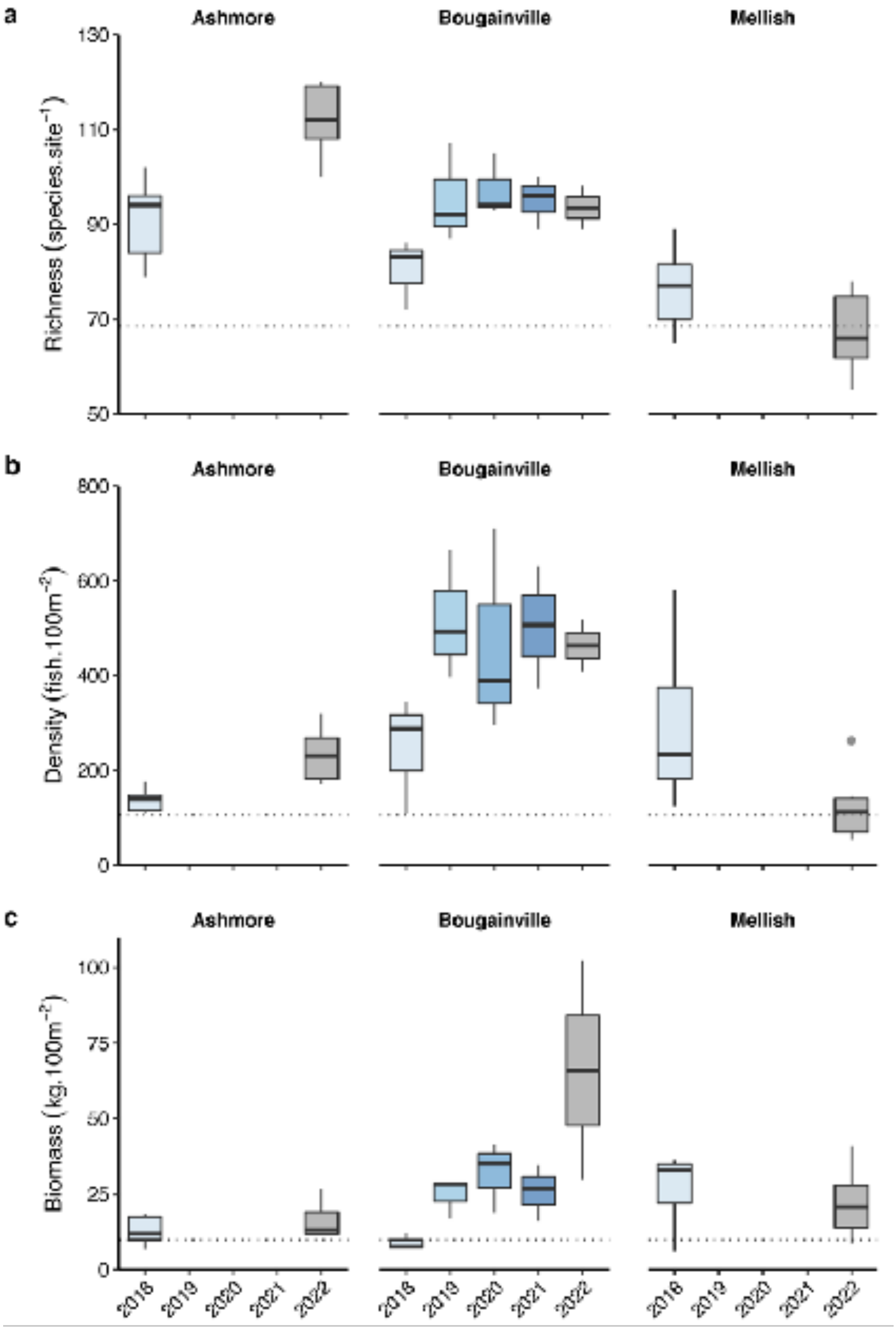


Figure 4.27 Temporal variation in the (a) richness (b) density, and (c) biomass of reef fish and sharks on three 'bright spot' reefs in the Coral Sea Marine Park (CSMP). Data are based on the 50m belt transects, with data for richness based on the number of fish species recorded at each site (i.e., pooled across transects and slope and crest habitats). Dotted lines represent CSMP average.

northern CSMP, there were declines in the richness, density and biomass of reef fishes at Mellish Reef in central CSMP (Figure 4.27). Fish species richness declined by 12.3% from 76 species per site in 2018 to 67 species per site in 2022, reef fish density decreased by 59.4% (2018: 293.4 individuals per 100m^2; 2022: 119.1 individuals per 100m^2), and reef fish biomass declined by 17.7% (2018: 27.0 kg per 100m^2; 2022: 22.2 kg per 100m^2; Figure 4.27). These apparent declines occurred despite limited change in the richness or cover of coral assemblages over the same period (Figure 4.26), and may be related to unfavourable weather conditions at the time of our surveys that prevented us from safely accessing and hence surveying the reef crest habitat at several of the sites around Mellish Reef. Future surveys at Mellish Reef will be necessary to assess the true nature and extent of any declines in reef fish and shark assemblages.

4.3.6 Within-reef variation in coral and fish communities

As well as revisiting sites that had been surveyed during the 2020 bleaching event, the 2022 voyage allowed additional time (up to 2-days) to survey new sites on reefs in the central and northern CSMP, and where possible sites on the exposed aspect of each reef. While previous voyages allowed for 2 days of surveys at each of Lihou, Flinders, and Holmes Reefs, additional sites were surveyed during the November 2021 and February-March 2022 voyages on Ashmore, Mellish, and Osprey Reefs, Diamond Islets, and Herald Cays, as well as two reefs (Flora and Herald Surprise Reefs) that had not been surveyed in the four previous years of this project (2018-2021). These surveys not only increased the spatial coverage of our surveys and provide some insight into the composition of sites on the exposed aspects of reefs in the CSMP, but importantly highlight the variability among sites with seemingly similar exposure and environmental conditions.

On Mellish Reef for example, coral cover was generally highest at the two sites (Mellish 5 and 8) on the exposed southern aspect of the reef (ca. 46%), however coral cover was highly variable among sites on the western or leeward aspect of the reef (12-35% cover; Figure 4.28). Similarly, reef fish biomass was generally greatest, although more variable than coral cover, at the two southern sites, compared to those on the western aspect of the reef. In contrast, the highest coral cover on Osprey Reef was recorded at two sites (Osprey 2: 43.0%; Osprey 10: 39.3%) on the western aspect of the reef (Figure 4.29). Coral cover was, however, highly variable among sites along the western aspect of the reef with the site with the lowest coral cover (Osprey 7: 9.3%) being situated adjacent to the site with the highest coral cover (Osprey 2: 43.0%). Reef fish biomass was less variable among the eight sites on Osprey Reef, with the exception of Osprey 4 that had substantially greater fish biomass (99.99 kg per 100m^2) than the other seven sites (5.62 – 26.32 kg per 100m^2; Figure 4.29).

Similar variation in coral cover and/or fish biomass was evident among sites at other reefs (e.g., Ashmore Reef, Figure 4.30; Diamond Islets, Figure 4.31), and highlights the advantages of surveying a greater number of sites at each reef to gain a better understanding of the status and health of these unique reef systems. Even on the wave-swept exposed south-eastern aspects of reefs, where the habitat complexity is low, coral cover can be highly variable (Figure 4.32). Maps showing the coral cover and fish biomass at all reefs surveyed in 2022 are provided in Appendix 5.

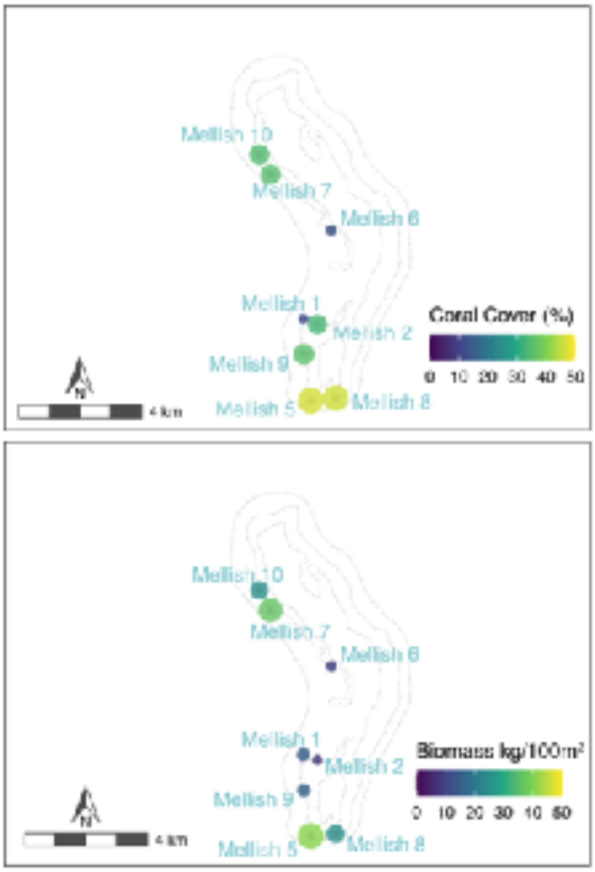


Figure 4.28 Spatial variation in **(a)** coral cover and **(b)** biomass of reef fish and sharks among eight sites on Mellish Reef in the central Coral Sea Marine Park (CSMP). Data are based on replicate 50m transects at each site. Size of points is proportional to coral cover or total fish biomass at each site.

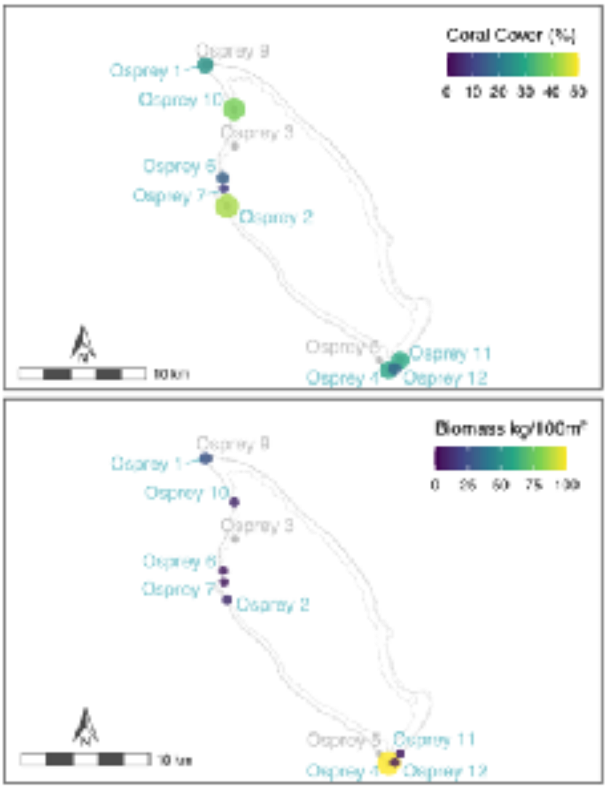
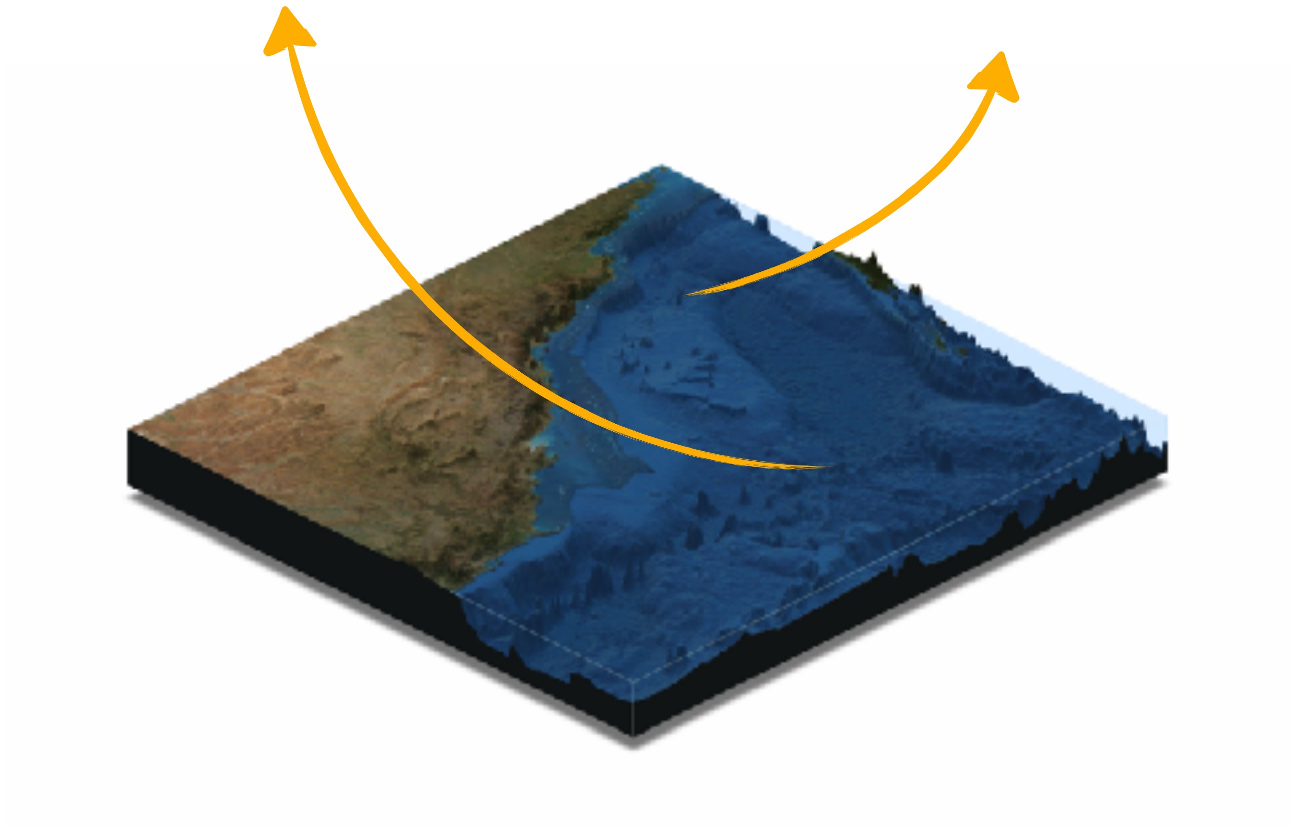


Figure 4.29 Spatial variation in **(a)** coral cover and **(b)** biomass of reef fish and sharks among eight sites on Osprey Reef in the northern Coral Sea Marine Park (CSMP) in 2022. Sites that were previously surveyed, but not surveyed in 2022 are shown in grey. Two sites on the exposed aspect (Osprey 11 and 12) and one site on the leeward aspect of the reef (Osprey 10) were surveyed for the first time in 2022. Data are based on replicate 50m transects at each site. Size of points is proportional to coral cover or total fish biomass at each site.



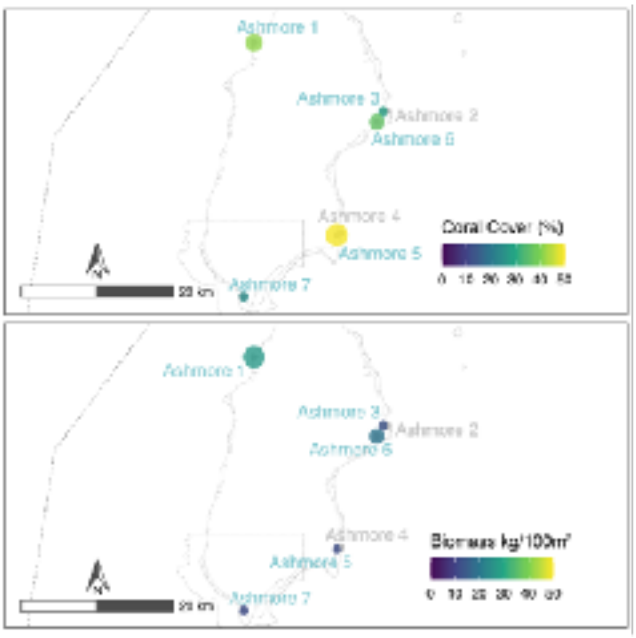


Figure 4.30 Spatial variation in **(a)** coral cover and **(b)** biomass of reef fish and sharks among five sites on Ashmore Reef in the northern Coral Sea Marine Park (CSMP) in 2022. Sites that were previously surveyed, but not surveyed in 2022 are shown in grey. Data are based on replicate 50m transects at each site. The size of individual points is proportional to coral cover or total fish biomass at each site.

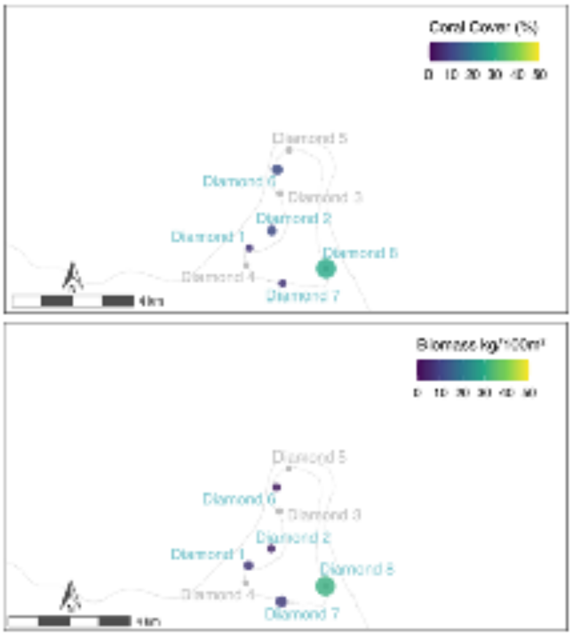
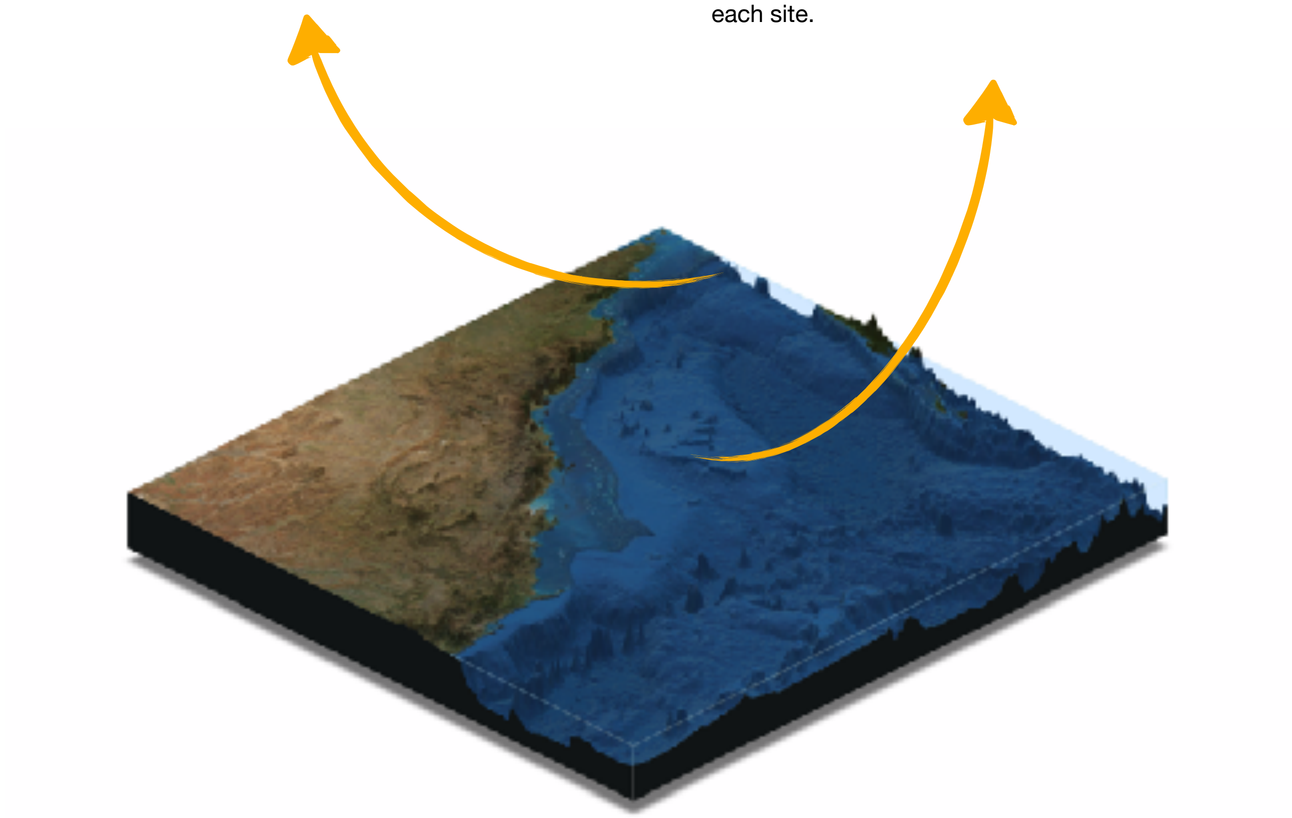


Figure 4.31 Spatial variation in **(a)** coral cover and **(b)** biomass of reef fish and sharks among five sites on Diamond Islets in the central Coral Sea Marine Park (CSMP) in 2022. Sites that were previously surveyed, but not surveyed in 2022 are shown in grey. Two sites on the exposed aspect of the reef (Diamond 7 and 8) were surveyed for the first time in 2022. Data are based on replicate 50m transects at each site. The size of individual points is proportional to coral cover or total fish biomass at each site.



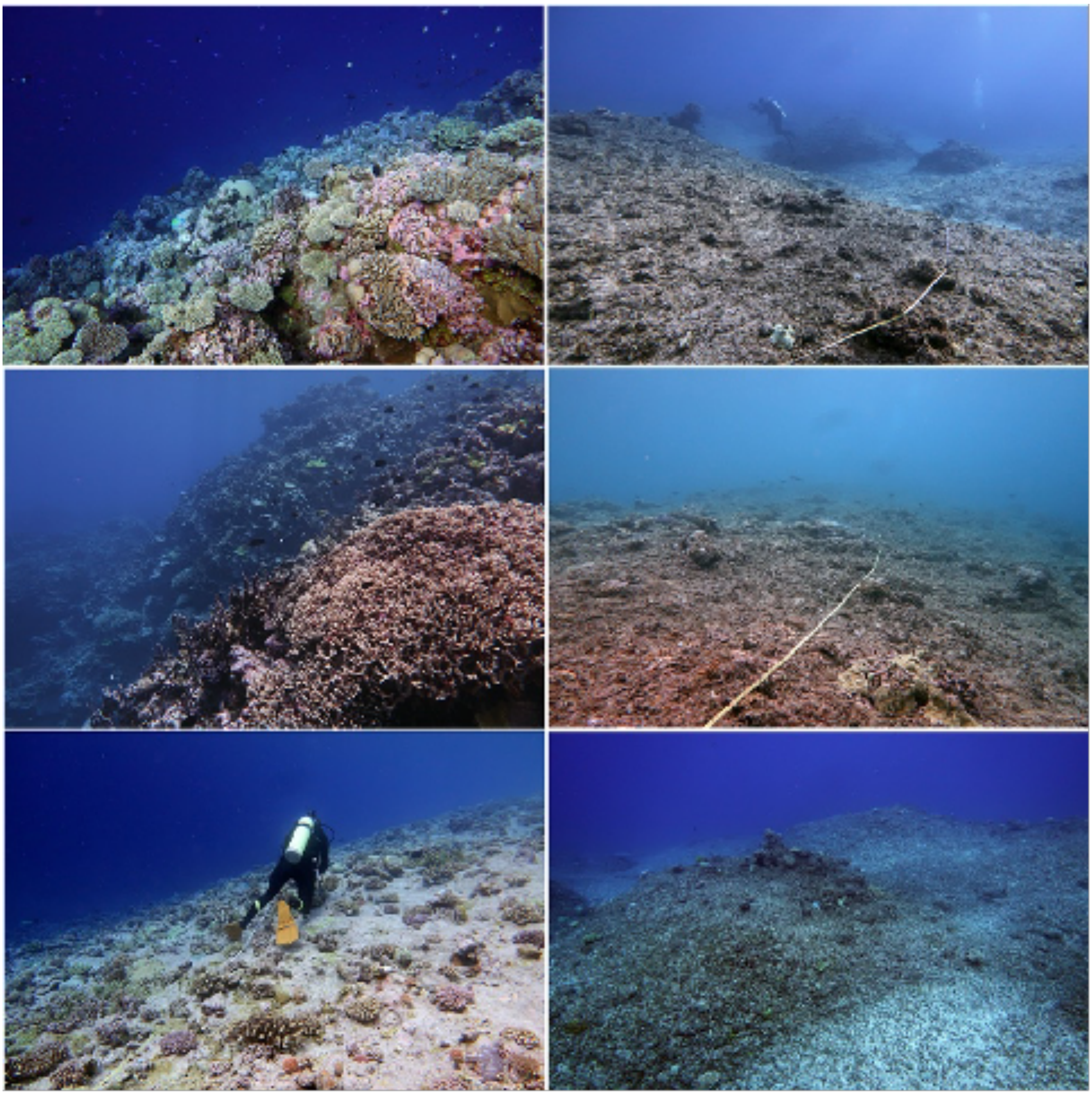


Figure 4.32 Photographs showing the variation in the coral cover and structural complexity of shallow reef habitats at weather exposed sites on reefs in the Coral Sea Marine Park that were surveyed for first time in 2022. Top left: Mellish 5, middle left: Marion 11, bottom left: Osprey 11, top right: Heralds Surprise 1, middle right: Flora 1, bottom right: Herald 8. Image credits: Andrew Hoey

4.4 Other reef taxa

4.4.1 Sea snakes

A total of 50 sea snakes were recorded across the 15 CSMP reefs in 2022 compared to 28 individuals in 2021 and 20 individuals in 2020. The vast majority of sea snakes recorded across all years were the olive sea snake *Aipysurus laevis* (2022: 92%, 2021: 90%, 2020: 95%; of sea snakes observed). Consistent with previous surveys in 2019-2021 (Hoey et al. 2021) sea snakes were regularly observed on all reefs in the southern CSMP and at Marion Reef, the southernmost reef of the central CSMP, but were not observed (and presumably absent) at all other reefs in the central CSMP, and Bougainville and Osprey Reefs in the northern CSMP (Figure 4.33). Interestingly, sea snakes (all *A. laevis*) were commonly observed at Ashmore Reef in the far north of the CSMP, with a mean density of 0.2 individuals per 250m^2 (Figure 4.33). Sea snakes were not included in our surveys of CSMP reefs in 2018, and were first included as part of our surveys in 2019. Importantly, the densities of sea snakes recorded on each of the three reefs in the southern CSMP (i.e., Saumarez, Kenn and Frederick Reefs) and Marion Reef in the central CSMP increased from 2020 to 2021 (Figure 4.34). The number of sea snakes increased on Saumarez (2020: 5 individuals; 2021: 10 individuals; 2022: 13 individuals), Kenn (2020: 8 individuals; 2021: 7 individuals; 2022: 10 individuals), Frederick (2020: 3 individuals; 2021: 5 individuals; 2022: 11 individuals), and Marion (2020: 3 individuals; 2021: 3 individuals; 2022: 10 individuals) Reefs. It should be noted, however, that sea snakes inhabit a wide range of reef habitats and depths (e.g., Udyawer et al. 2016), and as such the observed increase in the abundance of sea snakes in shallow reef habitats on these four reefs may not be indicative of an increase in the overall population size.

The marked latitudinal gradient in the abundance of sea snakes within the CSMP is similar to that reported on the GBRMP using baited remote underwater video station (BRUVS) sampling (Udyawer et al. 2014), with the highest prevalence and diversity of sea snakes occurring in central and southern GBRMP. Such latitudinal gradients in the distribution and diversity of sea snakes of the genera *Aipysurus* and *Emydocephalus* (e.g., Lukoschek et al. 2007) are generally attributed to the limited thermal tolerance of these species (Heatwole et al. 2012). However, the olive sea snake *Aipysurus laevis*, which is by far the most abundant species observed in shallow reef habitats in the CSMP (accounting for >90% of individuals observed) was also recorded at the northernmost CSMP reef (i.e., Ashmore Reef) and is also found in the warmer, lower latitude waters of the north Western Australian coast, Timor Sea, Gulf of Carpentaria, and southern New Guinea (O'Shea 1996; Lukoschek et al. 2007). The disjunct distribution of sea snakes, and in particular *A. laevis*, with the CSMP suggest these are separate populations (or even sub-species), that may have different tolerances to environmental temperatures. While dedicated research would be required to identify the drivers of the distribution of sea snakes within the CSMP and the potential connectivity between southern and northern populations, the potential susceptibility of sea snakes to increasing water temperatures highlights the need to continue to monitor populations in the southern and northern CSMP.

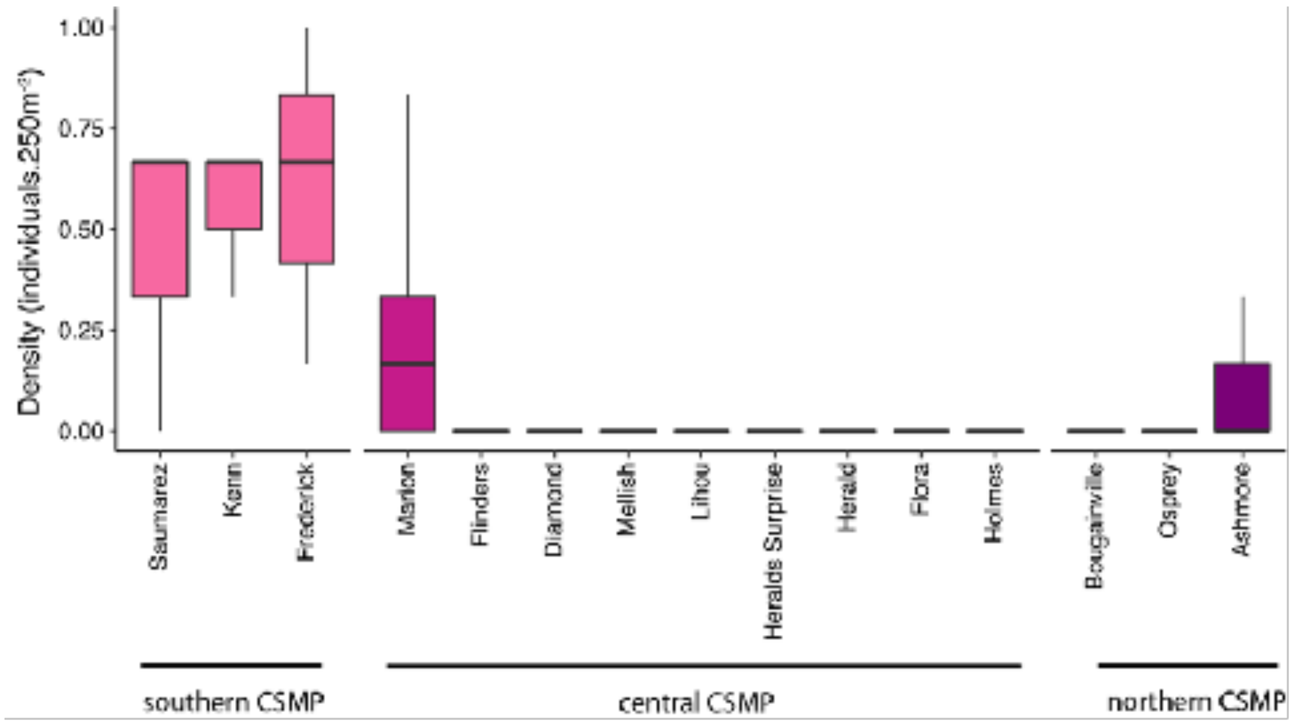


Figure 4.33 Variation in the abundance of sea snakes among 15 reefs in the Coral Sea Marine Park (CSMP) in 2022. Data are based on the 50m belt transects at each of the 68 sites. Reefs are arranged into the southern, central, and northern CSMP and coloured by *a priori* regional assignments (following Figure 3.1).

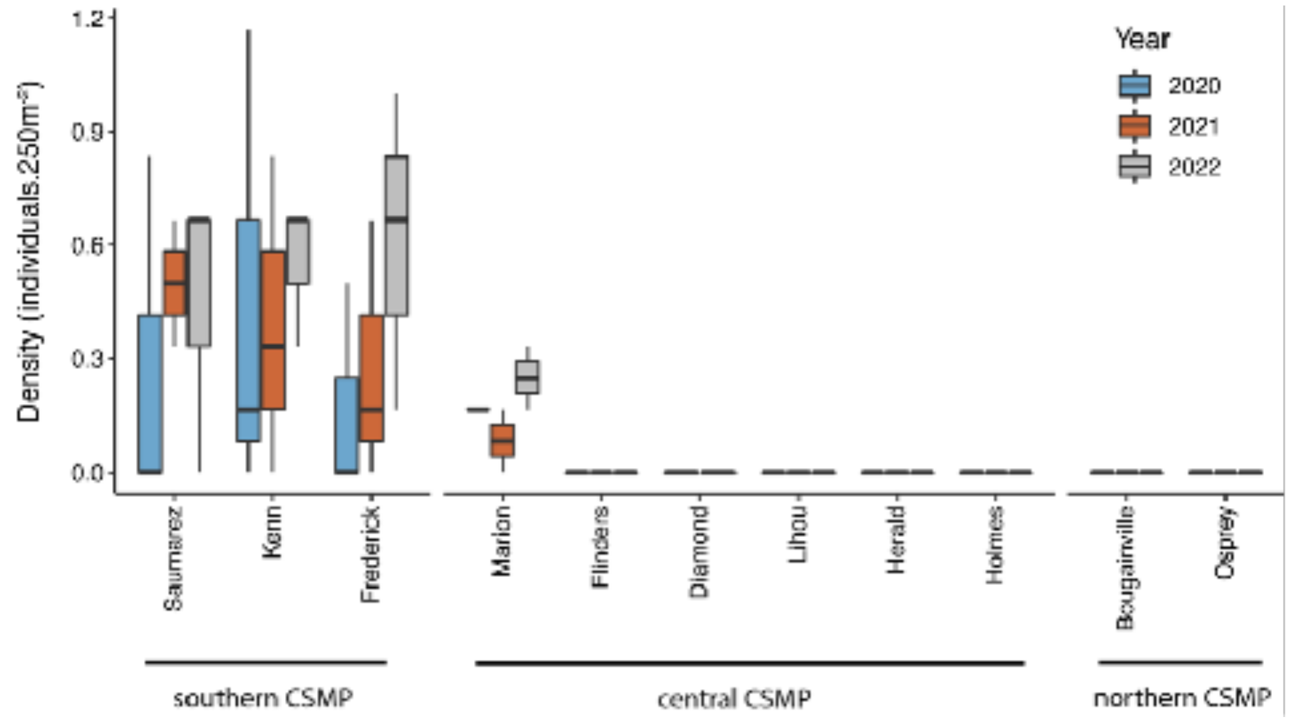


Figure 4.34 Temporal variation in the abundance of sea snakes among 11 reefs in the Coral Sea Marine Park that were surveyed in 2020, 2021, and 2022. Data are based on surveys of matching sites in each year and pooled between habitats (reef slope and reef crest) within each site.

4.4.2 Macro-invertebrates

Giant Clams – A total of 745 giant clams (*Tridacna* spp. and *Hippopus hippopus*) were recorded across the 15 CSMP reefs in 2022, with the vast majority (725 individuals, 97.3%) being *Tridacna maxima* and *Tridacna squamosa*. The other species recorded were *Tridacna derasa* (14 individuals, 1.9%), and *Tridacna gigas* (4 individuals, 3 of which were recorded on Ashmore Reef, 0.5%), *Tridacna crocea* (1 individual, 0.1%), and *Hippopus hippopus* (1 individual, 0.1%). The density of giant clams (*Tridacna* spp.) in 2022 was relatively consistent among CSMP reefs, with < 2.5 clams per 100m^2 being recorded on 14 of the 15 reefs surveyed (Figure 4.35a). The only exception to this was Kenn Reef in the southern CSMP where an average of 14.4 clams per 100m^2 were recorded, with densities being relatively consistent across all three sites at Kenn Reef (10.7 – 17.8 clams per 100m^2). The reasons for the 6-fold greater densities of giant clams at Kenn Reef are unknown but may be related to a chance recruitment event, and/or high levels of self-recruitment at this reef.

Comparisons of the eleven CSMP reefs that were surveyed annually from 2020-2022 reveal there has been a 20% decline in the abundance of giant clams within the CSMP from 2021 to 2022 (2021: 2.7 clams per 100m^2; 2022: 2.1 clams per 100m^2), which build on a 14% decline in the abundance of giant clams from 2020 to 2021 (Hoey et al. 2021). These declines were almost solely driven by a 44% decrease in the densities of clams recorded in the southern CSMP (2020: 10.6 clams per 100m^2; 2022: 5.9 clams per 100m^2), and in particular Kenn Reef (2020: 28.3 clams per 100m^2; 2022: 14.4 clams per 100m^2; Figure 4.36a). There were also small decreases in the density of giant clams in the central (2021: 1.3 clams per 100m^2; 2022: 1.0 clams per 100m^2) and northern CSMP (2021: 2.4 clams per 100m^2; 2022: 2.2 clams per 100m^2), however the current densities are still above those recorded in 2020 (Figure 4.36a). Despite the decrease in the densities of giant clams recorded, there was no apparent increase in the density of recently dead clams recorded across any of the eleven reefs surveyed.

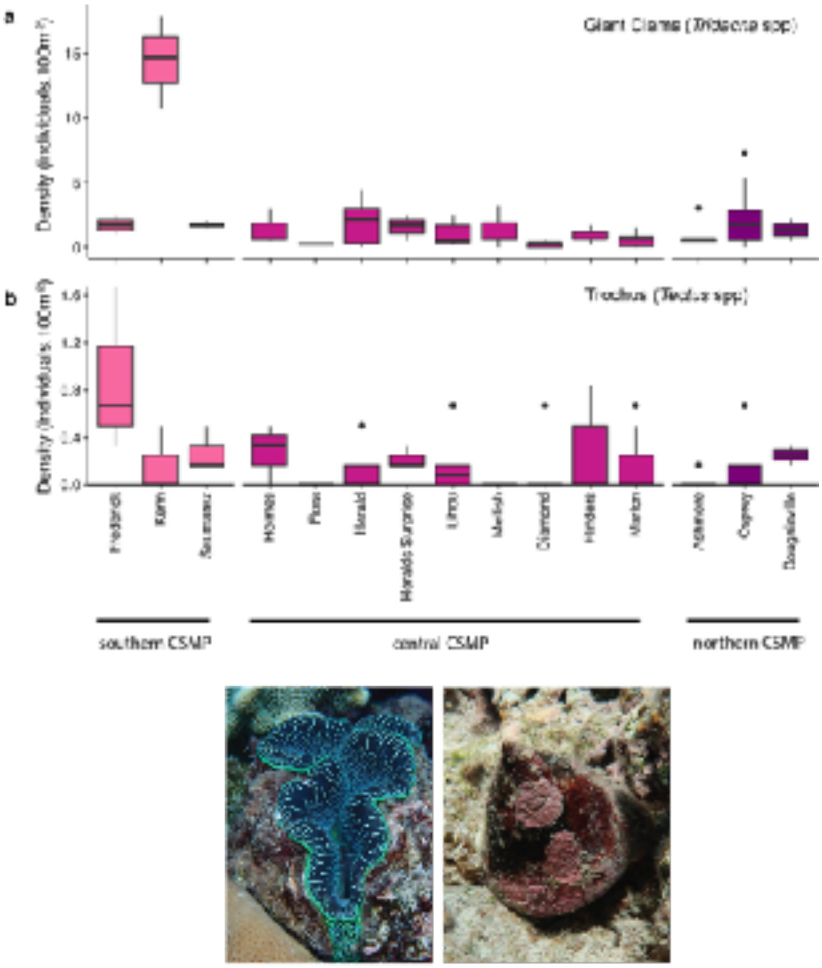


Figure 4.35 Spatial and temporal variation in the abundance of (a) giant clams, and (b) *Trochus* among the 15 reefs surveyed in the Coral Sea Marine Park during 2022. Reefs are arranged into the southern, central, and northern CSMP and coloured by *a priori* regional assignments (following Figure 3.1). The majority of giant clams recorded were *Tridacna maxima/ squamosa* (left), while *Tectus* sp. (right) were relatively rare and well camouflaged. Image credits: Deborah Burn

When interpreting these density estimates and the species composition of giant clams across the CSMP, consideration needs to be given to the sampling design, and in particular the habitats surveyed. Our surveys were designed primarily to provide robust estimates of coral and associated reef fish assemblages, and as such were conducted on areas of contiguous reef with a defined reef crest adjacent to a reef slope. However, most giant clam species, and *Tridacna gigas* in particular, are most abundant in lagoonal and shallow reef flat habitats (e.g., Braley 1987), and would require dedicated surveys in these habitats to assess spatial and temporal changes in their populations.

Trochus –*Tectus* spp. (formerly *Trochus*) were relatively rare across the CSMP, with 72 individuals recorded across the 15 CSMP reefs in 2022 (mean density: 0.2 individuals per 100m^2), and varied from 0 to 0.9 individuals per 100m^2 among individual reefs (Figure 4.35b). Comparisons of the eleven CSMP reefs that were surveyed annually from 2020-2022 show after an initial decline in density from 2020 to 2021 (2020: 0.22 individuals per 100m^2; 2021: 0.18 individuals per 100m^2), the density of *Tectus* increased in 2022 (0.23 individuals per 100m^2), with current densities being directly comparable to those of 2020 (Figure 4.36b). The densities of *Tectus* were relatively stable across most of the CSMP reefs from 2020 to 2022, the exceptions being increases in densities at Frederick and Bougainville Reefs, and a decrease in density at Herald Cays (Figure 4.36b).

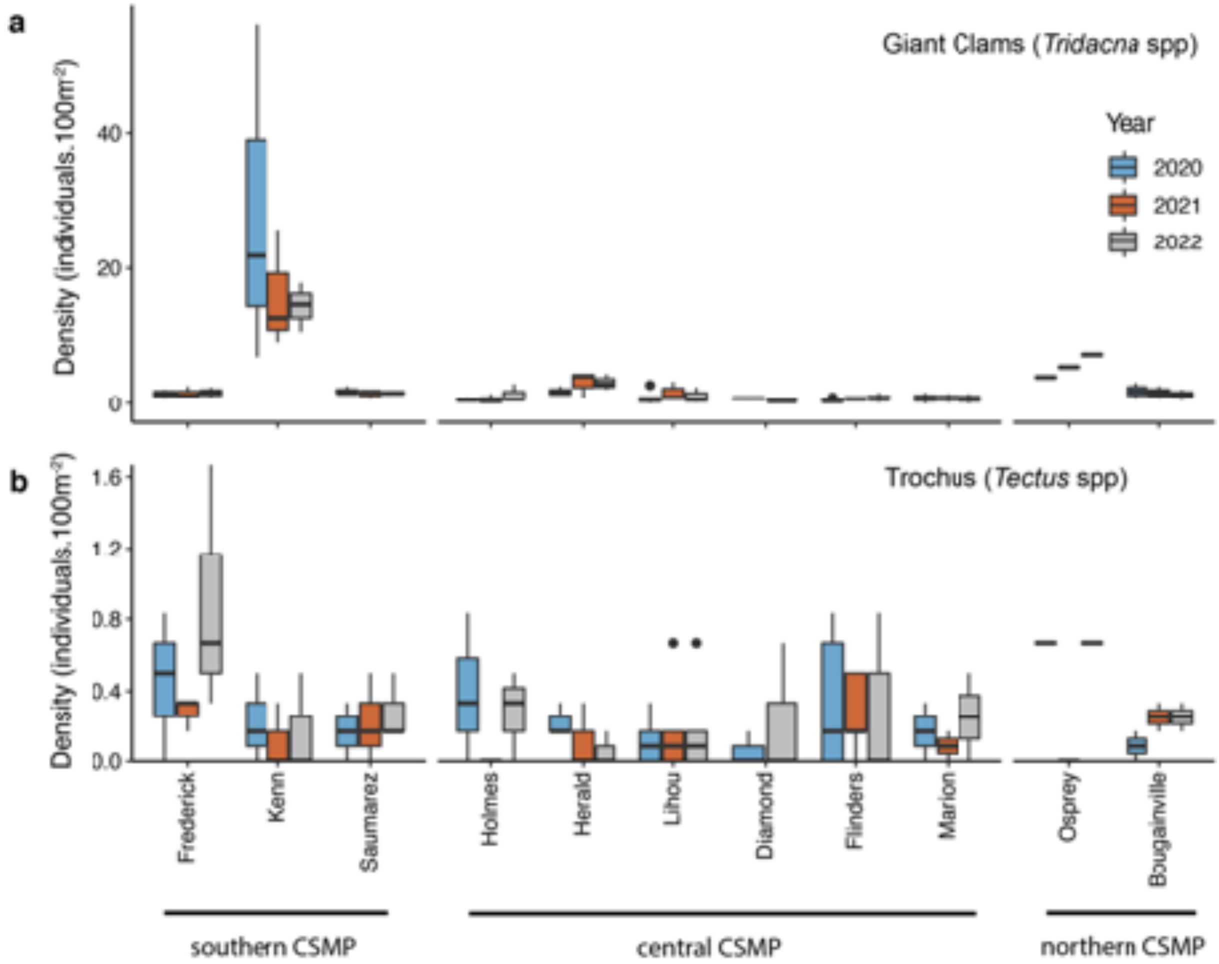


Figure 4.36 Spatial and temporal variation in the abundance of **(a)** giant clams, and **(b)** *Trochus* among the 11 reefs surveyed in the Coral Sea Marine Park during 2020, 2021, and 2022.

Sea urchins – A total of 2,531 long-spined sea urchins (*Diadema* spp.) were recorded across the 15 CSMP reefs in 2022, with the vast majority (2,512 urchins; 99.2%) being recorded at a single reef (Kenn Reef) in southern CSMP (Figure 4.37a). The density of long-spined sea urchins (*Diadema* spp.) was low (< 0.7 urchins per 100m^2) on the other two southern CSMP reefs, and were largely absent from reefs in the central and northern CSMP (Figure 4.37a). Only a single urchin was recorded in the northern CSMP (Ashmore Reef) and two urchins in the central CSMP (Lihou Reef) in 2022. Overall, the mean density of sea urchins across the CSMP has increased between 2021 and 2022 (2021: 7.8 urchins per 100m^2; 2022: 8.5 urchins per 100m^2), but is still below the densities recorded in 2020 (11.7 urchins per 100m^2). These changes are almost solely attributable to changes in the density of urchins at Kenn Reef (154.3, 97.3, 139.6 urchins per 100m^2 in 2020, 2021, and 2022, respectively; Figure 4.38a). The causes of the exceptionally high densities of sea urchins at Kenn Reef are unknown but may, like the high densities of giant clams at this reef, be related to a chance recruitment event, and/or high levels of self-recruitment at this reef. Many echinoderms (including sea urchins and crown-of-thorns starfish) are known for their 'boom and bust' population dynamics, that rely on chance recruitment of large numbers of larvae (Uthicke et al. 2009). *Diadema* are generally more abundant on subtropical reefs, such as Lord Howe Island, and Elizabeth and Middleton Reefs several hundred kilometres to the south of Kenn Reef, where densities of up to 90 urchins per 100m^2 have been recorded (Hoey et al. 2011, 2018). It is possible that the high densities of *Diadema* at Kenn Reef, and Wreck Reef in previous years (Hoey et al. 2021) may have resulted from a chance recruitment of larvae that was spawned on these subtropical reefs to the south.

Many sea urchin species (including *Diadema* spp.) are herbivorous, and as such are often viewed as having a positive effect on coral reefs through their ability to reduce the biomass of macroalgae and prevent shifts to macroalgae dominance (e.g., Humphries et al. 2020; Williams 2022). Indeed the shift from coral- to macroalgal dominance on many Caribbean reefs was partly attributed to a disease that decimated *Diadema* populations (e.g., Hughes 1994). However, many sea urchins, and *Diadema* in particular, also erode the internal structure of the reef (in contrast to parrotfishes that erode external surfaces; Hoey and Bellwood 2008). When present in high densities these urchins can destabilise the reef framework and result in net erosion of reef carbonates (Glynn et al. 1979; Eakin 1996). Given the potential implications of high densities of sea urchins, the population status and effects of *Diadema* on reef carbonate budgets (i.e., accretion versus erosion) at Kenn Reef warrants further investigation.

Sea cucumbers – A total of 148 sea cucumbers (Holothuroidea) from 12 species were recorded across the 15 CSMP reefs in 2022, equating to an average of 0.38 individuals per 100m^2 (ranging from 0 individuals per 100m^2 at Frederick Reef to 0.71 individuals per 100m^2 at Marion Reef; Figure 4.37b). The most abundant species were *Actinopyga mauritiana* (28.4%), *Thelenota ananas* (25.0 %), *Holothuria atra* (12.8%), *Holothuria whitmaei* (8.1%), and *Bohadschia argus* (7.4%). The other species recorded were *Stichopus chloronotus*, *Synapta maculate*, *Holothuria edulis*, *Holothuria fuscopunctata*, *Actinopyga palauensis*, *Pearsonothuria graeffei*, and *Thelenota anax*. The density of sea cucumbers within the shallow reef habitats surveyed showed limited change between years (Figure 4.38b). As noted previously (Hoey et al. 2020, 2021), these density estimates are substantially lower than those of previous dedicated sea cucumber surveys in the central CSMP (average of 1.33 individuals per 100m^2 for all species combined; 1.06 individuals per 100m^2 for *H. atra*; Skewes and Persson 2017), and likely reflect differences in the habitats surveyed, rather than a significant decline in sea cucumber populations. Robust assessments of sea cucumber populations would require dedicated surveys over the preferred habitat of each species, including deeper lagoonal habitats dominated by sand (*sensu* Kinch et al. 2008).

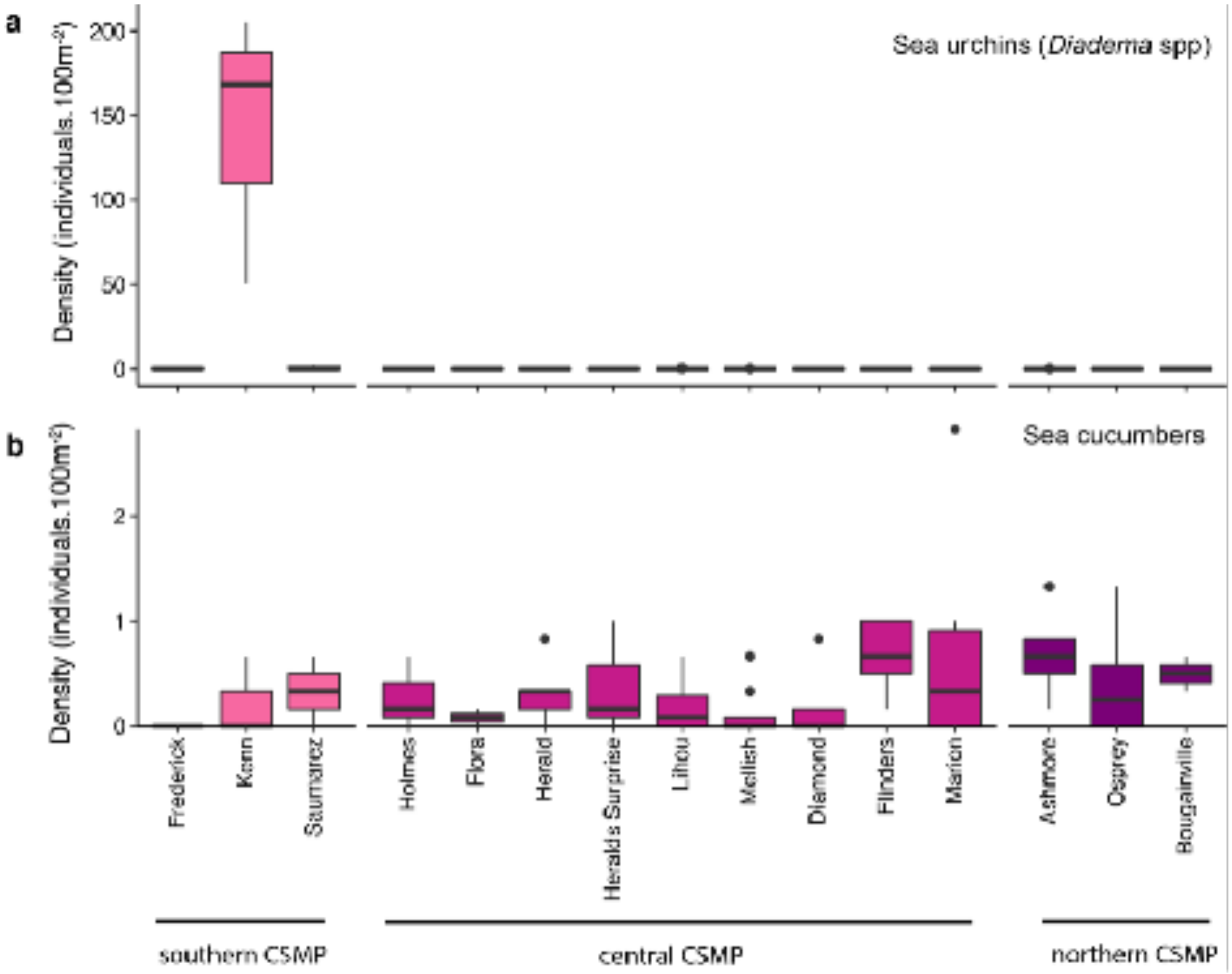


Figure 4.37 Spatial and temporal variation in the abundance of **(a)** the sea urchin, *Diadema* spp., and **(b)** sea cucumbers among the 15 reefs surveyed in the Coral Sea Marine Park during 2022. Data are based on 50 x 2 m belt transects. Reefs are arranged into the southern, central, and northern CSMP and coloured by *a priori* regional assignments (following Figure 3.1).

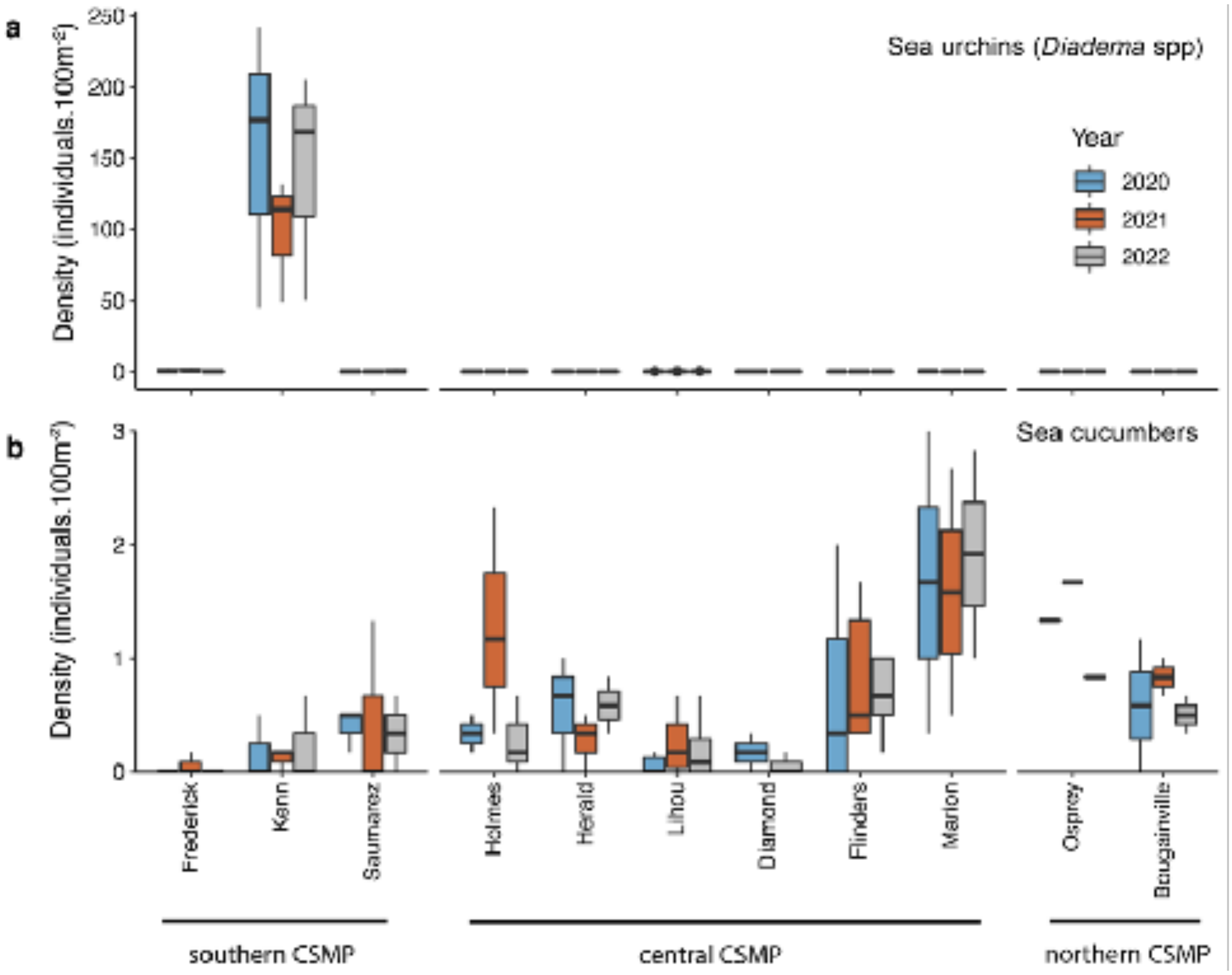


Figure 4.38 Spatial and temporal variation in the abundance of **(a)** sea urchins – *Diadema* spp., and **(b)** sea cucumbers among 11 reefs in the Coral Sea Marine Park during 2020, 2021 and 2022. Note that sea urchins (*Diadema* spp.) were extremely rare or absent from reefs in the central and northern Coral Sea Marine Park.

4.5 Coral health and injury

4.5.1 Coral colony size distribution

Shallow coral assemblages of the 15 CSMP reefs surveyed in 2022 were dominated by relatively small coral colonies (<20cm diameter), with very few colonies recorded larger than 40cm diameter (Figures 4.39, 4.40). This predominance of small colonies has been evident in the CSMP since this series of surveys was initiated in 2018 (Figure 4.40; Hoey et al. 2020, 2021). Declines in the abundance of most coral colony size classes in the southern and central CSMP were evident from 2020 to 2021 (i.e., following the 2020 coral bleaching event; Figure 4.39). However, from 2021 to 2022 there were increases in the abundance of the two smaller size classes of corals (i.e., <5cm and 6-20cm), and a decline in the 21-40cm colony size class in the southern and central CSMP (Figure 4.39). In contrast to the southern and central CSMP, the size structure of coral colonies in the northern CSMP remained relatively unchanged between 2020 and 2022, except for an increase in the 6-20cm size class from 2020 to 2021 (Figure 4.39). While the increases in the two smaller size classes of corals in the southern and central CSMP could reflect the growth and survival of previously settled corals, the concurrent reduction in abundance of larger corals suggest that some of this increase may be attributable to partial mortality of these larger colonies, resulting in a greater number of smaller colonies through fission. This provides further evidence for the likely bleaching related mortality due to heat stress after our surveys in February 2021 (see also Section 4.1.2). In the absence of major disturbances, it would be expected that abundance of each size class would increase.

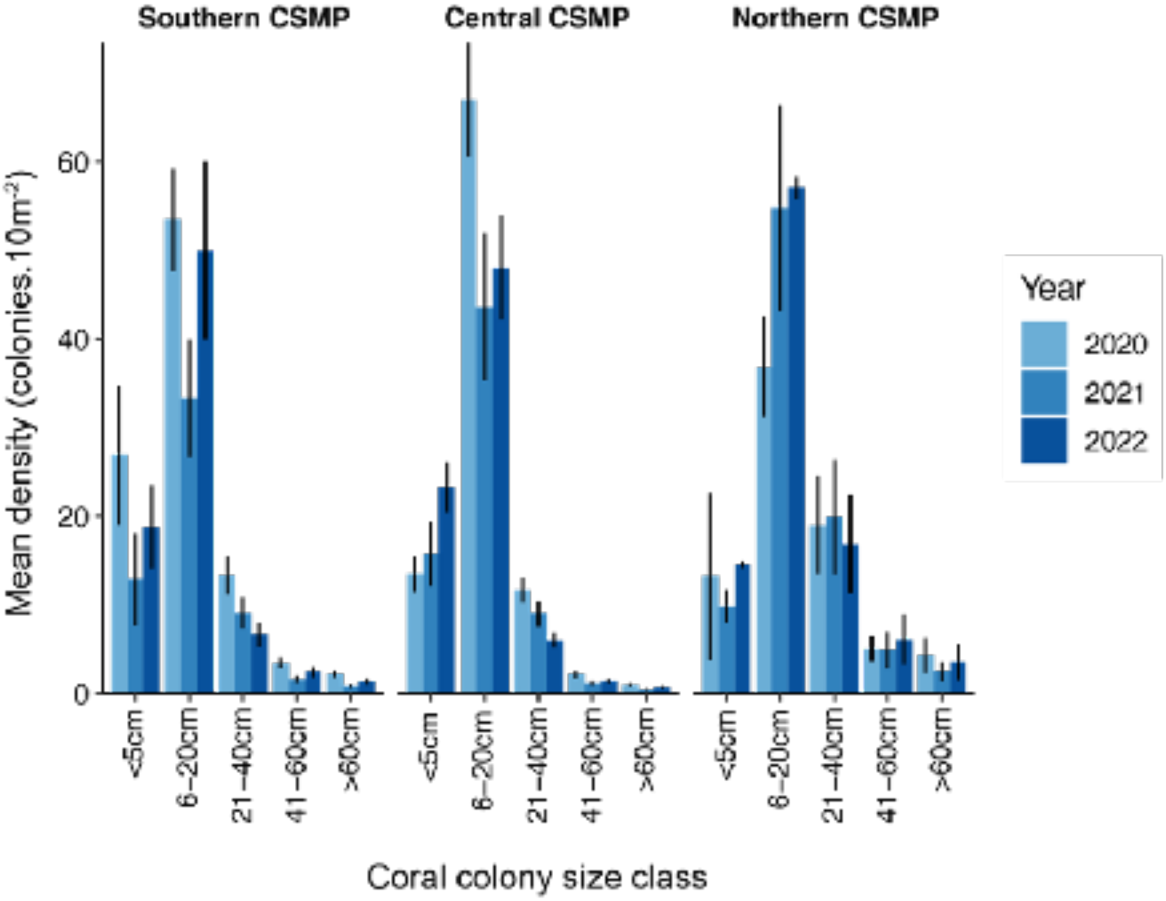
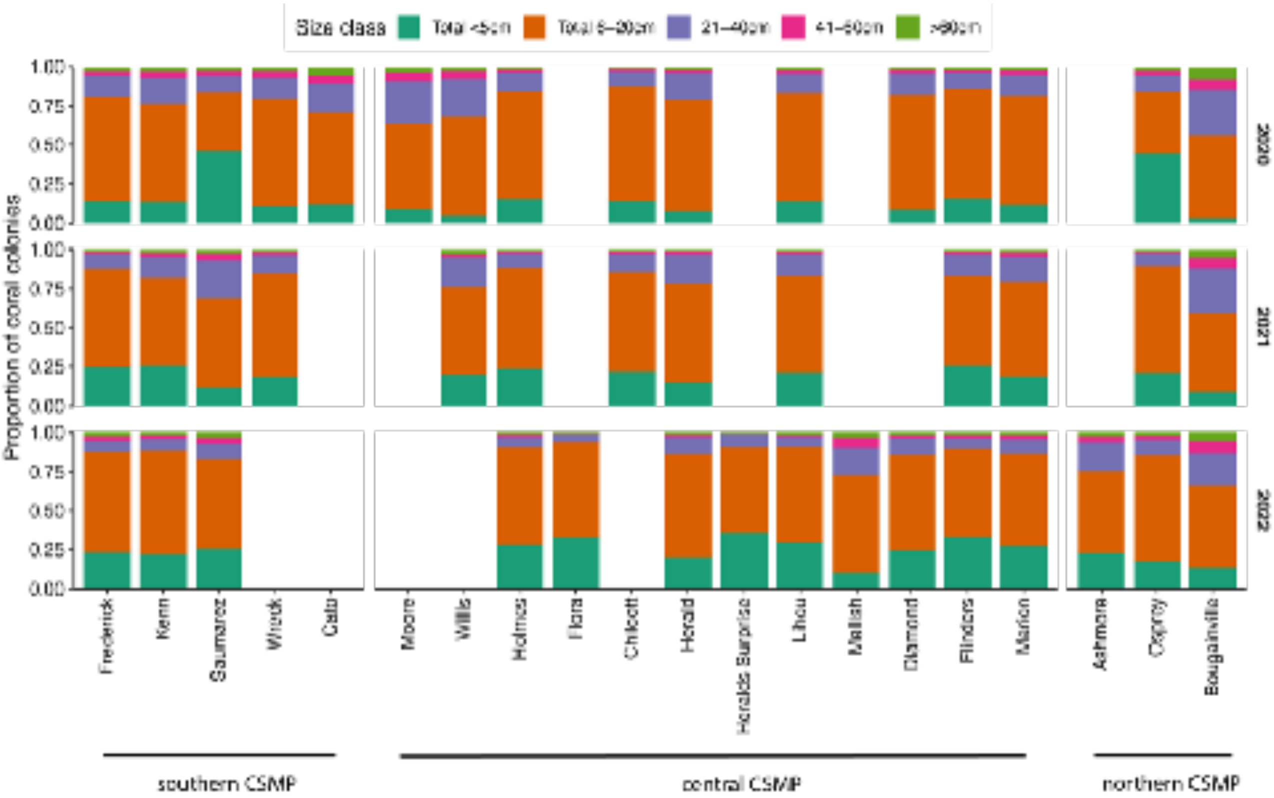


Figure 4.39 Temporal variation in the size frequency distribution of coral colonies surveyed across three regions of the Coral Sea Marine Park. Data are based on 10 reefs that were surveyed in 2020, 2021, and 2022.

There has been a marked reduction in the abundance of larger coral colonies (>20cm diameter) across all CSMP reefs surveyed from 2018-2022, with the smaller colonies (<20cm diameter) accounting for 70-90% of colonies surveyed on each reef in 2022. Interestingly, the reefs with the highest proportion of larger coral colonies in 2022 (ca. 20-30%) are the three 'bright spot' reefs; Mellish, Ashmore, and Bougainville Reefs (Figure 4.40).

4.5.2 Coral condition

In 2022, the majority of corals surveyed at each reef were healthy (Figure 4.41). As in previous surveys (i.e., 2018-2021), the proportion of colonies exhibiting signs of injury (5-100% recent mortality) as a result of various stressors was low (Burn et al. 2022; Figure 4.41). There were, however, moderate levels of bleaching at some reefs in the central CSMP, although it was variable among sites within each reef (Figure 4.41). Within the central CSMP the percent of coral colonies showing signs of bleaching (pale – recent mortality) ranged from 10.8% at Holmes Reef to 37.8% at Marion Reef (Figure 4.41). As expected, bleaching also varied among taxa, with the heat sensitive taxa such as *Acropora*, *Stylophora* and *Pocillopora* showing greater signs of bleaching than any other taxon (Loya et al. 2001; Figure 4.42). Importantly, at the time of our surveys, the majority of bleaching stress manifested primarily as the paling of colonies, rather than the complete loss of zooxanthellae from the tissue, which would cause an entirely white or fluorescent appearance (Figures 3.2, 4.42). The level of bleaching observed during our 2022 surveys was significantly less than that observed during the 2020 bleaching event, and assuming there was no continued or future heat stress would likely result in complete recovery of colonies in the subsequent weeks-



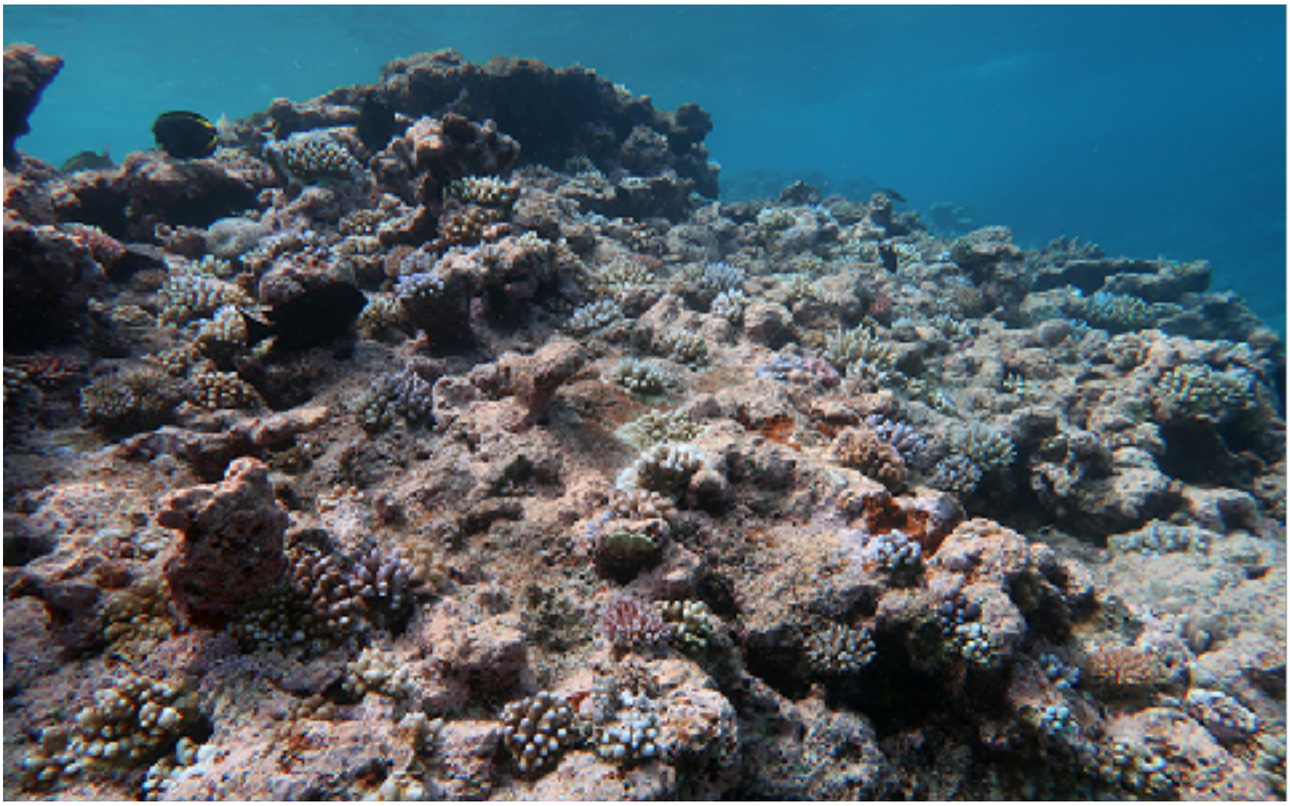
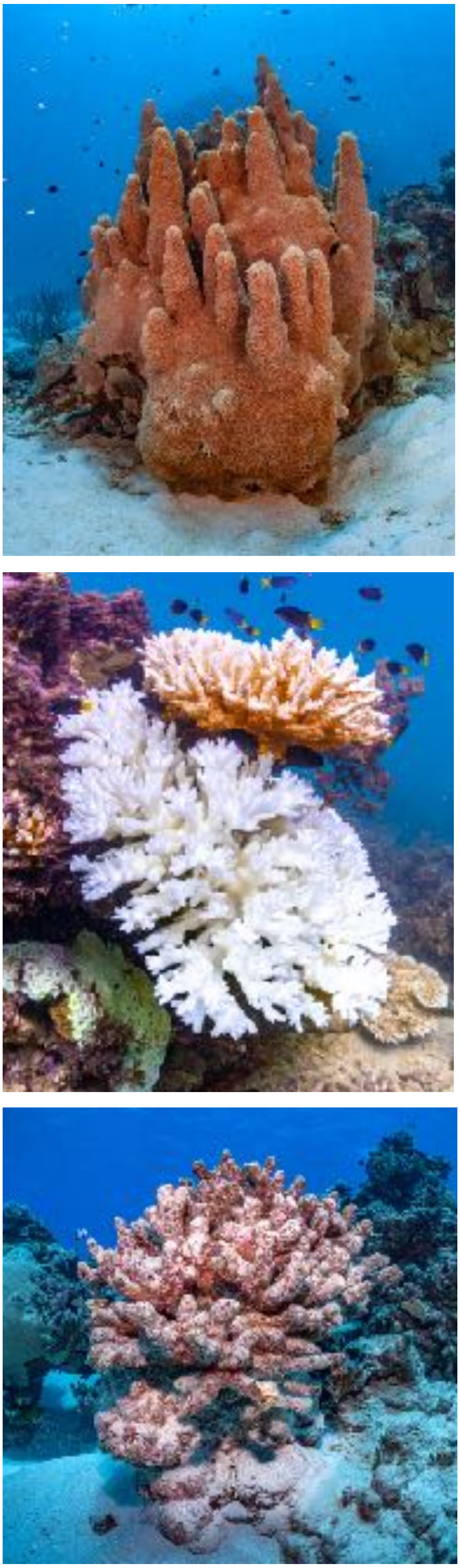


Figure 4.40 Proportion of coral colonies within each size class at 20 reefs within the Coral Sea Marine Park from 2020 to 2022. Photograph shows a high density of small corals (mainly *Acropora*) at Osprey Reef in March 2022. Image credit: Andrew Hoey

months. It is important to note, however, that the heat stress experienced in the CSMP did not reach its peak until March 2022, several weeks after our surveys were complete. During March 2022, large areas of the central CSMP were exposed to >8 DHW, and up to 12 DHW in some areas (Figure 4.5), levels of heat stress where severe bleaching and mortality may be expected (Hughes et al. 2018). The accumulated heat stress experienced over much of the central CSMP was, in fact, higher than that recorded at the same time for the Great Barrier Reef, when the 6th mass coral bleaching event was officially announced by the Great Barrier Reef Marine Park Authority (https://www.gbrmpa.gov.au/the-reef/reef-health). Given the additional heat stress, and likely further bleaching on these central CSMP reefs, it is imperative that any subsequent surveys in 2023 include these central CSMP reefs to determine the impacts, if any, of this latest coral bleaching event. It is also important to consider that the 2022 bleaching event on the GBR, and likely 2022 bleaching within the CSMP, occurred under La Niña conditions (which generally results in cooler seawater temperatures across the region). Future heat stress events within the CSMP are inevitable, and as such continued monitoring will be critical to not only quantify the impacts and potential recovery of coral and fish populations, but also to understand the capacity of coral and fish populations to adapt to changing environmental conditions.



Conditions of coral colonies. From top to bottom: healthy *Goniopora* colony, bleached *Pectinia* colony, and dead colony (likely *Isopora*). Image credits: Victor Huertas

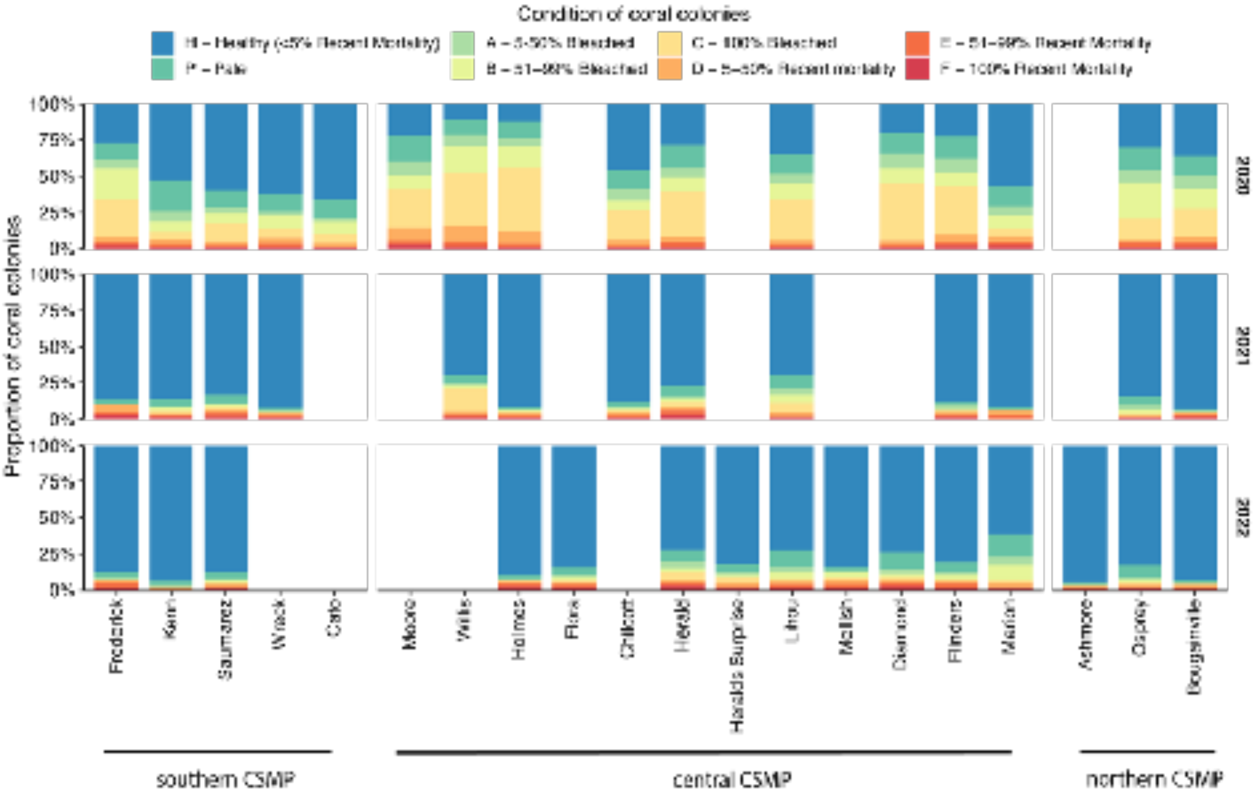


Figure 4.41 The proportion of coral colonies in each of eight health categories from 'healthy' to 'recently dead' recorded at 20 reefs within the Coral Sea Marine Park from 2020 to 2022. Note: not all reefs were surveyed in each year, with 15 reefs surveyed in 2022.

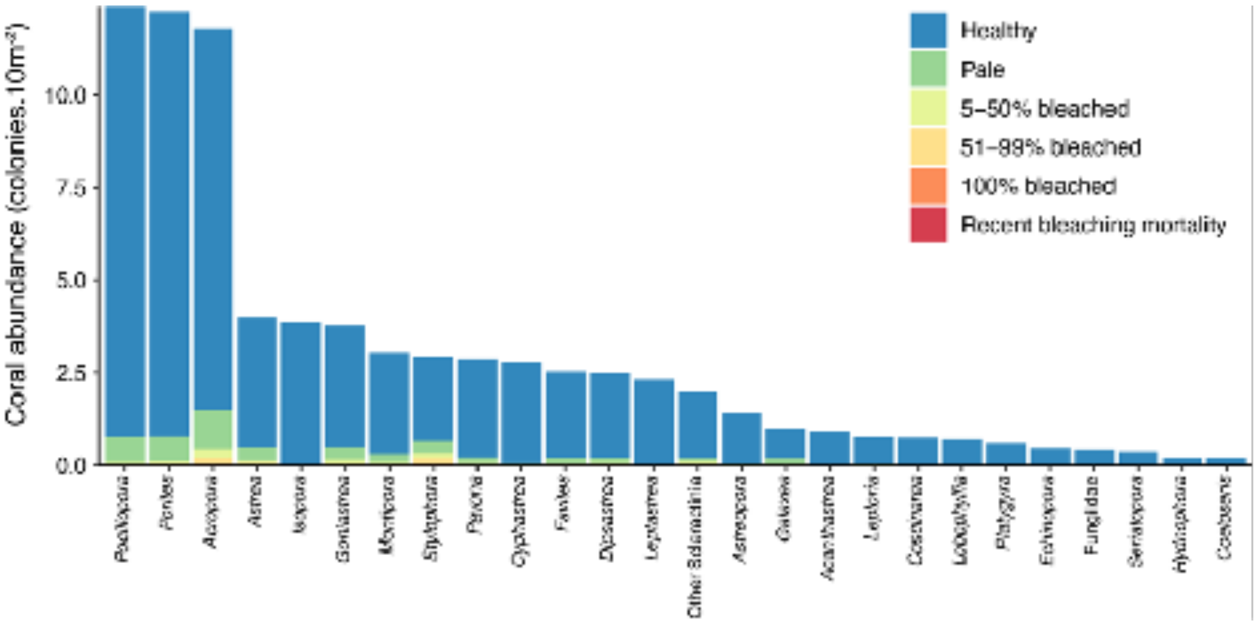


Figure 4.42 Mean density of coral colonies (per $10m^2$) in the 26 most common scleractinian genera (including a pooled 'other scleractinia' category) in each of six bleaching health categories from 'healthy' (blue) to 'recent bleaching mortality' (red) observed at sites across 15 reefs in the CSMP during February – March 2022.

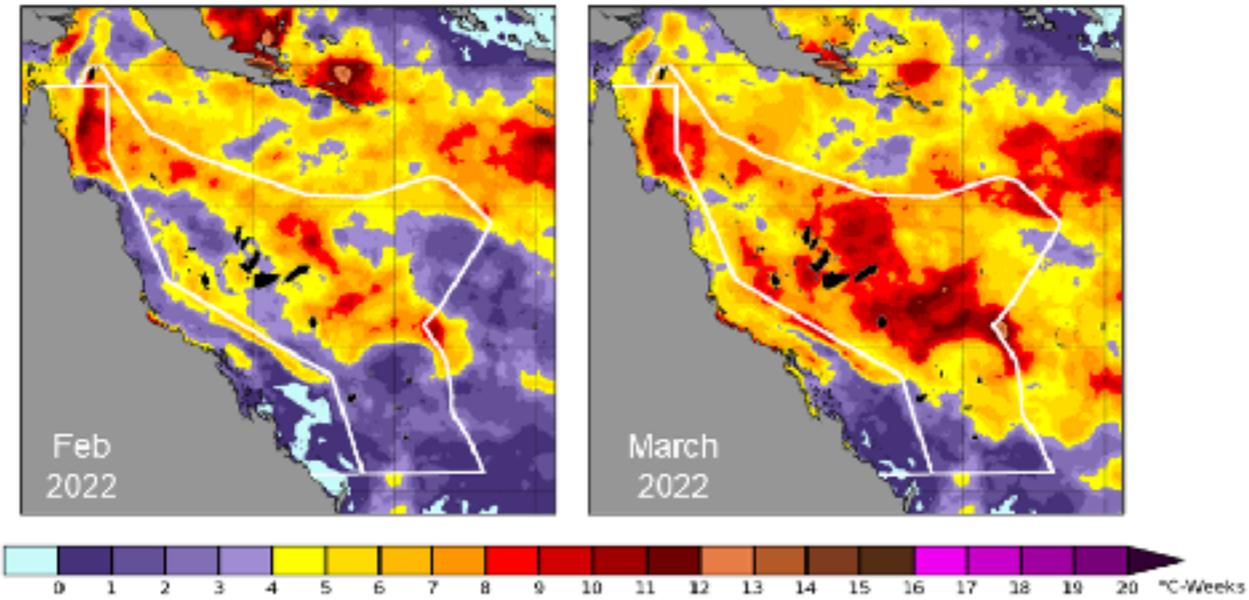


Figure 4.43 Mean monthly maximum degree heating weeks (DHW) in the Coral Sea Marine Park for February 2022 (during our surveys) and March 2022 (immediately following our surveys). Images produced using the NOAA CRW 5km product v3.1

4.5.3 Juvenile corals

A total of 8,570 juvenile corals (≤5cm diameter; Rylaarsdam 1983) were recorded across the 15 reefs surveyed in the CSMP in 2022, equating to a mean density of 23.1 juvenile corals per 10m^2, and representing an increase in the densities of juvenile corals reported in previous years (2020: 15 juvenile corals per 10m^2; 2021: 16.4 juvenile corals per 10m^2). Overall, the mean densities of juvenile corals were lowest in the southern CSMP (18.8 juvenile corals per 10m^2) and highest in the northern CSMP (29.04 juvenile corals per 10m^2), however there was considerable variation among individual reefs, ranging from 10.1 to 41.9 juvenile corals per 10m^2 at Frederick Reef and Ashmore Reef, respectively (Figure 4.44). Notably, the density of juvenile corals was relatively low (ca. 11.5 juvenile corals per 10m^2) at Mellish and Bougainville Reefs, two of the 'bright spot' reefs within the CSMP.

Comparisons of the eleven reefs that were surveyed annually since 2020 show an increase in the density of juvenile corals in 2022 compared to 2020 and 2021 in each of the three regions (Figure 4.44). The only exception was in the southern CSMP where the densities of juvenile corals were greater in 2022 than 2021, but broadly similar between 2022 and 2020.

Within individual reefs the densities of juvenile corals either increased or remained largely unchanged between 2021 and 2022, with the majority of reefs having densities of juvenile corals that are equal to, or above those recorded during 2020 (i.e., prior to bleaching-induced mortality) (Figure 4.45). While these increases in the densities of juvenile corals will aid in the recovery of the coral populations in the wake of the widespread 2020 coral bleaching event and associated mortality, the majority of these juvenile corals likely settled onto these reefs during or prior to 2020 (e.g., Doropoulos et al. 2021). Consequently, the effects of the 2020 coral bleaching event on the replenishment of coral populations in the CSMP through larval supply are yet to be fully realised.

The densities of juvenile corals in the CSMP in 2022, while greater than those reported in previous years, are considerably lower than densities reported for mid-shelf reefs of the GBR (6.1-8.2 juvenile corals per m^2, Trapon et al. 2013) and other tropical locations across the Pacific Ocean (e.g., Palmyra Atoll: 17.1 juvenile corals per m^2 on slope habitats (10m), Roth and Knowlton 2009; New Caledonia: 2 - 11.6 juvenile corals per m^2 on crest habitats (2-3m), Adjeroud et al. 2010). That said, the densities of juvenile corals in the

CSMP in 2022 (i.e., 23.1 juvenile corals per $10m^2$) are broadly comparable to those recorded one year following a major bleaching event on oceanic reefs in the Maldives (2.9 juvenile corals per m^2, Pisapia et al. 2019).

The abundance of juvenile corals on a reef is a product of the supply and successful settlement of larvae, together with the survival and growth of settled recruits. In the CSMP, larval supply from external sources (i.e., other reefs) is likely to be limited by the isolation and limited connectivity among reefs, with reefs relying largely on locally produced larvae for the replenishment of coral populations (i.e., self-recruitment; Gilmour et al. 2013). Following major disturbance events (e.g., mass bleaching) that cause extensive mortality of corals, local production of coral larvae is impeded due to the mortality of brood stock, and reduced fecundity as energy is partitioned away from reproduction and toward growth and colony repair (Hughes et al. 2019; Fisch et al. 2019). Continued monitoring of the juvenile assemblages in the CSMP will be critical to understand the full effects of the 2020 bleaching events, as well as that of any subsequent bleaching events, on the replenishment of coral populations and the future recovery of these isolated and unique reefs.

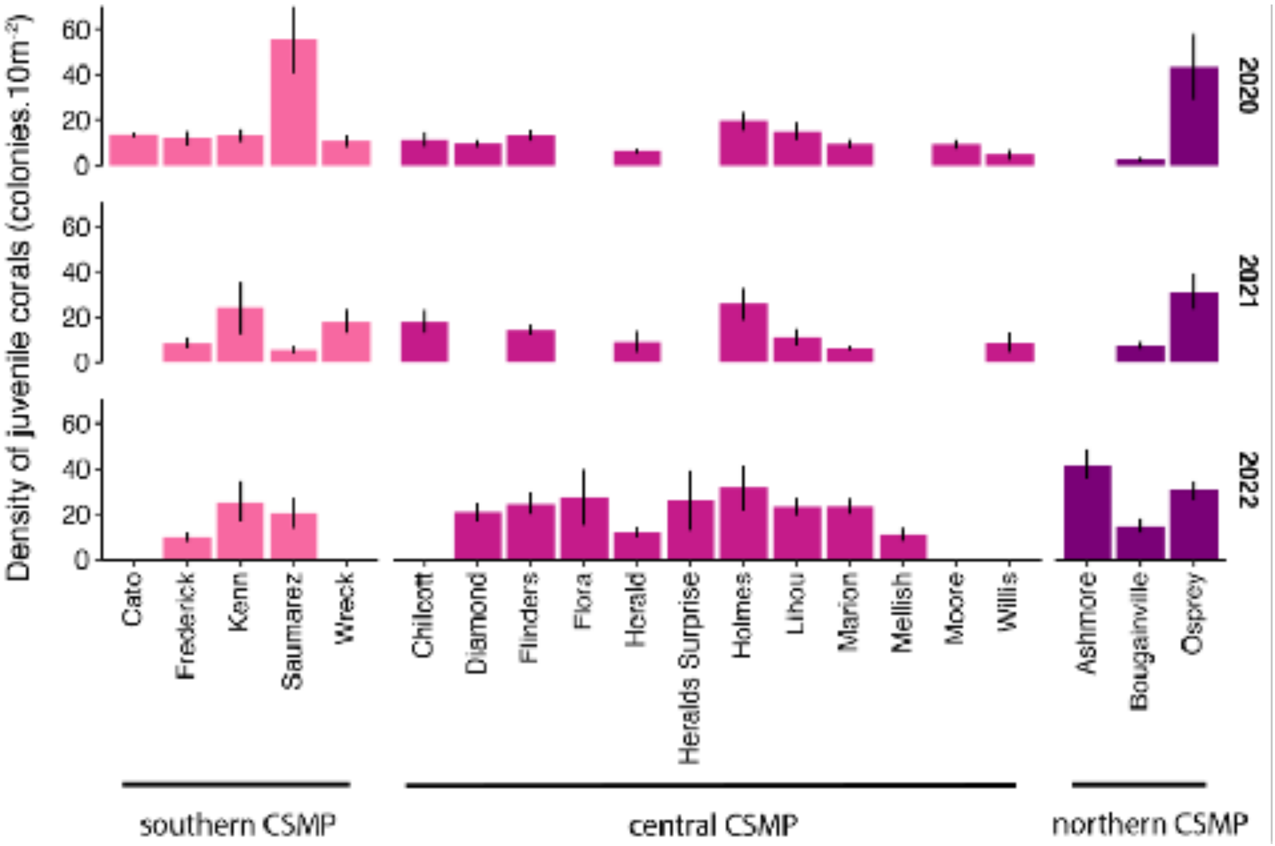


Figure 4.44 Mean (±SE) density of juvenile corals at each reef surveyed in the Coral Sea Marine Park from 2020 to 2022. Data are based on the number of juvenile corals (<5cm diameter) surveyed within 10 x 1 m belt transects at each site. Reefs are arranged into the southern, central, and northern CSMP and coloured by *a priori* regional assignments (following Figure 3.1). Densities of juvenile corals surveyed were always >1 colony.$10m^{-2}$, reefs with zero juveniles indicate they were not surveyed in that year.

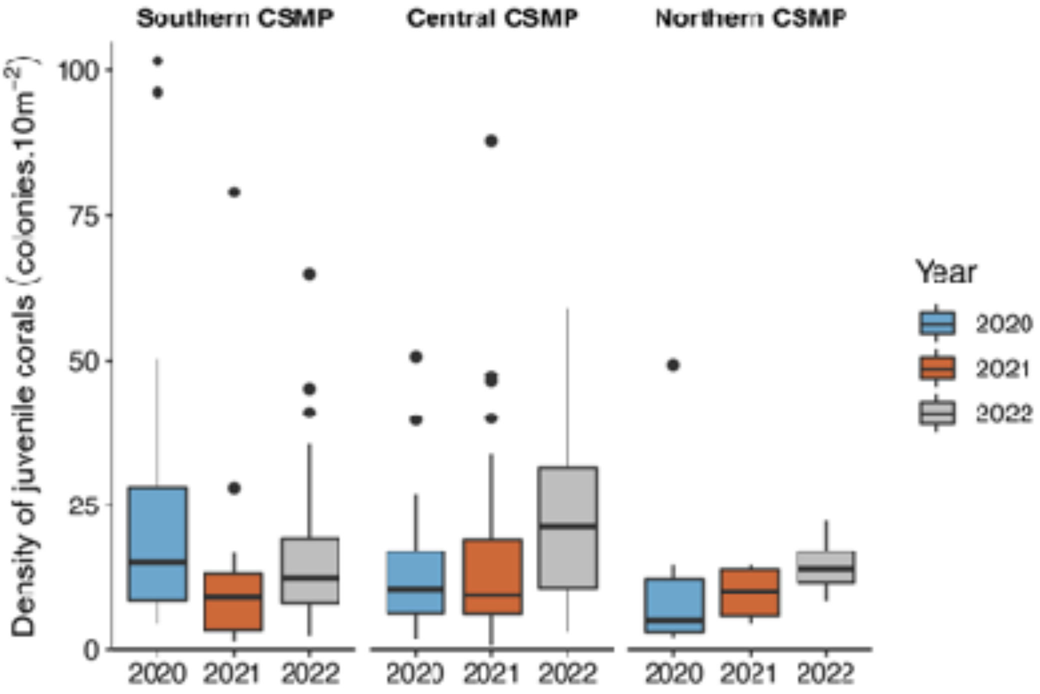


Figure 4.45 Spatial and temporal (2020-2022) variation in the density of juvenile corals (<5cm diameter) among three regions of the Coral Sea Marine Park. Data are based on surveys conducted at 31 sites across the 10 reefs in February-March of each year.

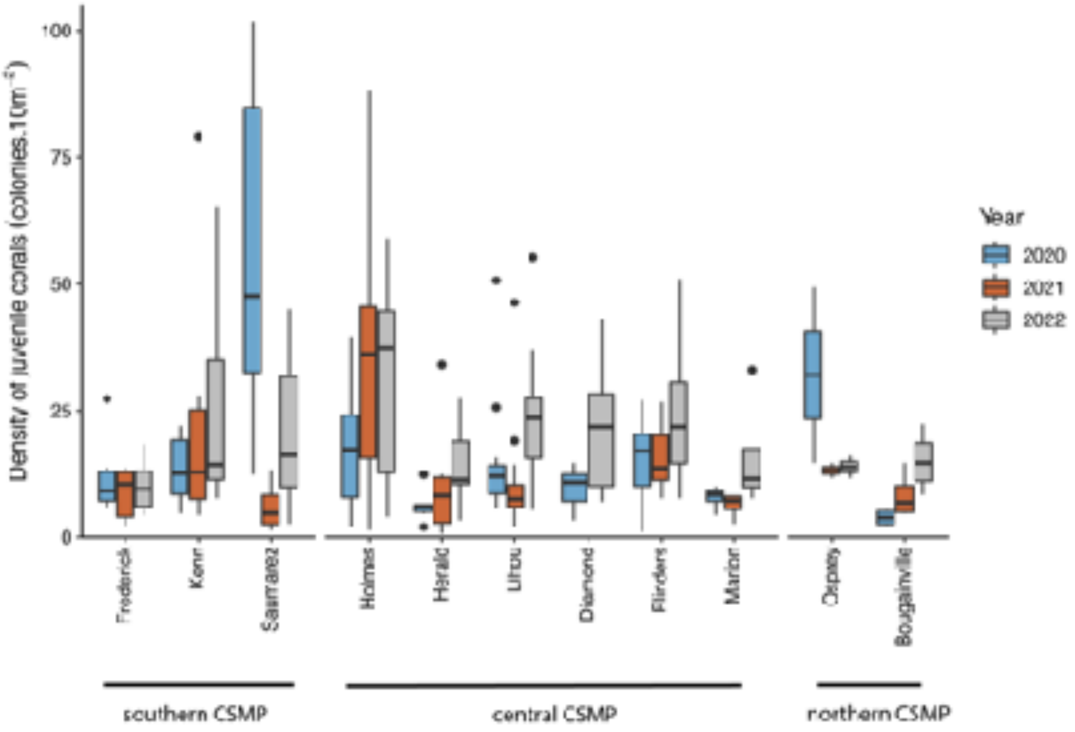


Figure 4.46 Spatial and temporal (2020-2022) variation in the density of juvenile corals (<5cm diameter) among 11 reefs within the Coral Sea Marine Park. Data are based on surveys conducted at 34 sites across the 11 reefs in February-March of each year.

4.5.4 *Coral recruitment*

The mean number of coral recruits recorded on the settlement tiles varied among the four CSMP reefs, ranging from 0.21 recruits per tile at Flinders Reef to 1.60 recruits per tile at Bougainville Reef (Figure 4.47). The density of recruits was broadly similar at Holmes (0.55 recruits per tile) and Osprey Reefs (0.49 recruits per tile). The density of coral recruits was generally similar between habitats at each reef, the only exception being Bougainville Reef where mean densities of recruits varied 25-fold between the reef crest (1.6 recruits per tile) and reef slope (0.06 recruits per tile) habitats (Figure 4.47).

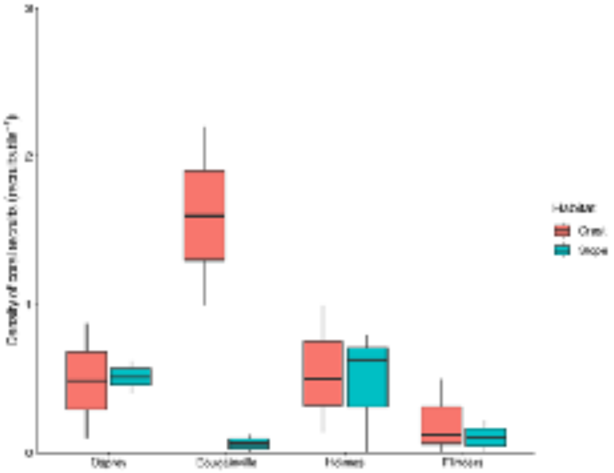


Figure 4.47 Variation in the density of coral recruits among reefs and habitats in the Coral Sea Marine Park (CSMP). Coral recruits were quantified on terracotta tiles (11 x 11 x 1cm) within two habitats at each of 2-3 sites per reef.

The number of coral recruits recorded on the settlement tiles from the reef crest habitat differed markedly between the CSMP and the GBR, with the densities of coral recruits being 10- to 65-fold greater on the GBR reefs (outer-shelf GBR: 6.9 recruits per tile; mid-shelf GBR: 17.8 recruits per tile; inner-shelf GBR: 46.2 recruits per tile) than on the CSMP reefs (0.7 recruits per tile; Figure 4.48). No tiles were deployed on the reef slope habitat on the GBR reefs. There was also a substantial shift in the composition of coral recruits among shelf positions, with *Acropora* being the most abundant coral recruits on the two inner-shelf GBR reefs (89.6%, 40.7 recruits per tile), but relatively rare on the two outer-shelf GBR reefs (5.1%, 0.3 recruits per tile), and the four CSMP reefs (8.2%, 0.05 recruits per tile; Figure 4.49). Conversely, coral recruit assemblages were dominated by *Pocillopora* and 'other' coral genera on the two outer-shelf GBR reefs (*Pocillopora*: 34.5%, 2.3 recruits per tile; 'other': 51.9%, 3.5 recruits per tile) and the four CSMP reefs (*Pocillopora*: 59.2%, 0.4 recruits per tile; 'other': 24.5%, 0.2 recruits per tile), but were only a minor component of recruit assemblages on the two inner-shelf GBR reefs (*Pocillopora*: 2.4%, 1.1 recruits per tile; 'other': 6.3%, 2.8 recruits per tile Figure 4.49).

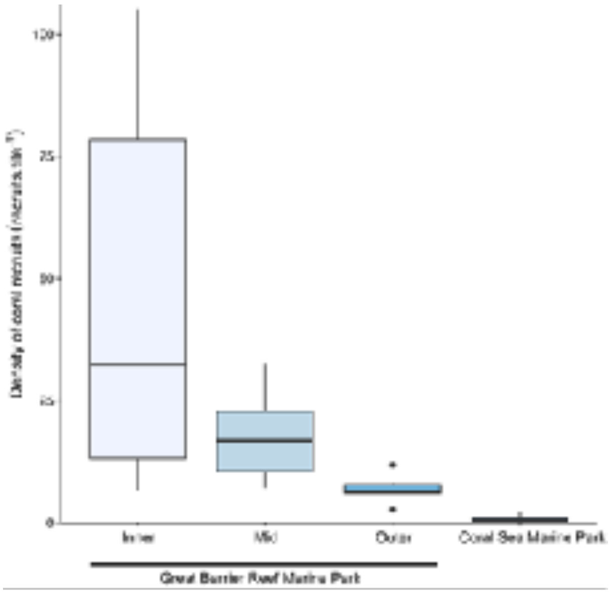


Figure 4.48 Variation in the density of coral recruits among three shelf positions on the Great Barrier Reef (GBR) and the Coral Sea Marine Park (CSMP). Tiles were deployed on each of 10 reefs (2 reefs on each of the inner-, mid-, and outer-shelf of the northern GBR, and four reefs within the CSMP: Flinders, Holmes, Bougainville, and Osprey Reefs). Each tile was 11 x 11 x 1cm.

The extremely low levels of coral recruitment recorded for the four CSMP reefs is a concern, especially if these densities are reflective of CSMP reefs more broadly, and will likely limit the recovery of coral populations. While the lack of temporal sampling of coral recruitment precludes any inferences regarding the underlying cause/s of this low recruitment, previous studies have recorded the near collapse of coral recruitment following major bleaching events (Gilmour et al. 2013; Hughes et al. 2019). For example, Hughes et al. (2019) reported an 89% decline in coral recruitment following the 2016 and

2017 bleaching events on the GBR, with *Pocillopora* replacing *Acropora* as the dominant taxon. Similarly, Gilmour et al. (2013) reported the recruitment of corals to tiles decreased from ca. 45 recruits per tile to 0 recruits per tile following the 1998 bleaching event on Scott Reef, an isolated reef off the Western Australian coast. Recruitment rates increased gradually, but were still extremely low (< 3 recruits per tile) up to eight years after the bleaching event (i.e., 2006), and only reaching pre-bleaching levels ten years after the bleaching event (Gilmour et al. 2013). The suppression of recruitment was driven by a limit of adult coral broodstock, combined with the isolated nature of Scott Reef and reliance on self-recruitment of corals, and led to a protracted recovery of coral populations. Continued monitoring of coral recruitment will be critical to assess the longer-term effects of the 2020 bleaching event on coral populations within the CSMP, as well as understanding the relative importance of larval supply, and post-settlement processes (e.g., growth, survival) in the recovery and dynamics of coral communities in the CSMP.

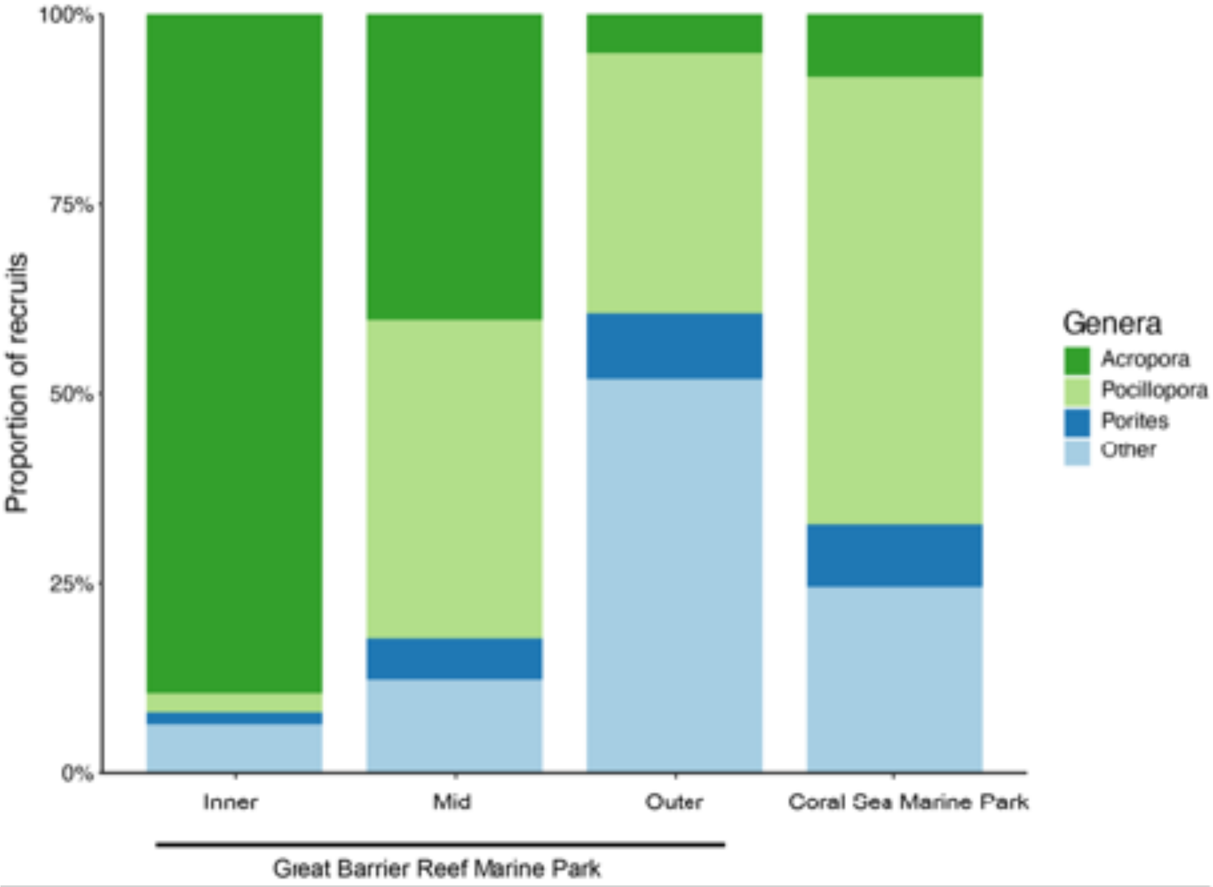


Figure 4.49 Variation in the composition of coral recruits that had settled to tiles among three shelf positions on the Great Barrier Reef (GBR) and the Coral Sea Marine Park (CSMP). Tiles were deployed on each of 10 reefs (2 reefs on each of the inner-, mid-, and outer-shelf of the northern GBR, and four reefs within the CSMP: Flinders, Holmes, Bougainville, and Osprey Reefs). Each tile was 11 x 11 x 1cm.

5. Conclusions

Coral reefs (including those of the CSMP) are being increasingly exposed to the effects of climate change, with climate-induced coral bleaching now recognised as the foremost threat to coral reefs globally (Hughes et al. 2017). The severity and frequency of marine heatwaves, and associated bleaching of corals, have increased over recent decades, with the likelihood of mass-coral bleaching events occurring in any given year now being three-fold higher than prior to 2000 (Hughes et al. 2018). While isolated reef systems, such as those in the CSMP, are often described as being 'pristine' or 'near pristine', due to their limited exposure to direct human pressures (e.g., fishing, nutrients and sediments from terrestrial run-off) relative to more accessible coastal or inshore reefs (e.g., McCauley et al. 2010; Graham and McClanahan 2013), the effects of climate change are pervasive. Indeed, previous surveys have recorded extensive coral bleaching across shallow reef habitats in the CSMP in three of the past six years (i.e., 2016, 2017, 2020; Harrison et al. 2018, Hoey et al. 2020). The 2020 bleaching event was the most severe and widespread event recorded within the CSMP, with 63% of all corals surveyed across 16 reefs exhibiting heat stress (from paling to recently dead) from high ocean temperatures in February 2020 (Hoey et al. 2020), which led to a 39% reduction in total shallow water coral cover across 13 CSMP reefs over the following 12 months (2020: 28% coral cover; 2021: 17% coral cover; Hoey et al. 2021). Assessing the potential recovery of shallow water coral assemblages following the 2020 bleaching event, and any ongoing effects of coral loss on associated fish and invertebrate communities, is critical to understand the longer-term health of this unique reef system.

The surveys conducted in February-March 2022 under this project revealed substantial declines in coral cover in the central and northern CSMP (but not the southern CSMP), compounding on the reductions in coral cover experienced the following the 2020 bleaching event (Hoey et al. 2021). While minimal bleaching of corals was recorded during the February 2021 surveys, large areas of the central and northern CSMP were exposed to considerable heat stress in March 2021 (i.e., after the 2021 surveys were completed; Figure 4.6). Given the similarity in the geographic footprint of the heat stress and declines in coral cover, it appears likely that there was widespread bleaching across the central and northern CSMP in 2021, that led to the observed declines in shallow water coral cover in 2022.

Total shallow water coral cover across the 10 CSMP reefs that were surveyed annually between 2020 and 2022 decreased from 15.7% in 2021 to 12.8% in 2022, a mean decline of 18.4%. This reduction in coral cover compounds on the decline in coral cover experienced across the CSMP the previous year (26.7% in 2020 to 15.7% in 2021; Hoey et al. 2021), an overall decline of 52%. There was considerable variation in the decline in coral cover among regions (northern CSMP: 27.9% decline; central CSMP: 26.3% decline; and southern CSMP: 4.3% increase), reefs (ranging from 59% decline at Holmes Reef, to a 22% increase at Saumarez Reef), and sites within reefs (e.g., 18% vs 45% declines at Herald 1 and Herald 4, respectively) in 2022. Although only low levels of bleaching (6.8% of colonies pale – recently dead) were observed across these reefs in February 2021 (Hoey et al. 2021), large areas of the northern and central CSMP were exposed to elevated temperatures (>8 degree heating weeks, DHW) throughout February and March 2021, with some areas being exposed to 12-16 DHW (Figure 4.5). These seawater temperatures are well above those expected to cause bleaching-induced coral mortality (>6 DHW), with exposure to 10 DHW during the 2016 bleaching event on the GBR leading to a ~90% decline in coral cover (Hughes et al. 2018). In the absence of any other major and widespread disturbance, the observed declines in coral cover in 2022 are most likely attributable to the elevated ocean temperatures across the central and northern CSMP in February-March 2021, and represents the fourth major bleaching event, and the second back-to-back bleaching event, in the CSMP in the past six years (i.e., 2016, 2017, 2020, and 2021; Harrison et al. 2018, 2019; Hoey et al. 2020, this study). Indeed, 2018 and 2019 appear to be the only years since 2016 in which the reefs in the CSMP have not been exposed to extended periods of elevated water temperatures (Figure 2.2).

The observed declines in coral cover on the central and northern CSMP reefs in 2022 were not as great as may have been expected based on recorded levels of DHW in February-March 2021, and like the coral mortality related to the 2020 bleaching event in the CSMP may reflect a shifted baseline toward more bleaching resistant coral communities following previous heat stress (i.e., 2016, 2017, and 2020 bleaching events), and/or a greater resilience to heat stress in coral populations within the CSMP. Similarly, changes in the incidence of bleaching in response to heat stress were observed in the 2016 and 2017 back-to-back bleaching on the GBR (Hughes et al. 2019). Reefs exposed to 8-9 DHW in 2016 were shown to have a >90% probability of severe bleaching, versus only a 50% probability for reefs exposed to the same heat stress in 2017 (Hughes et al. 2019). Spatial variation in heat tolerance among corals has also been linked to annual temperature ranges, the rate of warming, the frequency of, and prior exposure to, heat stress events (e.g., Ainsworth et al. 2016; Jurriaans and Hoogenboom 2020). Further, heat stress experiments using corals from the CSMP have also shown that historical exposure to mild heatwaves can increase the tolerance of corals to acute heat stress (Marzonie et al. in revision). Collectively, these findings highlight the need to understand the effects of, and interactions among, increasingly frequent and more intense heat stress events.

Current levels of coral cover on CSMP reefs in 2022 (mean = 16%), while considerably lower than that prior to the 2020 coral bleaching event (28%; Hoey et al. 2020), are broadly comparable to estimates for the GBR following the back-to-back bleaching events of 2016 and 2017 (18.6%; Mellin et al. 2019). Moreover, current coral cover on central CSMP reefs (mean: 13.9%; range: 5.8-28.9%) is greater than that of historical surveys at Herald Cays, Chilcott Islet and Lihou Reef where coral cover ranged from 1-5% in 2003 (following the 1998 coral bleaching event; Oxley et al. 2003) to ~6% in 2007 (Ceccarelli et al. 2008). It should be noted that many of these historical surveys were conducted on isolated bommies within the lagoons on these reefs, making direct comparisons with our surveys difficult. Importantly, coral cover on the majority of CSMP reefs is greater than levels which may lead to fundamental changes in the structure and functioning of reef systems. Very low levels of coral cover (<10%) in some systems have been shown to disrupt positive, or reinforcing, feedbacks, thereby limiting the recovery of coral and fish populations, and ultimately leading to shifts in habitat structure (Wilson et al. 2006; Graham et al. 2015). Once established, these shifts are difficult to reverse, and have lasting consequences for the diversity and functioning of such systems (Pratchett et al. 2021). Maintaining coral cover at levels >10% is therefore seen as critical to avoid ecosystem collapse in these reef systems. Of the 15 CSMP reefs surveyed in 2022, four reefs in the western section of the central CSMP had mean coral cover < 10% (Flinders: 9.3%; Holmes: 9.2%; Heralds Surprise: 6.8%; Flora: 5.8%), with two of these reefs (Flora and Heralds Surprise) being surveyed for the first time as part of this project in 2022. It is unknown if low coral cover will have the same consequences in systems such as the CSMP where coral cover has been historically low. The next few years may be critical in determining whether coral populations and coral cover on these reefs recovers, or collapses, as well as the implications for reef fish and invertebrate communities.

The recovery of coral populations following widespread bleaching is dependent on the supply and successful settlement of larvae, and the survival and growth of newly settled corals together with the growth of surviving corals. However, as the frequency of bleaching events (and other major disturbances) increases there is concern that the return time between successive mortality events is not sufficient for coral populations and communities to recover (Hughes et al. 2018). Even within well-connected reef systems (e.g., within the GBRMP) where the supply and settlement of coral larvae is not limiting, it has been estimated that reefs will require a minimum of 7-15 years free of any major disturbance to recover from a major bleaching event (Johns et al. 2014; Hughes et al. 2018). The recovery times for isolated reefs that are reliant on the recruitment of locally produced coral larvae, such as those in the CSMP, are likely to be considerably longer (Gilmour et al. 2013). Reefs in the CSMP have experienced four extensive coral bleaching events, and two back-to-back bleaching events the past 6 years (i.e., 2016, 2017, 2020, 2021; Harrison et al. 2018, Hoey et al. 2020), with a maximum return time of 3 years between successive events. Moreover, further bleaching on CSMP reefs in March 2022 (i.e., after our surveys) seems likely given the heat stress experienced and widespread bleaching reported for the GBRMP (Figure 4.43; https://www.gbrmpa.gov.au/the-reef/reef-health). Given sustained and ongoing increases in global ocean temperatures it is very likely that there will be further severe and widespread mass-bleaching in CSMP in the coming years, which is likely to further suppress coral cover and delay or inhibit recovery.

Although the density of juvenile corals was generally low across all CSMP reefs in 2022 (23 juvenile corals per 10m^2 compared to other Pacific reefs, the 2022 densities represented a 41% increase on those recorded in 2021 (16 juvenile corals per 10m^2). It should be noted, however, that the majority of these juvenile corals likely settled onto these reefs prior to the 2020 bleaching event yet were not quantified due to their small size and/or cryptic habitat. The majority of corals are <2 mm in diameter when they settle (e.g., Babcock et al. 2003), and depending on the species can take several years to attain a size (~10mm) that can be reliably detected by the naked eye (e.g., Trapon et al. 2013). Juvenile corals are also generally less susceptible to bleaching than larger corals due to the favourable surface area to volume ratio of small corals, higher concentrations of fluorescent proteins, and/or their cryptic habitat shading them from direct sunlight (Alvarez-Noriega et al. 2018), although declines in the abundance of juvenile corals of up to 70% have been reported following large-scale bleaching events (e.g., Alvarez-Noriega et al. 2018; Dajka et al. 2019). While the increase in the densities of juvenile corals recorded in 2022 will aid in the recovery of the coral populations in the wake of bleaching-induced mortality in 2020 and 2021, the full impacts of the 2020 (and 2021) bleaching event on the supply and settlement of coral larvae are yet to be realised.

The abundance of coral larvae that settled to artificial substrata (i.e., settlement tiles) on four CSMP reefs (Flinders, Holmes, Bougainville, and Osprey Reefs) over the 2021-2 summer was extremely low (0.6 coral recruits per tile) compared to that of reefs in the northern GBRMP over the same period (inner-shelf GBR: 46.2 recruits per tile; mid-shelf GBR: 17.8 recruits per tile; outer-shelf GBR: 6.9 recruits per tile). In the absence of any previous data on coral settlement for these CSMP reefs it is difficult to determine if rates of coral settlement are naturally low (i.e., due to their isolation) and/or if the low densities of coral recruits are a consequence of the 2020 and/or 2021 bleaching events. Several previous studies have reported the collapse of coral settlement in the years following major disturbances and widespread coral mortality (Gilmour et al. 2013; Hughes et al. 2018; Doropoulos et al. 2021). For example, there was an 89% decline in coral recruitment following the 2016 and 2017 bleaching events on the GBRMP (i.e., 2018, Hughes et al. 2018). Similarly, collapses in coral recruitment have been reported following the 1998 bleaching event on Scott Reef, an isolated reef off the Western Australia coast (Gilmour et al. 2013), and following a Super Typhoon in Palau (Dorpoulos et al. 2021). These collapses in coral recruitment are presumably due to decline in the abundance of adult (breeding) corals, and the suppressed growth and reproductive output of surviving corals (Howells et al. 2016; Anderson et al. 2019). Understanding the effects of previous (i.e, 2020 and 2021) and future bleaching events on the supply and recruitment of coral larvae, and the replenishment and recovery of coral populations will require continued use of both settlement tiles to quantify the composition and

Top: School of planktivorous fairy wrasses (*Cirrhilabrus punctatus*) hover over branching *Porites* corals at Kenn Reef. Bottom: A Klein's butterflyfish (*Chaetodon kleinii*) feeds on a coral at Osprey Reef. Image credits: Victor Huertas abundance of coral larvae settling to each reef, and monitoring of juvenile corals.

Together with the declines in coral cover, the abundance and biomass of reef fishes declined on southern and central CSMP reefs, and increased on northern CSMP reefs. Despite these declines, the biomass of reef fishes (a key indicator of reef health, together with coral cover) recorded across all reefs in the CSMP remained high (range: 470 - 6,590 kg per hectare; mean = 1,424 kg per hectare) relative to coral reef environments globally (Cinner et al. 2016) and likely reflects the isolation and limited fishing pressure on CSMP reefs. The reduction in the abundance and biomass of reef fishes in the southern and central CSMP coincided with reported reductions in coral cover from 2020 to 2021 (Hoey et al. 2021), and was largely driven by declines in small bodied planktivorous fishes (e.g., damselfishes), and corallivorous butterflyfishes. These declines are in agreement with numerous previous studies that have reported fishes that have a direct reliance on live corals for food (i.e., corallivores) and/or habitat (i.e., small bodied planktivores) are the first and most adversely affected by coral loss (reviewed by Pratchett et al. 2011, 2014).

Interestingly, the biomass of grazing fishes (primarily surgeonfishes) appeared to stabilise in 2022 following marked declines on central and northern CSMP reefs from 2020 to 2021. The causes of these initial declines in grazing fish populations on CSMP reefs is unclear, and contrasts with several previous studies that have reported substantial increases in the abundance, biomass, and/or growth of grazing fishes following large-scale coral mortality (e.g., Adam et al 2011; Gilmour et al. 2013; Taylor et al. 2020). Herbivorous fishes (i.e., grazers, scrapers, excavators, and browsers) are widely viewed as being important to the health and resilience of coral reefs (e.g., Bellwood et al. 2006b; Hoey and Bellwood 2009; Rasher et al. 2013). Through their feeding activities these fishes reduce algal biomass, clear benthic space for the settlement of corals and other organisms, reduce competition between algae and other benthic organisms, and are thought to prevent the expansion of macroalgae following widespread coral mortality. Indeed, the inability of coral populations to recover on some reefs has been linked to reduced densities and/or biomass of herbivorous fishes (e.g., Cheal et al. 2010; Rasher et al. 2013; Graham et al. 2015). Ongoing monitoring will be required to assess the potential effects of these declines in grazing fishes on the recovery and health of CSMP reefs.

On a more positive note, the three ‘bright spot’ reefs surveyed in 2022 appear to have been less adversely affected by the recent bleaching events than other CSMP reefs. In particular, coral cover on Ashmore Reef increased by 35% over the past 4 years (2018: 26.5%; 2022: 35.9%), while coral cover remained largely unchanged (ca. 30%) on Mellish Reef over the same period. Coral cover at Bougainville Reef declined to 24% in 2022, but is still considerably higher than that of the CSMP average (16%). All three reefs also had a greater proportion of large coral colonies than the remaining CSMP reefs, an indication of a less-disturbed or more resilient coral community (e.g., Pisapia et al. 2019). Similarly, the richness, density and biomass of reef fishes increased substantially at Ashmore and Bougainville from 2018 to 2022, although there were small declines in each of these metrics at Mellish Reef. Understanding the mechanisms driving the enhanced performance of these ‘bright spot’ reefs should be a focus of future research and monitoring within the CSMP.

The abundances of macroalgae, sea snakes and macro-invertebrates displayed limited change between 2020 and 2021. The only exceptions to this were an increase in the abundance of sea snakes (primarily *Aipysurus laevis*) across the southern CSMP and at Marion Reef, and a 14% decrease in the abundance of giant clams (primarily *T. maxima* and *T. squamosa*) at Kenn Reef in southern CSMP. This reduction in giant clams at Kenn Reef follows a reported 20% decline on the same reef from 2020 to 2021. While the initial (2020-2021) reduction in the abundance of giant clams at Kenn Reef may have been related to heat stress and bleaching-induced mortality, it appears unlikely that heat stress contributed to the reported decline in 2020. Rather the decline at Kenn Reef may reflect inherent patchiness and associated sampling error within sites at Kenn Reef, or natural mortality of an ageing population. The lack of any substantial increase in macroalgae is encouraging, especially in light of the observed decreases in grazing fishes and coral cover.

Climate change and associated disturbances are increasingly shaping the composition and state of coral reefs globally (e.g., Hughes et al. 2017, 2018; Pratchett et al. 2020), and it is becoming increasingly important to understand the patterns of disturbance, as well as the responses, recovery and resilience of individual reefs and reef systems. Indeed, reefs in the CSMP have experienced four extensive coral bleaching events, and two back-to-back bleaching events over the past 6 years (i.e., 2016, 2017, 2020, 2021), and potentially a fifth bleaching event in March 2022. This would be the first time major bleaching events have been recorded over three successive years. While previous research has highlighted the importance of reef geomorphology, reef size, habitat type, habitat complexity, and connectivity in shaping the status and health of reef communities in the CSMP (Ceccarelli et al. 2013), it will be increasingly important to understand how interactions between these contemporary factors and ongoing and future effects of climate change will shape these unique reefs into the future.

5.1. Recommendations

Regular comprehensive monitoring of coral reef environments in the CSMP is essential to understand its structure and function, ecological significance, and changing health and condition, especially in light of the increasing incidence of heat stress events. Annual monitoring of CSMP reefs over the past seven years has greatly improved our understanding of the unique nature of these reefs, and importantly identified drivers of change (i.e., major bleaching events). In the absence of regular monitoring, the causes of such changes would be largely unknown, severely limiting the capacity of managers to make informed decisions. As well as monitoring the current status of reefs (i.e., coral cover and population sizes of fishes and non-coral invertebrates), quantifying demographic processes of key reef taxa (e.g., recruitment, growth and mortality of corals, coralline algae and fishes) among reefs and regions within the CSMP will greatly improve our understanding of the vulnerability, recovery potential, and resilience of shallow coral reef environments in the CSMP to ongoing and future disturbances, as well as potential interactions among increasingly frequent and more intense heat stress events. Continued monitoring of both coral settlement and juvenile corals will be critical to understand the full effect of past disturbances (e.g., the 2020 bleaching event), the potential replenishment of coral populations following such disturbances, as well as local stock-recruitment relationships for shallow water corals within the CSMP.

To effectively monitor the potential recovery of coral populations and communities, as well as any changes in fish and invertebrate communities following major disturbances (including the 2020 and 2021 bleaching events) we recommend annual, or if resources allow biannual, monitoring of coral, fish, sea snakes and macro-invertebrate communities using the same methods and sites as the 2018-22 surveys. In the absence of any major environmental disturbances the time between recurrent surveys of individual reefs could be extended to 2-5 years, however this appears unlikely given predicted increases intensity of disturbances affecting reefs globally (Hughes et al. 2018). Indeed, the reefs in the CSMP have experienced four mass bleaching events in the past 6 years, with only two years (2018 and 2019) being relatively free of significant heat stress. Given this increased incidence of disturbance, coupled with the logistical constraints of working in the CSMP (i.e., isolation and exposure), regular (i.e., annual or biannual) surveys of at least a subset of representative reefs are critical. We recommend 9-12 representative reefs (2-5 reefs per region) should be surveyed each year, with all CSMP reefs to be surveyed every 3-5 years. When selecting the representative reefs, consideration needs to be given to the current status or health of the reef, the distance and travel time between reefs (to maximise cost-effectiveness of voyages), as well as the availability of suitable anchorages allowing access to survey sites under most, or all, weather conditions. With these considerations in mind, we recommend as a minimum the following 11 reefs be surveyed annually Saumarez, and Kenn Reefs in the southern CSMP, Flinders, Holmes, Lihou, Marion, and Mellish Reefs in the central CSMP, and Ashmore, Boot, Bougainville and Osprey Reefs in the northern CSMP. These reefs include four of the five identified ‘bright spots’ (the fifth ‘bright spot’, Moore Reef, is not included as there is no anchorage, but should be included when weather conditions allow), as well as two reefs (Holmes and Flinders Reefs) with low (<10%) coral cover and thereby vulnerable to ecosystem collapse. On reefs where suitable overnight anchorages are available, at least 2 days should be allocated to allow greater spatial coverage of surveys.

Our current understanding of other habitat types (e.g., weather exposed aspects, soft-bottom/lagoon habitats, seagrass and algal habitats, deep habitats) is limited and should be incorporated into future monitoring. While surveys of shallow weather exposed aspects of some CSMP reefs completed as part of this project, together with surveys of deeper habitats of the CSMP using remotely operated vehicles (ROV) and baited remote underwater video stations (BRUVs) as part of a separate project, are adding considerably to the biodiversity and habitats recorded within the CSMP, repeat surveys are critical to understand the dynamics of these habitats and their response to disturbance. Spending 2-3 days at each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of the selected reefs would provide much greater opportunity to survey a diversity of shallow, and potentially deeper, habitats and sites. Doing so would also allow the opportunity to conduct dedicated surveys of species of commercial and/or conservation interest (e.g., sea cucumbers and giant clams) that are not adequately captured through current surveys of shallow reef habitats, as well as the potential identification of novel habitats and important fish settlement, nursery and spawning sites and habitats. Additional shallow water habitats could be effectively surveyed using a range of techniques, such as timed-swims with a towed GPS (e.g., Lynch et al. 2015), manta tow (e.g., Friedman et al. 2011), or underwater scooter assisted diver surveys, while surveys of deeper habitats would require the use of remotely operated vehicles (ROV's), or towed video cameras (e.g., Skewes and Persson 2007). ROV's and towed video could also be adapted for surveying shallow habitats and would provide a permanent record (i.e., video footage) from which data on benthic, invertebrate and fish communities could be extracted.

The surveys of shallow water reef habitats (2018-2022) have revealed considerable variation in the coral cover, mortality, and recruitment (juvenile corals), and the density, biomass and composition of reef fish among reefs, and sites within individual reefs. Surveying a greater number of sites at each reef would provide some insight into the potential causes of this variation, and could thereby form the basis of future targeted research, while also providing greater certainty around reef-level estimates of reef health. The additional day spent surveying some of the reefs in the central CSMP in 2022 have provided greater resolution and understanding of the spatial variation in coral and fish communities around these reefs, and in particular differences between sheltered and exposed aspects of the reefs (see Appendix 5). In addition to the regular surveys of representative reefs, we recommend intensive sampling (5-7 days) of a single reef during each voyage, with a different reef to be surveyed in consecutive voyages. Spending 5-7 days at a reef would allow ca. 15-25 sites to be surveyed compared to the current 3-5 sites per reef, thereby providing a much more comprehensive understanding of the status and health of each reef, as well as allowing questions such as the following to be addressed: do reef areas that are adjacent to channels have higher coral cover and/or densities of juvenile corals than those in sheltered back reef or lagoonal environments?

Importantly, the three 'bright spot' reefs surveyed in 2022 appear to have been less adversely affected by the recent (2020 and 2021) heat stress and bleaching events than other CSMP reefs. Coral cover increased by 35% on Ashmore Reef and remained largely unchanged on Mellish Reef from 2018 to 2022, while coral cover declined substantially on non 'bright spot' reefs over this period. Moreover, these 'bright spot' reefs support more abundant and diverse fish communities than other CSMP reefs. While dedicated research would be required to ascertain the factors that contribute to these reefs being 'bright spots' (i.e., recruitment, growth and mortality of corals and fishes, primary and secondary productivity, nutrient inputs, local hydrodynamics), their potential resilience to heat stress may warrant additional management consideration. With the exception of Bougainville Reef that has been surveyed annually, the remaining four 'bright spot' reefs (Ashmore, Boot, Mellish and Moore Reef) have only been surveyed twice in the past 5 years, largely due to their isolation in the far east and far north of the CSMP. We recommend future regular surveys of CSMP reefs should include, and prioritise these 'bright spot' reefs.

The potential recovery of coral populations and communities on CSMP reefs will be dependent on supply and settlement of coral larvae, together with the growth of both these newly-settled corals and surviving corals. The use of settlement tiles in 2022, that to our knowledge represents the first study to quantify coral settlement within the CSMP, revealed that the supply and settlement of coral larvae to four CSMP reefs was extremely low compared to adjacent GBRMP reefs, and will likely inhibit the recovery of coral populations.

However, in the absence of temporal sampling of coral recruitment within the CSMP it is difficult to determine if rates of coral settlement are naturally low on CSMP reefs (i.e., due to their isolation), or are a consequence of the 2020 and/or 2021 bleaching events. We recommend the targeted monitoring of coral settlement as well as the monitoring of juvenile corals be continued to gain a greater understanding of the potential replenishment of coral populations, and local stock-recruitment relationships for shallow water corals within the CSMP. It should be noted that directly quantifying the settlement of corals requires two voyages, the first to deploy terracotta 'settlement' tiles several weeks prior to the predicted coral spawning (i.e., October-November), and the second to collect and process the tiles 2-4 months later (February-March).

Continued monitoring of reef fish and invertebrate communities is essential to understand the full impacts of coral loss following prior (i.e., 2020 and 2021) and future bleaching events. Declines in the abundance of small-bodied planktivorous fishes and corallivorous butterflyfishes have already been realised on CSMP reefs following the 2020 bleaching event. While these fishes that rely on live corals for food and/or shelter are typically the first and most adversely affected groups following coral loss, many other fish species display protracted declines over several years as the physical structure of the habitat erodes, and/or the loss of juvenile habitat limits the replenishment of populations (e.g., Graham et al. 2007; Pratchett et al. 2014). A key to understanding these relationships in the CSMP will be to repeat the 3-dimensional habitat mapping of sites mapped during 2019-2020 in the next 3-4 years. Matching the sites previously mapped will allow the relative contribution of live corals versus the underlying reef matrix and coralline algae in providing habitat structure to be assessed.

Coral cover on many CSMP reefs, especially those in the central CSMP have been historically low, yet these reefs support abundant and seemingly healthy fish communities. Much of the 3-dimensional structure on these reefs appears to be provided by coralline algae that form a diversity of columns and pinnacles (Figure 5.1). Coralline algae also appear to rapidly colonise and cover dead coral skeletons, and may be the dominant calcifying organism on these low coral cover reefs. Quantifying rates of settlement and growth (or calcification) of these coralline algae would provide important insights into the creation and persistence of 3-dimensional structures on these reefs.

Figure 5.1 Coralline algae are a potentially major contributor to the 3-dimensional structure and calcification of CSMP reefs. Top: complex reef structure formed primarily by coralline algae; bottom: dead *Acropora* colony covered by coralline algae. Image credits: Andrew Hoey (February 2022).

The current scheduling of surveys for late summer-early autumn (i.e., February-April) is designed to capture the incidence and extent of bleaching. Indeed the 2020 surveys coincided with the peak in the heat stress, although it appears the surveys were conducted prior to the peak in heat stress in 2021, and 2022. However, targeting this period for the surveys limits the capacity to explore other important biological and ecological processes, especially those related to the spawning and settlement of corals, fishes and invertebrates. Biannual surveys would allow for much more detailed understanding of reproduction and other seasonal processes, as well as allowing for the more effective deployment and maintenance of in-water sampling devices (e.g., tilt current meters only record for ~3 months). Given the logistics and costs of undertaking voyages to the CSMP we recommend any voyage in mid- to late-spring be limited to a small number of accessible innermost reefs (e.g., Flinders, Holmes, Bougainville and Osprey Reefs), and could potentially make use of existing dive tourism expeditions to these reefs.

Finally, surveys conducted over the past 5 years have highlighted the importance and unique nature of shallow water reef communities of the CSMP. Comparable monitoring and research in all regions within and bordering the CSMP, including the GBRMP, Australia's Temperate East Marine Parks Network, New Caledonia, Solomon Islands and Papua New Guinea, is required to establish the biogeographical significance of the CSMP. Cross-jurisdictional meetings, workshops, and ultimately scientific expeditions would be invaluable to better understand biological and ecological connections among these regions.

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A school of barracuda (*Sphyraena qenie*) swims near the Watanabe Pinnacle on Flinders Reef, in the central Coral Sea Marine Park.

6. APPENDIX 1 - Leveraged projects

Five additional projects were leveraged from this collaboration between James Cook University and Parks Australia and capitalised on available space during the voyage. * indicates projects funded under an Our Marine Parks – Round 2 Grant, however the scope of these projects was increased substantively through activities completed during the 2022 voyage.

Project description	Key Personnel	Institution
Movement and population structure of sharks and large fishes within the CSMP*	Dr Adam Barnett Prof Andrew Hoey Prof Morgan Pratchett Mr Ben Cresswell	James Cook University James Cook University James Cook University James Cook University
The ecology of deep reef habitats in the CSMP*	Dr Gemma Galbraith Mr Ben Cresswell Prof Andrew Hoey Prof Morgan Pratchett Dr Eva McClure Dr Victor Huertas	James Cook University James Cook University James Cook University James Cook University James Cook University James Cook University
Island-reef connectivity within the CSMP	Prof Andrew Hoey Dr Gemma Galbraith Dr Eva McClure Mr Ben Cresswell Dr Victor Huertas	James Cook University James Cook University James Cook University James Cook University James Cook University
Taxonomy and diversity of the coralline algae *Porolithon* within the CSMP	Prof Andrew Hoey Prof Morgan Pratchett Dr Soyoung Jeong Assoc. Prof. Guillermo Diaz-Pulido	James Cook University James Cook University Griffith University Griffith University
Opportunistic surveys for fish spawning aggregations	Prof Andrew Hoey Prof Morgan Pratchett Mr Martin Russell	James Cook University James Cook University Science and Conservation of Fish Aggregations

7. APPENDIX 2 - Sites surveyed

List of sites surveyed across 15 reefs in the Coral Sea Marine Park (CSMP) during November 2021 (Ashmore Reef only) and February - March 2022. * indicates sites that were surveyed in 2020, 2021, and 2022, and form the basis of the temporal comparisons. # indicates new sites that were surveyed for the first time in 2022.

Sector	Site	Exposure	Aspect	Lat	Long
Southern	Frederick 1*	Sheltered	NE	-21.0111	154.351
Southern	Frederick 2*	Semi-sheltered	W	-21.0104	154.3474
Southern	Frederick 4*	Sheltered	W	-20.9384	154.3974
Southern	Kenn 1*	Sheltered	NE	-21.2476	155.7662
Southern	Kenn 2*	Sheltered	NE	-21.2532	155.7622
Southern	Kenn 4*	Sheltered	W	-21.2046	155.7724
Southern	Saumarez 3*	Sheltered	NW	-21.9178	153.5845
Southern	Saumarez 5*	Sheltered	W	-21.75	153.7697
Southern	Saumarez 7*	Sheltered	NW	-21.9119	153.5912
Central	Diamond 1*	Semi-sheltered	NE	-17.442	151.0626
Central	Diamond 2*	Sheltered	N	-17.4368	151.0697
Central	Diamond 6*	Sheltered	W	-17.4187	151.0712
Central	Diamond 7 #	Exposed	S	-17.4527	151.0727
Central	Diamond 8 #	Exposed	E	-17.4482	151.0865
Central	Flinders 1*	Sheltered	NW	-17.7136	148.4371
Central	Flinders 2*	Sheltered	N	-17.7022	148.4666
Central	Flinders 5*	Sheltered	W	-17.8616	148.4665
Central	Flinders 6*	Sheltered	S	-17.8309	148.5135
Central	Flinders 7*	Exposed	NE	-17.5368	148.5511
Central	Flora 1 #	Exposed	S	-16.7703	147.7486
Central	Flora 2 #	Exposed	S	-16.7702	147.7573
Central	Herald 1*	Semi-exposed	N	-16.9435	149.1857
Central	Herald 4*	Sheltered	SW	-16.9725	149.1287
Central	Herald 6*	Sheltered	W	-16.9919	149.1308
Central	Herald 8	Exposed	S	-16.9513	149.1933
Central	Herald 9	Exposed	S	-16.951	149.1898
Central	Heralds Surprise 1 #	Exposed	S	-17.3305	148.4689
Central	Heralds Surprise 2 #	Semi-exposed	NE	-17.3207	148.4821
Central	Heralds Surprise 3 #	Semi-exposed	N	-17.3158	148.4762
Central	Holmes 2*	Semi-sheltered	W	-16.5118	147.840
Central	Holmes 5*	Semi-sheltered	NW	-16.5053	147.9675
Central	Holmes 7*	Semi-sheltered	NW	-16.4269	147.9844

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Sector	Site	Exposure	Aspect	Lat	Long
Central	Lihou 1*	Sheltered	NW	-17.5971	151.4896
Central	Lihou 2*	Sheltered	N	-17.5907	151.5003
Central	Lihou 4*	Semi-sheltered	N	-17.1253	151.8254
Central	Lihou 5*	Semi-sheltered	N	-17.1211	151.8294
Central	Lihou 7*	Exposed	SE	-17.4173	151.8661
Central	Lihou 9*	Lagoon	SE	-17.1302	151.8393
Central	Marion 11 #	Exposed	S	-19.237	152.1776
Central	Marion 12 #	Exposed	E	-19.1165	152.4016
Central	Marion 13 #	Exposed	E	-19.1254	152.4038
Central	Marion 6*	Exposed	SE	-19.1213	152.3999
Central	Marion 7*	Sheltered	N	-19.2951	152.2378
Central	Marion 8b*	Exposed	W	-19.2983	152.2342
Central	Marion 9	Lagoon	NE	-19.2314	152.1785
Central	Mellish 1	Sheltered	NE	-17.4161	155.8531
Central	Mellish 10 #	Sheltered	W	-17.3684	155.8397
Central	Mellish 2	Sheltered	N	-17.4177	155.8574
Central	Mellish 5	Exposed	S	-17.44	155.8553
Central	Mellish 6	Sheltered	SW	-17.3904	155.8616
Central	Mellish 7	Sheltered	SW	-17.3742	155.8431
Central	Mellish 8	Exposed	S	-17.4393	155.8629
Central	Mellish 9	Sheltered	W	-17.4265	155.8533
Northern	Ashmore 1	Sheltered	W	-10.138	144.4412
Northern	Ashmore 3	Lagoon	W	-10.2195	144.5967
Northern	Ashmore 5	Lagoon	W	-10.366	144.5412
Northern	Ashmore 6	Lagoon	W	-10.2319	144.5891
Northern	Ashmore 7	Sheltered	N	-10.4391	144.429
Northern	Bougainville 4 *	Semi-exposed	SW	-15.5067	147.1123
Northern	Bougainville 5 *	Semi-exposed	SW	-15.5008	147.0989
Northern	Osprey 1	Exposed	N	-13.8013	146.5461
Northern	Osprey 10 #	Exposed	W	-13.8326	146.5671
Northern	Osprey 11 #	Exposed	SE	-14.0092	146.6878
Northern	Osprey 12 #	Exposed	SW	-14.0155	146.6839
Northern	Osprey 2	Sheltered	W	-13.901	146.5619
Northern	Osprey 4	Exposed	SW	-14.0163	146.6793
Northern	Osprey 6*	Sheltered	S	-13.8808	146.5588
Northern	Osprey 7*	Lagoon	E	-13.8885	146.5594

8. APPENDIX 3 - Fish species surveyed

List of fish species recorded from the southern, central and northern reefs in the CSMP and GBRMP and the area in which fish are counted in each transect.

Species	Transect area	Species	Transect area
Abudefduf sexfasciatus	50 x 2	*Acanthurus olivaceus*	50 x 5
Abudefduf vaigiensis	50 x 2	*Acanthurus pyroferus*	50 x 5
Abudefduf whitleyi	50 x 2	*Acanthurus thompsoni*	50 x 5
Acanthochromis polyacanthus	50 x 2	*Acanthurus triostegus*	50 x 5
Amblyglyphidodon aureus	50 x 2	*Acanthurus xanthopterus*	50 x 5
Amblyglyphidodon curacao	50 x 2	*Anyperodon leucogrammicus*	50 x 5
Amblyglyphidodon leucogaster	50 x 2	*Aphareus furca*	50 x 5
Amphiprion akindynos	50 x 2	*Aprion virescens*	50 x 5
Amphiprion chrysopterus	50 x 2	*Balistapus undulatus*	50 x 5
Amphiprion clarkii	50 x 2	*Balistoides conspicillum*	50 x 5
Amphiprion melanopus	50 x 2	*Balistoides viridescens*	50 x 5
Amphiprion perideraion	50 x 2	*Bolbometopon muricatum*	50 x 5
Chromis agilis	50 x 2	*Caesio cuning*	50 x 5
Chromis alpha	50 x 2	*Caesio lunaris*	50 x 5
Chromis amboinensis	50 x 2	*Calotomus carolinus*	50 x 5
Chromis atripectoralis	50 x 2	*Carangoides bajad*	50 x 5
Chromis atripes	50 x 2	*Carangoides ferdau*	50 x 5
Chromis chrysura	50 x 2	*Carangoides fulvoguttatus*	50 x 5
Chromis flavomaculata	50 x 2	*Carangoides orthogrammus*	50 x 5
Chromis iomelas	50 x 2	*Caranx ignobilis*	50 x 5
Chromis lepidolepis	50 x 2	*Caranx lugubris*	50 x 5
Chromis margaritifer	50 x 2	*Caranx melampygus*	50 x 5
Chromis retrofasciata	50 x 2	*Caranx sexfasciatus*	50 x 5
Chromis ternatensis	50 x 2	*Caranx sp.*	50 x 5
Chromis vanderbilti	50 x 2	*Carcharhinus albimarginatus*	50 x 5

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Amblyglyphidodon aureus

Caranx melampygus

Scarus spinus

Species	**Transect area**	**Species**	**Transect area**
Chromis viridis	50 x 2	*Carcharhinus amblyrhynchos*	50 x 5
Chromis weberi	50 x 2	*Cephalopholis argus*	50 x 5
Chromis xanthochira	50 x 2	*Cephalopholis cyanostigma*	50 x 5
Chromis xanthura	50 x 2	*Cephalopholis leopardus*	50 x 5
Chrysiptera biocellata	50 x 2	*Cephalopholis miniata*	50 x 5
Chrysiptera brownriggii	50 x 2	*Cephalopholis spiloparea*	50 x 5
Chrysiptera flavipinnis	50 x 2	*Cephalopholis urodeta*	50 x 5
Chrysiptera glauca	50 x 2	*Cetoscarus ocellatus*	50 x 5
Chrysiptera rex	50 x 2	*Cheilinus chlorourus*	50 x 5
Chrysiptera rollandi	50 x 2	*Cheilinus fasciatus*	50 x 5
Chrysiptera talboti	50 x 2	*Cheilinus oxycephalus*	50 x 5
Chrysiptera taupou	50 x 2	*Cheilinus trilobatus*	50 x 5
Dascyllus aruanus	50 x 2	*Cheilinus undulatus*	50 x 5
Dascyllus reticulatus	50 x 2	*Chlorurus bleekeri*	50 x 5
Dascyllus trimaculatus	50 x 2	*Chlorurus frontalis*	50 x 5
Dischistodus melanotus	50 x 2	*Chlorurus japanensis*	50 x 5
Dischistodus pseudochrysopoecilus	50 x 2	*Chlorurus microrhinos*	50 x 5
Hemiglyphidodon plagiometopon	50 x 2	*Chlorurus spilurus*	50 x 5
Lepidozygus tapeinosoma	50 x 2	*Choerodon cyanodus*	50 x 5
Neoglyphidodon melas	50 x 2	*Choerodon fasciatus*	50 x 5
Neoglyphidodon nigroris	50 x 2	*Choerodon graphicus*	50 x 5
Neopomacentrus asyzron	50 x 2	*Cromileptes altivelis*	50 x 5
Neopomacentrus cf cyanomos	50 x 2	*Ctenochaetus binotatus*	50 x 5
Plectroglyphidodon dickii	50 x 2	*Ctenochaetus cyanocheilus*	50 x 5
Plectroglyphidodon imparipennis	50 x 2	*Ctenochaetus striatus*	50 x 5
Plectroglyphidodon johnstonianus	50 x 2	*Diploprion bifasciatum*	50 x 5
Plectroglyphidodon lacrymatus	50 x 2	*Elagatis bipinnulatus*	50 x 5
Plectroglyphidodon leucozonus	50 x 2	*Epibulus insidiator*	50 x 5
Plectroglyphidodon phoenixensis	50 x 2	*Epinephelus coeruleopunctatus*	50 x 5
Pomacentrus adelus	50 x 2	*Epinephelus coioides*	50 x 5
Pomacentrus amboinensis	50 x 2	*Epinephelus fasciatus*	50 x 5

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Cephalopholis miniata

Chrysiptera taupou

Plectroglyphidodon lacrymatus

Species	Transect area	Species	Transect area
Pomacentrus bankanensis	50 x 2	*Epinephelus fuscoguttatus*	50 x 5
Pomacentrus brachialis	50 x 2	*Epinephelus hexagonatus*	50 x 5
Pomacentrus chrysurus	50 x 2	*Epinephelus howlandensis*	50 x 5
Pomacentrus coelestis	50 x 2	*Epinephelus lanceolatus*	50 x 5
Pomacentrus grammorhynchus	50 x 2	*Epinephelus merra*	50 x 5
Pomacentrus imitator	50 x 2	*Epinephelus polyphekadion*	50 x 5
Pomacentrus lepidogenys	50 x 2	*Epinephelus quoyanus*	50 x 5
Pomacentrus moluccensis	50 x 2	*Epinephelus tukula*	50 x 5
Pomacentrus nagasakiensis	50 x 2	*Gnathodentex aureolineatus*	50 x 5
Pomacentrus pavo	50 x 2	*Gracilla albomarginata*	50 x 5
Pomacentrus philippinus	50 x 2	*Gymnocranius euanus*	50 x 5
Pomacentrus vaiuli	50 x 2	*Gymnocranius microdon*	50 x 5
Pomacentrus wardi	50 x 2	*Hemigymnus fasciatus*	50 x 5
Pomachromis richardsoni	50 x 2	*Hemigymnus melapterus*	50 x 5
Stegastes apicalis	50 x 2	*Hipposcarus longiceps*	50 x 5
Stegastes fasciolatus	50 x 2	*Hologymnosus annulatus*	50 x 5
Stegastes gascoynei	50 x 2	*Hologymnosus doliatus*	50 x 5
Stegastes nigricans	50 x 2	*Kyphosus cinerascens*	50 x 5
Anampses caeruleopunctatus	50 x 4	*Kyphosus vaigiensis*	50 x 5
Anampses femininus	50 x 4	*Lethrinus atkinsoni*	50 x 5
Anampses meleagrides	50 x 4	*Lethrinus erythracanthus*	50 x 5
Anampses neoguinaicus	50 x 4	*Lethrinus miniatus*	50 x 5
Anampses twistii	50 x 4	*Lethrinus nebulosus*	50 x 5
Apolemichthys trimaculatus	50 x 4	*Lethrinus obsoletus*	50 x 5
Bodianus axillaris	50 x 4	*Lethrinus olivaceus*	50 x 5
Bodianus dictynna	50 x 4	*Lethrinus sp. 1*	50 x 5
Bodianus loxozonus	50 x 4	*Lethrinus xanthocheilus*	50 x 5
Bodianus mesothorax	50 x 4	*Lutjanus argentimaculatus*	50 x 5
Bodianus perditio	50 x 4	*Lutjanus bohar*	50 x 5
Centropyge bicolor	50 x 4	*Lutjanus carponotatus*	50 x 5
Centropyge bispinosus	50 x 4	*Lutjanus fulviflamma*	50 x 5

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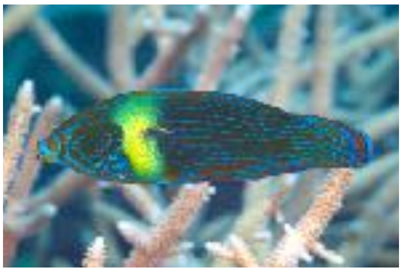

Labrichthys unilineatus

Pseudocheilinus hexataenia

Epinephelus merra

Species	Transect area	Species	Transect area
Centropyge fisheri	50 x 4	*Lutjanus fulvus*	50 x 5
Centropyge flavissimus	50 x 4	*Lutjanus gibbus*	50 x 5
Centropyge heraldi	50 x 4	*Lutjanus kasmira*	50 x 5
Centropyge loricula	50 x 4	*Lutjanus monostigma*	50 x 5
Centropyge smokey	50 x 4	*Lutjanus rivulatus*	50 x 5
Centropyge tibicen	50 x 4	*Lutjanus semicinctus*	50 x 5
Centropyge vrolikii	50 x 4	*Luzonichthys sp*	50 x 5
Chaetodon auriga	50 x 4	*Macolor macularis*	50 x 5
Chaetodon baronessa	50 x 4	*Macolor niger*	50 x 5
Chaetodon bennetti	50 x 4	*Melichthys vidua*	50 x 5
Chaetodon citrinellus	50 x 4	*Monotaxis grandoculis*	50 x 5
Chaetodon ephippium	50 x 4	*Monotaxis heterodon*	50 x 5
Chaetodon flavirostris	50 x 4	*Mulloidichthys flavolineatus*	50 x 5
Chaetodon kleinii	50 x 4	*Mulloidichthys vanicolensis*	50 x 5
Chaetodon lineolatus	50 x 4	*Naso annulatus*	50 x 5
Chaetodon lunula	50 x 4	*Naso brachycentron*	50 x 5
Chaetodon lunulatus	50 x 4	*Naso brevirostris*	50 x 5
Chaetodon melannotus	50 x 4	*Naso caesius*	50 x 5
Chaetodon mertensii	50 x 4	*Naso hexacanthus*	50 x 5
Chaetodon meyeri	50 x 4	*Naso lituratus*	50 x 5
Chaetodon ocellicaudus	50 x 4	*Naso tonganus*	50 x 5
Chaetodon ornatissimus	50 x 4	*Naso unicornis*	50 x 5
Chaetodon oxycephalus	50 x 4	*Naso vlamingii*	50 x 5
Chaetodon pelewensis	50 x 4	*Odonus niger*	50 x 5
Chaetodon plebeius	50 x 4	*Oxycheilinus digramma*	50 x 5
Chaetodon punctatofasciatus	50 x 4	*Oxycheilinus orientalis*	50 x 5
Chaetodon rafflesi	50 x 4	*Oxycheilinus oxycephalus*	50 x 5
Chaetodon rainfordi	50 x 4	*Oxycheilinus unifasciatus*	50 x 5
Chaetodon reticulatus	50 x 4	*Paracanthurus hepatus*	50 x 5
Chaetodon semeion	50 x 4	*Parupeneus barberinoides*	50 x 5
Chaetodon speculum	50 x 4	*Parupeneus barberinus*	50 x 5

Continues on next page.

Chaetodon lunulatus

Chaetodon plebeius

Mellichthys vidua

Species	Transect area	Species	Transect area
Chaetodon trifascialis	50 x 4	*Parupeneus ciliatus*	50 x 5
Chaetodon ulietensis	50 x 4	*Parupeneus crassilabris*	50 x 5
Chaetodon unimaculatus	50 x 4	*Parupeneus cyclostomus*	50 x 5
Chaetodon vagabundus	50 x 4	*Parupeneus multifasciatus*	50 x 5
Chaetodontoplus meredithi	50 x 4	*Parupeneus pleurostigma*	50 x 5
Chelmon rostratus	50 x 4	*Platax pinnatus*	50 x 5
Cirrhilabrus exquisitus	50 x 4	*Plectorhinchus albovittatus*	50 x 5
Cirrhilabrus laboutei	50 x 4	*Plectorhinchus chaetodontoides*	50 x 5
Cirrhilabrus lineatus	50 x 4	*Plectorhinchus lessoni*	50 x 5
Cirrhilabrus punctatus	50 x 4	*Plectorhinchus lineatus*	50 x 5
Cirrhilabrus scottorum	50 x 4	*Plectorhinchus picus*	50 x 5
Coris aygula	50 x 4	*Plectropomus areolatus*	50 x 5
Coris batuensis	50 x 4	*Plectropomus laevis*	50 x 5
Coris dorsomacula	50 x 4	*Plectropomus leopardus*	50 x 5
Coris gaimard	50 x 4	*Pomacanthus imperator*	50 x 5
Diproctacanthus xanthurus	50 x 4	*Pomacanthus semicirculatus*	50 x 5
Forcipiger flavissimus	50 x 4	*Pomacanthus sexstriatus*	50 x 5
Forcipiger longirostris	50 x 4	*Pomacanthus xanthometopon*	50 x 5
Gomphosus varius	50 x 4	*Prionurus maculatus*	50 x 5
Halichoeres biocellatus	50 x 4	*Pseudanthias cooperi*	50 x 5
Halichoeres hortulanus	50 x 4	*Pseudanthias pascalus*	50 x 5
Halichoeres margaritaceus	50 x 4	*Pseudanthias pleurotaenia*	50 x 5
Halichoeres marginatus	50 x 4	*Pseudanthias squamipinnis*	50 x 5
Halichoeres melanurus	50 x 4	*Pseudanthias tuka*	50 x 5
Halichoeres ornatissimus	50 x 4	*Pseudobalistes flavimarginatus*	50 x 5
Halichoeres prosopeion	50 x 4	*Pseudobalistes fuscus*	50 x 5
Halichoeres trimaculatus	50 x 4	*Pterocaesio digramma*	50 x 5
Hemitaurichthys polylepis	50 x 4	*Pterocaesio tile*	50 x 5
Heniochus acuminatus	50 x 4	*Pterocaesio trilineata*	50 x 5
Heniochus chrysostomus	50 x 4	*Rhinecanthus rectangulus*	50 x 5
Heniochus monoceros	50 x 4	*Scarus altipinnis*	50 x 5

Continues on next page.

Pomacanthus imperator

Halichoeres trimaculatus

Hemitaurichthys polylepis

Species	Transect area	Species	Transect area
Heniochus varius	50 x 4	*Scarus chameleon*	50 x 5
Labrichthys unilineatus	50 x 4	*Scarus dimidiatus*	50 x 5
Labroides bicolor	50 x 4	*Scarus flavipectoralis*	50 x 5
Labroides dimidiatus	50 x 4	*Scarus forsteni*	50 x 5
Labroides pectoralis	50 x 4	*Scarus frenatus*	50 x 5
Labropsis australis	50 x 4	*Scarus ghobban*	50 x 5
Labropsis xanthonota	50 x 4	*Scarus globiceps*	50 x 5
Macropharyngodon choati	50 x 4	*Scarus longipinnis*	50 x 5
Macropharyngodon kuiteri	50 x 4	*Scarus niger*	50 x 5
Macropharyngodon meleagris	50 x 4	*Scarus oviceps*	50 x 5
Macropharyngodon negrosensis	50 x 4	*Scarus psittacus*	50 x 5
Paracentropyge multifasciata	50 x 4	*Scarus rivulatus*	50 x 5
Pseudocheilinus evanidus	50 x 4	*Scarus rubroviolaceus*	50 x 5
Pseudocheilinus hexataenia	50 x 4	*Scarus schlegeli*	50 x 5
Pseudocoris yamashiroi	50 x 4	*Scarus spinus*	50 x 5
Pseudodax moluccanus	50 x 4	*Scarus viridifucatus*	50 x 5
Pteragogus sp.	50 x 4	*Scarus xanthopleura*	50 x 5
Pygoplites diacanthus	50 x 4	*Scolopsis bilineatus*	50 x 5
Stethojulis bandanensis	50 x 4	*Scomberoides lysan*	50 x 5
Stethojulis interrupta	50 x 4	*Scomberoides sp*	50 x 5
Stethojulis strigiventer	50 x 4	*Serranocirrhites latus*	50 x 5
Thalassoma amblycephalum	50 x 4	*Siganus argenteus*	50 x 5
Thalassoma hardwicke	50 x 4	*Siganus corallinus*	50 x 5
Thalassoma lunare	50 x 4	*Siganus doliatus*	50 x 5
Thalassoma lutescens	50 x 4	*Siganus puellus*	50 x 5
Thalassoma nigrofasciatum	50 x 4	*Siganus punctatissimus*	50 x 5
Thalassoma purpureum	50 x 4	*Siganus punctatus*	50 x 5
Thalassoma quinquevittatum	50 x 4	*Siganus vulpinus*	50 x 5
Acanthurus albipectoralis	50 x 5	*Siganus woodlandi*	50 x 5
Acanthurus blochii	50 x 5	*Stegostoma fasciatum*	50 x 5
Acanthurus dussumieri	50 x 5	*Sufflamen bursa*	50 x 5
Acanthurus grammoptilus	50 x 5	*Sufflamen chrysopterus*	50 x 5
Acanthurus guttatus	50 x 5	*Trachinotus blochii*	50 x 5
Acanthurus lineatus	50 x 5	*Triaenodon obesus*	50 x 5
Acanthurus mata	50 x 5	*Variola louti*	50 x 5
Acanthurus nigricans	50 x 5	*Zanclus cornutus*	50 x 5
Acanthurus nigricauda	50 x 5	*Zebrasoma scopas*	50 x 5
Acanthurus nigrofuscus	50 x 5	*Zebrasoma veliferum*	50 x 5
Acanthurus nigroris	50 x 5		

9. APPENDIX 4 - Fish species records

List of conspicuous (i.e., non-cryptic) fish species recorded and/or observed within each region of the CSMP during 2018-2022. A separate column is provided for cryptobenthic fish species that were identified during targeted collections using clove oil.

* indicates species that were recorded for the first time in 2022.

Count	Species	Southern	Central	Northern	Cryptobenthic
1	*Abudefduf sexfasciatus*	1		1	
2	*Abudefduf vaigiensis*	1	1	1	
3	*Acanthochromis polyacanthus*		1	1	1
4	*Acanthurus albipectoralis*	1	1	1	
5	*Acanthurus blochii*	1	1	1	
6	*Acanthurus dussumieri*	1	1	1	
7	*Acanthurus grammoptilus*		1		
8	*Acanthurus guttatus*	1	1	1	
9	*Acanthurus lineatus*	1	1	1	
10	*Acanthurus maculiceps*		1		
11	*Acanthurus mata*		1	1	
12	*Acanthurus nigricans*	1	1	1	
13	*Acanthurus nigricauda*	1	1	1	
14	*Acanthurus nigrofuscus*	1	1	1	1
15	*Acanthurus nigroris*	1	1	1	
16	*Acanthurus nubilis*		1		
17	*Acanthurus olivaceus*	1	1	1	
18	*Acanthurus pyroferus*	1	1	1	
19	*Acanthurus thompsoni*	1	1	1	
20	*Acanthurus triostegus*	1	1	1	
21	*Acanthurus xanthopterus*	1	1	1	
22	*Aethaloperca rogaa*			1	
23	*Aetobatus narinari*		1		
24	*Aetobatus ocellatus*	1			
25	*Aluteres scriptus*	1	1	1	
26	*Amanses scopas*	1		1	
27	*Amblycirrhitus bimacula*				1
28	*Amblyeleotris steinitzi*		1	1	
29	*Amblyglyphidodon aureus*	1	1	1	
30	*Amblyglyphidodon curacao*	1	1		
31	*Amblyglyphidodon leucogaster*	1	1	1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
32	*Amphiprion akindynos*	1	1		
33	*Amphiprion chrysopterus*		1	1	
34	*Amphiprion clarkii*	1		1	
35	*Amphiprion melanopus*	1	1	1	
36	*Amphiprion perideraion*		1	1	
37	*Anampses caeruleopunctatus*	1	1	1	
38	*Anampses femininus*	1	1		
39	*Anampses geographicus*		1	1	
40	*Anampses meleagrides*	1			
41	*Anampses neoguinaicus*	1	1	1	
42	*Anampses twistii*	1	1	1	
43	*Antennarius nummifer*				1
44	*Antennarius pictus*				1
45	*Anyperodon leucogrammicus*			1	
46	*Aphareus furca*	1	1	1	
47	*Apogon crassiceps*				1
48	*Apogon doederleini*			1	
49	*Apogon doryssa*				1
50	*Apogon seminigricaudus*				1
51	*apogonid sp.*				1
52	*Apolemichthys trimaculatus*			1	
53	*Aprion virescens*	1	1	1	
54	*Arothron hispidus*	1			
55	*Arothron nigropunctatus*	1	1	1	
56	*Arothron stellatus*	1	1		
57	*Aseraggodes sp.*				1
58	*Assessor flavissimus*			1	
59	*Asterropteryx semipunctata*				1
60	*Aulostomus chinensis*	1	1	1	
61	*Balenoperca chabanaudi*		1	1	
62	*Balistapus undulatus*	1	1	1	
63	*Balistoides conspicillum*	1	1	1	
64	*Balistoides viridescens*	1	1	1	
65	*Belonoperca chabanaudi*			1	
66	*Bodianus anthioides*		1	1	
67	*Bodianus axillaris*	1	1	1	
68	*Bodianus dictynna*		1	1	
69	*Bodianus loxozonus*		1	1	
70	*Bodianus mesothorax*	1	1	1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
71	*Bodianus perditio*	1			
72	*Bolbometopon muricatum*		1	1	
73	*Brachaluteres prionurus*		1		
74	*Brosmophyciops pautzkei*				1
75	*Bryaninops sp.*				1
76	*bythitid sp.*				1
77	*Cabillus tongarevae*				1
78	*Caesio caerulaurea**			1	
79	*Caesio cuning*		1		
80	*Caesio lunaris*		1	1	
81	*Caesio teres*		1	1	
82	*Callogobius sclateri*				1
83	*Calotomus carolinus*	1	1	1	
84	*Cantherhines dumerilii*	1	1		
85	*Cantherhines pardalis**		1		
86	*Canthigaster amboinensis*	1	1		
87	*Canthigaster axiologus*	1			
88	*Canthigaster bennetti*	1	1		
89	*Canthigaster janthinoptera**		1		
90	*Canthigaster papua*		1		1
91	*Canthigaster valentini*	1	1	1	1
92	*Caracanthus maculatus*	1	1	1	1
93	*Caracanthus unipinna*				1
94	*Carangoides ferdau*		1	1	
95	*Carangoides fulvoguttatus*			1	
96	*Carangoides orthogrammus*	1	1	1	
97	*Carangoides plagiotaenia*			1	
98	*Caranx ignobilis*	1	1	1	
99	*Caranx lugubris*		1	1	
100	*Caranx melampygus*	1	1	1	
101	*Caranx papuensis**		1		
102	*Caranx sexfasciatus*	1	1	1	
103	*Caranx sp.*			1	
104	*Carcharhinus albimarginatus*	1	1	1	
105	*Carcharhinus amblyrhynchos*	1	1	1	
106	*Celotomus carolinus*	1			
107	*Centropyge bicolor*	1	1	1	
108	*Centropyge bispinosa*	1	1	1	1
109	*Centropyge fisheri*		1		

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
110	*Centropyge flavissima*	1	1	1	
111	*Centropyge heraldi*	1	1	1	1
112	*Centropyge hybrid 'smokey'*	1	1		1
113	*Centropyge loricula*	1	1	1	
114	*Centropyge tibicen*	1			1
115	*Centropyge vrolikii*	1	1	1	
116	*Centropyge woodheadi*	1			
117	*Cephalopholis argus*	1	1	1	
118	*Cephalopholis leopardus*		1	1	1
119	*Cephalopholis miniata*		1	1	
120	*Cephalopholis spiloparaea*		3		
121	*Cephalopholis urodeta*	1	1	1	1
122	*Cercamia eremia*				1
123	*Cetoscarus ocellatus*	1	1	1	1
124	*Chaetodon auriga*	1	1	1	
125	*Chaetodon baronessa*			1	
126	*Chaetodon bennetti*	1		1	
127	*Chaetodon citrinellus*	1	1	1	
128	*Chaetodon ephippium*	1	1	1	
129	*Chaetodon flavirostris*	1	1	1	
130	*Chaetodon kleinii*	1	1	1	
131	*Chaetodon lineolatus*	1	1	1	
132	*Chaetodon lunula*	1	1	1	
133	*Chaetodon lunulatus*	1	1	1	
134	*Chaetodon melannotus*	1	1	1	
135	*Chaetodon mertensii*	1	1	1	
136	*Chaetodon meyeri*		3	1	
137	*Chaetodon ocellicaudus*	1			
138	*Chaetodon ornatissimus*	1	1	1	
139	*Chaetodon oxycephalus*			1	
140	*Chaetodon pelewensis*	1	1	1	
141	*Chaetodon plebeius*	1	1	1	
142	*Chaetodon punctatofasciatus*			1	
143	*Chaetodon rafflesi*		1		
144	*Chaetodon reticulatus*	1	1	1	
145	*Chaetodon semeion*		1	1	
146	*Chaetodon speculum*	1	1	1	
147	*Chaetodon trifascialis*	1	1	1	
148	*Chaetodon ulietensis*	1	1	1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
149	*Chaetodon unimaculatus*	1	1	1	
150	*Chaetodon vagabundus*	1	1	1	
151	*Chanos chanos*			1	
152	*Cheilinus chlorourus*	1	1	1	
153	*Cheilinus fasciatus*		1	1	
154	*Cheilinus oxycephalus*	1	1	1	
155	*Cheilinus trilobatus*	1	1	1	
156	*Cheilinus undulatus*	1	1	1	
157	*Cheilodipterus macrodon*		1		
158	*Chlorurus bleekeri*			1	
159	*Chlorurus frontalis*	1	1		
160	*Chlorurus japanensis*	1		1	
161	*Chlorurus microrhinos*	1	1	1	
162	*Chlorurus spilurus*	1	1	1	
163	*Choerodon fasciatus*		1		
164	*Chromis agilis*	1	1	1	
165	*Chromis alpha*		1		
166	*Chromis amboinensis*	1	1	1	
167	*Chromis atripectoralis*	1	1	1	
168	*Chromis atripes*	1	1	1	
169	*Chromis chrysura*	1	1	1	
170	*Chromis flavomaculata*	1			
171	*Chromis fumea**		1		
172	*Chromis iomelas*	1	1	1	1
173	*Chromis lepidolepis*	1	1	1	
174	*Chromis margaritifer*	1	1	1	1
175	*Chromis retrofasciata*	1	1	1	
176	*Chromis ternatensis*	1	1	1	
177	*Chromis vanderbilti*	1	1	1	1
178	*Chromis viridis*	1	1		
179	*Chromis weberi*		1	1	
180	*Chromis xanthochira*	1	1		
181	*Chromis xanthura*	1	1	1	
182	*Chrysiptera biocellata*	1	1	1	
183	*Chrysiptera brownriggii*		1	1	
184	*Chrysiptera flavipinnis*		1		
185	*Chrysiptera glauca*	1			
186	*Chrysiptera rollandi*		1		1
187	*Chrysiptera talboti*			1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
188	*Chrysiptera taupou*	1	1	1	1
189	*Cirrhilabrus exquisitus*	1	1	1	
190	*Cirrhilabrus laboutei*	1	1		1
191	*Cirrhilabrus lineatus*		1		
192	*Cirrhilabrus punctatus*	1	1	1	1
193	*Cirrhilabrus scottorum*	1	1	1	
194	*Cirrhitichthys falco*	1	1		1
195	*Cirrhitichthys oxycephalus*			1	
196	*Cirrhitus pinnulatus*	1			
197	*Cirripectes castaneus*		1	1	1
198	*Cirripectes filamentosus*				1
199	*Cirripectes stigmaticus*	1	1		1
200	*Coris aygula*	1	1	1	
201	*Coris batuensis*			1	1
202	*Coris dorsomacula*	1	1		
203	*Coris gaimard*	1	1	1	
204	*Cosmocampus banneri*				1
205	*Crossosalarias macrospilus*				1
206	*Ctenochaetus binotatus*	1	1	1	
207	*Ctenochaetus cyanocheilus*	1	1	1	
208	*Ctenochaetus striatus*	1	1	1	
209	*Ctenogobiops pomastictus*				1
210	*Cypho purpurascens*	1	1	1	1
211	*Dascyllus aruanus*	1			
212	*Dascyllus reticulatus*	1	1	1	1
213	*Dascyllus trimaculatus*	1	1	1	
214	*Dasyatis kuhlii*		1		
215	*Decapterus macarellus*		1		
216	*Dinematichthys ilucoetiodes*				1
217	*Dinematichthys sp.?*				1
218	*Diodon hystrix*		1		
219	*Diplogrammus goramensis*				1
220	*Dischistodus melanotus*	1			
221	*Dischistodus prosopotaenia **			1	
222	*Dischistodus pseudochrysopoecilus*	1			
223	*Doryrhamphus melanopleura*				1
224	*Doryrhamphus sp.*				1
225	*Echeneis naucrates*	1	1	1	
226	*Echidna polyzona*				1

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
227	*Ecsenius bicolor*			1	
228	*Ecsenius fourmanoiri*	1			
229	*Ecsenius stictus*				1
230	*Ecsenius tigris*				1
231	*Elegatis bipinnulata*		1	1	
232	*Encheliophis homei?*				1
233	*Enneapterygius atrogulare?*				1
234	*Enneapterygius flavoccipitis*				1
235	*Enneapterygius sp.*				1
236	*Enneapterygius sp. 1*				1
237	*Enneapterygius sp. 1*				1
238	*Enneapterygius tutuilae*				1
239	*Epibulus insidiator*	1	1	1	
240	*Epinephelus coioides*		1		
241	*Epinephelus cyanopodus*	1			
242	*Epinephelus fasciatus*	1		1	
243	*Epinephelus fuscoguttatus*			1	
244	*Epinephelus hexagonatus*	1	1	1	
245	*Epinephelus howlandensis*	1			
246	*Epinephelus lanceolatus*		1		
247	*Epinephelus merra*	1	1	1	
248	*Epinephelus polyphekadion*	1	1	1	
249	*Epinephelus quoyanus*		1		
250	*Epinephelus tauvina*		1		
251	*Epinephelus tukula*			1	
252	*Euthynnus affinis*	1			
253	*Eviota afelei*				1
254	*Eviota ancora*				1
255	*Eviota atriventris*				1
256	*Eviota cf. teresae*				1
257	*Eviota cometa*				1
258	*Eviota distigma*				1
259	*Eviota fallax*				1
260	*Eviota fasciola*				1
261	*Eviota flebilis*				1
262	*Eviota guttata*		1		
263	*Eviota herrei*				1
264	*Eviota infulata*				1
265	*Eviota latifasciata*				1

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
266	*Eviota melanosphena*				1
267	*Eviota melasma*				1
268	*Eviota monostigma*				1
269	*Eviota nebulosa*				1
270	*Eviota occasa*				1
271	*Eviota prasites*	1			1
272	*Eviota punctulata*				1
273	*Eviota queenslandica*				1
274	*Eviota readeri*				1
275	*Eviota sigillata*				1
276	*Eviota singula*				1
277	*Eviota sp.*				1
278	*Eviota sp. 1*				1
279	*Eviota sp. 1a*				1
280	*Eviota sp. 1b*				1
281	*Eviota sp. 3*				1
282	*Eviota sp. 4*				1
283	*Eviota sp. 5*				1
284	*Eviota sparsa*				1
285	*Eviota specca*				1
286	*Eviota variola*				1
287	*Eviota zebrina*				1
288	*Exallias brevis*	1	1		
289	*Fistularia commersonii*	1	1	1	
290	*Forcipiger flavissimus*	1	1	1	
291	*Forcipiger longirostris*	1	1	1	
292	*Fowleria aurita*				1
293	*Fowleria vaiulae*				1
294	*Fusigobius gracilis*				1
295	*Fusigobius humeralis*				1
296	*Fusigobius neophytus*				1
297	*Fusigobius sp.*				1
298	*Galeocerdo cuvier*	1			
299	*Genicanthus melanospilos*		1	1	
300	*Genicanthus watanabei*		1		
301	*Glyptoparus delicatulus*				1
302	*Gnathanodon speciosus*	1			
303	*Gnathodentex aureolineatus*	1	1	1	
304	*Gnatholepis cauerensis*		1		1

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
305	*Gnatholepis sp.*				1
306	*gobiid sp.*				1
307	*Gobiodon prolixus*				1
308	*Gobiodon quinquestrigatus*				1
309	*Gobiodon rivulatus*				1
310	*Gomphosus varius*	1	1	1	
311	*Gracila albomarginata*			1	
312	*Grammistes sexlineatus*		1	1	
313	*Gymnapogon philippinus*				1
314	*Gymnapogon sp.*				1
315	*Gymnocranius euanus*	1	1		
316	*Gymnocranius grandoculis*			1	
317	*Gymnocranius microdon*	1	1		
318	*Gymnosarda unicolor*	1	1	1	
319	*Gymnothorax favagineus*		1		
320	*Gymnothorax flavimarginatus*				1
321	*Gymnothorax fuscomaculatus*				1
322	*Gymnothorax gracilicauda*				1
323	*Gymnothorax javanicus*	1	1	1	
324	*Gymnothorax meleagris*	1			
325	*Gymnothorax sp.*				1
326	*Gymnothorax zonipectis*				1
327	*Halicampus dunckeri*				1
328	*Halichoeres biocellatus*	1	1	1	1
329	*Halichoeres chrysus*			1	
330	*Halichoeres hortulanus*	1	1	1	
331	*Halichoeres margaritaceus*	1	1	1	
332	*Halichoeres marginatus*	1	1	1	
333	*Halichoeres melanurus*			1	1
334	*Halichoeres nebulosus*	1			
335	*Halichoeres ornatissimus*	1	1	1	
336	*Halichoeres prosopeion*		1	1	
337	*Halichoeres trimaculatus*	1	1	1	1
338	*Helcogramma sp.*				1
339	*Helcogramma striatum*				1
340	*Hemiglyphidodon plagiometopon* *			1	
341	*Hemigymnus fasciatus*	1	1	1	
342	*Hemitaurichthys polylepis*	1	1	1	
343	*Heniochus acuminatus*		1	1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
344	*Heniochus chrysostomus*	1	1	1	
345	*Heniochus monoceros*	1	1	1	
346	*Heniochus singularis* *		1	1	
347	*Heniochus varius*	1	1	1	
348	*Heteropriacanthus carolinus*				1
349	*Heteropriacanthus cruentatus*			1	
350	*Himantura fai*		1		
351	*Hipposcarus longiceps*	1	1	1	
352	*Hologymnosus annulatus*	1	1	1	
353	*Hologymnosus doliatus*	1	1		
354	*Hoplolatilus starcki*			1	
355	*Iniistius pavo*	1			
356	*Kaupichthys brachychirus*				1
357	*Kyphosus bigibbus*	1			
358	*Kyphosus cinerascens*	1	1	1	
359	*Kyphosus vaigiensis*	1	1	1	
360	*Labrichthys unilineatus*			1	1
361	*labrid sp.*				1
362	*Labroides bicolor*	1	1	1	
363	*Labroides dimidiatus*	1	1	1	1
364	*Labroides pectoralis*	1		1	
365	*Labropsis australis*	1	1	1	
366	*Labropsis xanthonota*		1	1	
367	*Lepadichthys frenatus*				1
368	*Lepadichthys sp.*				1
369	*Lepidozygus tapeinosoma*		1	1	
370	*Lethrinus atkinsoni*		1		
371	*Lethrinus erythracanthus*		1	1	
372	*Lethrinus nebulosus*	1	1	1	
373	*Lethrinus olivaceus*	1	1	1	
374	*Lethrinus sp. 1*		1		
375	*Lethrinus xanthocheilus*	1	1	1	
376	*Limnichthys fasciatus*				1
377	*Liopropoma susumi*	1			1
378	*Luposicya lupus*				1
379	*Lutjanus argentimaculatus*			1	
380	*Lutjanus bohar*	1	1	1	
381	*Lutjanus fulvus*		1	1	
382	*Lutjanus gibbus*	1	1	1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
383	*Lutjanus kasmira*	1	1	1	
384	*Lutjanus monostigma*		1	1	
385	*Lutjanus rivulatus*	1	1	1	
386	*Lutjanus semicinctus*			1	
387	*Luzonichthys sp*			1	
388	*Luzonichthys waitei*			1	
389	*Macolor macularis*	1	1	1	
390	*Macolor niger*	1	1	1	
391	*Macropharyngodon choati*		1		
392	*Macropharyngodon kuiteri*		1		
393	*Macropharyngodon meleagris*	1	1	1	
394	*Macropharyngodon negrosensis*	1	1		
395	*Malacanthus latovittatus*	1	1	1	
396	*Meiacanthus atrodorsalis*		1	1	1
397	*Melichthys vidua*	1	1	1	
398	*Monotaxis grandoculis*	1	1	1	
399	*Monotaxis heterodon*	1	1	1	
400	*Mulloidichthys flavolineatus*	1	1		
401	*Mulloidichthys vanicolensis*	1	1	1	
402	*Myripristis adusta*			1	
403	*Myripristis kuntee*	1	1	1	
404	*Myripristis murdjan*		1		
405	*Myripristis vittata*		1		
406	*Naso annulatus*	1	1	1	
407	*Naso brachycentron*		1	1	
408	*Naso brevirostris*	1	1	1	
409	*Naso caesius*	1	1	1	
410	*Naso hexacanthus*	1	1	1	
411	*Naso lituratus*	1	1	1	
412	*Naso tonganus*	1	1	1	
413	*Naso unicornis*	1	1	1	
414	*Naso vlamingii*	1	1	1	
415	*Neamia octospina*				1
416	*Nebrius ferrugineus*	1	1	1	
417	*Nemateleotris magnifica*	1		1	1
418	*Neocirrhites armatus*	1	1	1	1
419	*Neoglyphidodon nigroris* *			1	
420	*Neoniphon sammara*	1	1	1	
421	*Neopomacentrus azysron* *			1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
422	*Neopomacentrus cf cyanomos*		1		
423	*Neosynchiropus morrisoni*				1
424	*Neotrygon kuhlii*	1	1		
425	*Norfolkia thomasi*				1
426	*Novaculichthys taeniourus*	1	1		1
427	*Odonus niger*		1		
428	*Ogilbyina queenslandiae*				1
429	*Opistognathus seminudus*				1
430	*Opistognathus stigmosus*				1
431	*Ostorhinchus cyanosoma*				1
432	*Ostracion cubicus*	1	1		
433	*Ostracion meleagris*		1	1	
434	*Oxycheilinus digramma*	1	1	1	
435	*Oxycheilinus orientalis*	1	1	1	1
436	*Oxycheilinus unifasciatus*	1	1	1	
437	*Oxymonacanthus longirostris*	1	1	1	
438	*Paracaesio sordida*			1	
439	*Paracanthurus hepatus*	1	1	1	
440	*Paracentropyge multifasciatus*		1	1	
441	*Paracirrhites arcatus*	1	1	1	1
442	*Paracirrhites forsteri*	1	1	1	
443	*Paracirrhites hemistictus*	1	1		
444	*Paragobiodon echinocephalus*				1
445	*Paragobiodon lacunicolus*				1
446	*Paragobiodon xanthosoma*				1
447	*Parapercis clathrata*				1
448	*Parupeneus barberinoides*		1		
449	*Parupeneus barberinus*	1	1	1	
450	*Parupeneus ciliatus*	1	1	1	
451	*Parupeneus crassilabris*	1	1	1	
452	*Parupeneus cyclostomus*	1	1	1	
453	*Parupeneus multifasciatus*	1	1	1	
454	*Parupeneus pleurostigma*	1	1	1	
455	*Parupeneus spilurus* *		1		
456	*Pempheris oualensis*	1			
457	*Pentapodus aureofasciatus* *				
458	*Pervagor alternans*	1	1		
459	*Pervagor janthinosoma*	1	1		1
460	*Plagiotremus rhinorhynchos*		1	1	

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
461	*Plagiotremus tapeinosoma*		1	1	
462	*Platax batavianus* *		1		
463	*Platax pinnatus*		1		
464	*Platax teira*		1		
465	*platycephalid sp.*				1
466	*Plectorhinchus albovittatus*		1	1	
467	*Plectorhinchus chaetodonoides*	1	1	1	
468	*Plectorhinchus lessonii*		1	1	
469	*Plectorhinchus lineatus*		1	1	
470	*Plectorhinchus picus*	1	1		
471	*Plectranthias nanus*				1
472	*Plectroglyphidodon dickii*	1	1	1	
473	*Plectroglyphidodon imparipennis*	1	1	1	
474	*Plectroglyphidodon johnstonianus*	1	1	1	
475	*Plectroglyphidodon lacrymatus*	1	1	1	1
476	*Plectroglyphidodon leucozonus*			1	
477	*Plectroglyphidodon phoenixensis*	1	1		
478	*Plectropomus areolatus*		1	1	
479	*Plectropomus laevis*	1	1	1	
480	*Plectropomus leopardus*	1	1	1	
481	*Plectropomus oligacanthus*			1	
482	*Plectrypops lima*				1
483	*Plesiops caeruleolineatus*				1
484	*Pleurosicya mossambica*				1
485	*Plotosus lineatus*	1	1	1	1
486	*Pomacanthus imperator*	1	1	1	
487	*Pomacanthus sexstriatus*			1	
488	*Pomacentrus amboinensis*			1	1
489	*Pomacentrus auriventris*			1	
490	*Pomacentrus bankanensis*	1	1	1	
491	*Pomacentrus brachialis*	1		1	1
492	*Pomacentrus chrysurus*		1	1	
493	*Pomacentrus coelestis*	1	1	1	
494	*Pomacentrus imitator*	1	1	1	
495	*Pomacentrus lepidogenys*	1	1	1	
496	*Pomacentrus moluccensis*	1	1	1	
497	*Pomacentrus nagasakiensis*		1	1	1
498	*Pomacentrus pavo*			1	
499	*Pomacentrus philippinus*	1		1	1

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
500	*Pomacentrus vaiuli*	1	1	1	1
501	*Pomacentrus wardi*	1			
502	*Pomachromis richardsoni*	1	1	1	
503	*Priacanthus blochii*		1		
504	*Priacanthus hamrur*		1		
505	*Priolepis cincta*				1
506	*Priolepis compita*				1
507	*Priolepis inhaca*				1
508	*Priolepis kappa*				1
509	*Priolepis pallidicincta*				1
510	*Priolepis psygmophila*				1
511	*Priolepis sp.*				1
512	*Prionurus maculatus*	1			
513	*Pristiapogon exostigma*				1
514	*Prteragogus sp.*	1			
515	*Pseudanthias cooperi*		1		
516	*Pseudanthias pascalus*	1	1	1	
517	*Pseudanthias pleurotaenia*		1	1	
518	*Pseudanthias squamipinnis*	1	1	1	
519	*Pseudanthias tuka*	1	1	1	
520	*Pseudobalistes flavimarginatus*		1	1	
521	*Pseudobalistes fuscus*	1	1	1	
522	*Pseudocheilinus evanidus*	1	1	1	1
523	*Pseudocheilinus hexataenia*	1	1	1	1
524	*Pseudocheilinus octotaenia* *		1		
525	*Pseudochromis sp.*				1
526	*Pseudochromis tapeinosoma*				1
527	*Pseudocoris yamashiroi*			1	
528	*Pseudodax moluccanus*	1	1	1	
529	*Pseudogramma polyacanthus*				1
530	*Pseudojuloides cerasinus*		1		
531	*Pseudoplesiops annae*				1
532	*Pseudoplesiops sp.*				1
533	*Pseudoplesiops wassi*				1
534	*Pteragogus cryptus*	1	1		1
535	*Pteragogus sp.*	1	1		
536	*Ptereleotris evides*	1	1	1	
537	*Ptereleotris zebra*		1	1	
538	*Pterocaesio digramma*	1	1		

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
539	*Pterocaesio marri*		1	1	
540	*Pterocaesio tile*	1	1	1	
541	*Pterocaesio trilineata*	1	1	1	
542	*Pterois volitans*	1		1	1
543	*Pygoplites diacanthus*	1	1	1	1
544	*Rhinecanthus aculeatus*			1	
545	*Rhinecanthus rectangulus*	1	1	1	
546	*Sargocentron caudimaculatum*		1		
547	*Sargocentron ittodai*				1
548	*Sargocentron spiniferum*	1	1	1	
549	*Saurida gracilis*	1			
550	*Scarini sp.*				1
551	*Scarus altipinnis*	1	1	1	
552	*Scarus chameleon*	1	1	1	
553	*Scarus dimidiatus*		1	1	
554	*Scarus forsteni*	1	1	1	
555	*Scarus frenatus*	1	1	1	
556	*Scarus ghobban **			1	
557	*Scarus globiceps*	1	1	1	
558	*Scarus longipinnis*	1	1	1	
559	*Scarus niger*	1	1	1	
560	*Scarus oviceps*	1	1	1	
561	*Scarus psittacus*	1	1	1	
562	*Scarus rubroviolaceus*	1	1	1	
563	*Scarus schlegeli*	1	1	1	
564	*Scarus spinus*	1	1	1	
565	*Scarus viridifucatus*			1	
566	*Scarus xanthopleura*	1	1	1	
567	*Scolopsis bilineata*	1		1	
568	*Scomberoides commersonianus*		1		
569	*Scomberoides lysan*		1	1	
570	*Scomberoides sp*			1	
571	*Scomberomorus commerson*			1	
572	*scorpaenid sp.*				1
573	*Scorpaenodes corallinus*				1
574	*Scorpaenodes guamensis*				1
575	*Scorpaenopsis macrochir*				1
576	*Scorpaenopsis sp.*				1
577	*Sebastapistes corallinus*				1

Continues on next page.

Count	Species	Southern	Central	Northern	Cryptobenthic
578	*Sebastapistes cyanostigma*				1
579	*Sebastapistes cyanostigma*			1	
580	*Serranocirrhites latus*	1	1	1	
581	*Siganus argenteus*	1	1	1	
582	*Siganus corallinus*	1	1		
583	*Siganus doliatus **				
584	*Siganus puellus*	1			
585	*Siganus punctatissimus*		1		
586	*Siganus punctatus*	1	1	1	
587	*Siganus vulpinus*	1	1	1	
588	*Siganus woodlandi*	1	1		
589	*Siphamia tubifer*				1
590	*Sphyraena barracuda*	1	1	1	
591	*Sphyraena forsteri*		1		
592	*Stegastes fasciolatus*	1	1	1	
593	*Stegastes gascoynei*	1			
594	*Stegastes nigricans*	1	1	1	1
595	*Stegostoma fasciatum*	1	1		
596	*Stethojulis bandanensis*	1	1	1	1
597	*Stethojulis interrupta*	1			
598	*Stethojulis strigiventer*	1	1	1	
599	*Sufflamen bursa*	1	1	1	
600	*Sufflamen chrysopterum*	1	1	1	
601	*Suttonia lineata*				1
602	*Synodus binotatus*				1
603	*Synodus dermatogenys*				1
604	*Synodus variegatus*	1	1	1	
605	*Synodus varigatus*				1
606	*Taeniura lymma*		1		
607	*Taeniura meyeni*	1	1		
608	*Thalassoma amblycephalum*	1	1	1	1
609	*Thalassoma hardwicke*	1	1	1	
610	*Thalassoma lunare*	1	1	1	
611	*Thalassoma lutescens*	1	1	1	1
612	*Thalassoma nigrofasciatum*	1	1	1	
613	*Thalassoma purpureum*	1	1	1	
614	*Thalassoma quinquevittatum*	1	1	1	
615	*Thalassoma trilobatum*		1	1	
616	*Thysanophrys celebicus*				1

Continues on next page.

Count	**Species**	**Southern**	**Central**	**Northern**	**Cryptobenthic**
617	*Trachinotus baillonii*			1	
618	*Trachinotus blochii*			1	
619	*Triaenodon obesus*	1	1	1	
620	*Trimma caesiura*				1
621	*Trimma emeryi*				1
622	*Trimma lantana*				1
623	*Trimma macrophthalma*				1
624	*Trimma maiandros*				1
625	*Trimma milta*				1
626	*Trimma necopinna*				1
627	*Trimma okinawae*				1
628	*Trimma sp.*				1
629	*Trimmatom eviotops*				1
630	*Trimmatom macropodus*				1
631	*Trimmatom nanus*				1
632	*Trimmatom sp.*				1
633	*Ucla xenogrammus*				1
634	*Valenciennea strigata*		1	1	
635	*Variola albimarginata*		1	1	
636	*Variola louti*	1	1	1	
637	*Xenisthmus eirospilus*				1
638	*Zanclus cornutus*	1	1	1	
639	*Zebrasoma scopas*	1	1	1	
640	*Zebrasoma velifer*	1	1	1	
		318	**385**	**355**	**213**

10. APPENDIX 5 - Supplemental figures of within reef variation

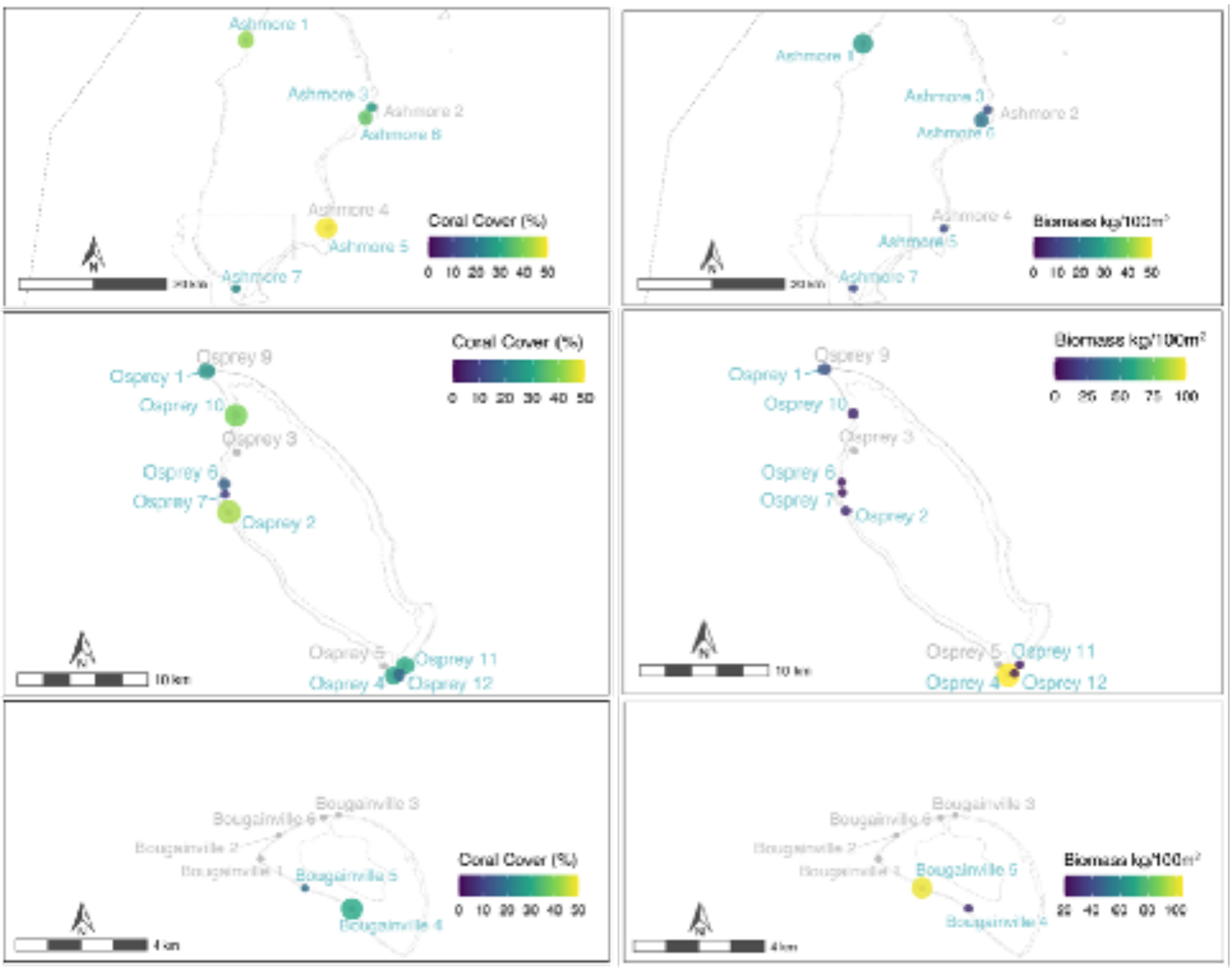

Figure A5.1 Spatial variation in coral cover (left) and biomass of reef fish and sharks (right) within Ashmore, Osprey and Bougainville Reefs in the northern Coral Sea Marine Park (CSMP) in 2022. Data are based on replicate 50m transects at each site. The size of individual points is proportional to coral cover or total fish biomass at each site.

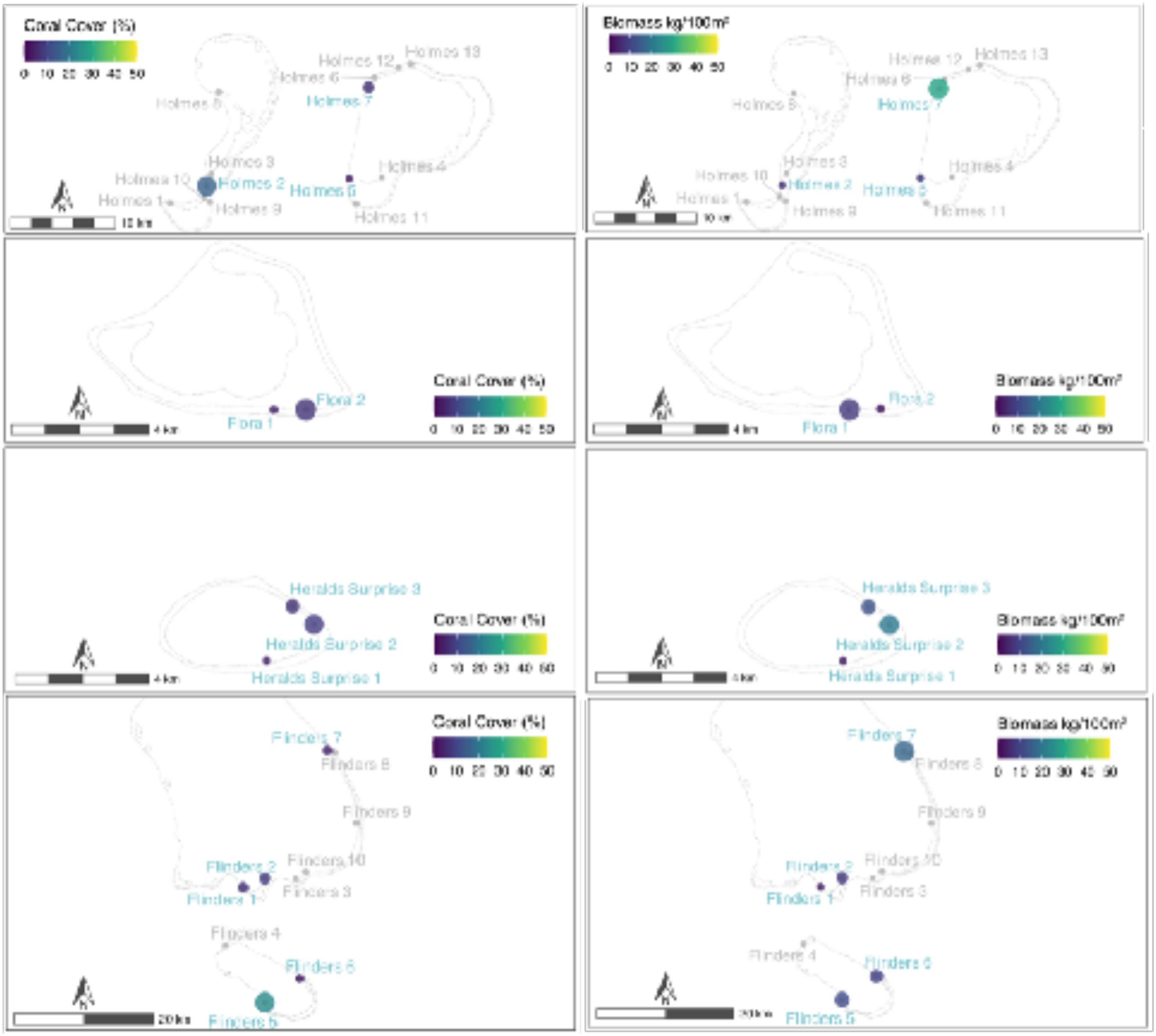

Figure A5.2 Spatial variation in coral cover (left) and biomass of reef fish and sharks (right) within Holmes, Flora, Herald Surprise, and Flinders Reefs in the central Coral Sea Marine Park (CSMP) in 2022. Data are based on replicate 50m transects at each site. The size of individual points is proportional to coral cover or total fish biomass at each site.

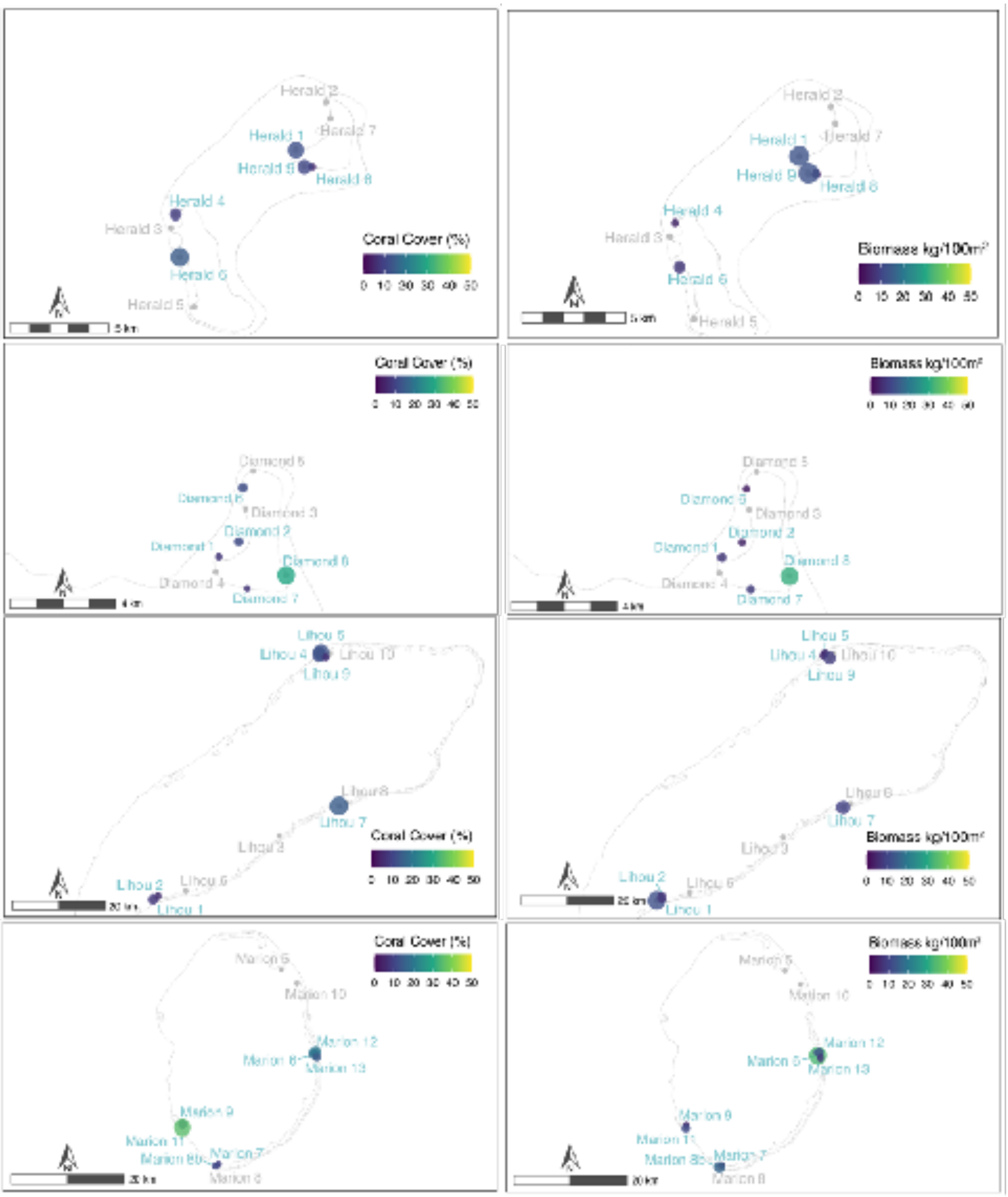

Figure A5.3 Spatial variation in coral cover (left) and biomass of reef fish and sharks (right) within Herald Cays, Diamond Islets, Lihou and Marion Reefs in the central Coral Sea Marine Park (CSMP) in 2022. Data are based on replicate 50m transects at each site. The size of individual points is proportional to coral cover or total fish biomass at each site.

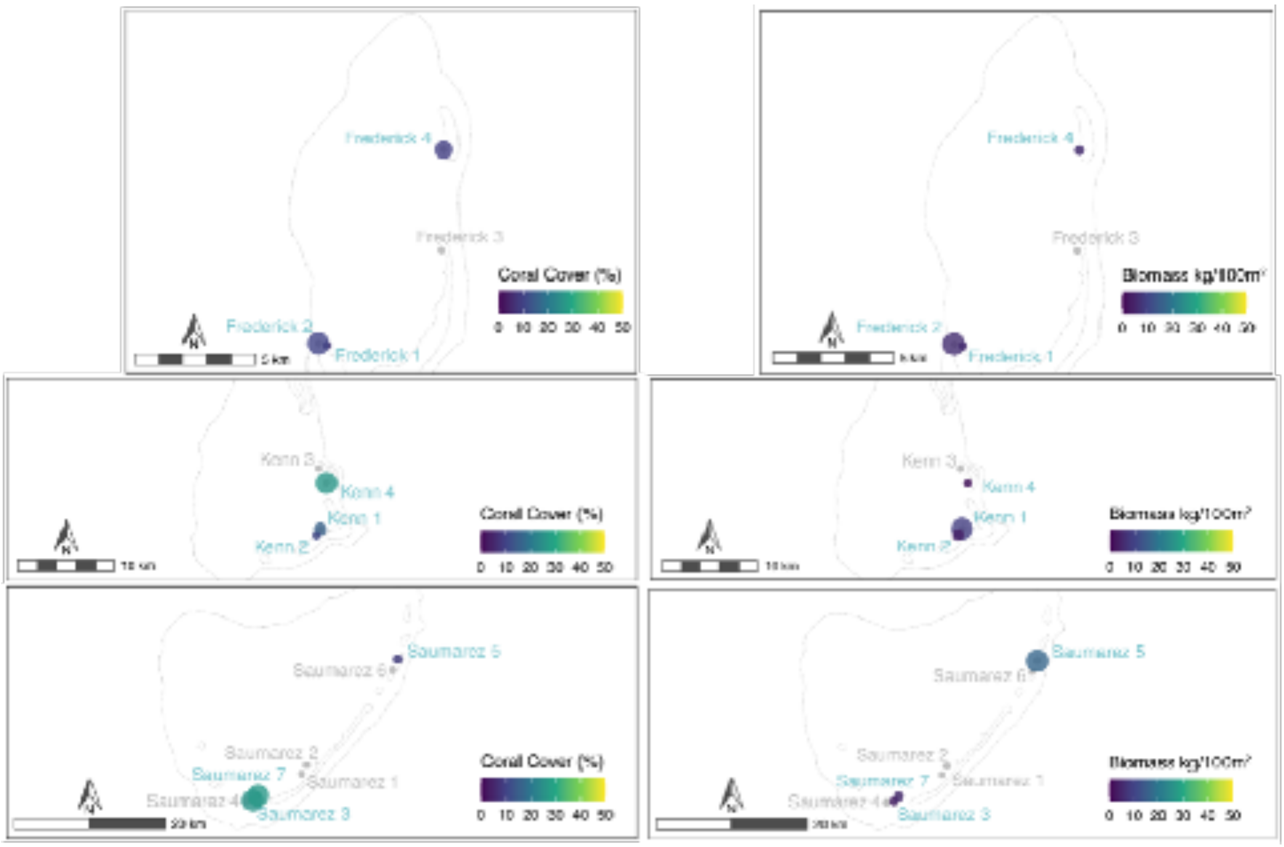

Figure A5.4 Spatial variation in coral cover (left) and biomass of reef fish and sharks (right) within Frederick, Kenn, and Saumarez Reefs in the southern Coral Sea Marine Park (CSMP) in 2022. Data are based on replicate 50m transects at each site. The size of individual points is proportional to coral cover or total fish biomass at each site.