Diving into the Deep

The Unique Deep Habitats of the Coral Sea Marine Park

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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 – Hard and soft coral colonies in a mesophotic coral ecosystem at 57m, Bougainville Reef, CSMP.

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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

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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. To date, the majority of research and monitoring in the Coral Sea Marine Park (CSMP) has focused on shallow (<20m) reef habitats, with limited research into deep (>30m) reef habitats. As such our understanding of these deep habitats, the ecological communities they support, and the connectivity between them is lacking. Given these deep reef habitats likely occupy a much greater area than shallow reef habitats in the CSMP and have been suggested to provide a refuge from anthropogenic disturbance, there is a critical need to advance our understanding of these unique ecosystems.

James Cook University was awarded funding through an Our Marine Parks Round 2 grant to explore and document the deep (>30m) reef habitats of the Coral Sea Marine Park. Specifically, the key objectives of this project were to:

(i) use emerging technologies, such as remotely operated vehicles (ROV), to describe, for the first time, the composition and nature of coral and other benthic communities in deep reef habitats (30-100m) of the CSMP.
(ii) describe the fish communities that occupy these deep reef habitats within the CSMP.
(iii) use acoustic tracking to quantify movement, and thus connectivity, of large fishes and sharks among reefs within the CSMP, and between the CSMP and adjacent reefs of the Great Barrier Reef Marine Park (GBRMP).

The project undertook detailed surveys of benthic and fish communities in deep habitats using ROV and baited remote underwater video systems (BRUVS) at sixteen CSMP reefs over four voyages in February 2021, July 2021, October-November 2021, and February 2022. These surveys were conducted to provide rigorous quantitative information on spatial patterns among depths, reefs and regions in the (i) cover, richness and composition of major benthic taxa, namely hard corals, soft corals, seagrass and macroalgae; and (ii) abundance, species richness, composition and biomass of reef fishes. In doing so, these surveys also provided quantitative data on range and depth extensions of fish species, presence of marine debris, and environmental temperature.

The project surveyed 46 sites across 16 reefs in the CSMP, spanning 12.5 degrees of latitude (~1,600 km) from Ashmore Reef in the north (10.3ºS) to Saumarez Reef in the south (22.8ºS). The surveys revealed the composition and cover of major benthic taxa is highly variable among habitat types (i.e., lagoon, channels, outer and inner reef habitats), depths, and reefs, with no apparent structuring among CSMP regions (i.e., southern, central and northern CSMP). Overall, coral cover (averaged across reefs and sites) ranged from 8% to 32% across the depths surveyed (0-100m), with distinct peaks in coral cover at depths of 71-80m and 11-20m (32% and 17%, respectively). Importantly, these estimates of coral cover in deep reef habitats are comparable to, or greater than, recent estimates of shallow water (2-10m) coral cover across the CSMP (2022: 12.8%). This high coral cover at depth, together with a general lack of recently dead corals, suggests that coral assemblages in these deep habitats have largely escaped the effects of recent marine heatwaves that have caused >50% reduction in shallow water coral cover in the CSMP.

The results of this project revealed that the deep marine habitats of the CSMP are diverse and support distinct and biodiverse ecological communities. In particular, our ROV and BRUV surveys revealed a diversity of habitats and associated fish assemblages within the deep and spatially extensive lagoons that are characteristic of many CSMP reefs. For example, the lagoon at Lihou Reef is up to 60m deep, and covers an area that is more than 20-times that of the shallow reef area (2,500km^2 vs 110km^2). These extensive lagoon systems contain a range of habitats, including isolated bommies, meadows of *Halimeda* and other macroalgae, seagrass (although these were uncommon and generally sparse), sponges, soft corals, and sediment banks, as well as diverse and abundant fish communities. Importantly, juveniles of several fish species were observed using these deep lagoonal non-reef habitats, including the commercially important Red Emperor, *Lutjanus sebae*. In relatively shallow nearshore reef systems (e.g., GBRMP), non-reef habitats are often identified as nursery habitats for newly-settled and juvenile reef fishes, providing refugia from reef-based predators. Our results suggest that these deeper lagoonal habitats may be providing a similarly important habitat for juvenile fishes in the CSMP, however, further surveys are needed to understand the composition and spatial extent of these non-coral habitats, and their importance to different species and life stages of fishes.

Surveys of deep habitats of the CSMP also revealed diverse and abundant fish assemblages, with fish species richness generally declining with depth, while the highest densities and biomass of reef fish were recorded at intermediate (40-60m) depths. We recorded a total of 407 fish species across the ROV and BRUV surveys combined, including 68 fish species that had not previously been recorded during recent extensive surveys of shallow water reef habitats within the CSMP (2018-22). These 68 'new' species records increase the total number of fish species recorded in the CSMP from 661 to 729 species. Seven of these species (Balistidae: *Xanthichthys auromarginatus*, *Abalistes filamentosus*; Malacanthidae: *Hoplolatilus marcosi*, *Hoplolatilus* sp.; Mullidae: *Mulloidichthys pfluegeri*; Acanthuridae: *Acanthurus nubilus*; Labridae: *Anampses melanurus*) appear to be new records for the region, others are rare species seldom seen by divers and are targeted by the aquarium industry (e.g., *Geniacanthus bellus, Pseudanthias pictilis*), and also included several commercially important species (e.g., *Lethrinus miniatus*, *Lutjanus sebae*, and *Pristipomoides filamentosus*). Together with these 'new' species records, depth extensions were recorded for 156 fish species (38% of all species recorded), with 77 species recorded at depths greater than double their previously reported maximum depth. Given the extensive coverage of these deep reef and non-reef habitats throughout the CSMP it is likely that many other species remain unreported and the true taxonomic diversity of the CSMP is considerably greater than current estimates.

Our ROV surveys identified several deep 'bright spots' that had exceptionally high coral cover together with a high abundance of reef fish (Herald's Surprise Reef, Bougainville Reef, and adjacent to Edna and Juliette Cays, Lihou Reef). For example, coral cover at a deep site (20-70m) on Bougainville Reef ranged from 39-54%, considerably greater than the 24% coral cover in shallow (<12m) reef habitats on the same reef. Similarly, coral cover at the deep sites on Herald's Surprise and Lihou Reefs was the highest recorded (up to 70% cover) in recent surveys of both shallow and deep habitats in the CSMP, and were up to 7-times higher than coral cover in shallow (<12m) reef habitats on the same reefs (7% and 10%, respectively). Understanding the environmental and biological conditions that contribute to the high coral cover and abundant fish assemblages at these deep 'bright spots' should be a focus of future research, together with continued and expanded surveys of deep water habitats to quantify how common and widespread these deep 'bright spots' are.

Acoustic tags were surgically implanted into 112 sharks and fish as part of this project. Our acoustic and satellite tracking data show that both small- and large-bodied sharks make significant movements among reefs within the CSMP, and between the CSMP and adjacent areas. In particular, we recorded a female grey reef shark *Carcharinus amblyrhynchos* (164cm TL) to undertake a journey of ~760km from Osprey Reef (CSMP) to the GBRMP and back over 25 days, the largest recorded movement for this species. We also detected several tiger sharks *Galeocerdo cuvier* moving between the CSMP and adjacent areas (e.g., GBRMP, Norfolk Island, New Caledonia), and a juvenile white shark *Carcharodon carcharias* that was tagged in northern NSW was detected at Osprey Reef in the northern CSMP. While these active movements of individuals provide some insights into the ecological connectivity among these reefs and reef systems, continuing to maintain and/or expand the coverage of the acoustic receiver array would greatly add to our understanding of the longer-term movements of these animals and the ecological connectivity among reef systems.

In summary, our surveys revealed:

- Deep habitats within the CSMP support diverse benthic and fish assemblages that include both species that are common in shallow reef habitats, and species that are unique to these deep environments
- CSMP wide coral cover (i.e., averaged across reefs and sites) ranged from 8% to 32% across the depths surveyed (0-100m), with distinct peaks in coral cover at depths of 71-80m and 11-20m (32% and 17%, respectively). This

relatively high coral cover at depth, together with a general lack of recently dead corals, suggests that coral assemblages in these habitats have largely escaped the effects of recent marine heatwaves that have caused significant mortality of corals in shallow CSMP reef habitats.

- There were four deep ‘bright spots’ (sites on Herald’s Surprise, Bougainville and Lihou reefs) that had substantially greater coral cover (up to 71%), and reef fish abundance and biomass than other sites or reefs. These are the first records of such extensive mesophotic coral ecosystems at these reefs and suggests that deep ‘bright spots’ may be common throughout the CSMP.
- The extensive and deep lagoon systems that characterise many CSMP reefs contain a range of habitats, including isolated bommies, meadows of *Halimeda* and other macroalgae, seagrass (although these were uncommon and generally sparse), sponges, and soft corals. Many of these deep non-reef habitats supported a high abundance of juvenile fishes, and may represent important settlement and/or nursery habitat.
- Reef fish assemblages on deep reef habitats of the CSMP are diverse and abundant, with the highest densities and biomass of reef fish being recorded at intermediate (40-60m) depths.
- Sixty-eight fish species that had not been recorded during surveys of shallow reef habitats (2018-2022) were recorded during these surveys of deep habitats, taking the total fish species recorded in the CSMP during the past five years of surveys to 721 species.
- Our acoustic tracking data show that both small- and large-bodied sharks make significant movements among reefs within the CSMP, and between the CSMP and adjacent areas. Notably, a grey reef shark *Carcharinus amblyrhynchos* (164cm TL) moved ~760km from Osprey Reef (CSMP) to the GBRMP and back in 25 days, the largest recorded movement for this species. Several other sharks tagged as part of other projects were recorded to move into the CSMP, including a white shark *Carcharodon carcharias* that was tagged in northern NSW.
- Several species tagged with satellite tags were also recorded to migrate through or use areas within the CSMP, including tiger sharks, whale sharks and manta rays.

Recommendations:

- Regular monitoring of deep reef habitats within the CSMP will be critical to determine any changes in the condition and health of these unique ecosystems, to identify any drivers of change, and to compare the response of shallow vs deep reef habitats to a range of stressors (e.g., heat stress, cyclones). We recommend monitoring deep reef habitats at sites that offer access to a broad range of depths (i.e., 20-100m), and are adjacent to, or paired with, existing shallow reef monitoring sites.
- We recommend to continue using the ROV as the primary method for surveys of deeper habitats as it provides the most comprehensive data of fish and benthic communities, and if resources allow including additional surveys using complementary methods (e.g., BRUV and/or towed video systems).
- Expanding the spatial coverage of these surveys of deep CSMP habitats to include a greater range of habitats, depths, and sites is critical to understand the spatial distribution of these habitats, the ecological communities they support, and to provide insights into the processes that structure these habitats.
- Dedicated and targeted surveys of deep lagoonal habitats are needed to understand the distribution of non-reef habitats (e.g., macroalgae, seagrass, sponge) and the importance of these habitats to juvenile reef fishes, and commercially important fishes and invertebrates (i.e., sea cucumbers).
- Any future surveys of deep habitats in the CSMP should include, and prioritise, the four deep ‘bright spots’ identified by this project (i.e., sites on Bougainville, Herald’s Surprise and Lihou Reefs), as well as dedicated research on key environmental and ecological processes (e.g., primary and secondary productivity, nutrient inputs, local hydrodynamics) that may differentiate these sites from others.
- We strongly recommend the existing array of acoustic receivers on Osprey, Bougainville, Holmes and Flinders reefs is maintained and data downloaded regularly (i.e., annually). The acoustic tags implanted in the animals have a

battery life of ~10 years, and valuable information on the longer term movements of these animals, and connectivity of CSMP reefs could be quantified if these receivers were maintained for up to 9 years.

- Expanding the receiver array to include other reefs in the central and northern CSMP (e.g., Herald Cays, Diamond Islets, Lihou, Mellish, Ashmore and Boot Reefs), and/or tagging additional animals would provide an understanding of movements and connectivity among the broader CSMP. The deployment and maintenance of these receivers could be combined with other planned voyages, thereby minimising costs.
- Comparable research and monitoring of both shallow and deep habitats 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.

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2 Background

2.1 The Coral Sea Marine Park

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. 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.

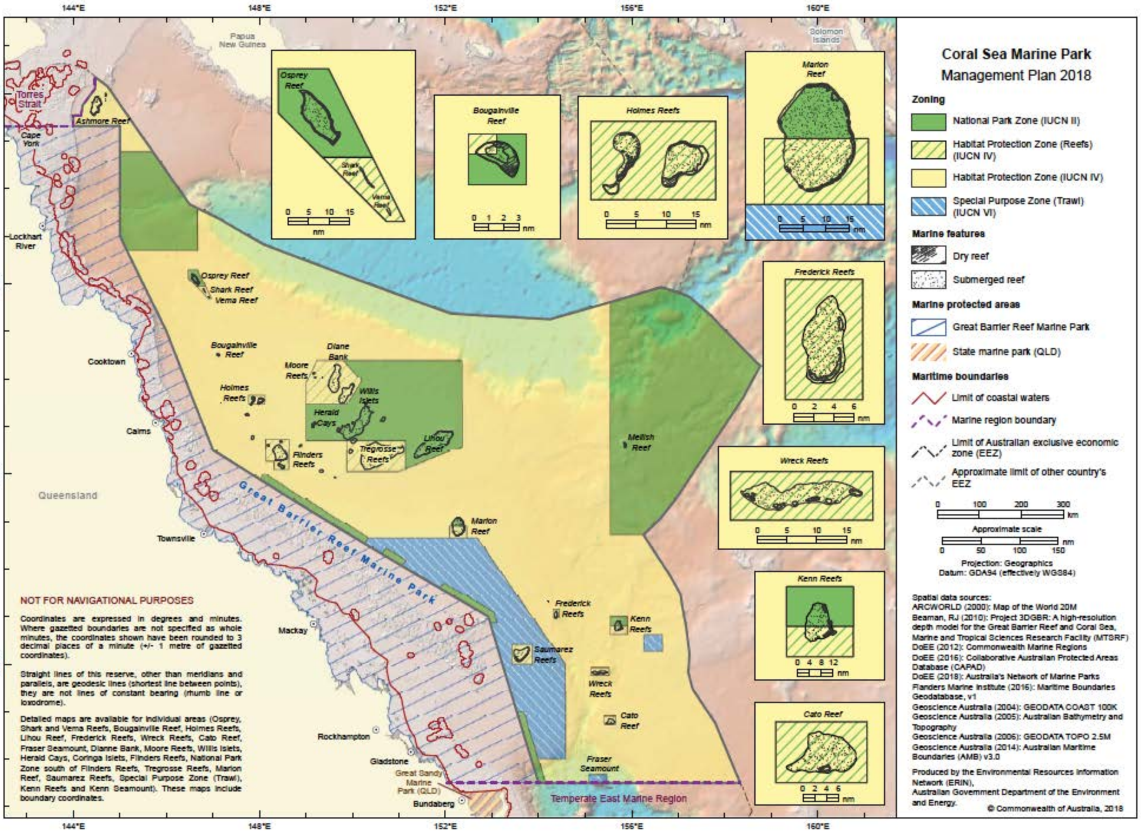


Figure 2.1 Map of the Coral Sea Marine Park, showing management zones implemented in July 2018. (Source: parksaustralia.gov.au)

Unlike the more inter-connected barrier and fringing reefs of the GBRMP that arise from relatively shallow waters of the continental shelf, 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 (Davies et al.1989; Collot et al. 2011). The nature of these shallow water (<20m) CSMP reef habitats are relatively well understood, and have been shown to support unique coral and reef fish communities that are distinct from those of the adjacent GBRMP (Hoey et al. 2020), a high diversity of reef fish (>600 species) and high abundance and biomass of sharks and other large predatory fishes (Ceccarelli et al. 2013; Stuart-Smith et al. 2013; Hoey et al. 2020, 2021, 2022). Coral cover on many shallow reef habitats 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) and is likely related to repeated exposure to disturbance (i.e., severe tropical cyclones and more recently climate-induced coral bleaching; Ceccarelli et al. 2013; Harrison et al. 2019; Hoey et al. 2020, 2021, 2022).

Given that individual CSMP reefs are separated by oceanic waters up to 4,000 m deep (DNP 2018), there are considerable coral reef habitats below depths that are readily accessible by divers using SCUBA (i.e., >30m). Australian coral reefs have been extensively studied for nearly 100 years but nearly all research has focused on shallow coral reefs in near-coastal waters (Eyal et al. 2021). There is a pressing need to understand the full continuum of coral reef ecosystems and functions in a rapidly changing global environment, in particular those below the well-lit and well-studied shallow waters of Australia’s extensive coral reef ecosystems, including those of the CSMP. Advances in technology and growing recognition that `Australia’s mesophotic coral ecosystems are understudied and underexplored` (Eyal et al. 2021) are prompting targeted research efforts to ‘*dive into the deep*’ and expand our knowledge of these unique mesophotic habitats.

2.2 *Mesophotic coral ecosystems*

Mesophotic (meaning ‘middle light’) coral ecosystems (MCEs) are the deeper extensions of shallow coral reef habitats and are generally defined as occurring from depths of 30 m to 150 m (Lesser et al. 2009). They are characterised by the presence of zooxanthellate scleractinian corals and, like shallow coral reefs, are light-dependent ecosystems. Within MCE’s several key environmental variables, namely light and temperature, covary with water depth. These variables, together with depth and shifts in ecological communities, are commonly used to define zones within MCEs from the well-lit shallows into low-light adapted deep reef habitats (Figure 2.2).

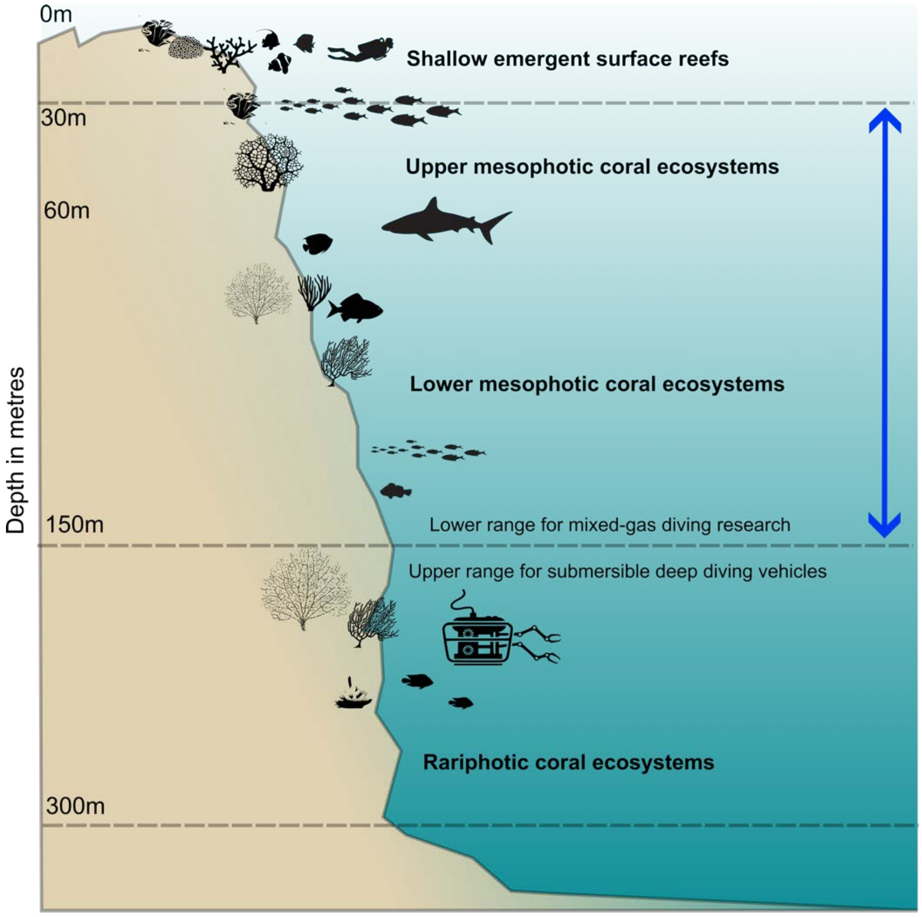


Figure 2.2 – Depth zonation of coral reef habitats. Shallow coral reefs found at 0 -30m, upper mesophotic coral ecosystems ~ 30-60m, lower mesophotic coral ecosystems ~60 - 150m and rariphotic coral ecosystems at ~ 150 – 300m. The blue line indicates the broadly accepted depth range for mesophotic coral ecosystems between 30 -150m.

Shallow coral reef communities occupy the altiphotic (“high light”) zone between 0 - 30m, are readily accessed by divers using SCUBA, and as such have been the subject of the vast majority of ecological research and monitoring on the coral reefs globally (Pyle and Copus 2019). This zone typically coincides with the highest reported diversity of scleractininan corals and reef fishes (e.g., Huston 1985; Brokovich et al. 2008). Beyond 30m, communities transition into the mesophotic (“middle light”) zone from 30-150m (Tamir et al. 2019), the rariphotic (“scarce light”) zone (150-300m) which is the final component of the depth continuum for tropical reef taxa, before descending into the aphotic (“no light”) deep sea (>300m; Baldwin et al., 2018). At times referred to as the “twilight zone”, MCE’s are often divided into upper, middle and lower mesophotic zones, based on the occurrence of community breaks and assemblage shifts (Lesser et al. 2019; Pinheiro et al. 2016). Upper mesophotic reefs (30-60 m) are commonly taxonomically and functionally similar to adjacent shallow (<30 m) reefs, sharing many species, and benthic assemblages are typically dominated by phototrophic taxa (Loya et al. 2016). With increasing depth (i.e., >60m) lower mesophotic reefs represent distinct ecosystems where there is typically a community shift towards depth specialist species that do not occur on shallow coral reefs, and benthic assemblages are characterised by decreases in phototrophic and increases in heterotrophic taxa (Kahng et al. 2017).

Given the current global coral reef crisis driven by the increasing frequency, intensity and diversity of disturbances affecting shallow water reefs (Bellwood et al. 2004; Hughes et al. 2017, 2018), it is frequently hypothesised that MCEs may act as refugia for shallow water species (Lesser et al. 2009, Bongaerts et al. 2011, MacDonald et al. 2016). The key premise of this hypothesis is that reef communities extend into mesophotic depths, these deeper communities are less vulnerable to increasing environmental stressors, and share taxa with and could ultimately provide propagules to replenish shallow populations and communities. Whilst MCEs do share some species with shallow reef ecosystems, there are many reef taxa found exclusively in either deep or shallow reef habitats. Further, although MCEs may be buffered to some degree from threats associated with global climate change, overfishing and extreme storm events (e.g., Bongaerts et al. 2010; Perez-Rosales et al. 2021; but see Rocha et al. 2018), there is significant regional variation in the nature and extent of these stressors on MCEs. To assess how changing global environmental conditions may affect deeper reefs and the level of connectivity between shallow and deep coral ecosystems, considerably more research and exploration of MCEs is required globally.

MCEs are estimated to represent close to 80% of all available global coral reef habitat, yet our knowledge of MCE’s is in its infancy with the vast majority (70%) of studies on MCEs being published in the last 10 years (Pyle and Copus 2019). Although MCEs occur across all tropical and some sub-tropical regions of the world, they remain poorly studied and explored due to the logistical challenges of conventional marine scientific survey techniques by SCUBA divers (Kahng et al.

2010; Eyal et al. 2021). This is particularly true for remote, yet unique and highly diverse, reef systems like those within the CSMP.

2.2.1 Mesophotic coral ecosystems within the CSMP

The reefs of the CSMP are situated on top of seamounts on two main plateaus (Figure 2.3). The Marion Plateau in the south of the CSMP supports six major reef systems (Marion, Saumarez, Frederick, Kenn, Wreck and Cato Reefs) and the Queensland Plateau to the north supports reef systems with ~30 individual reefs (Bridge et al. 2019). In the most northerly reaches of the CSMP, the Boot-Ashmore-Portlock reef complex are a group of detached reefs that have formed on pinnacles of continental crust, rising from the Ashmore Trough (Davis 2011). Shallow reefs within the CSMP rise from considerable depths, and have a combined reef area of 15,024 km^2; equating to 1.5% of the total CSMP area (DNP 2018). Multiple sites supporting mesophotic coral ecosystems (> 30m) have also been recently confirmed within the CSMP (e.g., Bongaerts et al. 2011; Muir et al. 2015; Englebert et al. 2017), however, these have focused on a limited number of CSMP reefs. The true extent of MCE's within the CSMP, and the communities they support, is largely unknown. Given the geomorphology of the Coral Sea, the spatial extent of MCEs within the CSMP is likely significant, and would therefore substantially increase the total area of coral reef habitat in the Marine Park.

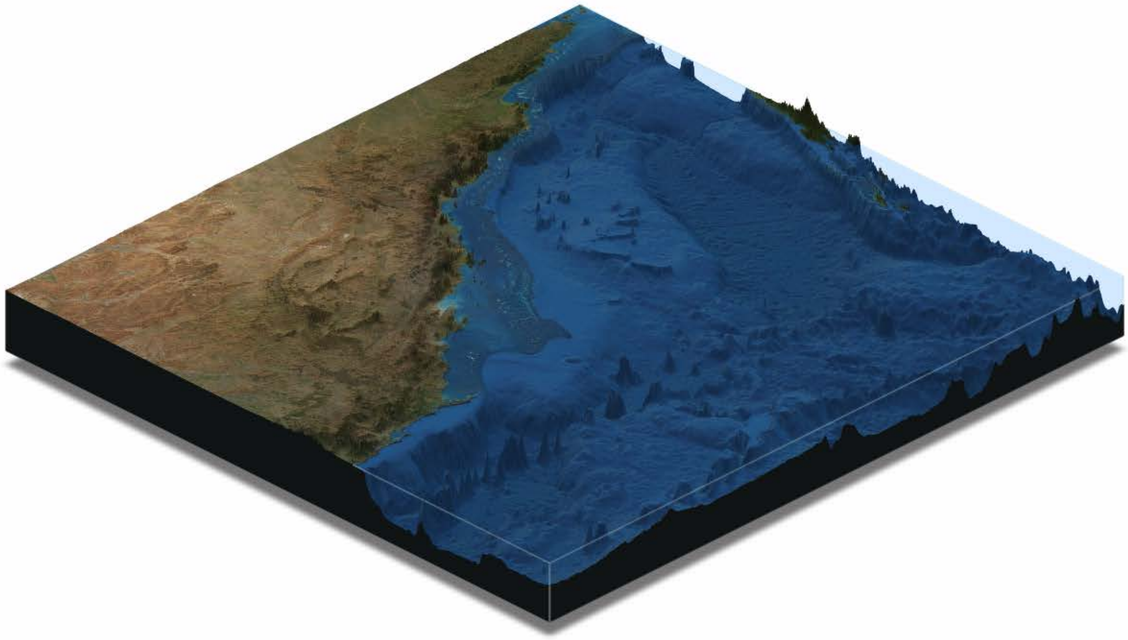


Figure 2.3 – Three-dimensional bathymetric map of the Coral Sea and Great Barrier Reef region

To date, the vast majority of research of MCE’s within the CSMP has been spatially and/or taxonomically restricted, focusing on select taxa and/or a limited number of sites. Most studies have focused on benthic organisms and MCEs have typically been found to be dominated by hard corals (Scleractinia), soft corals and gorgonians (Octocoralia) and/or the green calcifying macroalga *Halimeda* (Bongaerts et al. 2011; Englebert et al. 2015, 2017; Bridge et al. 2019). Recent hydrographic survey efforts to map the seafloor at depths of 80 – 2,800 m have considerably expanded bathymetric knowledge of many reefs within the CSMP and provided novel qualitative data (i.e., observations) of deep reef ecosystems (Beaman 2020; Beaman et al. 2022). There has, however, been relative few quantitative assessments of MCE’s and other deep-water ecosystems within the CSMP. Most CSMP reefs remain poorly documented at depths greater than 30m, and their diverse morphologies and oceanic seascape position mean there are also large areas of deep lagoonal habitat and isolated submerged bathymetric features (e.g., bommies, terraces and banks) that are also yet to be explored.

Another key feature of reefs within the CSMP is their isolation. Unlike the highly connected reefs of the GBRMP, reefs within the CSMP are separated from other reefs by 10's-100's km of deep oceanic waters. Such isolation has important implications for genetic and ecological connectivity among reefs, limiting the supply of marine larvae among reefs. For example, a reliance on self-recruitment on isolated reefs has been shown to lead to protracted recovery of coral assemblages following disturbance (e.g., Scott Reef, Gilmour et al. 2013). Similarly, the large expanses of deep water separating reefs within the CSMP is likely to limit the movements of animals among reefs. Animal movements between and within habitats significantly influence biological interactions and ecological processes across broad spatial and temporal scales (Jelsch et al. 2013). One of the only studies to have investigated animal movements within the CSMP found the majority of reef sharks (whitetip reef sharks *Triaenodon obesus*, and grey reef sharks *Carcharhinus amblyrhynchos*) at Osprey Reef, a steep-sided seamount in the northern CSMP, were highly site attached, although some grey reef sharks and a silvertip shark *Carcharhinus albimarginatus* were detected to have moved ~15km across open water to Shark Reef (Barnett et al. 2012). How marine species use and move within and among reefs of the CSMP, and the adjacent GBRMP, are fundamental to understanding the connectivity of reef habitats, and thereby informing marine park management.

There is growing evidence to suggest that MCEs do not conform to major biogeographic patterns described for shallow coral reefs and that MCEs harbor proportionally more endemic species than shallow coral reefs (Pyle and Copus 2019). Given that the shallow water habitats of the CSMP have been shown to support unique coral and reef fish communities that are distinct from those of the GBRMP (Hoey et al. 2020), MCE's are a particularly pertinent knowledge gap for the region that requires a combination of approaches, expertise and technologies.

2.3 Remote sampling technology

Video-based remote sampling methods are increasingly being used by marine scientists to obtain quantitative data on benthic habitats, species abundance, assemblage composition, body size distributions and behavior (Goetze et al. 2019). This is particularly true of remote, deep-water habitats which present considerable challenges compared to shallow-water *in-situ* survey methods. Remote video-based sampling also enhances the ability to sample rare or diver-negative (i.e., shy) species (Willis and Babcock 2000), is non-destructive in its application, provides a permanent record of survey data, and can generate video footage and still images for effective science communication (Langlois et al. 2020).

Baited Remote Underwater Video Systems (BRUVS) are one of the most widely used forms of remote video-sampling technologies. Briefly, a BRUV consists of a weighted base frame with a forward mounted camera housing and a container containing bait (e.g., crushed pilchards) fixed in front of the camera. BRUVS are particularly effective at capturing data on large predatory fishes, such as fisheries target species and sharks, that are attracted to the bait (Harvey et al. 2007). However, there are limitations in using BRUVS, as they provide only an estimate of relative abundance, can be influenced by current direction and speed, and hence dispersal of bait plume, and only provide a snapshot of benthic communities.

Another emerging video technology, Remotely Operated Vehicles (ROVs), are being increasingly trialed and used to survey marine habitats and communities in areas and depth that are inaccessible to divers or where steep bathymetry prevents the use of static video stations (i.e., BRUVS). ROVs are tethered underwater robots (or drones), typically equipped with cameras and other environmental sensors. Like BRUVS, ROVs offer the advantage of being operated at depths greater than the limit of scientific diving, are non-destructive and provide permanent survey records (i.e., video and/or still imagery). Unlike BRUVs, however, the mobile and unbaited nature of ROVs allow for the survey of fish (and benthic) communities that are more akin to in-situ visual surveys by divers (Jessop et al. 2022). This generates further opportunity to compare shallow and deep water communities, following sufficient validation. ROVs are also capable of covering considerable distances in a relatively short period of time providing a rapid method of habitat and community assessment (i.e., multiple transects at multiple depths can be completed in a single dive).

2.4 Movement ecology and tracking technology

Acoustic telemetry is one of the principal methods used to track the movement of marine animals (Matley et al. 2022). Historically, scientific methods used to quantify and understand animal movements relied on mark-recapture techniques. The development of acoustic technologies have, however, enabled the tracking of animals in environments that were not conducive to mark-recapture techniques, while also providing greater resolution of animal movements across expanded spatial and temporal scales. Broadly speaking, acoustic telemetry involves acoustic transmitters (or tags) that are implanted or attached to animals (the size and mode of attachment being dependent on animal size, behavior and the nature of the study), and a network (or array) of acoustic receivers that detect and record the presence of a tagged animal within the vicinity of each receiver. Acoustic telemetry has been used to monitor animal movements over scales from hundreds of metres to hundreds of kilometres, leading to a greater understanding of habitat use, home range size, migratory patterns, and the effectiveness of marine protected areas for certain species (IMOS 2022).

2.5 Objectives and scope

The CSMP 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).

Yet, little is known about deep habitats in the CSMP, and the ecological communities they support. The objective of this project was to describe and explore the unique deep-water (>30m) habitats and ecological communities of the CSMP, and the potential ecological connectivity within and among CSMP reefs, and between reefs of the CSMP and GBRMP. This project used an effective combination of BRUV, ROV and acoustic telemetry technology to collect ecological and environmental data for a range of species and a diverse seascape of deep-water habitats.

Data attained from BRUV and ROV surveys at 15 reefs throughout the CSMP at depths between 30 -100m provided qualitative information on spatial and depth-related patterns in:

i) size, abundance and composition of reef fish assemblages, including mobile predator species and reef-associated species
ii) patterns of reef fish biodiversity, including new depth and spatial range extensions, based on species lists global observation data sets and established shallow water monitoring surveys,
iii) benthic cover and composition, including the percentage cover for hard (Scleractinian) and soft (Alcyonarian) corals, macroalgae, and other sessile organisms,
iv) structural complexity of reef habitats,
v) environmental data on depth-gradient temperature profiles and the presences of marine debris,

An array of 19 acoustic receivers were deployed at four CSMP reefs in Feb 2021: Flinders (6), Holmes (4), Bougainville (2) and Osprey (7), and a total of 112 animals tagged on these four CSMP reefs. Detection data recorded by the receiver arrays aimed to provide information on:

vi) inter- and intra-reef movements of sharks and teleost fishes,
vii) residency patterns of large mobile predators
viii) movement of animals not tagged in this project in and around the CSMP

As well as the objectives and scope listed above, additional opportunities were leveraged from the partnership between James Cook University and Parks Australia and/or capitalised on available vessel space during the voyages. These leveraged opportunities include:

ix) An additional 7 acoustic receivers installed at Osprey reef in October 2021, 27 of the total animals tagged were part of a PhD project investigating vertical movements of reef fish in response to water temperatures (Ben Cresswell, James Cook University);
x) Additional ROV and BRUV surveys conducted on voyages as part of the Coral Reef Health and Island Health projects in the CSMP;
xi) Access to satellite tag data for large animals (sharks and manta rays) that were tagged in regions adjacent to the CSMP.

3 Methods

3.1 Sampling design

Diving into the Deep

81 days at sea

16 reefs - 46 sites

25 km^2 of ROV surveys

70 BRUV drops

112 fish and sharks tagged

Video surveys (ROV and BRUV) and tagging were conducted during four voyages. The first a 21-day voyage (Feb – March 2021) as part of the CSMP 2021 Coral Reef Health project, the second a 17-day voyage (July 2021) as part of the CSMP Island Health project, the third a 15-day voyage (October-November 2021) directly funded by this project, and the final voyage a 28-day voyage (Feb 2022) CSMP 2022 Coral Reef Health project. Video surveys were conducted across a total of 46 sites at 16 reefs in the CSMP.

3.1.1 ROV and BRUV Surveys

ROV surveys were undertaken at 28 sites across 15 reefs; Saumarez, Wreck, Kenn, Marion, Lihou, Flinders, Frederick, Holmes, Bougainville, Osprey, and Herald's Surprise Reefs, Chilcott, Diamond, and Willis Islets, and Herald Cays. Analyses of the surveys from Diamond Islet are ongoing and are not included in this report. BRUV surveys were conducted at 18 sites across 11 reefs; Saumarez, Wreck, Kenn, Marion, Lihou, Flinders (north and south), Holmes and Ashmore Reefs, Chilcott and Willis Islets, and Herald Cays (Figure 3.1). No BRUV drops were possible at either Bougainville or Osprey reefs due to their steep sided morphologies and the prevailing sea conditions at the time of the survey.

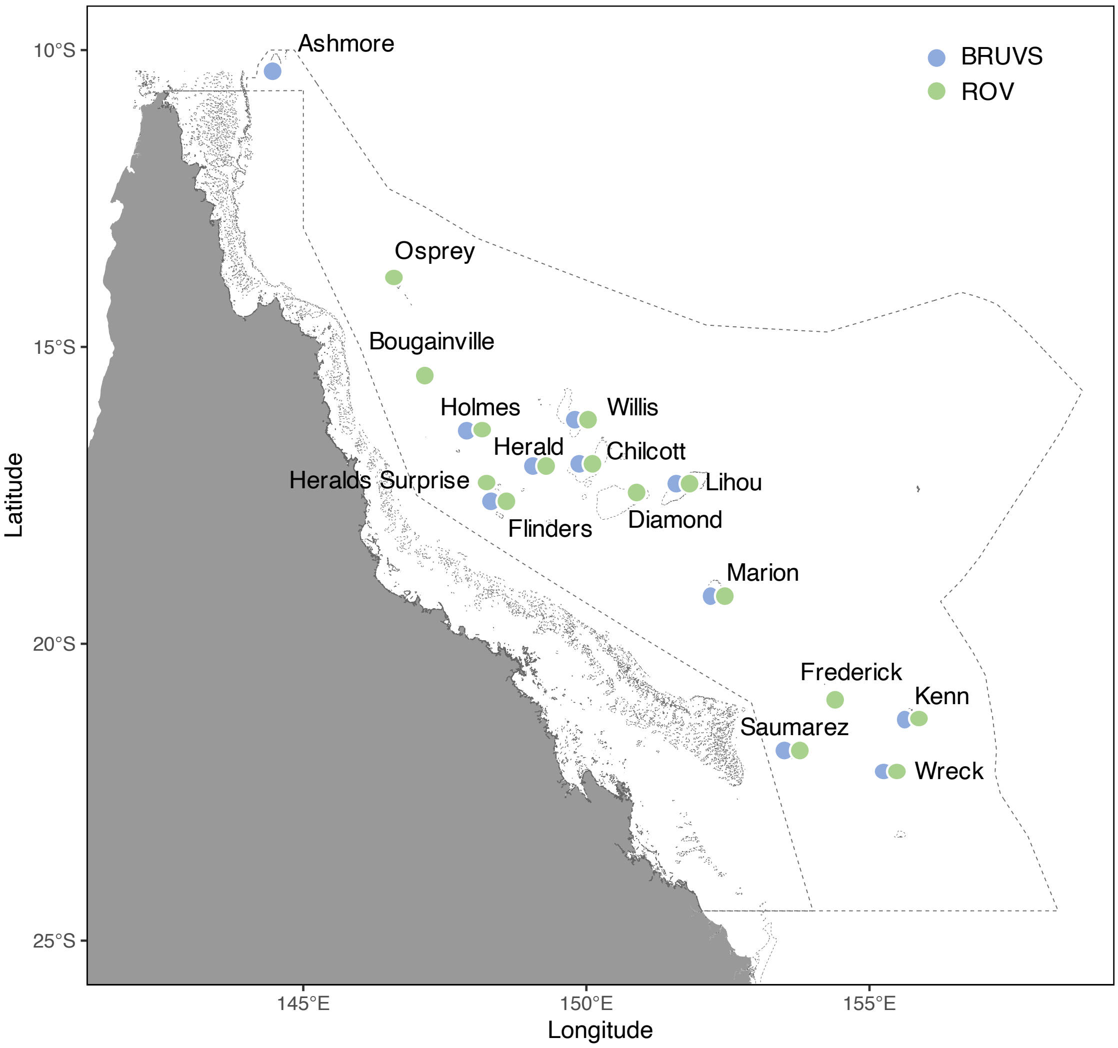


Figure 3.1 - Map of 16 reefs within the Coral Sea Marine Park that were surveyed using Remotely Operated Vehicles (ROV) and Baited Remote Underwater Video (BRUV) during four voyages from February 2021 – February 2022.

At each reef, ROV and/or BRUV survey sites were selected based on proximity to shallow reef monitoring sites (Hoey et al. 2020, 2021, 2022) and the feasibility of deploying, piloting (ROV only) and retrieving survey equipment given the prevailing sea and weather conditions. For lagoon surveys, sites were selected based on bathymetric charts to enable surveys below 30m in these habitats. Individual sites were marked with a handheld GPS and the habitat type classified as one of four broad categories: “channel”, “outer reef”, “inner reef” or “lagoon”.

3.2 ROV configurations and operations

All deep-habitat transect surveys were conducted using a BlueROV 2 high-performance underwater ROV. The ROV was constructed with an 8-thruster vectored configuration and 2 high-powered lumen Subsea lights. In addition to the onboard high-definition (1080p, 30fps), wide-angle, low-light optimized camera that was used for piloting the ROV, we also fitted the ROV with a custom-designed forward-facing Stereo-Video System (SVS) to allow fish communities to be surveyed. Stereo-video surveys are an established sampling technique used to collect species, abundance and size measurements on marine assemblages from video footage and photo stills (Goteze et al. 2019). We used two Paralenz + dive cameras, calibrated as a SVS prior to each voyage using the specialist software “CAL” and “EventMeasure” (SeaGis Pty, Australia). The cameras were mounted to the ROV facing forward and recorded each transect conducted by the ROV. The inclusion of the SVS to the ROV survey methodology allowed for length (fork length, FL) of each fish on the video footage to be estimated. The length data was then used to calculate fish biomass using known length-weight relationships for each species.

Additionally, during the second voyage for this project (July 2021), a time-lapse benthic camera system was developed, tested and implemented. This consisted of three GoPro Hero 7 action cameras inside deep rated aluminum T-housings. Two cameras were mounted on the left and right side of the ROV to allow the benthic communities on steep habitats (i.e., walls) to be photographed, and one camera mounted facing downwards on the ROV payload skid to allow the benthic assemblages on relatively flat, or horizontal, habitats to be photographed. The cameras were set to take timelapse photos resulting in 5 benthic photos per transect.

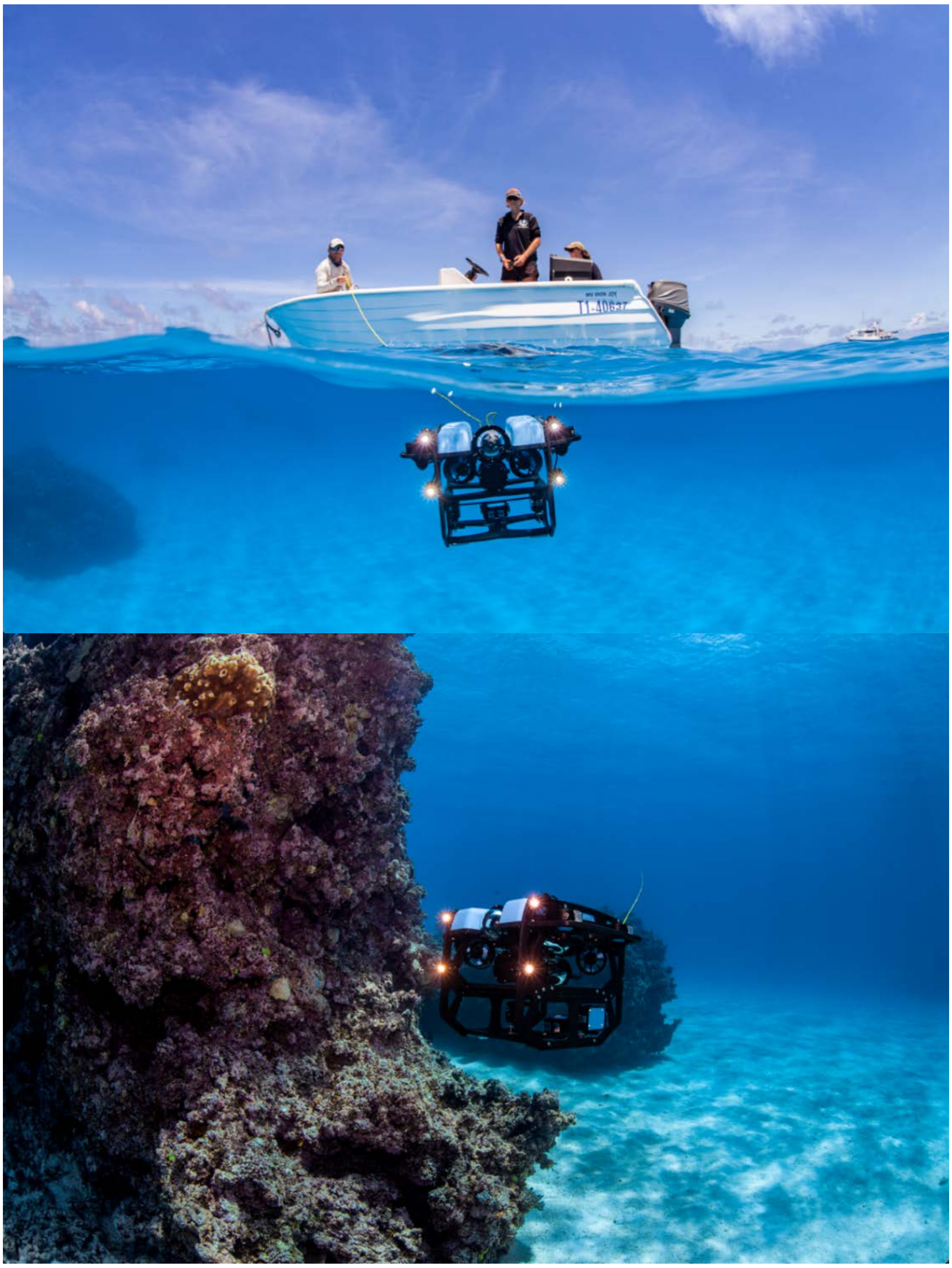


Figure 3.2 – Photographs showing the operation of the Remotely Operated Vehicle (ROV) from a tender to the *MV Iron Joy* in the Coral Sea Marine Park. Top: The ROV being deployed from the tender with the operator (Gemma Galbraith, standing) piloting the ROV, while an assistant manages the tether (Ben Cresswell). Bottom: The ROV navigating around a shallow bommie. Image credits: Victor Huertas

The ROV was deployed, piloted and retrieved from a tender deployed from the main vessel (Figure 3.2). At each site, the ROV was deployed and descended to the maximum depth possible depending on the habitat type, sea conditions, and maximum depth rating of the ROV (i.e. 100m). Once at the target depth the ROV was positioned ~0.5m above the substratum (or alongside for vertical reef walls), and two timed transects were conducted at a constant depth. Each transect was 2.5 minutes long and by travelling at a known speed of 0.2m/s^{-1}, equated to a distance of approximately 30m. Transects within each depth band were separated horizontally by 5-10m. After the second transect, the ROV ascended by 5 -10m and two more transects were conducted at this depth in the opposite direction to the previous two transects (i.e., at the depth band immediately below). This survey pattern was repeated at ~10m depth bands until the two final transects were conducted in the upper 10m (Figure 3.3).

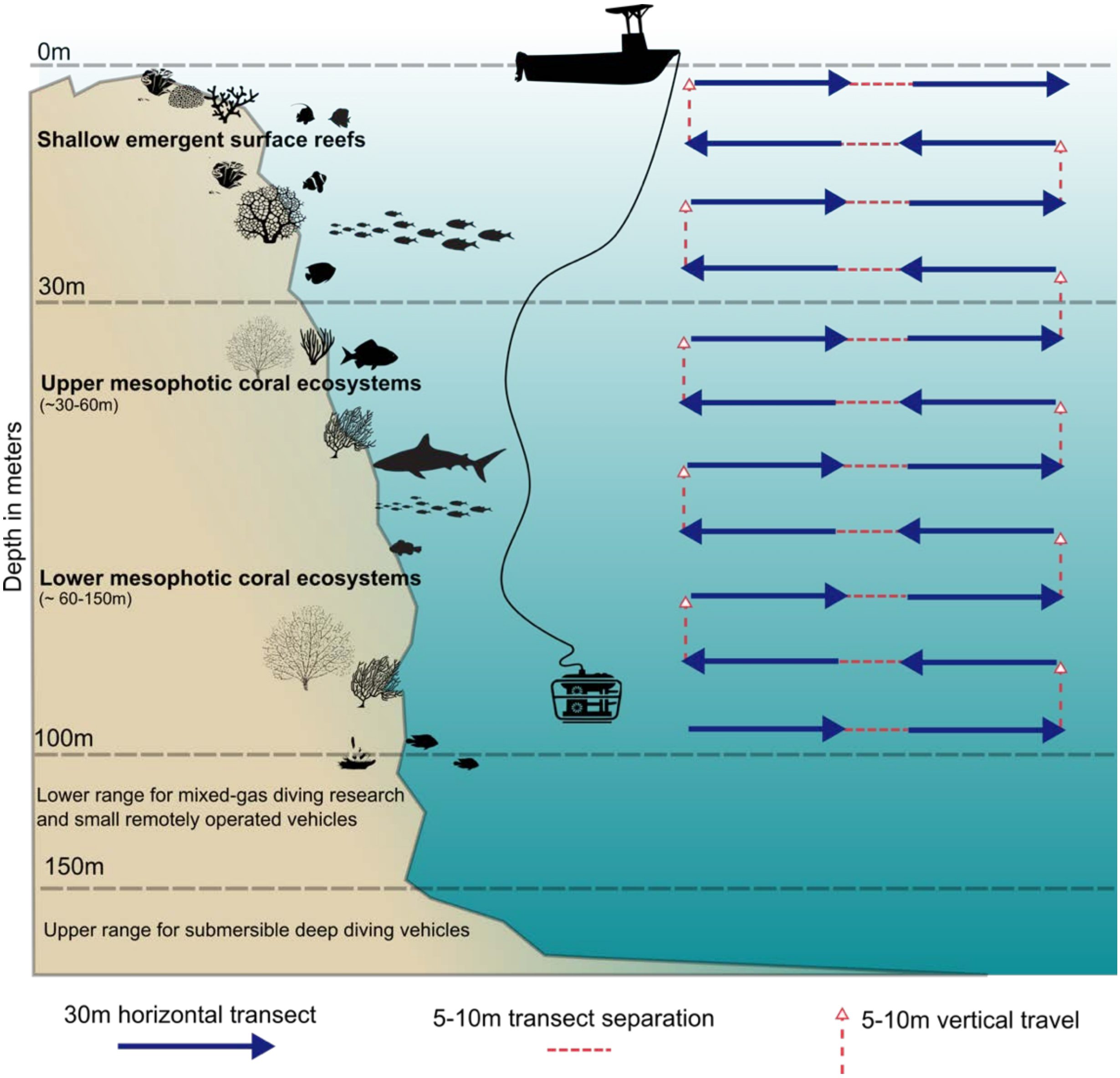


Figure 3.3 – Remotely Operated Vehicle (ROV) transect survey methodology used to survey fish and benthic communities in the Coral Sea Marine Park. All ROV surveys were conducted at depths between 5 – 100m using the BlueRobotics BlueRov2.

3.3 BRUV configuration and operations

All BRUVS used in this project were constructed by SeaGis (SeaGIS Pty Ltd, Australia). Each system consisted of a weighted frame, waterproof camera housing, bait arm and bait bag (Figure 3.4). GoPro Hero7 cameras were used in each BRUV and set to 1080 resolution, 60fps and medium field of view. 1kg of frozen pilchards was used as bait for each drop. Bait was thawed and crushed prior to surveys and placed in the mesh bag positioned 1.2m from the camera by the bait arm. BRUVS were deployed from a tender to the main vessel between daylight hours of 0800 and 1600. Individual BRUV drops at a given site were separated by at least 500m to reduce the likelihood of non-independence due to individual animals being sampled by adjacent BRUV systems (Langlois et al. 2020). Each BRUV was set for at least 1hr, starting from the time the system reached the seafloor. BRUVS were recovered by hand-hauling or using a lightweight pot-hauler fitted to the tender. In areas of high current speed or deeper sites, additional ballast, floats and rope were used to stabilize the unit on the seafloor and ensure successful recovery.

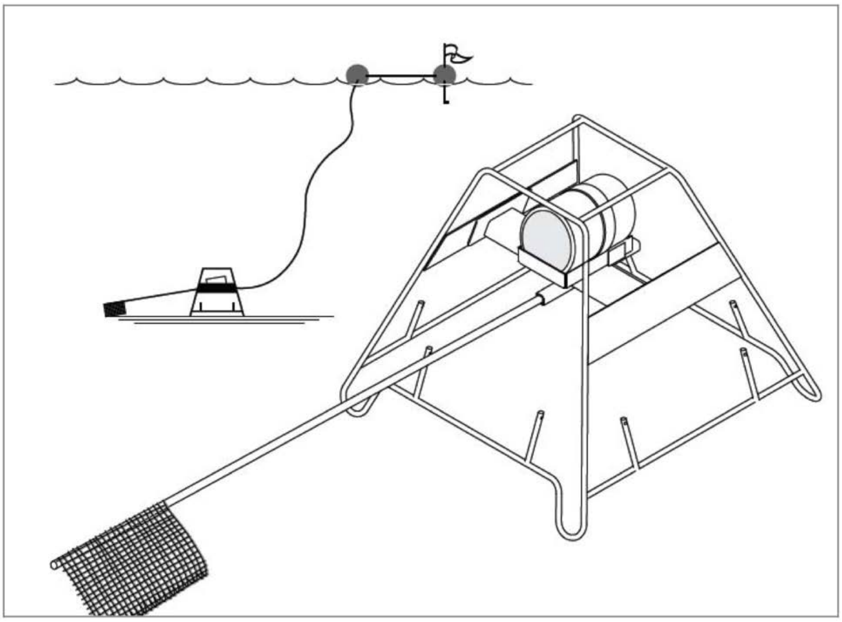


Figure 3.4 – The design of Baited Remote Underwater Video System (BRUVS) and tether-float setup used in this study, as developed by the Australian Institute of Marine Science (AIMS) (Image from Stowar et al. 2008).

3.4 Acoustic receiver array

An array of 19 VEMCO VR2 acoustic receivers was deployed across four CSMP reefs, to study animal connectivity between locations. At each reef, representative sites were chosen based on previous studies, the presence and abundance of sharks and large fishes, and proximity to established dive tourism sites (to enable receivers to be retrieved and maintained via tourist vessels if required). For example, Osprey Reef previously had an acoustic array deployed for 15 months (Barnett et al. 2012), which provided information on the key sites used by some shark species. Seven receivers were therefore deployed at those sites, including three receivers that extended from the lagoon entrance into the lagoon, to detect the movements of animals into and out of the lagoon. Deployments at other reefs included six receivers at Flinders Reef, four at Holmes Reef, and two at Bougainville Reef (Figure 3.5). Complementing this array on the four CSMP reefs, there are currently >300 acoustic receivers deployed along the Queensland coast (Figure 3.6) allowing for movements between the CSMP and GBRMP to be investigated.

In reef areas, the acoustic receivers were moored to dead reef or to rocks using a chain, to which receivers were tied with a rope and suspended above the reef with a subsurface buoy that was positioned approximately 1.5m above the reef. In sandy areas, star pickets were hammered into the sand, and receivers attached to the top of the star pickets with cable ties so that the receiver was position 1-1.5m above the substratum. Acoustic receivers were deployed in February 2021, and retrieved, downloaded and redeployed in February 2022.

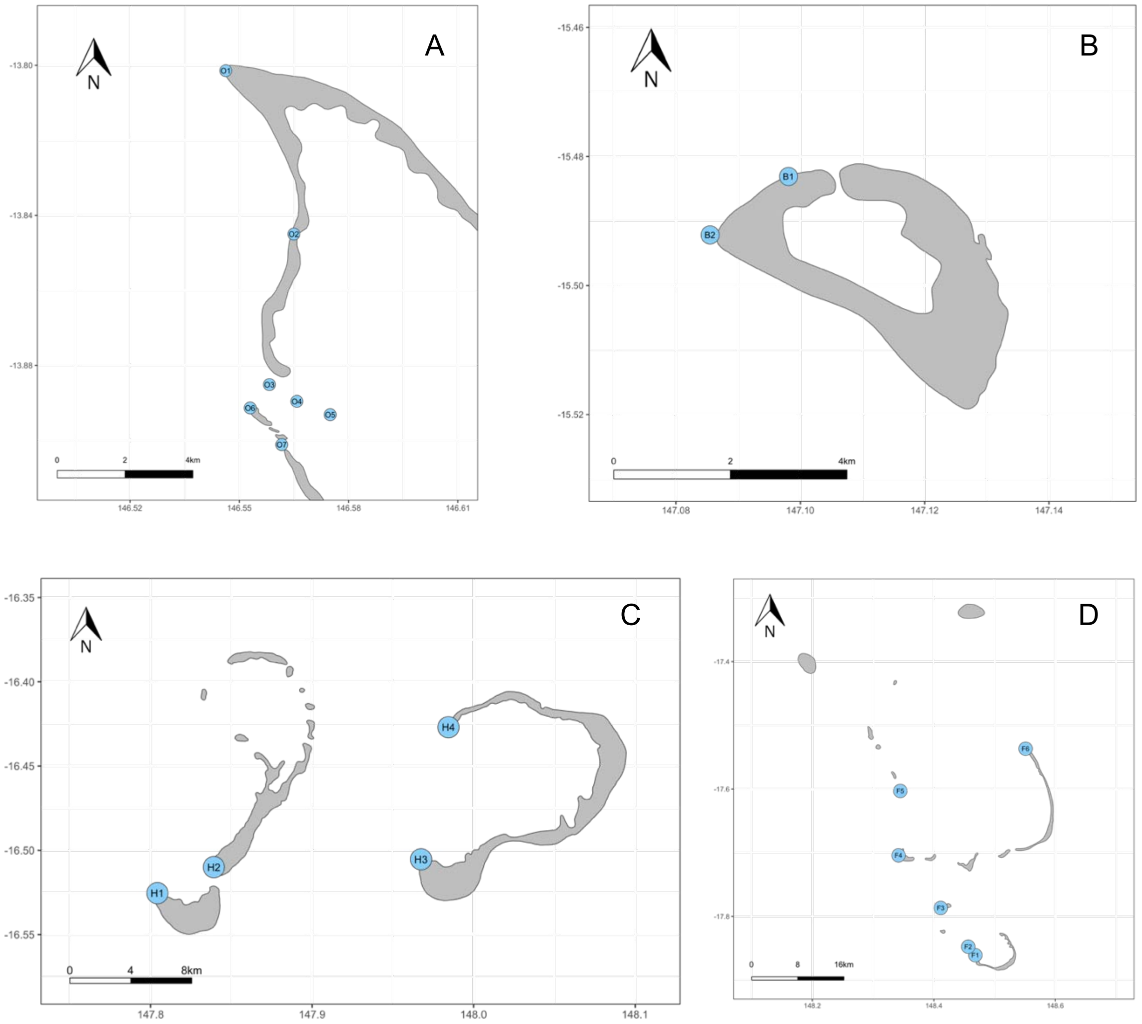


Figure 3.5 Maps of A. Osprey Reef, B. Bougainville Reef C. Holmes Reef and D. Flinders Reef, in the Coral Sea Marine Park showing the deployment locations of the acoustic receivers at each reef.

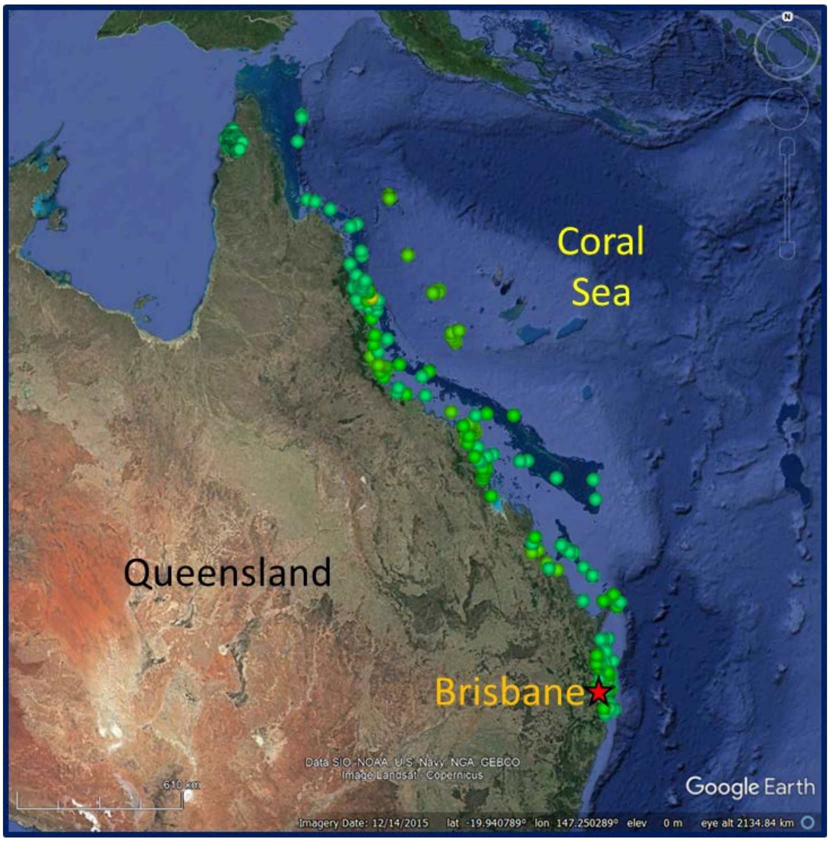


Figure 3.6 A map showing the location of acoustic receivers (green circles) along the Queensland coast as part of the Integrated Marine Observing System (IMOS) Queensland acoustic telemetry array project. The project is funded by the Department of Environment and Science, Queensland and operated by the Australian Institute of Marine Science.

3.5 Animal tagging methods

Grey reef (*Carcharhinus amblyrhynchos*) and silvertip (*C. albimarginatus*) sharks were targeted for acoustic tagging as they are relatively common on CSMP reefs (e.g., Hoey et al. 2020), and given their body size and mobility were the ideal candidate species to investigate movement within and among reefs. Sharks were captured on hook and line, brought alongside the vessel, and an acoustic transmitter (VEMCO, Nova Scotia, Canada) was surgically implanted into the peritoneal cavity through a small incision, which was then closed with surgical sutures. Acoustic transmitters used on sharks were mostly V16-6H, but 15 *C. amblyrhynchos* were tagged with dual sensor tags, V16TP-4H. To avoid tagging the same animals twice, sharks were also tagged with external identification tags (Drovers, Australia) with unique numbers allowing individual identification.

Several species of bony fishes, namely giant trevally (*Caranx ignobilis*), black trevally (*C. lugubris*) and blue-spot coral trout (*Plectropomus laevis*) were also targeted for acoustic tagging at Osprey Reef. Fish were captured with hook and line and placed into an aerated holding tank with diluted anaesthetic (Aquis ms-222), where they were held until loss of equilibrium indicated effective anaesthesia. Once anaesthetised, V13-1H or V13TP-1H dual sensor acoustic transmitters were surgically implanted into the peritoneal cavity through a small incision, which was then closed with surgical sutures. Ambient water was continuously flushed across the gills during surgery, using a hose connected to a bilge pump. Post-surgery, fish were transferred to a recovery pen attached to the side of the vessel to allow them to recover from the surgery. Fish were monitored and released a few minutes after regaining equilibrium (Baker et al. 2018).

3.5.1 Satellite tagging

Together with the tracking of sharks and fishes using acoustic telemetry, this project was able to gain access to satellite tracking for several animals that were tagged outside the CSMP, but subsequently moved in the CSMP. Two satellite tag models were used for these animals: smart position and temperature (SPOT) transmitting tags, and pop-up satellite archival tags (PSAT) (Wildlife Computers, Redmond, Washington, USA). SPOT tags were used on two species of shark, tiger sharks and whale sharks. For tiger sharks (*Galeocerdo cuvier*), SPOT tags were attached to the first dorsal fin by four 5 mm diameter threaded nylon rods that were passed through the fin and secured on the other side by washers and nuts. Most tiger sharks also had an acoustic tag surgically implanted into the peritoneal cavity following the methods described above. For whale sharks (*Rhincodon typus*), custom-designed clamps that hold the SPOT tags were attached to the first dorsal fin of free-swimming sharks. The position of the transmitter on the fin was such that the antenna of the tag extended out of the water when the fin broke the surface.

Pop-up satellite archival transmitters (PSATs) (Wildlife computers, Redmond, Washington, USA) were used on manta rays. The transmitters were attached to free-swimming animals using a modified Hawaiian sling and a purpose-built tag adaptor and tag anchor, which were shot into the back quarter of the wing, on the dorsal surface of the animal. PSATs were programmed to detach after 6 months.

3.6 Video analyses

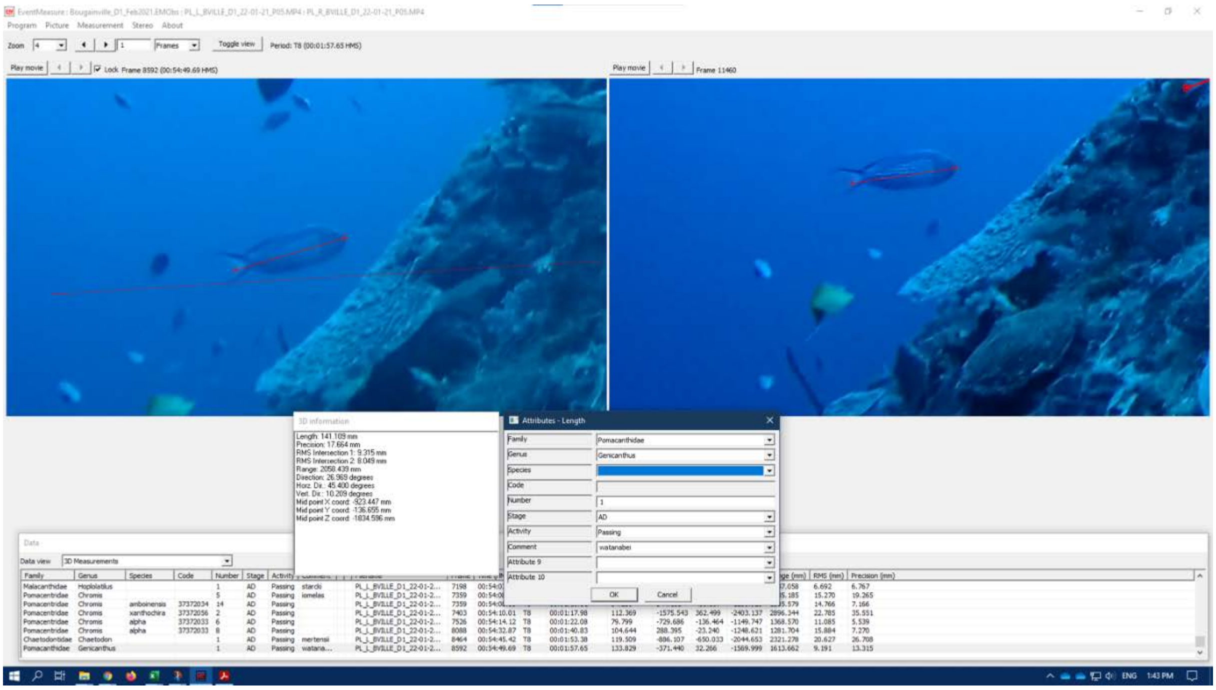
Video surveys from the BRUVs and ROV were analysed in the specialised software EventMeasure, EventMeasure Stereo and TransectMeasure (SeaGis Pty Ltd, Australia). Videos were interrogated by reef fish ecologists with both *in-situ* underwater visual survey experience and experience identifying fishes from video surveys.

3.6.1 Coral Reef Fishes

For BRUV surveys, 1 hour of video footage was viewed, starting 1 minute after the BRUV camera system arrived on the seabed to allow the fish community to resettle after the deployment. This 60 min “soak time” has been shown to effectively sample elasmobranch species (i.e., sharks and rays) in shallow coral reef habitats (Currey-Randall et al. 2020) and is the recommended duration for BRUV deployments (Langlois et al. 2020). The videos were annotated in EventMeasure, where every fish entering the field of view was identified to species and recorded. The maximum number of individuals observed in a single video frame for each species (MaxN) in each video (drop) was used as an estimate of relative abundance (Ellis and DeMartini 1994; Willis and Babcock 2000). MaxN is a well-used relative abundance metric for BRUV and other stationary video surveys as it avoids repeatedly counting the same individual, which may enter, exit and then re-enter the field of view. For the ROV, the onboard Stereo-Video-System was calibrated prior to the survey voyages using the software CAL (SeaGis Pty Ltd, Australia). Stereo-video footage from each

ROV survey was then played back in EventMeasure Stereo (SeaGis Pty Ltd, Australia). Each fish entering the transect was identified to species level and the fork length (FL) measured (the distance from the tip of the snout to end of the centre of the caudal fin) (Figure 3.7). The ability to make measurements in the video footage also allowed us to define a known transect width of 2.5m either side of the central field-of-view. ROV transects therefore approximated 30 m long by 5 m wide. For both BRUV and ROV footage, any individual fish that could not be identified to species level were recorded to genus or family.

From ROV and BRUV surveys, fish species richness, diversity (Shannon-Weiner H') and density were calculated for each drop or transect. Using length estimates obtained by ROV surveys, fish biomass estimates were calculated using the length-weight equation $W = aL^b$, where W is fish weight (g), L is fish length (cm) and a and b are species specific constants. Length-weight constants were obtained from fishbase.org (Froese and Pauly 2022) using the R library rfishbase (Boettiger et al. 2012). For individuals that could not be identified to species standardised constants for the relevant genus or family from the MERMAID database (Marine Ecological Research Management AID; www.datamermaid.org) were used. In ROV survey videos, fish length measurements were not always possible (e.g., the individual was obscured by other fauna and habitat in the frame). In these cases, we used the mean fork length of all other individuals of that species recorded on the transect as an estimate. If no other individuals of the species were recorded on the transect, the mean of all other individuals of the species across all ROV transects at that site and were used.



3D information

Length: 141.109 mm
Precision: 17.664 mm
RMS Intersection 1: 9.315 mm
RMS Intersection 2: 8.049 mm
Range: 2058.439 mm
Direction: 26.969 degrees
Horz. Dir.: 45.400 degrees
Vert. Dir.: 10.209 degrees
Mid point X coord: -923.447 mm
Mid point Y coord: -136.655 mm
Mid point Z coord: -1834.596 mm

Attributes - Length

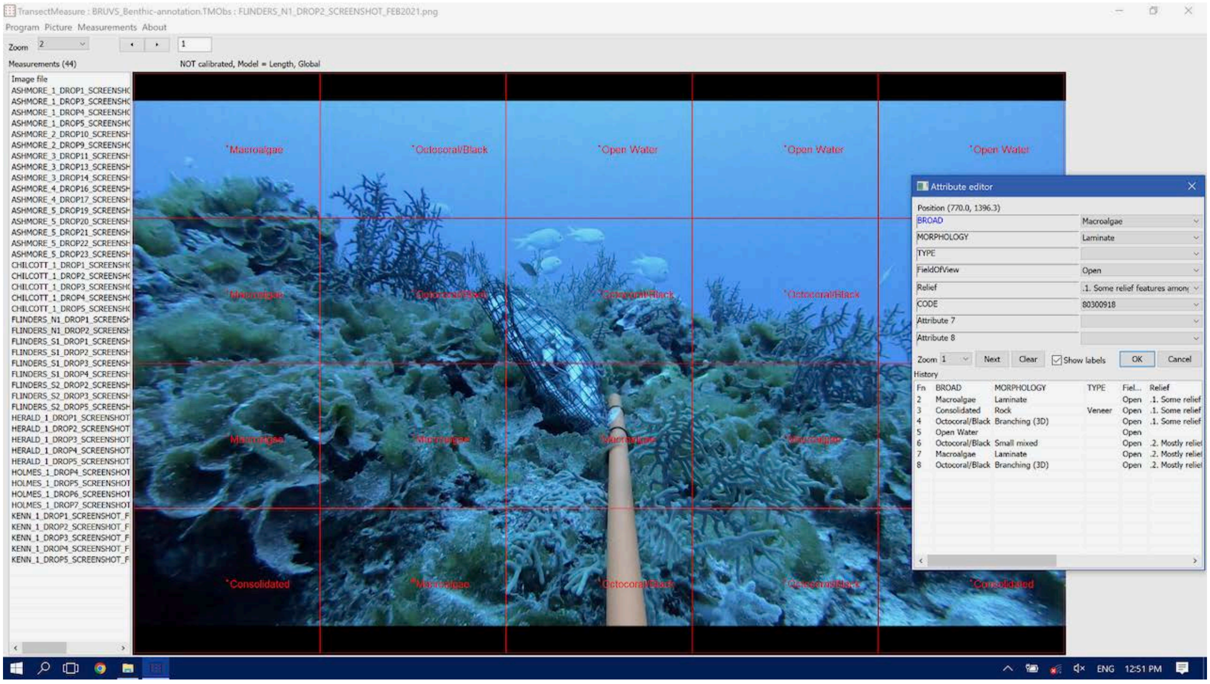
Family: Pomacanthidae
Genus: Genicanthus
Species:
Code:
Number: 1
Stage: AD
Activity: Passing
Comment: watanabei
Attribute 9:
Attribute 10:

Figure 3.7 - Screenshot of fish length measurements made in EventMeasure Stereo Software (SeaGIS Pty Ltd, Australia). The fork length of the fish in the centre of the screen, *Genicanthus watanabie,* was estimated to be 14.1cm.

3.6.2. Coral reef and benthic habitats

Benthic habitat data was obtained from both ROV and BRUV surveys. For each BRUV drop, a screenshot was taken at the beginning of the video. For ROV video surveys, five screen shots from the forward facing Paralenz cameras were taken at random intervals in each video. Each still screen shot was analysed in TransectMeasure (SeaGIS Pty Ltd, Australia) following established protocols (see Hill et al. 2014) and using predefined benthic categories. Briefly, the screen is split into 20 squares and the dominant benthic substrata in that square is identified (Figure 3.8). Benthic categories are assigned hierarchically, starting with a ‘broad’ category, further defined by ‘morphology’ and ‘type’ where applicable (e.g., Stony [Hard] coral > branching > live; Macroalgae > articulated calcareous). Categories were grouped following annotation into like-forms and substrata for ease of interpretation (Table 3.1). Classifications of ‘open water’ and ‘unknown’ substrata (due to low light or visibility, and distance of reef from camera) were removed before calculating percent benthic cover estimates for each classification. This left 10-20 points (out of a possible 20) per BRUV drop, and 20-90 (out of a possible 100) per ROV transect from which to calculate benthic percent cover estimates.

In addition to benthic cover, topographic complexity was estimated visually from each video still, 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. The aspect of the slope was also categorised as a 5 point scale where the angle of the slope was estimated as ~0 degrees, <45 degrees, ~45 degrees, >45 degrees or ~90 degrees.



Zoom 2

Measurements (44)

NOT calibrated, Model = Length, Global

Image file
ASHMORE_1_DROP1_SCREENSHO
ASHMORE_1_DROP3_SCREENSHO
ASHMORE_1_DROP4_SCREENSHO
ASHMORE_1_DROP5_SCREENSHO
ASHMORE_2_DROP10_SCREENSH
ASHMORE_2_DROP9_SCREENSHO
ASHMORE_3_DROP11_SCREENSH
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ASHMORE_5_DROP23_SCREENSH
CHILCOTT_1_DROP1_SCREENSHO
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CHILCOTT_1_DROP4_SCREENSHO
CHILCOTT_1_DROP5_SCREENSHO
FLINDERS_N1_DROP1_SCREENSH
FLINDERS_N1_DROP2_SCREENSH
FLINDERS_S1_DROP1_SCREENSH
FLINDERS_S1_DROP2_SCREENSH
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FLINDERS_S1_DROP4_SCREENSH
FLINDERS_S2_DROP2_SCREENSH
FLINDERS_S2_DROP3_SCREENSH
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HERALD_1_DROP1_SCREENSHOT
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HOLMES_1_DROP5_SCREENSHOT
HOLMES_1_DROP6_SCREENSHOT
HOLMES_1_DROP7_SCREENSHOT
KENN_1_DROP1_SCREENSHOT_F
KENN_1_DROP2_SCREENSHOT_F
KENN_1_DROP3_SCREENSHOT_F
KENN_1_DROP4_SCREENSHOT_F
KENN_1_DROP5_SCREENSHOT_F

Position (770.0, 1396.3)

BROAD	Macroalgae
MORPHOLOGY	Laminate
TYPE	
FieldOfView	Open
Relief	.1. Some relief features amonç
CODE	80300918
Attribute 7	
Attribute 8	

Zoom 1 ☑ Show labels

History

Fn	BROAD	MORPHOLOGY	TYPE	Fiel...	Relief
2	Macroalgae	Laminate		Open	.1. Some relief
3	Consolidated	Rock	Veneer	Open	.1. Some relief
4	Octocoral/Black	Branching (3D)		Open	.1. Some relief
5	Open Water			Open	
6	Octocoral/Black	Small mixed		Open	.2. Mostly relief
7	Macroalgae	Laminate		Open	.2. Mostly relief
8	Octocoral/Black	Branching (3D)		Open	.2. Mostly relief

Figure 3.8 - Screenshot of benthic annotation in TransectMeasure Software (SeaGIS Pty Ltd, Australia) of a BRUV drop at Flinders Reef

Table 3.1 - Predefined TransectMeasure hierarchical benthic categories and corresponding grouped benthic categories presented here.

TransectMeasure Hierarchical Categories	Grouped Categories
Biota: Consolidated: Boulder: Turf mat	Turf algae
Biota: Consolidated: Rock: Turf mat	
Biota: Consolidated: Cobbles: Turf mat	
Biota: Consolidated: Boulder: Veneer	Rock
Biota: Consolidated: Cobbles: Veneer	
Biota: Consolidated: Rock: Veneer	
Biota: Hydrocoral: Branching	Hydrocoral
Biota: Hydrocoral: Sub-massive/encrusting	
Biota: Macroalgae: Articulated calcareous	Halimeda
Biota: Macroalgae: Encrusting: Unknown	CCA
Biota: Macroalgae: Filamentous and filiform	Macroalgae
Biota: Macroalgae: Laminate	
Biota: Macroalgae: Small mixed	
Biota: Octocoral/Black: Branching (3D)	Complex Octocoral
Biota: Octocoral/Black: Fan (2D)	
Biota: Octocoral/Black: Pipe organ coral	
Biota: Octocoral/Black: Massive soft corals	Other Octocoral
Biota: Octocoral/Black: Small mixed	
Biota: Octocoral/Black: Whip	
Biota: Seagrasses: Elliptical leaves	Seagrass
Biota: Sponges: Crusts	Sponge
Biota: Sponges: Erect forms	
Biota: Sponges: Small mixed	
Biota: Stony corals: Branching: Live	Complex Hard Coral
Biota: Stony corals: Corymbose: Live	
Biota: Stony corals: Staghorn: Live	
Biota: Stony corals: Bottlebrush: Live	
Biota: Stony corals: Corymbose: Bleached	Bleached Hard Coral
Biota: Stony corals: Branching: Bleached	
Biota: Stony corals: Small mixed: Bleached	
Biota: Stony corals: Tabulate: Dead	Dead Coral
Biota: Stony corals: Foliose / plate: Dead	
Biota: Stony corals: Tabulate: Dead	
Biota: Stony corals: Corymbose: Dead	
Biota: Stony corals: Encrusting: Live	Encrusting Hard Coral
Biota: Stony corals: Tabulate: Live	Plate Hard Coral
Biota: Stony corals: Foliose / plate: Live	
Biota: Stony corals: Small mixed: Live	Other Hard Coral
Biota: Stony corals: Massive: Live	Massive and Sub-Massive Hard Coral
Biota: Stony corals: Sub-massive: Live	
Biota: Unconsolidated: Pebble / gravel (biogenic)	Unconsolidated substrate
Biota: Unconsolidated: Sand / mud (coarse sand)	
Biota: Unconsolidated: Sand / mud (fine sand)	
Biota: Unconsolidated: Sand / mud (mud/silt)	

3.7 Environmental impacts: marine debris and temperature profiles

The potential role for MCEs to act as a refuge for shallow water reef taxa has been widely hypothesized and debated (Bongearts et al. 2011; Lesser et al. 2009; MacDonald et al. 2016). However, substantial evidence continues to emerge demonstrating that deep reefs are also susceptible to anthropogenic and natural disturbances (Rocha et al. 2018). Like shallow reefs, pollution from terrestrial and marine sources can negatively impact mesophotic coral ecosystems (Smith et al. 2019). Specifically, marine debris arriving at a reef can be transported downslope into deep reef environments where it may accumulate, impacting coral growth and habitat structure (Lamb et al 2018; Hajbane et al. 2021). To quantify the prevalence of anthropogenic sources of physical pollution to deep reefs in the CSMP, we recorded all observations of marine debris in ROV and BRUV surveys. Debris was classified as one of three broad categories, fishing associated (e.g., ropes, fishing lines, floats), plastics (e.g., bags, bottles) or other debris (e.g. general litter, cans), with items specifically identified where possible. If recorded by an ROV survey, we also made size measurements of the debris item using the SVS and footage analysed in EventMeasure.

Thermal anomalies generated by anthropogenic driven climate change are increasing in frequency and magnitude and have caused multiple global mass coral bleaching events over the past 25 years (Hughes et al. 2018). Reduced temperatures at depth have been suggested as one of the environmental parameters that may confer resilience to deeper reefs during heat stress events (Glyn 1996; Riegl and Piller 2003; Bridge et al 2013). However, many MCEs exhibit variable temperature profiles with depth, which may reflect site-specific mechanisms (e.g., localised currents) or reef morphology. Although it is not the absolute difference in temperature between shallow and deep reef habitats that is key in providing refugia, characterising the thermal environments of deep reefs is important to calculate longer-term measures of thermal change (e.g., anomalous monthly or seasonal averages). Baseline data for temperatures along depth gradients in the CSMP are generally scarce but will clearly be essential for quantifying temperature change over time and how deep reef communities may respond to these changes. To collect temperature data and quantify thermal profiles at the CSMP reefs surveyed in this project, the cameras fitted to the ROV SVS were equipped with onboard temperature and pressure sensors. Water temperature (^{o}C) and depth (m) was recorded continuously during each ROV dive. These data were then paired with the camera timestamp in video files to provide environmental parameters for each ROV transect.

3.8 Data handling and analysis

All data were analysed in R Version 4.1.1. (R Core Team 2022). 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 CSMP and reef boundaries were reproduced from shapefiles contained in *gisaimsr* (Barneche and Logan 2021) and *dataaimsr* (AIMS Datacentre 2021), data courtesy of the Great Barrier Reef Marine Park, or 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.

3.8.1 Survey data

ROV survey data were averaged across independent transects within depth bins to obtain a site-depth average prior to summarising data at the level of reefs and/or regions. BRUV drops were treated independently and summarised at the level of site, reefs, then regions. For calculations of taxonomic richness, the number of species/taxa were calculated at the level of site (i.e., pooled among transects or drops) 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 a combination of stacked column plots when comparing proportions of taxa and percent benthic cover, and box and whisker plots (i.e., box plots) for comparing abundance (ROV), relative abundance (MaxN – BRUV). 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) were used to identify similarities in benthic habitats and fish assemblages among reefs in *a priori* defined regions (i.e., southern, central, and northern CSMP) or reefs. 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, 'sites' (i.e., BRUV drops or ROV transects) that are closer to one another are likely to be more similar in 'species' 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. The data were then standardised following a Wisconsin scaling, which removes the effect of absolute species abundance (or relative abundance (MaxN) for BRUV data) 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). Permutation tests for homogeneity of multivariate dispersions were performed using the *betadisper* function, to test for differences in dispersion among drops (BRUV) or transects (ROV) at the level of region and reef. To understand the influence of environmental (latitude, longitude, depth) and habitat variables (relief/structural complexity, slope, and habitat variables listed in Table x) on fish communities, environmental data were modelled against nMDS scores and overlaid using the *envfit* function. For depth, each transect or drop was assigned into a 10m-depth bin (0-10m, 11-20m, 21-30m etc. to 91-100m) and a category of Shallow (<30m) Mid (31-65m) or Deep (>65m). All candidate variables were regressed to test for multicollinearity, with conflicting variables not used in the same model. For example, unconsolidated substrates and relief_0 were strongly correlated and thus only one variable was included in an envfit model.

3.8.2 Acoustic Tagging Data

To assess the connectivity within and among CSMP reefs and between the CSMP and neighbouring regions (e.g., GBRMP and Norfolk Island), acoustic and satellite detections were used to map the animals' large-scale movements. SPOT tags relay location data (date, time, latitude, longitude) to overhead satellites when the fins break the water surface via the Argos satellite system. Data were downloaded and locations of low quality (e.g., on land, and obvious outliers) were removed prior to mapping animal movements. PSATs collect and record time-stamped data on pressure (depth), temperature and light level, at set intervals. Tags were programmed to detach after six months, after which they floated to the surface and transmitted recorded information to the Argos satellites. Data was downloaded and processed using the GPE3 geolocation algorithm (Wildlife Computers, Inc.), where locations were computed using light level and sea surface temperature data. Results were used to map movement pathways, depth, and temperature used.

For sharks, the residency index (RI) was calculated for each installation (reef) using acoustic tracking data. RIs were calculated as number of days an animal was detected at each reef divided by the number of days monitored (i.e. number of days from the tagging date to the date of receiver retrieval), following Barnett et al. (2019, 2022). Teleost RIs were calculated at the receiver (station) level, and only for Osprey Reef. Teleost RIs were also used to examine temporal patterns (examining day vs. night, lunar cycle) in residency.

4 Findings

4.1 Coral Reef Fishes

Fish assemblages from MCE's have historically been understudied due to the difficulty in surveying fishes in water depths greater than 30m (Cappo et al. 2007; Harvey et al. 2007). Indeed, there have been multiple surveys of fish assemblages within shallow reef habitats of the CSMP (e.g., Ceccarelli et al. 2008; Stuart-Smith et al. 2013; Hoey et al. 2020, 2021, 2022), however, the distribution, abundance, species richness and uniqueness of fish assemblages of deeper (>30m) CSMP reef habitats is largely unknown.

Video surveys of coral reef fish assemblages by BRUV and ROV methodologies recorded 3,865 and 17,253 individuals from 261 and 301 species, respectively. BRUV drops were carried out at depths between 10-90m (average 43.8m, median 42.5m) across 11 reefs (northern CSMP: Ashmore Reef; central CSMP: Chilcott, Flinders, Herald, Holmes, Lihou, Marion, Willis; southern CSMP: Kenn, Saumarez, Wreck) and ROV surveys conducted between 0 -100m (average 44.7m, median 43.9m) across 14 reefs (northern CSMP: Bougainville, Osprey reefs; central CSMP: Chilcott, Flinders, Herald, Herald's Surprise, Holmes, Lihou, Marion, Willis; southern CSMP: Kenn, Saumarez, Wreck, Frederick).

Combining the 261 species identified using BRUVs and the 301 species from the ROV transects, revealed a total of 407 fish species were recorded across the two methods. Of the 407 species recorded 155 species (38%) were recorded using both methods, 146 species (36%) were unique to the ROV transects, and 106 species (26%) were only recorded using the BRUVs (Figure 4.1).

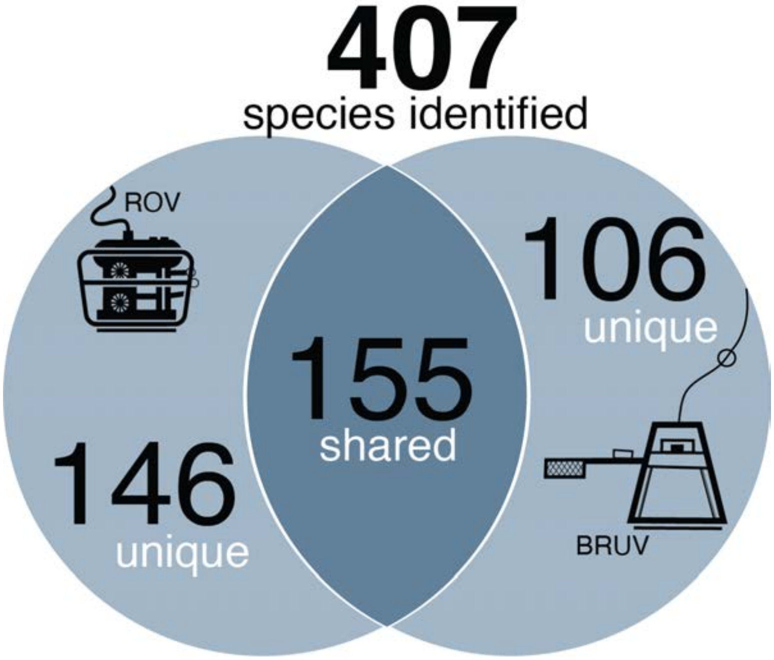


Figure 4.1 – Schematic showing the number of fish species recorded by Remotely Operated Vehicles (ROV) and Baited Remote Underwater Video (BRUV) surveys within deep (>30m) habitats across 16 reefs in the Coral Sea Marine Park.

4.1.1 Functional composition of fish assemblages

Fishes were categorised into eleven functional groups (piscivore, carnivore, benthic invertivore, planktivore, omnivore, corallivore, excavator, scraper, browser, grazer (includes detritivores), and farmer) based on their diet, morphology and feeding behaviour. BRUVs are particularly effective at capturing data on predatory or carnivorous fishes that are attracted to the bait, and other demersal species (Harvey et al. 2007). This was highlighted in our surveys, with a higher proportion of benthic invertivores, carnivores and piscivores species seen on BRUVS than ROV in general (Figure 4.2a). Taxa unique to BRUVS included species of sharks and ray (Tiger shark *Galeocerdo cuvier*, Lemon shark *Negaprion acutidens*, Wobbegong *Orectolobus ornatus,* lagoon ray *Neotrygon kuhlii*), five species of trevally (Family Carangidae: *Carangoides ferdau, Carangoides fulvoguttatus, Carangoides oblongus, Carangoides orthogrammus, Caranx sexfasciatus*), five species of emperor (Family Lethrinidae: *Lethrinus erythracanthus, Lethrinus nebulosus, Lethrinus olivaceus, Lethrinus rubrioperculatus, Lethrinus semicinctus*), a high value jobfish species (Family Lutjanidae: *Pristipomoides filamentosus*), two species of moray eel (Family

Muraenidae: *Gymnothorax favagineus*, *Gymnothorax javanicus*), and 7 groupers (Family Serranidae: *Cephalopholis argus, Cephalopholis sonnerati, Epinephelus cyanopodus, Epinephelus maculatus, Epinephelus tauvina* and *Plectropomus leopardus*). In contrast, ROVs generally surveyed a higher proportion of planktivores (damselfishes, anthias, surgeonfishes and fusiliers) and herbivorous fish species, particularly grazer/detritivores (Figure 4.2b). The abundance of planktivores was, however, highly variable across both methods (Figure 4.2), likely due to the schooling nature of many planktivorous species, and the influence of hydrodynamics. For example, on Chilcott Islet the ROV surveys were conducted within lagoonal habitats with few planktivores recorded, while at Marion Reef the reef fish assemblages were dominated by planktivores with a school of ca. 400 fusiliers recorded.

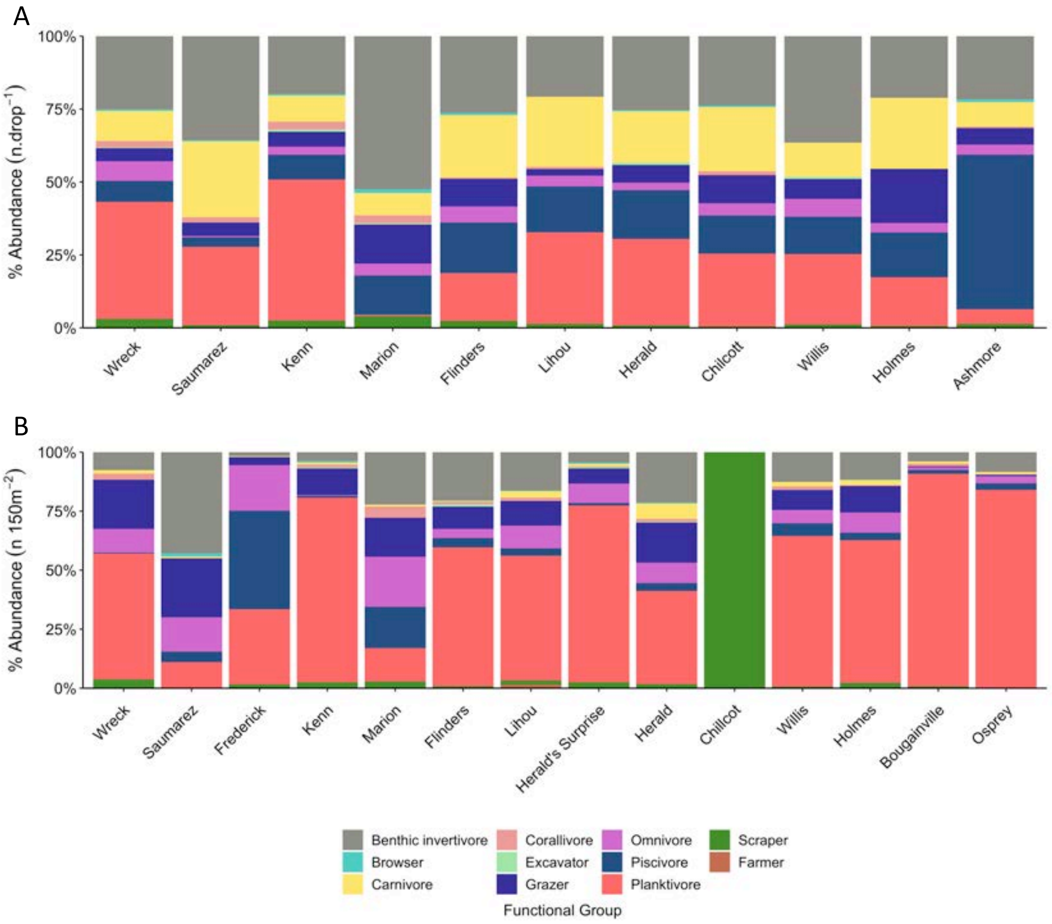


Figure 4.2 – Average relative abundance of fishes recorded by (a) BRUVS at 11 CSMP reefs between 10-90m, and (b) ROV survey at 14 CSMP reefs between 0 -100m. All species recorded are classified by functional group and the mean percentage of total abundance for each reef is calculated across all transects at all depths.

4.1.2 Among-reef variation in density, richness and biomass of fishes

The density, richness and biomass of fishes was variable among reefs with no consistent differences among CSMP regions (Figure 4.3 and 4.4). This is in contrast to shallow water fish assemblages of the CSMP where the abundance, richness and/or biomass of fishes tend to increase with decreasing latitude (e.g., Hoey et al. 2022). For example, the mean density of reef fishes from the ROV surveys ranged from 19 (Saumarez Reef) to 174 individuals per 150m^2 (Kenn Reef) in the southern CSMP, from 62 (Marion Reef) to 223 individuals per 150m^2 (Herald's Surprise Reef) in the central CSMP, and from 61 (Osprey Reef) to 163 individuals per 150m^2 (Bougainville Reef) in the northern CSMP, (Figure 4.3 and 4.4). The richness and biomass of fishes from the ROV surveys and the relative abundance, and richness of fishes from the BRUVs showed broadly similar patterns, with the greatest variation being among reefs within each region. The only exception to this was the lower fish species richness and relative abundance from the BRUV drops in the northern CSMP (Figure 4.4). This lower richness, and to a lesser extent relative abundance, of reef fishes is likely attributable to the limited sampling in the northern CSMP using this technique. Only a single reef (Ashmore Reef) was sampled by BRUVs in the northern CSMP due to the steep walls at Bougainville and Osprey reefs) and only shallow lagoonal habitats were surveyed at Ashmore Reef due to the prevailing and unfavourable weather conditions at the time of the surveys, and are unlikely to be indicative of other habitats within Ashmore Reef or the northern CSMP more broadly. Similarly, the low richness and abundance of reef fishes recorded during the ROV surveys at Chilcott Islets (Figure 4.3) is likely due to the habitat sampled (lagoonal habitat only). Future and more extensive sampling of deep habitats are necessary to reveal the generality of any patterns in richness and/or abundance among reefs and regions.

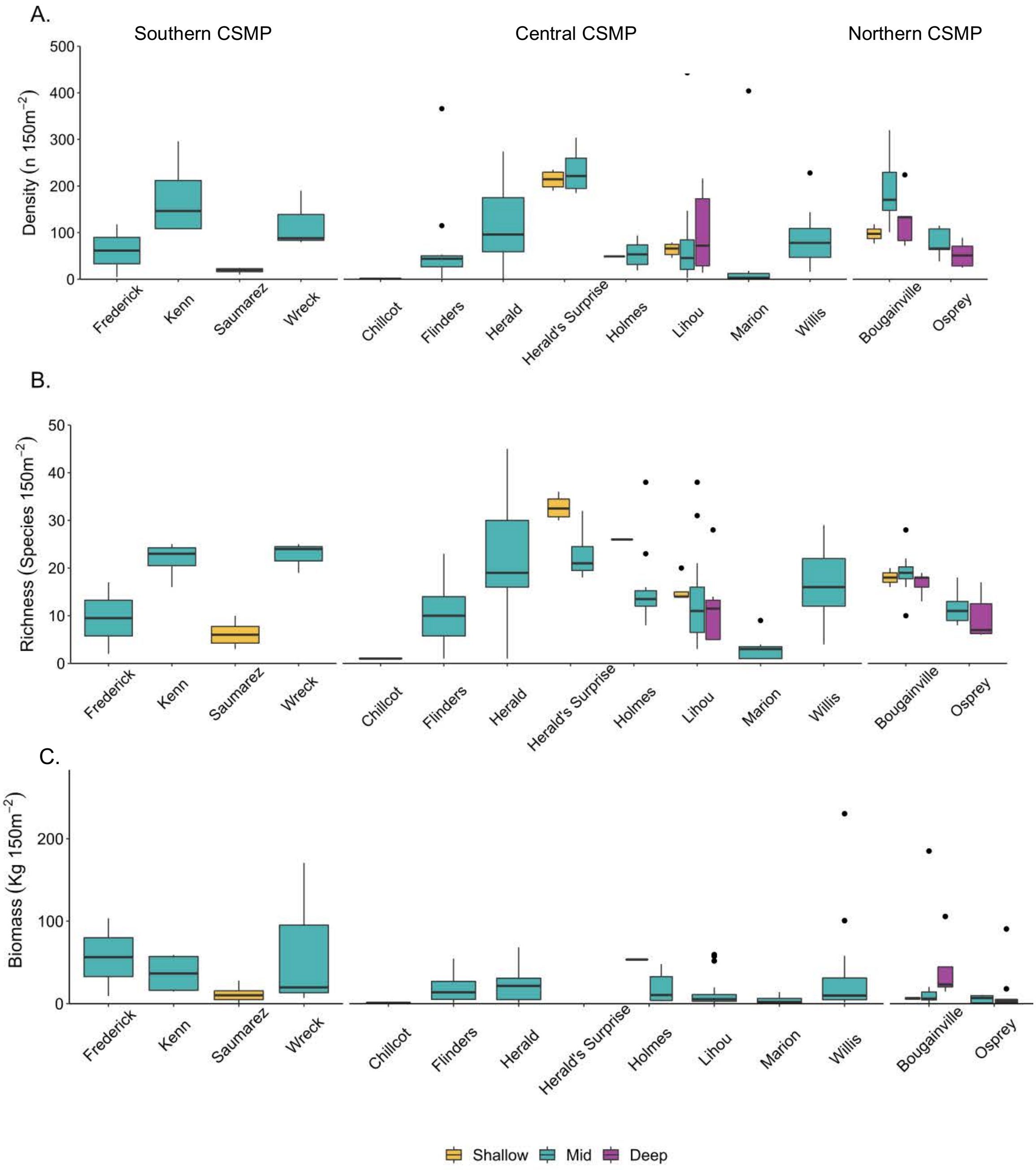


Figure 4.3 Spatial variation in the (a) density, (b) richness, and (c) biomass of coral reef fishes and sharks among the 14 reefs surveyed using Remotely Operated Vehicles (ROV) in the Coral Sea Marine Park (CSMP) during 2021. Data are based on 150m^2 belt transects. Reefs are grouped by *a priori* regional assignments arranged into the southern, central and northern CSMP. Values for each metric are presented for three depth bands which represent shallow (<30m), mid (30-65m) and deep (65 – 100m) habitats.

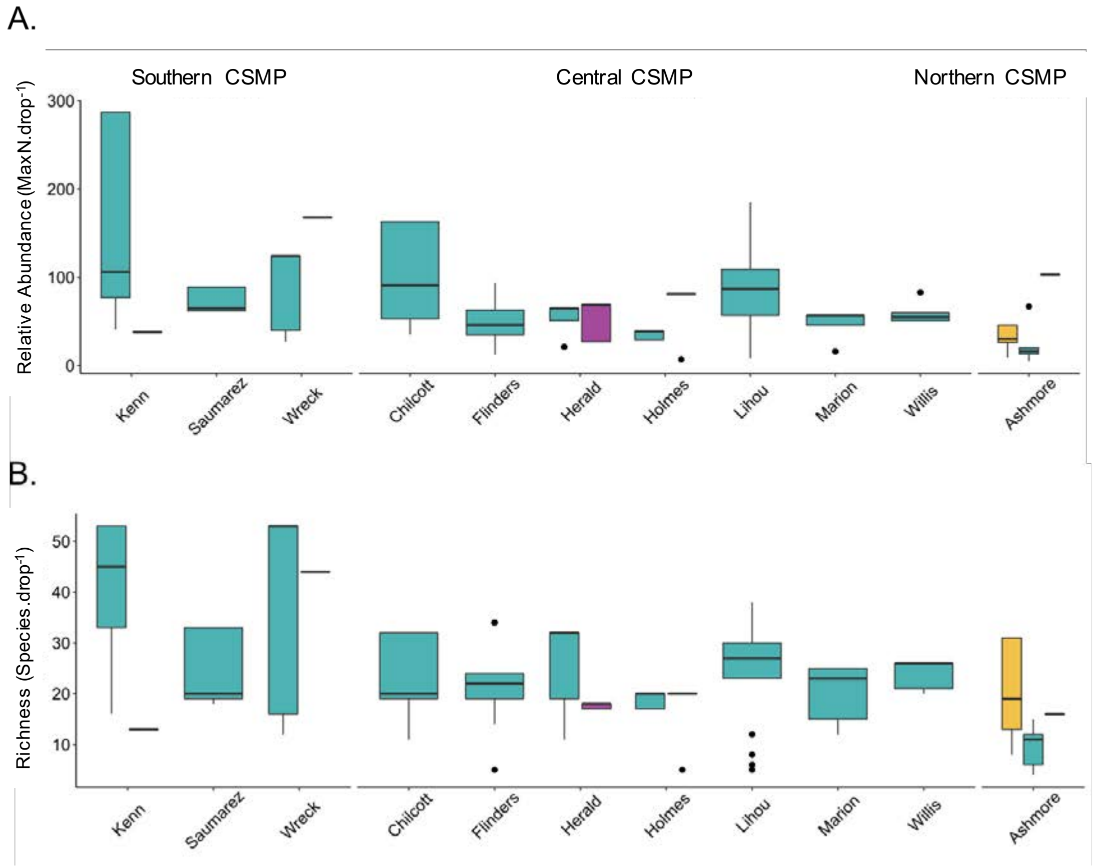


Figure 4.4 – Spatial variation in the (a) relative abundance, and (b) richness of coral reef fishes and sharks among the 11 reefs surveyed using Baited Remote Underwater Video (BRUV) in the Coral Sea Marine Park (CSMP) during 2021. Reefs are grouped by a priori regional assignments arranged into the southern, central and northern CSMP. Values for each metric are presented for three depth bands: shallow (<30m), mid (30 -65m) and deep (65 – 100m) habitats.

4.1.3 Depth related variation in density, richness, diversity, and biomass of fishes

Across the 15 reefs surveyed, the abundance of fishes peaked at intermediate depths, with the highest abundance of fishes from the ROV surveys (163 individuals per 150m^2) being recorded between 40 – 50m (Figure 4.5). Similarly, the highest relative abundance (MaxN) from the BRUV surveys (50 individuals per drop) was recorded for the 30-40m depth band (Figure 4.6).

Interestingly, the estimates of reef fish abundance from the ROV surveys showed a bimodal distribution with depth, with an initial peak at 10-20m (146 individuals per 150m^2), after which abundance declined to 57 individuals per 150m^2 at 20-30m, before reaching a second peak at 40-50m (Figure 4.5). Similar bimodal patterns in the abundance of reef fish with depth have been observed on deep reefs in other regions, and have been suggested to indicate the turnover of species shifts in community composition due to changing environmental conditions (Lesser et al. 2019).

Fish species richness and diversity from the ROV surveys exhibited a gradual decline with increasing depth, consistent with most studies of mesophotic fish communities from other regions (e.g., Indo-Pacific: Abesamis et al. 2018; MacDonald et al. 2016; Caribbean: Bejarano et al. 2014; Andradi-Brown et al. 2016). For example, on the Great Barrier Reef, fish species richness has generally been shown to decline with depth, from shallow (<30m) to deeper habitats (Scott et al. 2022) and from 50m to 100m and beyond (Sih et al. 2017). The highest species richness on the CSMP reefs was found between 0 – 20m, where an average of 23 species were recorded per 150m^2, declining by 64% to 8.4 species per 150m^2 at 90-100m (Figure 4.5b). The biomass of reef fishes was generally variable among depths, and often driven by the presence of large fishes (tuna and trevally) and sharks (Figure 4.5c).

In contrast to the ROV surveys, the species diversity and richness of fishes recorded from the BRUV surveys remained relatively stable between depths of 20-90m (Figure 4.6). The differences in the patterns of richness and diversity with depth between the two methods likely reflect the bias toward predatory fishes and the attraction to the bait plume in the BRUV surveys. Indeed, previous studies of other Indo-Pacific MCEs using BRUVs have shown that species richness of predators and generalist carnivores remain relatively stable between depths of 10-90m, while the richness of other groups declined with depth (e.g., Abesamis et al. 2020).

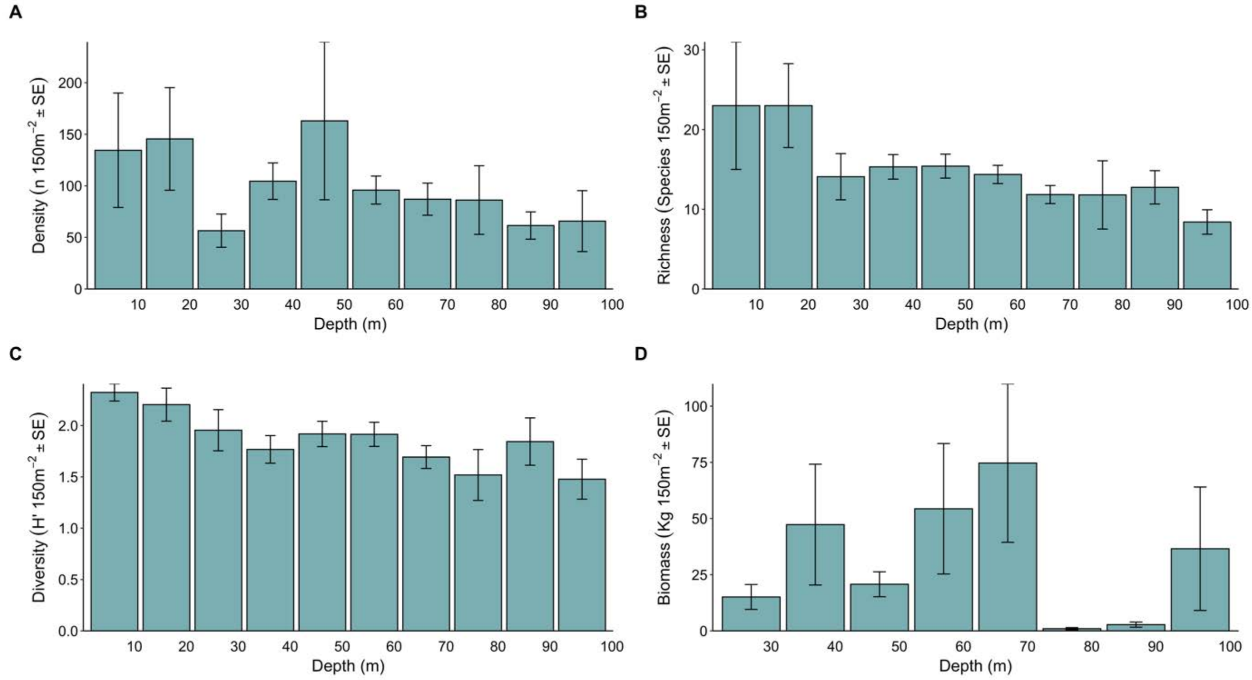


Figure 4.5 – Variation in the (a) density, (b) richness, (c) diversity, and (d) biomass of coral reef fishes and sharks among the 14 reefs surveyed using Remotely Operated Vehicles (ROV) in the Coral Sea Marine Park (CSMP) during 2021. Data are based on the 150m^2 belt transects. Average values for each 10m depth band are summarised across all transects at all reefs to provide a broad assessment of trends with depth across the CSMP.

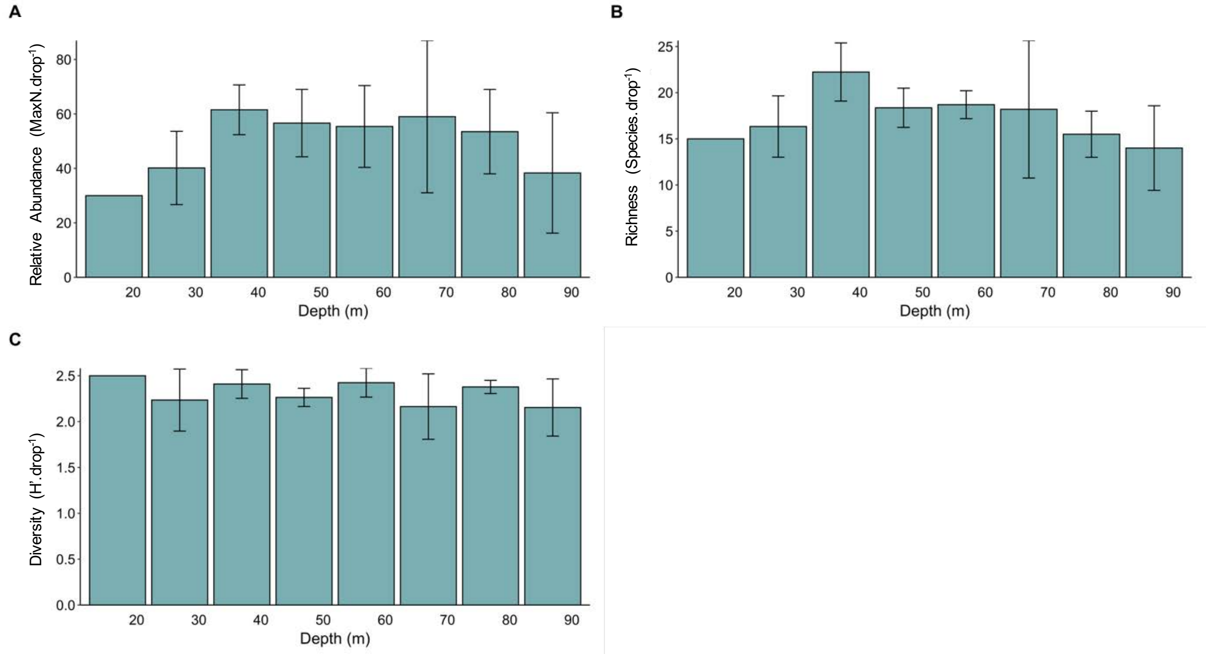


Figure 4.6 - Variation in the (a) relative abundance, (b) richness, and (c) diversity of coral reef fishes and sharks among the 11 reefs surveyed using Baited Remote Underwater Video (BRUV) in the Coral Sea Marine Park (CSMP) during 2021.

4.1.4 Fish community composition

Data from the BRUV surveys revealed some differences in fish assemblages among CSMP regions, with fish communities in the northern CSMP (Ashmore Reef) being separated from those in the southern CSMP, and to a lesser extent the central CSMP (Figure 4.7). The variation in fish assemblages among reefs and regions was related to latitude ($r^2 = 0.56$), depth (shallow, $r^2 = 0.22$, $P = 0.001$) and habitat (lagoon, $r^2 = 0.52$, $p = 0.001$; outer reef, $r^2 = 0.18$, $p = 0.001$). In particular, the northern CSMP fish assemblages were generally characterised by shallow and/or lagoonal habitats and fish species. Interestingly, while BRUVS generally attract (and thus bias toward) carnivorous and piscivorous species, it was not these groups or species that were dissimilar among region or environmental variables (Figure 4.7, right panel), implying that many of the predatory species were ubiquitous throughout the BRUVS drops. Indeed, species of emperor (*Lethrinus rubrioperculatus, Lethrinus olivaceus, Lethrinus semicinctus*), seabream (*Gymnocranius euanus*), threadfin bream (*Pentapodus aureofasciatus*), snapper (*Lutjanus bohar*), an invertivorous goatfish (*Mulloidichthys pfluegeri*), and sharks (*Carcharhinus amblyrhyncos, C. albimarginatus*) were common among BRUVS drops throughout the CSMP. Previous studies have shown these species to be among the most common species in deep water habitats of the central Great Barrier Reef shelf-break (Sih et al. 2017, 2019). The non-metric Multidimensional Scaling analysis failed to converge for the fish data from the ROV transects.

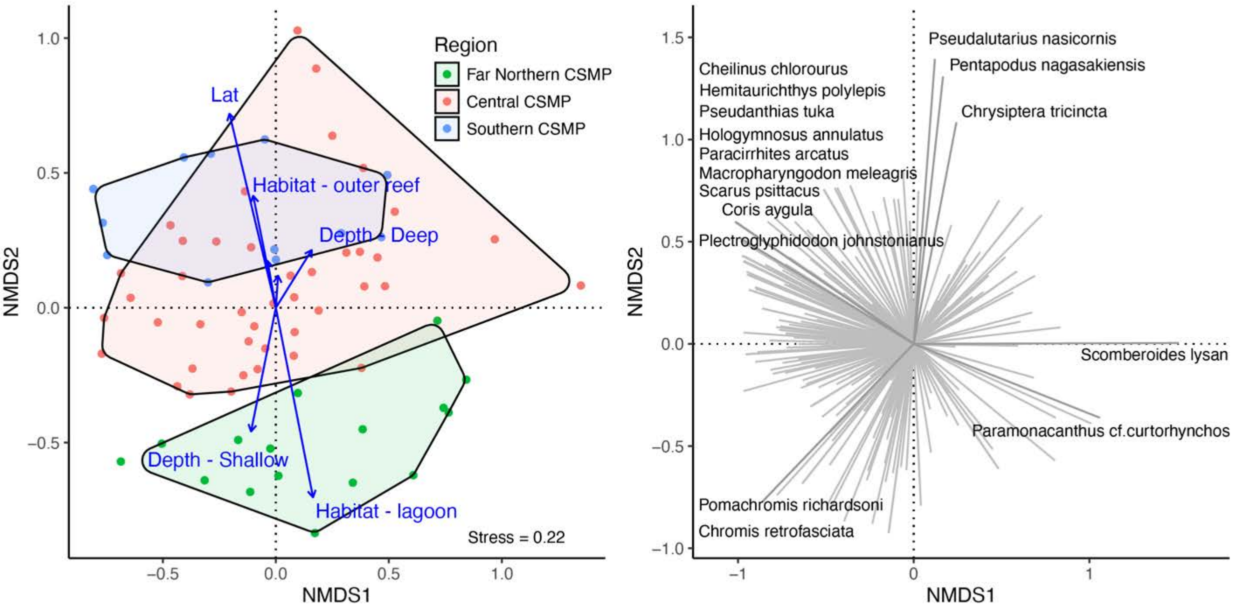


Figure 4.7 - Variation in fish communities within the Coral Sea Marine Park. Non-metric multidimensional scaling (nMDS) plots show the variation in fish communities among the far northern CSMP (green dots and shaded area), central CSMP (red dots and shaded area) and southern CSMP (blue dots and shaded area), with influential environmental variables overlayed (blue arrows). Analyses are based on the relative abundance (MaxN) of fish species observed in each of 70 BRUVS drops. Vectors (right plot) indicate key taxa that account for the variation among drops (left plot), grouped by CSMP region.

4.1.5 New fish species records

From BRUV and ROV surveys, 68 species were observed that had not previously been recorded during extensive surveys of shallow water reef habitats within the CSMP over the past five years (2018-22: Hoey et al. 2022) (Figure 4.8). Whilst these species are not necessarily unknown to the region, many are rare taxa seldom seen by divers or recorded in shallow water scientific surveys. These newly recorded species increase biodiversity records from shallow water monitoring by almost 10%, taking the total number of fish species observed by monitoring surveys from 661 to 729 species in the CSMP.

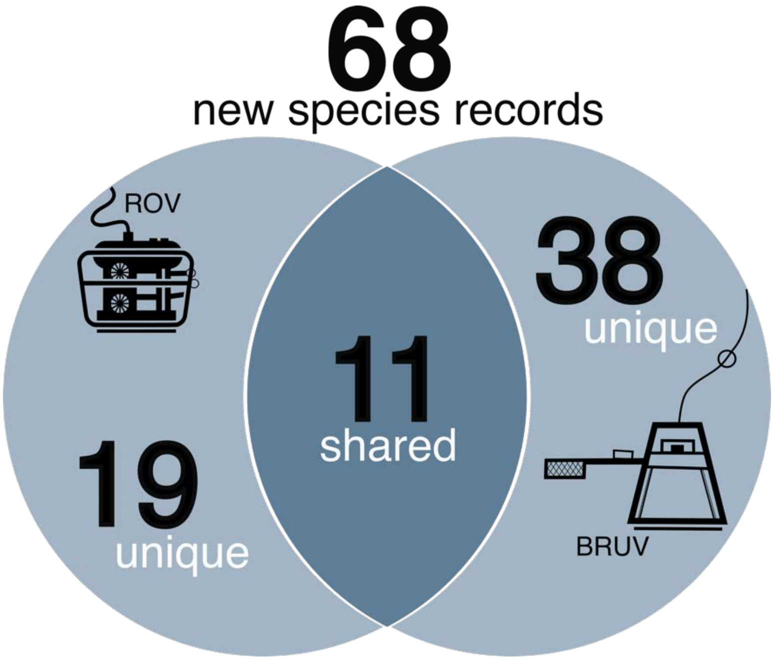


Figure 4.8 Schematic showing the number of ‘new’ fish species recorded by Remotely Operated Vehicles (ROV) and Baited Remote Underwater Video (BRUV) surveys within deep (>30m) habitats across 15 reefs in the Coral Sea Marine Park.

Of the 68 fish species that had not previously been recorded in shallow reef monitoring of the CSMP, seven species are, to our knowledge, new species records for the CSMP, based on records available through online repositories Fishbase, Reef Life Survey, Fishes of Australia and the Australian Faunal Directory. These species include (Figure 4.9), two species of triggerfish, *Xanthichthys auromarginatus* and *Abalistes filamentosus*, two species of deep-water tilefish *Hoplolatilus marcosi* and an unidentified *Hoplolatilus* sp.*,* a deep water goatfish *Mulloidichthys pfluegeri*, a planktivorous surgeonfish *Acanthurus nubilus*, and wrasse *Anampses melanurus*. Many of these species are more commonly known from French Polynesia and New Caledonia.

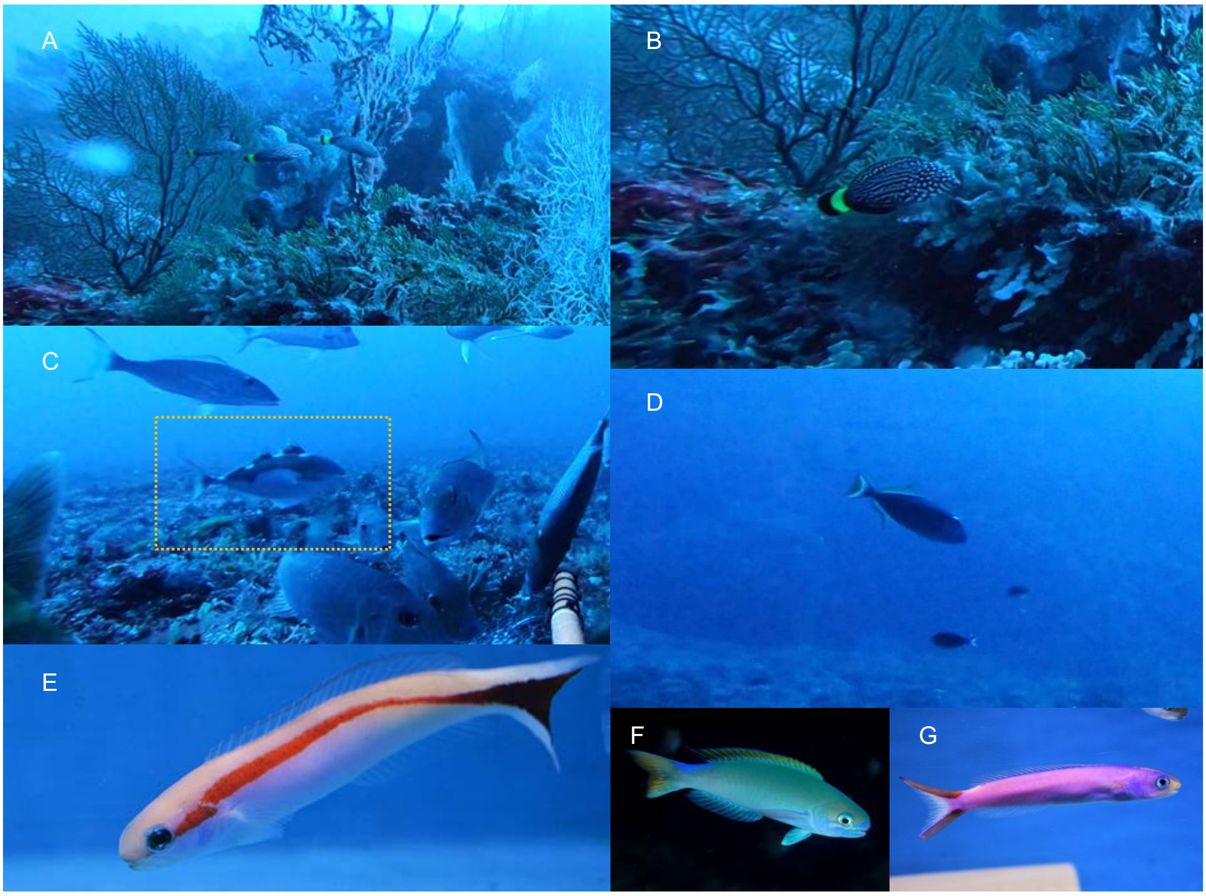


Figure 4.9 Figure 4.9 Photographs of fish species recorded by Remotely Operated Vehicles (ROV) and Baited Remote Underwater Video (BRUV) surveys within deep (>30m) habitats across 15 reefs in the Coral Sea Marine Park, that have not previously been recorded in the CSMP, based on online species records. A. and B. *Anampses melanurus* observed in a complex soft coral garden at Holmes Reef, BRUV in 51m, C. A single individual of *Abalistes filamentosus* was observed at Chilcott Reef on a BRUV in 50m. D. three individuals of *Xanthichthys auromarginatus* observed on an outer reef at Willis Island in 62m BRUV drop, E. *Hoplolatilus marcosi* in an aquarium. *H.marcosi* was seen in multiple transects around Lihou Reef at depths between 60 -100m F. *Hoplolatilus randalli and* G. *Hoplolatilus purpureus.* Unconfirmed sightings of tilefish species with very similar markings were made at Lihou Reef. *Photo credits: E and F* Wikicommons/Jokuyken, Licence: CC 4.0, G Izuzuki/reefapp Licence CC 3.0

The bluelined surgeonfish, *Acanthurus nubilus* was observed on 3 ROV surveys, from Lihou (north and south) and Osprey reefs, on outer reefs and lagoonal habitat at depths between 45 – 55 m. *Acanthurus nubilus* is generally known from the Indo-West Pacific of Indonesia, Society Islands and New Caledonia (Randall 1986) and reported from the Austral Islands, Pitcairn, Philippines, and the Marianas (Lieske and Myers 1994), but not Australian waters.

A single individual of *Abalistes filamentosus* was observed at Chilcott Reef on a BRUV in 50m (Figure 4.9c). This species is distinguished from *A. stellatus* by having long tail filaments (Bray 2022) that were evident in the BRUV footage (Figure 4.9c). This species is known from Barrow Island, Western Australia, to the Timor Sea, Northern Territory. Elsewhere the species occurs in the Indo-West Pacific from southern Japan to northern and north-western Australia, and New Caledonia; depth range 60-180 m (Bray 2022).

Mulloidichthys pfluegeri is a recent species record for Australia, having been identified from BRUV drops on the Great Barrier Reef Shelf-break (Sih et al. 2017). During this study, *M. pfluegeri* was observed the CSMP on BRUV drops at Chilcott, Flinders, Herald, Holmes, Kenn, Lihou, Willis, Wreck Reefs, mainly on outer reefs in 34 – 85m depth. Previously, it was known from Reunion to the Hawaiian, Marquesan, and Society islands, north to the Ryukyu Islands, south to Tonga, as well as Mariana and Marshall Islands in Micronesia (Froese and Pauly 2022).

Seven individuals of the wrasse *Anampses melanurus* were observed in a complex soft coral garden at Holmes Reef from a BRUV drop in 51m (Figure 4.9a,b, see also Section 4.3, Figure 4.37d) and 1 individual seen at Wreck Reef from a BRUV drop in 65m. This species is otherwise known from Scott Reef off Australia's west coast (Allen and Russell 1986), as well as Indonesia to the Marquesas and Society Islands and north to Ryukyu Islands (Lieske and Myers 1994).

In Australia, *Xanthichthys auromarginatus* has been reported at one location on the northern GBRMP (Escape Reef), in Christmas and Cocos (Keeling) Islands and Lord Howe Island (Allen and Steene 1990). Elsewhere in the world it is known from Mauritius eastward to Hawaii and Society Islands (Froese and Pauly 2022). During BRUV surveys of the CSMP three individuals were identified on outer reef habitat at Willis Island in 62m (Figure 4.9d).

The deep water skunk tilefish, *Hoplolatilus marcosi* was observed at 60 – 100m at Juliette Cay and Edna Cay, Lihou Reef. This species has been recorded from Indonesia, the Philippines, Palau, Papua New Guinea and the Solomon Islands, however, we believe that this is the first observation of individuals in the Coral Sea. Further to this new regional record, *H. marcosi* appears to have never been reported from Australian waters. During our surveys, three individuals were seen beside their rubble mounds which are used as nests and shelter. *H. marcosi* is a deep water specialist, typically not occurring above 18 - 20m but mostly found below 30m and up to 200m depth (Mazza 2021; Froese and Pauly 2022) (Figure 4.9e). They are found on areas of sand or rubble and form monogamous pairs to spawn. Pairs may live in aggregations and have been observed to steal rubble from neighbouring mounds (Mazza 2021).

We observed multiple individuals of at least two different species of deep-water tilefish at Juliette and Edna Cay, Lihou Reef. Individuals were seen beside or on top of large mounds of rubble at depths between 70 -100m. Whilst definitive identification of these species has not been possible from ROV survey footage, the distinct colour and pattern of some individuals suggest that these are potential observations of rare deep-water *Hoplolatilus* species. Potential identifications for individuals with green bodies and a defined blue saddle above the caudal peduncle include *Hoplolatilus fronticinctus, Hoplolatilus randalli* or *Hoplolatilus erdmani*. Smaller, purple individuals also observed but not definitively identified could possibly be *Hoplolatilus purpureus*. Two species of deep-water tilefish, *Hoplolatilus chlupatyi* and *Hoplolatilus fronticinctus* were recently recorded in the west-Indian Ocean, observations which significantly extended these species ranges though previously to only occur in the western Pacific (Lisher et al. 2020). Given the difficulty in observing deep-water species such as *Hoplolatilus sp.* it is likely that their distribution may extend into the deeper reefs of the CSMP.

4.1.6 Fish depth extension records

Of the 407 species observed across all BRUV and ROV surveys, 156 were observed at depths below the known depth range as listed on fishbase (www.fishbase.org; Froese and Pauly 2022). While some records only represented relatively small increases in the maximum recorded depth (e.g., 5m depth increase), almost half (77 species) were observed at depths greater than double their reported maximum depth. The full list of species observed below maximum known depths is reported in Appendix 1. Here we describe a selection of the species with new depth observations (Figure 4.10).

Figure 4.10 – Fish species that extended previously recorded depth ranges were from a variety of families and functional groups, including A. *Labroides dimidiatus*, the bluestreak cleaner wrasse, B. *Chromis iomelas*, the half-and-half puller, C. Butterflyfish *Chaetodon plebeius* and D. *Chaetodon pelewensis*, E. Moon wrasse *Thalassoma lunare*, and F. Orange-fin anemonefish *Amphiprion chrysopterus*. Photo credits - A, C and D: Victor Huertas; B: Ian Shaw / iNaturalist.org (CC BY Attribution); E: Bernard Dupont / Flickr (CC BY Attribution); F: Lakshimi Sawitri/Wiki Commons (CC 2.0)

Labroides dimidiatus, the bluestreak cleaner wrasse (Figure 4.10a), is widespread across the Indo-Pacific and Red Sea (Allen et al. 2012). ROV surveys recorded *L. dimidiatus* at 70m on Juliette Cay, Lihou Reef and 94.1m at Osprey Reef. These observations are 30-55m deeper than the known depth range for this species of 2 - 40m (Froese and Pauly 2022). Observations consisted of both individuals and small groups (2-3 individuals), however we did not observe any cleaning behaviour that is characteristic of this species. *L. dimidiatus* establish “cleaning stations” in prominent positions on reefs to attract larger fishes for the removal of ectoparasites (Grutter and Bshary 2004). The benthic habitat in the transects on which *L. dimidiatus* was observed at these depths was characterised by relatively high coral cover (%) and abundant complex octocorals, including large gorgonian sea fans.

Chromis iomelas, the half-and-half puller (Figure 4.10b), were observed on multiple occasions at depths of over 30m beyond its typical known depth range of 3 -35m. These observations included at 67m (Bougainville), 52m (Osprey), 45m at Willis Island and 45m at Lihou. *C. iomelas* are found individually or in small groups in coral rich areas in outer reefs and slopes (Bray et al. 2020). Whilst well known from surveys of shallow habitats within the CSMP, these are the deepest observations of this species in the region to date.

Ten species of butterflyfishes were recorded at depth more than 10m below maximum known depth ranges. Of these species, five species of *Chaetodon* were seen at depth between 20-58m deeper than current records. *Chaetodon plebeius* (Figure 4.10c) was recorded at 67.8m at Bougainville Reef. Adults of this species are obligate corallivores, and are found at depths down to 10-15m (Froese and Pauly 2022), where they feed mostly on *Pocillopora* corals (Pratchett 2005). Given the high dietary dependency on live scleractinian corals, it is unusual to record *C. plebeius* at these depths. *Chaetodon pelewensis* (Figure 4.10d) is a facultative corallivore (Harmelin-Vivien and Bouchon-Navaro 1983) and was recorded at depths between 50-68m on Bougainville and Wreck reefs, and Willis Islet, significantly below the known depth range (8-30m; Froese and Pauly 2022) for this species.

The Moon Wrasse, *Thalassoma lunare* (Figure 4.10e), is a widespread Indo-Pacific species (Randall et al. 1990), well known from the Coral Sea (Stuart-Smith et al.

2015). *T. lunare* occurs solitary or in small groups in lagoons and seaward reefs (Myers 1991). ROV and BRUV surveys found this species on multiple occasions deeper than the known maximum depth of 20m, including 58.1m at Bougainville Reef and 43m at Herald Cay

The Orange-fin anemonefish, *Amphiprion chrysopterus* (Figure 4.10f), was recorded by ROV survey at 49m and 74m at two sites on Lihou Reef. Typically known to occur between 1 - 40m, our observation of a pair within their host anemone at 74m represents an 85% increase in the known depth range for this species.

4.2 Ecological Processes

4.2.1 Predation

Predation is one of the most important ecological processes in all natural systems (Hariston et al. 1960; Estes et al. 2011). As an ecological function, the dynamics between predators and prey contribute to the maintenance of biodiversity through numerous and often complex interactions (Polis and Holt 1992; Ritchie and Johnson 2009). On coral reefs, predation and predatory fishes have evolved in many forms, sizes and mechanisms (Hixon 2015). From smaller *Cephalopholis* spp. waiting to ambush passing prey, to high-intensity hunts of larger carangids and mobile predators. The CSMP is known to support a high abundance of large predatory fishes, particularly sharks (Ceccarelli et al. 2013, Stuart-Smith et al. 2013, Hoey et al. 2020, 2021). Given that three-quarters of oceanic sharks are now classed as at risk, threatened or critically endangered (Pacoureau et al 2021), regional marine protected area networks supporting high abundance of these larger predators are important in supporting future shark populations and the ecosystem functions they perform (Roff et al. 2016; Dwyer et al. 2020). Most studies examining the distribution and abundance of predatory species, however, have historically been restricted to shallow depths of < 30m (Asher et al. 2017). Many shark and other predator teleost species are however, known to make significant vertical movements (e.g., Papastamatiou et al. 2015; Bejarano et al. 2014). The lack of studies examining predator distributions below 30m mean that these biodiversity patterns are still not well known in most deep reef habitats.

Predator biodiversity and species distributions

Of the 407 species recorded by BRUV and ROV surveys, almost 25% (94 species) were piscivores or carnivores. Notably, sharks were recorded at all reefs surveyed by this project. In total, five species of shark were recorded by ROV and BRUV surveys combined, with three species (Grey reef sharks: *Carcharhinus amblyrhynchos*, Silvertip sharks *Carcharinus albimarginatus* and White tip reef sharks *Triaenodon obesus*) being recorded by both survey methods (Figure 4.11). In addition, a Scalloped hammerhead (*Sphyrna lewini*) was recorded by the ROV at Osprey Reef and Tiger sharks (*Galeocerdo cuvier*) were recorded by BRUV surveys at Herald Cay and Kenn Reef (Figure 4.12). All five of these species are known from the CSMP, although observations of *S. lewini and G. cuvier* are less commonly observed and neither of these species have been formally recorded in the CSMP Coral Reef Health monitoring surveys from 2018-2022 (Hoey et al. 2022).

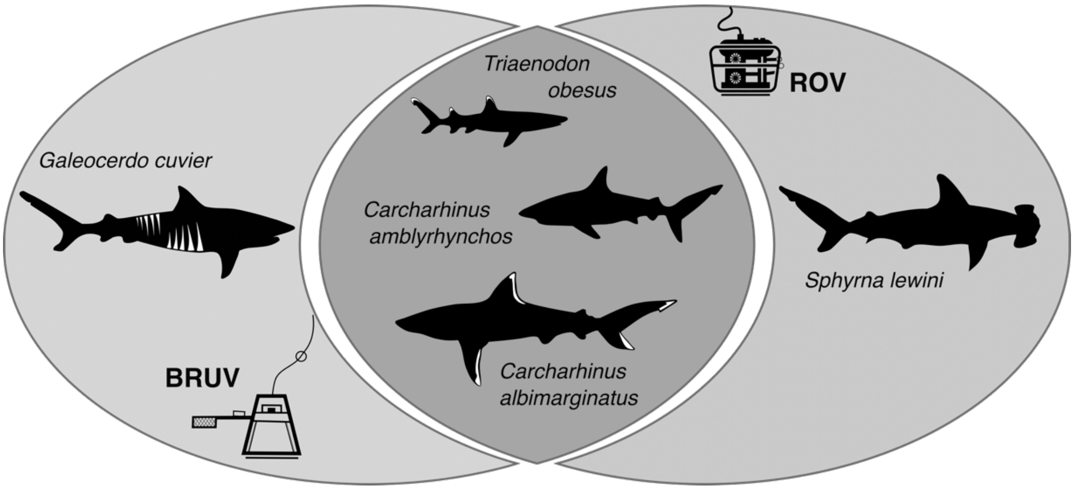


Figure 4.11 – Schematic showing the number of shark species recorded by Remotely Operated Vehicles (ROV) and Baited Remote Underwater Video (BRUV) surveys within deep (>30m) habitats across 15 reefs in the Coral Sea Marine Park.

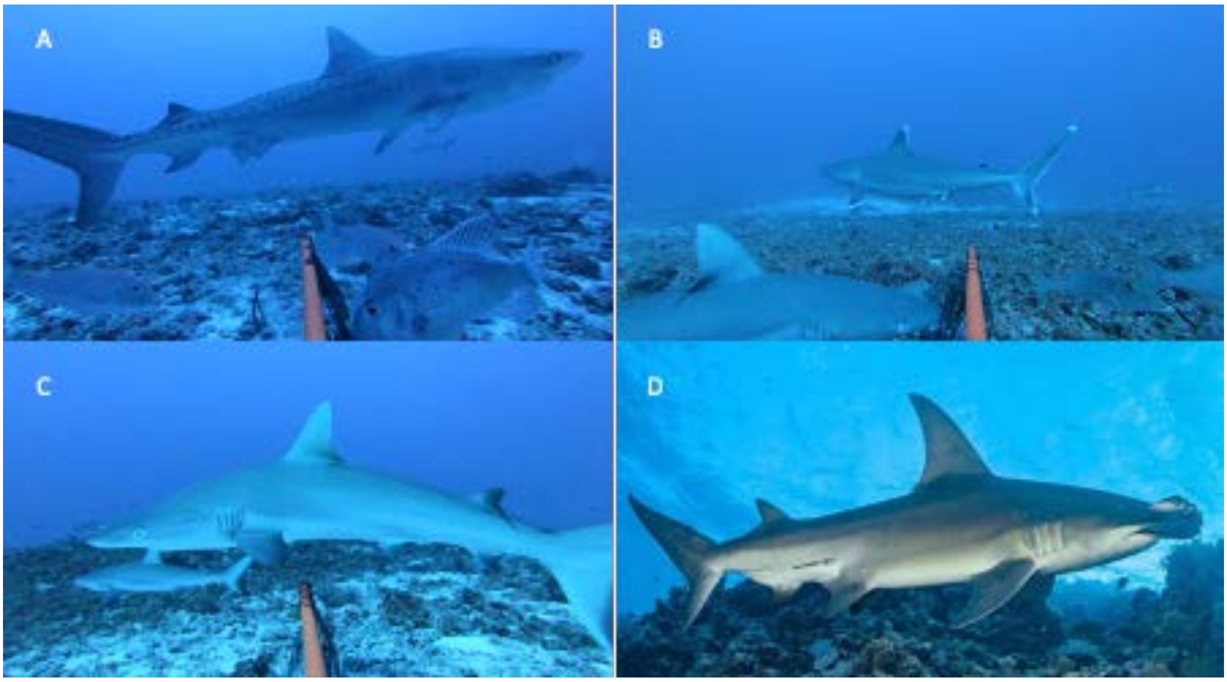


Figure 4.12 – Photographs showing four of the shark species that were recorded on reefs within the Coral Sea Marine Park. A. *Galeocerdo cuvier* at Kenn Reef, B. *Carcharinus albimarginatus* at Chilcott Reef, C. *Carcharinus amblyrhyncos* at Chilcott Reef, D. *Sphyrna lewini* at Osprey Reef. A-C are screenshots from BRUVS footage, D courtesy of V. Huertas.

In both BRUV and ROV surveys, predatory species were recorded along the entire depth gradient surveyed by each method. Predator abundance in ROV surveys was generally more variable between depth bands (Figure 4.13a) compared to predator abundance recorded by BRUV surveys (Figure 4.14a). Overall, the number of predatory species was higher for the BRUV surveys (3-17 species per drop across all reefs and depths) compared to ROV surveys (0-7 species per 150m^2 across all reefs and depths). This is perhaps unsurprising given BRUVs are specifically designed to attract and record predator species.

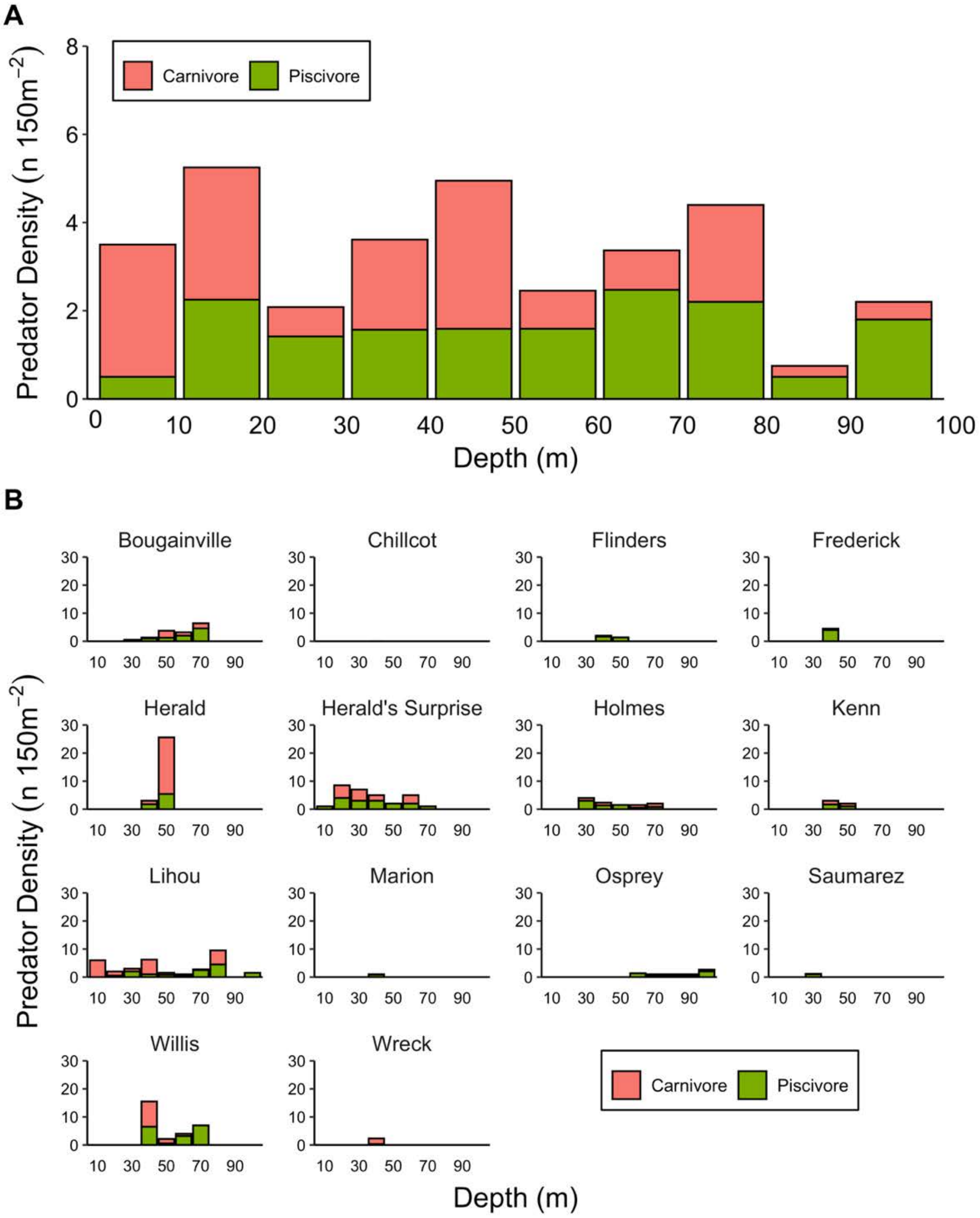


Figure 4.13 – Average predator density (individuals per 150m^2) recorded by ROV surveys across 14 CSMP reefs between 0 -100m. Stacked bar represent average density of carnivorous and piscivorous fishes in each 10m depth bin. **A**. Average density of predators summarised across all transects and all reefs and **B.** Average density of predators summarised across all transects at individual reefs.

Overall, the abundance of predatory fishes was variable among reefs and depths, ranging from 0.75 individual per 150m^2 at 80-90m to 5.25 individuals per 150m^2 at 10-20m (Figure 4.13). Similarly, the abundance of predators among reefs ranged from 0 individuals per 150m^2 at Chilcott Islets to 8 individuals per 150m^2 at Herald

Cays. The high predator abundance recorded at Herald Cays was driven primarily by a peak in predator density (25.6 individuals per $150m^2$) between 40 - 50m. Conversely, the lack of predators recorded at Chilcott is likely due to the limited number of ROV transects at this reef (4 transects in the inner lagoon) rather than a true lack of predatory fishes at this reef.

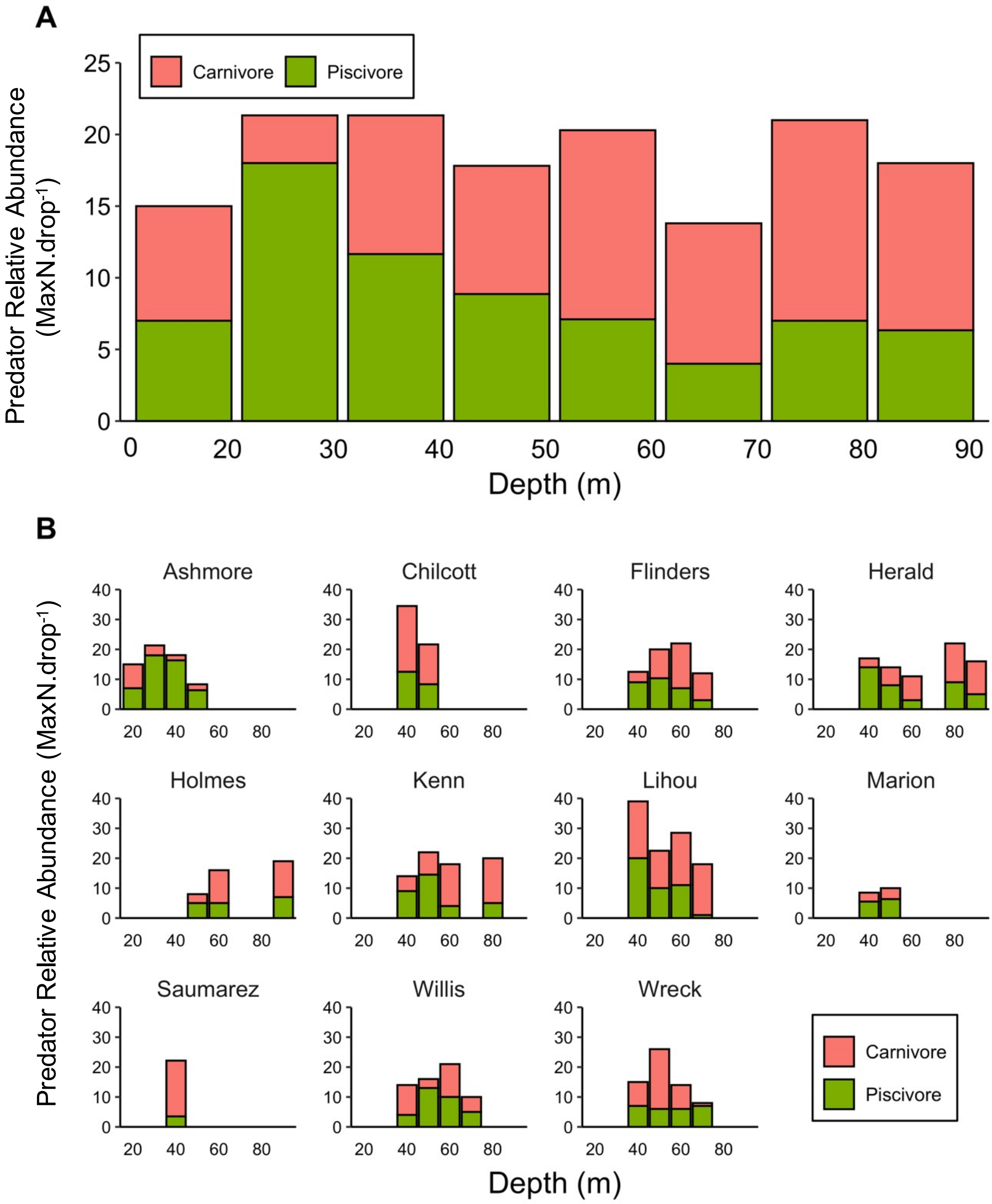


Figure 4.14 – Average predator relative abundance (MaxN per drop) recorded by BRUV surveys across 11 CSMP reefs between 10 -90m. Stacked bar represent average relative abundance (MaxN) of carnivorous and piscivorous fishes in each 10m depth bin. **A**. Average relative abundance (MaxN) of predators summarised across all drops and all reefs and **B.** Average relative abudance (MaxN) of predators summarised across all drops at individual reefs. All sharks are classed as piscivores except *G. cuvier* which is classed as carnivorous.

The relative abundance (MaxN) of predatory fishes recorded using the BRUVs was broadly comparable among depths (ranging from 14.8 individuals per drop at 60-70m to 23.3 individuals per drop at 20-40m), however there was considerable variation among reefs (ranging from 4.7 individuals per drop at Marion Reef to13.7 individuals per drop at Lihou Reef; Figure 4.14). BRUV surveys also found comparable high predator relative abundance at Chilcott Islet and Saumarez Reef with average predator densities of 13.4 and 12.6 individuals per drop respectively. Notably, Willis Islet had the highest abundance of sharks recorded by both ROV and BRUV surveys, with an average of 2 sharks per 150m^2 in ROV surveys and 2.3 sharks per drop in BRUV surveys across all depths. The relative abundance of sharks on Chilcott Islet was also high in BRUV (2.4 sharks per drop), but not ROV surveys (0 sharks per 150m^2).

The deepest observations of predatory fishes and sharks were made by ROV surveys which spanned the full depth range from 0 - 100m. Many large predatory fishes are known to occupy significant depth ranges. For example, the maximum known depth for the silvertip shark, *C. albimarginatus*, and giant trevally, *Caranx ignobilis*, are 800m (Last and Stevens 1994) and 188m (Mundy 2005), respectively. The deepest observations of predatory fishes in the CSMP recorded by ROV were *Carcharhinus amblyrhynchos*, (98m Juliette Cay, Lihou Reef), and the red bass, *Lutjanus bohar*, and potato cod, *Epinephelus tukula* (both recorded at 97m, Osprey Reef). From BRUV surveys, deepest records for predators were all from a single drop (85m at Holmes Reef) and included *Caranx lugubris, Caranx melampygus, Carcharhinus amblyrhynchos, Triaenodon obesus, Epinephelus maculatus, Lethrinus miniatus, Lethrinus olivaceus, Lethrinus rubrioperculatus, Aphareus furca, Lutjanus bohar, Pristipomoides filamentosus* and *Mulloidichthys pfluegeri* (new species record).

Commercially important species

Several commercially important species were recorded in deep habitats within the CSMP, including the red throat emperor (*Lethrinus miniatus*), red emperor (*Lutjanus sebae*) and the crimson jobfish (*Pristipomoides filamentosus*). While these species are generally known to occur within the CSMP, and studies in other locations have reported them at depths similar to, or greater than, those reported here (e.g., Sih et al. 2017, 2019), these species have not been recorded in extensive surveys of shallow reef habitats in the CSMP (e.g., Hoey et al. 2022).

Lethrinus miniatus (Red throat emperor) (Figure 4.15a) were observed at 72m at Juliette Cay, Lihou Reef via ROV and 85m at Holmes Reef via BRUV. To our knowledge these are the deepest records of this species in the CSMP, although they have been observed on the shelf-break of the GBR at depths between 54 – 128m (Sih et al. 2017). Typically, *L. miniatus* inhabit coral reefs and adjacent sand and rubble areas between 5-45m (Carpenter and Allen 1989). A predatory species, *L. miniatus* were observed on eight separate BRUV drops across 5 locations, including Chilcott, Holmes, Lihou and Kenn Reefs. *L. miniatus* are an important species in the GBR Reef Line Fishery by catch weight (Northrop and Campbell 2020) and among the 10 most important species in the Coral Sea Fishery Trap and Line Sector in 2005-2009 (AFMA 2012). Increased knowledge of the known depth ranges for commercially important species, including *L. miniatus*, will inform strategies for fisheries and protected area management in the CSMP.

Pristipomoides filamentosus (Figure 4.15b) is a new species record not previously recorded in shallow monitoring surveys in the CSMP, but have been found at similar latitudes and depths on the Great Barrier Reef Shelf-break, with *Pristipomoides filamentosus* being a high value fisheries species (Sih et al. 2017).

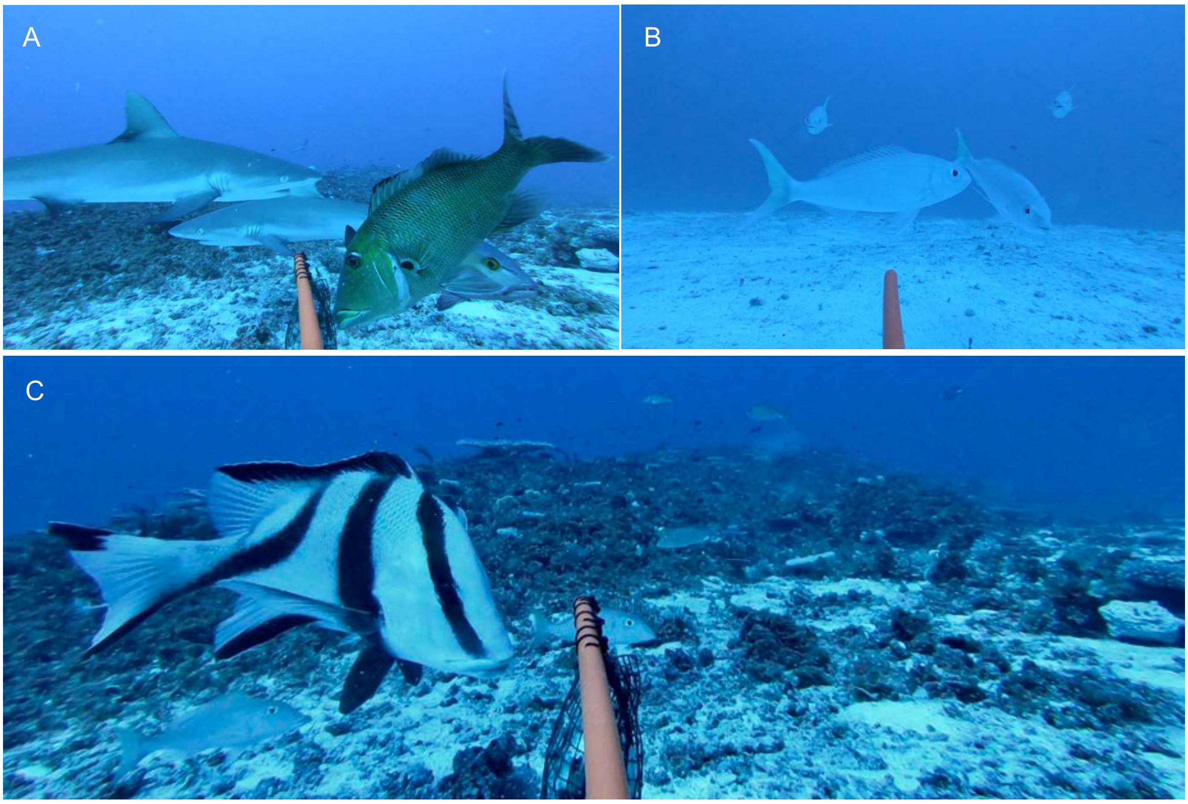


Figure 4.15 - Photographs of commercially important fish species recorded from Baited Remote Underwater Video Surevys (BRUVS). A. *Lethrinus miniatus* with *Lutjanus bohar* and *Carcharhinus amblyrhynchos* at Chilcott Reef in 35m, B. *Pristipomoides filamentosus* at Herald Reef in 71m, and C. juvenile / sub-adult *Lutjanus sebae*, at Chilcott Reef in 35m.

Lutjanus sebae, (Red emperor) (Figure 4.15c) were observed at three locations in the CSMP, including Chilcott (35m – BRUV) and Lihou Reefs (55m – BRUV) and West Diamond Islets (59m – ROV). *Lutjanus sebae* is a species of high commercial and recreational fisheries value, and has been historically caught by the trap and line sector in the Coral Sea Fishery (CSF), being in the three most common species by weight in the CSF in 2005-2009 (AFMA 2012). Red Emperor are also an ecologically significant species as a large mesopredator and due to their complex lifecycle. Small juveniles typically inhabit inshore turbid habitats such as mangrove areas (Allen 1985), moving to deeper outer and offshore reefs as they grow (Cappo and Kelley 2001). Given that it is unlikely juvenile *L. sebae* would migrate from coastal Queensland waters to the reefs of the CSMP, the presence of juveniles in deep habitats of the CSMP suggests that these reefs may support distinct populations. While dedicated research is required to identify the settlement and juvenile habitats of this (and other) species, and to determine if the CSMP and GBRMP populations are distinct, structured surveys of deep reef and non-reef habitats will be required to provide fisheries independent information on the abundance, size structure and status of important fisheries species throughout the CSMP. Similar monitoring is currently being developed and implemented for fisheries targets (including *L. sebae*) in deep habitats of the GBRMP.

Deepwater sharks are known to inhabit the submerged plateaus, slopes and rises of the Coral Sea (Compagno and Stevens 1993). Large *Carcharhinus albimarginatus* individuals were recorded by ROV at the deepest depths surveyed in this project (90-100m), some of which measured ~2.6- 2.8m long, near the maximum known length for this species (3m). We also observed a white-tip reef shark, *Triaenodon obesus,* resting on a ledge at 60m, Osprey Reef (Figure 4.16). *T. obesus* is one of the few requiem shark species that is not required to constantly swim in order to move water over the gills. Instead, small holes behind the eyes draw water through the buccal cavity and over the gills, allowing individuals to rest on the seafloor, on ledges or in caves (Kelly et al. 2019). The steep walls of Osprey are interspersed by numerous ledges and cervices which likely provide important deep habitats for some fish species.

Figure 4.16 - Photograph from the Remotely Operated Vehicle (ROV) of a white-tip reef shark, *Triaenodon obesus* resting on a ledge at 60m on a wall at Osprey Reef.

4.2.2 Herbivory

Herbivory is widely viewed as a key process on shallow coral reefs, maintaining a healthy balance between corals and algae (Bellwood et al. 2004). The mechanical removal of algal material by herbivorous taxa (predominantly herbivorous fishes) when feeding helps to maintain algal communities in a cropped and productive state (e.g., Russ 2003), prevent the establishment and/or expansion of macroalgae (e.g., Lewis 1986; Bellwood et al. 2006), and clears space for the settlement of other benthic organisms, including corals. Indeed, marked reductions in herbivory through overfishing or experimental exclusion have been linked to increases in the cover, diversity and/or biomass of macroalgae, and subsequent reductions in the settlement, survival and growth of corals (Hughes et al. 2007; Rasher et al. 2003; Clements et al. 2018). The potential role of herbivorous fishes is becoming increasingly important as reefs are exposed to more frequent, intense and diverse disturbances (Hughes et al. 2017, 2018), leading to declines in coral cover and increases in other benthic taxa, namely macroalgae.

In recognition of the potential importance of herbivory to the health and resilience of coral reefs the *Herbivorous fishes of the Queensland Plateau* is listed as a Key Ecological Feature (KEF) of the CSMP. While there have been extensive surveys of herbivorous fish assemblages within shallow reef habitats of the CSMP, their distribution, abundance and relationship with benthic communities within deeper reef habitats is unknown.

Species distributions

Our ROV and BRUV surveys recorded 53 species of herbivorous fish on deep (30-100 m) reef habitats across the 15 CSMP reefs, with the deepest record being a *Centropyge heraldi* recorded at a depth of 98.0m on Lihou reef. Interestingly, 36 species of herbivorous fish were recorded at depths that were at least 5m greater than their maximum depth listed on fishbase (Table 4.1). These depth extension records were not restricted to particular families, trophic or functional groups, and represented substantial increases in the maximum for some species. For example, the scraping parrotfishes (Labridae: Scarini) *Scarus niger* (Figure 4.17) and *S. chameleon* were recorded at 67.8m and 66.7m in the CSMP, representing a 2.3- to 3.4-fold increase in the maximum recorded depth. Similarly, the highfin parrotfish, *Scarus longipinnis*, which was the most common parrotfish recorded on BRUVS and ROV transects, was observed down to 79m at Edna Cay, Lihou Reef, an increase of 24m on the previously reported range of 1-55m (Table 2). *S. longipinnis* is one of the most common parrotfish recorded in shallow reef habitats of the CSMP (Hoey et al. 2020), although is rarely observed on the GBR. Why this species appears to thrive across a broad depth range in the CSMP, yet is rare or absent on GBR reefs is currently unknown.

Comparable increases in the maximum depth were recorded for surgeonfishes (e.g., *Ctenochaetus striatus* from 30 to 65m; *Acanthurus nigrofuscus*: 25 to 51m, Figure 4.17), rabbitfishes (e.g., *Siganus woodlandi*: 15 to 47m) and damselfishes (e.g., *Plectroglyphidodon johnstonianus*: 18 to 42m) (Table 4.1).

Table 4.1 – Depth extension records for 36 species of nominally herbivorous fishes. Observed depth is depth at which the individual was recorded by BRUV or ROV survey, Fishbase max depth is the maximum known depth as recorded on www.fishbase.org and depth increase is the difference between observed and fishbase depth. Functional groups were obtained from fishbase. Note *Acanthurus albipectoralis* is a planktivorous surgeonfish, but is included here for comparison.

Species	Observed Depth (m)	Fishbase Max Depth (m)	Depth Increase (m)	Reef	Method	Functional Group
Scarus niger	67.8	20	47.8	Bougainville	ROV	Scraper
*Acanthurus albipectoralis**	63.0	20	43.0	Lihou	ROV	Planktivore
Scarus chameleon	66.7	30	36.7	Bougainville	ROV	Scraper
Siganus woodlandi	47.0	15	32.0	Flinders	BRUV	Grazer
Acanthurus blochii	46.4	15	31.4	Lihou	ROV	Grazer
Ctenochaetus striatus	65.0	35	30.0	Wreck	BRUV	Grazer/ Detritivore
Acanthurus auranticavus	46.2	20	26.2	Lihou	ROV	Grazer

Acanthurus nigrofuscus	51.0	25	26.0	Willis	BRUV	Grazer
Acanthurus nigricauda	55.0	30	25.0	Flinders	BRUV	Grazer
Plectroglyphidodon johnstonianus	42.0	18	24.0	Kenn	BRUV	Farmer
Scarus longipinnis	79.0	55	24.0	Lihou	ROV	Scraper
Centropyge bicolor	47.6	25	22.6	Herald's Surprise	ROV	Grazer
Scarus frenatus	46.6	25	21.6	Lihou	ROV	Scraper
Centropyge bispinosa	80.6	60	20.6	Osprey	ROV	Grazer
Scarus psittacus	45.5	25	20.5	Bougainville	ROV	Scraper
Chlorurus spilurus	50.4	30	20.4	Willis	ROV	Excavator
Acanthurus pyroferus	79.0	60	19.0	Lihou	ROV	Grazer
Ctenochaetus binotatus	71.6	53	18.6	Osprey	ROV	Grazer/ Detritivore
Chlorurus microrhinos	68.0	50	18.0	Osprey	ROV	Excavator
Siganus argenteus	58.0	40	18.0	Kenn	BRUV	Grazer
Stegastes fasciolatus	47.7	30	17.7	Lihou	ROV	Farmer
Scarus oviceps	37.1	20	17.1	Herald	ROV	Scraper
Scarus dimidiatus	42.0	25	17.0	Willis	ROV	Scraper
Centropyge vrolikii	41.7	25	16.7	Herald	ROV	Grazer
Scarus rubroviolaceus	51.0	36	15.0	Holmes	BRUV	Scraper
Naso brachycentron	44.0	30	14.0	Chilcott	BRUV	Browser
Hipposcarus longiceps	53.0	40	13.0	Wreck	BRUV	Scraper
Scarus flavipectoralis	52.3	40	12.3	Willis	ROV	Scraper
Naso tonganus	52.0	40	12.0	Herald	BRUV	Browser
Acanthurus olivaceus	55.2	46	9.2	Lihou	ROV	Grazer
Scarus forsteni	39.0	30	9.0	Lihou	ROV	Scraper
Centropyge heraldi	98.0	90	8.0	Lihou	ROV	Grazer
Pomacentrus brachialis	48.0	40	8.0	Lihou	BRUV	Farmer
Siganus punctatissimus	36.4	30	6.4	Bougainville	ROV	Grazer
Cetoscarus ocellatus	35.0	30	5.0	Herald	BRUV	Excavator
Scarus schlegeli	55.0	50	5.0	Lihou	BRUV	Scraper

Figure 4.17 - Herbivorous fish from a variety of families, trophic or functional groups were recorded at depths that were at least 5m greater than their maximum depth listed on fishbase. A. *Chlorurus microrhinos,* recorded at 68m at Osprey Reef (an 18m depth extension), B. *Scarus niger,* recorded at 67.8 m (a 47.8m depth extension), C. *Acanthurus nigrofuscus*, doubled its known depth range from 25m at 51m, D. *Ctenochaetus striatus* more than doubled its known depth range from 30m at 65m. Photographs courtesy of Victor Huertas

Species richness, abundance and biomass of herbivorous reef fishes

Within shallow coral reef ecosystems the richness, abundance and/or biomass of herbivorous reef fishes are generally greatest on the reef crest (2-4m depth) and decrease both across the reef flat and down the reef slope (e.g., Russ 2003; Fox and Bellwood 2007; Hoey and Bellwood 2008). Interestingly, our surveys revealed the greatest species richness of herbivorous fishes occurred within the 30-40m depth band, and decreased gradually at both shallower and greater depths (Figure 4.18). This pattern in species richness was evident across three of the four major functional groups, with the highest species richness of excavating and scraping parrotfishes, and grazing fishes being recorded within the 30-40m depth band. This is in contrast to studies of other mesophotic reef systems that have generally reported the species richness of herbivorous fishes to decline with depth (e.g., Brokovich et al. 2010; Cure et al. 2021).

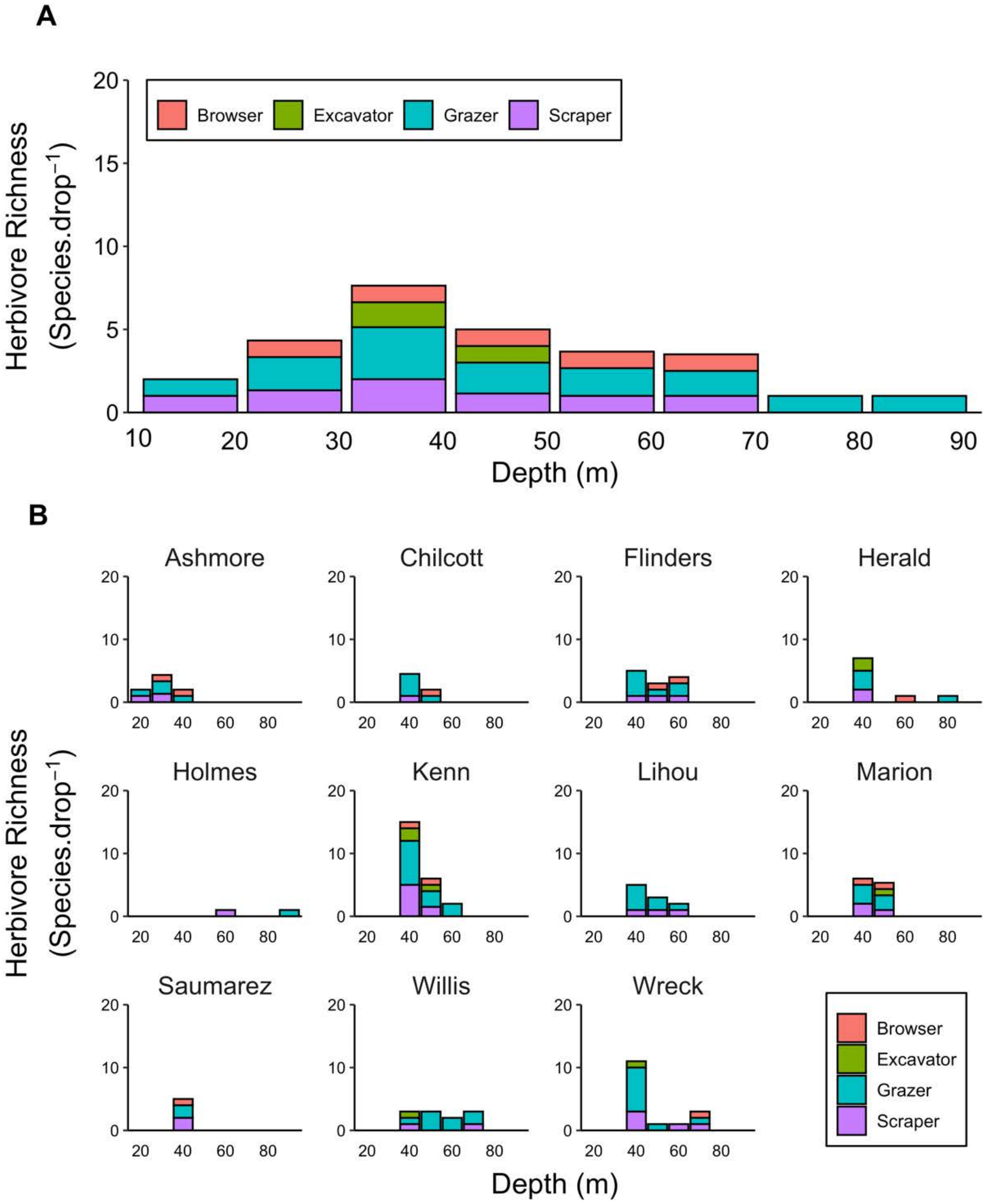


Figure 4.18 – Average richness (mean species per drop) of herbivorous fishes recorded by BRUV drops between 10 -90m. Each bar represents a 10m depth bin and is proportionally shaded according to functional group **A.** richness summarised across all drops at all reefs surveyed and **B.** richness summarised across all drops at individual reefs. For 6B the depth below each bar represents the upper range of the bin.

The abundance of herbivorous fishes displayed slightly contrasting patterns with depth between the BRUV and ROV surveys (Figures 4.19, 4.20). The relative abundance (i.e. MaxN) of herbivorous fishes recorded on the BRUVs generally mirrored that of species richness, with the relative abundance of herbivorous fishes being greatest within the 30-40m depth band (15 individuals per BRUV drop), and decreasing in both shallower and deeper habitats (Figure 4.19). The high abundance of grazing of fishes in the 80-90m depth band was driven by a single BRUV drop at Holmes Reef in which a school of 29 *Acanthurus dussumieri* were recorded (Figure 4.19b), and is unlikely to be representative of the broader CSMP. The greater relative abundance of fishes was largely consistent across excavating, scraping and grazing groups, while the greatest relative abundance of browsing fishes was recorded in the 60-70m depth band (Figure 4.19). Although there were some differences among reefs in the overall relative abundance of herbivorous fishes (e.g., ~ 30 individuals per drop on Kenn Reef vs 7 individuals per drop at Lihou Reef) the greatest abundance of herbivorous fish was generally recorded between 20 – 50m, the only exception being Holmes Reef where the highest abundance was recorded at 80-90m (discussed above).

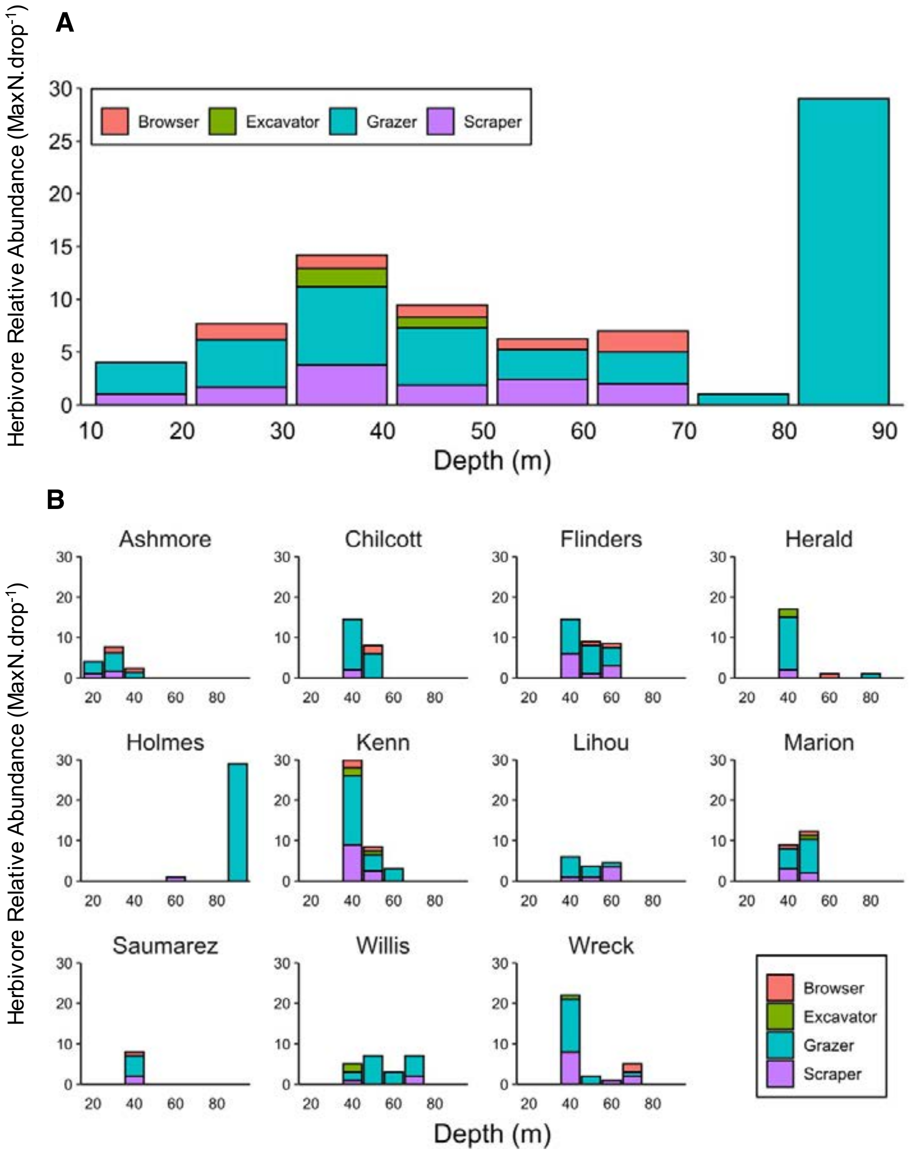


Figure 4.19 – Average relative abundance (mean MaxN) of herbivorous fishes recorded by BRUV drops between 10 - 90m. Each bar represents a 10m depth bin and is proportionally shaded according to functional group **A.** Relative abundance summarised across all drops at all reefs surveyed and **B.** Relative abundance summarised across all drops at individual reefs, where depth below each bar represents the upper range of the bin.

In contrast to the BRUV surveys, the ROV surveys revealed a gradual decline in the abundance of herbivorous fishes with increasing depth (Figure 4.20). Similar declines in the abundance of herbivorous fishes have been recorded across similar depth ranges on coral reef ecosystems globally (e.g., Brokovich et al. 2010; Bejarano et al. 2014; Fukunaga et al. 2016; Kane and Tissot 2017; Coleman et al. 2018; Cure et al. 2021). The observed differences between the BRUV and ROV surveys are likely related to differences in methodology, specifically the BRUVs only sample a limited area, provide an estimate of relative abundance, and attract larger predators, whereas the ROV essentially replicates diver-based surveys of belt transects, and also the habitat sampled. BRUVs are restricted to sampling habitats with a relatively flat horizontal topography, whereas the ROV can be used to survey a range of habitats, including the steep walls that are characteristic of many CSMP reefs.

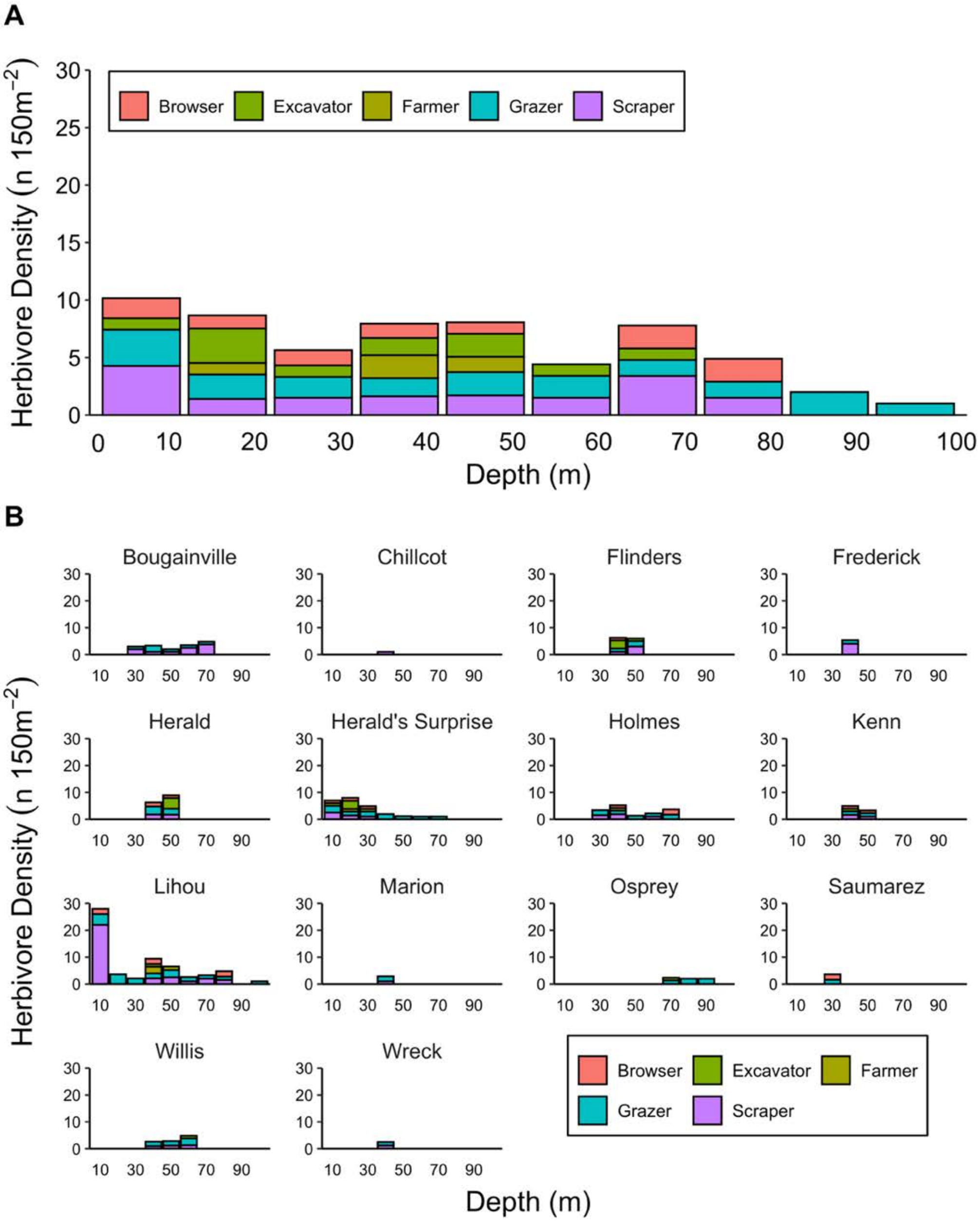


Figure 4.20 - Average density (mean individuals per 150m^2) of herbivorous fishes recorded by ROV surveys between 0 -100m. Each bar represents a 10m depth bin and is proportionally shaded according to functional group **A.** density summarised across all transects at all reefs surveyed and **B.** density summarised across all transects at individual reefs. For 7B the depth below each bar represents the upper range of the bin.

Algal communities

The distribution of macroalgae is often shown to be negatively correlated to the abundance of herbivorous fishes across a range of spatial scales in shallow coral reef ecosystems (e.g., Fox and Bellwood 2007; Wismer et al. 2009; Rasher et al. 2013). While such correlative approaches provide a useful comparison for deeper reef habitats, it is important to recognise that the cover and composition of macroalgal assemblages are shaped by a range of environmental and biotic factors.

Macroalgae and turf algae were common and abundant substrata recorded by both ROV and BRUV benthic surveys. The cover of macroalgae displayed a contrasting pattern with depth between the BRUV and ROV surveys (Figures 4.21, 4.22). The BRUV surveys indicated a general increase in the cover of macroalgae (predominantly the brown alga *Lobophora*, and the calcifying green alga *Halimeda*) with depth, from 10.5 % at 30-40m, to 25 % at 70-80m (Figure 4.21). In contrast, the ROV surveys showed a rapid increase in macroalgal cover (predominantly *Padina*, *Lobophora* and *Halimeda*) from 1.7 % at 0-10m to a maximum of 21.8 % at 20-30m, after which it gradually declined to <3% at 70-100m (Figure 4.22). The differences in macroalgal cover between the two survey methods likely reflect differences in the habitats sampled, with BRUVs only sampling relatively flat habitats (see also Section *4.3 Benthic Communities*).

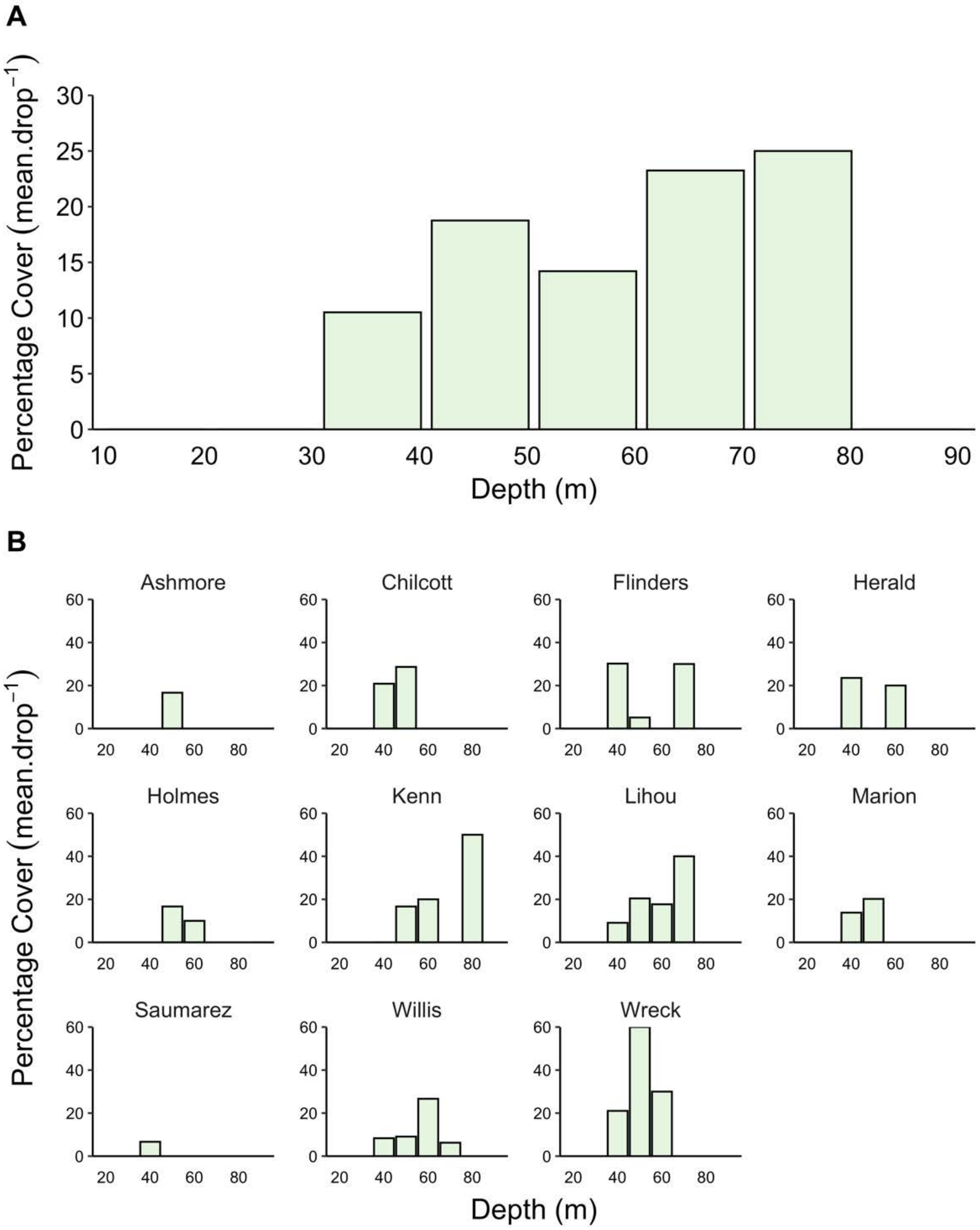


Figure 4.21 - Average percentage cover of macroalgae recorded by BRUV drops within 10m depth bins from 10 - 90 m **A.** summarised across all drops at all reefs and **B.** summarised across all drops at individual reefs. The depth below each bar in panel B represents the upper bound of each bin.

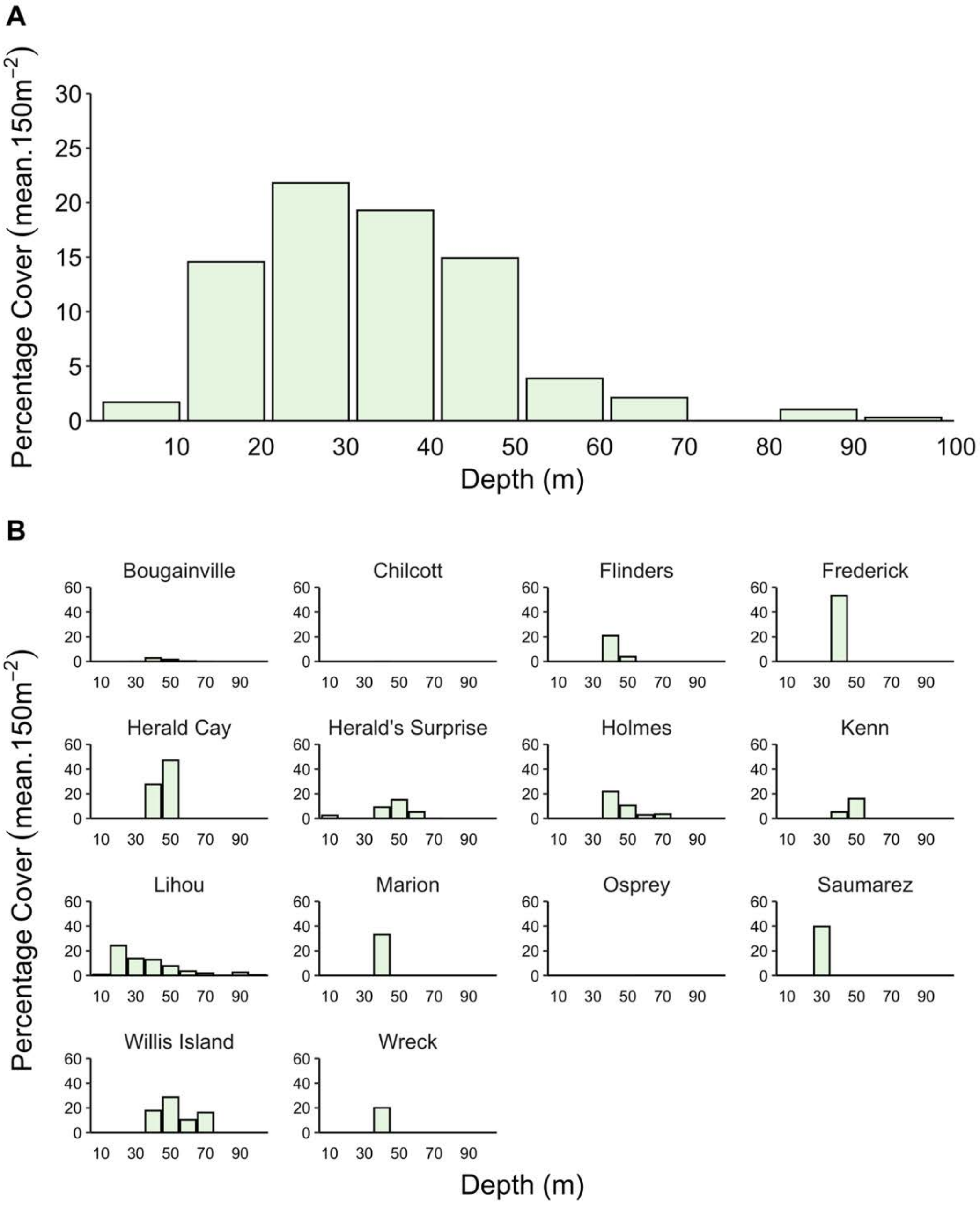
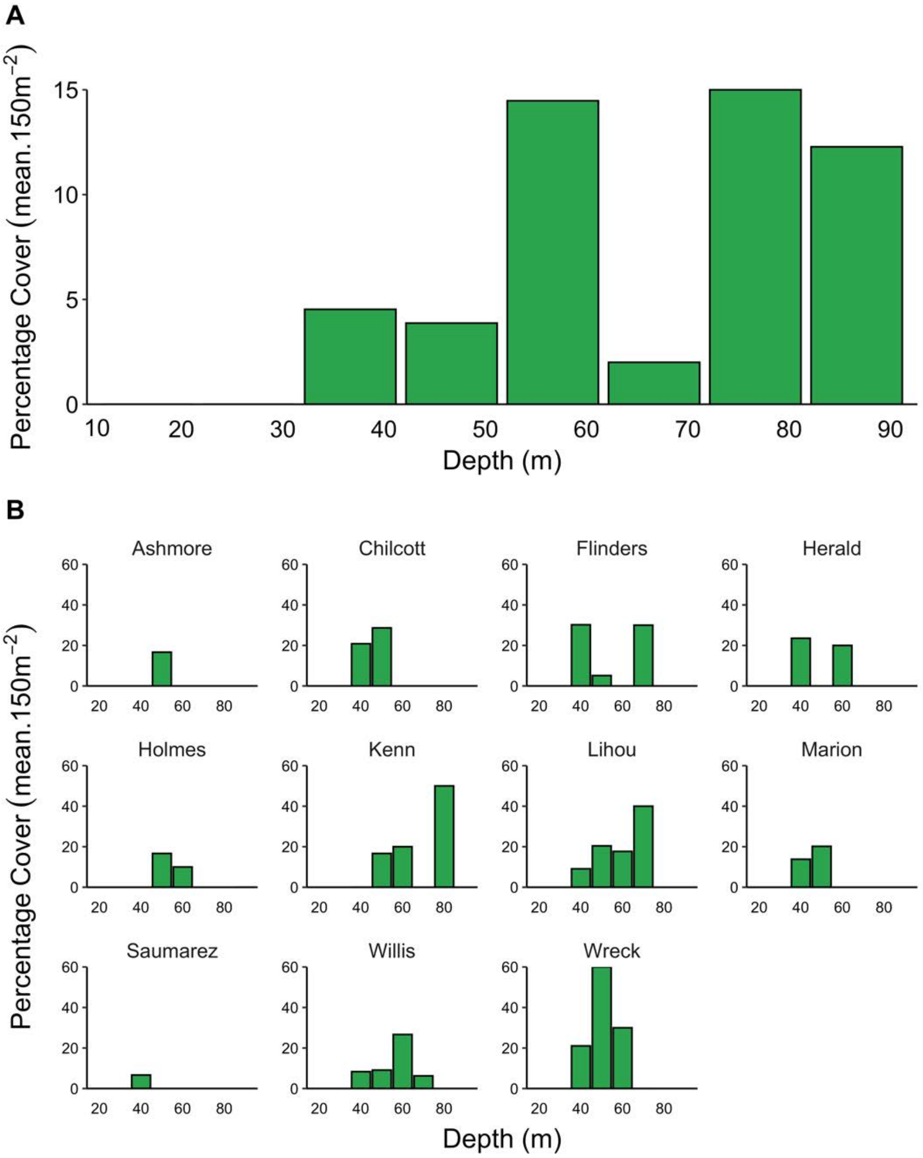


Figure 4.22- Average percentage cover of macroalgae recorded on ROV transects (150m^2) within 10m depth bins from 0 - 100 m **A.** summarised across all transects at all reefs and **B.** summarised across all transects at individual reefs. The depth below each bar in panel B represents the upper bound of each bin.

Differences in the cover of turf algae with depth were also evident between the BRUV and ROV surveys (Figures 4.23, 4.24). Data from the BRUV surveys show that the cover of turf algae was variable among depth with the cover of turf algae being <5% for three of the six depth bands sampled (i.e., 30-40m, 40-50m, and 60-70m), and >12% cover for the other three depth bands sampled (Figure 4.23). In contrast, the estimates of turf algal cover from the ROV surveys were generally higher (up to 57% for the 0-10m depth band) than those from the BRUV surveys (up to 14%), and displayed a decrease in cover from 57% at 0-10m to 12% at 40-50m, after which it was relatively constant across the remaining depth gradient (i.e., 40-100m) (Figure 4.24). While grazing, excavating and scraping fishes typically feed on substrata colonised by turf algae and associated microbes, the abundance of these fishes has been shown to be related to the productivity, but not cover, of turf algae (Russ 2003). The high cover of turf algae in the 0-20m depth range on CSMP reefs in this study likely reflects the rapid colonisation of dead coral skeletons by algal assemblages (Diaz-Pulido and McCook 2002) following the recent bleaching events in the CSMP (Hoey et al 2020, 2021, 2022).



Figures 4.23 - Average percentage cover of turf algae recorded by BRUV drops within 10m depth bins from 10 -90 m **A.** summarised across all drops at all reefs and **B.** summarised across all drops at individual reefs. The depth below each bar in panel B represents the upper bound of each bin.

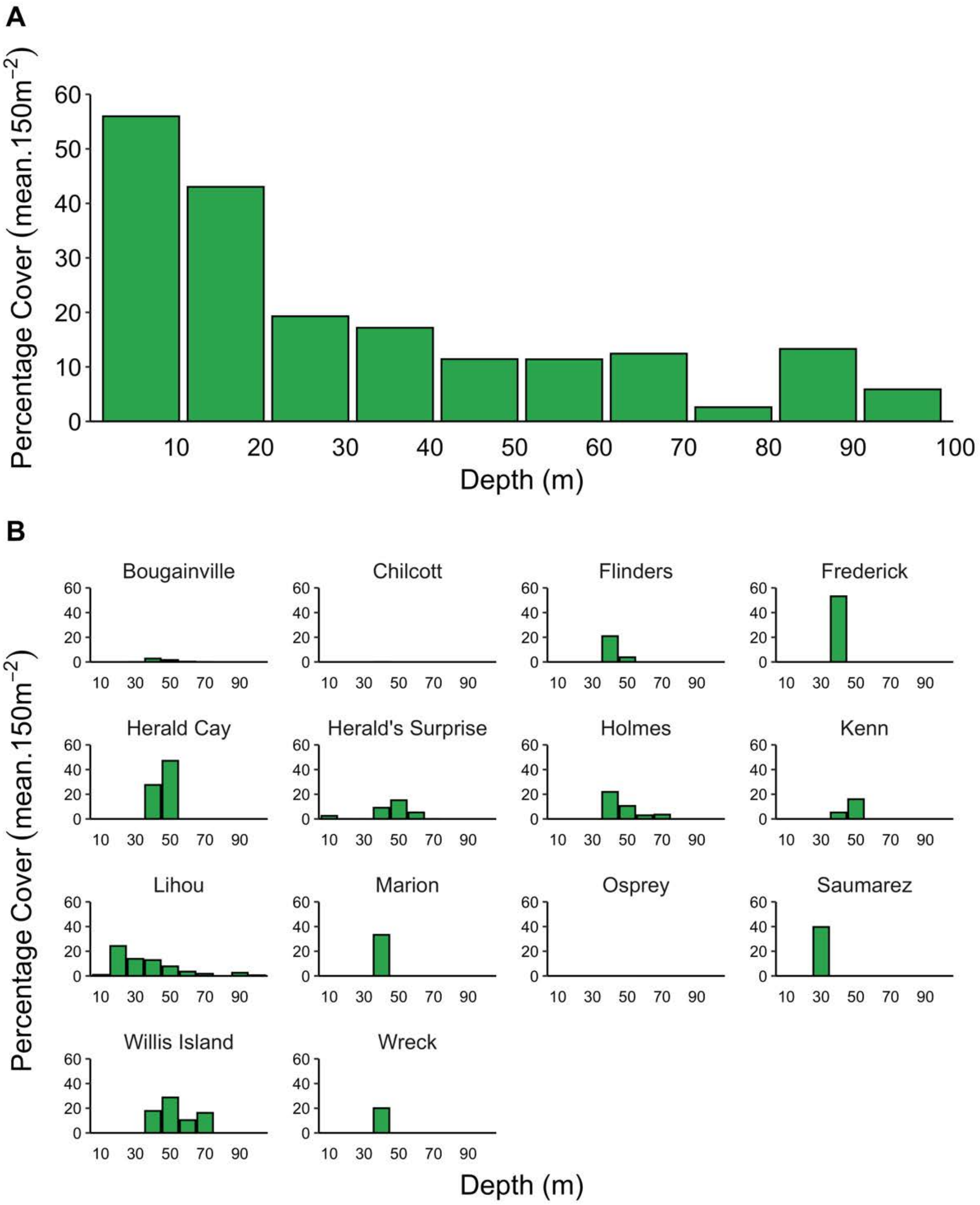


Figure 4.24 - Average percentage cover of turf algae recorded on ROV transects (150m^2) within 10m depth bins from 0 - 100 m **A.** summarised across all transects at all reefs and **B.** summarised across all transects at individual reefs. The depth below each bar in panel B represents the upper bound of each bin.

4.3 Benthic communities

4.3.1 *Spatial variation among reefs*

ROV surveys were conducted in range of deep water habitats across the CSMP, including the channels between areas of shallow reef, lagoon and outer reef habitats. There was considerable variation in the cover of the twelve major benthic categories both among and within habitats (Figure 4.25). Lagoon habitats were typically dominated by unconsolidated substrata, predominately sand (45.7 – 82.9%), the green calcareous alga *Halimeda* (1.1 – 33.3%), and other macroalgae (0 - 39.7%). Whilst hard coral was present on small patch reefs or bommies within some lagoon sites, the average cover was low (0 - 3.1%; Figure 4.26). Interestingly, no seagrass was observed across all lagoonal sites.

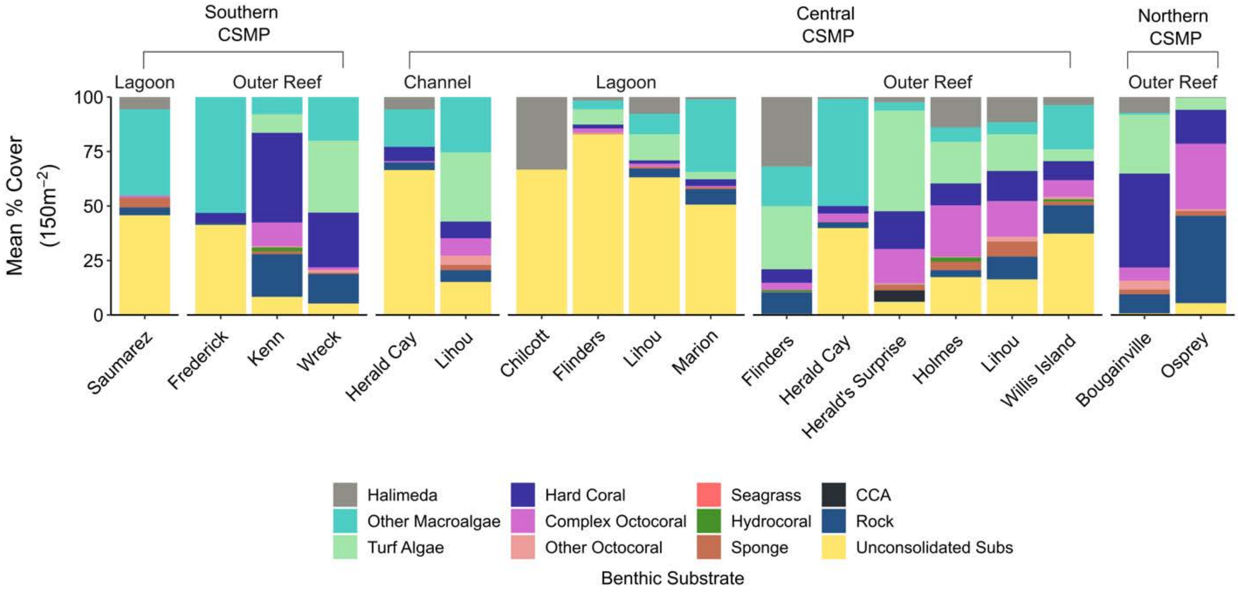


Figure. 4.25 Variation in the percentage cover of main benthic substrata among and within three main habitat types; Channel, Lagoon and Outer Reef. Percent cover is averaged across transects, sites and depths for each reef where ROV surveys were conducted.

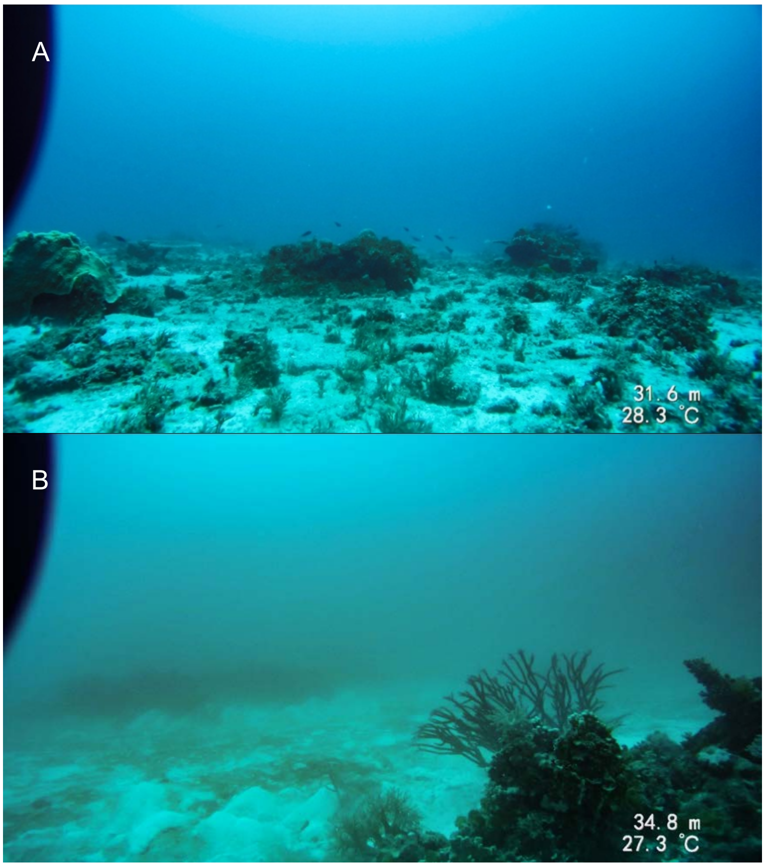


Figure 4.26 Small patch reefs and bommies among unconsolidated substrates in lagoonal habitat supported a low cover of hard corals (e.g., encrusting, branching and tabulate hard corals pictured). A Lihou Reef (31.6 m) and B Marion Reef (34.8m)

Surveys of channel habitat (openings between shallow reefs that connected lagoon and pelagic environments) were limited due to difficulties in operating the ROV in conditions of high current flow and turbulence, and the accessibility of other deep habitats in the vicinity. ROV surveys of channel habitat were successfully conducted at Herald Cay and Lihou Reef, with the benthic composition of channels at Lihou Reef being more diverse than the channels at Herald Cay. The channels at Herald Cays were dominated by unconsolidated substrata (66.5%) and ‘other’ macroalgae (17.2%), while *Halimeda*, hard corals, complex octocorals and rock accounted for the remaining 16.33 % (Fig 4.25). In contrast, the benthic communities of channels at Lihou Reef were dominated by turf algae (31.8%), other macroalgae (25. 3%), and unconsolidated substrata (15.1 %), with hard corals, complex octocorals, other octocorals, sponge and rock collectively accounting for 27.8 % (Figure 4.25, 4.27).

Figure 4.27 Image of a channel habitat at Lihou Reef (35.8m) characterised by unconsolidated substrata, turf algae, macroalgae and octocorals (fans and branching soft corals) attached to a small bommie

Benthic composition on outer reef habitats was highly variable reefs, with some outer reef habitats being dominated by unconsolidated substrata and ‘other’ macroalgae (e.g., Frederick Reef and Herald Cay), while others were dominated by hard corals and octocorals (e.g., Bougainville and Kenn Reefs; Figure 4.25). Overall, hard coral cover was most prevalent in outer reef habitats compared to channels and lagoons, although was also highly variable among reefs ranging from 3.5% at Herald Cay to 43.1% at Bougainville Reef (Figure 4.25). These differences among reefs didn’t appear to be related to reef geomorphology or region. For example, Osprey and Bougainville reefs in the northern CSMP both have steep-sided seamount-like geomorphologies, yet the outer reef habitats of Osprey Reef were dominated by complex octocorals (30.1%) and rock (40.1%) (Figure 4.28) and had relatively low cover of hard coral (15.5%), whereas similar habitats on Bougainville Reef were dominated by hard corals (43.1%) and turf algae (27.0%).

Figure 4.28 – Image of a typical outer reef habitat on Osprey Reef (83.3m), showing the steep gradient with benthic community characterised by complex octocorals and rock

4.3.2 *Variation in benthic composition among depths*

The ROV surveys show that coral cover in the CSMP followed a bimodal distribution with depth, with peaks in coral cover of 17.4% between 11-20m and 32.3% between 71-80m, averaged across reefs (Figure 4.29). These estimates of coral cover on deep reef habitats with the CSMP are comparable to, or greater than, recent estimates of shallow water (2-10m) coral cover on eleven CSMP reefs (2021: 15.7%; 2022: 12.8%; Hoey et al. 2022), and highlight the potential importance of these deep habitats in supporting the biodiversity and functioning of the CSMP. The peak in coral cover at 11-20m was driven by a diversity of growth forms, however, the cover of complex and, to a lesser extent, massive and submassive growth forms tended to decrease with depth (Figure 4.29). The peak in coral cover at 71-80m was driven almost entirely by an increase in the cover of plating corals (primarily *Montipora* and *Pachyseris*), from 4% at 41-50m to 30% at 71-80m. These areas of high cover of plating corals at depth were particular evident at Bougainville and Lihou reefs, where the cover of these corals approached 70% at some sites (Figure 4.30, Figure 4.31, Section *4.6 Deep Water Bright Spots*).

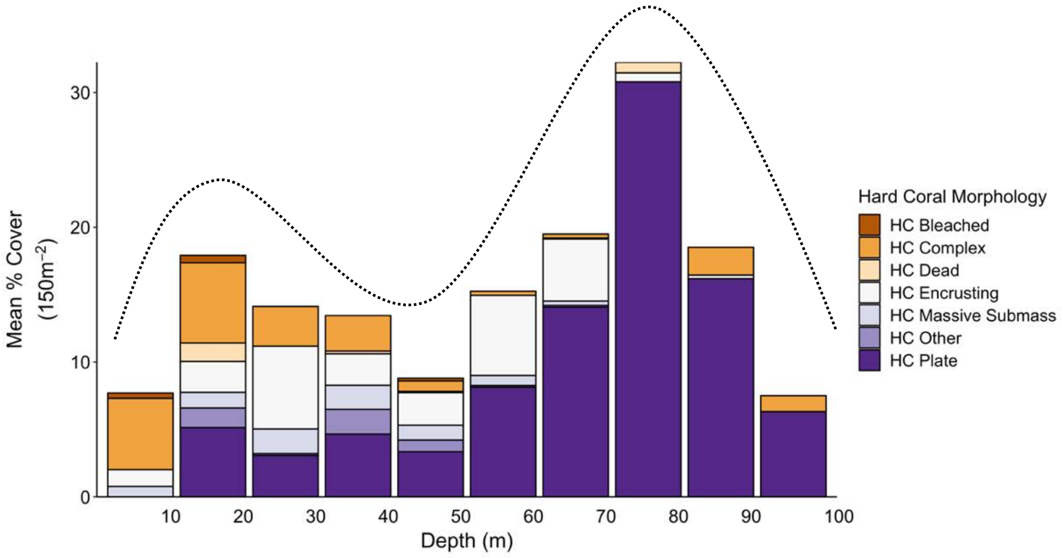


Figure 4.29 – Average percentage cover of hard coral with depth, averaged across all reefs from 171 ROV transects. Dotted line has been overlayed to highlight bimodal trend in hard coral cover with depth.

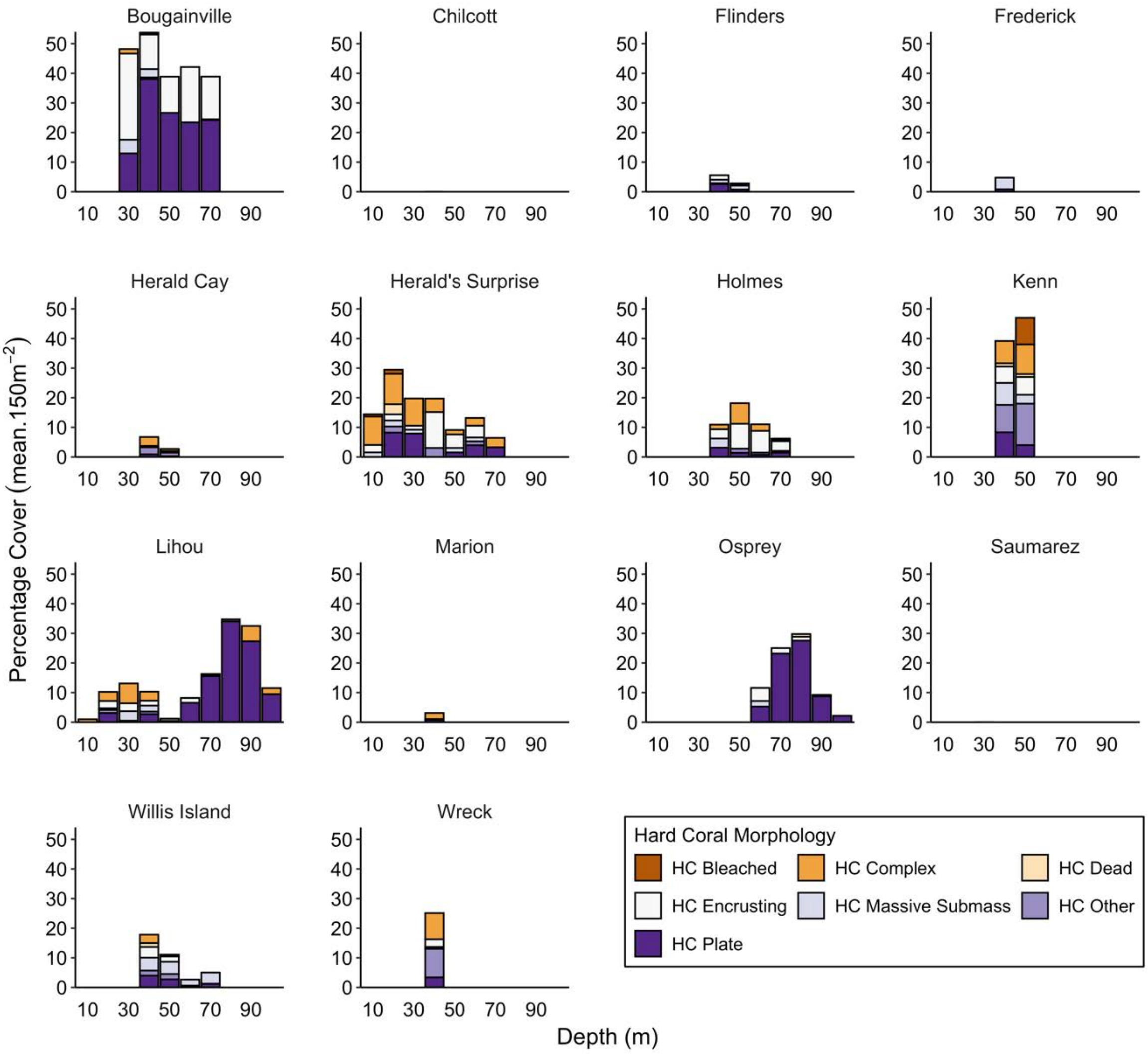


Figure 4.30 - Average percentage cover of all hardcoral (HC) types recorded by Remotely Operated Vehicle (ROV) surveys at each reef. Percentage cover is summarised in 10m depth bands at the reef level

Coral cover on reef habitats was, however, variable among reefs. For example, coral cover on reef habitat >50m at Lihou, Bougainville and Osprey reefs was 2- to 4-fold higher than corresponding habitats on Holmes and Herald's Surprise reefs, and Willis Islet (Figure 4.30 and 4.31). Notably, coral cover on Lihou Reef averaged 40.0% between 71-100m which is considerable higher than current (10%; Hoey et al. 2022) and historic (ca. 1-6%: Ayling and Ayling 1985; Oxley et al. 2003; Ceccarelli et al. 2008) estimates of shallow water coral cover. Moreover, Herald's Surprise Reef which could be considered as a 'dark spot' among CSMP reefs in terms of recent shallow water coral cover (6.8%; Hoey et al. 2022) had average coral cover of 17.3%

from 10-80m, with a low of 6.5% at 71-80m and a high of 29.4% at 21-30m. These deep water reef habitats appear to be supporting significant coral communities, that are likely to escape the effects of disturbances that are increasingly impacting shallower water coral communities (i.e., marine heat waves and severe storms), and may be critical to the future functioning of CSMP reefs.

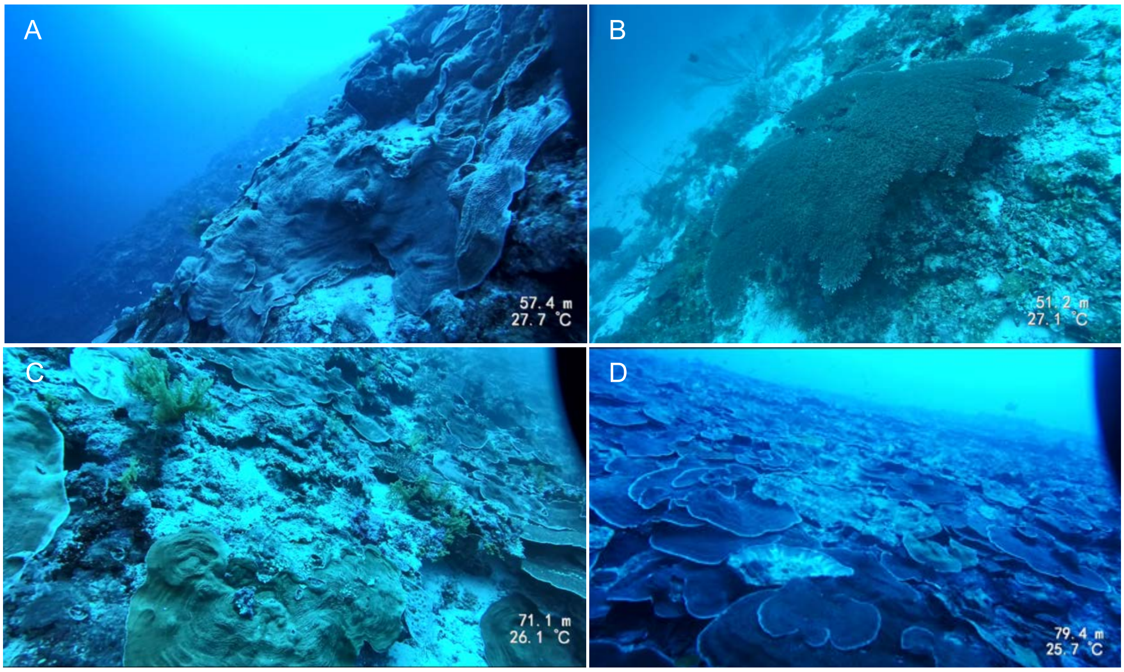


Figure 4.31– Images of deep reef habitats in the Coral Sea Marine Park showing areas of high coral cover A. Encrusting and plating *Pachyseris* at 57.4m on Bougainville Reef, B. A large tabular *Acropora* at 51.2m on Willis Islet, C. Encrusting and plating *Pachyseris* at Osprey Reef in 71.1m and D. very high cover of plating *Montipora* at 79.4m at Lihou Reef (Edna Cay).

ROV surveys show total algal cover generally decreased with depth across the CSMP surveyed, from 72.8% at 0-10m to 23.6% at 51-60m, after which it was relatively stable (Figure 4.32). The overall decline in algal cover with depth was driven by declines in turf algae and CCA. In contrast, the cover of *Halimeda* tended to increase in cover with depth, from 2.9% at 0-10m to 10.2% at 81-90m, while the cover of ‘other’ macroalgae (primarily the foliose macroalgae *Lobophora* and *Udotea*) was highest (19.3%) at moderate (30-50m) depths, and decreased in both shallower and deeper habitats (Figure 4.33, Figure 4.34a,b). There was, however, considerable variation among reefs, with algal cover at Lihou Reef reflecting a general decline in algal cover with depth, while algal cover at Herald’s Surprise Reef was high (52.4%) and relatively consistent between 11-80m (Figure 4.32, Figure 4.33).

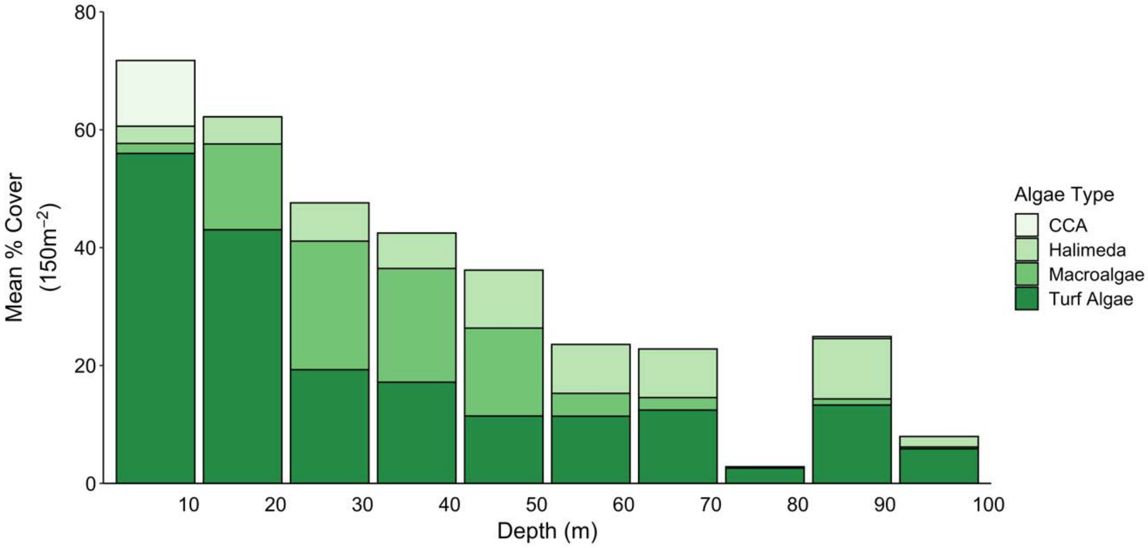


Figure 4.32 – Average percentage cover of all algae types recorded in ROV surveys. Average percent cover is summarised for 10m depth bands across all reefs in the CSMP surveyed by ROV.

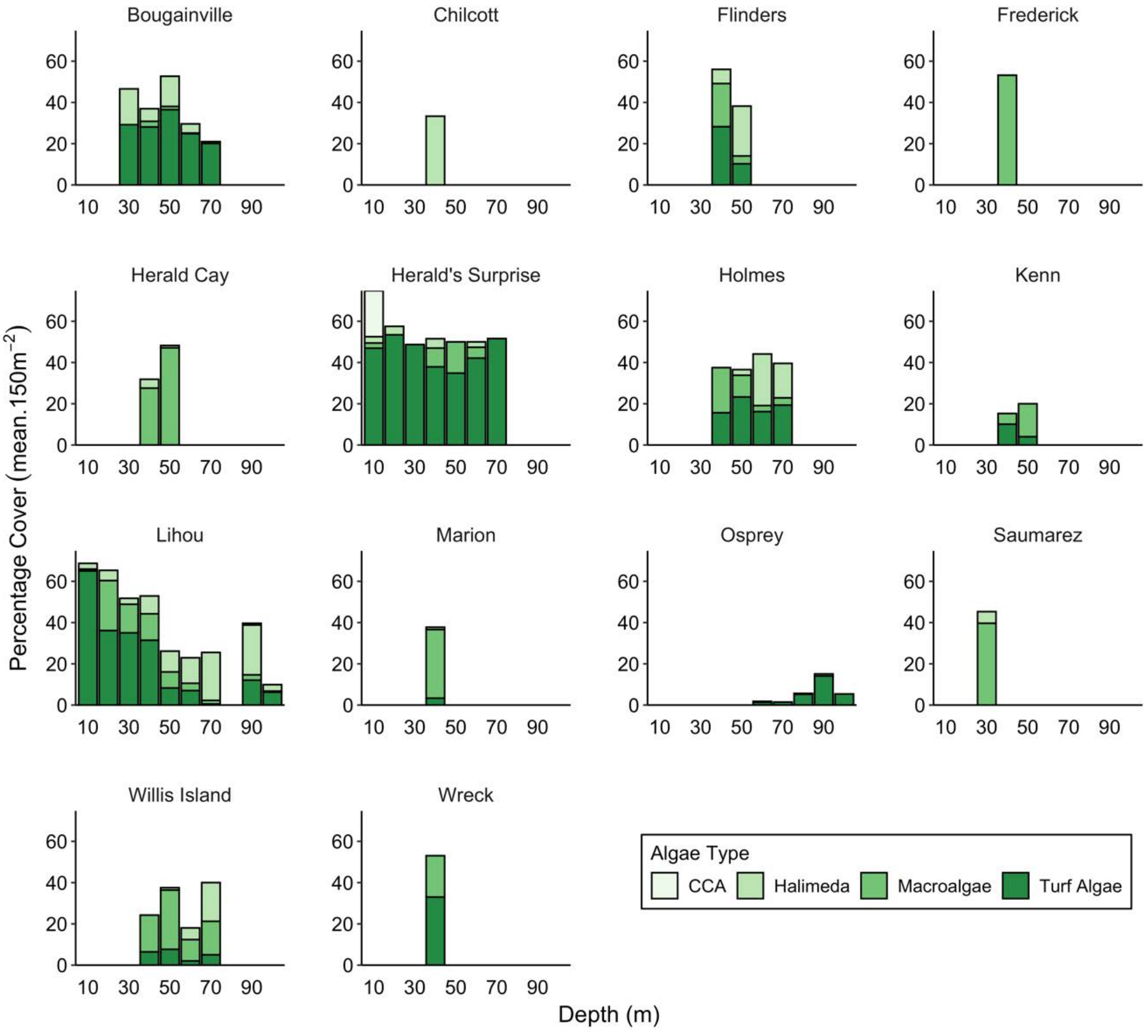


Figure 4.33 – Average percentage cover of all algae types recorded by ROV surveys at each reef. Percentage cover is summarised in 10m depth bands at the reef level.

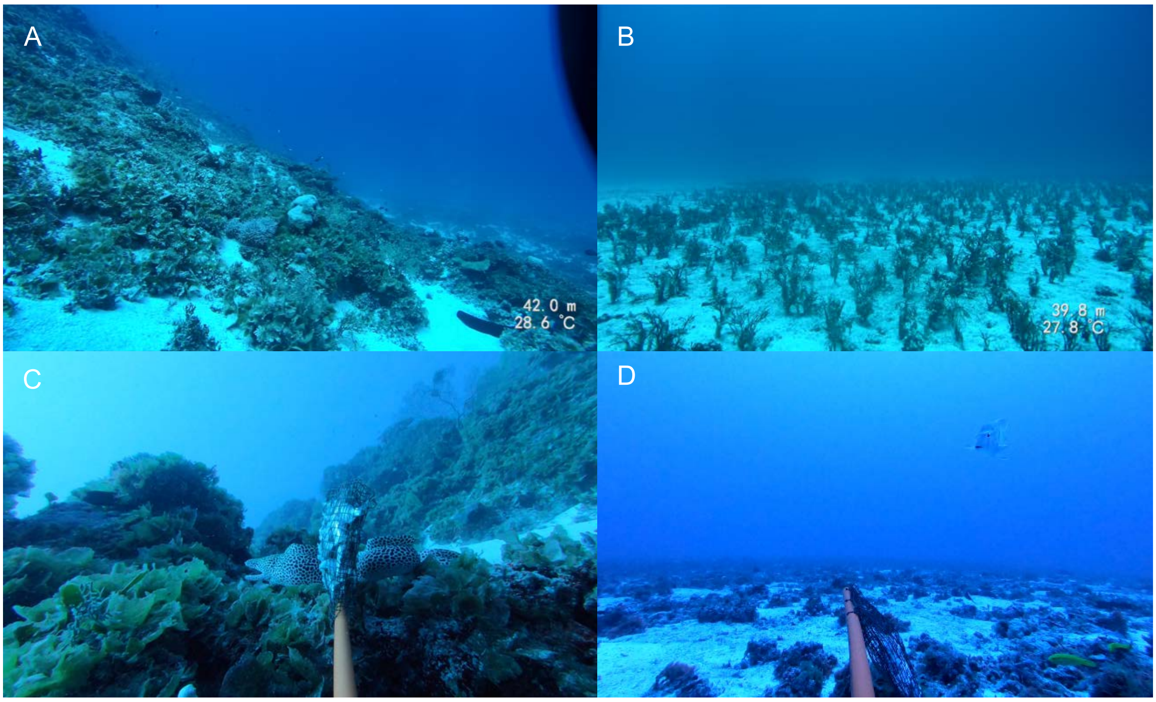


Figure 4.34 - Deep water macroalgae assemblages within the Coral Sea Marine Park were observed on ROV. **A.** High cover of *Lobophora* and other macroalgae at 42m Willis Island **B.** High cover of *Halimeda* cf. *cylindrica* in the lagoon of Chilcott Reef at 40m, and BRUV **C.** Laminate macroalgae in outer reef habitat, Lihou Reef, 45m, with a moray eel *Gymnothorax favagineus* pictured, **D.** Filamentous turf and macroalgae on patchy outer reef habitat at Kenn Reef, 72m.

The structural complexity of deep reef habitats on CSMP reefs was generally low (complexity scores of 1-3), with no/few areas being highly complex (complexity scores of 4-5). Estimates of structural complexity were relatively consistent among depth with each reef (Figure 4.35) and likely reflect the geomorphologies of individual reefs, rather than changes in the cover and composition of coral assemblages. For example, the steep slopes and walls (~90° slope) of Bougainville and Osprey reefs were generally consistent at moderate complexity (~2-2.5) despite changes in coral cover with depth. In contrast, the structural complexity of reef habitats on Lihou Reef varied from 0.5 to 2.3 and largely mirrored that of changes in the cover of hard and soft corals, in particular large gorgonians at Juliette and Edna Cays.

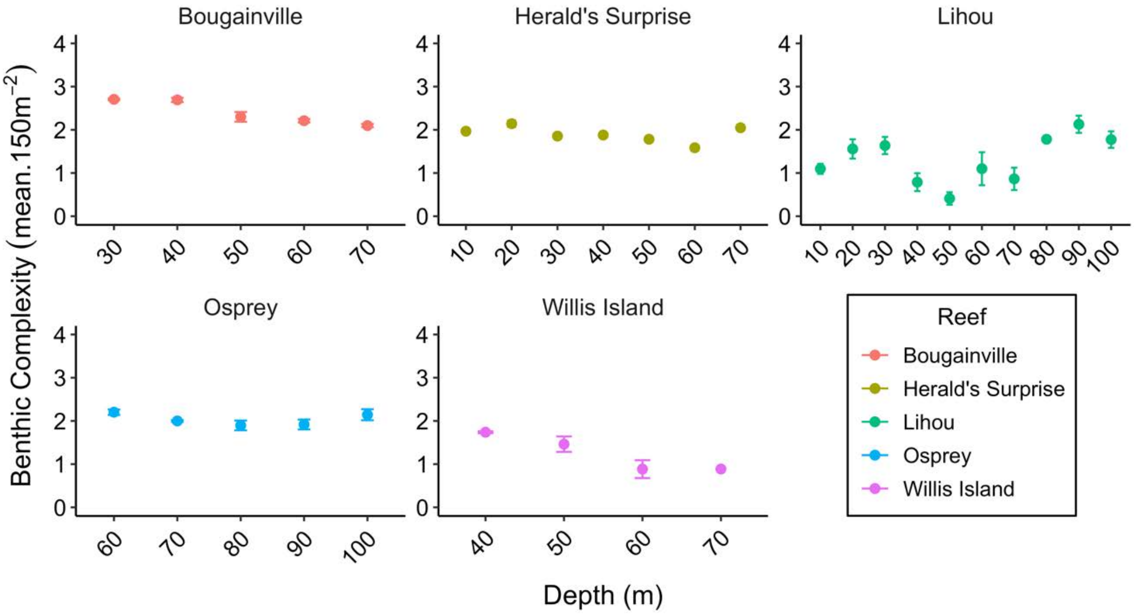


Figure 4.35 - Average benthic complexity at reefs where ROV surveys were conducted over the most extensive depth ranges.

Community composition

The spatial resolution afforded by the ROV showed variation in benthic communities among CSMP regions and with environmental conditions (Figure 4.35). There was a clear separation of benthic communities between the northern CSMP (Bougainville and Osprey Reefs) compared to the southern CSMP (Wreck, Kenn and Frederick Reefs), while benthic communities of the central CSMP (Flinders, Holmes, Herald's Surprise, Lihou, and Marion Reefs, Willis and Chilcott Islets, and Herald Cay) were more variable. The northern CSMP was characterised by plating hard coral and complex octocorals (i.e., gorgonian fans and/or branching soft coral), with outer reef habitats ($r^2 = 0.52$, $p = 0.001$), slopes of ~90° (i.e., reef walls; $r^2 = 0.16$, $p = 0.001$), and greater depths > 65m ($r^2 = 0.34$, $p = 0.001$) contributing to these distinct habitats. In contrast, the southern CSMP was characterised by a higher cover of macroalgae, with moderate (30 - 65m) depths ($r^2 = 0.17$, $p = 0.001$), slope / terrace habitats ($r^2 = 0.10$, $p = 0.001$), and water temperature ($r^2 = 0.21$, $p = 0.001$) being related to these distinct communities.

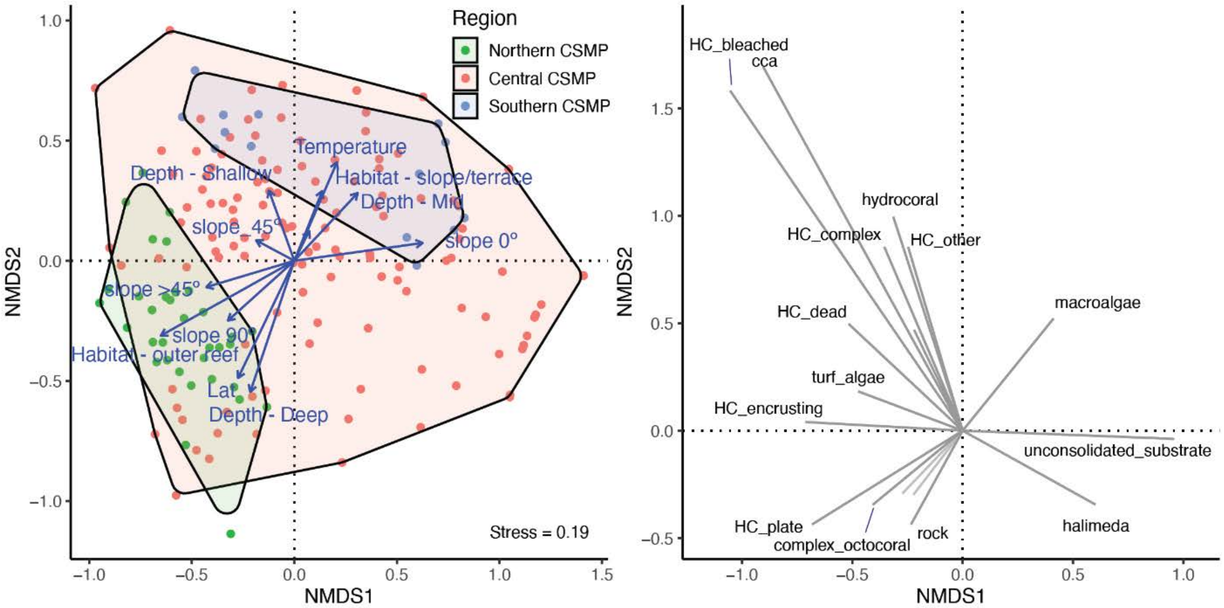


Figure 4.35 - Variation in the composition of benthic communities within the Coral Sea Marine Park, observed on ROV transects. Non-metric multidimensional scaling (nMDS) plots show the variation in benthic composition among the Northern CSMP (Bougainville and Osprey Reefs - green dots and shaded area), Central CSMP (red dots and shaded area) and Southern CSMP (blue dots and shaded area), with influential environmental variables overlayed (blue vectors). Analyses are based on benthic data extracted from 171 ROV transects. Vectors (right plot) indicate key taxa that account for the variation among transects (left plot), grouped by CSMP region.

4.3.3 BRUV Benthic Surveys: Habitat composition and complexity

BRUVS drops were conducted in Channel, Inner Reef, Lagoon and Outer Reef habitats (Figure 4.36), Notably, different habitats were surveyed using BRUVS vs ROV at the same reef (Figure 4.25). For example, at Chilcott, BRUVS were deployed on outer reefs while the ROV surveyed the lagoon. Additionally, BRUVS were deployed at Ashmore Reef lagoon in the Far Northern CSMP, when weather prohibited using the ROV. Inner reefs, surveyed using BRUVS only, were the inside edge, lee or lagoonal side of contiguous reefs (i.e. not facing the open ocean). It should be noted that irrespective of the habitat type, BRUVS were typically deployed on gentler slopes than the ROV was able to operate, to ensure deployment success. Extending the spatial coverage in this way allowed for more comprehensive and complementary survey of reef benthos and fishes at each reef.

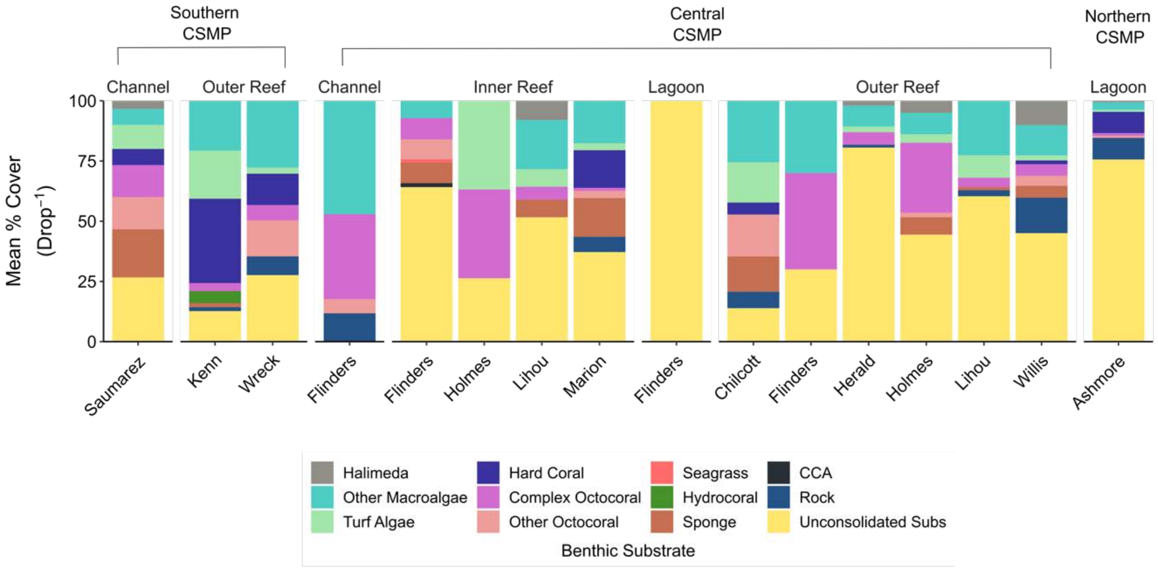


Figure 4.36 - Mean percentage cover of main benthic substrata estimated using BRUVS, grouped by habitat type. Percent cover is averaged across drop, site and depth for each reef where BRUV surveys were conducted.

Inner reefs of Flinders, Holmes, Lihou and Marion all had a relatively high proportion of unconsolidated substrates, the presence of octocorals (fans and/or soft corals), and a low proportion of hard corals. Three of four inner reefs surveyed had between 7.3 – 16.1% sponge cover. Outer reefs, surveyed using BRUVS, were typically characterised by macroalgae at low (8.7% - Herald Cay) to moderate cover (30.0% - Flinders Reef) and unconsolidated substrates at moderate (12.7% - Chilcott) to high cover (80.6% - Herald). In general, compared to the ROV surveys, the areas suitable for BRUV deployment favoured generally lower cover of hard corals and consolidated substrates (rock, turf covered rock), higher unconsolidated substrates, a relatively high proportion of macroalgae (Figure 4.34) and unconsolidated substrates, and the presence of sponges and octocorals.

4.3.4 Octocoral communities

Octocorals, including gorgonians and branching soft corals, contributed significantly to the three-dimensional structure of deep reefs, and were observed on ROV surveys (Figure 4.37a-c) and BRUVS (Figure 4.37d-f). For example, deep outer reef habitats on Holmes Reef had a high proportion of complex octocorals (ROV: 23.8%; BRUVS: 31%) compared to other high cover benthic categories that tended to provide little three-dimensional structure (ROV: turf algae 19.1%, unconsolidated substrates 17.4%, Halimeda 13.9%; BRUV: unconsolidated substrates 44.4%, macroalgae 8.9%, sponge 7.2%) (Figure 4.25, Figure 4.36, Figure 4.37), with these habitats supporting diverse and abundant fish assemblages. A BRUV drop at 85m on Holmes Reef revealed benthic communities characterised by unconsolidated substrates and large fans, and also had the highest relative abundance (MaxN) of many fish species, including long-nosed emperor *Lethrinus olivaceus* (10 individuals), highfin grouper *Epinephelus maculatus* (4 individuals), pencil surgeonfish *Acanthurus dussumieri* (29 individuals), slender unicornfish *Naso lopezi* (9 individuals, and one of only two observations of this species and a new depth record by 15m), and emperor angelfish *Pomacanthus imperator* (2 individuals).

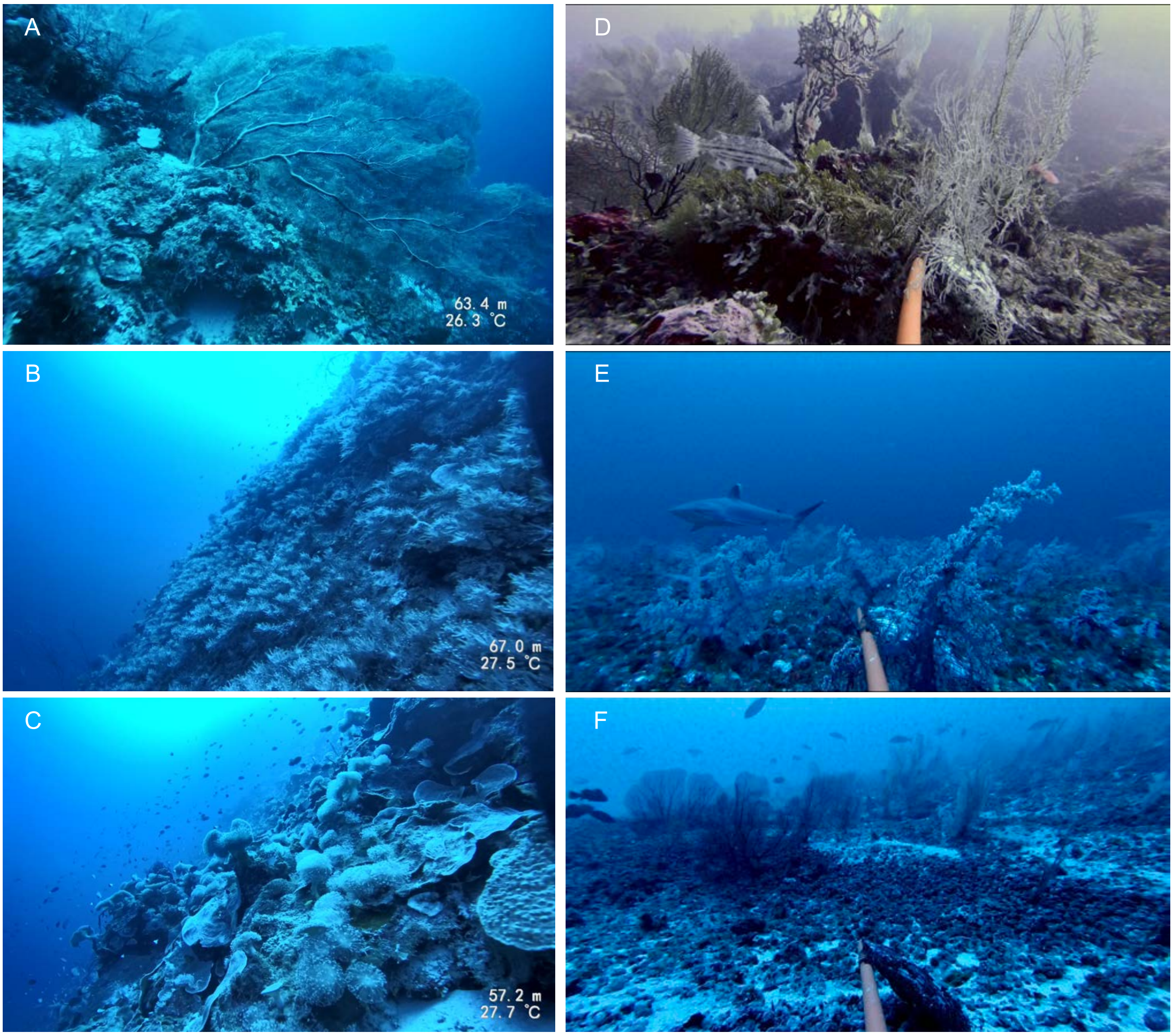


Figure 4.37 – Contributions of octocorals (gorgonians and branching soft corals) to the structure and complexity of deep reef habitats in the Coral Sea Marine Park (CSMP), observed on ROV **A**. A large gorgonian sea fan at 63.4m at Holmes Reef, **B.** An extensive bank of soft coral found at 67m at Bougainville Reef, **C**. High habitat complexity below 50m comprised of soft corals and plating hard coral at Bougainville Reef, and BRUV **D.** Dense small fans provided habitat for wrasses *Oxycheilinus* and *Pteragogus* species, juvenile emperor, and Serranids at 51m Holmes Reef, **E.** Large branching soft corals at Holmes Reef in 85m, **F.** Unconsolidated substrate and large gorgonian habitat at Holmes Reef in 85m were associated with the highest relative abundance of many fish species recorded across all BRUV drops.

4.3.5 Lagoon Habitats

Deep (> 30m) lagoonal habitats are characteristic on many of CSMP reefs and constitute large areas of non-reef habitat on these reefs. In this section we present findings from exploratory ROV dives conducted in the deep lagoons of Lihou, Marion, and Flinders reefs, and Chilcott Islet. Whilst formal deep lagoon surveys were not possible at every reef, either due to the shallow nature of some lagoons or weather conditions, these observations suggest that many CSMP lagoons provide a range of non-reef habitats (including bommies, soft coral, macroalgae, and soft sediment) which are likely important components of overall biodiversity, connectivity and ecological processes (Figure 4.38).

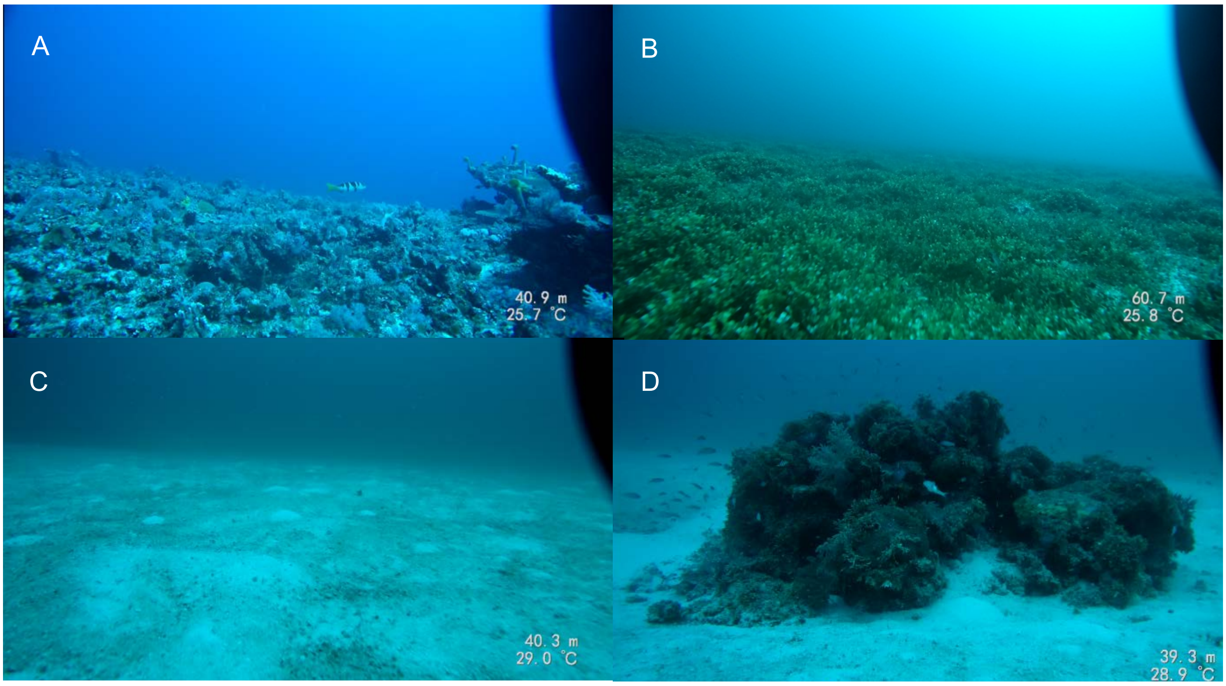


Figure 4.38 – A variety of habitats found at mesophotic depths of CSMP reef lagoons. A. A soft coral and macroalgal dominated habitat, 40m, Lihou. B. An extensive halimeda bed, 60m, South Diamond Islet. C. Unconsolidated soft sediment habitat, 40m, Flinders Reef. Evidence of bioturbation was observed in most soft-sediment areas, D. A small patch bommie, 40m, Lihou Lagoon (Middle Cay).

Lagoonal Bommies

Many deep lagoonal areas were interspersed with bommies (i.e., distinct structure composed of hard substrate) that rose various heights from the lagoon floor. Whilst many of the larger bommies within CSMP reef lagoons are mapped from aerial imagery or hydrographic charts, we found many others that are not mapped and typically did not rise above 10m depth. These bommies appeared to be composed of either unconsolidated or consolidated calcium carbonate with benthic organisms (e.g. hard corals, macroalgae, sponges) colonizing the available hard substrate. Bommies varied in size, from small patches less than 2m in diameter (Figure 4.38d) to large structures with 100-200m circumference (Figure 4.39).

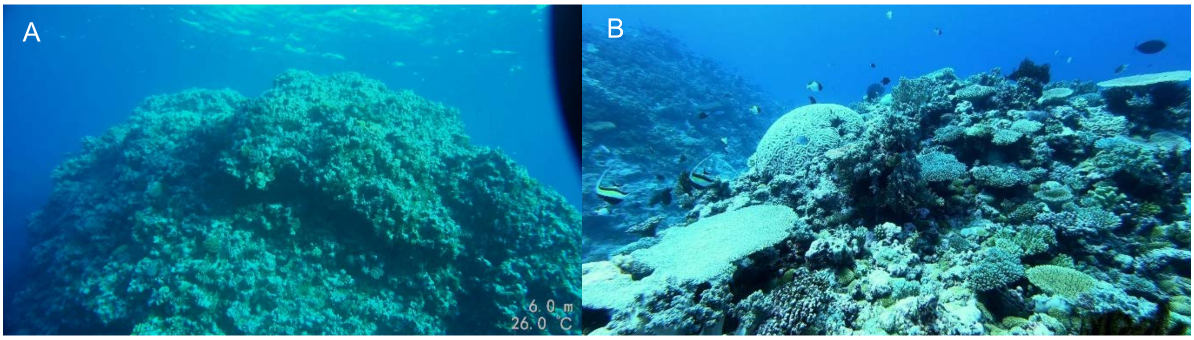


Figure 4.39 – A. A large bommie rising from 45m to <5m, Lihou Lagoon (Juliette Cay), **B.** Hard coral cover at a bommie in Marion Lagoon rising from 40m to 10m depth.

Fish are well known to aggregate around bathymetric structures, such as bommies and pinnacles (Samoilys 1997; Russell 2000: Galbraith et al. 2021). Although these features were generally too small to conduct dedicated transects with the ROV, they were notable hotspots of fish abundance and diversity in otherwise homogenous soft-substrate habitat. Hard coral colonies were also present on many of the larger lagoon bommies (Figure 4.2.18), along with fish species more typically found on outer reef slope habitats. One bommie, in particular, in the Marion Reef lagoon supported a high abundance of sharks, barracuda, carangids, lutjanids and serranids (Figure 4.39b, Figure 4.40). In total, 20-30 juvenile *Carcharhinus amblyrhynchos* were seen schooling at 30m around the slope of the bommie (Figure 4.40), as well as high abundance of *Sphyraena qenie* (30 + individuals), *Lutjanus gibbus* (20 + individauls), *Monotaxis heterodon* (30 + individuals) and *Plectropomus leopardus* (15 + individuals). The apparent abundance of these bommies suggests that there is potentially considerable additional coral habitat for reef taxa and other organisms within CSMP lagoons.

Figure 4.40 Images showing the high abundance of fishes at a deep bommie in the Marion lagoon.

We also recorded 8 individual lengths of monofilament fishing line on the bommie in the Marion Reef lagoon, ranging in estimated length between 1-30m (Figure 4.41). The presence of fishing line and the high abundance of fishes suggests that many CSMP bommies are known and targeted by fishing activities, despite their isolation from most anthropogenetic activities. Although it is not unusual for fishers to target such sites, the number and biodiversity of bommies in CSMP reef lagoons has not been quantified and so vulnerability of these habitats is unknown.

Figure 4.41– Monofilament fishing line found on a bommie at 30m in Marion lagoon. Several of these lines extended from the base of the bommie at ~40m to the summit at 10m.

Triggerfish nests

Nests of multiple species of triggerfish (f. Balistidae) were observed in soft sediment areas of the lagoons of Lihou and Flinders reefs and Chilcott Islet (Figure 4.42). *Pseudobalistes fuscus, Pseudobalistes flavimarginatus*, *Balistoides viridicens* and *Odonus niger* were observed either in pairs or as individuals guarding nests at depths between 30 - 50m.Triggerfishes construct their nests by excavating depressions in sand and other soft sediment habitats (Lobel and Johannes 1980). Once eggs are laid, the male and females of many triggerfish species guard and actively defend their nests. Triggerfishes are important predators of benthic invertebrates, including crown-of-thorns starfish (*Acanthaster planci*) (Ownes 1971; Ormond et al. 1973) and Diadematidae urchins (McClanahan and Muthiga 2016). Although triggerfish nesting is commonly reported in lagoonal habitats of reefs globally, the extensive lagoonal habitats of many CSMP reefs may support abundant populations of triggerfish.

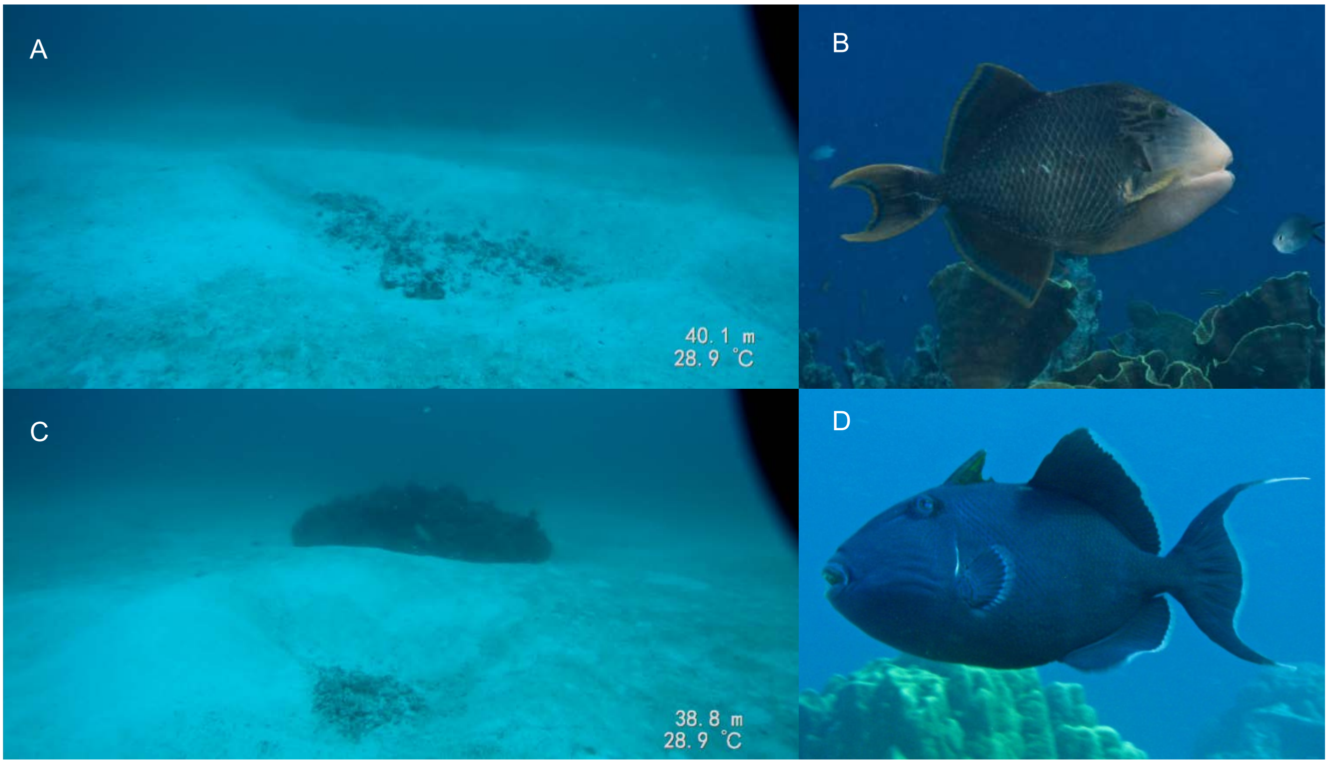


Figure 4.42 Images of triggerfish nests in deep lagoonal habitats in the Coral Sea Marine Park. **A.** *Pseudobalistes flavimaginatus* nest recorded by ROV in Flinders lagoon at 40m **B**. *Pseudobalistes flavimaginatus* Source:Mark Rosenstein / iNaturalist. License: CC 3.0. **C**. *Pseudobalistes fuscus* nest in Lihou lagoon at 39m **D**. *Pseudobalistes fuscus* Source: Anne Hoggett / Lizard Island Research Station. License: CC 3.0

Seagrass

Of all the sites using the ROV, seagrass was only observed at two sites in the leeward lagoon at East Diamond Islet (Figure 4.43). A small patch of seagrass (*Halophila decipiens*) was observed at 42m at one site, and multiple small patches of seagrass (*Halophila decipiens*) between 33-35m at a second site. In both observations, patches were relatively sparse and consisted of short (approximately 5-8cm) paired blade leaves. These patches were also associated with groups of garden eels (*Heterocong* sp. and *Gardiasa sp.*) and solitary burrowing blennies. From over 70 BRUV drops across 14 reefs, seagrass (*Halophila* cf. *decipiens*) was recorded from a single site at 43m within the lagoon at Flinders (south) Reef. This habitat was broadly characterised by unconsolidated substrata, sponges and black coral sea whips. Given the enhanced clarity of the oligotrophic waters in the lagoons of many CSMP reefs it is surprising that more extensive areas of seagrass were not observed during our surveys. More extensive surveys of these deep lagoonal habitats are needed to understand the true extent of seagrass habitat within the CSMP.

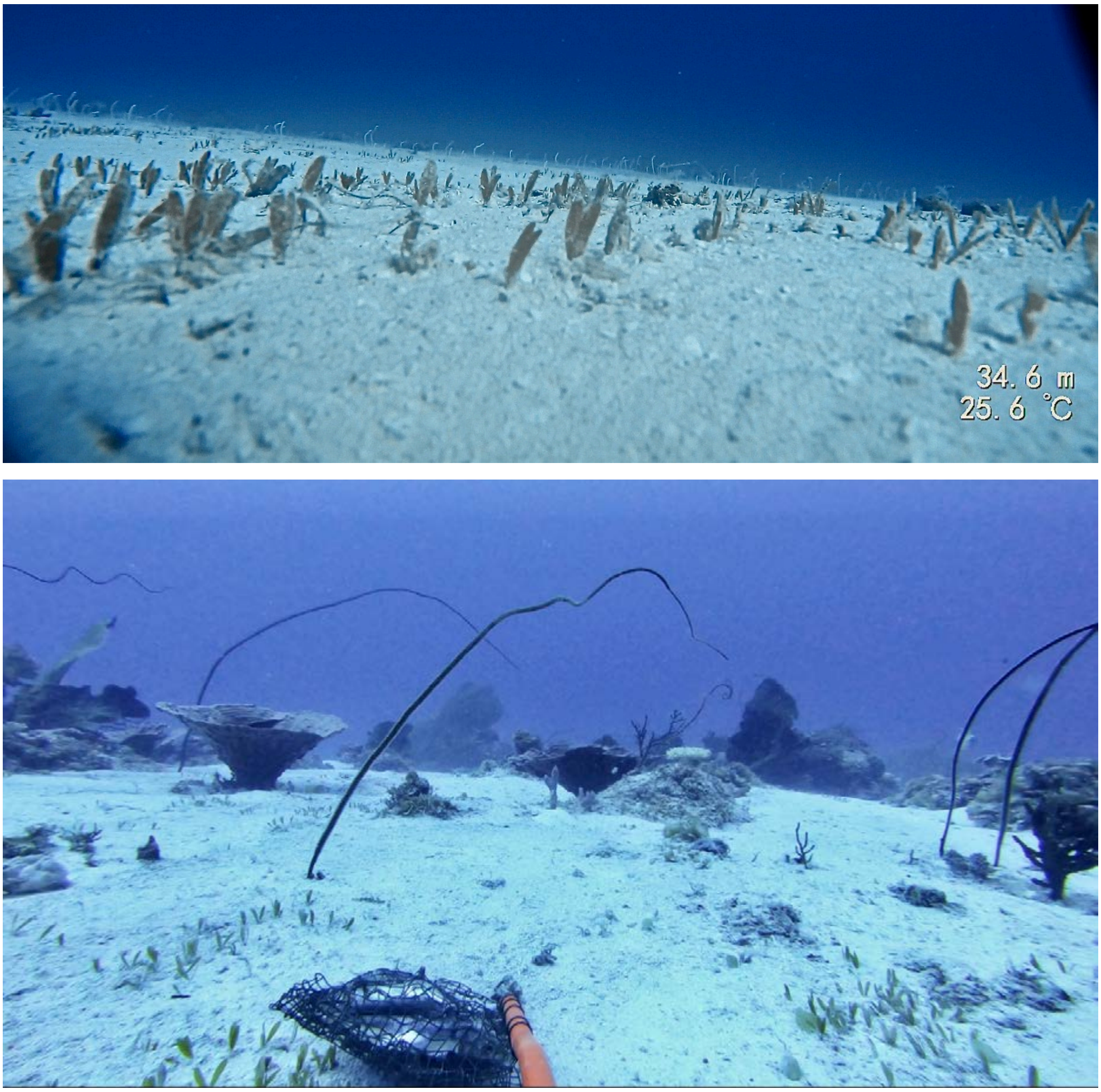


Figure 4.43 (top) *Halophila decipiens* at 34.6m in the lagoon at East Diamond Islet. (bottom) Seagrass (likely *Halophila decipiens*) recorded by a Baited Remote Underwater Video (BRUV) drop at 43m, south Flinders Reef.

Halimeda meadows

Halimeda is a genus of jointed calcareous green algae that is widespread and common of tropical reefs globally, and is an important contributor to carbonate production on reefs (Hillis-Colinvaux 1980). *Halimeda* can cover extensive areas of reef slopes as meadows or beds of living algae (Drewe and Abel 1983) and when the calcium carbonate ‘skeletons’ of dead plants break down, the aragonite can accumulate and form thick banks or bioherms (Davis and Marshall 1985; Roberts et al 1987). *Halimeda* skeletons contribute significantly to sediment formation in the tropics and is a fundamental component of the carbonate budget on coral reefs (Rees et al. 2007). *Halimeda* also provide important non-reef habitat for diverse and distinct fish and invertebrate communities (McNeil at al. 2021, Fukunaga 2008). *Halimeda* is known to occur in deep coral reef lagoons and seaward slopes to reported depths of up to 140m (Hillis-Colinvaux 1985; Littler et al. 1986).

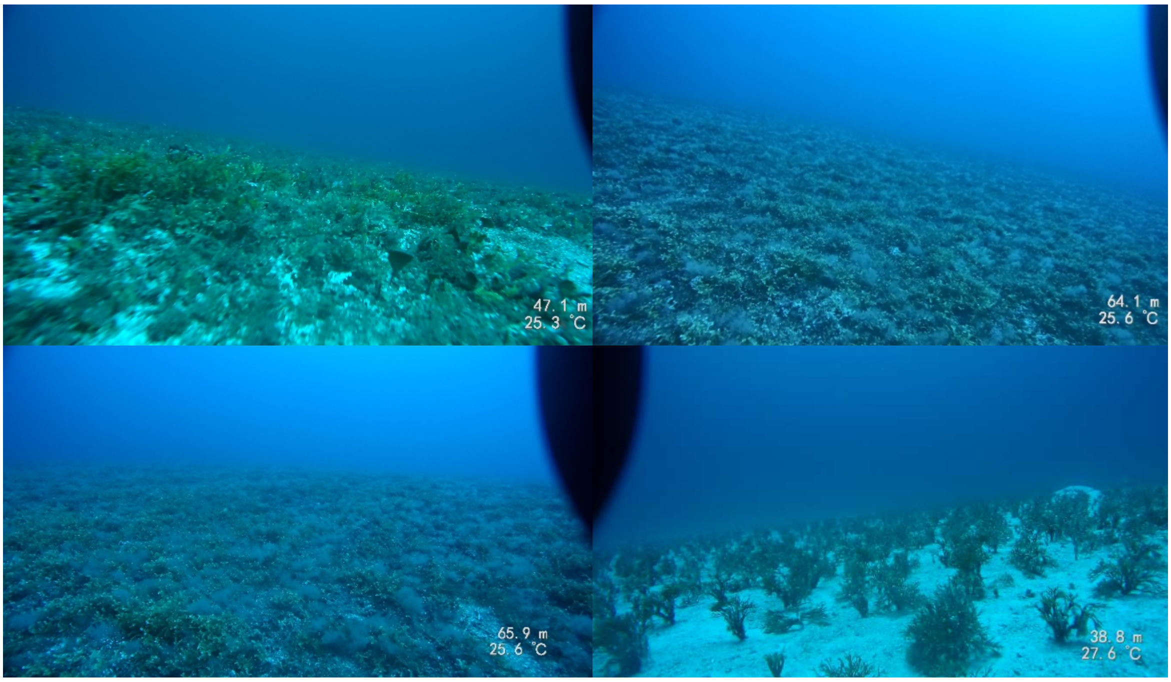


Figure 4.44 Clockwise from top left: areas of high *Halimeda* cover found at A. the outer reef slope at Juliette Cay, Lihou Reef, 47m B. Outer slope of Edna Cay, Lihou Reef, 67m C. Lagoon of South Diamond Islet, 65m and D. lagoon of Chilcott Reef, 38m.

Results from benthic community composition analyses (Section 4.3) found variable patterns of *Halimeda* percent cover between habitats, depths and reefs, as recorded by ROV and BRUV surveys. Outside of quantitative ROV transect surveys, exploratory ROV dives found extensive areas of *Halimeda* meadows on the outer slopes of Lihou Reef, and the lagoons of South Diamond and Chilcott Islets (Figure 4.44). Some of these meadows (Lihou and South Diamond lagoon) appear to be a mixture of *Halimeda* species (the dominant cover), other green macroalgae (e.g., *Caulerpa*), as well as sponges and soft corals. Many small wrasses and other fishes (likely juveniles) were highly abundant in these meadows, suggesting that deep water *Halimeda* meadows may be important nursery habitats on CSMP reefs. Unfortunately the small size, cryptic nature, and often uniform colouration of these fishes precluded species identification. The *Halimeda* meadow observed within the lagoon at Chilcott Islet was mostly composed of relatively sparse patches of *Halimeda cylindrica*, interspersed with bare soft sediment. Similar patches of *Halimeda cyclindrica* are often observed in shallow (<20m) lagoon habitats in the CSMP (Hoey pers. obs.).

On the GBR, recent mapping has found *Halimeda* bioherms to cover over 6,000km^2 of the outer continental shelf, representing the largest known area of actively growing *Halimeda* deposits worldwide (McNeil et al. 2016; Beaman 2017). The distribution and extent of *Halimeda* habitats in the CSMP however is currently not known. Our preliminary observations of *Halimeda* meadows at multiple CSMP reefs and lagoons, suggest that these are significant deep inter-reef habitats that potentially support distinct and diverse ecological communities, and serve as nursery habitats for some fish species. Further, given the isolation of CSMP form other sources of sediment production, *Halimeda* is likely an even more critical component of reef sediment and carbonate budgets compared to other more connected reef morphologies (e.g. the GBR) and an essential primary producer at mesophotic depths (Spalding et al. 2019).

4.4 Environmental Conditions

To explore other environmental aspects of deep CSMP reefs we recorded temperature data continuously during ROV dives and also recorded observations of marine debris during ROV video footage analysis. Characterising thermal profiles for both deep and shallow reefs will be a valuable addition to our understanding of how reefs may respond to rising ocean temperatures. Given that many of the CSMP reefs are distinct in morphologies and support unique ecological communities, there are likely numerous differences in environmental drivers, including temperature, which have not been quantified on a reef-by-reef scale. Similarly, the nature of disturbance caused by marine debris on mesophotic reefs can vary markedly depending on reef morphology, location and distance from human populations (Smith et al. 2019). Marine debris is also more readily observed in shallow reefs, which are more accessible to divers or clean-up efforts and on emergent cays and islets. Both thermal anomalies and marine debris are well known stressors to coral reef ecosystems but data for both these environmental parameters are lacking for deeper areas CSMP reefs.

4.5.1 Temperature profiles

We characterised thermal profiles at 6 sites from 5 reefs where temperature data from ROV surveys was collected over the most continuous depth gradient (i.e., the full spectrum of depths were available at each site). Although water temperature generally declined with depth at each site, the rate of decline and nature of the relationship varied considerably among sites (Figure 4.45). Interestingly, several "breaks", or relatively rapid changes in temperature over a short depth range, were noticeable at the sites at Holmes (Holmes_2) and Osprey reefs (Osprey_Entrance2 and Osprey_N1), and Willis Islet (Willis_N1). At these sites there were marked regions of the thermal profile that did not continue a consistent trajectory of declining temperature with increasing depth. For example, at Willis_N1, water temperature generally declined at a rate of 0.1 - 0.2 ^{o}C with every 5m increase in depth, however there was a 1.1 ^{o}C decline in water temperature between 30 - 35m, after which temperature stabilised at 27.6 – 27. 2 ^{o}C from 35 – 60m. A similar trend was noticeable from an ROV dive at Holmes, where a sudden temperature change of 1.0 ^{o}C occurred within the 40 - 45m depth band.

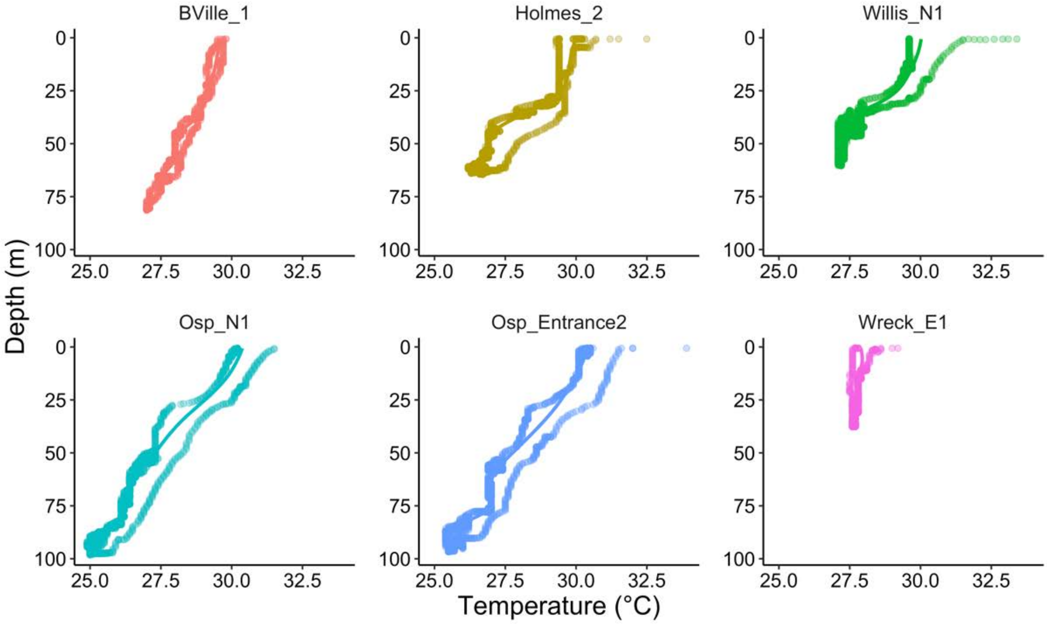


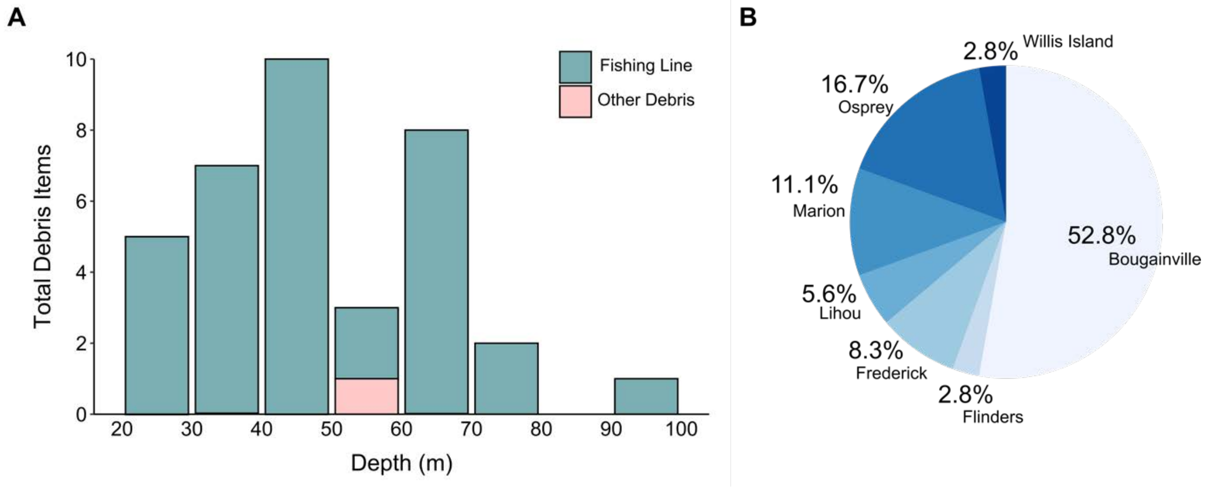
Figure 4.45 Thermal profiles for six sites at five reefs in the Coral Sea Marine Park. Temperature was logged every 10 seconds where multiple lines in each plot show the decent and accent of the Remotely Operated Vehicle (ROV) across the full dive.

Average water temperature in the upper 5m was between 29.6 – 30.3^{o}C for four of the five reefs. The only exception to this was Wreck Reef site (Wreck_E1) which was considerably cooler (27.9 ^{o}C) and displayed limited change in water temperature with depth. The thermal profile recorded by this ROV dive at Wreck Reef represents both the coolest temperatures recorded and also the smallest temperature range with increasing depth.

Temperature profiles from two dives at Osprey Reef show the largest thermal range across the depth gradient and sites sampled, with water temperature declining by 5.2 ^{o}C from 0 – 100m at the North Horn site (Osprey_N1), and by by 4.7 ^{o}C from 0 - 100m near the entrance to the Osprey lagoon (Osprey_Entrance2). Thermal breaks were also evident in the two Osprey Reef site profiles where temperatures would rapidly drop by up to 1 ^{o}C within a 5m depth band.

4.5.2 Marine Debris

We recorded a total of 36 individual items of marine debris in ROV surveys. This included 3 observations of debris on a bommie at Marion Reef (30m depth) which were not part of formal ROV transects. The remining debris observations were all made during individual 30 x 5m ROV video transect surveys. Of the 36 debris items, 35 were monofilament fishing line and 1 item was a section rope with floats attached. Most debris was recorded between 40 - 50m (10 items) with a secondary peak at 60 -70m (8 items) (Figure 4.46a).



1. **Figure 4.46** Distribution of marine debris among depths and reefs within the Coral Sea Marine Park. **A**. Total number of marine debris items recorded by Remotely Operated Vehicle (ROV) surveys within 10m depth bins; **B**. Proportion of total debris found at individual reefs.

Bougainville, Osprey and Marion reefs recorded the highest number of debris items, accounting for 52.8%, 16.7% and 11.1% of all debris, respectively (Figure 4.36b). All items at these sites were fishing line. The rope and float debris was observed at Willis Island and was the only item of debris observed at that reef. The deepest item of marine debris recorded was a length of fishing line (>30m in length) at 94m on Osprey Reef, that extended beyond the 100m depth contour. Most observations of marine debris were made at Bougainville reefs (19 individual fishing lines) where

ROV survey sites were mostly conducted within the Habitat Protect Zone (IUCN IV) area of the reef (Figure 4.47).

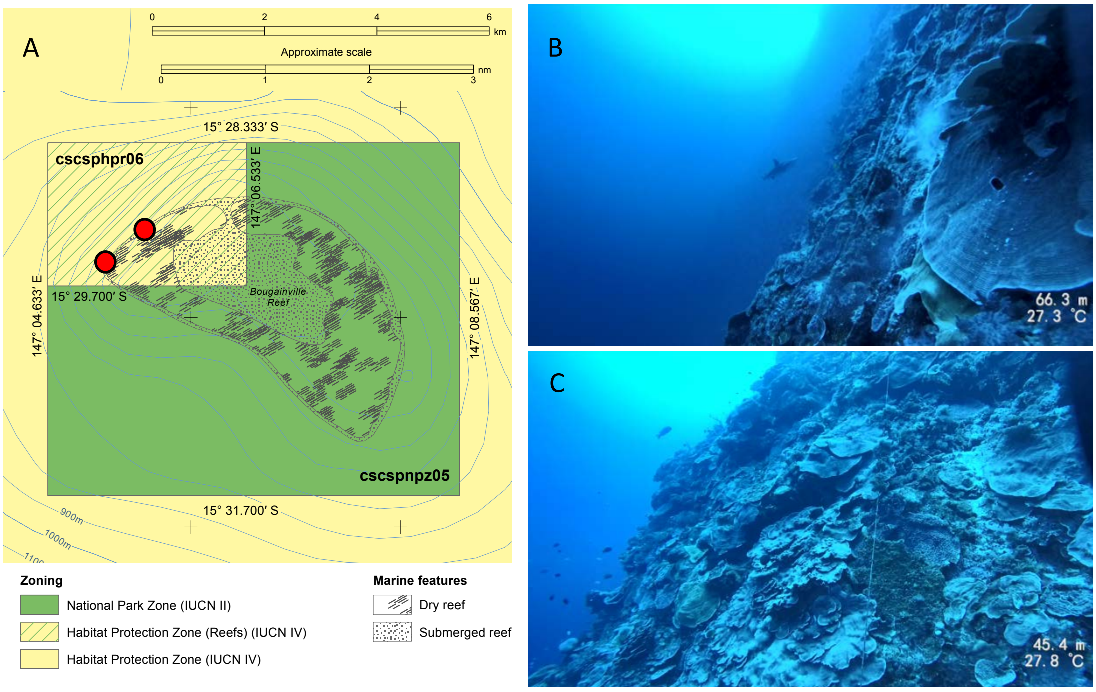


Figure 4.47 A. Adapted management plan map of Bougainville Reef, reproduced with permission of Parks Australia. Red circles indicate the starting positions of Remotely Operated Vehicle (ROV) survey dives where a total of 19 items of marine debris were observed at depths between 28 – 67m. **B.** Monofilament fishing line, Bougainville Reef at 66m **C.** Monofilament fishing line, Bougainville Reef at 45m.

4.5 Deep Water Bright Spots

Following the global and now chromic degradation of the world's ecosystems, the term "bright spot" is frequently used to describe and identify locations that are above average in terms of structure and function (e.g., Cinner et al. 2016; Sully et al. 2022). This concept of 'bright spots' is being increasingly applied to shallow coral reefs (e.g., Cinner et al. 2016; Hoey et al. 2020), however is rarely applied to deeper reef habitats. The exploration of deep reef habitats in this project identified several sites with notable coral cover at mesophotic depths. It should be acknowledged that although an important component of overall reef structure, the extent of hard coral cover should be interpreted alongside multiple other measures of reef complexity and diversity. This said, these first observations of high coral cover and high fish density at mesophotic depths make these sites both promising and important for further research and monitoring of MCEs in the CSMP. Here, we present preliminary findings as three case studies of ROV dives at Herald's Surprise Reef, and two sites adjacent to Edna and Juliette Cays, Lihou Reef.

Case Study 1: Herald's Surprise Reef

Herald's Surprise Reef was surveyed during the February 2022 voyage, with ROV surveys being conducted between 0 - 70 m on the southern aspect of the reef. It was immediately apparent during the survey that both fish and benthic communities differed substantially between shallow and deeper areas of the reef. Analyses of benthic imagery showed a peak in hard coral cover (19.7 – 29.5%) between 10 - 40m, declining to 13.2% at 50-60m (Figure 4.48a). These estimates of coral cover at depth were either greater than (10-40m) or broadly comparable to coral cover in the shallow 0 – 10m depth band (14.4%). Further, overall habitat complexity was highest at depths below 60m which was driven by diverse morphologies of soft corals, sponges and sea fans in this distinct MCE (Figure 4.49a,c,e). These benthic organisms were noticeably absent in the upper 20m at this site (Figure 4.49b,d,f), likely reflecting the greater disturbance from wave action, storms, and recently thermal stress that have affected shallow reef habitats throughout the CSMP (Hoey et al. 2020, 2022).

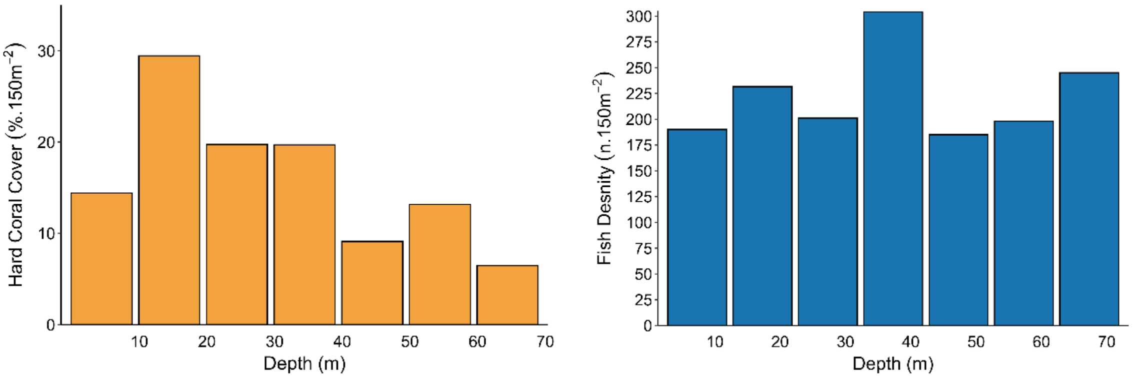


Figure 4.48 A. Average percentage cover of hard coral at Herald's Surprise from 0 -70m. **B.** Average fish density (individuals per 150m^2) at Herald's Surprise between 0 – 70m. Both hard coral cover and fish density are summarised within 10m depth bins.

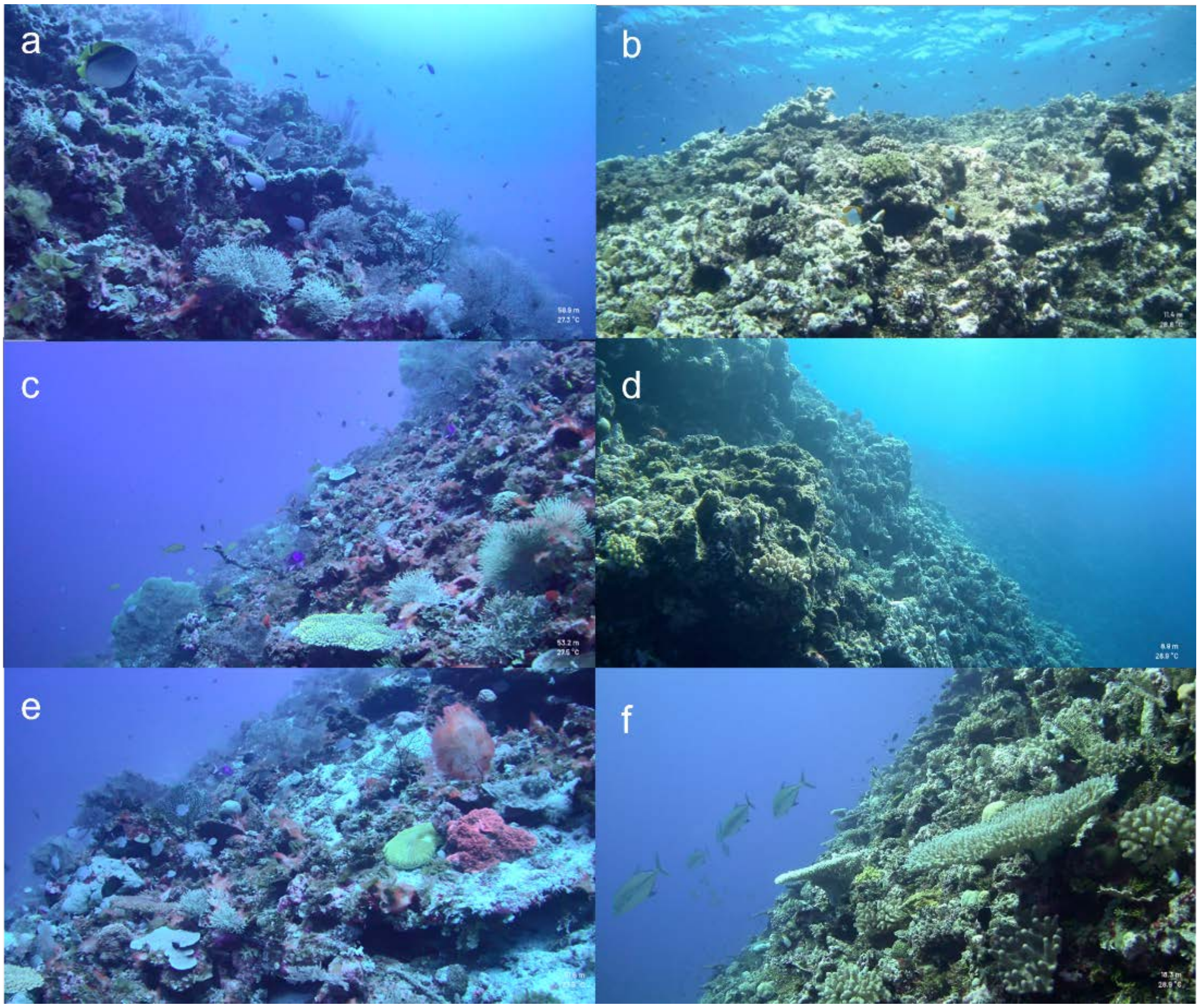


Figure 4.49 – Forward facing ROV video stills from surveys conducted at Herald's Surprise between 0 – 70m**. A, C** and **E** show the reef slope between 50-60m. Panels **B,D** and **F** show the reef slope and crest between 18 – 8m.

The abundance of reef fishes was relatively consistent (ca. 180-245 individuals per 150m^2) among depth bands on Herald's Surprise Reef, except for a peak of 304 individuals per 150m^2 at a depth of 30 – 40m (Figure 4.48b). This included observations of *Pseudanthias pictilis*, a new fish species record from this project which has previously not been recorded during shallow reef monitoring surveys of the CSMP.

Case Study 2: Bougainville Reef

Bougainville Reef has previously been identified as a `bright spot` in shallow reef monitoring conducted between 2018 – 2022 (Hoey et al. 2020, 2021,2022). Although shallow monitoring methods and ROV surveys are not directly comparable between these projects, ROV surveys at Bougainville in Feb 2021 found that both hard coral cover and the abundance of reef fishes was relatively high in deep reef habitats (20-70m) at Bougainville Reef. Hard coral cover was remarkably consistent throughout the depth gradient, ranging between 38.9% (40-50m) and 54.0% (30 – 40m) (Figure 4.50a). This included branching acroporid species at depths between 30 -40m (Figure 4.51a) and large plates of *Montipora sp, Porites sp* and *Leptastrea sp* (Figure 4.51b, c). Soft corals, sponges and large sea fans again contributed to overall habitat complexity of the MCE habitat including an extensive bank of soft coral at 67m (Figure 4.51d). In contrast to the Herald's Surprise Reef, there was a defined peak in the abundance of reef fish at 40 - 50m on Bougainville Reefs, where there were over double the number of individuals (205 per 150m2) compared to 20 - 30m (98 per 150m2) (Figure 4.50b). Although this trend declined with increasing depth, fish density at 60 -70m was still higher than at 20 – 30m.

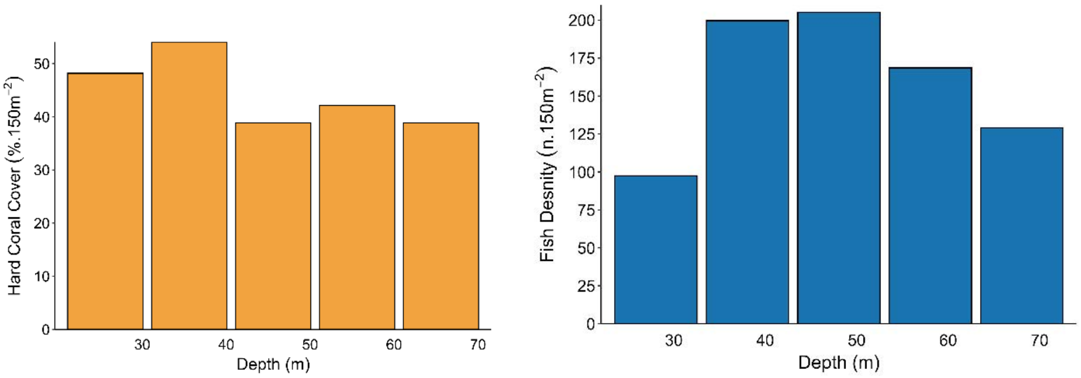


Figure 4.50 A. Average percentage cover of hard coral at Bougainville Reef from 20 -70m. **B.** Average fish density (individuals per 150m2) at Bougainville Reef between 20 – 70m. Both hard coral cover and fish density are summarised within 10m depth bins.

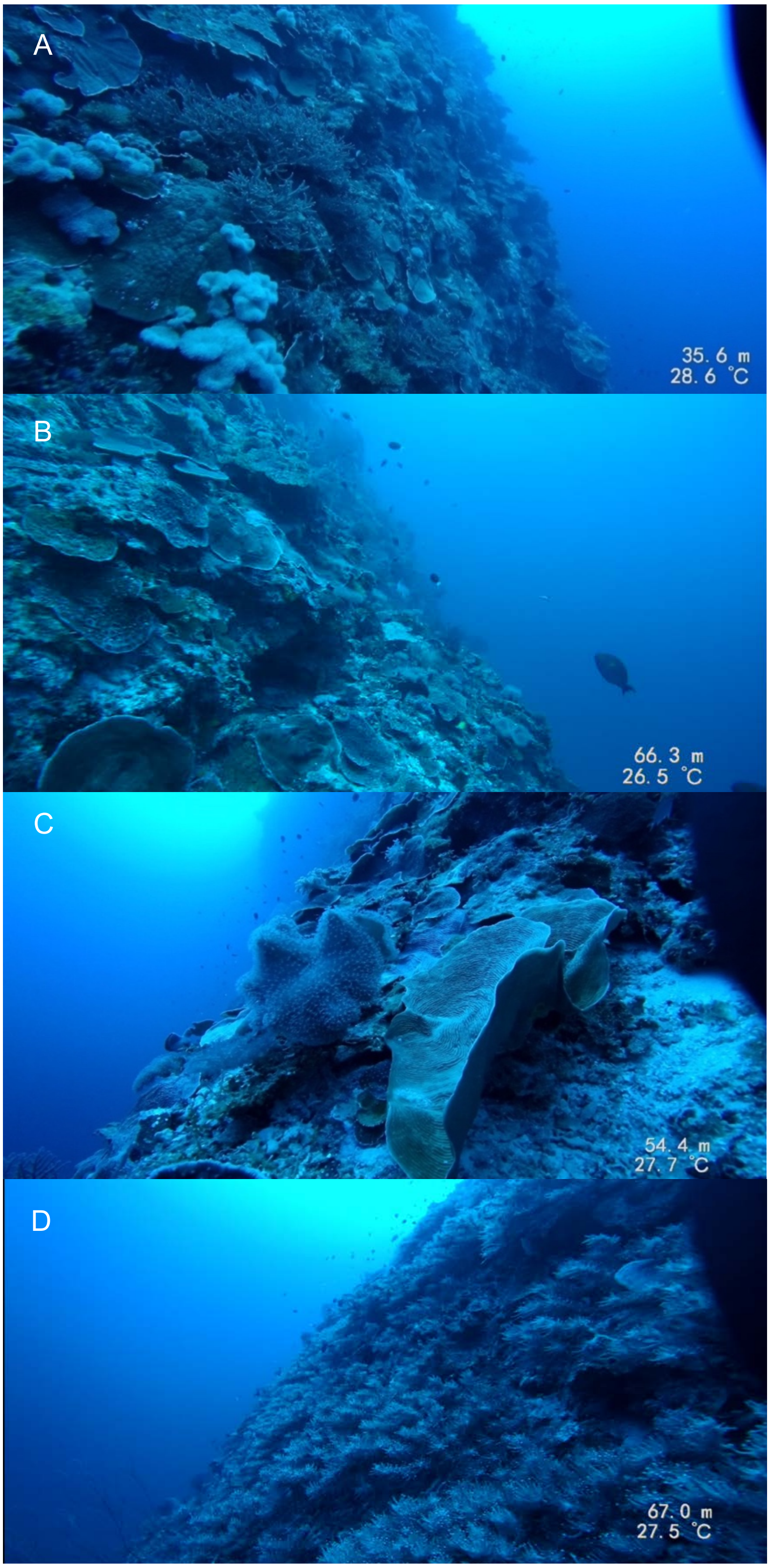


Figure 4.51 – Frames from Remotely Operated Vehicle (ROV) surveys at Bougainville Reef **A.** Branching *Acropora* sp at 35m, **B.** Large plating and foliose hard coral colonies at 66m, **C.** Hard and soft coral colonies contributing to habitat complexity at 54m, **D.** Extensive area of soft coral at 67m.

Case Study 3: Lihou Reef

Extensive areas of hard coral cover and MCE habitat were found at two sites (Edna Cay in the south-west and Juliette Cay on the north-west) at Lihou Reef. The areas of high coral cover at Edna Cay were extensive (>400m in length) at 70-80m (Figures 4.52a, 4.53). At both Edna and Juliette sites, large plating hard coral colonies were seen at depths below 100m, though these areas were beyond the depth capabilities of the ROV to survey formally. Quantifying the full extent of these habitat is a significant and important avenue for future research in the CSMP and would greatly enhance our understanding of large complex reefs such as Lihou Reef.

At Edna Cay, our preliminary findings show a bimodal trend in hard coral cover, with peaks of 34% and 71% at 10 - 40m and 70 – 90m, respectively (Figure 4.52a). This is closely mirrored by the abundance of reef fish, with peaks in reef fish abundance occurring at 30-40m and again at 70 – 80m (Figure 4.52b). These estimates of coral cover are up to 7-fold greater than recent estimates of coral cover in shallow reef habitats on Lihou Reef (10% cover; Hoey et al. 2022), and highlight the potential significance of these extensive areas of high coral cover in deeper reef habitats.

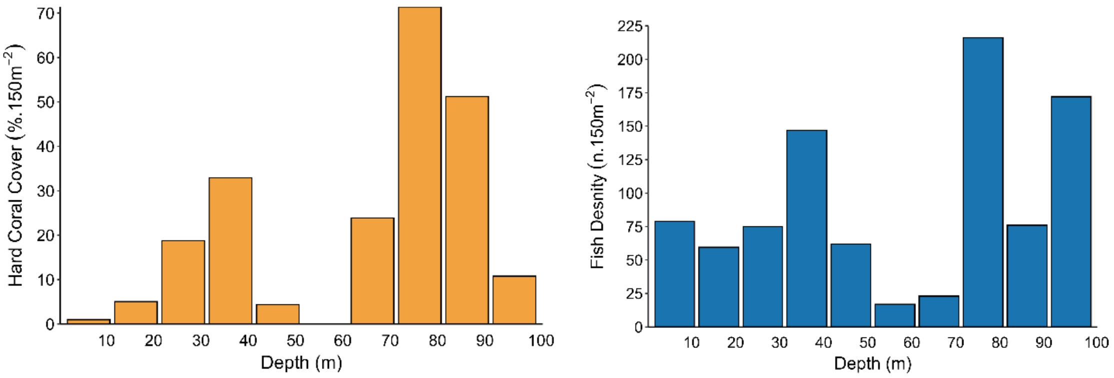


Figure 4.52 - **A**. Average percentage cover of hard coral at Edna Cay, Lihou Reef from 0 - 100m. **B.** Average fish density (individuals per 150m2) at Edna Cay between 0 – 100m. Both hard coral cover and fish density are summarised across transects within 10m depth bins.

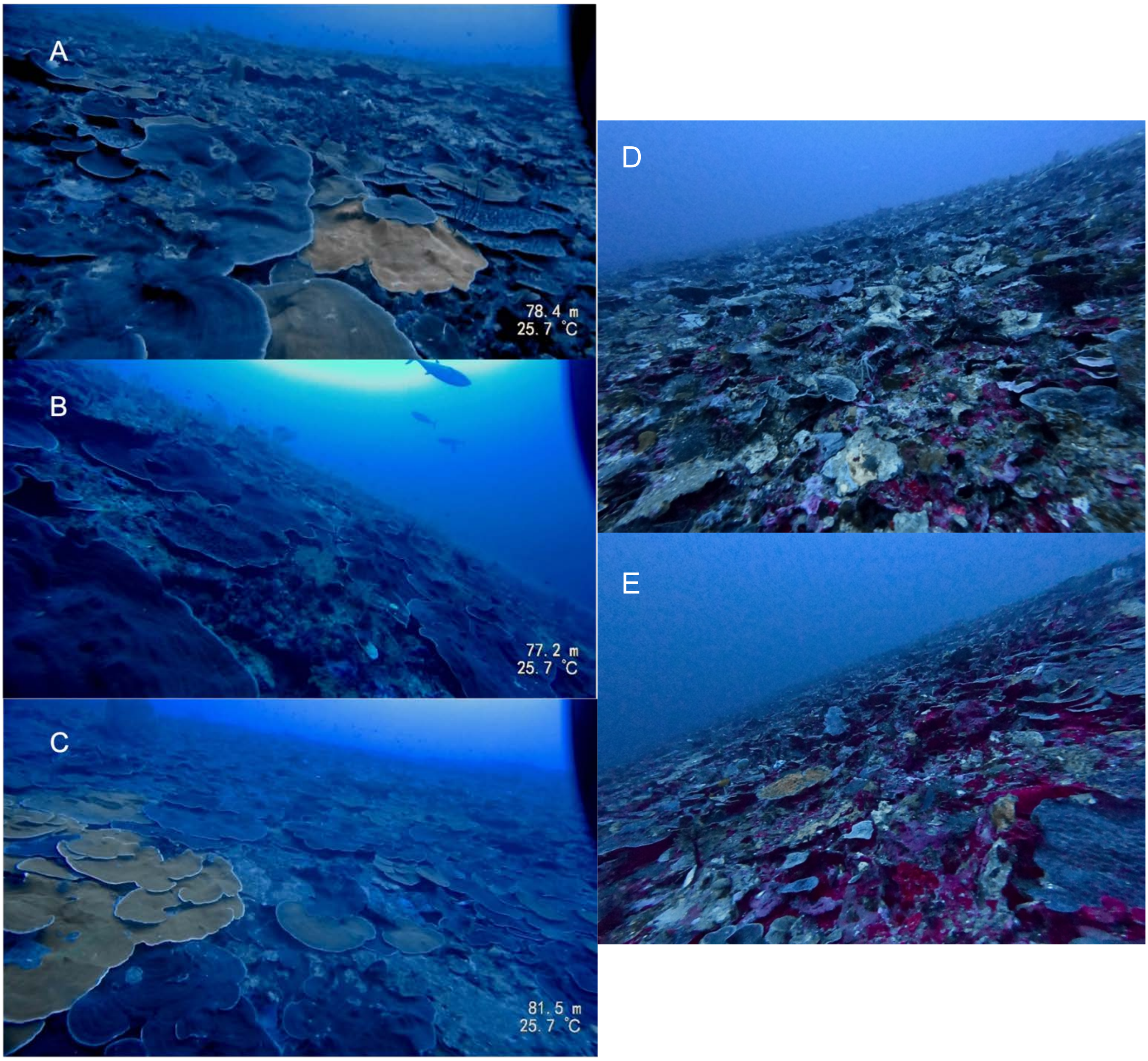


Figure 4.53 – The high coral cover MCE found at Edna Cay, Lihou Reef, **A.** MCE at 78m **B.** MCE at 77m with dogtooth tuna (*Gymnosarda unicolor*) swimming above and **C.** MCE at 81.5m, and at Juliette Cay, Lihou reef. **D.** MCE at 77m depth and **E**. MCE at 79m depth.

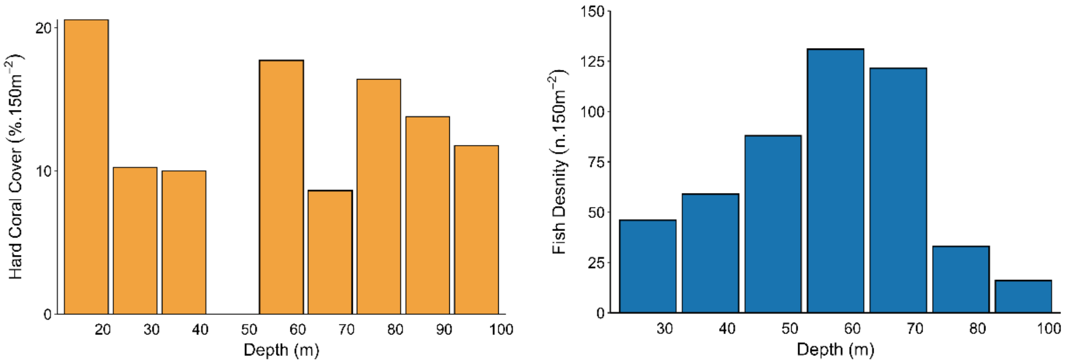


Figure 4.54 - A. Average percentage cover of hard coral at Juliette Cay, Lihou Reef from 0 - 100m. **B.** Average fish density (individuals per 150m2) at Juliette Cay between 0 – 100m. Both hard coral cover and fish density are summarised across transects within 10m depth bins.

The MCE at Juliette Cay had lower hard coral cover compared to the Edna site (Figure 4.53d,e), with greatest mesophotic coral cover at 50 -60m (17.1%). This was lower than cover in the upper 10 – 20m (20.6%) but only declined to. 11.8% in transects at 90 -100m (Figure 4.54). Interestingly, no hard coral was recorded in transects between 40 -50m, where there was a distinct band of rubble separating the MCE at 50 -100m from the shallower areas of coral reef habitat in the upper 10 – 40m. Fish density increased between 20 – 60m, with highest average density found at 50 -60m (131 individuals per $150m^2$). Beyond 70m, fish density dramatically dropped to between 16 -33 individuals ($150m^2$) in the deepest depth bands surveyed (70 -100m).

4.7 Animal Tagging and Movement

In total, 112 animals were acoustically tagged across four CSMP reefs, including 99 sharks (85 grey reef sharks, *C. amblyrhynchos* and 14 silvertip sharks, *C. albimarginatus*) and 13 teleosts (nine giant trevally, *Caranx ignobilis*, three black trevally, *C. lugubris*, and one blue-spot coral trout *Plectropomus laevis* (Figure 4.55; Appendix 3). The number of animals tagged varied among reefs, with 24 *C. amblyrhynchos* and seven *C. albimarginatus* tagged at Flinders Reef, 18 *C. amblyrhynchos* and four *C. albimarginatus* at Holmes Reef, 7 *C. amblyrhynchos* and two *C. albimarginatus* at Bougainville Reef, 36 *C. amblyrhynchos* and one *C. albimarginatus* and all 13 teleosts at Osprey Reef (Figure 4.55; Appendix 3). Of the 112 animals tagged, nine were not detected by acoustic receivers (five *C. amblyrhynchos*, one *C. albimarginatus* and three *C. ignobilis*), although two animals (both *C. ignobilis*) were tagged during the February 2022 field trip when the acoustic receivers were downloaded, so those individuals had no chance to be detected.

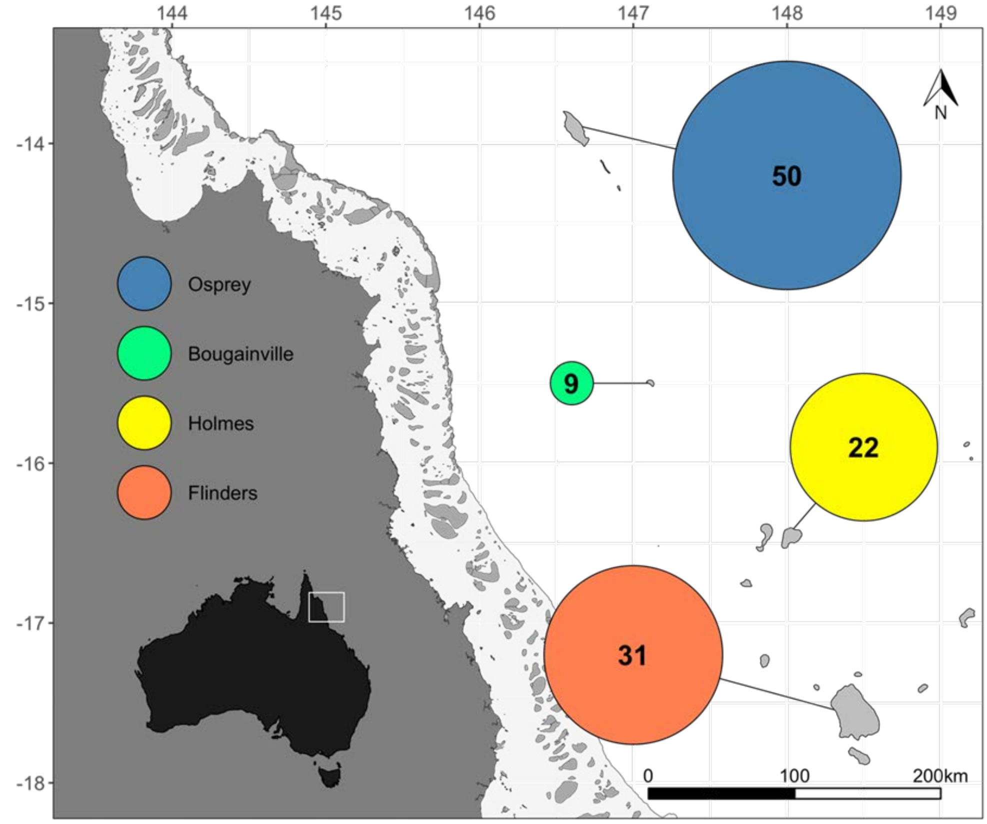


Figure 4.55 Map showing the total number of animals tagged on the four reefs within the Coral Sea Marine Park. Points are scaled by numbers of individuals tagged.

4.7.1. Movement and residency of sharks

Carcharhinus amblyrhynchos. In general, the residency of *C. amblyrhynchos* at the reefs where they were tagged was moderate to high (Residency Index, RI: 0.60-0.82), with the highest mean residency (RI = 0.82) being recorded at Osprey Reef (Figure 4.56a). There were no significant differences in residency between sexes for *C. amblyrhynchos* with males and females having similar RI (Figure 4.56b). This is consistent with other studies from Osprey Reef (CSMP), the GBRMP, and New Caledonia showing high residency of *C. amblyrhynchos* in the vicinity of their tagging locations (Barnett et al. 2012; Espinoza et al. 2015; Bonnin et al. 2019).

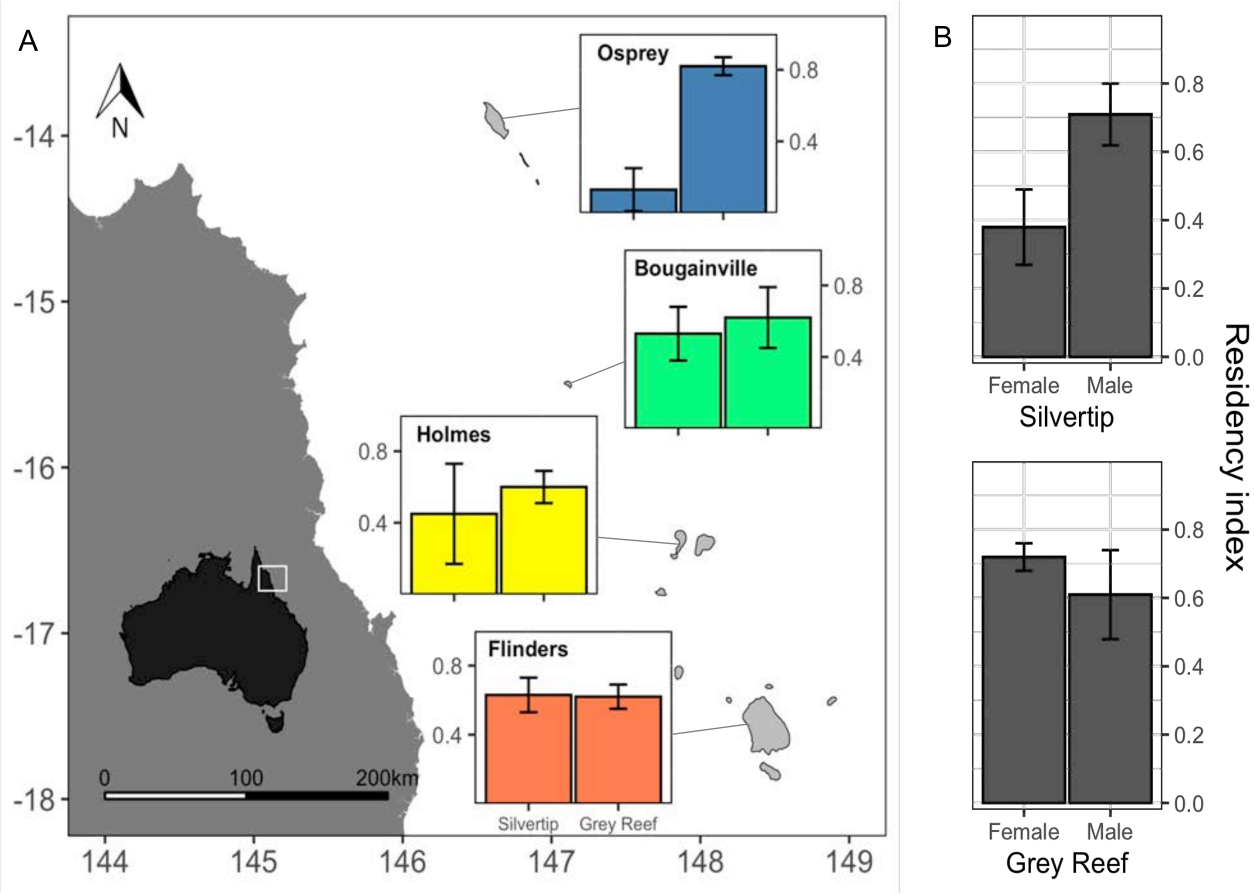


Figure 4.56 A. Residency index (RI) (± SE) of silvertip sharks *Carcharinus albimarginatus* (left bars) and grey reef sharks *Carcharinus amblyrhynchos* (right bars) for each of the four Coral Sea Marine Park (CSMP) reefs. **B**. Mean sex specific RI for silvertip (top) and grey reef (bottom) sharks across the four CSMP reefs

Despite the high residency of *C. amblyrhynchos* on individual reefs, two large-scale movements were detected. A mature female *C. amblyrhynchos* (164cm TL; tag ID 64103) was detected to move from Osprey Reef to Saunders Reef (in the northern

GBRMP) and then returned to Osprey Reef, a round trip of ~760 km completed over 25 days (Figure 4.57), and a mature male *C. amblyrhynchos* (157cm TL; tag ID 60580) that was tagged on Flinders Reef was recorded to move to Holmes Reef (a distance of ~150km) and then out of array (Figure 4.57). Despite evidence from genetic studies that suggest some gene flow and connectivity between GBRMP and some CSMP reef populations of *C. amblyrhynchos* (Momigliano et al. 2015; Boussarie et al. 2022), direct evidence of large-scale movements is limited. For example, a recent study of 183 tagged *C. amblyrhynchos* found no large-scale movements between acoustic array networks deployed along the east coast of Australia (Ledee et al. 2021). The only previous evidence of large-scale movements of *C. amblyrhynchos* are a single sub-adult male shark (likely approaching maturity), that moved ~250km from Osprey Reef (CSMP) to the Ribbon Reefs (GBRMP) and returned (Barnett et al. 2012), and six mature male *C. amblyrhynchos* that undertook return journeys of up to 700 km in New Caledonia (Bonnin et al. 2019). The ~760km round trip in the present study is the largest known movement undertaken by *C. amblyrhynchos*, and given it was completed in 25 days corresponds to an average distance of 30 km a day. While the drivers of such large movements over a short period of time are unknown, such movements may be more widespread than currently recognised (e.g., tagged individuals could move to other reefs or seamounts with no receiver coverage).

Carcharhinus albimarginatus. In contrast to the relatively consistent residency of *C. amblyrhynchos,* the residency of *C. albimarginatus* was variable both among reefs and between sexes, ranging from 0.13 mean residency at Osprey Reef to 0.63 at Flinders Reef (Figure 4.56a). Interestingly, male *C. albimarginatus* showed a higher degree of residency to individual reefs than females (Figure 4.56b). Although these estimates of residency are comparable to those of acoustically tagged *C. albimarginatus* in the GBRMP (mean residency: 0.57; range 0.05 to 0.97; Espinoza et al., 2015), they are higher than expected given their semi-pelagic nature and use of depths of up to 800m (Last and Stevens 2009).

Of the 14 *C. albimarginatus* tagged, only one individual was detected moving among reefs within the CSMP. An immature female *C. albimarginatus* (174cm TL; tag ID

64080) that was tagged on Holmes Reef moved south to Flinders Reef, then north to Osprey Reef, before moving out of array (one way trip >600km) (Figure 4.57). Although there has been relatively limited research on the movement and population connectivity of this species, Green et al. (2019) reported some evidence of genetic connectivity between samples from Papua New Guinea and the GBRMP, suggesting stepping-stone patterns of movement between regions. The limited movements of *C. albimarginatus* among CSMP reefs, and between the CSMP and GBRMP in the present study may be related to the limited coverage, or absence, of receivers at many CSMP reefs, the limited number of *C. albimarginatus* tagged (i.e., 14 individuals) and/or the limited time frame of the present study.

Interestingly, a mature female *C. albimarginatus* (224cm TL; tag ID 64106) tagged at Osprey Reef, the largest shark acoustic tagged and the only *C. albimarginatus* tagged at Osprey Reef, moved from its tagging location at the reef entrance into the lagoon, where it remained for the entire winter. This behaviour is unexpected for this species and is in contrast to *C. amblyrhynchos* tagged at Osprey Reef in the present study, which appeared to mostly avoid the lagoon area. Further, a previous study that tagged a limited number of *C. albimarginatus* at Osprey Reef did not use the lagoonal area, rather spending most of the time in sections of the outer reef with relatively steep walls (e.g., North Horn CS-01; Barnett et al. 2012).

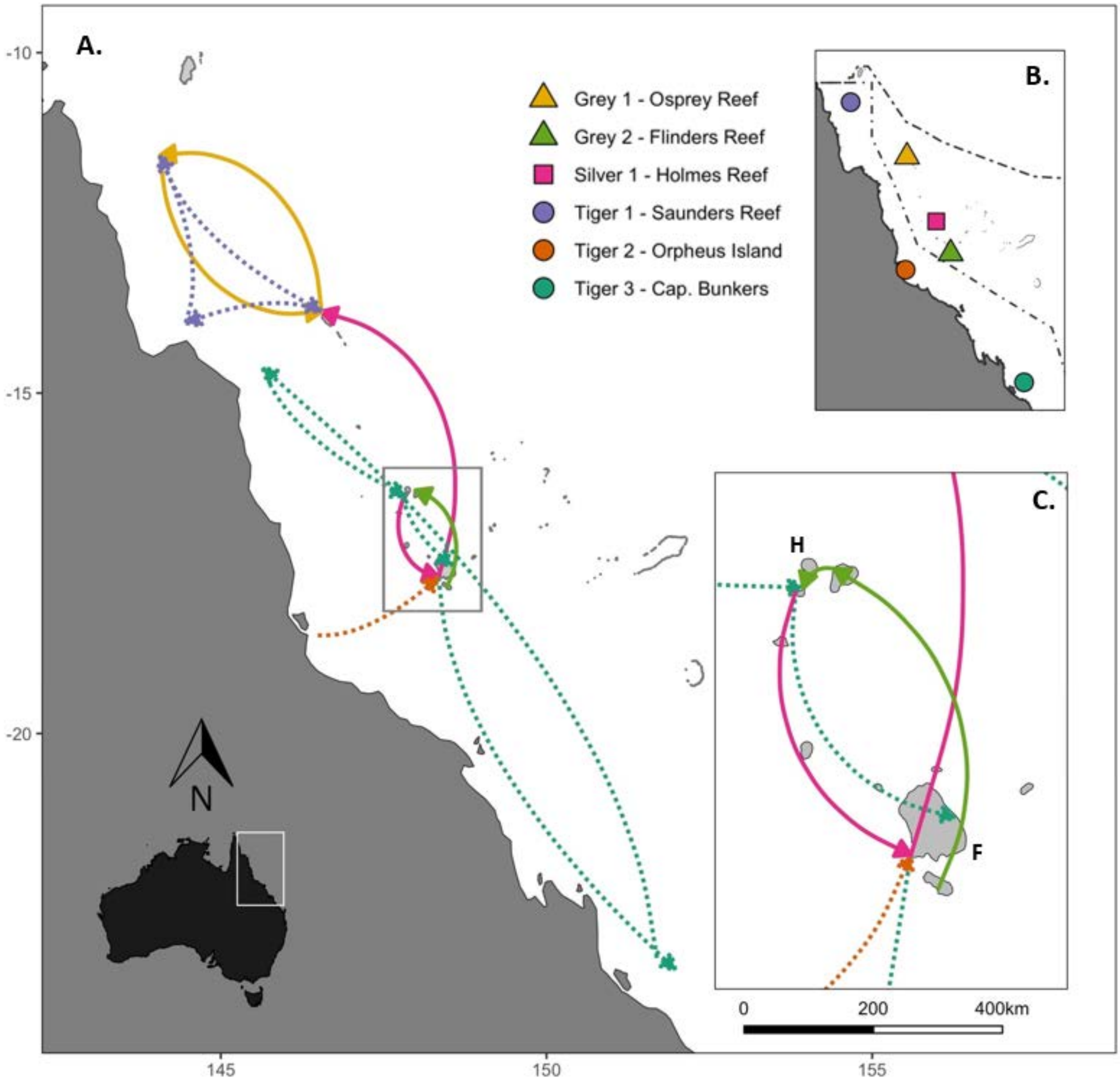


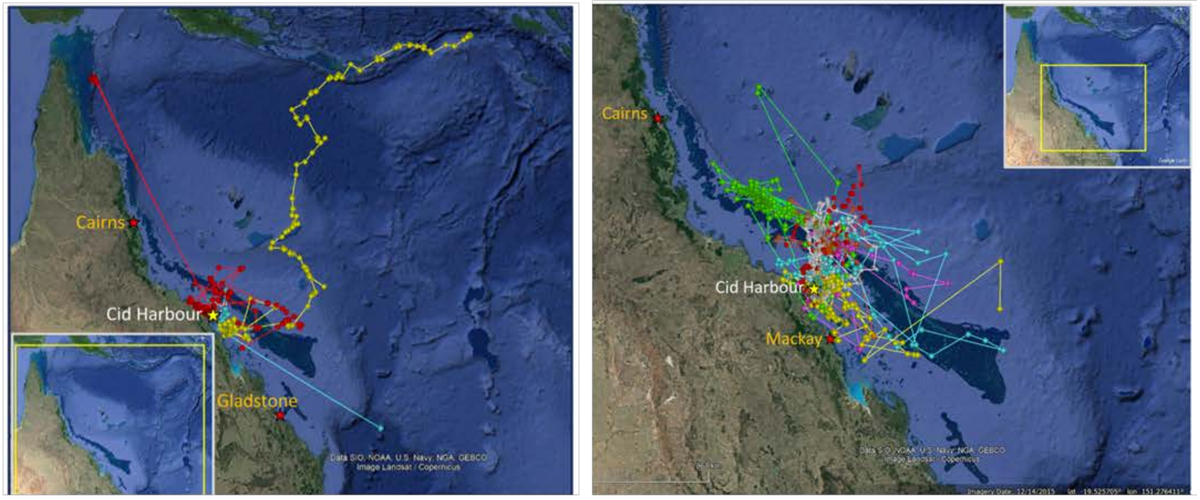
Figure 4.57 Large-scale movements of sharks across and between reefs of the CSMP and GBRMP **A**. Solid arrows are movements of grey reef sharks *Carcharhinus amblyrhynchos* and silvertip sharks *Carcharhinus albimarginatus* tagged during the present study. Dashed lines represent movements of tiger sharks *Galeocerdo cuvier* that moved into the CSMP from other GBRMP tagging locations **B.** Original tagging locations of the individuals shown in A. **C.** Details of blue-water movements throughout Holmes (H) and Flinders (F) reefs.

Other acoustically tagged sharks. During this study, three tiger sharks *Galeocerdo cuvier* that had been acoustically tagged on the Great Barrier Reef were also detected by our receivers in the CSMP. This included a mature female *G. cuvier* tagged in the Capricorn Bunker group in the southern GBRMP, which moved to Holmes Reef and then to Flinders Reef, before moving south back to the Capricorn Bunker Group, on a round trip ~1600 km (Figure 4.57, Tiger 3). Another *G. cuvier* female close to maturity tagged at Saunders Reef in the northern GBRMP moved to Osprey Reef (CSMP), then to Davie Reef (GBRMP), and was later detected back in Saunders Reef, a round trip ~800km (Figure 4.57, Tiger 1). The third *G. cuvier* large-scale movement was made by an immature (subadult) female, which moved from Orpheus Island (an inshore island in the central GBRMP) to Flinders Reef (>200 km away), and then moved out of the array (Figure 4.57, Tiger 2). Two other sharks were detected in our acoustic array in the CSMP during the current study that had both been tagged in Ballina, New South Wales, by Fisheries NSW. These were an immature female tiger shark *G. cuvier*, and an immature female white shark *Carcharodon carcharias*, both detected at Osprey Reef (>1,800km from Ballina). Each of these five sharks that were tagged outside the CSMP and subsequently detected by our receivers in the CSMP were only detected a single day, suggesting they were migrating through the CSMP.

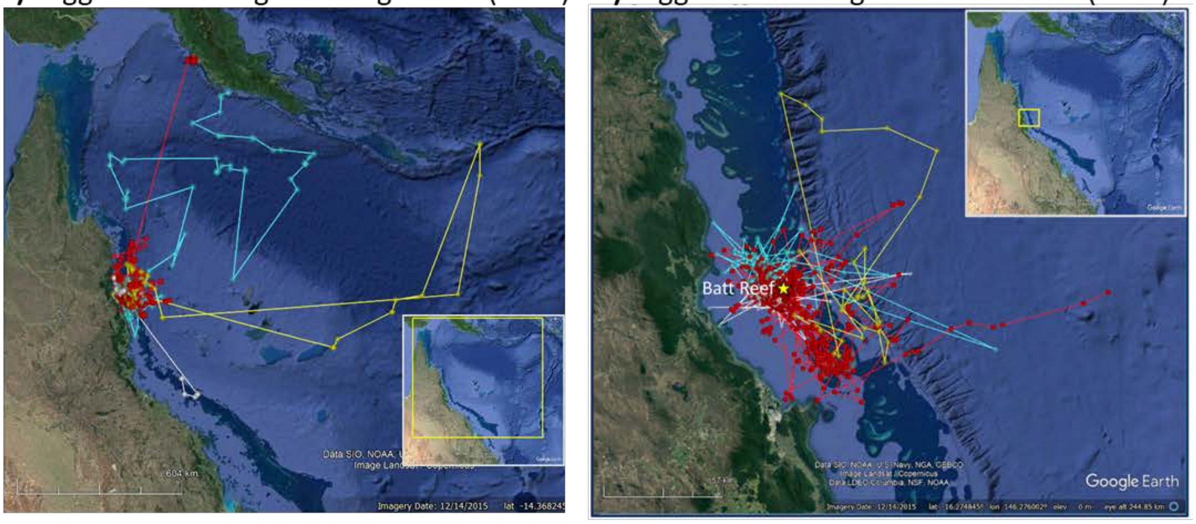
4.7.2. Satellite tracking

Several species of sharks and rays that have been fitted with satellite tags in regions bordering the CSMP, have been recorded to move into the CSMP, indicating a level of ecological connectivity among these regions. Since 2002, 88 tiger sharks *G. cuvier* have been satellite tagged in the areas adjacent to the CSMP (53 in the GBRMP, and 35 at Norfolk Island). Of these sharks, 25 individuals were recorded to move into the CSMP (Appendix 4). The movements of these sharks were highly variable, with some individuals only moving a short distance into the CSMP before returning the GBRMP, while others move across the CSMP and into neighbouring regions including Papua New Guinea and the Solomon Islands (Figure 4.58). In general, tiger sharks *G. cuvier* tagged in the GBRMP appear to make short-term forays into the CSMP, but do not remain at any location for significant periods of time (weeks to months), and often return to the sites they were tagged (Figure 4.58).

a) Tagged Whits– large scale (*n* = 3) **b)** Tagged at Whits – small scale (*n* = 7)



c) Tagged Cairns Region – large scale (*n* = 4) **d)** Tagged Cairns Region – small scale (*n* = 4)



e) Tagged at NWI (*n* = 1) **f)** Tagged at Raine Is (*n* = 2)

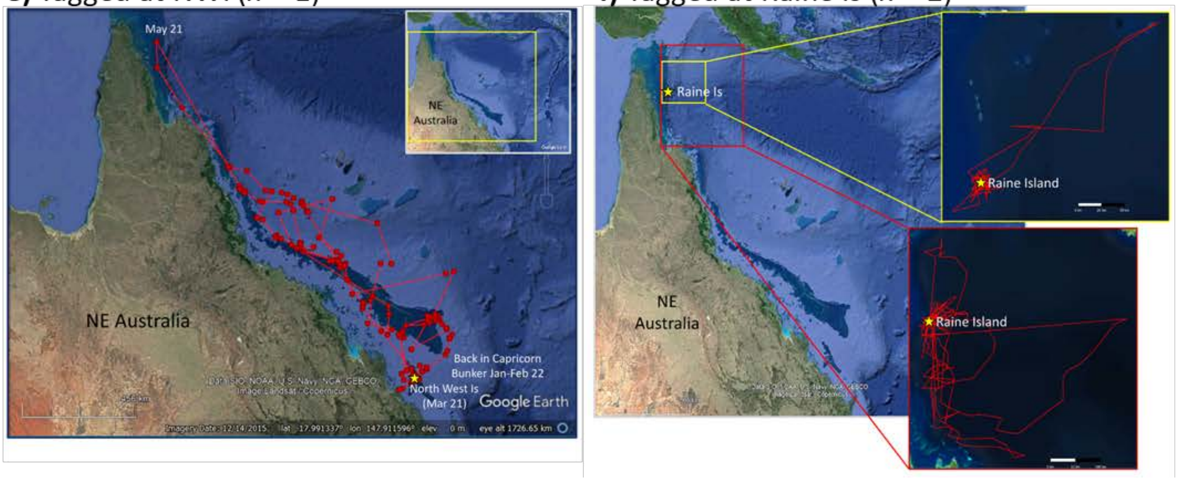


Figure 4.58 Satellite tracks of tiger sharks *Galeocerdo cuvier* that were tagged along the Queensland coast and moved into the Coral Sea. The individual panels are arranged by the tagging site (a,b) Whitsundays, (c,d) Cairns, (e) North West Island, (f) Raine Island . For sharks tagged at Whitsundays (Whits) and Cairns Region, large-scale and small-scale tracks are presented in separate panels. Whits – Whitsundays, NWI – North West Island. Yellow stars indicate tagging sites.

Of the 35 tiger sharks *G. cuvier* tagged at Norfolk Island, four were recorded to move into the Coral Sea region, with two of these individuals (shown in yellow and red in Figure 4.59) moving to the Chesterfield Islands regions. Two other individuals (Blue and green in Figure 4.59) were recorded to have moved from Norfolk Island to New Caledonia, and across the CSMP to the GBRMP. These movements of *G. cuvier* build on previously identified movements of *G. cuvier* between the Chesterfield Islands reefs and the east coast of Australia (Werry et al. 2014), suggesting there is considerable connectivity between the CSMP and adjacent regions for this species.

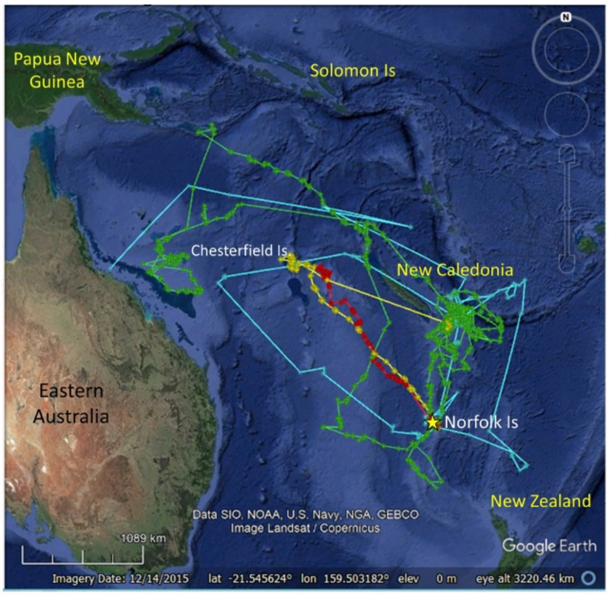


Figure 4.59 Satellite tracks of four tiger sharks *Galeocerdo cuvier* tagged at Norfolk Island that made movements into the Coral Sea Marine Park

Data from both acoustic and satellite tagged *G. cuvier* are consistent with individuals transiting through the CSMP, rather than being attracted to any particular feature/s. That is, there are no specific areas that are used by multiple individuals, and no individuals remained in an area for any length of time. Similarly, satellite tracking of an immature *C. carcharias* that moved through the CSMP to Papua New Guinea was consistent with transiting behaviours (Spaet et al. 2022). While these two apex predators both use the waters of the CSMP, the importance of the CSMP to their ecology is unknown.

Six whale sharks *Rhincodon typus* satellite tagged on the outer edge of the GBRMP between October 2018 and December 2021 spent between one and two months in the Wreck Bay region of the GBRMP before moving across the northern CSMP and spending considerable time (months) in waters to the north and northeast of the CSMP (Figure 4.60). This is the first data on habitat use of whale sharks in the CSMP and given the time spent in these areas it is likely they are areas of high productivity, and dietary resources.

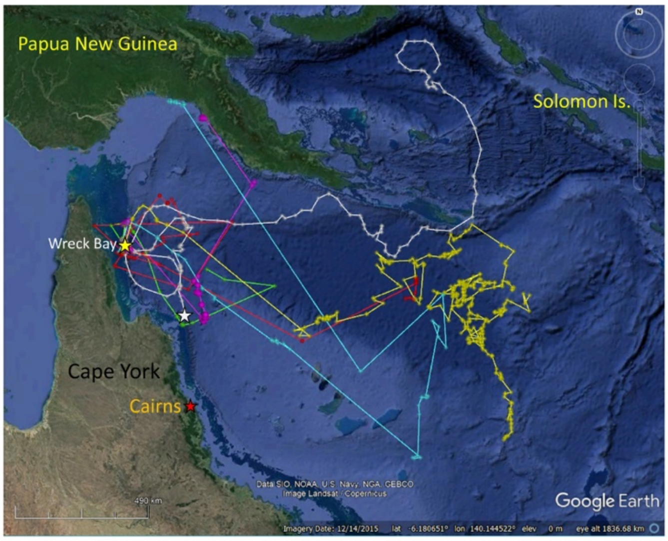


Figure 4.60 Satellite tracks of six whale sharks *Rhincodon typus* (tagged on the outer edge of the Great Barrier Reef) that moved into the Coral Sea Marine Park

Two reef manta rays *Mobula alfredi* satellite tagged on the northern GBRMP were also detected to have moved into the CSMP (Figure 4.61), where they descended to depths of up to 350 m (Figure 4.62). Similar deep diving (down to 670m) has been reported for *M. alfredi* in New Caledonia, with this behaviour being hypothesised to be related the distribution of important food sources (Lassauce et al. 2020).

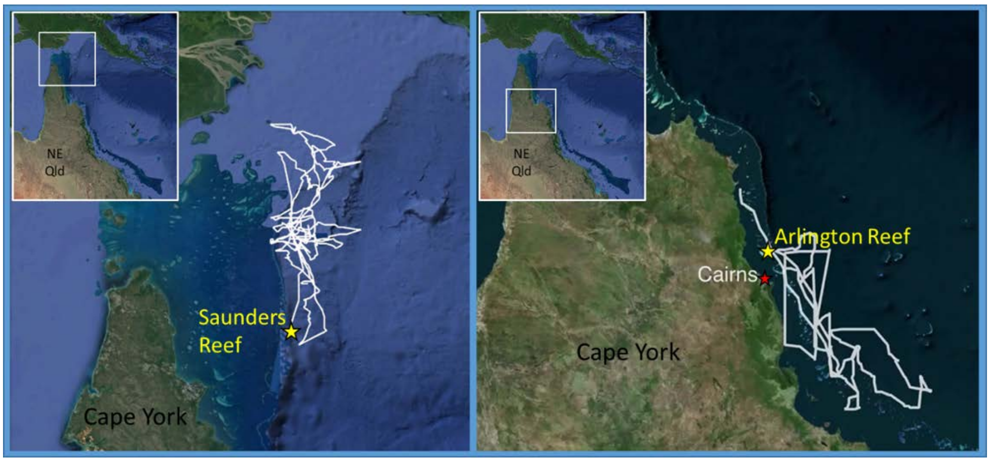
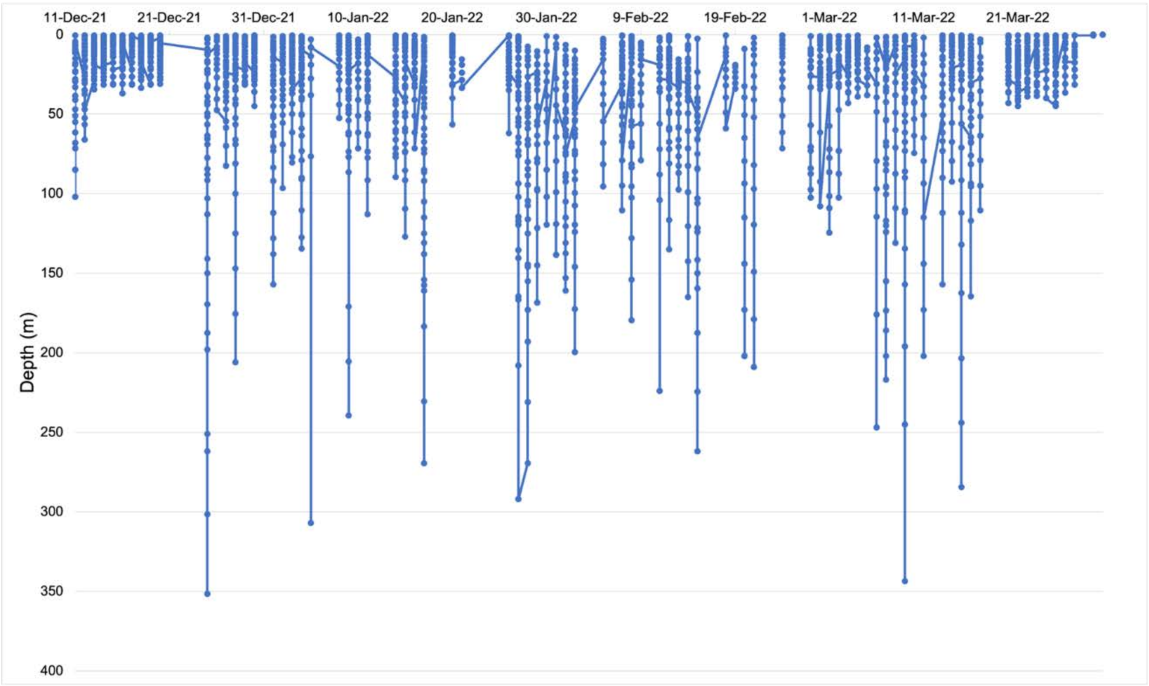


Figure 4.61 - Satellite tracks of Reef manta rays *Mobula alfredi* tagged at Arlington and Saunders reefs, Great Barrier Reef Marine Park, and subsequently moved into the Coral Sea Marine Park


Manta ray tagged at Sunders Reef

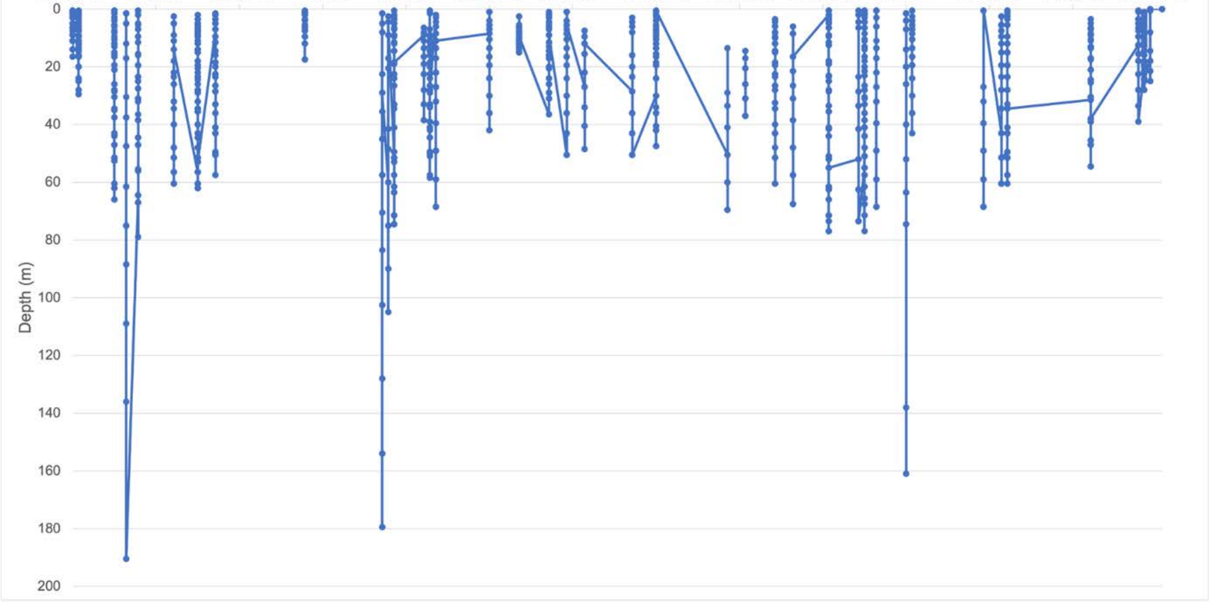

Manta ray tagged at Arlington Reef

Figure 4.62 - Depth profile of the reef manta rays *Mobula alfredi* tagged at Saunders and Arlington Reefs (Great Barrier Reef Marine Park) and subsequently moved into Coral Sea Marine Park.

4.7.3. Movement and residency of teleosts

The three teleost species (*C. ignobilis, C. lugubris,* and *P. laevis*) tagged at Osprey Reef all displayed low levels of residency within our receiver array (Figure 4.63). This low residency likely reflected individuals moving outside of the detection range of our receivers rather than of individuals leaving Osprey Reef. There were, however, differences in space use between the two species. The highest residency for *Caranx lugubris* was recorded at the tagging location in the entrance to the lagoon (CS-03), yet it was not detected on either of the receivers within the lagoon (Figures 4.64, 4.66). In contrast, detections of tagged *C. ignobilis* were more evenly spread among the seven receivers, including the two receivers (CS-04 and CS-05) within the lagoon (Figure 4.64, 4.65). Despite these differences, individuals of both *C. ignobilis* and *C. lugubris* were recorded to have moved from the lagoon entrance (CS-O3) to the northern tip of Osprey Reef (North Horn CS-O1) and back, a distance of ~20 km.

Both trevally species also displayed diel patterns in habitat use. *Caranx ignobilis* were primarily detected at the entrance of lagoon, the first lagoon receiver (CS-03 and CS-04), and outer-reef locations during the day, and moved to the two lagoon sites (CS-04, CS-05) at night (Figure 4.65). In contrast, detections for *C. lugubris* were greatest at the entrance to the lagoon and western reef edge (CS-03, CS-06) during the day, while detections at night were primarily along the reef edge (CS-06), and considerably lower than during the day (Figure 4.66), suggesting they were moving outside the array.

The single *Plectropomus laevis* tagged had an extremely low residency index (RI=0.04; Figure 4.63) being detected on only 16 days (108 detections) throughout the year. Interestingly, it was only detected at the receiver closest to where it was tagged (CS-03 at the entrance to the lagoon), the detections were dispersed throughout the year, and the vast majority of detections (106 out of 108) were at night (Figure 4.67). The remaining two detections were between 06:00 and 07:00.

No patterns emerged in the timing of teleost movements that would link lunar phase to spawning times or aggregation locations. Continued work on teleost movement at Osprey reef may provide valuable insights into such movements.

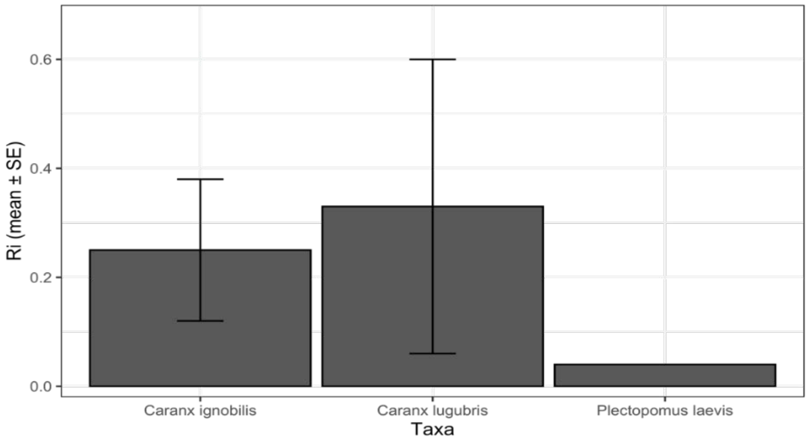


Figure 4.63 - Residency Index for teleosts tagged at Osprey Reef. Note: only one *P. laevis* was tagged in this study.

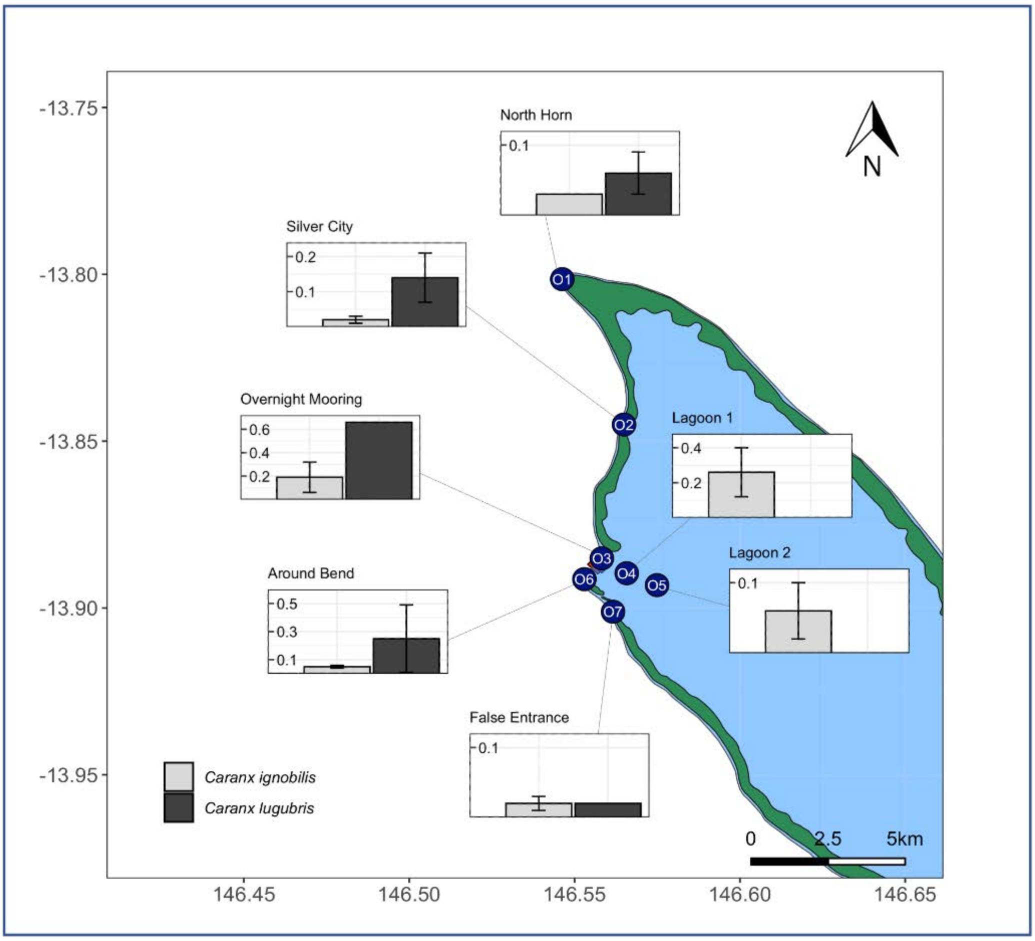


Figure 4.64 - Residency index (RI) for teleosts at each VR2W receiver at Osprey Reef. Absence of bar indicates no individuals of that taxa were detected at that receiver station and absence of error bars indicates that only one individual was recorded at that location. NB: *P. laevis* only detected at CS-03 so not included here and depicted in Figure 4.57.

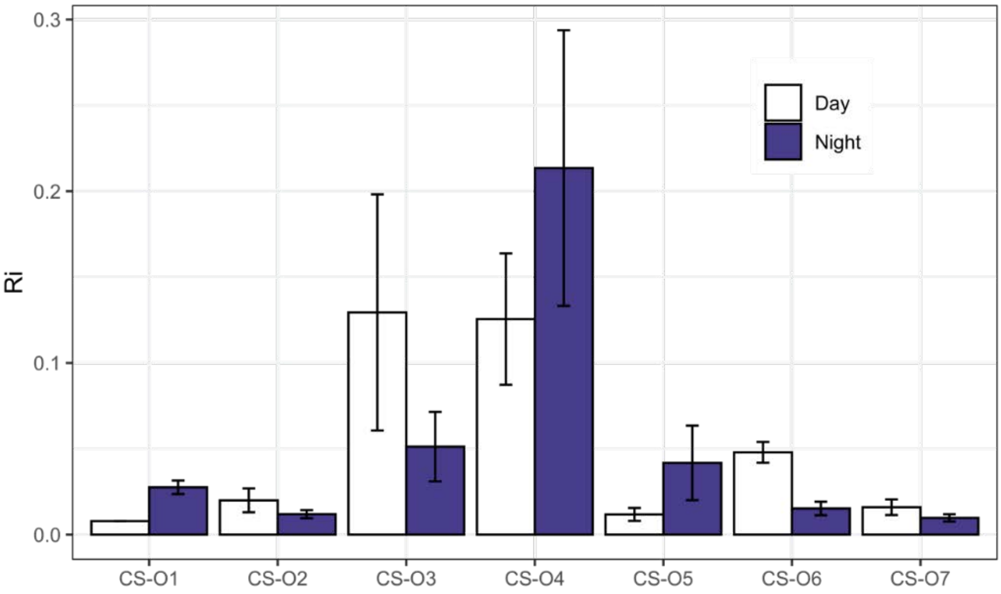


Figure 4.65 - Diurnal pattern in *Caranx ignobilis* RI at each receiver station Osprey Reef. Osprey Reef. Station CS-03 is the closest to tagging locations at the entrance to Lagoon. Stations CS-04 & CS-05 are lagoonal.

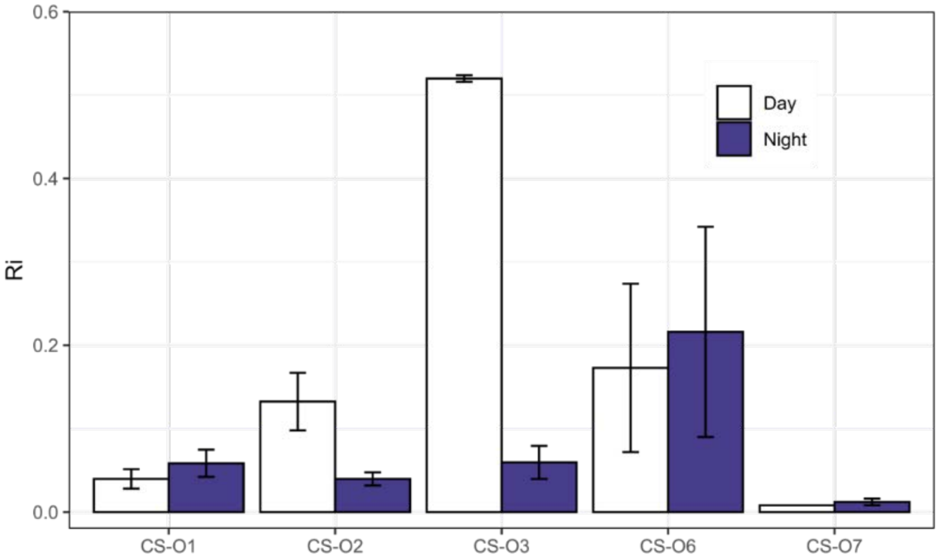


Figure 4.66 - Diurnal pattern in *Caranx lugubris* RI at each Osprey Reef receiver station. Station CS-03 is the closest to tagging locations at the entrance to the lagoon. *C. lugubris* was not detected at the two receivers in the lagoon (CS-04 & CS-05; see Figure 4.54).

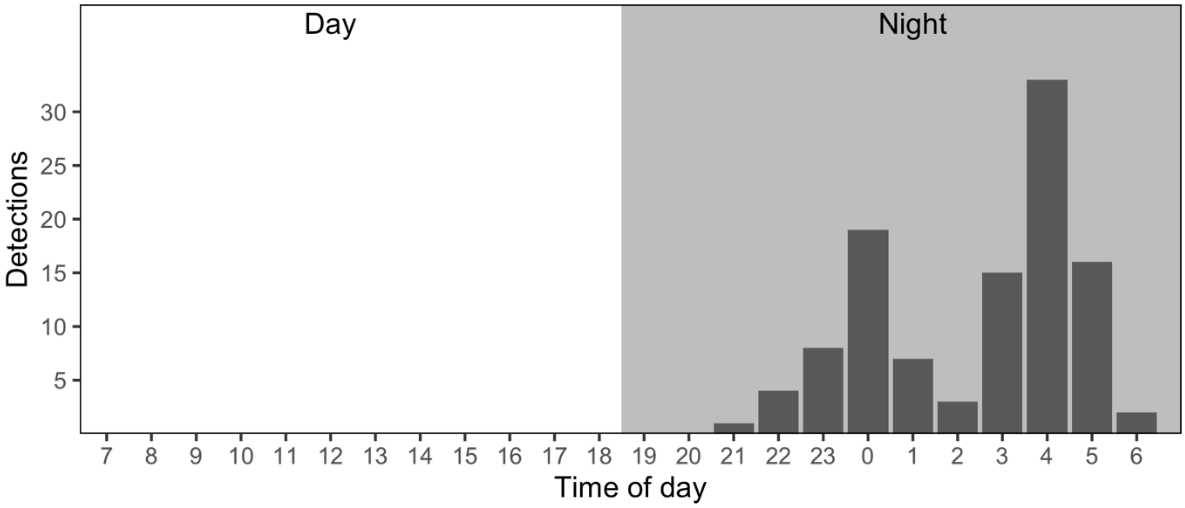


Figure 4.67 – Diel variation in the frequency of detections of the tagged blue-spot coral trout, *Plectropomus laevis*, at the receiver station closest to its site of capture and tagging (CS-03 at the entrance to the Osprey Reef lagoon). The number of detections are presented in 1-hour bins

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 in shallow reef habitats, 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, the CSMP has experienced multiple coral bleaching events in the past six years (i.e., 2016, 2017, 2020, 2021; Harrison et al. 2018, Hoey et al. 2020, 2021, 2022), with overall coral cover in shallow (<12m) reef habitats decreasing from 26.7% in 2020 to 12.8% in 2022, a 52% decline (Hoey et al. 2022). Despite the recent declines and current state of coral assemblages in shallow reef habitats in the CSMP, very little is known of the composition or condition of extensive deep habitats of the CSMP.

The surveys of deep (20-100m) habitats conducted as part of this project revealed a high degree of variability in the composition and cover of major benthic taxa among habitat types (i.e, lagoon, channels, outer and inner reef habitats), depths, and reefs. Unlike shallow reef communities there was no apparent regional structuring of deep habitats among the 15 CSMP reefs (i.e., benthic composition was highly variable among reefs within each of the southern, central and northern CSMP). Despite this variability, our surveys identified many areas of high coral cover at depth. Coral cover ranged from *ca.* 8% to 32% across the full depth range (0-100m), with two distinct peaks in average coral cover (71-80m: 32% and 11-20m: 17%). These estimates of coral cover on deep reef habitats with the CSMP are comparable to, or greater than, recent estimates of shallow water (2-10m) coral cover across the CSMP (2022: 12.8%; Hoey et al. 2022). Such high coral cover at depths of up to 80m is likely related to the exceptionally clear waters of the CSMP, and hence the penetration of sufficient light to support photosynthetic organisms. This high coral cover at depth, together with a general lack of recently dead corals, also suggests that coral assemblages in these habitats have largely escaped the effects of recent marine heatwaves that have caused >50% reduction in shallow water coral cover in the CSMP from 2020 to 2022 (Hoey et al. 2022). Previous studies have documented declines in bleaching (e.g., Bridge et al. 2013; Crosbie et al. 20-19) and effects of other anthropogenic stressors (e.g., fishing: Lindfield et al. 2016; Pinheiro et al. 2016) with depth, and have led to suggestions that these deeper habitats may act as a refugia from disturbance, and a potential source of coral, fish and invertebrate larvae to repopulate shallow reefs (e.g., Lesser et al. 2009, Bongaerts et al. 2011, MacDonald et al. 2016). Although the refuge potential of these MCE's and their capacity to replenish shallow population is debated (e.g., Rocha et al. 2018), the high coral cover of deep habitats are likely important in supporting the biodiversity and functioning of the CSMP.

As well as areas of high coral cover, our ROV and BRUV surveys revealed a diversity of habitats and associated fish assemblages within deep lagoonal habitats of the CSMP. Many CSMP reefs have extensive lagoons surrounded by a relatively narrow rim of shallow coral reef habitat, For example, at Lihou Reef the lagoon covers an area of approx. 2,500km^2 and is up to 60m deep, while shallow reef habitats only cover *ca.* 110km^2. Our surveys of these extensive lagoon systems yielded some of the most interesting results from the project, including observations of isolated patch reefs, bommies, meadows of *Halimeda* and other macroalgae, seagrass (although these were uncommon and generally sparse), sponges and sediment banks, as well as diverse and abundant fish communities. In nearshore coral reefs, these non-reef habitats provide important resources for many species and life stages of fishes, providing nursery habitat for newly-settled and juvenile fishes, refugia from reef-based predators, and foraging grounds for mobile species (e.g., Sambrook et al. 2019). Our surveys identified several species of juvenile fish using these deep non-reef habitats, including the commercially important Red Emperor, *Lutjanus sebae*. On the GBR, *L. sebae* settles to coastal seagrass habitat, before moving to deeper offshore habitats, including *Halimeda* banks, as it grows (Cappo and Kelley 2002). It is likely that other ecologically and economically important species that settle to shallow coastal non-coral habitats on the GBR and elsewhere (e.g., the bumphead parrotfish, *Bolbometopon muricatum*; Hamilton et al. 2017) may also rely on these deep lagoonal habitats in the CSMP. Further surveys of these extensive lagoonal systems are needed to understand the composition and spatial extent of these non-coral habitats, and their importance to different species and life stages of fishes.

Surveys of deep habitats of the CSMP also revealed diverse and abundant fish assemblages. Overall, there was a gradual decline in the species richness and diversity of CSMP fish assemblages with increasing depth, yet the abundance and biomass of fishes was greatest at intermediate (40-60m) depths. These patterns in fish richness and abundance are comparable to studies of mesophotic fish communities from other regions (e.g., Indo-Pacific: Abesamis et al. 2018, MacDonald et al. 2016; Caribbean: Bejarano et al. 2014, Andradi-Brown et al. 2016). Interestingly, many fish species that are common in shallow reef environments in the CSMP were also common or abundant in these deep habitats, with these species representing a broad range of functional or trophic groups. For example, the highfin parrotfish, *Scarus longipinnis*, the most common parrotfish recorded in shallow (<12m) reef habitats of the CSMP (Hoey et al. 2020), was also the most common parrotfish recorded on deep habitats, and was observed as deep as 79m at Edna Cay, Lihou Reef. Why this species appears to thrive across a broad depth range in the CSMP, yet is rare or absent on GBR reefs is currently unknown.

Of the 407 fish species recorded by ROV and BRUV surveys combined, 68 fish species had not previously been recorded during extensive surveys of shallow water reef habitats within the CSMP over the past five years (2018-22: Hoey et al. 2022), taking the total number of fish species observed by monitoring surveys from 661 to 729 species in the CSMP. Whilst these species are not necessarily unknown to the region, some are rare taxa seldom seen by divers and are targeted by the aquarium industry (e.g., *Geniacanthus bellus, Pseudanthias pictilis, Pseudanthias flavicauda*), and at least three species (*Hoplolatilus marcosi*, *Hoplolatilus* sp.1, *Hoplolatilus* sp. 2) appear to be new records for the region. Together with these ‘new’ species records, 156 fish species (38% of all species recorded) were observed at depths below their known depth range, and 77 species at depths greater than double their reported maximum depth. The surveys of deep habitats in the CSMP have greatly increased our understanding of the biodiversity and unique nature of the region, and the distribution of species among and within reefs. Given the extensive coverage of these deep reef and non-reef habitats throughout the CSMP it is likely that many other species remain unreported and the true taxonomic diversity is considerably greater than current estimates.

Several commercially important fish species were recorded in deep habitats within the CSMP, including the Red Throat Emperor (*Lethrinus miniatus*), Red Emperor (*Lutjanus sebae*) and the Crimson Jobfish (*Pristipomoides filamentosus*). *L. miniatus* and *L. sebae* are important species in the GBR Reef Line Fishery (Northrop and Campbell 2020) and all three species are among the most important species in the Coral Sea Fishery Trap and Line Sector (AFMA 2012). Given these three species are rarely observed, if at all, during surveys of shallow reef habitat, the current status of their populations is unknown. Structured surveys of deep reef and non-reef habitats are required to provide fisheries independent information on the abundance, size structure and population (or stock) status of these valuable fisheries species throughout the CSMP.

Recent monitoring of shallow coral reef habitats throughout the CSMP have identified five ‘bright spot’ reefs that have substantially higher coral richness, coral cover, fish richness and/or fish biomass than other CSMP reefs (Hoey et al. 2020). Similarly, our ROV surveys identified several deep sites that had exceptionally high coral cover and a high abundance of reef fish (Herald’s Surprise Reef, Bougainville Reef, and adjacent to Edna and Juliette Cays, Lihou Reef). Although these deep ‘bright spots’ were individual sites, and not comparable in scale to the shallow bright spots reefs, the coral cover they support is not insignificant. For example, coral cover at the deep site (20-70m) on Bougainville Reef ranged from 39-54%, considerably greater than the 24% coral cover in shallow (<12m) reef habitats on the same reef, a shallow reef ‘bright spot’ (Hoey et al. 2022). Similarly, coral cover at the deep sites on Herald’s Surprise and Lihou Reefs (up to 70% cover) were markedly higher than coral cover in shallow (<12m) reef habitats on the same reefs (7% and 10%, respectively; Hoey et al. 2022). Understanding the environmental and biological conditions that contribute to the high coral cover and abundant fish assemblages at these deep ‘bright spots’ should be a focus of future research, together with continued and expanded surveys of deep water habitats to quantify how common and widespread these deep 'bright spots' are.

Sharks (primarily *C. amblyrhynchos* and *C. albimarginatus*) were commonly observed and abundant in deep habitats throughout the CSMP, being recorded on all 15 reefs surveyed. Our ROV and BRUV surveys also recorded several individuals of larger-bodied sharks that are rarely observed during diver-based surveys of shallow reef habitats in the CSMP, namely Tiger Sharks *G. cuvier* and Scalloped Hammerhead *S. lewini*. The high abundance of sharks in the CSMP has been previously reported for shallow reef habitats (Ceccarelli et al. 2013; Stuart-Smith et al. 2013; Hoey et al. 2020, 2021, 2022), and is indicative of a system with relatively limited fishing pressure. This is in contrast to many other tropical marine regions that have experienced significant declines in the abundance of sharks and other Chondrichthyes over recent decades (Dulvy et al. 2014). Results from this project not only support existing evidence that the CSMP supports high shark abundance but also that these trends extend across a considerable depth gradient.

Together with the high abundance of sharks throughout the CSMP, our results show that both small- and large-bodied sharks make significant movements among reefs within the CSMP, and between the CSMP and adjacent areas. Such movements requiring travelling distances of several hundred km's across deep (up to 4,000m) oceanic waters. Such depths can be a barrier to gene flow, particularly for species that lack a planktonic stage and require active dispersal of individuals to move across permeable barriers (Hirschfeld et al., 2021). Despite our array of acoustic receivers being relatively sparse (19 receivers across four reefs), and the limited temporal scale of our study we detected several significant movements of sharks across these deep oceanic waters. Of particular note, we recorded a female *C. amblyrhynchos* (164cm TL) to undertake a journey of ~760km in 25 days, from Osprey Reef to Saunders Reef, northern GBRMP and back again. While the reason for this movement is unknown, it is to our knowledge the largest movement recorded for this species. Several other individuals that were acoustically tagged during this project (i.e., *C. amblyrhynchus* and *C. albimarginatus*) were recorded to move among reefs within the CSMP. In addition, our receivers detected several larger-bodied sharks that had been acoustically tagged elsewhere moving into the CSMP, including *G. cuvier* from the GBRMP and surprisingly a White Shark *C. carcharius* that had moved from northern NSW to the northern CSMP. This is not the first time a *C. carcharius* has been recorded to move through the CSMP, with an immature *C. carcharius* being tracked from NSW, through the CSMP to southern Papua New Guinea (Spaet et al. 2021). Given the relatively low number of animals tagged, and the limited number of acoustic receivers in this project, the movement of sharks and potentially other large animals among CSMP reefs, and between the CSMP and adjacent regions may be more common than reported here. Extending the current study (i.e., maintaining and downloading receivers), and/or increasing the number of animals tagged and number of receivers will provide greater certainty around the frequency of these movements and hence the connectivity among CSMP reefs, and between the CSMP and adjacent regions.

5.1 Recommendations

This project has provided the most extensive and detailed examination of deep (up to 100m) habitats in the CSMP to date, including the first observations of deep-water habitats and the fishes that use them at many CSMP reefs. However, given the sheer size of the CSMP (~990,000 km^2), and the morphologies of CSMP reefs, the spatial extent of mesophotic coral and non-coral (i.e., lagoon) ecosystems is considerably larger than that of shallow coral reef ecosystems (15,024 km^2). The BRUV and ROV surveys conducting during this project have yielded important insights into these unique ecosystems, however they have only scratched the surface. Similar to the surveys of shallow water reef habitats (2018-2022), the surveys of deep reef and lagoonal habitats have revealed considerable variation in the richness, composition and cover of corals and other benthic taxa, 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, providing greater certainty around reef-level estimates of reef health, and also providing a basis for future targeted research. In particular, several of the deep lagoonal habitats supported high densities of juvenile fishes, including commercially important species such as Red Emperor (*Lutjanus sebae*). To provide a greater understanding and appreciation of the unique nature of these habitats and the species they support we recommend continuing to survey these deep habitats using a range of techniques (discussed below). Specifically, we recommend expanding the spatial coverage of these surveys to include a greater range of habitats and depths, and at a greater number of sites within each CSMP reef.

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. Indeed, regular (i.e., annual) monitoring of shallow reef habitats in the CSMP reefs over the past seven years (2016-2022) has greatly improved our understanding of these shallow reefs, and importantly identified drivers of change (i.e., marine heatwaves). 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. Deep reef habitats have often been suggested to provide a spatial refuge for shallow water taxa from anthropogenic stressors (e.g., MacDonald et al. 2016), however recent evidence has shown these MCE’s are impacted by a range of anthropogenic stressors (Rocha et al. 2018). Regular monitoring of deep reef habitats within the CSMP will be critical to determine any changes in the condition and health of these unique ecosystems, to identify any drivers of change, and to compare the response of shallow vs deep reef habitats to a range of stressors (e.g., heat stress, cyclones). We recommend monitoring deep reef habitats at sites that offer access to a broad range of depths (i.e., 20-100m), and are adjacent to, or paired with, existing shallow reef monitoring sites (Hoey et al. 2022).

Our surveys identified several ‘bright spots’ among these deep water habitats. These ‘bright spot’ sites support higher coral cover (up to 70%), and more abundant and diverse fish communities than other deep sites surveyed in the CSMP. Given the spatial extent of deep reef habitats in the CSMP there is likely to be many more of these deep ‘bright spots’ yet to be discovered. Identifying additional ‘bright spots’, and understanding what makes these areas unique will require expanding on the present surveys and continued comprehensive monitoring of coral and fish assemblages at these sites and adjacent areas, together with dedicated research on key environmental and ecological (e.g., primary and secondary productivity, nutrient inputs, local hydrodynamics) processes. Monitoring and research on these deep 'bright spots' should be a future priority.

A range of video-based remote sampling methods (e.g., BRUV, ROV) have been developed and are being increasingly used to obtain quantitative data on benthic habitats and associated mobile species in deep water habitats. Each of these methods has its own benefits and limitations, and these should be considered when selecting the most appropriate method/s. For example, there were some differences in the fish species recorded by the two methods used in this project, with 146 species being unique to the ROV surveys, 106 species being unique to the BRUV and 155 species recorded by both methods. The BRUVS also recorded a greater number of predatory species, but only provide an estimate of relative abundance (Max N) of fishes, limited coverage of benthic habitats, only a single depth and replicate can be sampled per deployment, and can only be deployed in relatively flat or horizontal habitats. In contrast, the ROV transects recorded a greater coverage of the broader fish assemblage, provided an estimate of abundance and density, allowed fish and benthic communities to be sampled along the same transects, allowed multiple depths, and multiple transects within each depth to be sampled in a single deployment, however they can be difficult to deploy and retrieve when conditions are unfavourable. We would recommend to continue using the ROV as the primary method for surveys of deeper habitats, and if resources allow including additional surveys using BRUV and/or towed video systems (e.g., Skewes and Persson 2007).

Results from our tagging study show that both small- and large-bodied sharks make significant movements among reefs within the CSMP, and between the CSMP and adjacent areas. In particular, we recorded a female grey reef shark *C. amblyrhynchos* (164cm TL) to undertake a journey of ~760km in 25 days, the largest recorded movement for this species. These active movements of individuals provide some insights into the ecological connectivity among these reefs and reef systems. Given the relatively short duration of the study (1 yr), the limited number of receivers

(19 receivers in the CSMP) and animals tagged (112 individuals), and the relatively high number of individuals that moved outside the array, these large-scale movements may be more common. The tags we implanted in the sharks have a battery life of ~10 years. As such, we strongly recommend the existing array is maintained and data downloaded regularly (i.e., annually) as a minimum for the next 9 years, allowing the longer term movements of these animals to be quantified. Expanding the receiver array to include other reefs in the central and northern CSMP (e.g., Herald Cays, Diamond Islets, Lihou, Mellish, Ashmore and Boot Reefs) would also provide an understanding of movements and connectivity among the broader CSMP.

This project has highlighted the importance and unique nature of deep water reef communities of the CSMP, and, through the tracking of tagged animals, the connectivity of the CSMP with several of the adjacent regions (i.e., Norfolk Island, the GBRMP, New Caledonia, Solomon Islands and Papua New Guinea). Comparable monitoring of both shallow and deep reef habitats, together with targeted and collaborative research in all regions bordering the CSMP is needed 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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7 Appendices

Appendix 1

Extended fish depth records recorded by ROV and BRUV surveys (Feb-March 2021, July 2021, October 2021, Feb 2022). Depth increase in meters is presented based on the maximum known depth from fishbase records (Froese and Pauly, 2022).

Species	Observed Depth (m)	Fishbase Max Depth (m)	Depth Increase (m)	Reef	Method
Chromis margaritifer	94.10	20	74.10	Osprey	ROV
Chaetodon plebeius	67.80	10	57.80	Bougainville	ROV
Lethrinus miniatus	85.00	30	55.00	Holmes	BRUV
Labroides dimidiatus	94.10	40	54.10	Osprey	ROV
Neoniphon opercularis	79.00	25	54.00	Lihou	ROV
Genicanthus melanospilos	97.20	45	52.20	Osprey	ROV
Gymnocranius euanus	98.00	50	48.00	Lihou	ROV
Scarus niger	67.80	20	47.80	Bougainville	ROV
Pentapodus aureofasciatus	79.00	35	44.00	Lihou	ROV
Acanthurus albipectoralis	63.00	20	43.00	Lihou	ROV
Chrysiptera flavipinnis	80.60	38	42.60	Osprey	ROV
Ostracion meleagris	71.60	30	41.60	Osprey	ROV
Cephalopholis leopardus	80.60	40	40.60	Osprey	ROV
Choerodon jordani	70.00	30	40.00	Lihou	ROV
Neoniphon sammara	86.00	46	40.00	Lihou	ROV
Chromis agilis	87.60	48	39.60	Osprey	ROV
Thalassoma lunare	58.10	20	38.10	Bougainville	ROV
Chaetodon pelewensis	67.30	30	37.30	Bougainville	ROV
Anampses geographicus	62.00	25	37.00	Willis	BRUV
Scarus chameleon	66.70	30	36.70	Bougainville	ROV
Hologymnosus longipes	65.00	30	35.00	Wreck	BRUV

Naso lopezi	85.00	50	35.00	Holmes	BRUV
Naso vlamingii	85.00	50	35.00	Holmes	BRUV
Oxycheilinus nigromarginatus	62.00	27	35.00	Willis	BRUV
Pomacentrus moluccensis	48.90	14	34.90	Lihou	ROV
Chromis iomelas	67.80	35	32.80	Bougainville	ROV
Gomphosus varius	67.80	35	32.80	Bougainville	ROV
Siganus woodlandi	47.00	15	32.00	Flinders	BRUV
Acanthurus blochii	46.40	15	31.40	Lihou	ROV
Balistoides viridescens	81.00	50	31.00	Herald	BRUV
Malacanthus brevirostris	81.00	50	31.00	Herald	BRUV
Odonus niger	71.00	40	31.00	Herald	BRUV
Pseudobalistes flavimarginatus	81.00	50	31.00	Herald	BRUV
Pseudobalistes fuscus	81.00	50	31.00	Herald	BRUV
Rhinecanthus rectangulus	50.10	20	30.10	Lihou	ROV
Sufflamen chrysopterum	60.10	30	30.10	Willis	ROV
Ctenochaetus striatus	65.00	35	30.00	Wreck	BRUV
Hologymnosus doliatus	65.00	35	30.00	Wreck	BRUV
Monotaxis heterodon	54.60	25	29.60	Osprey	ROV
Myripristis murdjan	79.00	50	29.00	Lihou	ROV
Pseudanthias tuka	67.80	40	27.80	Bougainville	ROV
Ptereleotris evides	42.30	15	27.30	Willis	ROV
Thalassoma amblycephalum	42.30	15	27.30	Willis	ROV
Chromis amboinensis	97.20	70	27.20	Osprey	ROV
Acanthurus auranticavus	46.20	20	26.20	Lihou	ROV
Lutjanus adetii	46.20	20	26.20	Lihou	ROV
Acanthurus nigrofuscus	51.00	25	26.00	Willis	BRUV
Lethrinus semicinctus	61.00	35	26.00	Lihou	BRUV
Pseudanthias engelhardi	96.00	70	26.00	Lihou	ROV
Sargocentron diadema	86.00	60	26.00	Lihou	ROV
Acanthurus nigricauda	55.00	30	25.00	Flinders	BRUV

Anampses melanurus	65.00	40	25.00	Wreck	BRUV
Chaetodon guentheri	65.00	40	25.00	Wreck	BRUV
Chromis flavomaculata	65.00	40	25.00	Wreck	BRUV
Labroides bicolor	65.00	40	25.00	Wreck	BRUV
Pseudanthias pictilis	65.00	40	25.00	Wreck	BRUV
Chaetodon melannotus	44.40	20	24.40	Willis	ROV
Plectroglyphidodon johnstonianus	42.00	18	24.00	Kenn	BRUV
Scarus longipinnis	79.00	55	24.00	Lihou	ROV
Balistoides conspicillum	98.00	75	23.00	Lihou	ROV
Naso thynnoides	63.00	40	23.00	Lihou	ROV
Centropyge bicolor	47.60	25	22.60	Herald's Surprise	ROV
Acanthochromis polyacanthus	87.60	65	22.60	Osprey	ROV
Chrysiptera taupou	32.50	10	22.50	Lihou	ROV
Gymnocranius superciliosus	42.00	20	22.00	Lihou	BRUV
Scarus frenatus	46.60	25	21.60	Lihou	ROV
Pterocaesio marri	51.00	30	21.00	Lihou	BRUV
Bodianus anthioides	80.60	60	20.60	Osprey	ROV
Centropyge bispinosa	80.60	60	20.60	Osprey	ROV
Naso annulatus	80.60	60	20.60	Osprey	ROV
Scarus psittacus	45.50	25	20.50	Bougainville	ROV
Chaetodon lunulatus	50.40	30	20.40	Willis	ROV
Chlorurus spilurus	50.40	30	20.40	Willis	ROV
Gnathodentex aureolineatus	50.40	30	20.40	Willis	ROV
Chromis chrysura	65.00	45	20.00	Wreck	BRUV
Acanthurus pyroferus	79.00	60	19.00	Lihou	ROV
Novaculichthys taeniourus	44.00	25	19.00	Wreck	BRUV
Pseudanthias flavicauda	80.00	61	19.00	Lihou	ROV
Chromis xanthochira	66.70	48	18.70	Bougainville	ROV
Ctenochaetus binotatus	71.60	53	18.60	Osprey	ROV
Chaetodon kleinii	79.00	61	18.00	Lihou	ROV

Chlorurus microrhinos	68.00	50	18.00	Osprey	ROV
Heniochus monoceros	48.00	30	18.00	Lihou	BRUV
Siganus argenteus	58.00	40	18.00	Kenn	BRUV
Stegastes fasciolatus	47.70	30	17.70	Lihou	ROV
Pseudodax moluccanus	77.20	60	17.20	Osprey	ROV
Labrichthys unilineatus	37.10	20	17.10	Flinders	ROV
Scarus oviceps	37.10	20	17.10	Herald	ROV
Hemigymnus fasciatus	42.00	25	17.00	Willis	ROV
Scarus dimidiatus	42.00	25	17.00	Willis	ROV
Centropyge vrolikii	41.70	25	16.70	Herald	ROV
Thalassoma hardwicke	31.50	15	16.50	Wreck	ROV
Chromis ternatensis	52.30	36	16.30	Willis	ROV
Thalassoma lutescens	46.20	30	16.20	Lihou	ROV
Halichoeres biocellatus	51.00	35	16.00	Willis	BRUV
Hoplolatilus marcosi	96.00	80	16.00	Lihou	ROV
Genicanthus watanabei	96.00	81	15.00	Lihou	ROV
Naso caesius	65.00	50	15.00	Wreck	BRUV
Pseudanthias hypselosoma	65.00	50	15.00	Wreck	BRUV
Scarus rubroviolaceus	51.00	36	15.00	Holmes	BRUV
Arothron mappa	44.80	30	14.80	Willis	ROV
Chromis weberi	54.70	40	14.70	Bougainville	ROV
Naso brachycentron	44.00	30	14.00	Chilcott	BRUV
Nemateleotris magnifica	84.00	70	14.00	Osprey	ROV
Anampses femininus	43.30	30	13.30	Flinders	ROV
Hipposcarus longiceps	53.00	40	13.00	Wreck	BRUV
Meiacanthus atrodorsalis	42.30	30	12.30	Willis	ROV
Scarus flavipectoralis	52.30	40	12.30	Willis	ROV
Anampses neoguinaicus	42.00	30	12.00	Kenn	BRUV
Anampses twistii	42.00	30	12.00	Willis	ROV
Balistapus undulatus	62.00	50	12.00	Willis	BRUV

Bodianus bimaculatus	72.00	60	12.00	Kenn	BRUV
Chaetodon trifascialis	42.00	30	12.00	Kenn	BRUV
Chaetodon ulietensis	42.00	30	12.00	Kenn	BRUV
Gymnocranius microdon	62.00	50	12.00	Willis	BRUV
Naso tonganus	52.00	40	12.00	Herald	BRUV
Cheilinus fasciatus	71.60	60	11.60	Osprey	ROV
Plectropomus areolatus	31.20	20	11.20	Holmes	ROV
Coris dorsomacula	51.00	40	11.00	Lihou	BRUV
Halichoeres hartzfeldii	81.00	70	11.00	Herald	BRUV
Amblyglyphidodon aureus	55.60	45	10.60	Lihou	ROV
Chaetodon flavirostris	40.40	30	10.40	Herald	ROV
Pomacanthus semicirculatus	50.10	40	10.10	Lihou	ROV
Chaetodon vagabundus	40.00	30	10.00	Lihou	ROV
Coris pictoides	65.00	55	10.00	Wreck	BRUV
Dascyllus trimaculatus	65.00	55	10.00	Wreck	BRUV
Labropsis australis	65.00	55	10.00	Wreck	BRUV
Pomacentrus pavo	28.00	18	10.00	Ashmore	BRUV
Macropharyngodon meleagris	39.60	30	9.60	Herald's Surprise	ROV
Cirrhilabrus exquisitus	49.30	40	9.30	Lihou	ROV
Acanthurus olivaceus	55.20	46	9.20	Lihou	ROV
Halichoeres melasmapomus	65.00	56	9.00	Wreck	BRUV
Plectorhinchus chaetodonoides	39.00	30	9.00	Lihou	ROV
Scarus forsteni	39.00	30	9.00	Lihou	ROV
Amphiprion chrysopterus	48.90	40	8.90	Lihou	ROV
Chaetodon ornatissimus	44.80	36	8.80	Lihou	ROV
Centropyge heraldi	98.00	90	8.00	Lihou	ROV
Pomacentrus brachialis	48.00	40	8.00	Lihou	BRUV
Oxycheilinus digramma	67.30	60	7.30	Bougainville	ROV
Macolor niger	97.20	90	7.20	Osprey	ROV
Chromis fumea	79.00	72	7.00	Lihou	ROV

Cirrhilabrus lineatus	62.00	55	7.00	Willis	BRUV
Naso minor	62.00	55	7.00	Willis	BRUV
Scolopsis bilineata	32.00	25	7.00	Ashmore	BRUV
Epinephelus fuscoguttatus	66.70	60	6.70	Bougainville	ROV
Rhinecanthus lunula	36.50	30	6.50	Wreck	ROV
Chaetodon speculum	36.40	30	6.40	Bougainville	ROV
Cirrhilabrus scottorum	46.40	40	6.40	Lihou	ROV
Siganus punctatissimus	36.40	30	6.40	Bougainville	ROV
Pomacentrus vaiuli	51.00	45	6.00	Willis	BRUV
Pseudalutarius nasicornis	61.00	55	6.00	Lihou	BRUV
Pseudocoris yamashiroi	36.00	30	6.00	Lihou	BRUV
Heniochus chrysostomus	45.50	40	5.50	Bougainville	ROV
Cetoscarus ocellatus	35.00	30	5.00	Herald	BRUV
Epinephelus polyphekadion	51.00	46	5.00	Holmes	BRUV
Scarus schlegeli	55.00	50	5.00	Lihou	BRUV

Appendix 2: New species records of reef fish for the Coral Sea Marine Park that had not previously been recorded or observed during shallow water surveys (Hoey et al. 2020, 2021, 2022). ‘1’ indicates where species were observed on BRUV, ROV or both. *indicates likely new species records not previously recorded as being present in the CSMP, based on records available in online repositories Fishbase, Reef Life Survey, Fishes of Australia and the Australian Faunal Directory.

Species	BRUV	ROV
*Abalistes filamentosus**	1	
Abalistes stellatus	1	
*Acanthurus nubilus**		1
*Anampses melanurus**	1	
Arothron caeruleopunctatus	1	1
Arothron mappa		1
Bodianus bimaculatus	1	
Carangoides oblongus	1	
Cephalopholis sonnerati	1	
Chaetodon guentheri	1	
Choerodon jordani	1	1
Chromis analis		1
Chrysiptera starcki	1	1
Chrysiptera tricincta	1	1
Cirrhilabrus bathyphilus	1	
Coris pictoides	1	1
Cyprinocirrhites polyactis	1	
Dipterygonotus balteatus		1
Genicanthus bellus		1
Gymnocranius superciliosus	1	1
Halichoeres hartzfeldii	1	
Halichoeres melasmapomus	1	
Heniochus diphreutes	1	
Heteroconger hassi	1	
Hologymnosus longipes	1	
*Hoplolatilus marcosi**		1
*Hoplolatilus sp1**		1
*Hoplolatilus sp2**		1
Leptojulis cyanopleura	1	
Lethrinus rubrioperculatus	1	
Lethrinus semicinctus	1	
Lutjanus sebae	1	1
Malacanthus brevirostris	1	
*Mulloidichthys pfluegeri**	1	
Naso lopezi	1	
Naso minor	1	

Naso thynnoides		1
Neoniphon opercularis		1
Orectolobus ornatus	1	
Oxycheilinus bimaculatus	1	
Oxycheilinus nigromarginatus	1	
Paramonacanthus cf. curtorhynchos	1	
Parapercis hexophthalma	1	
Parupeneus heptacanthus	1	
Pentapodus nagasakiensis	1	
Pomacentrus nigromarginatus	1	1
Pristipomoides filamentosus	1	
Pseudalutarius nasicornis	1	
Pseudanthias engelhardi		1
Pseudanthias flavicauda		1
Pseudanthias hypselosoma	1	
Pseudanthias pictilis	1	1
Pseudanthias rubrizonatus		1
Pseudanthias ventralis		1
Pseudocaranx dentex		1
Remora remora	1	
Rhabdamia gracilis		1
Rhinecanthus lunula		1
Sargocentron diadema		1
Scolopsis affinis	1	
Selar crumenophthalmus	1	
Seriola dumerili		1
Seriola rivoliana	1	
Sphyraena qenie	1	1
Sufflamen fraenatum	1	1
Taeniurops meyeni	1	
*Xanthichthys auromarginatus**	1	
Xanthichthys caeruleolineatus	1	

Appendix 3: Details of sharks and teleosts acoustically tagged in the Coral Sea Marine Park, including tagging site, date tagged, sex, total length (cm), maturity stage (J = juvenile (imature); S-A = Sub-adult; M = mature), tag ID and residency index (RI, in %). Ukn = unknown. NDAT = not detected after tagging.

Tagging site	Tagging date	Sex	TL (cm)	Maturity stage	Tag ID	RI (%)
C. amblyrhynchos						
Osprey Reef	23/02/2021	F	139	J	64090	55.8
Osprey Reef	23/02/2021	F	162	M	64091	96.8
Osprey Reef	23/02/2021	F	145	M	64092	4.6
Osprey Reef	23/02/2021	F	169	M	64093	99.5
Osprey Reef	23/02/2021	F	157	M	64094	95.2
Osprey Reef	23/02/2021	F	160	M	64095	56.8
Osprey Reef	24/02/2021	F	178	M	64096	99.7
Osprey Reef	24/02/2021	F	180	M	64097	99.7
Osprey Reef	24/02/2021	F	162	M	64098	79.0
Osprey Reef	24/02/2021	F	172	M	64099	99.5
Osprey Reef	24/02/2021	F	152	M	64100	100.0
Osprey Reef	24/02/2021	F	163	M	64101	100.0
Osprey Reef	24/02/2021	F	166	M	64102	17.7
Osprey Reef	24/02/2021	F	164	M	64103	55.6
Osprey Reef	24/02/2021	F	150	M	64104	81.5
Osprey Reef	24/02/2021	F	178	M	64105	100.0
Osprey Reef	24/02/2021	F	158	M	64107	97.6
Osprey Reef	24/02/2021	F	152	M	64108	97.8
Osprey Reef	24/02/2021	F	166	M	64109	5.9
Osprey Reef	25/02/2021	F	161	M	64110	74.7
Osprey Reef	25/02/2021	F	150	M	64111	53.6
Osprey Reef	28/10/2021	H	138	M	14036	100.0
Osprey Reef	29/10/2021	H	130	S-A	14038	100.0
Osprey Reef	29/10/2021	H	141	M	14040	100.0
Osprey Reef	29/10/2021	H	126	J	14042	98.4
Osprey Reef	29/10/2021	H	174	M	14044	77.6
Osprey Reef	29/10/2021	H	136	M	14046	100.0
Osprey Reef	29/10/2021	H	128	J	14048	36.0
Osprey Reef	29/10/2021	H	161	J	14050	100.0
Osprey Reef	29/10/2021	H	166	M	14052	96.8
Osprey Reef	29/10/2021	H	161	M	14054	97.6
Osprey Reef	29/10/2021	H	129	J	14056	100.0
Osprey Reef	29/10/2021	H	171	M	14058	78.4
Osprey Reef	29/10/2021	F	161	M	14060	100.0
Osprey Reef	29/10/2021	H	175	M	14062	97.6
Osprey Reef	29/10/2021	H	168	M	14064	99.2
Holmes Reef - West	20/02/2021	F	147	M	64079	11.3
Holmes Reef - West	20/02/2021	F	106	J	64081	4.8
Holmes Reef - West	20/02/2021	F	170	M	64082	31.4
Holmes Reef - West	20/02/2021	F	145	M	64083	3.8
Holmes Reef - West	25/10/2021	F	166	M	60568	100.0
Holmes Reef - East	21/02/2021	F	143	M	64084	97.0
Holmes Reef - East	21/02/2021	M	147	M	64085	NDAT

Tagging site	Tagging date	Sex	TL (cm)	Maturity stage	Tag ID	RI (%)
Holmes Reef - East	21/02/2021	F	167	M	64086	74.2
Holmes Reef - East	21/02/2021	M	132	S-A	64087	94.4
Holmes Reef - East	21/02/2021	F	165	M	64088	69.6
***C. amblyrhynchos* (cont.)**						
Holmes Reef - West	25/10/2021	F	123	J	60569	100.0
Holmes Reef - West	25/10/2021	F	143	M	60570	100.0
Holmes Reef - West	25/10/2021	F	100	J	64015	87.3
Holmes Reef - West	25/10/2021	F	105	J	64056	92.9
Holmes Reef - East	26/10/2021	F	140	M	60572	73.6
Holmes Reef - East	26/10/2021	F	175	M	60573	86.4
Holmes Reef - East	26/10/2021	M	197	M	60574	7.2
Holmes Reef - East	26/10/2021	F	150	M	60576	42.4
Flinders Reef - South	16/02/2021	M	155	M	64062	99.7
Flinders Reef - South	16/02/2021	F	168	M	64063	36.7
Flinders Reef - South	16/02/2021	F	174	M	64064	85.5
Flinders Reef - South	16/02/2021	F	167	M	64065	39.4
Flinders Reef - South	16/02/2021	F	155	M	64066	0.8
Flinders Reef - South	16/02/2021	M	125	J	64067	79.1
Flinders Reef - South	16/02/2021	F	165	M	64068	95.4
Flinders Reef - South	16/02/2021	F	128	J	64069	25.7
Flinders Reef - South	16/02/2021	F	155	M	64070	98.7
Flinders Reef - South	16/02/2021	F	131	M	64071	99.7
Flinders Reef - South	17/02/2021	F	153	M	64073	90.6
Flinders Reef - South	23/10/2021	F	168	M	60577	51.6
Flinders Reef - South	23/10/2021	F	170	M	60579	93.5
Flinders Reef - South	23/10/2021	M	157	M	60580	26.6
Flinders Reef - South	23/10/2021	F	151	M	60581	58.9
Flinders Reef - South	23/10/2021	F	155	M	60582	NDAT
Flinders Reef - South	23/10/2021	M	160	M	60583	23.4
Flinders Reef - South	23/10/2021	F	153	M	60584	58.9
Flinders Reef - South	23/10/2021	F	146	M	60585	NDAT
Flinders Reef - South	23/10/2021	F	150	M	60586	15.3
Flinders Reef - South	23/10/2021	M	105	J	60587	93.5
Flinders Reef - North	24/10/2021	F	158	M	60565	51.2
Flinders Reef - North	24/10/2021	F	171	M	60567	43.9
Flinders Reef - North	24/10/2021	F	159	M	60588	97.6
Bougainville	22/02/2021	F	132	M	64089	100.0
Bougainville	27/10/2021	F	126	J	60589	44.4
Bougainville	27/10/2021	F	181	M	60591	NDAT
Bougainville	27/10/2021	F	150	M	60592	96.0
Bougainville	27/10/2021	F	153	M	60593	59.5
Bougainville	27/10/2021	F	166	M	60594	9.5
Bougainville	27/10/2021	M	125	M	64059	NDAT
C. albimarginatus						
Osprey Reef	24/02/2021	F	224	M	64106	24.7
Holmes Reef - West	18/02/2021	F	155	J	64078	NDAT
Holmes Reef - West	20/02/2021	F	174	J	64080	7.0
Holmes Reef - West	25/10/2021	M	165	J	60571	100.0
Holmes Reef - East	26/10/2021	F	198	M	60575	28.0
Flinders Reef - South	16/02/2021	M	170	M	64072	56.8
Flinders Reef - South	17/02/2021	F	146	J	64074	71.2
Flinders Reef - South	17/02/2021	F	130	J	64075	50.0

Tagging site	Tagging date	Sex	TL (cm)	Maturity stage	Tag ID	RI (%)
Flinders Reef - North	18/02/2021	M	138	J	64076	83.3
Flinders Reef - North	18/02/2021	F	122	J	64077	90.8
***C. albimarginatus* (cont.)**						
Flinders Reef - South	23/10/2021	F	143	J	60578	68.5
Flinders Reef - North	24/10/2021	M	156	J	60566	80.5
Bougainville	27/10/2021	M	208	M	60590	68.3
Bougainville	27/10/2021	M	223	M	63870	38.1
C. ignobilis						
Osprey Reef	23/02/2021	Unk	70	M	50959	4.8
Osprey Reef	28/10/2021	Unk	75	M	6249	4.0
Osprey Reef	28/10/2021	Unk	75	M	6251	77.8
Osprey Reef	29/10/2021	Unk	80	M	6253	12.8
Osprey Reef	30/10/2021	Unk	81	M	6259	NDAT
Osprey Reef	30/10/2021	Unk	70	M	6261	4.0
Osprey Reef	30/10/2021	Unk	89	M	6263	49.2
Osprey Reef	4/03/2022	Unk	74	M	6266	-
Osprey Reef	5/03/2022	Unk	74	M	6268	-
C. lugubris						
Osprey Reef	29/10/2021	Unk	74	M	6255	1.6
Osprey Reef	29/10/2021	Unk	61	M	6257	85.6
Osprey Reef	30/10/2021	Unk	62	M	50961	10.5
P. laevis						
Osprey Reef	23/02/2021	Unk	58	M	50960	4.3

Appendix 4: Details of the satellite-tagged sharks from other projects that moved into the Coral Sea.

Sex	Size (m)	Tagging date	Tagging site	Tag ID
Tiger sharks				
F	2.1	Feb-15	Batt Reef (Cairns)	146706
F	3.2	Feb-15	Batt Reef (Cairns)	141148
M	2.3	Feb-15	Batt Reef (Cairns)	141156
F	3.7	Feb-22	Batt Reef (Cairns)	209947
F	2.4	Oct-18	Batt Reef (Cairns)	176405
F	2.3	Oct-18	Batt Reef (Cairns)	176409
F	2.6	Oct-18	Batt Reef (Cairns)	176410
F	3.6	Feb-15	Opal Reef (Cairns)	146708
M	3.2	Jun-19	Cid Harbour (Whitsundays)	41821
F	3.0	Sep-19	Cid Harbour (Whitsundays)	178947
F	3.3	Sep-19	Cid Harbour (Whitsundays)	175014
M	3.4	Oct-20	Cid Harbour (Whitsundays)	202529
F	3.2	Dec-19	Cid Harbour (Whitsundays)	178942
F	3.7	Dec-19	Cid Harbour (Whitsundays)	178943
M	2.5	Dec-19	Cid Harbour (Whitsundays)	178941
F	3.8	Sep-21	Cid Island (Whitsundays)	209945
F	4.1	May-21	Repulse Bay (Whitsundays)	184220
M	3.5	Oct-21	Repulse Bay (Whitsundays)	209946
F	3.8	Mar-21	North West Island	184221
M	2.9	Dec-05	Raine Island	62849
M	2.9	Dec-07	Raine Island	79974
F	3.8	Feb-20	Norfolk Island	178956
F	4.1	Feb-20	Norfolk Island	198173
F	3.6	Feb-20	Norfolk Island	198177
F	3.8	Feb-21	Norfolk Island	209122
Whale sharks				
Unknown	<5	Oct-18	Ribbon 4 (Far North GBR)	172899
M	~4	Nov-19	Wreck Bay (Far North GBR)	176413
M	~7	Dec-21	Henry Reef (Far North GBR)	178951
M	~6	Dec-21	Henry Reef (Far North GBR)	178953
F	~6	Dec-21	Wreck Bay (Far North GBR)	178957
F	~6	Dec-21	Wreck Bay (Far North GBR)	178954
Manta rays				
Unknown	Adult	Nov-17	Arlington Reef (Cairns)	165338
F	Adult	Dec-21	Saunders Reef (northern GBR)	146001