Ecological Service Professionals
Sustainable Science Solutions

Tweed Sand Bypassing Project

Reef Biota Monitoring 2022

Prepared for: Tweed Sand Bypassing

Prepared by Ecological Service Professionals Pty Ltd

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Acknowledgement of Country: In the spirit of reconciliation, Ecological Service Professionals acknowledges the Yugambeh language peoples, Traditional Custodians of the part of Bundjalung Country where we have worked, and we recognise their connection to land, sea and community. We pay our respect to their Elders, past and present, and extend that respect to all Aboriginal and Torres Strait Islander peoples through our scientific work on country.

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Executive Summary

The Tweed Sand Bypassing (TSB) project is a joint initiative of the New South Wales and Queensland State Governments, with the objectives to establish and maintain the entrance to the Tweed River, and to restore and maintain the coastal sand drift to the Southern Gold Coast. This report has been prepared by Ecological Service Professionals (ESP) to meet the environmental obligations of the TSB project to assess ecological changes in reef habitat, including changes in the composition, coverage, and diversity of benthic faunal and floral communities at Kirra and Cook Island reefs due to the TSB operations.

Changes in the extent of Kirra Reef were assessed using bathymetric survey data as well as aerial and satellite imagery, including a comparison of the historical changes in the areal extent. Field surveys were completed to assess differences in benthic communities (algae, sessile invertebrates and mobile invertebrates) and fish assemblages among reefs. Six reef locations were surveyed in June 2022: Kirra Reef (previously impacted reef); Cook Island West and South Reefs (potentially impacted reef); and Cook Island North Reef, Palm Beach Bait Reef, and Palm Beach Reef (comparative reefs). Differences in the composition of benthic communities among reefs were assessed over time using available historical data collected over the past seven years.

Previous estimates of the areal extent of Kirra Reef indicate there have been substantial changes in reef area through time. The maximum extent of Kirra Reef was measured in 1995 (40,813 m^2), with the area declining following the commencement of the TSB project (as was predicted in the Project Environmental Impact Assessment) to be completely buried in 2007 and 2008, then uncovered and increasing in extent again from 2009 (1,009 m^2) onwards. There are three distinct reef areas at Kirra Reef, a shallow inner western reef, a shallow eastern reef near the Kirra groyne, and a northern reef in deeper water. In recent years, generally only the northern section located in deeper waters has been uncovered, with the eastern section also uncovered at times. In June 2022, the total areal extent of Kirra Reef was 3,014 m^2, which was less than measured in 2021. This is due to the offshore movement of the sand bar at Kirra Beach smothering the inner section of the reef. Despite this recent reduction, it is not substantially different to the relatively stable reef area that has been observed since 2012. The inner western and eastern sections of Kirra Reef have a low profile (or relief) and are naturally subject to increased frequency of disturbance, including sand burial. The combination of a low profile, and high frequency of physical disturbance associated with being in shallow water, close to the shoreline, is likely to limit the development of a diversity community of reef dwelling organisms on these inner reef sections.

In the past seven years (since 2016), the composition of benthic communities on all reefs assessed has differed over time, which demonstrates the potential for interannual variation. Differences in the composition of benthic communities also occurred among sites on each reef and among reefs in 2022. There continues to be a diverse benthic community on Kirra Reef dominated by turf forming and foliose macroalgae, although the coverage of longer-lived hard coral species recorded on the reefs around Cook Island, were limited on Kirra Reef. Benthic communities around Cook Island differ in composition, including reefs separated by only a few hundred metres, indicating a diverse array of communities around the island and more generally in the region. Small-scale spatial variation among locations

may also be related to different physical conditions (e.g. nutrient availability and wave energy), disturbance regimes and ecological interactions around the island. These variations highlight the importance of sampling numerous comparative locations that are representative of the variety of reef habitats to provide confidence in attributing any changes detected to the TSB operations.

The composition of algal assemblages were similar among the reefs in June 2022. The algal assemblages on reefs were dominated by turf forming algae in June 2022, with other groups, such as foliose macroalgae (e.g. *Sargassum* spp. *Dictyota* sp. and *Padina* sp.), crustose coralline algae and articulate coralline algae (e.g. *Jania* sp.) also present.

In June 2022, the composition of sessile invertebrate assemblages (including ascidians, sponges, hard and soft corals, hydrozoans, zoanthids, bryozoans, bivalves and barnacles) on Kirra Reef remained dissimilar to assemblages on the other reefs; however, there was no difference in the average taxonomic richness or coverage of sessile invertebrates on Kirra Reef compared with the comparative reefs. Ascidians and sponges remained the dominant sessile invertebrates on Kirra Reef, with a lack of hard coral species on Kirra Reef. Hard and soft coral species have consistently been absent or covered a small area on Kirra Reef over time. Hard corals averaged between 0 and 2% prior to TSB (in 1995 and 1996) and following the initial commencement of TSB (between 2003 and 2005); and have averaged between 0 and 0.5% following emergence from burial (between 2010 and 2022). Soft corals averaged between 2 and 10% prior to TSB (in 1995 and 1996), 1–6% following the commencement of TSB (between 2003 and 2005), and 0 to 2% following emergence from burial (between 2010 and 2022). Low coverage of hard and soft corals at Kirra Reef may be related to ongoing physical factors (e.g. wave energy and sand scouring due to the position of the reef), but is also likely to be related to the relatively recent disturbance history (i.e. Kirra Reef was completely buried in 2007 and 2008) and the prolonged period of time required for coral communities to become established.

The reefs around Cook Island generally had a high cover of long-lived hard corals (such as those from the genus *Paragoniastrea, Turbinaria* and encrusting *Porites*) compared with other reefs in the region, with the highest coverage recorded on horizontal surfaces at Cook Island North and Cook Island South. On reefs around Cook Island, the coverage of hard coral was similar to or increased relative to previous surveys at Cook Island North and Cook Island West between 2021 and 2022 surveys. In contrast, the average coverage of hard coral declined by 8% at Cook Island South between 2021 and 2022. Where present, the coverage of soft corals remained similar among surveys on reefs around Cook Island.

A variety of echinoderms dominated the mobile invertebrates observed on the reefs in June 2022, with Cook Island North and Kirra Reef having the highest density and Cook Island North and Cook Island West having the highest diversity. Feather stars (primarily *Cenolia* spp) had the highest densities at most reefs (except for Cook Island South and Palm Beach Reef) and several sea star, sea urchin, sea snail and sea cucumber species were also relatively common at most reefs.

A total of 126 bony and cartilaginous fish species from 40 families were recorded across all reefs in June 2022. Most fish species recorded were common to the region; however, 20 species were observed among the reefs that had not been recorded in previous surveys. The fish assemblage only differed between Kirra Reef and Cook Island South, and between Palm Beach Reef and Cook Island North. The main difference in fish assemblages between reefs was the absence of yellowtail scad (*Trachurus novaezelandiae*) at Cook Island South, which was abundant at Kirra Reef; and the absence of yellowtail scad and striped barracuda (*Sphyraena obtusata*) and the presence of scalyfin (*Parma unifasciata*) and mado (*Atypichthys strigatus*) at Cook Island South compared to Palm Beach Reef. The highest abundance of fish was recorded at Kirra Reef due to dense schools of yellowtail scad that occurred there. The average species richness was also highest at Kirra Reef, followed by Cook Island West. The fish assemblage at Kirra Reef was dominated by reef-associated, carnivorous fish species, with omnivores being the second most diverse group.

The benthic communities around Cook Island had a diverse assemblage of sessile invertebrates, including abundant hard and soft corals, and a diverse fish assemblage representative of reef communities in the region. In 2022, there were obvious signs of impact from recent prolonged flooding, in particular the presence of coral disease and damage to soft corals on some reefs. Despite differences in the composition, the benthic communities at Kirra Reef are considered to be representative of a mature assemblage of both algae and sessile invertebrates. This reflects the ecology of the reef community, which is comparable to that found on other reefs with similar exposure and depth characteristics (i.e. Palm Beach Reef and Palm Beach Bait Reef). Understanding the natural variability among reefs not exposed to disturbance from TSB is essential when assessing changes in these communities due to sand burial and other factors of disturbance. At Kirra Reef, the differences in the composition of reef communities reflect the subtle differences in ecological and abiotic conditions (particularly recruitment, nutrient availability, wave climate and local sand dispersal), as well as potential differences in anthropogenic pressures (e.g. recreational fishing) among reefs.

Recommendations

The TSB monitoring program has provided evidence of the recovery in reef communities through time in response to almost complete burial of Kirra Reef in 2007 and 2008. Since 2009, there has generally been an increase in the coverage and diversity of algal and sessile invertebrate assemblages growing on the reef and an increase in the diversity of the fish assemblage indicative of the variety of ecological niches available on Kirra Reef. Unless there is a substantial change in the sand delivery planned to manage coastal erosion due to storm and wave activity, annual ecological monitoring of Kirra Reef is likely to only provide an understanding of the processes contributing to community succession over the coming years. It is therefore recommended that monitoring of the response in benthic communities is completed before and after any planned changes to the program, such as the development of thresholds for changes in the monthly or annual volume of sand delivered. The environmental monitoring components could also be reviewed to better reflect a leading indicator of potential changes to the environment, such as hydrographic surveys and a comparison of the change in bottom depth year to year allowing for a degree of natural variability due to normal wave action and long-shore sand transport. An event or trigger-based monitoring program with the proposed triggers including operational changes in TSB (relative to those between 2012 and 2021), and/or indicators directly related to sand deposition such as sedimentation above a set threshold (as measured using hydrographic survey) or a substantial change in the accretion / erosion of sand around the reef measured through changes in reef area from aerial photos or hydrographic survey would be suitable for future ecological assessments.

To assess potential impacts at Cook Island reef due to sand placement activities, ongoing monitoring at both Cook Island and nearby comparative locations is recommended during and after planned disposal activities. It is recommended that the monitoring program focus on key indicator species that are known to be impacted by sedimentation changes in the coverage of hard and soft corals, ascidians and seagrass. Seagrass has only been recorded at one area around Cook Island, therefore good baseline data on the extent and condition of seagrass over time will provide comparative data against which direct impact can be measured, as suitable comparative areas may be difficult to identify. Monitoring the impacts of sand deposition including a direct measure of sedimentation at comparative areas adjacent to sensitive ecological receptor communities (i.e. coral reefs and seagrass areas that could be smothered) would provide a leading indicator of the potential for any negative impact and could also be used as a trigger for additional assessment of the reef communities, where background sedimentation is exceeded.

1 Introduction

1.1 Background

The Tweed Sand Bypassing (TSB) project is a joint initiative of the New South Wales and Queensland State Governments, with the objectives to establish and maintain the entrance to the Tweed River, and to restore and maintain coastal sand drift to the Southern Gold Coast beaches.

As part of the TSB, the fixed sand bypass system commenced operation in 2001 and comprises a sand collection jetty on the southern side of the Tweed River entrance at Letitia Spit. Sand is pumped under the river through a series of buried pipelines to four outlets on the northern side of the River (Figure 1.1). The majority of sand collected is delivered to Snapper Rocks East, but discharge outlets have also been established at Duranbah Beach, Snapper Rocks West and Kirra Point to allow for flexibility in sand delivery. Sand discharged from the outlets is predominantly transported northwards by waves and currents to nourish southern Gold Coast beaches. Supplementary dredging to clear the Tweed River entrance is also commissioned by TSB when required. Dredging is generally carried out using a trailer suction hopper dredge, which typically removes 50,000 to 200,000 m^3 of sand per dredge event.

During a period (2001 to 2008) of Supplementary Increment, quantities of sand greater than the natural littoral drift were transported via the fixed sand bypass system and dredging to replenish eroded beaches. Since 2009, the system has been transporting quantities closer to the natural movement of sand northwards along the coast (i.e. 500,000 m^3 per year).

Figure 1.1 Fixed sand bypassing system (TSB, 2021)

Kirra Reef is a rocky reef outcrop, located approximately 500 m offshore of Kirra Beach on the Southern Gold Coast. The nearshore location of the reef makes it subject to naturally shifting sand movements that cover and expose parts of the reef, and makes the reef susceptible to physical disturbance from sand scour, storms and wave action. The extent of reef exposed at Kirra Reef has also varied due to anthropogenic changes to the coastal environment, including an increase in areal extent following extension of the Tweed River training walls (in 1965) and almost complete burial by sand following the period of Supplementary Increment by TSB (in 2007 and 2008). Indeed, a reduction in the exposed extent of Kirra Reef as a consequence of the recovery of the offshore bathymetry of Kirra Beach was predicted the Environmental Impact Statement / Impact Assessment Study (EIS / IAS) (Hyder Consulting et al. 1997). Since 2009, Kirra Reef has been partly uncovered and the extent of reef exposed has been relatively stable since 2012 (Ecosure 2016; frc environmental 2019; ESP 2020). The TSB operates under several environmental and planning approvals covering different project elements. As part of approval requirements from the EIS / IAS (Hyder Consulting et al. 1997; DoE 1998), ongoing monitoring of the marine biota at Kirra Reef has been completed for over 20 years. Most recently the monitoring has been completed as part of the Environmental Management System (EMS) Operations Sub-Plan B.14 Kirra Reef Management Plan (Revision 2; TRESBP 2010), which is currently under review.

When dredging occurs, the dredge deposits sand in approved placement areas along the Tweed Coast and Southern Gold Coast (Figure 1.2). In 2019, additional placement areas at Fingal and Dreamtime were approved to provide greater flexibility in the operations. Sand was placed at Fingal in 2019, 2020 and 2021, but no sand has been placed at Dreamtime to date. Sand placed in these areas (annual placement of less than 50,000 m^3 across both areas) is predicted to move predominantly in a northerly direction. Any sand placed at Dreamtime (up to 20,000 m^3) is likely to move with the natural transport pathway around Fingal Head to the west of Cook Island in water depths less than 4 m (Jacobs 2017). The movement of sand around the headland is expected to occur during suitable conditions in episodic ‘slugs’ or sand waves of relatively large quantities of sand over a short period of time (Jacobs 2017). The Review of Environmental Factors (REF) for the back-passing placement areas (Fingal and Dreamtime) specified a monitoring program was required to detect any impacts to reef habitat within potential impact areas of Fingal Head and Cook Island Aquatic Reserve, inclusive of a mix of biotic and abiotic variables and collection of sufficient baselines dataset to account for temporal variability (APP 2019).

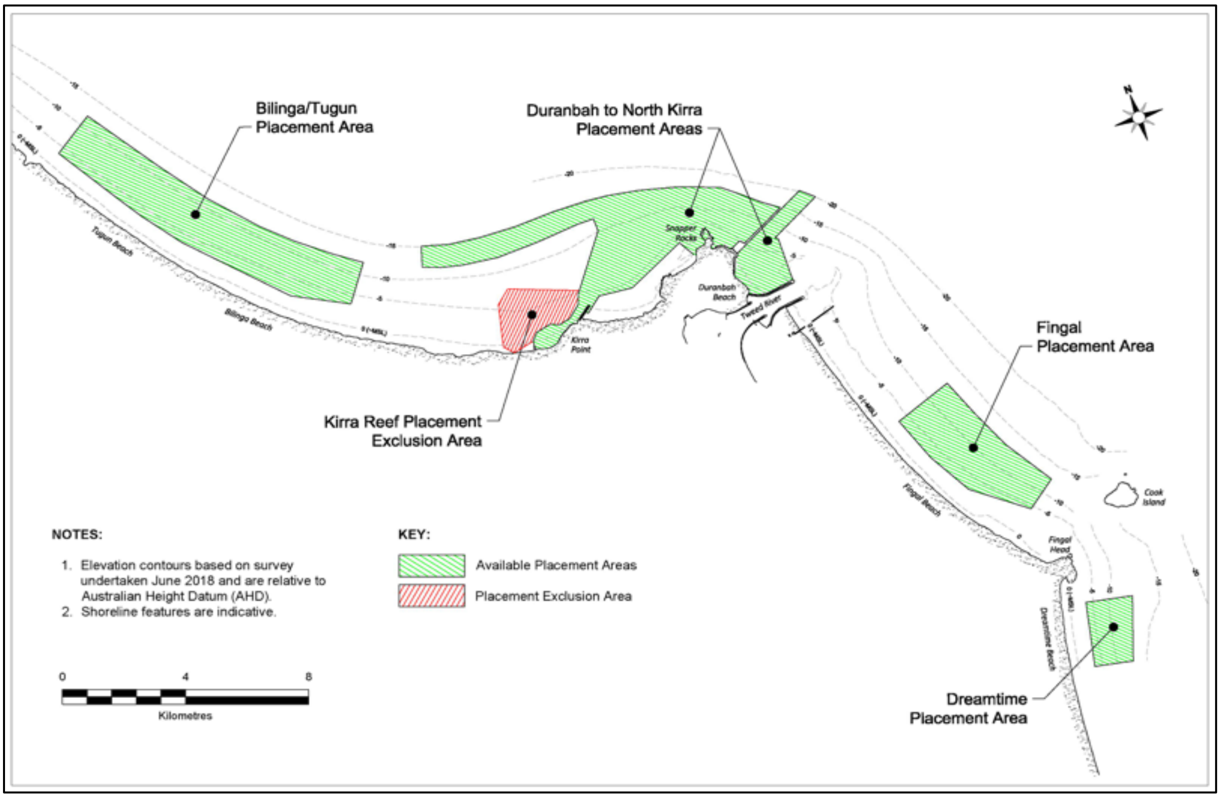


Figure 1.2 Current approved placement areas for disposing dredged sand (TSB, 2021)

1.2 Scope of Works

The overall objective of the reef biota monitoring program in 2022 was to investigate changes in reef habitat, including changes in the composition, coverage, and diversity of benthic faunal and floral communities at Kirra and Cook Island reefs due to the TSB operations.

2 Methods

2.1 Reef Extent

2.1.1 Aerial Imagery

Image analysis of the current areal extent of exposed reef at Kirra Reef was completed using imagery obtained from Queensland Government 2021c, NearMaps 2022 for May 2022 and aerial mosaic for June 2022, in ESRI ArcGIS and compared with previous assessments of reef area obtained from past assessments. The total areal area exposed was calculated in square metres (m^2).

2.1.2 Bathymetric Surveys

Annual bathymetric survey data for Kirra Reef was obtained by TSB for 2021 and 2022. The depth and coordinate data were converted to the same datum (GDA2020) prior to converting to a digital elevation model in ESRI ArcGIS using interpolation among the point cloud. The Kriging method was used by averaging among the nearest 12 points. Differences in the depth of subsequent digital elevation models for each year were then subtracted to assess the increase or decrease in depth around Kirra Reef. The digital elevation model for 2022 and change in depth were then mapped between 2020 and 2021, and 2021 and 2022.

2.2 Field Survey

2.2.1 Reef Locations

Six reef locations were surveyed in 2021 (Figure 2.1) based on a review of reefs previously surveyed (ESP 2020), including:

- Kirra Reef (KR) – previously impacted (Figure 2.2)
- Cook Island West Reef (CIW) and Cook Island South Reef (CIS) – potentially impacted (Figure 2.3), and
- Cook Island North Reef (CIN), Palm Beach Bait Reef (PBBR) and Palm Beach Reef (PBR) – comparative (Figure 2.3 & Figure 2.4).

Ideally the comparative reefs would be standardised for reef depth and distance from the shore so that they are exposed to relatively similar physical disturbance vectors; however, there are limited reefs along the coast that experience conditions similar to Kirra Reef. Therefore, the reefs selected provide a broad range of ambient environmental conditions occurring on reefs in the southern Gold Coast.

2.2.2 Timing

The reefs were surveyed over two days between the 1 – 2 June 2022. This aligned with previous surveys, which have historically occurred between April and July. Sea conditions were favourable with low to moderate (0.5–2.0 m) southeast to easterly swell and west-south-westerly to southerly winds (5–10 knots). Water clarity was moderate (approximately

4–12 m) although at some reefs was less than 0.1 m. There was high rainfall in the month leading up to the survey, with 211 mm recorded in May 2022 (and an average rainfall of 129 mm for May), but only light rainfall (3.8 mm) during the survey.

Figure 2.1 Reef locations for Biota Monitoring in 2022

2.2.3 Benthic Communities

Benthic communities (including algal, sessile invertebrate and conspicuous mobile invertebrate assemblages) were quantified at each reef location using 15 photo quadrats each separated by at least 1 metre and taken from both horizontal and vertical surfaces along three 25 m long transects (i.e. a total of 45 horizontal quadrats and 45 vertical quadrats were collected at each reef location). The position of the start and end points of each transect were recorded using a handheld GPS (accuracy ± 1 m) attached to a surface buoy led by SCUBA divers (Table 2.1; Figure 2.2 to Figure 2.4). Photo quadrats were taken using a pole camera to maintain consistent depth above the bottom. Given the very low visibility (0.3 m) during diving on Palm Beach Bait Reef, the dive was aborted. As such, remotely operated underwater vehicle (ROV) was used to capture images on that reef when water clarity had improved a little (the creek plume had moved further inshore). Due to the poor water clarity at the time of the survey, images at Palm Beach Bait Reef were unsuitable for assessment of benthic sessile organisms.

In-situ ROV searches were also complete to targeting taxonomic identification, as well as cryptic, invasive and threatened species were completed at Kirra Reef and Cook Island West reef (Figure 2.5a).

Table 2.1 Location of transects (sites) at each reef location

Reef Location	Transect	Transect Start *		Transect End *	
		Easting	Northing	Easting	Northing
Kirra Reef (KR)	KRN1	552104.0	6884649.0	552100.0	6884671.0
	KRN2	552126.5	6884662.5	552114.2	6884684.0
	KRN3	552156.5	6884677.8	552147.5	6884706.2
Palm Beach Reef (PBR)	PB1	546853.2	6890777.0	546827.5	6890789.4
	PB2	546817.1	6890803.0	546798.1	6890823.4
	PB3	546829.1	6890764.7	546803.4	6890783.2
Palm Beach Bait Reef (PBBR)	PBB1	546660.6	6890130.9	546665.6	6890113.4
	PBB2	546669.0	6890103.6	546673.1	6890076.3
	PBB3	546667.6	6890129.4	546675.3	6890094.9
Cook Island North Reef (CIN)	CIN1	556636.0	6881190.2	556656.6	6881205.7
	CIN2	556616.9	6881173.8	556597.2	6881154.7
	CIN3	556580.9	6881138.9	556560.7	6881115.0
Cook Island South Reef (CIS)	CIS1	556568.2	6880901.9	556549.0	6880915.3
	CIS2	556588.5	6880891.8	556612.2	6880879.3
	CIS3	556635.8	6880866.6	556670.8	6880858.5
Cook Island West Reef (CIW)	CIW1	556381.7	6881027.2	556406.4	6881035.7
	CIW2	556423.8	6881038.7	556444.3	6881032.3
	CIW3	556460.2	6881032.3	556478.1	6881046.0

*Datum: GDA2020 UTM Zone 56J

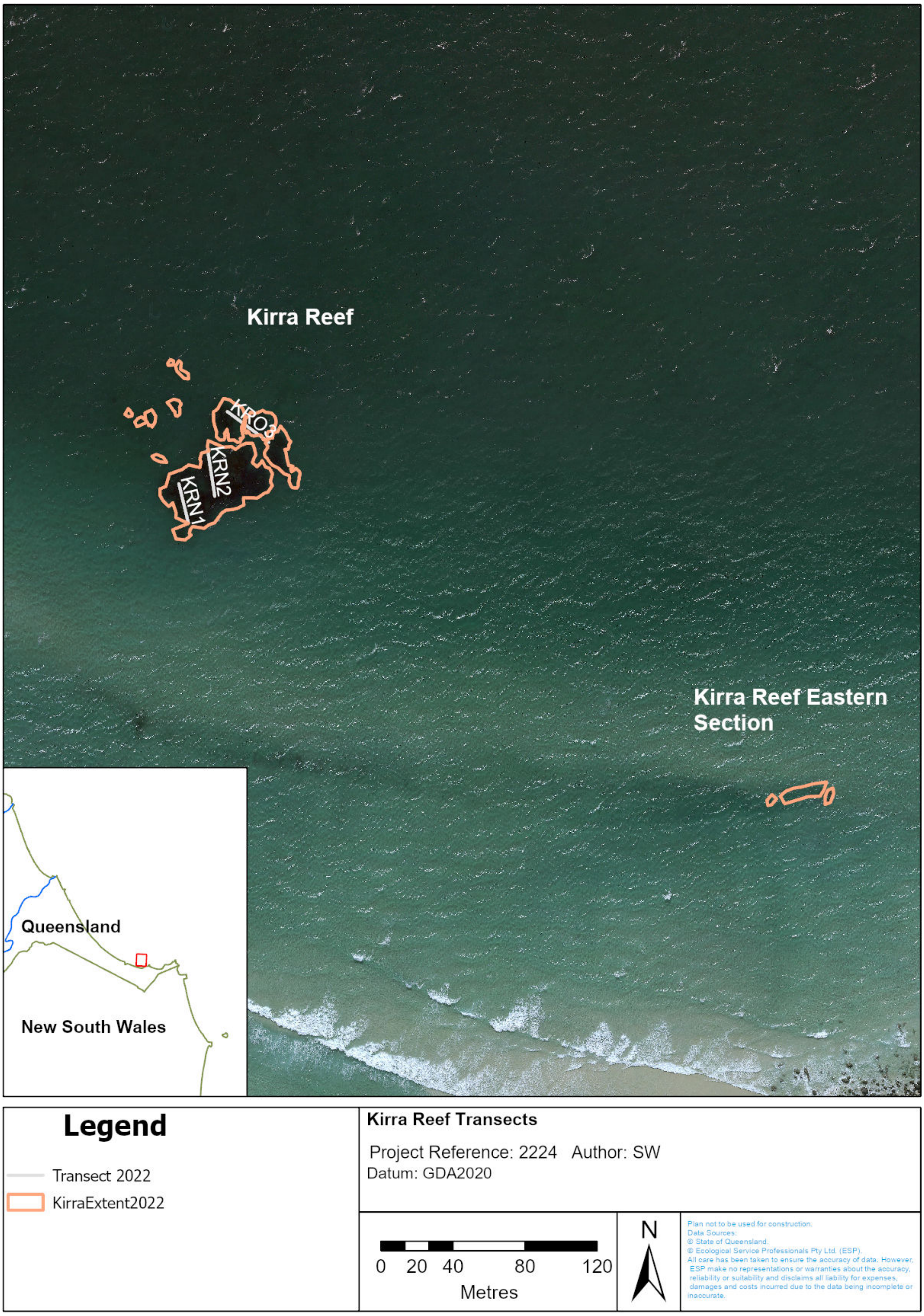


Figure 2.2 Location of transects surveyed in 2022 at Kirra Reef

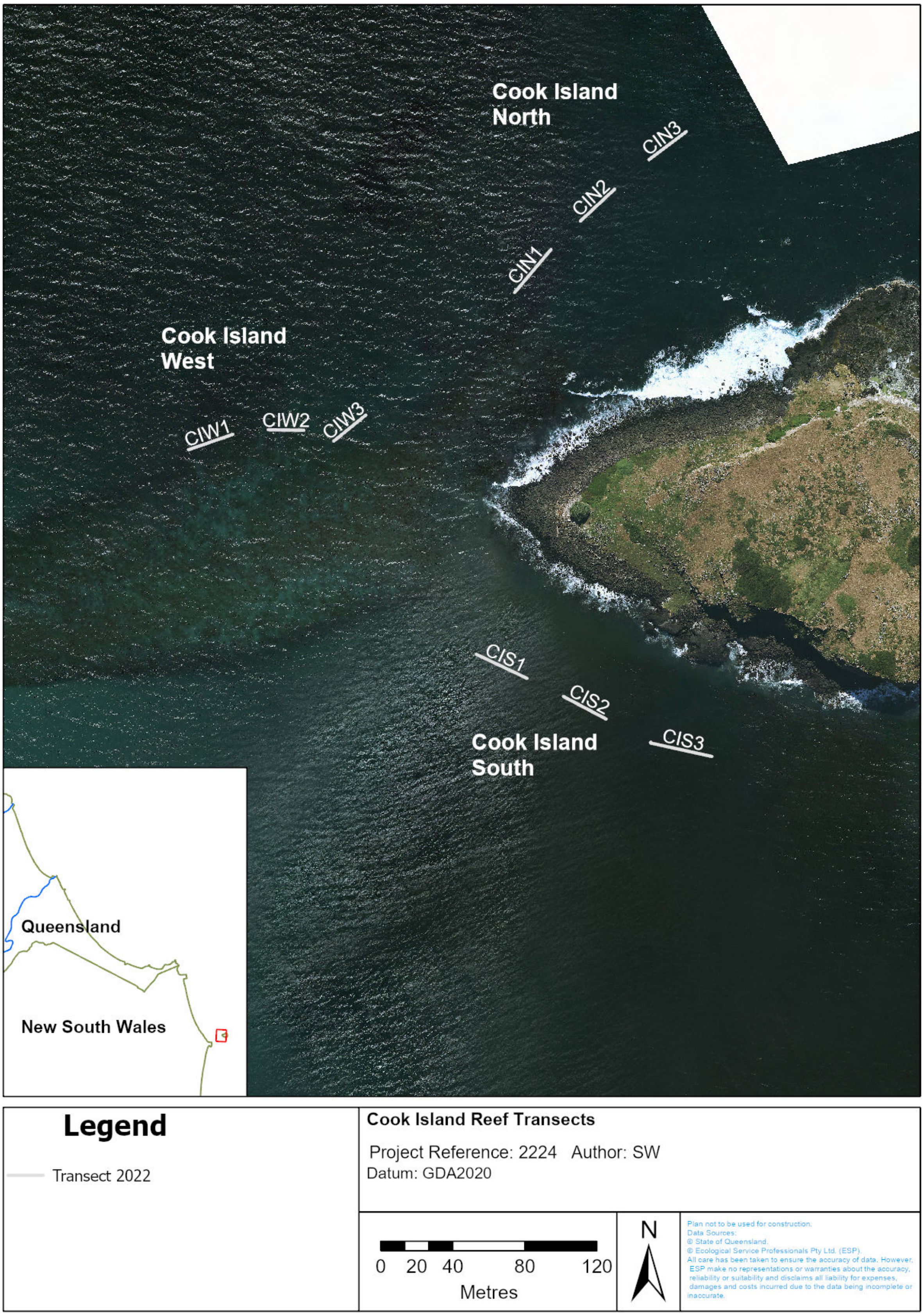


Figure 2.3 Location of transects surveyed in 2022 at the three reef locations around Cook Island

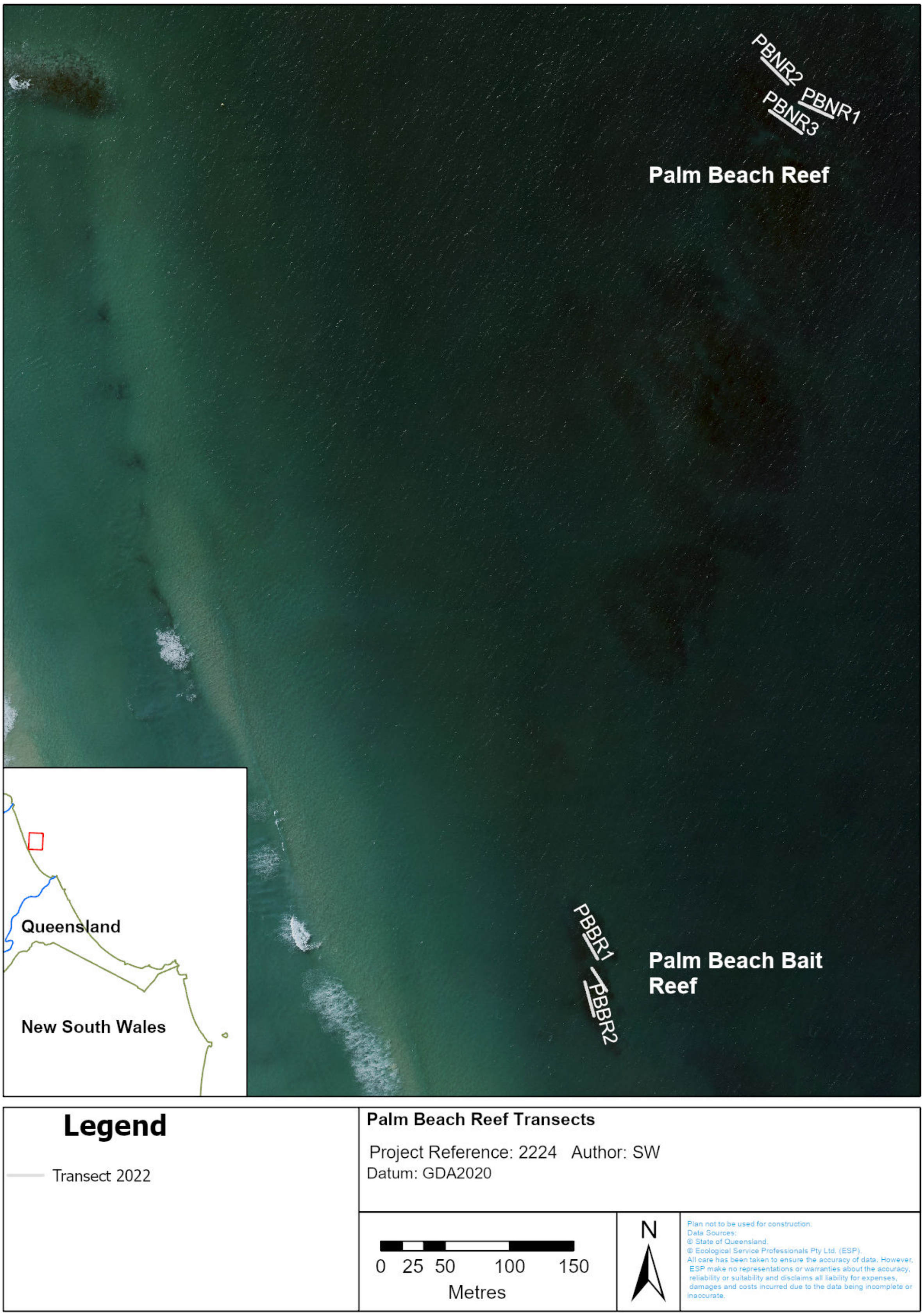


Figure 2.4 Location of transects surveyed in 2022 at Palm Beach Reef and Palm Beach Bait Reef

2.2.3.1 Data Management and Analysis

Processing of photo-quadrats was completed using standard image processing techniques (Kohler & Gill 2006; Walker et al. 2007) to determine composition and coverage of benthic communities (algal and sessile invertebrate assemblages). Fifty stratified random points were overlayed on each of the photo-quadrats based on standard approaches modified where appropriate and using Coral Point Count (CPCe) software (Kohler & Gill 2006), adapted where required to characterise the composition of benthic temperate rocky and artificial reefs in region (Schlacher-Hoenlinger et al. 2009; Walker et al. 2007; Walker and Schlacher 2014). The benthic communities (including hard and soft corals, hydrozoans, zoanthids, sponges, ascidians, bryozoans, bivalves, barnacles, macroalgae, turf forming algae and coralline algae) were identified to lowest taxonomic level possible (sites and taxa were aggregated to a taxonomic resolution comparable to previous monitoring to allow temporal comparisons among previous surveys). Voucher specimens were used to identify sessile species present where required (e.g. many species of sponges in Australia remain undescribed and are commonly identified to Operational Taxonomic Units or morphospecies; Walker et al. 2008).

In 2022, differences in the composition and coverage of benthic communities and assemblages (i.e. algal and sessile invertebrates) among reef locations were compared using a three factor permutational multivariate analysis of variance (PERMANOVA[1]; Anderson 2001) on untransformed data, with orientation (vertical surface and horizontal surface) and reef location (Cook Island South, Cook Island North, Cook Island West, Kirra Reef, Palm Beach Reef & Palm Beach Bait Reef) as fixed factors, and site (transects nested in reef location) included as a random factor. Differences between vertical and horizonal surfaces within each reef location were assessed specifically in the first instance, as a potential impact to horizontal but not vertical surfaces provides a direct test of the potential impacts of smothering at each reef. It was expected that if there was a substantial impact of smothering that the magnitude of any impact would be greater on horizontal than vertical surfaces at Kirra Reef relative to comparative reefs. The degree of multivariate dispersion was assessed using the PERMDISP[2] routine to determine the degree of within and between site variation (Anderson 2001). Taxonomic groups contributing to the differences among sites and locations were identified using the SIMilarity PERcentages (SIMPER) routine[3] (Clarke & Warwick 1994). Spatial differences in the composition of the benthic assemblages were

[1] Permutational Multivariate Analysis of Variance (PERMANOVA) is used to test the response of one of more variables to a priori derived structured factors, using a random permutation of the existing data to test significance. This non-parametric test of significance is similar to the generalised linear models completed using ANOVA; however, allows for the testing of significance without the need to meet a strict set of assumptions required in ANOVA.

[2] The Permutational Dispersion (PERMDISP) routine allows for an assessment of the degree of multivariate dispersion among different factors relative to a centroid or median value. This is similar to tests for homogeneity of variance used in parametric tests. Where there is significant differences in the dispersion of data, caution in interpretation of significance in PERMANOVA results should be used.

[3] The SIMilarity PERcentages (SIMPER) routine allows for a test of the rank order contribution of the variables to the measure of dissimilarity between pairs of groups being assessed. Therefore it can allow for an assessment of the magnitude at which different taxa contribute to the differences between pairwise groups of interest.

visualised using non-metric multidimensional scaling (nMDS[4]) ordinations (Clarke & Warwick 1994).

A range of biodiversity indices such as taxonomic richness, abundance (% cover for sessile organisms and density for mobile species) were calculated, where appropriate. Differences in the diversity of benthic communities and dominant species were assessed among reefs using PERMANOVA; however, data were converted to a Euclidean distance matrix prior to analyses to account for the univariate nature of each index. The mean taxonomic richness and coverage (± standard error (SE)) for each variable were graphed.

To compare differences among reef locations (location) over the previous six years (between 2016 and 2021), the data for benthic assemblages on vertical and horizontal surfaces were aggregated to an appropriate taxonomic level to match previous assessments (usually basic benthic cover categories such as hard corals, ascidians, sponges, coralline algae and macroalgae). Spatial and temporal differences were then assessed with a 2-factor PERMANOVA based on untransformed data, with survey year and location as the fixed factors. Differences in the composition of the benthic assemblages among locations through time were visualised using non-metric multidimensional scaling ordinations. Sites were aggregated within each reef locations as there was no differentiation provided for sites within reefs in 2018 and 2019.

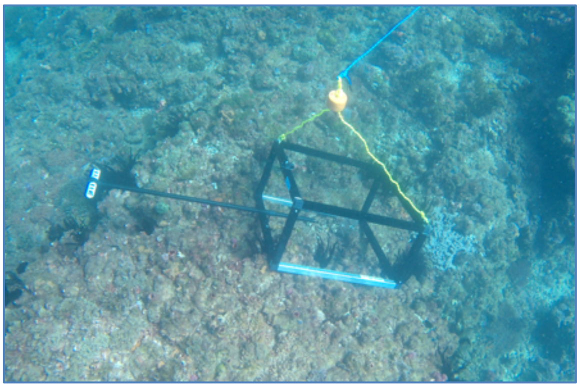
Conspicuous mobile invertebrates (> 50 mm) were quantified from photo quadrats collected along georeferenced transects (refer to Section 2.2.3). In addition, taxa observed using other survey methods (for fish communities; refer to Section 2.2.4) were also recorded to compile a species inventory for each reef. The abundance and type of large benthic invertebrates, including echinoderms (e.g. urchins, sea stars, holothurians), crustaceans (e.g. crabs, stomatopods and lobsters), and molluscs (e.g. octopus, clams, oysters and nudibranchs) were recorded. The density of conspicuous mobile invertebrates was compiled from photo quadrat data and compared among reefs.

2.2.4 Fish Communities

The established method of analysis of video from multiple unbaited remote underwater video stations (UBRUVS; Figure 2.5a) was used to assess the abundance and diversity of fish assemblages among reefs (Cappo et al. 2003). Three UBRUVS, separated by more than 25 m, were deployed at each reef location for a minimum of one hour (only 60 minutes of footage per UBRUVS unit was viewed). In addition, active searches for rare and threatened fish species were completed using an ROV (reducing behavioural bias caused by diver-fish interactions) at Kirra Reef and Cook Island (Figure 2.5a). Targeted searches by divers in both open water and specific habitat types (overhangs, caves and in structurally complex habitat like macroalgae) were completed for species of conservation significance, cryptic and invasive species. Additional species filmed by divers (not already observed on UBRUVS and ROV footage) were also incorporated into fish assemblage records for all sites.

[4] Non-metric multi-dimensional scaling (nMDS) ordinations provide a two-dimensional map so that the rank order distance between samples match the rank order similarity from a matrix. The placement represents the similarity or difference in the composition of assemblages (presence and abundance of each taxon) among samples, so that samples that appear closer on the ordination are more similar in composition, and those further apart more dissimilar or share fewer traits.

a)



b)

Figure 2.5 Survey methods used included b) UBRUVS; and a) ROV deployed at each reef location

2.2.4.1 Data Management and Analysis

Fish assemblages and other marine vertebrates were determined for each reef from UBRUVS, SCUBA diver and ROV video imagery, and were used to collate a species inventory for each reef. Biotic indices including species richness, abundance (based on a measure of Max N) and taxonomic distinctness were calculated for each reef. Abundance and taxonomic richness were compared among reef locations from UBRUVS data only, to ensure standardised comparisons among reefs. In some instances, identification of fish to species level was not possible due poor visibility (e.g., distance from camera, light and turbidity). These fish were identified to the lowest possible taxonomic level for the species inventory for each reef but were excluded from further analyses.

One UBRUVS at Palm Beach Bait Reef had no fish recorded due to very low visibility, and as such was excluded from the analyses. The number of species for each transect from UBRUVS were transformed by forth root transformation (due to the overabundance of some schooling species) and transformed to a Bray Curtis Similarity matrix. Differences in fish assemblages were compared among reefs using a one-factor PERMANOVA and where there were differences, Monte Carlo pairwise tests were used to determine which reef differed. Taxonomic groups contributing to the differences among sites and locations were identified using the SIMPER routine (Clarke & Warwick 1994). Assemblages for each transect on each reef were visualised using nMDS (Clarke & Warwick 1994). The total number of species (taxonomic richness) recorded on each UBRUVS was also calculated, transformed using Euclidean similarity matrix and compared among reefs using a one-factor PERMANOVA. Where there were differences, Monte Carlo pairwise tests were used to determine which reefs differed.

2.2.5 Quality Assurance and Control

Suitable Quality Control & Assurance (QAQC) measures, including use of suitably qualified ecologists, were included in the monitoring program. The methods were generally consistent with previous monitoring and repeatable to allow for temporal comparisons. Observer bias was reduced or removed using suitable repeatable methods such as UBRUVS and photo-quadrats. A subset of images and video footage were reanalysed by another suitably qualified ecologist for quality control.

2.3 Threatened and Invasive Species

A desktop assessment of threatened and invasive species that may occur at each reef was done using database searches and available literature and data, including the Commonwealth Department of Agriculture, Water and Environment (DAWE) Protected Matters Search Tool (PMST) for a 2 km buffer of the coastline between Cook Island and Palm Beach (DAWE 2022) and National Introduced Marine Pest Information System (NIMPIS 2022). Additional timed searches for species of significance for conservation and invasive species were completed using ROV and divers as outlined in Sections 2.2.3 and 2.2.4.

2.4 Abiotic Conditions

2.4.1 Water Quality

Duplicate water quality profiles were taken at each site using a calibrated YSI ProDSS hand-held water quality meter from the surface to the bottom to measure salinity, temperature, dissolved oxygen, pH and turbidity. Each parameter was logged continuously at 5 second intervals to collect at least three sample points per metre, vertically through the water column. Photosynthetic Active Radiation (PAR: available light spectrum used by coral and algae for photosynthesis) was also measured at all sites using PME mini PAR meter calibrated for use in marine water. Light attenuation coefficient (Kd) using Beer-Lambert's Law ($Kd = \ln(Iz_0/Iz)/(z)$, where Iz_0 was the surface PAR and Iz was the PAR at a depth of z) and % change with depth were calculated.

Water quality data was used to assist interpretation of spatial and temporal changes in benthic assemblages but was not used for a detailed water quality assessment (which would require much greater spatial and temporal sampling).

2.4.2 Wave Conditions

Wave height and wave direction data were sourced from the coastal data systems database (Queensland Government 2021a) for the Tweed Heads wave rider buoy, located approximately 1.6 km offshore in 22 m water depth. Data available for the year prior to the survey were graphed to provide a record of physical conditions preceding monitoring and compared to previous assessments of abiotic conditions of the region.

3 Results

3.1 Kirra Reef Extent

3.1.1 Aerial Imagery

Kirra Reef consists of three sections defined as the northern (referred to in some reports as the outer western section), inner western (referred to in some reports as the western or southern section) and eastern sections (Figure 3.3b). The inner western and eastern sections of Kirra Reef are naturally more prone to fluctuation in their exposed area compared with the northern section given their closer proximity to shore (and to Kirra Point) and shallower depth, making them more susceptible to the effects of expanding and retreating beach width, sand shoal movement, wave action, sand scour, nearshore bar formation and longshore sand flow (TRESBP 2009).

In June 2022, Kirra Reef had an estimated total aerial extent of 3,014 m^2 measured from visual interpretation of aerial and satellite imagery, which comprised 2,810 m^2 of reef in the northern section and 204 m^2 of reef in the eastern section. This was approximately 39% smaller than the extent measured in June 2021, which was the largest area of reef recorded since exhumation from complete burial in 2009 (i.e. 4,930 m^2, comprising 4,122 m^2 of reef in the northern section and 808 m^2 of reef in the eastern section). While there is a margin of error in the estimation of aerial extent, there are some obvious changes visible in the aerial images between 2021 and 2022, particularly on the south-eastern area of the northern reef. This is likely due to the movement of the offshore sandbar, rather than TSB given sand pumping has remained relatively consistent over the last year (and has only been delivered to Snapper Rocks East and Durranbah). Despite this recent reduction, the total area of Kirra Reef has remained relatively stable since 2012 compared to the extreme changes previously recorded (Appendix A, Table A.5.1).

Previous estimates of the extent of Kirra Reef from aerial photographs and satellite imagery indicate vast changes in the aerial extent through time (Appendix A, Table A.5.1). Prior to 1965, during a time of no major artificial changes to sand movements, the northern section of Kirra Reef had an estimated reef area ranging between 1,800 and 7,800 m^2 (Appendix A, Table A.5.1). The maximum area of the northern section of reef exposed from aerial photograph estimates was 10,200 m^2 in 1989 following a period of sand depletion in the area. The area of reef exposed decreased following the commencement of TSB project, with the northern section of reef almost completely covered by 2006 and an estimated area of reef <1000 m^2 estimated in 2009 and 2010. Storm and cyclone activities were also relatively low during this period, which may have reduced the frequency of large volumes of sand being displaced from the area. Since Kirra Reef emerged from complete burial in 2009, the estimated reef area of the northern section of Kirra Reef has remained relatively stable, ranging between 2,659 and 4,122 m^2 (Appendix A, Table A.5.1), despite cyclonic wave events in 2017 and 2019 which caused relatively minor changes to area of Kirra Reef (frc environmental 2019). While there were some clear areas of change (burial) in, the exposed area of the northern section of reef has still been relatively stable since 2012, which has supported the development of a diverse reef community.

The inner western and eastern sections of Kirra Reef are naturally subject to ongoing sand burial and exhumation. Prior to 1965 (and the artificial changes to sand movements in the region), the estimated areal extent for the inner western section of reef is 0 to 4,900 m^2, and for the eastern section of the reef is 0 to 2,150 m^2 (Appendix A, Table A.5.1). The extent of these sections reached a maximum in 1989, with 65,400 m^2 of reef estimated for the inner western section and 22,500 m^2 estimated for the eastern section. The inner western section of the reef has been buried for the last 20 years, which corresponds to the commencement of the TSB (in 2001). The eastern section of reef has only occasionally had small areas exposed during this time, with the maximum of 808 m^2 in 2021, which reduced to 204 m^2 in 2022. These inner western and eastern sections of Kirra Reef both have a low reef profile (or relief) and are naturally subject to increased frequency of disturbance including sand burial. For example, in June 2022, the vertical relief of the eastern section was approximately 30 cm above the bottom, while the northern section was approximately 1.5 to 3 m above the bottom. The low relief combined with greater potential for disturbance associated with being closer to the shoreline, is likely to limit the development of a biodiverse community of reef dwelling organisms on the eastern section of the reef (refer to Section 3.2.2 for community composition of the eastern section of reef).

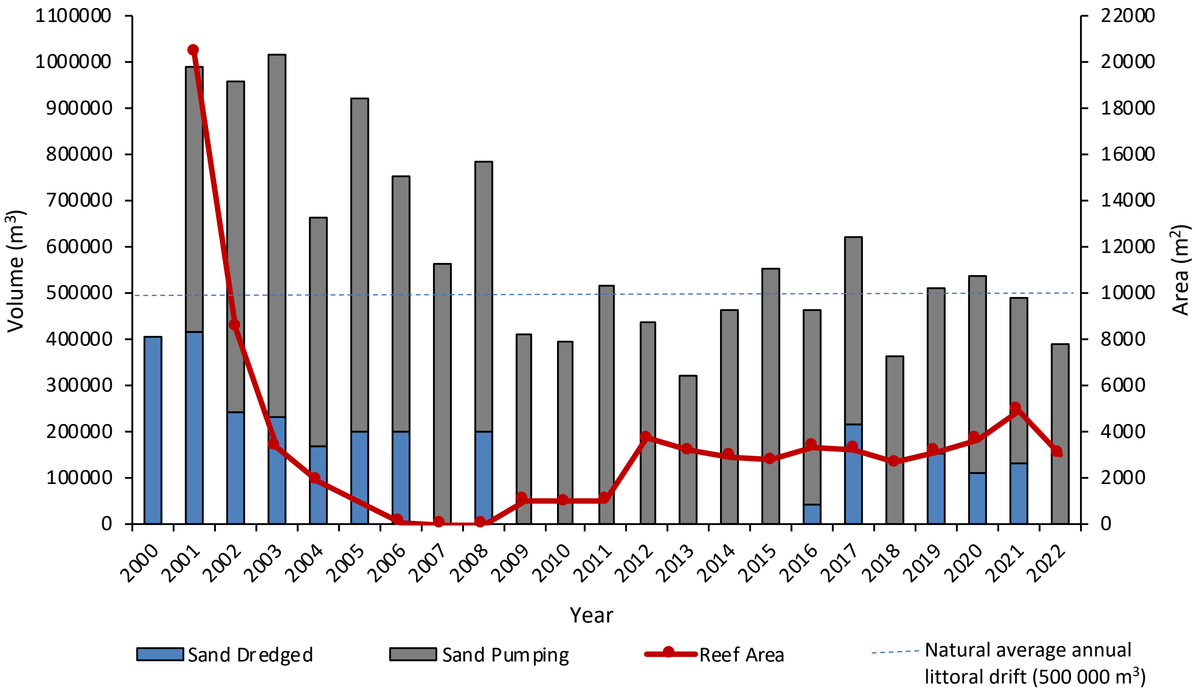


Figure 3.1 Estimated surface area (m^2) at Kirra Reef and total annual and dredging and pumping volumes (m^3) between 2000 and 2022 (data for 2022 includes sand volumes up to June)

a) 1956

Source: Queensland Government 2021b

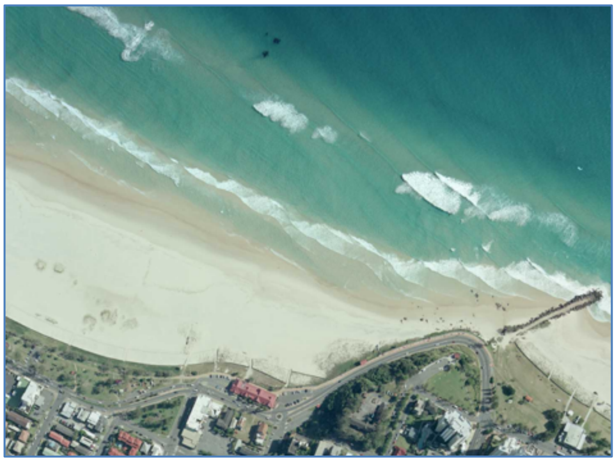
b) 1982

Source: WorleyParsons 2009

c) 1995

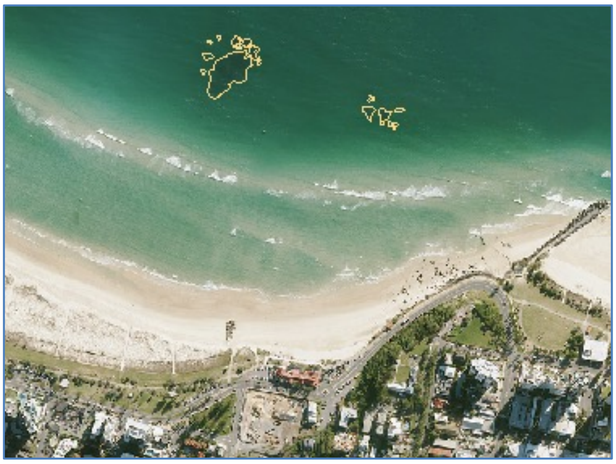
Source: Queensland Government 2021b

d) 2007



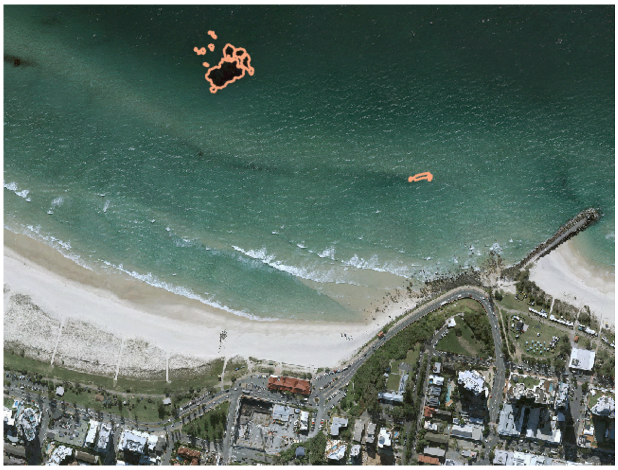
Source: Queensland Government 2021c

e) 2021



Source: Queensland Government 2021c

f) 2022



Source: NearMaps 2022

Figure 3.2 Photographs indicating major changes at Kirra Reef in (a) 1956 during a time with no major artificial changes to sand movements; (b) 1982 following sand depletion between the 1960s and 1980s; (c) 1995 at the measured maximum extent; (d) 2007 following an oversupply of sand during the early years of the TSB sand bypassing system; (e) 2021; and, (f) 2022 with sand delivery of the TSB now matching natural longshore drift of sand.

3.1.2 Bathymetric Surveys

There were some decreases in depth around Kirra Reef between May 2021 and June 2022 from bathymetric survey results, with a 1 to 1.5 m increase in sand height along the south-eastern edge of the northern section of reef (Figure 3.3; as shown by the light green colours). There were also some increases in depth, with depth decreasing 20 to 80 cm near some of the outcrops to the west and north of the northern section of Kirra Reef (Figure 3.3; as shown by the darker blue colours). The small outcrops of eastern reef exposed in 2021 (ESP 2021) were not present in 2022, with a different and smaller area exposed to the southeast, and landwards the offshore sandbar. Changes in reef depth were largely related to seaward movement of the offshore bar running along Kirra Beach (Figure 3.3). It is common for an offshore bar to form and migrate inshore and offshore on dynamic sandy beaches to dissipate wave energy (Short 2019).

The change in depth between May 2021 and June 2022 was more substantial than those observed in recent years (i.e. ± 20 cm change between July 2019 and May 2020 and ± 20 cm to 1 m change between May 2020 and May 2021), when depth around much of the reef either increased or stayed relatively similar (ESP 2020; ESP 2021).

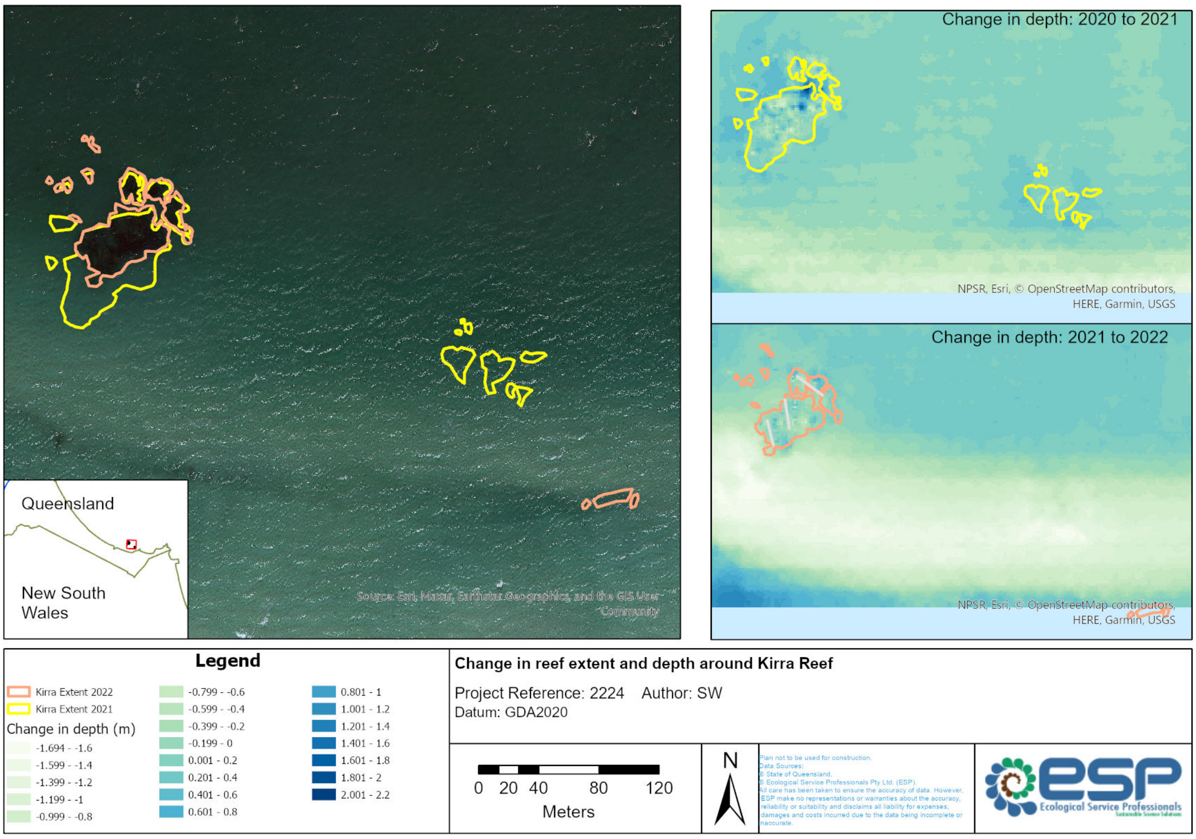


Figure 3.3 Areal extent (left) and changes in depth (yellow / green indicating shallower and blue indicating deeper water) from May 2020 to May 2021 (top right); and May 2021 to June 2022 (bottom right)

3.2 Benthic Communities

3.2.1 Composition of Benthic Communities

The composition of benthic communities (including both algal and sessile invertebrate assemblages) on the reefs in the region differed at a range of spatial scales, including between Kirra and the comparative reefs, on both horizontal and vertical surfaces [5] (Figure 3.5, Figure 3.6 and Figure 3.4a; PERMANOVA, Appendix B, Table B.5.2). There were also differences in the composition of benthic communities among reef locations including those separated by only a few hundred metres at Cook Island (Appendix B, Table B.5.2); although differences among reefs were only apparent on vertical surfaces. The differences in benthic communities between Kirra and the other reefs in the area was typically due to the coverage of turfing algae, low coverage of coralline algae and higher coverage of some sessile invertebrates such as solitary ascidians (refer to Section 3.2.2 & 3.2.3). The differences in the composition of benthic communities among reefs were likely due to a range of site-specific factors including differences in the disturbance regime and the length of time since sand burial (as Kirra Reef was almost completely buried in 2007 and 2008), abiotic factors

[5] Benthic communities PERMANOVA Orientation vs Reef interaction MS = 4227 pseudo-$F_{4,10}$ = 1.76, p = 0.036; Pairwise tests for differences among reefs for horizontal and vertical surfaces: KR≠CIW≠CIS≠CIN≠PBNR *p(MC)* < 0.05;

(such as wave action), settlement and recruitment of sessile species, water quality (including nutrient availability and recent impacts from flooding), and / or possible variation in the abundance of herbivorous fauna among reefs.

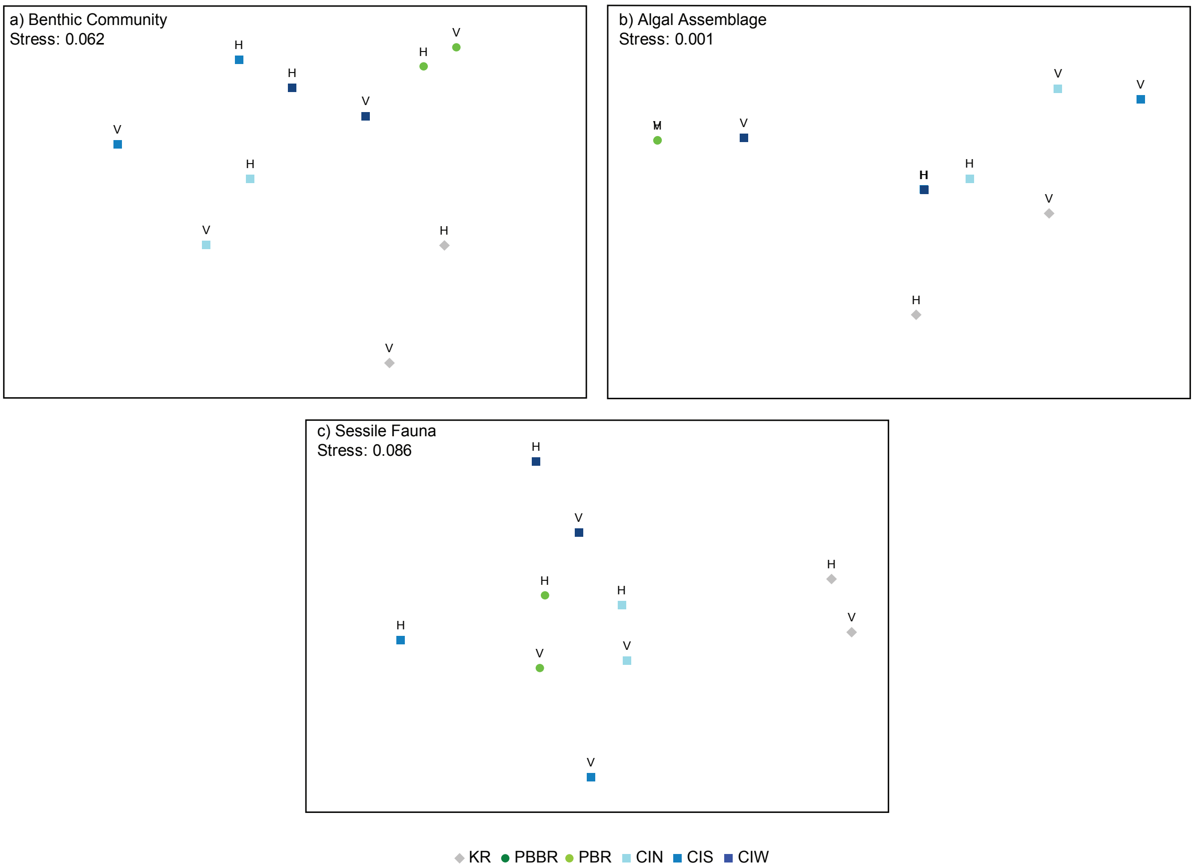


Figure 3.4 nMDS ordination showing difference in the composition of benthic assemblages between surface orientations and reefs for (a) the sessile community, (b) algal assemblages, and (c) sessile invertebrate assemblages [6]

On Kirra reef, the differences in the composition of benthic communities between horizontal and vertical surfaces were less pronounced in 2022 than in previous years (Appendix B, Table B.5.2). In 2022, there was no difference in the overall composition of the benthic community between horizontal and vertical surfaces (SIMPER Appendix B, Table B.5.3). The coverage of ascidians *Polycarpa procera, Pyura stolonifera* and *Herdmania momus* typically differed between surface orientations on Kirra Reef in previous surveys (ESP 2020); however, in 2022, the coverage of these dominant ascidian species was more similar with a combined 19% of the area on vertical surfaces and 12% on horizontal surfaces (SIMPER Appendix B, Table B.5.3).

[6] nMDS ordination plot provides a two-dimensional map so that the rank order distance between samples match the rank order similarity from a matrix of sample pairs. The placement of points represents the similarity or difference among samples (in this case in the composition of assemblages - presence and abundance of each taxon). Samples that appear closer on the ordination are more similar in composition, and those further apart are more dissimilar or share fewer traits.

The moderately dense patch of seagrass recorded in 2020 and 2021 at Cook Island West was still present in 2022, although the coverage of seagrass had declined, likely due to prolonged flood impacts, decreasing light availability at the site. The seagrass community occurred between macroalgae, rock and rubble on sand and was dominated by *Halophila ovalis*, covering approximately 10% of the space where it was recorded (Figure 3.7). Marine vegetation, including seagrass, are protected under the *NSW Fisheries Management Act 1995*.

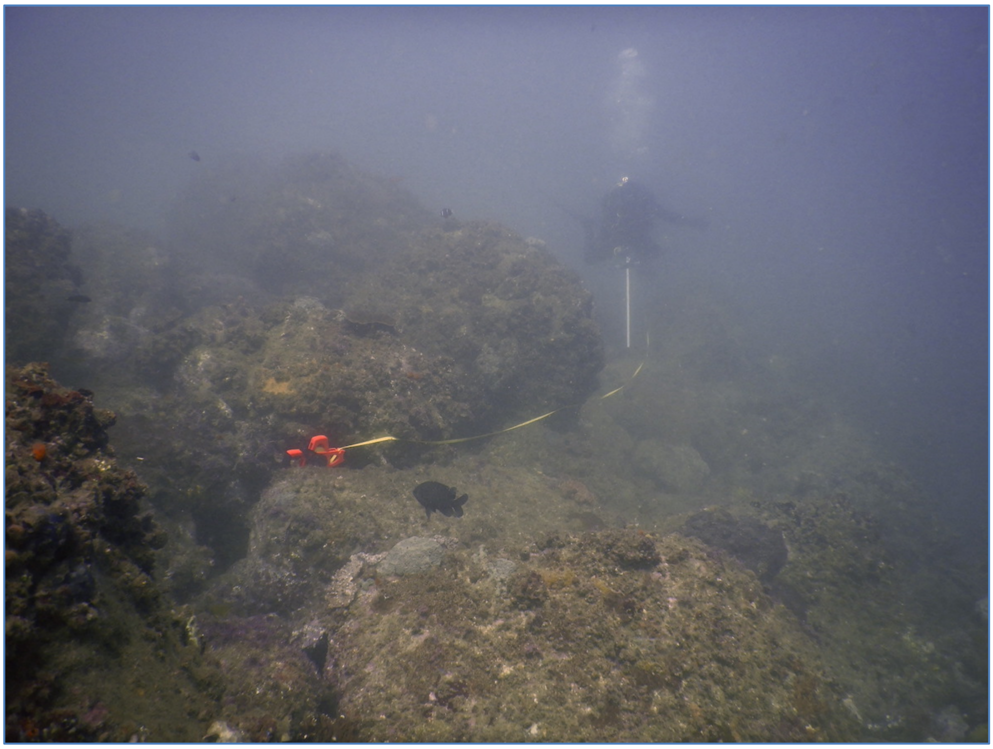
Bare sand and rubble habitat covered the most area of horizontal surfaces at Cook Island West (18%), Cook Island South (10%) and Kirra reefs (7%) (Figure 3.8). Elsewhere the coverage of sand and rubble was more similar among surface orientations and reef locations covering less than 3% of the surface area (Figure 3.8).

a)

b)

Figure 3.5 Example benthic assemblages at a) Kirra Reef and b) Palm Beach Reef

a)



b)

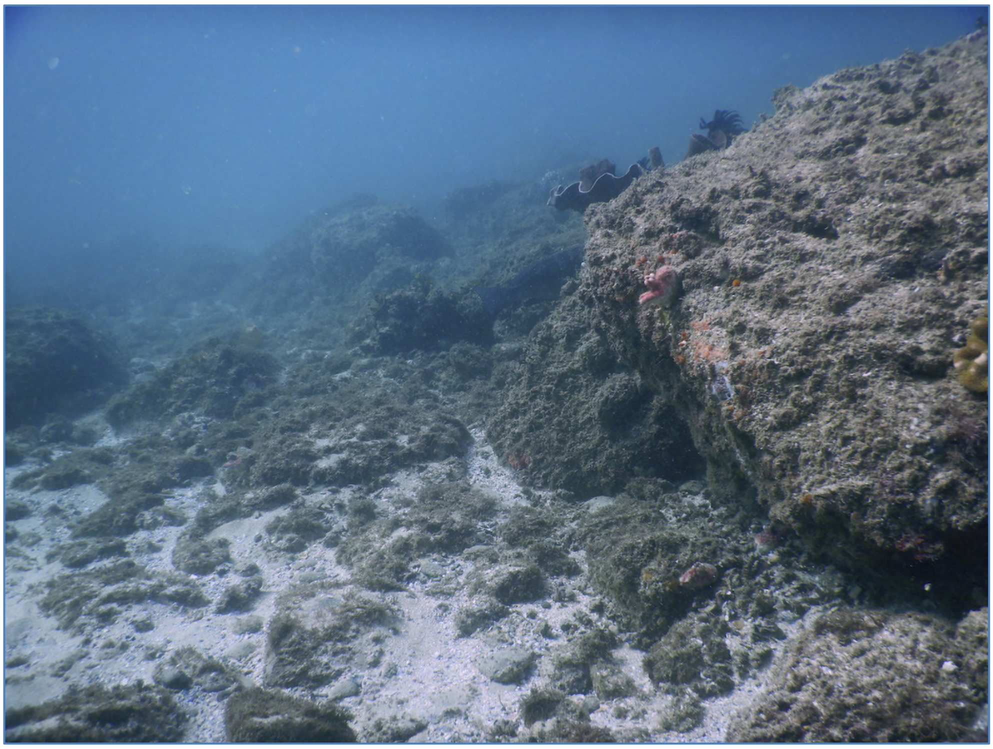
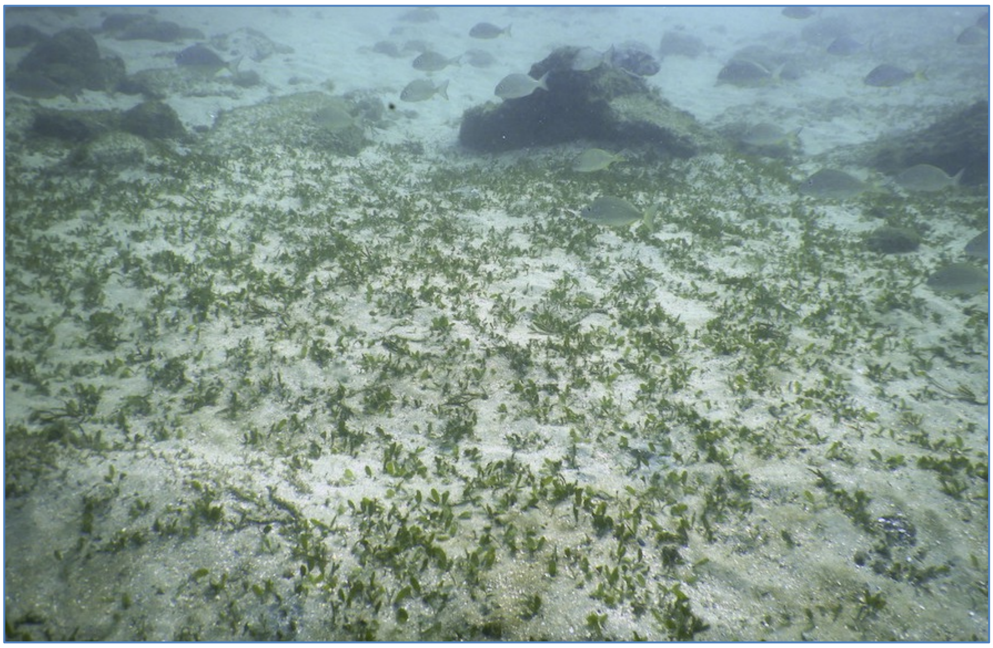


Figure 3.6 Example benthic assemblages at a) Cook Island North and b) Cook Island West

a)



b)

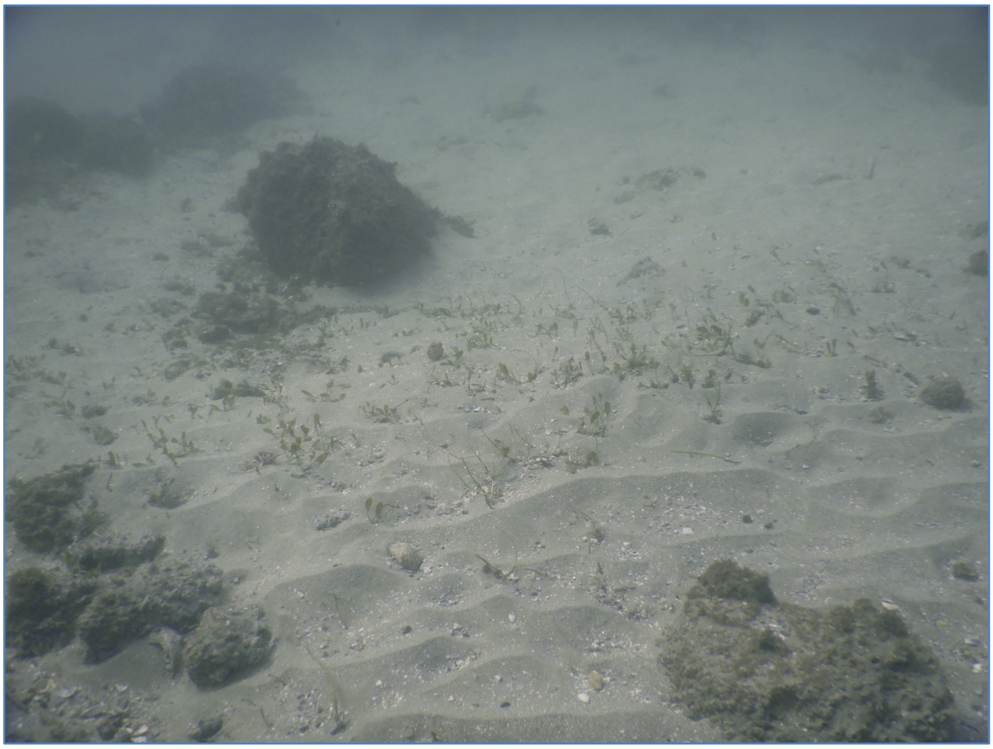


Figure 3.7 Seagrass *Halophila ovalis* at Cook Island West in (a) 2021 and (b) 2022

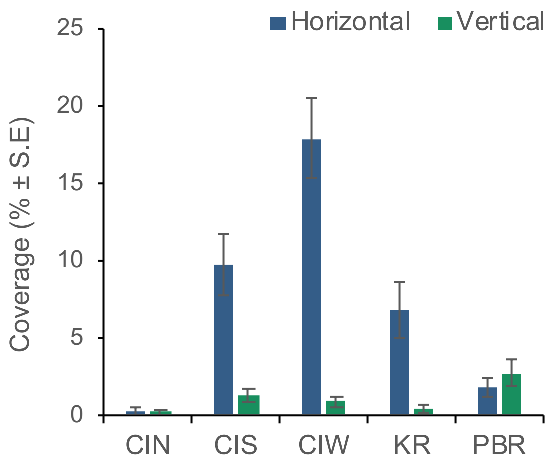


Figure 3.8 Average coverage (% ± S.E.) of bare (sand & rubble) habitat between surface orientations, among reefs

3.2.2 Algal Assemblages

The algal assemblages on all reefs were dominated by turf forming algae, which covered on average more than 40% of the reef areas. Other groups such as foliose macroalgae (including *Sargassum* sp., *Dictyota* sp. and *Padina* sp.), crustose coralline algae and articulate coralline algae (e.g. *Jania* sp.) were also present. The composition of algal assemblages differed at a range of spatial scales, with differences in the coverage of algae occurring among reefs on both horizontal and vertical surfaces[7] (Figure 3.4b & c; Figure 3.10; PERMANOVA, Appendix B, Table B.5.4). There were consistent differences in the composition of algal assemblages among the reefs, particularly between Palm Beach and other reefs (Figure 3.4b & c; PERMANOVA pairwise comparisons, Appendix B, Table B.5.4; Table B.5.5; SIMPER Table B.5.6), which may be due to impacts from recent flooding observed at Palm Beach Reef.

The average coverage of foliose macroalgae was similar between the surface orientations on each reef (Figure 3.9a; PERMANOVA Appendix B Table B.5.5a). The coverage of macroalgae on Kirra was generally higher than on the other reefs, although has declined since 2021 (Figure 3.9a; ESP 2021). Foliose macroalgae covered on average less than 6% of horizontal and vertical surfaces on Kirra Reef, compared with more than 14% in 2021 and more than 18% in 2020 (Figure 3.10). *Sargassum* spp. was largely absent at all other reefs surveyed, with differences among reefs due to the coverage of turf forming algae (SIMPER; Appendix B, Table B.5.6).

The coverage of turf forming algae was highest on both vertical and horizontal surfaces at Palm Beach Reef (69%) and was lowest on vertical surfaces at Cook Island South (39%) (Figure 3.9b; Figure 3.10; PERMANOVA Appendix B Table B.5.5b). Differences in the coverage of turf forming algae between Kirra and the other reefs contributed more than 84% of the difference in algal assemblages among those reefs (Figure 3.9b; SIMPER Appendix B, Table B.5.6).

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[7] Algal assemblages PERMANOVA Reef main effect $MS_{4,10}$ = 6928, pseudo-F = 6.20, p = 0.008; Pairwise tests for differences among reefs: PBNR≠CIS,CIN,KR *p(MC)* < 0.05

Articulate and crustose coralline algae typically covered less than 16% of the surface area on any one reef, and was highest on horizontal and vertical surfaces at Cook Island North (Figure 3.9c; PERMANOVA Appendix B Table B.5.5c). In 2022, the coverage of coralline algae did not differ significantly among the reefs, although was greatest on Cook Island North (Table B.5.6)

While the coverage of foliose macroalgae on the recently exhumed section of Kirra Reef (part of the eastern section) was not specifically assessed, the low relief reef was dominated by a moderate coverage of foliose macroalgae, in particular *Sargassum, Padina* and *Ulva* (Figure 3.10). These species colonise rocky reefs in the area, particularly where reef surfaces are available for colonisation during winter months when algae are known to spawn (Kennelly 1987).

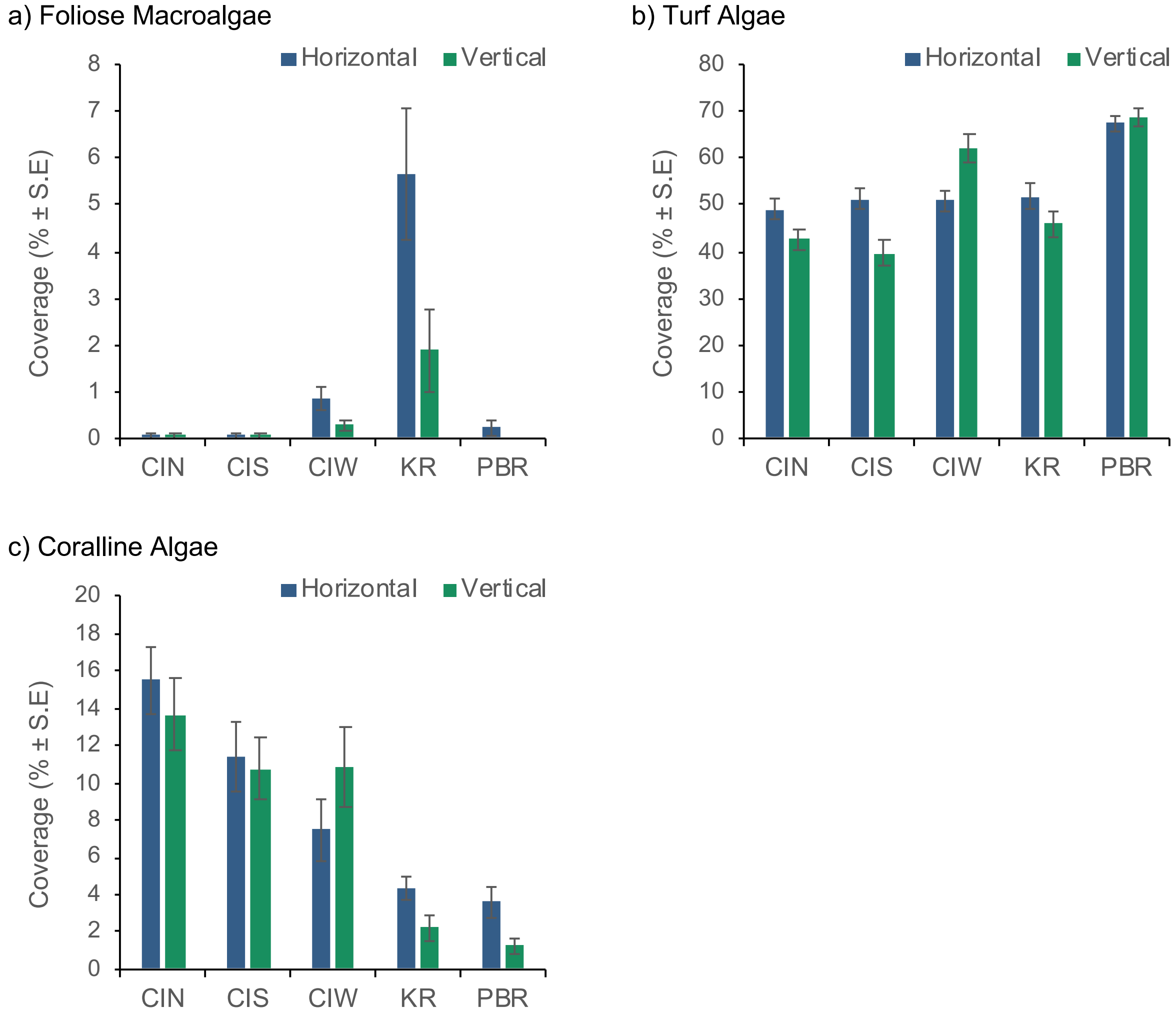
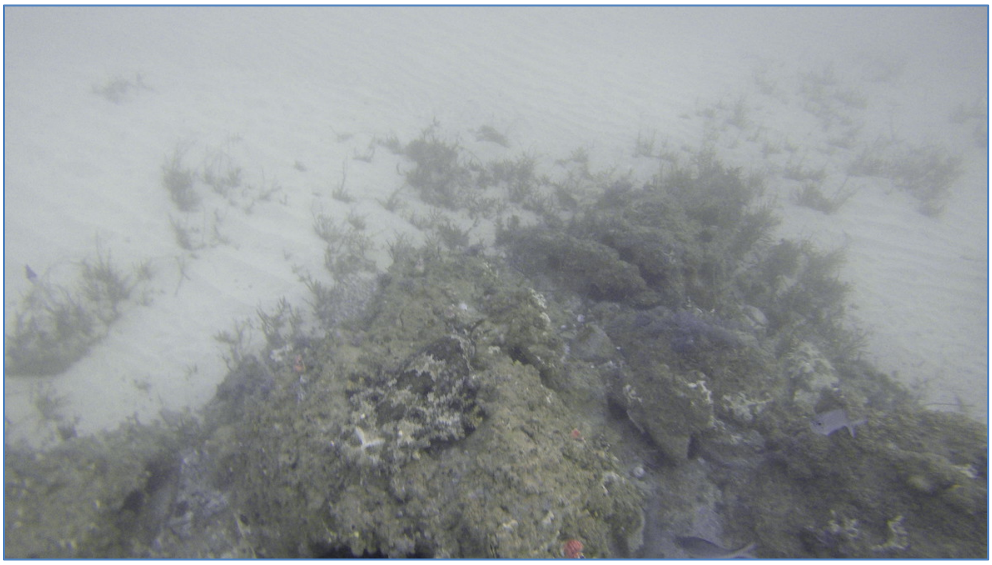


Figure 3.9 Average coverage (% ± SE) of foliose macroalgae, turf algae and coralline algae on vertical and horizontal surfaces, among reefs in 2022

a)



b)

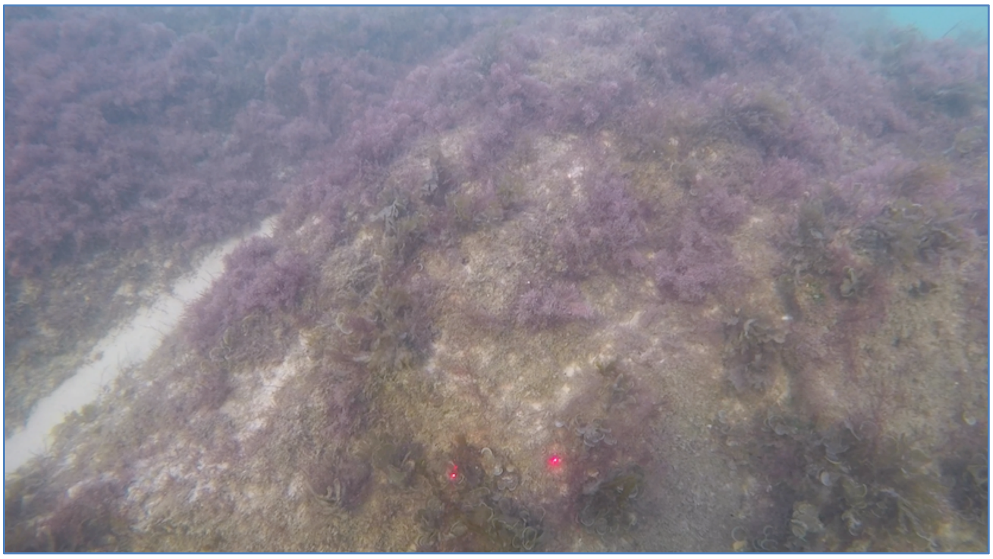


Figure 3.10 Algal communities at a) Kirra Reef northern section and b) recently exhumed eastern reef section

3.2.3 Sessile Invertebrate Assemblages

In 2022, a total of 104 taxa were recorded across all vertical surfaces and 93 taxa recorded across all horizontal surfaces on the reefs assessed. There were differences in the total number of taxa recorded between vertical and horizontal surfaces. The fewest taxa were recorded at Kirra Reef, with a total of 46 taxa recorded on vertical surfaces and 25 taxa on horizontal surfaces of the reef. By comparison, a total of 27 taxa were recorded on vertical surfaces and 23 taxa on horizontal surfaces in 2021 at Kirra Reef, and 62 taxa were recorded on vertical surfaces and 27 taxa on horizontal surfaces in 2020.

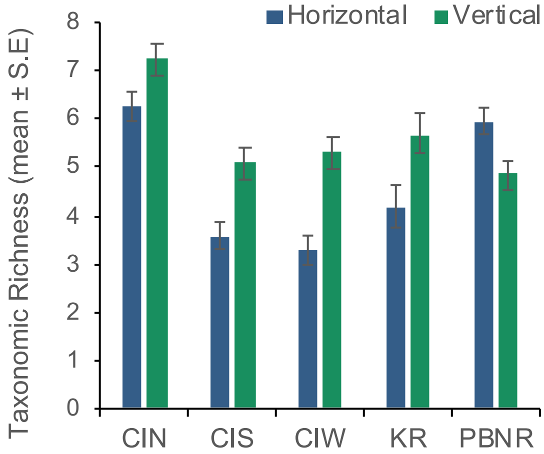
The composition of sessile invertebrate assemblages (presence and % coverage of each taxonomic group) generally differed between Kirra Reef and the other reefs surveyed regardless of surface orientation[8] (Figure 3.4d; PERMANOVA Orientation x Reef pairwise comparisons Table B.5.7). The average coverage of the dominant ascidians *Polycarpa procera*, *Pyura stolonifera* and *Herdmania momus*, was typically higher on horizontal surfaces at Kirra Reef than on other reefs and contributed 11 to 18% of the difference in assemblage composition (SIMPER Appendix B, Table B.5.8b,c). These dominant taxa also had a relatively high contribution to the differences in assemblage composition on Kirra Reef compared with that on the other reefs, contributing up to 60% of the differences in 2020 and up to 36% of the differences in 2021. The lack of hard corals (i.e. from genus *Paragoniastrea, Turbinaria* and encrusting *Porites*) and lower coverage of soft corals on Kirra Reef also contributed to differences in assemblage composition among reefs, particular with those assemblages surrounding Cook Island (SIMPER Appendix B, Table B.5.8). On vertical surfaces, the higher coverage of ascidians *Polycarpa procera*, *Pyura stolonifera* and *Herdmania momus,* and lower coverage of a range of sponges contributed most to the difference among assemblages on Kirra Reef and the other reefs (SIMPER Appendix B, Table B.5.9).

Both average taxonomic richness and coverage did not differ between Kirra Reef and the comparative reefs surveyed in 2022[9] (Figure 3.11a,b; PERMANOVA Appendix B, Table B.5.10a,b). On most reefs, the average taxonomic richness and coverage of sessile fauna was consistently higher on vertical than horizontal surfaces[10] (Figure 3.11a,b; PERMANOVA Appendix B, Table B.5.10b). This was to be expected as horizontal surfaces such as those on Kirra Reef typically had a greater coverage of foliose and turf forming algae (Figure 3.9), which can outcompete sessile invertebrates and cause physical disturbance preventing settlement. There was also a higher coverage of bare sand and rubble on horizontal than vertical surfaces, which can increase physical disturbance from sand scour and burial creating conditions that are unsuitable for sessile invertebrate recruitment and growth (Figure 3.8).

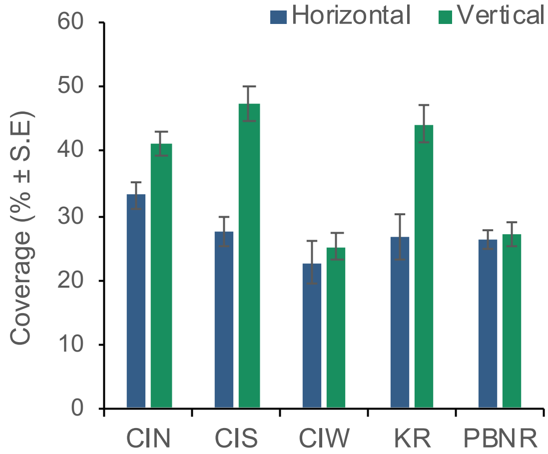
[8] Sessile Invertebrates - PERMANOVA Orientation vs Reef interaction $MS_{4,10}$ = 10860, pseudo-F = 3.01, p = 0.001; Pairwise tests for differences among reefs for horizontal and vertical surfaces: CIW≠CIS≠CIN≠KR≠PBR *p(MC)* < 0.05
[9] Richness of Sessile Invertebrates PERMANOVA Reef Main effect $MS_{4,10}$ = 92.4, pseudo-F = 5.44, p = 0.016, Pairwise tests for differences among reefs: CIN>CIS=CIW *p(MC)* < 0.05; Coverage of Sessile Invertebrates PERMANOVA Reef Main effect $MS_{4,10}$ = 3545, pseudo-F = 2.40, p = 0.110.
[10] Richness of Sessile Invertebrates PERMANOVA Orientation Main effect $MS_{1,10}$ = 111, pseudo-F = 7.78, p = 0.019; Coverage of Sessile Invertebrates PERMANOVA Orientation Main effect $MS_{4,10}$ = 10573, pseudo-F = 10.15, p = 0.009

At Cook Island and Palm Beach reefs longer lived hard and soft corals typically covered a large proportion of both vertical and horizontal surfaces (Figure 3.11c,d and Figure 3.12). In 2022, there was a higher incidence of diseased corals recorded on reefs around Cook Island and Palm Beach reefs, as well as damage to soft corals on some reefs due most likely to prolonged flooding impacts, which has not been as prevalent in previous years.

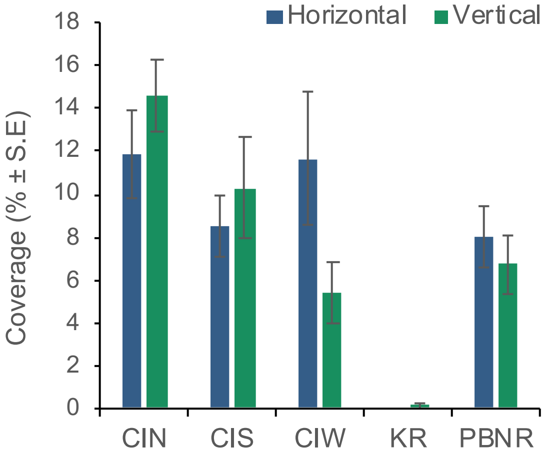
a) Taxonomic Richness of Sessile Invertebrates



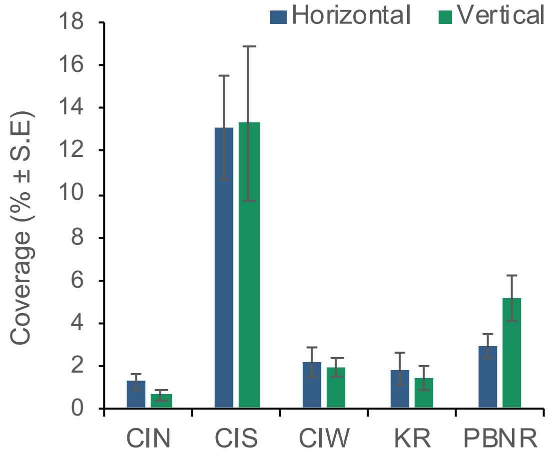
b) Coverage of Sessile Invertebrates



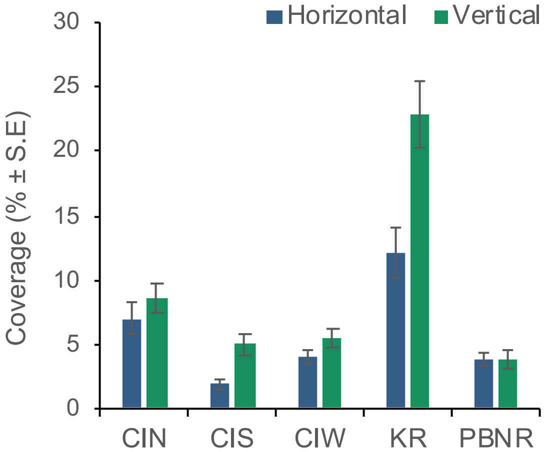
c) Hard Coral



d) Soft Coral



e) Ascidians



f) Sponges

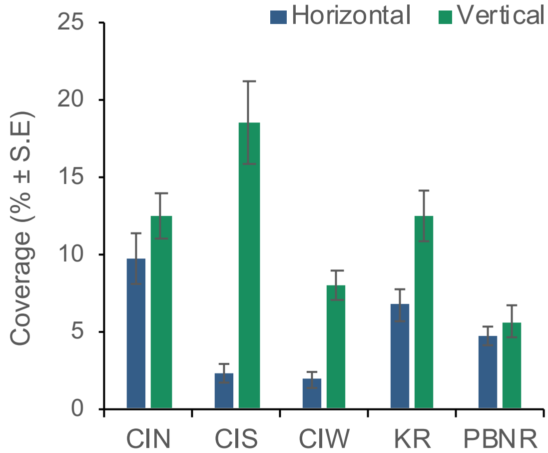
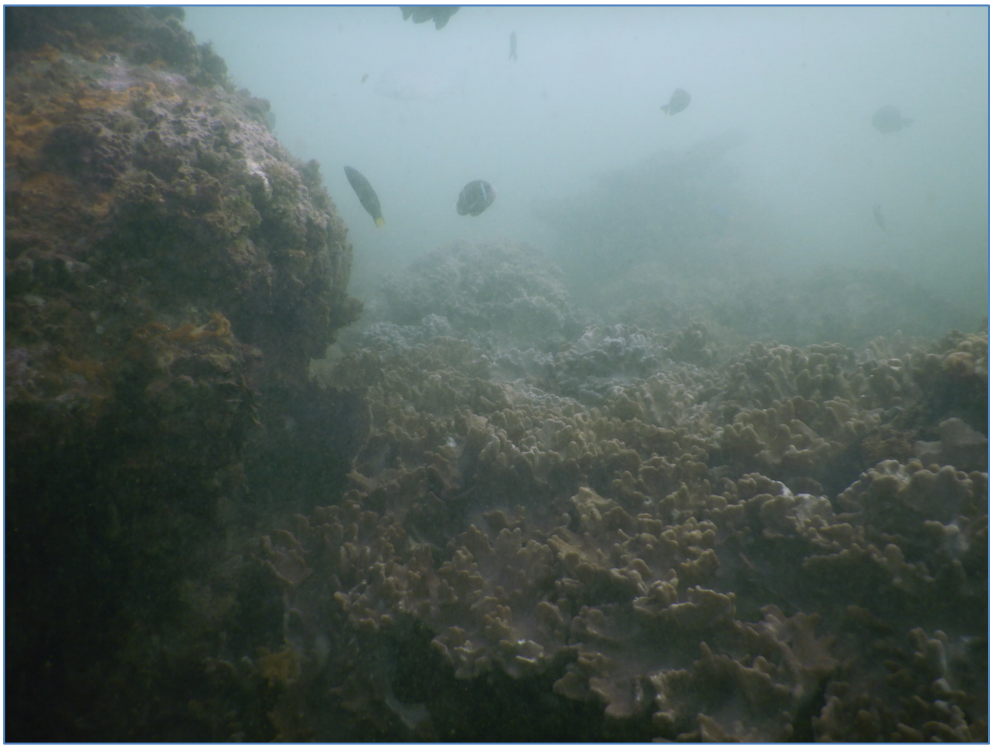


Figure 3.11 Average taxonomic richness and coverage (% ± SE) of all sessile invertebrates and average coverage of dominant sessile invertebrates categories on vertical and horizontal surfaces, among reefs in 2022 (Blue – Horizontal; Green – Vertical)

a)



b)

Figure 3.12 Hard and soft coral at a) Cook Island South and b) Cook Island North

3.2.4 Historic Comparison of Benthic Communities

The composition of benthic communities (algae and sessile invertebrates identified to a broad taxonomic level) continued to differ between Kirra and Palm Beach Reefs (most commonly surveyed) and the various other reefs assessed over time[11] (Figure 3.13; PERMANOVA Survey x Reef Interaction; pairwise comparisons Appendix B,). In the past seven years (since 2016), the composition of benthic communities on all reefs assessed have differed between successive years where surveys have been completed which demonstrates the potential interannual variation in the composition of benthic communities (PERMANOVA pairwise comparisons, Table B.5.11g). Although, there have been some differences in the methods of data collection among surveys, particularly between 2017 and 2019. Despite these differences, the composition of benthic assemblages were more similar among reefs in 2022 than in previous years, likely due to changes in the coverage of foliose macroalgae (Figure 3.13). In particular, the composition of assemblages on Kirra Reef has become more similar to reefs in the region as demonstrated by the closer proximity among points for the 2022 survey in the nMDS ordination, compared with previous years (Figure 3.13).

On Kirra Reef, the differences in composition between successive surveys were due primarily to changes in the average coverage of macroalgae, turf algae and ascidians, which combined accounted for up to 84% of the difference between the surveys on that reef (SIMPER Table B.5.12). Between 2021 and 2022, there has been an increased coverage of turf forming algae and sponges, and decreased coverage of macroalgae, and ascidians which contributed 80% of the differences in composition (Table B.5.12). Hard corals were also not recorded in the benthic community on Kirra Reef in 2022, despite covering 2% of the area in 2020. An increase in the coverage of hard and soft corals would likely result in more similar composition of benthic communities with those found on surrounding reefs, but many of these species are slow growing so may take considerable time to become established and cover a large area on Kirra Reef (Walker & Schlacher 2014).

On reefs around Cook Island, differences in the composition of benthic communities between successive surveys at each reef were due primarily to changes in the average coverage of macroalgae, coralline and turf forming algae, which contributed more than 37% of the dissimilarity between successive surveys at each reef (SIMPER Table B.5.13 to Table B.5.15). In 2022, the coverage of hard coral remained similar to the previous survey at Cook Island North, increasing on average by 1.2%, although coverage varied among the quadrats and transects (SIMPER Table B.5.13). The average coverage of hard corals also increased at Cook Island West by 7% between 2021 and 2022 (SIMPER Table B.5.14). In contrast, the coverage of hard corals had declined by 8% at Cook Island South between 2021 and 2022 (SIMPER Table B.5.15). The coverage of soft corals at Cook Island South remained consistent between 2021 and 2022 (SIMPER Table B.5.15).

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[11] Benthic Communities over time - PERMANOVA Survey x Reef interaction $MS_{20,1479}$ = 12451 pseudo-F = 126.12, p = 0.001; Pairwise tests for differences among reefs over time are provided in Appendix B Table B.5.11.

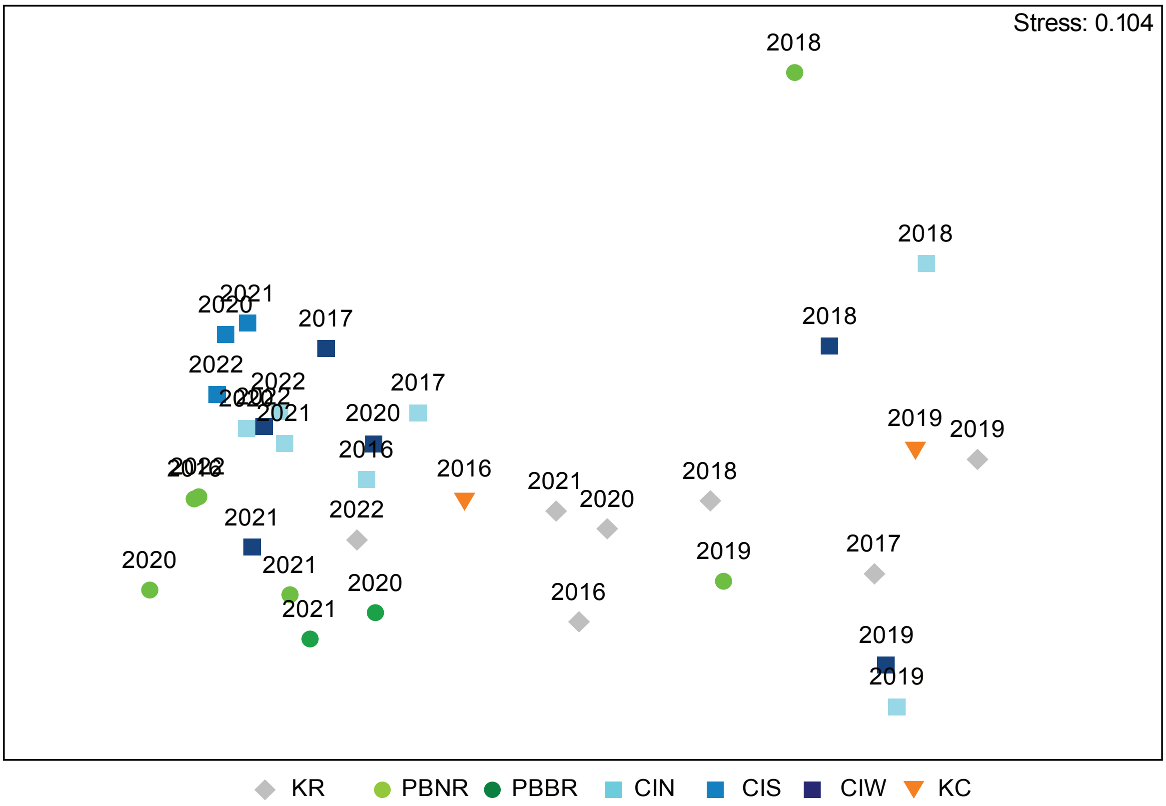

Figure 3.13 nMDS ordination of the difference in the composition of benthic assemblages on horizontal surfaces between Kirra and Palm Beach Reefs between 2016 and 2022 (KC = Kingscliff Reef – only surveyed in 2016 & 2019) [12]

3.2.5 Mobile Invertebrate Assemblages

In 2022, the average density of mobile invertebrate assemblages was highest at Cook Island North, followed closely by Kirra Reef; although reefs around Cook Island had the greatest diversity of mobile invertebrates (Appendix C). Echinoderms dominated the mobile invertebrate assemblages at all reefs in 2022, which is consistent with surveys in recent years (ESP 2020; ESP 2021) (Figure 3.14; Appendix C). Feather stars (primarily *Cenolia* spp.; Figure 3.15a) had the highest densities at all reefs, except for Cook Island South and Palm Beach Reef, where sea stars had higher densities (Figure 3.14; Figure 3.15b). Sea cucumbers and sea snails (Figure 3.15c) occurred in low densities at some reefs and an octopus (Figure 3.15d), a painted crayfish and banded coral shrimp were also observed in photo quadrats from Kirra Reef, Cook Island South and Cook Island West, respectively (Appendix C). Painted crayfish were also observed by divers at Kirra Reef. In addition to those mobile invertebrates recorded from photo quadrats, several other species were observed on ROV, UBRUVS or SCUBA diver footage, including:

[12] nMDS ordination plot provides a two-dimensional map so that the rank order distance between samples match the rank order similarity from a matrix of sample pairs. The placement of points represents the similarity or difference among samples (in this case in the composition of assemblages - presence and abundance of each taxon). Samples that appear closer on the ordination are more similar in composition, and those further apart are more dissimilar or share fewer traits.

- sea stars (including *Pentagonaster duebeni*, *Pseudonepanthia nigrobrunnea*, *Linckia laevigata* and *Tamaria sp.*) observed at Cook Island South, Cook Island West and Palm Beach Reef
- coral crayfish (*Panulirus longipes bispinosus*) observed at all Cook Island sites (Figure 3.15e)
- a bigfin reef squid (*Sepioteuthis lessoniana*) observed at Cook Island South
- a Spanish dancer (*Hexabranchus sanguineus*) observed at Cook Island North
- a magnificent nudibranch (*Miamira magnifica*) observed at Palm Beach Reef (Figure 3.15f), and
- cone snails (*Conus spp.*) observed at Cook Island West.

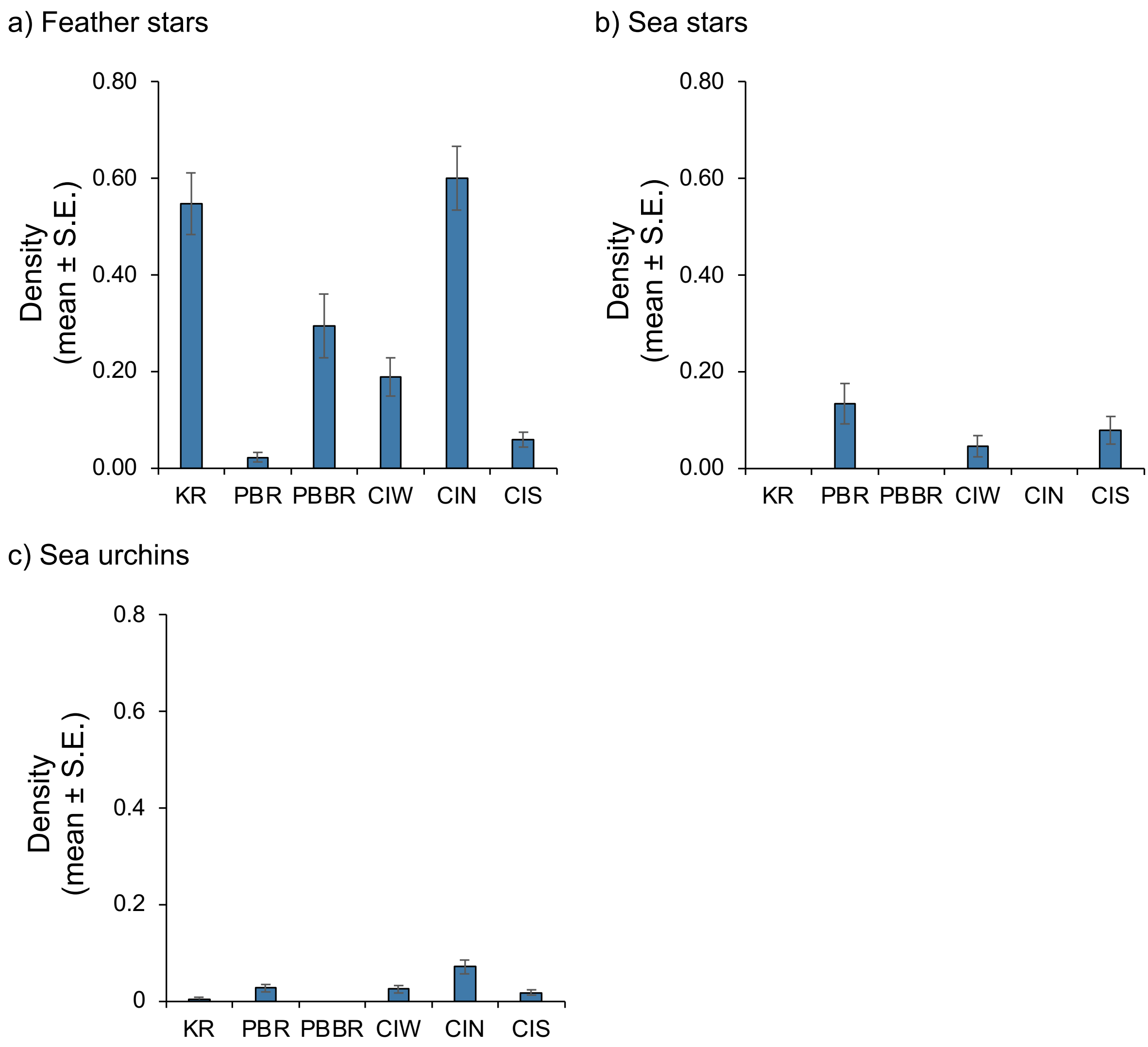

Figure 3.14 Density (number of individuals per photo quadrat; mean ± SE) of a) feather stars, b) sea stars, and c) sea urchins at each reef in 2022

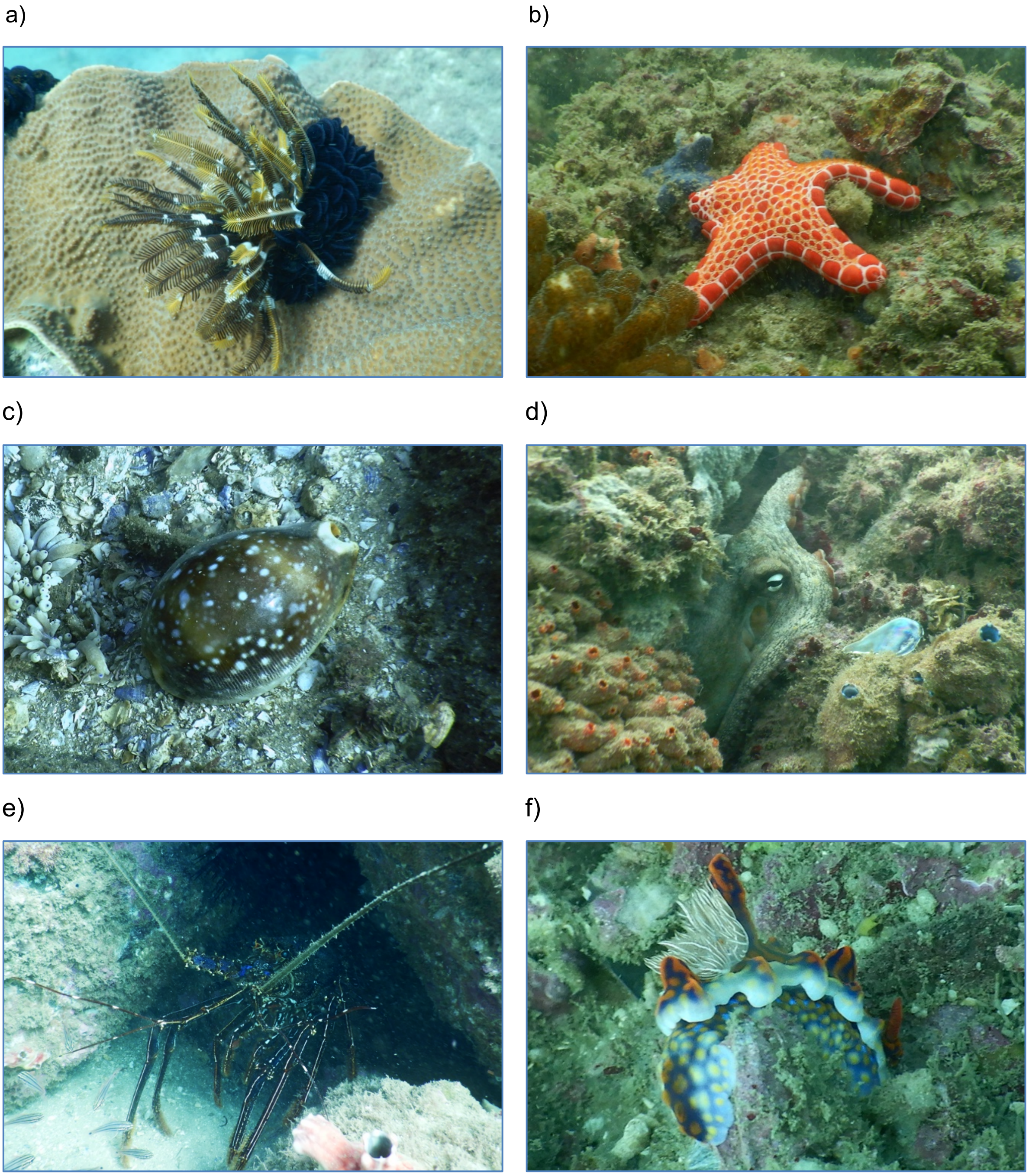

Figure 3.15 Mobile invertebrates recorded on reefs in 2022 including a) feather stars, b) vermillion sea star, c) milk-spot cowrie, d) common Sydney octopus, e) coral crayfish, and f) magnificent nudibranch

3.3 Fish Assemblages

A total of 126 bony and cartilaginous fish species, from 40 families were recorded across all reefs in the June 2022 survey (Appendix D). This was relatively similar to recent years, with a total of 129 species from 44 families in 2021 and 116 species from 34 families in 2020. Consistent with 2020 and 2021, Labridae (wrasses) and Pomacentridae (damselfishes) were the most diverse families. These families had 24 and 19 species, respectively, in June 2022. An additional 20 fish species were observed that have not been recorded in previous surveys (Appendix D). Cartilaginous fish recorded in June 2022 included:

- banded wobbegong (*Orectolobus ornatus*) at all reefs except for Cook Island South
- spotted wobbegong (*Orectolobus maculatus*) at all reefs except for Palm Beach Reef and Cook Island South
- whitespotted guitarfish (*Rhynchobatus australiae*) at Cook Island West and Cook Island South (Figure 3.16a)
- Australian cownose ray (*Rhinoptera neglecta*) at Cook Island South, and
- bluespotted maskray (*Neotrygon kuhlii*) at Kirra Reef.

The composition of fish assemblages differed among reefs [13], specifically between assemblages at Kirra Reef and Cook Island South, and between Palm Beach Reef and Cook Island North, with no significant difference in composition among the other reefs (Figure 3.17). Differences in fish assemblages at Kirra Reef and Cook Island South were largely attributed to the absence of several species at Cook Island South, particularly schooling yellowtail scad (*Trachurus novaezelandiae*). These schooling species were highly abundant at Kirra Reef. Differences in fish assemblages at Palm Beach Reef and Cook Island North were due to several different species, including an absence of yellowtail scad and striped barracuda (*Sphyraena obtusata*) at Cook Island South and an absence of scalyfin (*Parma unifasciata*) and mado (*Atypichthys strigatus*) at Palm Beach Reef. Differences in the habitat complexity (e.g. yellowtail scad are known to have increased abundance on reefs with higher vertical relief; Holland et al 2021), benthic composition (refer to Section 3.2), availability of prey or other ecological interactions (e.g. predator abundance). It may also be due to the differences in footage quality (e.g., there was very poor visibility at Cook Island South relative to other reefs).

Most fish species recorded were common to the region. No threatened or protected fish species listed under the Queensland's *Nature Conservation Act 1992* or nationally under the Commonwealth's *Environmental Protection and Biodiversity Conservation Act 1999* were recorded. The eastern blue groper (*Achoerodus viridis*) is partly protected under the NSW Fisheries Management (General) Regulation 2019 (i.e. must not be fished by any method other than a rod and line or a handline) and was recorded at Cook Island West and Cook Island North (Figure 3.16b). No invasive fish species were recorded.

[13] PERMANOVA for differences in fish assemblages among reefs $F_{5,11} = 2.45$, $p = 0.001$; Pairwise comparisons among reefs CIN≠PBNR; CIS≠KR; CIN=CIS=CIW=PBR=PBBR=KR at p=0.05.

a)

b)

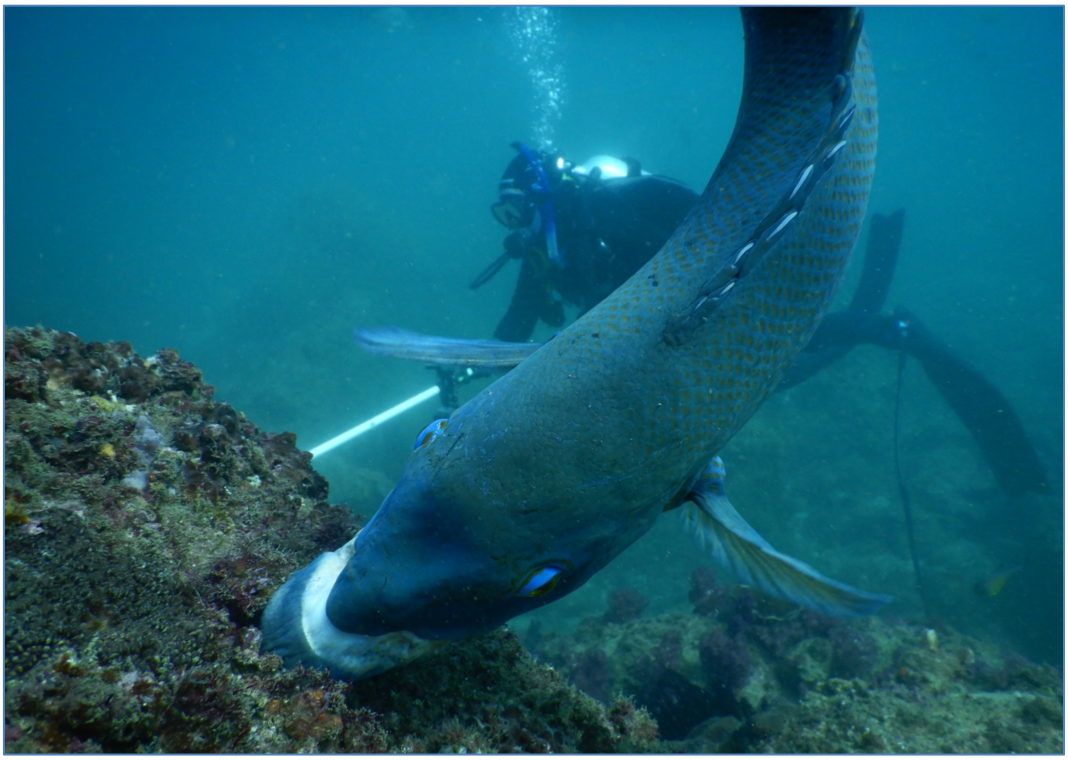

Figure 3.16 a) whitespotted guitarfish b) Eastern blue grouper recorded in 2022

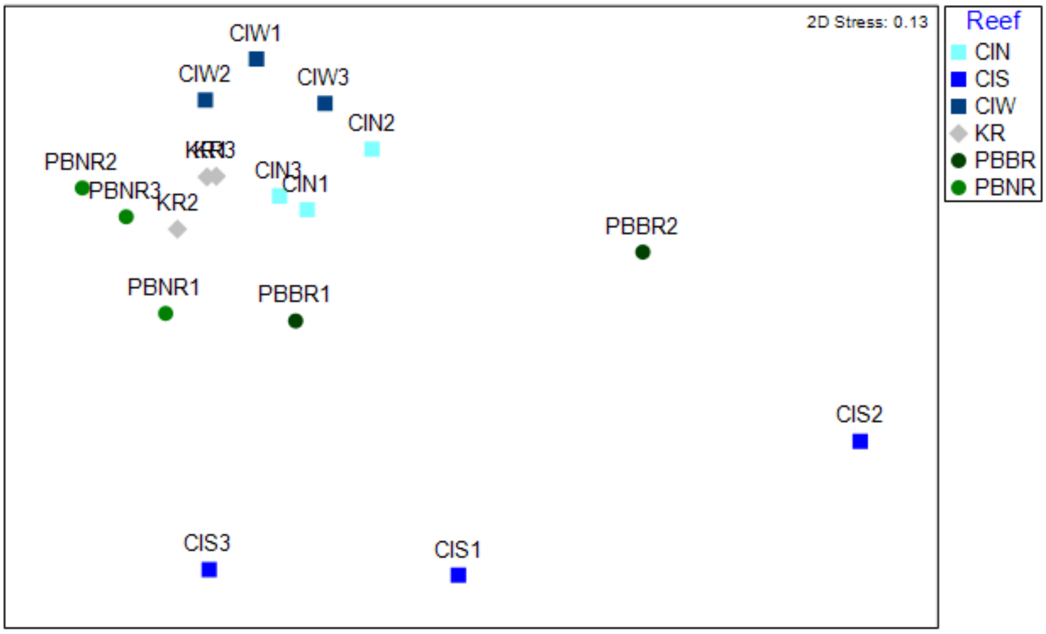

Figure 3.17 nMDS ordination of the differences in the composition of fish assemblage among reefs in 2022 [14]

3.3.1 Species Richness of Fish Assemblages

In 2022, total species richness varied among reefs, with the highest number of species recorded at Cook Island West (81 species) and the fewest species recorded at Cook Island South (24 species) (Table 3.1; Appendix D). This is consistent with results from 2021, with the highest number of species recorded at Cook Island West (68 species) and the fewest species recorded at Cook Island South (39 species). A variety of fish species have been recorded on the reefs during surveys between 1995 and 2022 and in the past few years. Temporal differences in the species richness during this period may be related to differences in sampling techniques, personnel completing the surveys and the timing of monitoring events which occurred at during different times of the year.

Species richness differed among most reefs in June 2022[15], with the lowest average species richness recorded at Cook Island South (consistent with 2021) and the highest average richness recorded at Kirra Reef (Figure 3.18). There has been little difference in the species richness between Kirra and the Palm Beach Reefs among surveys in the past few years, potentially due to these reefs having similar availability of primary food sources or providing relatively similar structural habitat in an otherwise featureless sandy bottom coastline (ESP 2020). However, in 2022, assemblages at these reefs differed, with a higher abundance of most species at Kirra Reef. In 2022, there was poor visibility at Palm Beach Bait Reef during

[14] nMDS ordination plot provides a two-dimensional map so that the rank order distance between samples match the rank order similarity from a matrix of sample pairs. The placement of points represents the similarity or difference among samples (in this case in the composition of assemblages - presence and abundance of each taxon). Samples that appear closer on the ordination are more similar in composition, and those further apart are more dissimilar or share fewer traits.

[15] PERMANOVA for differences in species richness among reefs $F_{5,11} = 16.83$, $p = 0.001$; Pairwise comparisons among reefs PBBR≠KR≠PBNR; CIW≠CIS≠CIN≠KR≠CIS; KR=CIW; CIN=PBNR=CIW; PBBR≠PBNR≠CIS; CIN=PBBR=CIS; PBBR≠CIW; CIW≠CIN≠CIS≠CIW at $p = 0.05$.

the survey, which reduced the quality of footage collected and potentially resulted in fewer fish being detected at the reef.

Table 3.1 Total species richness and abundance among the reefs in 2022

	Total Species Richness*	Total Abundance (Pooled Max N)^
Kirra Reef	72	1206
Palm Beach Reef	46	212
Palm Beach Bait Reef	28	32
Cook Island West	81	321
Cook Island North	56	66
Cook Island South	24	22

* Total Species Richness collated from UBRUVS, ROV and diver recordings

^ Total Abundance calculated from UBRUVS recordings only

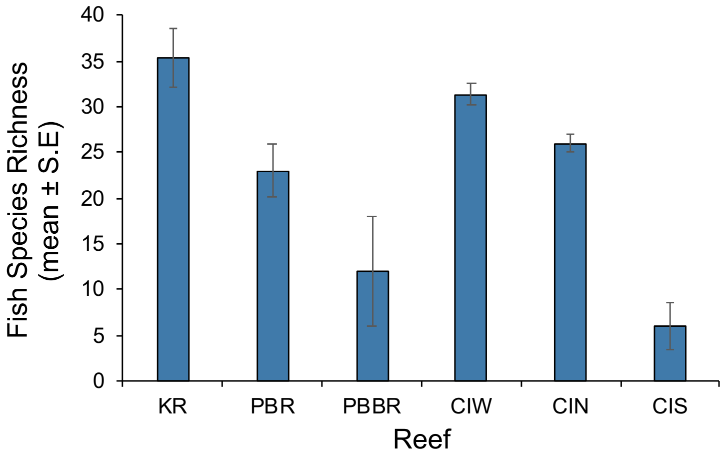

Figure 3.18 Average species richness (± SE) of fish assemblages among reefs

3.3.2 Relative Abundance of Fish Assemblages

The total abundance of fish, measured as the pooled Max N from UBRUVS, was highest at Kirra Reef (1206 individuals). The lowest abundance was recorded at Cook Island South with only 22 individuals (Table 3.1). Kirra Reef also had the highest total abundance of fish in 2021 (1132 individuals) and 2020 (496 individuals) and Cook Island South also had the lowest abundance in 2021 (49 individuals) and 2020 (27 individuals). Differences in abundance among reefs were primarily driven by high numbers of schooling fish at some reefs. For example, dense schools (approximately 1000 individuals) of yellowtail scad (*Trachurus novaezelandiae*) dominated fish assemblages at Kirra Reef (Figure 3.19a) and less dense schools (approximately 90 to 250 individuals) of eastern pomfred (*Schuettea scalaripinnis*) at Cook Island West, Cook Island North and Palm Beach Natural Reef (Figure 3.19b) as well as Whitley's sergeant (*Abudefduf whitleyi*) at Cook Island West. At Palm Beach Bait Reef, schooling species included black rabbitfish (*Siganus fuscescens*), silver sweep (*Scorpis fuscescens*; Figure 3.20a) and yellowtail scad, though individuals within schools were always ≤ 50 individuals. No species of schooling fish were detected on UBRUVS at Cook Island South in the June 2022 survey.

Common species among reefs included several wrasse species (such as moon wrasse, *Thalassoma lunare;* Günther's wrasse, *Pseudolabrus guentheri*; green moon wrasse, *Thalassoma lutescens*; crimsonband wrasse, *Notolabrus gymnogenis;* and common cleaner fish, *Labroides dimidiatus*), yellowfin bream or tarwhine (*Acanthopagrus australis* or *Rhabdosargus sarba*), black rabbitfish (*Siganus fuscescens*), and dwarf hawkfish (*Cirrhitichthys falco*) (Figure 3.20; Appendix D).

a)

c)

Figure 3.19 Schools of a) yellowtail scad at Kirra Reef and b) eastern pomfred at Cook Island North Reef

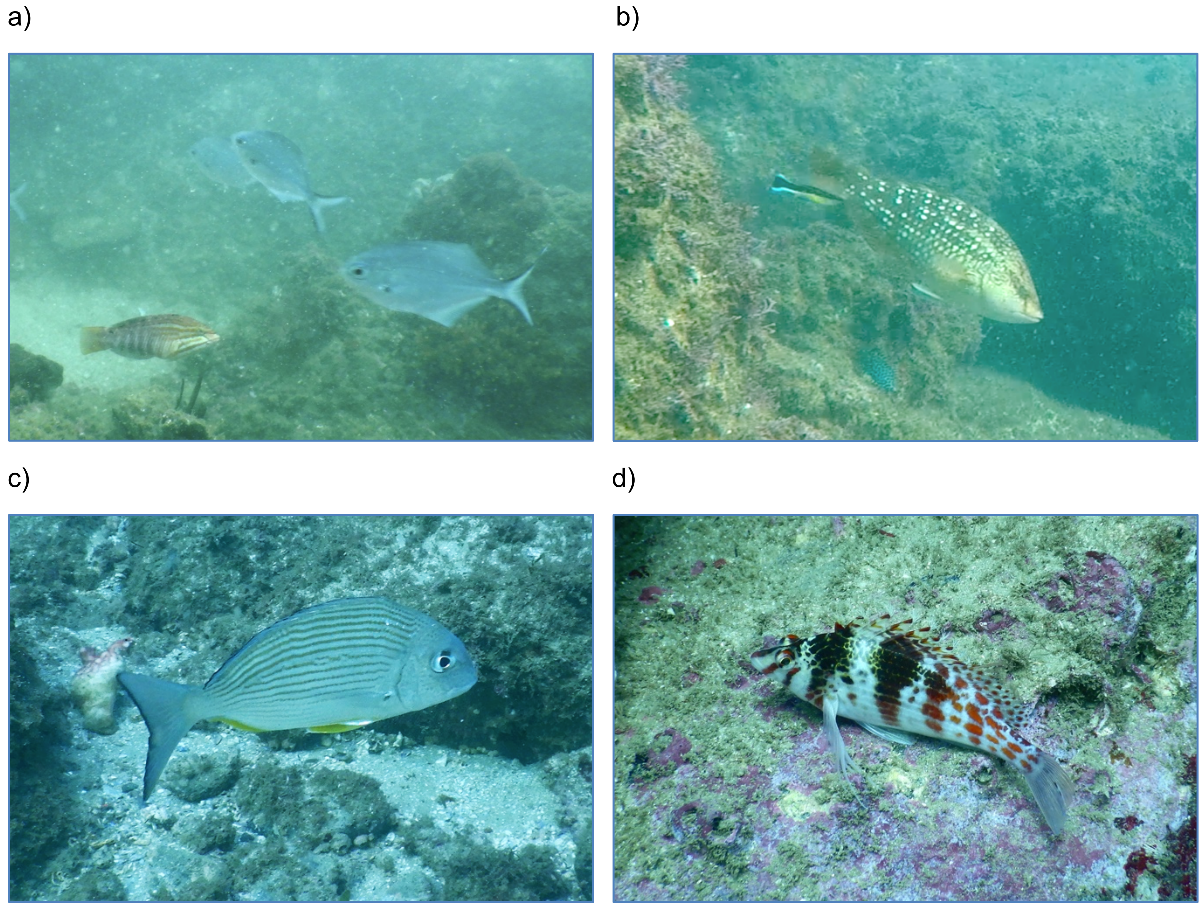

Figure 3.20 Fish species commonly seen at most reefs in 2022 including a) Günther's wrasse and silver sweep, b) crimsonband wrasse and common cleaner fish, c) yellowfin bream, and d) dwarf hawkfish

3.3.3 Trophic Level and Habitat Preferences of Fish

The contribution of different trophic levels to the diversity of fish assemblages (trophic composition) did not differ substantially among most reefs (Figure 3.21). Carnivorous species were the most diverse group at all reefs (46 to 64% of species), with omnivores generally the next most diverse group (17 to 26% of species). While there was some variation in the proportion of herbivores, omnivores with herbivorous tendencies and planktivores among reefs, these groups each contributed ≤ 21% to the trophic composition at each reef. In June 2022, corallivores were generally the least diverse group and were absent from the fish assemblage recorded at Cook Island South (as were herbivores) (Figure 3.21).

In June 2022, 85 to 90% of species recorded at each reef were reef-associated species, which was expected given the dominance of rocky reef habitat surveyed (Appendix D).

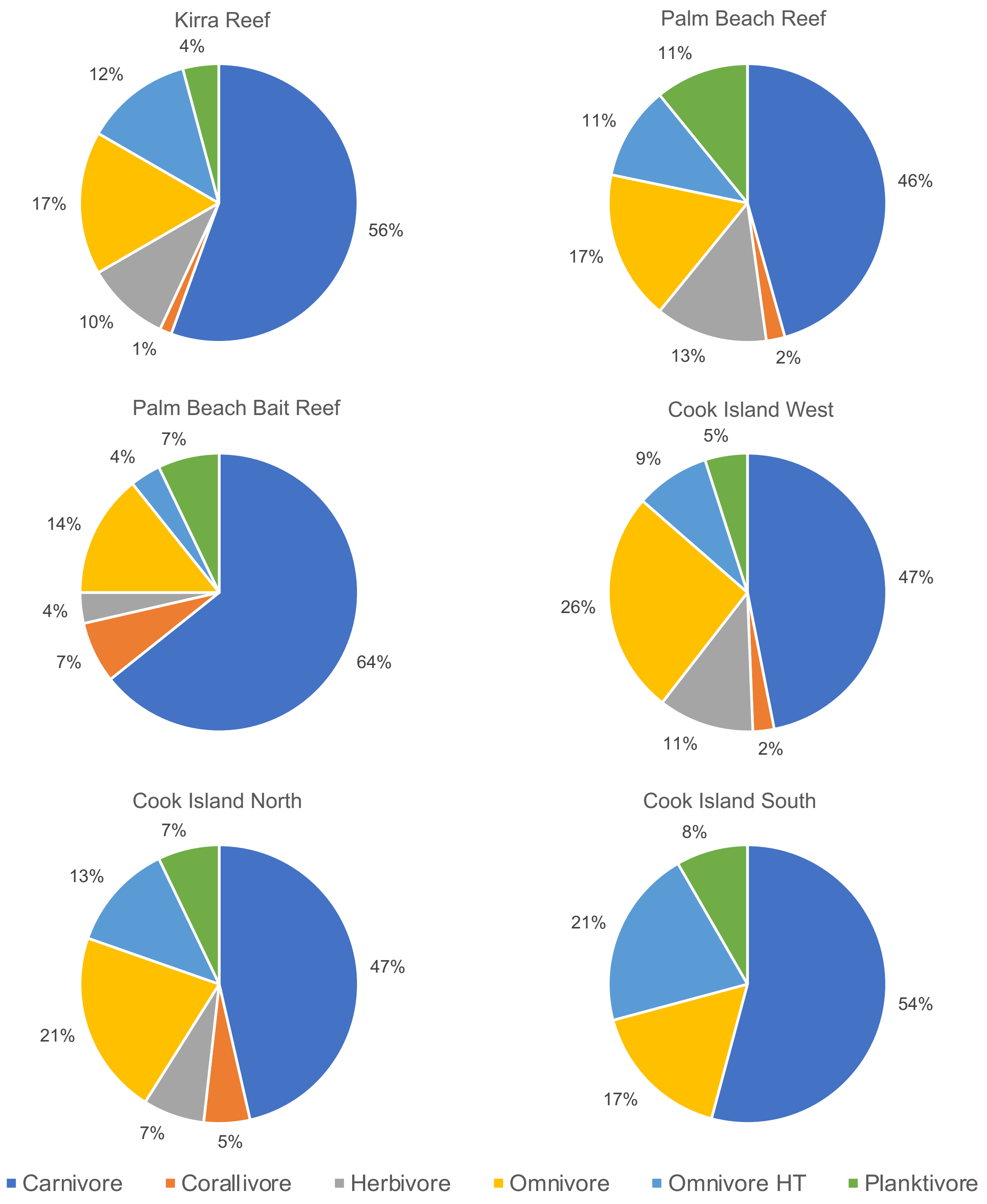

Figure 3.21 Trophic level composition of fish communities (% of species) recorded at each reef (based on UBRUVS, ROV and diver recordings)

3.4 Threatened and Invasive Species

3.4.1 Species of Conservation Significance

Of the species listed on the Protected Matters Search Tool as potentially occurring in the area, several species of conservation significance are known or likely to occur around the reefs, including:

- black rockcod (*Epinephelus daemelii*) listed as vulnerable
- white's seahorse (*Hippocampus whitei*) listed as endangered
- humpback whale (*Megaptera novaeangliae*) listed as vulnerable and migratory
- loggerhead turtle (*Caretta caretta*), listed as endangered and migratory
- green turtle (*Chelonia mydas*) listed as vulnerable and migratory
- leatherback turtle (*Dermochelys coriacea*) listed as endangered and migratory
- hawksbill turtle (*Eretmochelys imbricate*) listed as vulnerable and migratory
- flatback turtle (*Natator depressus*) listed as vulnerable
- grey nurse shark (*Carcharias taurus*) listed as critically endangered
- great white shark (*Carcharodon carcharias*) listed as vulnerable and migratory
- Indo-Pacific humpback dolphin (*Sousa chinensis*) listed as migratory, and
- manta ray (*Manta alfredi*) listed as migratory.

Several other species may occur or have suitable habitat recorded in the broader area, including:

- blue whale (*Balaenoptera musculus*) listed as endangered and migratory
- whale shark (*Rhincodon typus*) listed as vulnerable.
- olive southern right whale (*Eubalaena australis*), listed as endangered and migratory
- ridley turtle (*Lepidochelys olivacea*) listed as endangered and migratory

There are also several threatened and migratory bird species that are likely to use the reefs as feeding sites.

The only species of conservation significance (other than the blue grouper; refer to Section 3.3) recorded during the surveys was the green sea turtle (Figure 3.22), which were recorded at all Cook Island reef locations and Kirra Reef.

Figure 3.22 Green turtle (*Chelonia mydas*) at Kirra Reef in 2021

3.4.2 Introduced Species

There are over 200 marine pests reported in Australian waters (DES 2020). Of these, the white colonial sea squirt (*Didemnum perlucidum*), which is listed as a prohibited marine animal under the *Biosecurity Act 2014,* has been recorded in the region (in Brisbane, > 50 km) (Queensland Government 2020c; NIMPIS 2022). Two other introduced marine species have been recorded from Brisbane, sea lettuce (*Ulva lactuca*) and isopod (*Sphaeroma walkeri*) (NIMPIS 2022).

No exotic or invasive species were recorded during surveys or during the analysis of photo-quadrats and video.

3.5 Abiotic Conditions

3.5.1 Water Quality

To assess the ambient water quality at each reef during the field survey, depth profiles for several physicochemical parameters were completed. The temperature and pH were relatively consistent across sites and with depth, although Cook Island South had a slightly cooler temperature (Figure 3.23). The salinity was slightly lower, and the turbidity slightly higher in the surface waters at Kirra Reef compared with other sites, potentially due to freshwater inputs from recent rainfall. The concentration of dissolved oxygen varied among sites, being lowest at the Palm Beach Bait Reef and Palm Beach Natural reef sites (Figure 3.23). PAR was relatively similar between sites, with the light attenuation coefficient ranging from 0.28 μmol/s^2 (at CIW) to 0.43 μmol/s^2 (at PBNR). PAR can be influenced by a range of factors including the time when samples were collected and weather conditions (e.g. amount of incident sunlight due to cloud cover). Light attenuation increased with the site water depth, and was attenuated by between 82% (at the shallowest site, CIS) and 99% (at the deepest site, PBNR) with depth relative to surface measurements.

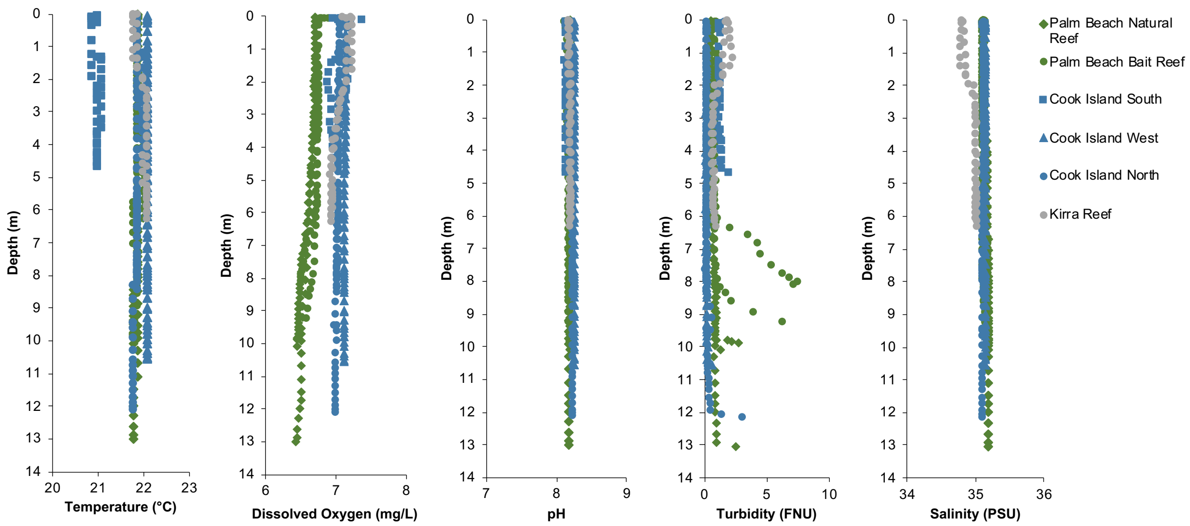

Figure 3.23 Vertical profiles of physicochemical water quality parameters among sites

3.5.2 Wave Conditions

The swell direction in the region typically ranges from a north-north-west to south-south-east direction (Ecosure 2016). Between 3 June 2021 and 2 June 2022, swell direction was predominantly from the northeast (47%) and east (45%), with most waves <1 m (29%) or 1 to 2 m (56%) (Figure 3.24). During the period assessed, significant wave heights (>3 m) were rare (<2%) and predominantly from the north-east or east (Figure 3.24). Previous analyses of long-term (01/01/2000 to 31/05/2016) wave data for Tweed Heads indicates swell occurs predominately from an east (36%) or east-south-east (34%) direction and waves are generally < 1 m (26%) or 1 to 2 m (40%), with significant wave heights (>3 m) also rare (<1%) (Ecosure 2016). Overall, swell in the year prior to the survey (3 June 2021 to 2 June 2022) was typical of the region, with significant wave events unlikely to cause major changes to sand movements in the region.

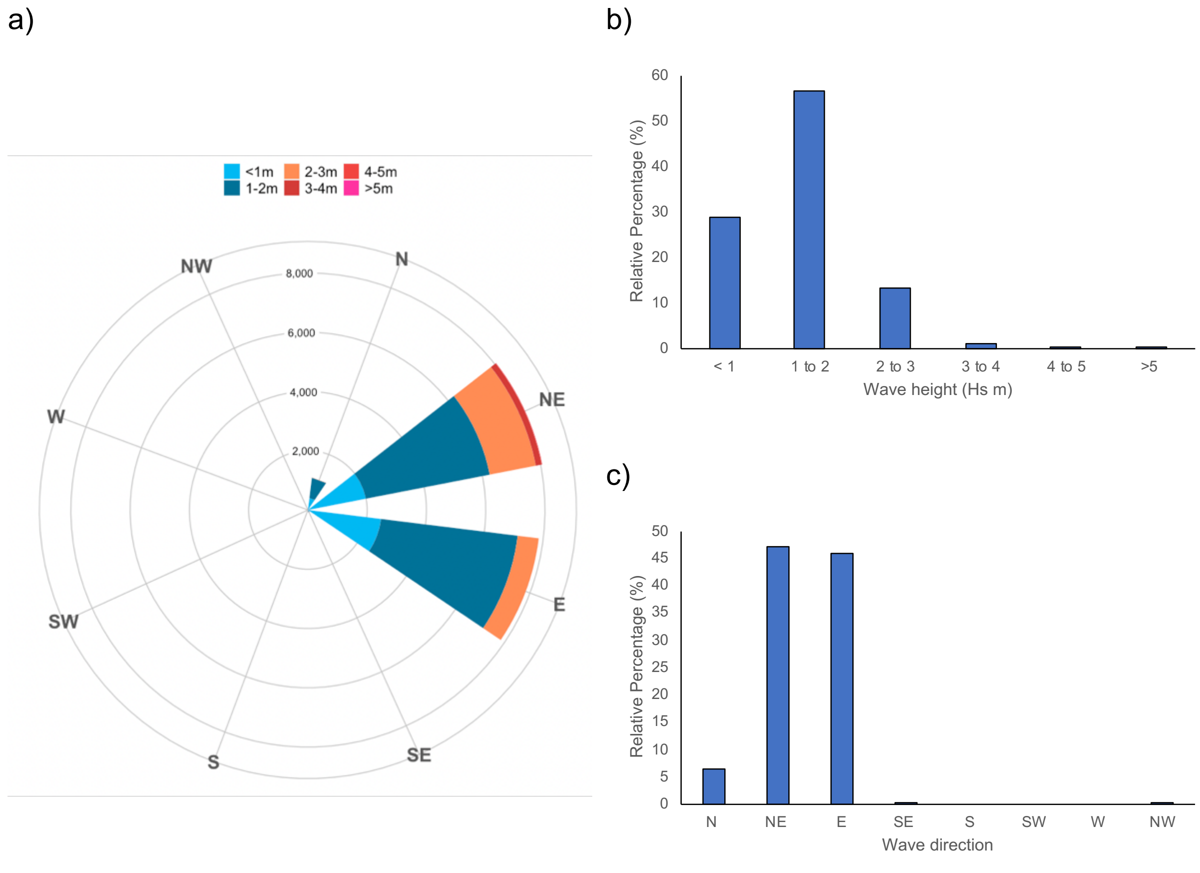

Figure 3.24 Wave data collected at Tweed Heads wave rider buoy between 3 June 2021 and 2 June 2022, showing a) wave heights and direction; b) relative percent frequency of wave direction and; c) relative precent frequency of wave height

4 Discussion and Conclusions

4.1 Changes in Reef Area at Kirra Reef

There have been large changes in the area of exposed rock at Kirra Reef through time, with periods of sand burial and exhumation, resulting in changes to the benthic communities growing on Kirra Reef. Prior to major artificial changes in sand movements (other than minor influences of the original Tweed River training walls built in 1891), Kirra Reef was partially covered by sand, which naturally varied as a result of longshore drift of sand and periods of storm activity. Between the 1960s to 1980s, sand supply to the area was depleted and large rocky reef areas to the south and east of the current extent of Kirra Reef were exposed, resulting from a range of factors including the extension of the Tweed River training walls completed 1965 and a series of successive high intensity east coast lows, including a cyclone in 1967. Beach nourishment works between the mid-1980s to 2001 (including stage 1 of the TSB project) resulted in sand accretion, with the extent of Kirra Reef decreasing (as predicted in the TSB EIS / IAS; Hyder Consulting 1997), but a relatively large area still remained uncovered. During the initial years of stage 2 of the TSB project, between 2001 to 2008, large quantities of sand were delivered to Southern Gold Coast beaches and as predicted in the EIS / IAS (Hyder Consulting 1997), the area of Kirra Reef decreased further. Between 2007 and 2008, Kirra Reef was almost completely covered with sand.

Sand delivery through the TSB project has been more consistent with natural longshore sand drift since 2009. In 2009, parts of Kirra Reef were uncovered, likely assisted by a series of storm events. The area of uncovered reef increased between 2009 and 2012, and while there was a clear reduction in area in 2022, it has been relatively stable since 2012. The extent of Kirra Reef is unlikely to change substantially unless there are successive major storms in the region causing substantial changes to the position of the offshore bar along the beach (noting that cyclones in 2017 and 2019 caused relatively minor changes in total area of Kirra Reef) or major changes to sand delivery through the sand bypassing system.

The areal extent of Kirra Reef in June 2022, and changes in depth (based on 2019, 2020, 2021 and 2022 hydrographic surveys) indicated the recent exhumation and increase observed in recent years did not occur in 2022. In June 2022, the reef area was smaller, and the water depth was generally shallower compared to recent years. The estimated areal extent of Kirra Reef was 3,014 m^2, which comprised 2,810 m^2 of reef in the northern section and 204 m^2 of reef in the eastern section. While the areal extent was smaller in 2022, it was not substantially different to the relatively stable reef area that has been observed consistently since 2012 (particularly considering the potential margin of error associated with calculating the area from aerial images and the extreme changes observed during the history of monitoring). This is indicative of balance in the sand transport budget as a result of past amendments to the TSB operation. The stability in the availability and extent of rock habitat has enabled the benthic community to increase in biodiversity, with an increase in the coverage of sessile invertebrates displacing foliose macroalgae and other early colonising species in some sections of the reef.

4.2 Benthic Communities

Following exhumation in 2009, the benthic faunal and floral communities on Kirra Reef have shown signs of ecological succession, starting with the recruitment of pioneer species such as foliose macroalgae and turf forming algae, and gradually becoming more similar in composition to reefs in the Gold Coast and Tweed Coast Region. However, in recent years the monitoring program has shown succession slowing with generally consistent differences in the composition of benthic communities on Kirra Reef and those at other reef locations. Benthic communities at Kirra Reef tend to be dominated foliose and / or turf forming macroalgae and ascidians, with a low coverage of soft and hard corals. In 2022, the benthic communities remained different to those on nearby reefs, although, they became more similar to nearby reefs than has been recorded in previous years (particularly in 2018 and 2019). Temporal variability in the composition of benthic assemblages among reefs has been attributed to natural variation (including physical disturbance from storm and ongoing disturbance from shifting sands and wave action) but may also be due to differences in the timing of when reef habitat became available, differences in the settlement and recruitment of benthic species and / or the survival due to differences in the assemblage of predators present at Kirra Reef relative to other reefs. Despite changes in the composition of benthic communities through time, it appears the overall coverage of sessile invertebrates on Kirra Reef has become more similar to that recorded on the other reefs over time. There continues to be a diverse benthic assemblage on Kirra Reef that is consistent (relative to the degree of natural variability) with that occurring on several of the other reefs in the area, although benthic assemblages on Kirra Reef are not yet dominated by longer-lived hard coral species that are found on the reefs around Cook Island. Many of these species require a long period of suitable conditions to establish and grow to dominate the benthic assemblages.

4.2.1 Algal Assemblages

In 2022, there was a relatively low average coverage of foliose macroalgae (6% on horizontal surfaces and 2% on vertical surfaces) at Kirra Reef compared to previous years (average coverage 16 to 39% on horizontal surfaces and 13 to 21% on vertical surfaces between 2016 and 2021). Turf algae dominated algal assemblages at Kirra Reef in 2022 and had increased (average coverage of 52% on horizontal surfaces and 46% on vertical surfaces) relative to previous surveys (average coverage 10 to 42% on horizontal surfaces and 14 to 43% on vertical surfaces between 2016 and 2021). While the coverage of macroalgae prior to 2020 was very high compared to more recent years (possibly due to spatial differences of locations through time or different sampling techniques), the average cover of macroalgae had declined and turf algae remained consistent at all Cook Island locations in 2022 compared to 2020 and 2021 surveys. Algal assemblages in 2022 may be indicative of recent physical disturbance, particularly to foliose macroalgae, from sand scour, storms and wave action as a result of frequent storm activity in the region prior to the survey and / or at Kirra Reef, the shifting offshore sandbar resulting in burial of rock.

Foliose macroalgae such as *Sargassum* can colonise bare substrata before other taxa such as sessile invertebrates, causing physical damage to sessile invertebrates that have recently settled, and preventing them from establishing on tropical coral reefs (Diaz-Pulido & McCook 2002). The high coverage of *Sargassum* on Kirra Reef in recent years is indicative of the more recent disturbance history at Kirra Reef, which may have been timed with a recruitment pulse enabling a high proportion of the area to be colonised by macroalgae (Kennelly 1987; McCook et al. 2001) or could reflect a reduced abundance of herbivorous fish and invertebrates such as sea urchins, which can be important in controlling fleshy macroalgae on reefs (McCook 1997; McCook et al. 2001). The recently exhumed eastern section of Kirra Reef is currently dominated by macroalgae including *Sargassum*. The exact mechanism for why the algal assemblages differ among the reefs has not been specifically assessed; however, it may be related to the timing of recruitment particularly given the dominance of macroalgae on sections of the recently exhumed eastern reef. Cook Island reefs and Palm Beach Reef are also likely to be more sheltered from sand burial and wave action than Kirra Reef. While horizontal and vertical surfaces differed in terms of their coverage at Kirra reef (indicative of potential impacts from smothering by sand), sedimentation impacts on algal communities such as reduced crustose coralline algae (Fabricius and De'ath 2001) or reduced density and growth of young Sargassum (Umar et al. 1998) only occurred on the landward edge of Kirra Reef associated with recent burial.

Of note, there was a moderate to dense patch of seagrass dominated by *Halophila ovalis* occurring on sand and boulder habitat adjacent to the Cook Island West location at Cook Island. Seagrass is protected under the NSW *Fisheries Management Act 1995.* Seagrass in this area has declined in coverage since the 2021 monitoring event, although a quantitative assessment of the distribution and density of seagrass habitat has not been completed.

4.2.2 Sessile Invertebrate Assemblages

Sessile invertebrate assemblages are often more diverse on vertical than horizontal surfaces due to a variety of factors such as the degree of competition or disturbance, availability of light, larval settlement preference and habitat complexity (Irving & Connell 2002; Walker & Schlacher 2014 and references cited within). Differences may also be due to variability in localised larval supply and recruitment processes among reefs. In 2022, the sessile invertebrate assemblages on Kirra Reef were more similar in diversity both in terms of the overall coverage and average number of species present between surface orientations and among reefs. While there was a lack of abundant hard coral species on Kirra Reef in 2022, and a small decline in the coverage of soft corals relative to 2020, ascidians and sponges remained the dominant sessile invertebrates on Kirra Reef. The coverage of both hard and soft corals have typically been low in previous surveys and remain low on Kirra Reef relative to other more established reefs at Cook Island and Palm Beach.

Ascidians are typically the dominant sessile invertebrate at Kirra Reef, on average covering between 7 and 18% in the last seven years (between 2016 and 2022), except for 2019 when a very high average coverage was recorded (41%). Hard and soft coral have consistently been absent or covered a small area on Kirra Reef. The average cover of hard corals was between 0 and 2% prior to TSB (in 1995 and 1996) and following the initial commencement of TSB (between 2003 and 2005); and less than 0.5% following emergence from burial (between 2010 and 2022). Average coverage of soft corals was 2 to 10% prior to TSB (in 1995 and 1996), 1 to 6% following the commencement of TSB (between 2003 and 2005), and 0 to 2% following reef emergence (between 2010 and 2022) (ESP 2021). Generally, many of sessile invertebrates growing on Kirra Reef are susceptible to impacts from smothering and sand scouring, and the occurrence of a diverse group of sessile invertebrates on Kirra Reef, in 2022 is indicative of assemblages that are recovering from past impacts.

In contrast, the reefs around Cook Island generally had a high coverage of long-lived hard corals (such as those from the genus *Paragoniastrea, Turbinaria* and encrusting *Porites*) compared with other reefs in the region. Particularly, Cook Island North and Cook Island South reef locations, which had a higher proportion of hard coral typically growing on vertical surfaces. Despite the high coverage of hard corals at these sites, there were still differences in benthic communities among reef locations separated by only a few hundred metres, indicating a diverse array of relatively unique reef communities around the island and the high degree of natural variability that exists among reefs in the region. On reefs around Cook Island, the coverage of hard coral was similar to or increased relative to previous surveys at Cook Island North and Cook Island West. In contrast, there was a decline in the average coverage of hard coral at Cook Island South between 2021 and 2022 of 8% (ESP 2021). Where present, the coverage of soft corals remained similar among surveys on reefs around Cook Island (ESP 2021).

Due to the disturbance history of natural and artificial sand movement (e.g. almost complete burial between 2007 and 2008) and unique position (e.g. shallow, close to shore and subject to shifting sands and wave action), benthic communities at Kirra Reef are likely to always differ from those on surrounding reefs. This may be due to natural spatial variation in a range of factors, including larval supply and survival, density of predators and disturbance regime. For example, Palm Beach Reef is generally deeper, further offshore and less prone to wave action and Cook Island is likely to have greater nutrient availability due to the large bird colonies in the area fertilising the water from faeces. Ideally the comparative reefs would be standardised for reef depth and also distance from the shore so that they are exposed to relatively similar physical disturbance vectors; however, there are limited reefs along the coast that are representative of the range of conditions experienced at Kirra Reef. Maximising the number of reef locations provides the greatest opportunity to assess the relative change over time given the degree of natural variability that occurs among reef communities. Assessing the relative difference in assemblages among these comparative reefs therefore provides the degree of natural variation likely to occur due to other coastal processes operating in the local area. Based on the changes in reef communities over time, there is variability in the composition of benthic communities year to year; however, the overall community at Kirra Reef is becoming more similar to reefs in the area.

4.2.3 Mobile Invertebrate Assemblages

In 2022, the mobile benthic invertebrate assemblages were similar with that observed previously in 2020 and 2021 (ESP 2020; ESP 2021), with Kirra Reef having a generally high density compared to other sites (although Cook Island North had the highest density in 2022). Also consistent with previous years, echinoderms dominated the mobile invertebrate assemblages at all reefs in 2022 (ESP 2020; ESP 2021). Assemblages were most diverse at Cook Island West.

4.3 Fish Assemblages

Collectively, across reefs, a total of 126 bony and cartilaginous fish species from 40 families were recorded in June 2022. Similar to the 2020 and 2021 surveys (ESP 2020; ESP 2021), Labridae (wrasses) and Pomacentridae (damselfishes) were the most diverse families. Fish species were generally common to the region, with most having been recorded during previous surveys; however, in the June 2022 survey, an additional 20 species were observed that had not been recorded in previous surveys.

Fish communities at Kirra Reef and Cook Island West were more diverse than all other reef locations in 2022; although, the overall composition of the community was generally similar among reefs. The exceptions were the community composition of fish assemblages at Cook Island South and Kirra Reef as well as Palm Beach Reef and Cook Island North. The main difference in fish assemblages between reefs was the absence of yellowtail scad (*Trachurus novaezelandiae*) at Cook Island South, which was abundant at Kirra Reef; and the absence of yellowtail scad and striped barracuda (*Sphyraena obtusata*) and the presence of scalyfin (*Parma unifasciata*) and mado (*Atypichthys strigatus*) at Cook Island South compared to Palm Beach Reef.

No threatened or protected fish species listed under the Queensland's *Nature Conservation Act 1992* or nationally under the Commonwealth's *Environmental Protection and Biodiversity Conservation Act 1999* were recorded in the 2021 survey. The eastern blue grouper (*Achoerodus viridis*) was recorded at all Cook Island West, Cook Island North and Palm Beach Reef, and is partly protected under the NSW Fisheries Management (General) Regulation 2019 (i.e. must not be fished by any method other than a rod and line or a handline). No invasive fish species were recorded in 2022.

The species richness was highest at Kirra Reef and Cook Island West, and lowest at Palm Beach Bait Reef (likely due to high turbidity or very poor visibility at this reef during the survey). The assemblage at Kirra Reef had the highest abundance of fish due to large schools of yellowtail scad. The trophic composition of the fish assemblage at Kirra Reef did not substantially differ compared with that surveyed at other reefs. Consistent with 2020 and 2021 (ESP 2020; ESP 2021), carnivorous species dominated the fish assemblage on all reefs, and omnivorous fish were also common. The fish assemblages were dominated by reef-associated species, which was expected given the dominance of rocky reef habitat surveyed.

4.3.1 Recommendations for Ongoing Monitoring

Sand delivery through the sand bypassing system has mimicked natural longshore movements since 2009, and in recent years (since 2016) benthic communities at Kirra Reef have been relatively stable (but subject to natural variation and ongoing disturbance from shifting sands and wave action). In recent years, results of the reef monitoring program have been relatively consistent, in that:

- The greatest temporal change at Kirra Reef has been in the area of exposed reef, which has remained relatively stable since 2012; with a large area of the northern reef exposed and small areas of the eastern section exhumed at times;
- Benthic communities at Kirra Reef have been dominated by macroalgae and ascidians, with generally low coverage of soft and hard corals relative to other reefs; however, in 2022 the coverage of foliose macroalgae had declined particularly on the shoreward end of Kirra Reef due to sand smothering from the offshore bar at Kirra Beach; and,
- Benthic communities at Kirra Reef have become more similar in composition over time to communities occurring on comparative reefs in the region, but still remain

significantly different, most likely due to differences in the disturbance history. Despite the apparent differences, the community on Kirra Reef has a diverse community of sessile invertebrates, macroalgae and fish, which is generally representative of the region.

Given the consistent results over the past few years of monitoring, it is recommended that the program shifts from an annual monitoring program to an event-based monitoring program using suitably derived environmental and operational based triggers for ecological monitoring components (i.e. monitoring of benthic communities). The proposed triggers could include operational changes in TSB and/or indicators directly related to sand deposition such as sedimentation above a threshold (as measured using hydrographic survey) or abiotic changes to the accumulation of sand including a substantial change in the accretion / erosion of sand around the reef measured through changes in reef area from aerial photos or hydrographic survey.

It is recommended that ongoing monitoring at Cook Island Aquatic Reserve following any sand disposal activities be completed at adequate spatial and temporal scales to determine any potential impacts of future TSB operations adjacent to the Reserve. An ongoing monitoring program should focus on key indicator species that are known to be impacted by changes in sedimentation such as the coverage of hard and soft corals, ascidians and seagrass. Note that seagrass has only been recorded at one area around Cook Island, therefore a direct measure of impact before, during and after sand disposal would be necessary as suitable comparative areas may be difficult to identify.

Monitoring sedimentation would also provide a leading indicator of the potential for any impact to benthic communities and may also be used to trigger additional assessment of the benthic communities, where background rates of sedimentation are exceeded.

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Appendix A Areal Extent

Table A.5.1 Approximate areal extent of Kirra Reef, Palm Beach Reef and Cook Island Reef (data not available in all years)[1]

Date	Area (m^2)					
	Kirra Reef				Palm Beach Reef	Cook Island Reef
	Northern	Inner Western	Eastern	Total		
June 2022	2,810	0	204	3,014	-	-
June 2021*	4,122	0	808	4,930	-	-
May 2020*	3,678	0	0	3,678	-	-
May-2019	3,161	0	0	3,161	-	-
May-2018	2,659	0	0	2,659	-	-
Feb-2017	3,263	0	0	3,263	-	-
May-2016	3,326	0	0	3,326	118,146	388,072
Mar-2015	2,672	0	116	2,788	-	-
Jun-2014	-	-	-	-	-	383,495
Apr-2014	2,920	0	0	2,920	117,960	-
Jun-2013	2,801	0	0	2,801	-	385,849
May-2013	3,589	0	0	3,539	-	-
Aug-2012	3,700	0	0	3,700	-	-
Nov-2011	1,044	0	0	1,044	-	-
Jul-2010	-	-	-	-	115,397	-
May-2010	965	0	0	965	-	-
Nov-2009	868	0	141	1,009	-	-
Apr-2004	1,578	0	273	1,851	-	-
Nov-2003	3,369	0	0	3,369	-	-
Aug-2002	8,442	0	73	8,515	-	-
Feb-2001	11,194	2,156	7,048	20,398	-	-
Oct-1996	3,700	3,600	9,200	16,500	-	-
Jan-1995	9,090	11,998	19,725	40,813	-	-
Nov-1989	10,200	65,400	22,500	38,100	-	-
Nov-1974	6,400	-	-	-	-	-
Feb-1972	6,800	100	17,800	24,700	-	-
1962 to 1965	4,850 to 7,800	0 to 4,900	600 to 2,150	7,000 to 13,300	-	-
Oct-1962	-	3,800	600	4,400	-	-
Nov-1935	1,800	-	1,600	3,400	-	-
Sep-1930	5,500	-	1,000	6,500	-	-

1 Data prior to 2020 sourced from Ecosure 2016 and frc environmental 2019, and references herein.
* Imagery based on 10 cm resolution imagery collected in May 2020 and June 2021 Datum: GDA2020
– Data not available
^ note that at this time there were three sections to the reef, an inner southern section, eastern section and the northern section of the reef, of which the present-day reef was part of, in deeper water. At this time the northern section of the reef was approximately 5900 m^2

Appendix B Detailed Statistical Analyses

Table B.5.2 PERMANOVA of the difference in the composition of benthic communities among reefs in 2022

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Orientation	1	8619	3.59	**0.006**
Reef	4	24554	5.36	**0.001**
Site (Reef)	10	4580	4.68	**0.001**
Orientation x Reef	4	4227	1.76	**0.036**
Orientation x Site (Reef)	10	2402	2.46	**0.001**
Error	420	978		
Pairwise Comparisons	b) Horizontal		c) Vertical	
	t Value	P (MC)	t Value	P (MC)
KR vs PBR	2.46	**0.002**	3.01	**0.001**
KR vs CIW	1.59	**0.032**	2.48	**0.001**
KR vs CIS	1.90	**0.006**	2.78	**0.001**
KR vs CIN	2.08	**0.003**	2.41	**0.002**
CIW vs CIN	1.17	0.224	1.76	**0.026**
CIW vs CIS	0.95	0.532	2.01	**0.009**
CIW vs PBR	1.59	**0.044**	1.66	**0.029**
CIN vs CIS	1.10	0.306	1.53	**0.048**
CIN vs PBR	2.64	**0.001**	2.91	**0.001**
CIS vs PBR	1.96	**0.006**	3.01	**0.001**
d) Horizontal vs Vertical	t Value	P (MC)		
KR	1.52	0.09		
PBR	0.96	0.54		
CIW	1.72	0.05		
CIN	1.64	**0.04**		
CIS	1.38	0.13		

Significant tests at $p < 0.05$ are **bold**. P(Perm) are the p-values derived using the permutational method. P(MC) are p-values derived using the Monte Carlo method, used when there are low numbers of possible permutations (i.e. <100).

Table B.5.3 SIMPER of the difference in the composition of benthic communities between horizontal and vertical surfaces on Kirra Reef

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
	Horizontal	Vertical	Average dissimilarity = 48.8		
Turf forming algae	51.9	46.0	11.3	1.4	23.2
Polycarpa procera	3.4	9.4	5.9	0.8	12.0
Sargassum	5.6	1.6	3.8	0.7	7.8
Pyura stolonifera	3.5	4.6	3.2	0.8	6.6
Herdmania momus	3.3	5.0	3.2	0.9	6.6
Cribrochalina sp. 3	4.2	4.8	2.8	1.0	5.7
Articulate Coralline Algae (ACA)	3.7	2.3	2.3	0.9	4.6
Trichomya hirsuta	2.3	3.0	2.2	0.7	4.6
Heteractis sp.	3.4	1.1	2.1	0.7	4.3
Amphibalanus sp.	0.1	3.1	1.7	0.6	3.5
Dendronephtya sp. 2	1.8	1.3	1.5	0.5	3.0
Cnemidocarpa stolonifera	1.4	1.4	1.2	0.7	2.5
Aplysilla sp. 2	0.9	1.5	1.1	0.6	2.3
Polycarpa pigmentata	0.1	1.6	0.9	0.6	1.8
Desmapsamma sp. 1	0.8	0.8	0.7	0.7	1.5
Hyattella sp. 2	0.0	1.1	0.6	0.2	1.2

Table B.5.4 PERMANOVA of the difference in the composition of algal assemblages among reefs in 2022

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Orientation	1	2105	2.18	0.148
Reef	4	6928	6.20	0.008
Site (Reef)	10	1118	3.80	0.001
Orientation x Reef	4	1567	1.63	0.204
Orientation x Site (Reef)	10	964	3.28	0.001
Error	420	294		
Pairwise Tests	b) Reefs			
	t Value	P (MC)		
KR vs PBNR	3.80	0.003		
KR vs CIW	1.17	0.286		
KR vs CIS	1.24	0.253		
KR vs CIN	1.20	0.282		
CIW vs CIN	1.65	0.134		
CIW vs CIS	1.62	0.148		
CIW vs PBNR	1.87	0.117		
CIN vs CIS	0.82	0.520		
CIN vs PBNR	8.59	0.002		
CIS vs PBNR	6.59	0.001		

Table B.5.5 PERMANOVA of the difference in the coverage of algae among reefs in 2022

Source	df	a) Macroalgae MS	Pseudo-F	P (perm)	(b) Turfing Algae MS	Pseudo-F	P (perm)	(c) Coralline Algae MS	Pseudo -F	P (perm)
Orientation	1	92.6	3.40	0.091	574	0.71	0.418	55	0.24	0.638
Reef	4	233.3	2.15	0.051	8302	9.20	0.012	2409	2.43	0.096
Site (Reef)	10	108.7	10.30	**0.001**	902	3.89	0.001	991	13.22	**0.001**
Orientation x Reef	4	58.8	2.16	0.122	1776	2.20	0.127	129	0.57	0.701
Orientation x Site (Reef)	10	27.2	2.58	0.001	808	3.48	0.002	225	3.01	**0.001**
Error	420	10.6			232			75		
Pairwise Tests					(d) Reef					
					t-value	P(MC)				
KR vs PBNR					5.44	0.004				
KR vs CIW					1.16	0.302				
KR vs CIS					1.00	0.372				
KR vs CIN					0.84	0.468				
CIW vs CIN					1.78	0.174				
CIW vs CIS					1.88	0.125				
CIW vs PBNR					2.00	0.120				
CIN vs CIS					0.14	0.876				
CIN vs PBNR					9.10	0.003				
CIS vs PBNR					11.21	0.002				

Table B.5.6 SIMPER of the differences in the average coverage of algae among pairs of reefs

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
	Kirra	Palm Beach	Average dissimilarity = 24.1		
Turf	49	68	21.1	1.3	87.6
	Kirra	Cook Is. West	Average dissimilarity = 25.4		
Turf	49	56	21.7	1.2	85.3
	Kirra	Cook Is. North	Average dissimilarity = 23.6		
Turf	49	46	20.0	1.3	84.8
	Kirra	Cook Is. South	Average dissimilarity = 26.2		
Turf	49	46	22.6	1.2	86.1
	Cook Is. West	Cook Is. North	Average dissimilarity = 22.5		
Turf	56	46	21.9	1.3	97.4
	Cook Is. West	Cook Is. South	Average dissimilarity = 25.0		
Turf	56	46	24.4	1.2	97.7
	Cook Is. North	Cook Is. South	Average dissimilarity = 21.8		
Turf	46	46	21.7	1.2	99.5
	Cook Is. West	Palm Beach	Average dissimilarity = 18.4		
Turf	56	68	17.8	1.1	97.1
	Cook Is. North	Palm Beach	Average dissimilarity = 22.8		
Turf	46	68	22.7	1.5	99.3
	Cook Is. South	Palm Beach	Average dissimilarity = 25.1		
Turf	46	68	25.0	1.3	99.4

Table B.5.7 PERMANOVA of the difference in the composition of sessile invertebrate assemblages among reefs in 2022

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Orientation	1	29720	4.55	**0.002**
Reef	4	52093	5.37	**0.001**
Site (Reef)	10	9695	3.01	**0.001**
Orientation x Reef	4	10860	1.66	**0.013**
Orientation x Site (Reef)	10	6537	2.03	**0.001**
Error	420	3224		
Pairwise Tests	b) Horizontal		c) Vertical	
	t Value	P (MC)	t Value	P (MC)
PBNR vs CIN	1.77	**0.002**	1.84	**0.001**
PBNR vs CIS	1.57	**0.006**	1.71	**0.010**
PBNR vs CIW	1.89	**0.001**	2.19	**0.001**
PBNR vs KR	2.16	**0.002**	2.59	**0.001**
CIN vs CIS	1.42	**0.020**	1.71	**0.005**
CIN vs CIW	1.57	**0.011**	1.97	**0.001**
CIN vs KR	2.02	**0.001**	2.26	**0.001**
CIS vs CIW	1.54	**0.011**	2.13	**0.001**
CIS vs KR	2.06	**0.001**	2.57	**0.001**
CIW vs KR	1.86	**0.005**	2.84	**0.001**
d) Horizontal vs Vertical	t Value	P (MC)		
KR	1.62	**0.03**		
PBNR	1.14	0.25		
CIW	1.50	**0.02**		
CIN	1.57	**0.02**		
CIS	1.52	**0.03**		

Significant tests at $p < 0.05$ are **bold**. P(Perm) are the p-values derived using the permutational method. P(MC) are p-values derived using the Monte Carlo method, used when there are low numbers of possible permutations (i.e. <100).

Table B.5.8 SIMPER of the differences in the average coverage of sessile invertebrate taxonomic groups among pairs of reefs on horizontal surfaces

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
	Kirra Reef	**Palm Beach**	**Average dissimilarity = 93.4**		
Cribrochalina sp. 3	4.2	0.0	8.62	0.83	9.23
Heteractis sp.	3.4	2.4	8.09	0.82	8.66
Trichomya hirsuta	2.3	2.7	7.47	0.82	7.99
Polycarpa procera	3.4	0.8	6.05	0.49	6.48
Pyura stolonifera	3.5	0.9	5.96	0.83	6.38
Herdmania momus	3.3	0.0	4.66	0.71	4.99
Turbinaria mesenterina	0.0	2.4	4.27	0.42	4.57
Cnemidocarpa stolonifera	1.4	0.4	3.29	0.62	3.53
Dendronephtya sp. 2	1.8	0.6	3.05	0.53	3.26
Spheciospongia confoederata	0.5	1.1	3.04	0.46	3.26
Porites sp. 1	0.0	1.4	2.58	0.28	2.77
Iotrochota sp. 1	0.0	1.1	2.38	0.6	2.55
Pseudodistoma inflatum	0.0	1.1	2.38	0.59	2.54
Amphibalanus sp.	0.1	0.9	2.2	0.38	2.36
Paragoniastrea australensis	0.0	0.8	1.87	0.3	2
	Kirra Reef	**Cook Is. West**	**Average dissimilarity = 95.1**		
Turbinaria mesenterina	0.0	8.9	12.45	0.51	13.1
Cribrochalina sp. 3	4.2	0.0	12.34	0.7	12.98
Cnemidocarpa stolonifera	1.4	2.4	9.02	0.62	9.48
Pyura stolonifera	3.5	0.3	6.29	0.71	6.62
Polycarpa procera	3.4	0.0	5.63	0.4	5.92
Herdmania momus	3.3	0.1	5.56	0.7	5.85
Heteractis sp.	3.4	0.4	5.55	0.6	5.83
Trichomya hirsuta	2.3	0.6	4.78	0.56	5.02
Cladiella sp. 1	0.0	1.0	2.54	0.32	2.67
Dendronephtya sp. 2	1.8	0.0	2.52	0.4	2.66
	Kirra Reef	**Cook Is. North**	**Average dissimilarity = 94.1**		
Herdmania momus	3.3	3.1	7.73	0.78	8.21
Cribrochalina sp. 3	4.2	0.1	7.56	0.82	8.03
Spheciospongia sp. 4	0.0	4.4	7.48	0.59	7.95
Turbinaria mesenterina	0.0	4.2	7.18	0.51	7.63
Pyura stolonifera	3.5	1.6	6.13	0.88	6.52
Polycarpa procera	3.4	0.5	5.13	0.44	5.45
Iotrochota sp. 1	0.0	2.3	4.58	0.48	4.87
Heteractis sp.	3.4	0.0	4.29	0.58	4.56
Acropora solitaryensis	0.0	1.6	3.66	0.42	3.89
Trichomya hirsuta	2.3	0.0	3.03	0.55	3.22
Dendronephtya sp. 2	1.8	0.4	2.87	0.44	3.05
Cnemidocarpa stolonifera	1.4	0.6	2.87	0.73	3.04
Entacmaea sp. 2	0.0	1.3	2.82	0.32	2.99

Spheciospongia confoederata	0.5	1.2	2.68	0.57	2.85
	Kirra Reef	**Cook Is. South**	**Average dissimilarity = 97.8**		
Cladiella sp. 2	0.0	5.9	10.11	0.46	10.33
Cribrochalina sp. 3	4.2	0.0	9.36	0.73	9.57
Cladiella sp. 1	0.0	3.2	6.42	0.37	6.56
Pyura stolonifera	3.5	0.6	5.94	0.79	6.07
Polycarpa procera	3.4	0.5	5.57	0.45	5.7
Lobophyton sp. 1	0.0	3.1	5.28	0.37	5.4
Herdmania momus	3.3	0.3	5.04	0.74	5.15
Heteractis sp.	3.4	0.2	5	0.62	5.11
Turbinaria mesenterina	0.0	1.8	4.35	0.45	4.45
Porites sp. 1	0.0	2.4	4.29	0.33	4.38
Pocillopora damicornis	0.0	1.8	3.94	0.53	4.03
Trichomya hirsuta	2.3	0.2	3.92	0.52	4
	Cook Is. North	**Cook Is. West**	**Average dissimilarity = 97.6**		
Turbinaria mesenterina	4.2	8.9	15.54	0.72	16.82
Spheciospongia sp. 4	4.4	0.8	8.36	0.64	9.05
Herdmania momus	3.1	0.1	5.89	0.57	6.37
Iotrochota sp. 1	2.3	0.4	4.99	0.52	5.4
Cnemidocarpa stolonifera	0.6	2.4	4.99	0.82	5.4
Acropora solitaryensis	1.6	0.7	4.49	0.5	4.86
Pyura stolonifera	1.6	0.3	3.4	0.6	3.68
Entacmaea sp. 2	1.3	0.3	3.25	0.36	3.52
Porites sp. 1	1.2	0.6	3.16	0.44	3.42
Cladiella sp. 1	0.4	1.0	2.52	0.46	2.73
Amphibalanus sp.	1.0	0.1	2.48	0.41	2.69
Spheciospongia confoederata	1.2	0.0	2.23	0.57	2.42
Polycarpa pigmentata	0.7	0.5	2.08	0.53	2.25
Discosoma sp. 1	0.0	1.6	2.01	0.21	2.17
	Cook Is. South	**Cook Is. West**	**Average dissimilarity = 95.6**		
Turbinaria mesenterina	1.8	8.9	14.36	0.65	15.02
Cladiella sp. 2	5.9	0.0	10.47	0.46	10.95
Cladiella sp. 1	3.2	1.0	8.16	0.46	8.53
Cnemidocarpa stolonifera	0.1	2.4	6.54	0.68	6.83
Lobophyton sp. 1	3.1	0.1	5.59	0.39	5.85
Porites sp. 1	2.4	0.6	5.29	0.39	5.54
Pocillopora damicornis	1.8	0.3	4.34	0.58	4.53
Iotrochota sp. 1	0.8	0.4	3.56	0.38	3.72
Spheciospongia sp. 4	0.9	0.8	3.36	0.36	3.51
Paragoniastrea australensis	0.6	0.2	2.25	0.24	2.36
Pyura stolonifera	0.6	0.3	2.23	0.46	2.33
Discosoma sp. 1	0.0	1.6	2.18	0.21	2.28
	Cook Is. North	**Cook Is. South**	**Average dissimilarity = 93.1**		
Cladiella sp. 2	0.0	5.9	8.33	0.47	8.95
Turbinaria mesenterina	4.2	1.8	8.25	0.67	8.86

Spheciospongia sp. 4	4.4	0.9	7.67	0.65	8.24
Cladiella sp. 1	0.4	3.2	5.62	0.43	6.03
Herdmania momus	3.1	0.3	5.21	0.59	5.59
Porites sp. 1	1.2	2.4	5.13	0.47	5.5
Lobophyton sp. 1	0.2	3.1	4.62	0.41	4.96
Iotrochota sp. 1	2.3	0.8	4.43	0.57	4.76
Acropora solitaryensis	1.6	0.3	3.44	0.48	3.7
Pocillopora damicornis	0.3	1.8	3.32	0.64	3.56
Entacmaea sp. 2	1.3	0.5	3.32	0.4	3.56
Pyura stolonifera	1.6	0.6	3.27	0.68	3.51
Spheciospongia confoederata	1.2	0.2	2.15	0.59	2.31
Paragoniastrea australensis	0.4	0.6	2.07	0.31	2.23
	Palm Beach	**Cook Is. West**	**Average dissimilarity = 94.0**		
Turbinaria mesenterina	2.4	8.9	14.22	0.65	15.13
Trichomya hirsuta	2.7	0.6	6.69	0.74	7.12
Cnemidocarpa stolonifera	0.4	2.4	5.93	0.82	6.31
Heteractis sp.	2.4	0.4	5.72	0.63	6.08
Porites sp. 1	1.4	0.6	3.58	0.36	3.81
Cladiella sp. 1	0.7	1.0	3.35	0.51	3.57
Discosoma sp. 1	0.5	1.6	3.12	0.26	3.32
Iotrochota sp. 1	1.1	0.4	3.06	0.61	3.26
Pyura stolonifera	0.9	0.3	2.49	0.51	2.65
Spheciospongia confoederata	1.1	0.0	2.48	0.41	2.64
Pseudodistoma inflatum	1.1	0.0	2.46	0.61	2.62
Amphibalanus sp.	0.9	0.1	2.34	0.39	2.49
Acropora solitaryensis	0.4	0.7	2.27	0.41	2.42
Paragoniastrea australensis	0.8	0.2	2.25	0.35	2.39
Acanthastrea bowerbanki	0.8	0.0	1.89	0.31	2.02
Polycarpa procera	0.8	0.0	1.81	0.42	1.92
Pocillopora damicornis	0.6	0.3	1.7	0.43	1.81
Spheciospongia sp. 4	0.1	0.8	1.67	0.3	1.78
	Palm Beach	**Cook Is. North**	**Average dissimilarity = 92.1**		
Turbinaria mesenterina	2.4	4.2	8.57	0.67	9.3
Spheciospongia sp. 4	0.1	4.4	6.76	0.62	7.34
Herdmania momus	0.0	3.1	4.98	0.57	5.41
Trichomya hirsuta	2.7	0.0	4.68	0.75	5.09
Iotrochota sp. 1	1.1	2.3	4.27	0.59	4.64
Heteractis sp.	2.4	0.0	4.12	0.65	4.48
Porites sp. 1	1.4	1.2	3.83	0.47	4.15
Pyura stolonifera	0.9	1.6	3.5	0.73	3.8
Acropora solitaryensis	0.4	1.6	3.49	0.52	3.79
Spheciospongia confoederata	1.1	1.2	3.2	0.7	3.48
Amphibalanus sp.	0.9	1.0	3	0.54	3.26
Acanthastrea bowerbanki	0.8	1.1	2.6	0.33	2.83
Entacmaea sp. 2	0.0	1.3	2.46	0.33	2.67

Paragoniastrea australensis	0.8	0.4	2.07	0.42	2.25
Pseudodistoma inflatum	1.1	0.1	1.93	0.67	2.1
Polycarpa procera	0.8	0.5	1.93	0.48	2.09
Cladiella sp. 1	0.7	0.4	1.75	0.52	1.9
Dendronephtya sp. 2	0.6	0.4	1.6	0.43	1.74
	Cook Is. South	**Palm Beach**	**Average dissimilarity = 93.4**		
Cladiella sp. 2	5.9	0.6	9.96	0.52	10.66
Cladiella sp. 1	3.2	0.7	6.56	0.47	7.02
Turbinaria mesenterina	1.8	2.4	6.43	0.64	6.88
Porites sp. 1	2.4	1.4	5.77	0.45	6.17
Trichomya hirsuta	0.2	2.7	5.42	0.75	5.81
Lobophyton sp. 1	3.1	0.3	5.11	0.42	5.47
Heteractis sp.	0.2	2.4	4.82	0.65	5.16
Pocillopora damicornis	1.8	0.6	3.96	0.68	4.24
Iotrochota sp. 1	0.8	1.1	3.08	0.7	3.3
Paragoniastrea australensis	0.6	0.8	2.92	0.37	3.13
Pyura stolonifera	0.6	0.9	2.68	0.6	2.87
Spheciospongia confoederata	0.2	1.1	2.32	0.44	2.48
Pseudodistoma inflatum	0.3	1.1	2.29	0.68	2.45
Polycarpa procera	0.5	0.8	2.07	0.53	2.22
Spheciospongia sp. 4	0.9	0.1	1.89	0.29	2.02
Amphibalanus sp.	0.0	0.9	1.81	0.38	1.94

Table B.5.9 SIMPER of the differences in the average coverage of taxonomic groups among pairs of reefs on vertical surfaces

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/ SD	Contrib%
	Cook Is. West	**Cook Is. North**	**Average dissimilarity = 96.1**		
Turbinaria mesenterina	0.6	5.1	8.61	0.7	9.57
Amphibalanus sp.	3.3	3.6	7.75	0.87	8.61
Spheciospongia sp. 4	1.7	4.3	7.28	0.72	8.1
Pyura stolonifera	0.3	4.2	6.27	0.91	6.97
Acanthastrea sp. 2	1.8	2.5	5.37	0.54	5.97
Porites sp. 1	1.3	2.5	4.96	0.48	5.51
Cnemidocarpa stolonifera	2.3	0.5	3.74	0.96	4.16
Spheciospongia confoederata	0.5	1.8	3.15	0.69	3.5
Herdmania momus	0.5	1.6	2.86	0.64	3.18
Oceanapia sp	1.5	0.0	2.5	0.51	2.78
Cliona sp. 2	0.5	1.2	2.28	0.47	2.54
Dysidea sp. 3	0.1	1.4	2.24	0.36	2.49
Iotrochota sp. 1	0.5	1.0	2.09	0.39	2.32
Tedania sp.	1.3	0.0	2.09	0.38	2.32
Paragoniastrea australensis	0.1	1.1	1.89	0.4	2.11
	Cook Is. West	**Cook Is. South**	**Average dissimilarity = 97.5**		
Cladiella sp. 1	1.0	11.5	14.69	0.6	15.63
Spheciospongia sp. 4	1.7	5.7	9.67	0.67	10.29
Spheciospongia confoederata	0.5	4.4	6.75	0.6	7.19
Amphibalanus sp.	3.3	0.0	4.37	0.58	4.65
Paragoniastrea australensis	0.1	3.0	3.8	0.32	4.04
Cnemidocarpa stolonifera	2.3	0.2	3.74	0.89	3.98
Tedania sp.	1.3	1.6	3.66	0.61	3.89
Pyura stolonifera	0.3	2.2	3.42	0.71	3.64
Oceanapia sp	1.5	0.8	3.14	0.59	3.34
Pocillopora damicornis	0.3	2.0	3.14	0.6	3.34
Haliclona sp. 2	0.1	2.2	2.72	0.48	2.9
Acanthastrea sp. 2	1.8	0.1	2.48	0.35	2.64
Cliona sp. 2	0.5	1.6	2.45	0.52	2.6
Didemnum sp. 1	0.5	1.3	2.15	0.57	2.28
	Cook Is. North	**Cook Is. South**	**Average dissimilarity = 90.4**		
Cladiella sp. 1	0.0	11.5	11.6	0.56	12.84
Spheciospongia sp. 4	4.3	5.7	9.18	0.8	10.15
Turbinaria mesenterina	5.1	0.2	6.26	0.69	6.92
Spheciospongia confoederata	1.8	4.4	5.79	0.70	6.4
Pyura stolonifera	4.2	2.2	4.86	1.00	5.38
Amphibalanus sp.	3.6	0.0	4.41	0.71	4.88
Paragoniastrea australensis	1.1	3.0	4.14	0.42	4.59
Porites sp. 1	2.5	0.2	2.92	0.42	3.23
Acanthastrea sp. 2	2.5	0.1	2.84	0.43	3.14

Pocillopora damicornis	0.7	2.0	2.73	0.66	3.02
Cliona sp. 2	1.2	1.6	2.69	0.65	2.97
Haliclona sp. 2	0.3	2.2	2.42	0.51	2.68
Herdmania momus	1.6	0.2	1.94	0.6	2.15
Tedania sp.	0.0	1.6	1.89	0.52	2.1
	Cook Is. West	**Kirra Reef**	**Average dissimilarity = 93.5**		
Polycarpa procera	0.5	9.4	12.23	0.77	13.08
Cribrochalina sp. 3	0.0	4.8	7.95	0.96	8.5
Amphibalanus sp.	3.3	3.1	7.44	0.77	7.95
Herdmania momus	0.5	5.0	6.75	0.81	7.22
Pyura stolonifera	0.3	4.6	6.59	0.64	7.05
Trichomya hirsuta	0.1	3.0	4.86	0.52	5.2
Cnemidocarpa stolonifera	2.3	1.4	4.38	0.95	4.69
Polycarpa pigmentata	0.4	1.6	2.75	0.59	2.94
Oceanapia sp	1.5	0.1	2.63	0.5	2.81
Speciospongia sp. 4	1.7	0.1	2.61	0.46	2.79
Acanthastrea sp. 2	1.8	0.0	2.4	0.32	2.57
Tedania sp.	1.3	0.0	2.11	0.36	2.25
Dendronephtya sp. 2	0.2	1.3	2.05	0.36	2.19
Aplysilla sp. 2	0.1	1.5	1.89	0.44	2.02
	Cook Is. North	**Kirra Reef**	**Average dissimilarity = 89.9**		
Polycarpa procera	0.4	9.4	9.92	0.75	11.03
Pyura stolonifera	4.2	4.6	6.99	0.91	7.78
Turbinaria mesenterina	5.1	0.0	6.6	0.67	7.35
Amphibalanus sp.	3.6	3.1	6.18	0.88	6.88
Cribrochalina sp. 3	0.4	4.8	5.96	1.02	6.63
Herdmania momus	1.6	5.0	5.82	0.88	6.48
Speciospongia sp. 4	4.3	0.1	4.98	0.59	5.54
Trichomya hirsuta	0.1	3.0	3.79	0.52	4.22
Porites sp. 1	2.5	0.0	2.91	0.39	3.24
Acanthastrea sp. 2	2.5	0.0	2.83	0.41	3.15
Dysidea sp. 3	1.4	0.9	2.38	0.43	2.64
Speciospongia confoederata	1.8	0.2	2.36	0.63	2.62
Polycarpa pigmentata	0.5	1.6	2.22	0.63	2.47
	Cook Is. South	**Kirra Reef**	**Average dissimilarity = 95.8**		
Cladiella sp. 1	11.5	0.0	11.48	0.55	11.99
Polycarpa procera	0.5	9.4	9.47	0.74	9.89
Speciospongia sp. 4	5.7	0.1	6.93	0.57	7.24
Pyura stolonifera	2.2	4.6	5.65	0.76	5.9
Cribrochalina sp. 3	0.3	4.8	5.6	1	5.85
Speciospongia confoederata	4.4	0.2	5.26	0.58	5.49
Herdmania momus	0.2	5.0	5.11	0.76	5.34
Trichomya hirsuta	0.2	3.0	3.63	0.53	3.79
Amphibalanus sp.	0.0	3.1	3.62	0.57	3.78
Paragoniastrea australensis	3.0	0.0	3.03	0.3	3.16

Pocillopora damicornis	2.0	0.0	2.33	0.55	2.43
Haliclona sp. 2	2.2	0.0	2.17	0.45	2.26
Polycarpa pigmentata	0.2	1.6	1.92	0.54	2.01
Tedania sp.	1.6	0.0	1.88	0.5	1.96
	Cook Is. West	**Palm Beach**	**Average dissimilarity = 94.2**		
Amphibalanus sp.	3.3	1.1	6.93	0.68	7.36
Cladiella sp. 1	1.0	2.1	5	0.62	5.31
Cnemidocarpa stolonifera	2.3	0.4	5	0.9	5.3
Trichomya hirsuta	0.1	2.3	4.41	0.53	4.68
Porites sp. 1	1.3	0.9	3.61	0.42	3.83
Pyura stolonifera	0.3	1.5	3.6	0.61	3.82
Spheciospongia sp. 4	1.7	0.3	3.56	0.51	3.78
Spheciospongia confoederata	0.5	1.4	3.29	0.63	3.49
Oceanapia sp	1.5	0.0	3.28	0.49	3.48
Acanthastrea sp. 2	1.8	0.1	3.17	0.35	3.36
Heteractis sp.	0.1	1.5	3.15	0.51	3.34
Paragoniastrea australensis	0.1	1.7	3.09	0.31	3.28
Acanthastrea bowerbanki	0.0	1.3	3.03	0.33	3.22
Tedania sp.	1.3	0.0	2.74	0.38	2.9
Didemnum sp. 1	0.5	0.9	2.33	0.47	2.48
encrusting porifera sp. 2	0.2	0.9	2.09	0.34	2.22
Pocillopora damicornis	0.3	0.8	2.08	0.36	2.21
Turbinaria mesenterina	0.6	0.6	2	0.46	2.12
Iotrochota sp. 1	0.5	0.5	1.88	0.37	1.99
Dysidea sp. 3	0.1	0.8	1.8	0.37	1.91
	Cook Is. North	**Palm Beach**	**Average dissimilarity = 91.5**		
Turbinaria mesenterina	5.1	0.6	8.25	0.71	9.02
Pyura stolonifera	4.2	1.5	6.22	1	6.8
Amphibalanus sp.	3.6	1.1	6.22	0.79	6.8
Spheciospongia sp. 4	4.3	0.3	6.13	0.63	6.7
Porites sp. 1	2.5	0.9	4.37	0.51	4.78
Paragoniastrea australensis	1.1	1.7	3.64	0.43	3.98
Spheciospongia confoederata	1.8	1.4	3.62	0.83	3.96
Acanthastrea sp. 2	2.5	0.1	3.52	0.43	3.85
Trichomya hirsuta	0.1	2.3	3.27	0.52	3.58
Dysidea sp. 3	1.4	0.8	2.97	0.47	3.25
Cladiella sp. 1	0.0	2.1	2.92	0.51	3.19
Acanthastrea bowerbanki	0.6	1.3	2.85	0.4	3.12
Herdmania momus	1.6	0.0	2.37	0.56	2.59
Heteractis sp.	0.1	1.5	2.31	0.51	2.52
Iotrochota sp. 1	1.0	0.5	2.15	0.4	2.36
Pocillopora damicornis	0.7	0.8	2.02	0.46	2.21
Cliona sp. 2	1.2	0.1	1.85	0.44	2.02
	Cook Is. South	**Palm Beach**	**Average dissimilarity = 93.3**		
Cladiella sp. 1	11.5	2.1	15	0.65	16.08

Spheciospongia sp. 4	5.7	0.3	8.55	0.6	9.16
Spheciospongia confoederata	4.4	1.4	6.79	0.67	7.28
Paragoniastrea australensis	3.0	1.7	5.36	0.41	5.74
Pyura stolonifera	2.2	1.5	4.03	0.84	4.31
Pocillopora damicornis	2.0	0.8	3.48	0.64	3.73
Trichomya hirsuta	0.2	2.3	3.15	0.53	3.38
Haliclona sp. 2	2.2	0.4	2.83	0.5	3.03
Didemnum sp. 1	1.3	0.9	2.51	0.53	2.69
Acanthastrea bowerbanki	0.4	1.3	2.31	0.36	2.47
Tedania sp.	1.6	0.0	2.27	0.51	2.44
Heteractis sp.	0.0	1.5	2.11	0.49	2.26
Cliona sp. 2	1.6	0.1	2.05	0.49	2.19
Lobophyton sp. 1	1.3	0.1	1.47	0.22	1.58
Amphibalanus sp.	0.0	1.1	1.47	0.36	1.57
Porites sp. 1	0.2	0.9	1.46	0.45	1.56
Iotrochota sp. 1	0.5	0.5	1.37	0.42	1.46
	Kirra Reef	**Palm Beach**	**Average dissimilarity = 94.2**		
Polycarpa procera	9.4	0.1	11.71	0.76	12.44
Cribrochalina sp. 3	4.8	0.0	7.6	0.98	8.07
Pyura stolonifera	4.6	1.5	6.98	0.74	7.41
Herdmania momus	5.0	0.0	6.4	0.77	6.8
Trichomya hirsuta	3.0	2.3	6.28	0.67	6.67
Amphibalanus sp.	3.1	1.1	5.49	0.65	5.83
Heteractis sp.	1.1	1.5	3.24	0.65	3.44
Cladiella sp. 1	0.0	2.1	2.92	0.49	3.1
Polycarpa pigmentata	1.6	0.2	2.45	0.54	2.6
Spheciospongia confoederata	0.2	1.4	2.27	0.56	2.41
Paragoniastrea australensis	0.0	1.7	2.23	0.28	2.37
Acanthastrea bowerbanki	0.0	1.3	2.18	0.32	2.31
Dysidea sp. 3	0.9	0.8	2.08	0.45	2.21
Cnemidocarpa stolonifera	1.4	0.4	2.08	0.6	2.21
Dendronephtya sp. 2	1.3	0.3	2.06	0.38	2.19

Table B.5.10 PERMANOVA of the difference in the taxonomic richness of sessile invertebrates among reefs in 2022

a) PERMANOVA Source		(a) Taxonomic Richness			(b) % Coverage		
	df	MS	Pseudo-F	P(perm)	MS	Pseudo-F	P(perm)
Orientation	1	110.5	7.78	**0.019**	10573	10.15	**0.009**
Reef	4	92.4	5.44	**0.016**	3545	2.40	0.110
Site (Reef)	10	17.0	3.64	**0.001**	1475	6.30	**0.001**
Orientation x Reef	4	33.4	2.35	0.120	1737	1.67	0.230
Orientation x Site (Reef)	10	14.2	3.04	**0.002**	1042	4.45	**0.001**
Error	420	4.7			234		
Pairwise Tests							
	t Value	P (MC)					
PBNR vs CIN	0.5	0.62					
PBNR vs CIS	0.6	0.58					
PBNR vs CIW	1.6	0.18					
PBNR vs KR	1.9	0.12					
CIN vs CIS	1.2	0.30					
CIN vs CIW	3.4	**0.03**					
CIN vs KR	4.0	**0.02**					
CIS vs CIW	2.4	0.06					
CIS vs KR	1.4	0.23					
CIW vs KR	1.1	0.35					

Significant tests at $p < 0.05$ are **bold**. P(Perm) are the p-values derived using the permutational method. P(MC) are p-values derived using the Monte Carlo method, used when there are low numbers of possible permutations (i.e. <100).

Table B.5.11 Comparisons of sessile assemblages on horizontal surfaces among reefs and survey periods (2016 to 2022)

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)			
Survey	6	48467	50.8	0.001			
Reef	6	120430	126.1	0.001			
Survey x Reef	20	12451	13.0	0.001			
Error	1479	955					
Pairwise Tests	b) 2016	c) 2017	d) 2018	e) 2019	f) 2020	g)2021	h)2022
	t Value	t Value	t Value	t Value	t Value	t Value	t Value
KR vs PBNR	10.74**		6.2**	4.8**	8.6**	7.1**	4.1**
KR vs PBBR					5.4**	6.5**	
KR vs CIW		5.7**	3.5**	4.6**	8.2**	7.6**	3.0**
KR vs CIS					10.5**	8.3**	4.0**
KR vs CIN	6.96**	4.6**	4.6**	4.5**	10.6**	7.6**	3.7**
CIW vs CIN		2.2**	1.7*	1.2	5.8**	6.3**	2.6**
CIW vs CIS					6.2**	7.3**	2.1**
CIW vs PBNR			3.5**	5.3**	10.6**	6.9**	2.9**
CIN vs CIS					3.2**	4.3**	3.0**
CIN vs PBNR			4.1**	5.7**	8.6**	5.1**	4.7**
CIS vs PBNR					9.2**	6.8**	4.0**
KR vs KC	5.90**			2.0*			
PBNR vs KC	6.16**			4.7**			
KC vs CIN	2.60**						
KC vs CIW				4.4**			
CIN vs PBBR					6.9**	7.3**	
PBNR vs PBBR					8.7**	3.5**	
CIW vs PBBR					6.0**	9.4**	
CIS vs PBBR					6.8**	8.4**	
h) Pairwise comparison within reefs over time	Kirra	Palm Beach	Cook Island North	Cook Island West	Cook Island South		
2016 vs 2017	4.94**		3.15**				
2017 vs 2018	3.37**		5.88**	5.41**			
2018 vs 2019	4.92**	6.51**	5.76**	4.47**			
2019 vs 2020	4.44**	14.05**	15.78**	12.29**			
2020 vs 2021	4.03**	9.34**		4.41**	1.76*		
2021 vs 2022	3.33**	3.77**	2.11**	3.59**	2.40**		

Significance level: * $p < 0.05$, ** $p < 0.01$

Table B.5.12 SIMPER differences in sessile assemblages at Kirra Reef among survey periods (2016 to 2022)

Taxonomic Group	Average Abundance		Average Dissimilarity	Dissimilarity/SD	Contribution%
	2016	2017	Average dissimilarity = 61.2		
Turf Algae	37.7	9.7	22.2	1.5	36.3
Macroalgae	29.7	22.3	15.8	1.3	25.8
Ascidians	16.4	16.6	13.6	1.1	22.2
Sponges	5.4	6.2	5.3	1.0	8.6
	2017	2018	Average dissimilarity = 67.4		
Turf Algae	9.7	28.6	19.1	1.1	28.3
Macroalgae	22.3	24.8	16.3	1.1	24.2
Ascidians	16.6	17.6	15.5	1.0	23.0
Coralline Algae	2.2	16.0	11.2	1.0	16.6
	2018	2019	Average dissimilarity = 59.5		
Ascidians	17.6	41.5	19.1	1.4	32.1
Macroalgae	24.8	35.7	14.2	1.4	24.0
Turf Algae	28.6	11.1	13.1	1.3	22.0
Coralline Algae	16.0	0.1	8.7	1.2	14.6
	2019	2020	Average dissimilarity = 53.4		
Ascidians	41.5	24.2	15.5	1.4	29.1
Macroalgae	35.7	20.5	14.9	1.5	27.96
Turf Algae	11.1	25.1	10.2	1.2	19.06
Sponges	2.8	8.6	4.2	1.0	7.91
Coralline Algae	0.1	7.6	4.0	1.1	7.47
	2020	2021	Average dissimilarity = 48.2		
Turf Algae	25.1	40.3	13.3	1.5	27.6
Macroalgae	20.5	14.9	11.2	1.1	23.2
Ascidians	24.2	19.6	10.6	1.3	21.9
Sponges	8.6	3.0	4.3	1.0	9.0
Coralline Algae	7.6	5.3	4.3	1.1	9.0
	2021	2022	Average dissimilarity = 43.6		
Turf Algae	37.1	51.9	12.87	1.30	29.5
Ascidians	16.5	12.1	9.10	1.28	20.9
Macroalgae	15.7	5.6	9.04	1.19	20.8
Coralline Algae	6.6	4.4	3.90	0.95	9.0
Sponges	2.2	6.8	3.65	0.96	8.4
Anemone	1.3	3.4	2.30	0.69	5.3

Table B.5.13 SIMPER differences in sessile assemblages at Cook Island North Reef among survey periods (2016 to 2022)

Taxonomic Group	Average Abundance		Average Dissimilarity	Dissimilarity/SD	Contribution%
	2016	2017	Average dissimilarity = 46.8		
Turf Algae	58.3	42.8	15.0	1.1	32.1
Macroalgae	14.4	17.4	10.4	1.1	22.2
Hard coral	4.0	10.9	6.7	0.7	14.4
Sponges	8.2	6.9	5.2	1.0	11.0
Coralline algae	3.7	5.7	3.9	0.7	8.3
Ascidians	6.4	1.8	3.3	0.9	7.1
	2017	2018	Average dissimilarity = 79.5		
Turf Algae	42.8	3.9	21.3	1.7	26.7

Ascidians	1.8	35.5	19.1	1.2	24.0
Macroalgae	17.4	22.1	13.6	1.0	17.1
Hard coral	10.9	20.7	11.9	1.0	15.0
Coralline algae	5.7	10.0	6.7	0.7	8.4
	2018	2019	Average dissimilarity = 67.1		
Macroalgae	22.1	59.8	22.8	1.7	34.0
Ascidians	35.5	15.2	15.8	1.3	23.6
Hard coral	20.7	1.4	10.4	1.0	15.6
Turf Algae	3.9	13.8	6.8	1.2	10.1
Coralline algae	10.0	0.0	5.1	0.6	7.6
	2019	2020	Average dissimilarity = 80.4		
Macroalgae	59.8	1.5	30.7	2.4	38.1
Turf Algae	13.8	60.8	24.8	2.9	30.8
Ascidians	15.2	2.7	7.5	0.9	9.3
Coralline algae	0.0	11.0	5.7	1.4	7.1
Hard coral	1.4	9.3	4.9	0.9	6.1
	2020	2021	Average dissimilarity = 32.6		
Turf Algae	60.8	56.0	7.8	1.3	24.1
Hard coral	9.3	12.1	6.8	1.0	20.9
Ascidians	2.7	11.1	5.2	0.9	15.9
Coralline algae	11.0	7.6	4.5	1.2	13.8
Sponges	2.9	7.2	3.8	0.8	11.6
Soft coral	2.3	1.6	1.8	0.4	5.5
	2021	2022	Average dissimilarity = 36.8		
Turf Algae	56.0	45.8	9.2	1.4	25.1
Hard coral	12.1	13.3	7.3	1.1	19.7
Coralline algae	7.6	14.6	6.0	1.1	16.4
Sponges	7.2	11.2	5.4	1.1	14.8
Ascidians	11.1	7.8	5.2	1.0	14.0

Table B.5.14 SIMPER differences in sessile assemblages at Cook Island South Reef among survey periods (2020 to 2022)

Taxonomic Group	Average Abundance		Average Dissimilarity	Dissimilarity/SD	Contribution%
	2020	2021	Average dissimilarity = 41.3		
Turf Algae	55.1	48.7	11.7	1.4	28.4
Hard coral	16.0	17.4	8.5	1.1	20.7
Soft coral	4.1	12.5	6.8	0.7	16.4
Coralline algae	8.5	4.7	4.8	0.9	11.6
Zoanthid	4.5	2.7	3.3	0.5	8.1
Sponges	2.2	4.8	2.9	0.8	7.0
	2021	2022	Average dissimilarity = 46.4		
Turf Algae	48.7	45.5	11.5	1.4	24.8
Soft coral	12.5	13.2	9.8	0.9	21.0
Hard coral	17.4	9.4	8.5	1.1	18.3
Sponges	4.8	10.4	5.9	0.8	12.8
Coralline algae	4.7	11.1	5.8	1.0	12.5
Ascidians	3.3	3.5	2.3	1.0	4.9

Table B.5.15 SIMPER differences in sessile assemblages at Cook Island West Reef among survey periods (2017 to 2022)

Taxonomic Group	Average Abundance		Average Dissimilarity	Dissimilarity/SD	Contribution%
	2017	2018	Average dissimilarity = 75.7		
Ascidians	3.4	34.7	22.0	1.1	29.1
Turf algae	40.5	16.9	20.7	1.6	27.3
Macroalgae	3.7	21.6	14.0	0.9	18.5
Hard coral	10.6	13.0	10.7	0.9	14.2
Coralline algae	3.1	3.4	3.3	0.7	4.4
	2018	2019	Average dissimilarity = 59.4		
Macroalgae	21.6	53.7	18.8	1.8	31.6
Ascidians	34.7	16.0	15.0	1.2	25.3
Turf algae	16.9	15.0	10.0	1.2	16.8
Hard coral	13.0	5.7	7.7	0.9	13.0
Soft coral	3.4	3.3	2.7	0.8	4.6
	2019	2020	Average dissimilarity = 67.3		
Macroalgae	53.7	10.9	24.8	2.4	36.8
Turf algae	15.0	49.7	20.2	2.3	30.0
Ascidians	16.0	3.3	8.4	1.0	12.4
Coralline algae	0.0	7.1	4.0	1.0	6.0
Hard coral	5.7	1.3	3.7	0.5	5.5
	2020	2021	Average dissimilarity = 31.8		
Turf algae	49.7	63.9	11.8	1.3	36.9
Macroalgae	10.9	8.7	5.8	1.2	18.1
Coralline algae	7.1	2.2	3.9	1.0	12.3
Ascidians	3.3	5.9	3.6	1.1	11.3
Seagrass	1.7	1.1	1.7	0.3	5.3
Hard coral	1.3	1.5	1.5	0.6	4.7
Sponges	1.5	1.6	1.5	0.7	4.6
	2021	2022	Average dissimilarity = 35.8		
Turf Algae	63.9	56.5	10.7	1.3	29.9
Coralline algae	2.2	9.2	5.0	0.8	14.0
Hard coral	1.5	8.5	4.9	0.6	13.6
Macroalgae	8.7	0.6	4.7	1.2	13.0
Ascidians	5.9	4.8	3.1	1.1	8.6
Sponges	1.6	5.0	2.8	0.9	7.8
Soft coral	1.7	2.0	1.6	0.7	4.6

Table B.5.16 PERMANOVA of the difference in the fish assemblages among reefs in 2022

a) PERMANOVA Source	(a) Max N			
	df	MS	Pseudo-F	P(perm)
Reef	5	4559.4	2.4579	**0.001**
Error	11	1855		
Pairwise Tests	t Value	P (MC)		
CIN, CIS	1.65	0.09		
CIN, CIW	1.10	0.33		
CIN, KR	2.53	**0.02**		
CIN, PBBR	1.58	0.12		
CIN, PBNR	1.98	**0.04**		
CIS, CIW	1.48	0.11		
CIS, KR	1.88	0.05		
CIS, PBBR	1.02	0.44		
CIS, PBNR	1.53	0.10		
CIW, KR	1.68	0.06		
CIW, PBBR	1.45	0.13		
CIW, PBNR	1.45	0.11		
KR, PBBR	1.72	0.09		
KR, PBNR	1.51	0.11		
PBBR, PBNR	1.46	0.18		

Significant tests at $p < 0.05$ are **bold**. P(Perm) are the p-values derived using the permutational method. P(MC) are p-values derived using the Monte Carlo method, used when there are low numbers of possible permutations (i.e. <100).

Table B.5.17 SIMPER of the differences in the fish assemblages

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
	Kirra Reef	Palm Beach Bait	Average dissimilarity = 71.4		
Trachurus novaezelandiae	4.91	0.84	7.1	2.8	10.0
Sphyraena obtusata	1.73	0.00	2.9	6.7	4.1
Pseudocaranx georgianus	1.64	0.00	2.9	3.4	4.0
Lutjanus fulviflamma	1.40	0.00	2.4	4.4	3.4
Stethojulis interrupta	1.33	0.00	2.3	4.7	3.2
Notolabrus gymnogenis	1.32	0.00	2.3	5.6	3.2
Parma oligolepis	1.27	0.00	2.2	6.9	3.1
Scorpis lineolata	1.60	0.50	2.0	1.4	2.8
Prionurus microlepidotus	1.13	0.00	1.9	7.6	2.7
Pomacentrus wardi	1.06	0.00	1.8	5.6	2.6
Thalassoma lunare	1.47	0.50	1.8	1.5	2.5
Morwong fuscus	1.00	0.00	1.7	5.6	2.4
Orectolobus ornatus	1.00	0.00	1.7	5.6	2.4
Acanthurus grammoptilus	1.00	0.00	1.6	1.2	2.3
Thalassoma lutescens	1.00	0.00	1.6	1.3	2.2
Siganus fuscescens	1.37	0.50	1.4	1.3	1.9
Labroides dimidiatus	1.20	0.50	1.3	1.1	1.9
Microcanthus strigatus	1.21	0.50	1.3	1.1	1.9
Thalassoma nigrofasciatum	0.79	0.00	1.3	1.3	1.8
Lutjanus russellii	0.67	0.00	1.2	1.3	1.7
Halichoeres nebulosus	0.73	0.00	1.2	1.2	1.6
Abudefduf bengalensis	0.73	0.00	1.2	1.3	1.6
Parma unifasciata	0.73	0.00	1.2	1.3	1.6
Ostorhinchus limenus	0.47	0.50	1.1	0.9	1.6
Schuettea scalaripinnis	0.71	0.00	1.1	0.6	1.5
Carangoides chrysophrys	0.67	0.00	1.1	1.3	1.5
Gerres subfasciatus	0.73	0.59	1.1	0.9	1.5
	Kirra Reef	Palm Beach	Average dissimilarity = 56.1		
Trachurus novaezelandiae	4.91	1.22	5.1	2.9	9.0
Pseudocaranx georgianus	1.64	0.00	2.3	4.1	4.1
Lutjanus fulviflamma	1.40	0.00	1.9	5.3	3.4
Schuettea scalaripinnis	0.71	1.05	1.7	0.9	3.0
*Acanthopagrus australis**	1.36	0.70	1.6	1.8	2.9
Notolabrus gymnogenis	1.32	0.33	1.4	1.8	2.5
Diagramma pictum labiosum	1.00	0.00	1.4	8.5	2.5
Morwong fuscus	1.00	0.00	1.4	8.5	2.5
Microcanthus strigatus	1.21	0.33	1.2	1.6	2.2
Prionurus microlepidotus	1.13	0.33	1.1	1.5	2.0
Acanthurus grammoptilus	1.00	0.73	1.1	1.2	1.9
Gerres subfasciatus	0.73	0.00	1.0	1.3	1.8
Thalassoma lutescens	1.00	0.80	1.0	1.1	1.8
Canthigaster bennetti	0.00	0.73	1.0	1.3	1.7
Pomacentrus wardi	1.06	0.33	1.0	1.4	1.7
Canthigaster valentini	0.00	0.73	1.0	1.3	1.7
Chaetodon flavirostris	0.67	0.00	1.0	1.3	1.7
Lutjanus russellii	0.67	0.00	1.0	1.3	1.7
Siganus fuscescens	1.37	0.79	1.0	1.0	1.7

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Halichoeres nebulosus	0.73	0.00	1.0	1.3	1.7
Parma unifasciata	0.73	0.00	0.9	1.3	1.7
Sufflamen chrysopterum	0.73	0.00	0.9	1.3	1.7
Acanthurus sp. 1	0.00	0.67	0.9	1.3	1.6
Carangoides chrysophrys	0.67	0.00	0.9	1.3	1.5
Stethojulis interrupta	1.33	0.97	0.8	1.1	1.4
Ostorhinchus limenus	0.47	0.00	0.7	0.7	1.3
Abudefduf bengalensis	0.73	0.67	0.7	1.0	1.3
Labroides dimidiatus	1.20	0.67	0.7	1.0	1.3
Plagiotremus tapeinosoma	0.40	0.33	0.7	0.9	1.2
Chaetodon vagabundus	0.00	0.44	0.7	0.7	1.2
Thalassoma nigrofasciatum	0.79	1.06	0.7	0.9	1.2
Cirrhitichthys falco	1.06	0.73	0.6	0.8	1.1
Abudefduf vaigiensis	0.33	0.33	0.6	0.8	1.1
Chaetodon kleinii	0.33	0.33	0.6	0.8	1.1
Epinephelus fasciatus	0.33	0.33	0.6	0.8	1.0
	Cook Island North	Kirra Reef	Average dissimilarity = 63.2		
Trachurus novaezelandiae	0.00	4.91	6.6	10.1	10.4
Sphyraena obtusata	0.00	1.73	2.3	8.9	3.7
Pseudocaranx georgianus	0.00	1.64	2.2	4.3	3.5
Lutjanus fulviflamma	0.00	1.40	1.9	5.7	3.0
Scorpis lineolata	0.33	1.60	1.7	1.9	2.7
Achoerodus viridis	1.13	0.00	1.5	7.6	2.4
Stegastes apicalis	1.13	0.00	1.5	9.4	2.4
Prionurus microlepidotus	0.00	1.13	1.5	24.7	2.4
Acanthurus sp. 1	1.11	0.00	1.5	6.0	2.4
Pomacentrus wardi	0.00	1.06	1.4	9.1	2.3
Cirrhitichthys falco	0.00	1.06	1.4	14.1	2.3
Siganus fuscescens	0.33	1.37	1.4	1.6	2.2
Orectolobus ornatus	0.00	1.00	1.4	10.5	2.1
Acanthurus grammoptilus	0.33	1.00	1.2	1.3	1.9
Kyphosus bigibbus	1.13	0.33	1.1	1.5	1.7
Atypichthys strigatus	1.17	0.33	1.1	1.5	1.7
Gerres subfasciatus	0.00	0.73	1.0	1.3	1.6
*Acanthopagrus australis**	0.84	1.36	1.0	1.0	1.5
Lutjanus russellii	0.00	0.67	0.9	1.3	1.5
Abudefduf bengalensis	0.00	0.73	0.9	1.3	1.5
Orectolobus maculatus	0.67	0.00	0.9	1.3	1.5
Stethojulis bandanensis	0.67	0.00	0.9	1.3	1.5
Diploprion bifasciatum	0.67	0.00	0.9	1.3	1.4
Thalassoma lunare	0.79	1.47	0.9	1.1	1.4
Halichoeres hortulanus	0.67	0.00	0.9	1.3	1.4
Parma polylepis	0.67	0.00	0.9	1.3	1.4
Schuettea scalaripinnis	0.00	0.71	0.9	0.7	1.4
Thalassoma lutescens	1.17	1.00	0.9	1.3	1.4
Plagiotremus tapeinosoma	0.67	0.40	0.8	1.2	1.3
Stethojulis interrupta	0.73	1.33	0.8	1.0	1.3
Parma unifasciata	1.26	0.73	0.8	0.9	1.2
Chaetodon flavirostris	0.33	0.67	0.8	1.0	1.2
Carangoides chrysophrys	0.33	0.67	0.7	1.1	1.2

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
	Cook Island South	Kirra Reef	Average dissimilarity = 89.6		
Trachurus novaezelandiae	0.00	4.91	9.4	8.7	10.4
Sphyraena obtusata	0.00	1.73	3.3	9.3	3.7
Pseudocaranx georgianus	0.00	1.64	3.2	3.6	3.6
Scorpis lineolata	0.00	1.60	3.0	3.8	3.4
Lutjanus fulviflamma	0.00	1.40	2.7	4.8	3.0
Siganus fuscescens	0.00	1.37	2.6	3.5	2.9
Stethojulis interrupta	0.00	1.33	2.6	5.3	2.9
Labroides dimidiatus	0.00	1.20	2.4	3.5	2.6
Microcanthus strigatus	0.00	1.21	2.4	4.4	2.6
Prionurus microlepidotus	0.00	1.13	2.2	10.4	2.4
Pomacentrus wardi	0.00	1.06	2.1	6.5	2.3
Cirrhitichthys falco	0.00	1.06	2.0	8.2	2.3
Pseudolabrus guentheri	0.33	1.35	2.0	1.9	2.2
Diagramma pictum labiosum	0.00	1.00	1.9	6.4	2.2
Morwong fuscus	0.00	1.00	1.9	6.4	2.2
Orectolobus ornatus	0.00	1.00	1.9	6.4	2.2
Notolabrus gymnogenis	0.33	1.32	1.9	1.8	2.2
Parma oligolepis	0.33	1.27	1.8	1.8	2.1
Acanthurus grammoptilus	0.00	1.00	1.8	1.2	2.0
Thalassoma lutescens	0.33	1.00	1.6	1.3	1.8
Thalassoma lunare	0.73	1.47	1.5	1.2	1.7
Gerres subfasciatus	0.00	0.73	1.5	1.2	1.6
*Acanthopagrus australis**	0.67	1.36	1.4	1.0	1.6
Thalassoma nigrofasciatum	0.00	0.79	1.4	1.3	1.6
Chaetodon flavirostris	0.00	0.67	1.4	1.3	1.5
Lutjanus russellii	0.00	0.67	1.4	1.3	1.5
Halichoeres nebulosus	0.00	0.73	1.3	1.3	1.5
Abudefduf bengalensis	0.00	0.73	1.3	1.3	1.4
	Cook Island West	Kirra Reef	Average dissimilarity = 63.8		
Trachurus novaezelandiae	0.00	4.91	5.8	9.0	9.0
Sphyraena obtusata	0.00	1.73	2.0	7.8	3.2
Pseudocaranx georgianus	0.00	1.64	2.0	4.5	3.1
Naso unicornis	1.39	0.00	1.6	4.4	2.6
Abudefduf vaigiensis	1.46	0.33	1.6	1.4	2.5
Lutjanus fulviflamma	0.82	1.40	1.5	4.6	2.4
*Acanthopagrus australis**	0.69	1.36	1.4	1.8	2.2
Prionurus microlepidotus	0.00	1.13	1.3	17.7	2.1
Kyphosus bigibbus	1.14	0.33	1.2	1.2	1.9
Notolabrus gymnogenis	0.40	1.32	1.1	1.5	1.7
Siganus fuscescens	1.18	1.37	1.0	1.5	1.6
Scorpis lineolata	1.18	1.60	1.0	1.2	1.6
Parupeneus spilurus	0.98	0.33	1.0	1.2	1.5
Stegastes apicalis	0.80	0.00	1.0	1.3	1.5
Acanthurus sp. 1	0.84	0.00	1.0	1.3	1.5
Monodactylus argenteus	0.78	0.00	1.0	0.7	1.5
Stethojulis bandanensis	0.79	0.00	0.9	1.3	1.4
Diagramma pictum labiosum	0.40	1.00	0.9	1.7	1.4
Gerres subfasciatus	0.00	0.73	0.9	1.3	1.4

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Acanthurus grammoptilus	1.26	1.00	0.9	1.3	1.4
Achoerodus viridis	0.73	0.00	0.9	1.3	1.3
Cirrhitichthys falco	0.33	1.06	0.9	1.4	1.3
Chaetodon flavirostris	0.00	0.67	0.8	1.3	1.3
Lutjanus russellii	0.00	0.67	0.8	1.3	1.3
Abudefduf bengalensis	0.00	0.73	0.8	1.3	1.3
Sufflamen chrysopterum	0.00	0.73	0.8	1.3	1.3
Halichoeres hortulanus	0.67	0.00	0.8	1.3	1.3
Thalassoma trilobatum	0.67	0.00	0.8	1.3	1.3
Thalassoma lutescens	1.06	1.00	0.8	1.7	1.2
Thalassoma nigrofasciatum	0.33	0.79	0.8	1.2	1.2
Schuettea scalaripinnis	0.00	0.71	0.8	0.7	1.2
Dascyllus reticulatus	0.67	0.00	0.8	1.3	1.2
Orectolobus ornatus	0.33	1.00	0.8	1.3	1.2
Centropyge tibicen	0.67	0.00	0.8	1.3	1.2
Orectolobus maculatus	0.67	0.00	0.8	1.3	1.2
Plagiotremus tapeinosoma	0.67	0.40	0.7	1.2	1.1
Stethojulis interrupta	0.73	1.33	0.7	1.0	1.1
Carangoides chrysophrys	0.40	0.67	0.7	1.2	1.1
Abudefduf whitleyi	0.56	0.00	0.7	0.7	1.1
Microcanthus strigatus	0.92	1.21	0.7	1.1	1.1
Parma unifasciata	0.79	0.73	0.7	1.0	1.0
	Palm Beach Bait	Palm Beach	Average dissimilarity = 77.8		
Sphyraena obtusata	0.00	1.50	4.0	2.9	5.2
Parma oligolepis	0.00	1.06	2.8	3.2	3.6
Thalassoma nigrofasciatum	0.00	1.06	2.8	3.2	3.6
Stethojulis interrupta	0.00	0.97	2.8	1.2	3.6
*Acanthopagrus australis**	1.00	0.70	2.7	4.6	3.5
Diagramma pictum labiosum	1.00	0.00	2.6	4.1	3.4
Orectolobus ornatus	0.00	1.00	2.6	4.1	3.4
Thalassoma lunare	0.50	1.39	2.6	1.2	3.4
Trachurus novaezelandiae	0.84	1.22	2.6	1.0	3.3
Schuettea scalaripinnis	0.00	1.05	2.3	0.6	3.0
Thalassoma lutescens	0.00	0.80	2.3	1.1	3.0
Scorpis lineolata	0.50	1.23	2.2	1.2	2.8
Acanthurus grammoptilus	0.00	0.73	1.8	1.2	2.3
Canthigaster bennetti	0.00	0.73	1.8	1.2	2.3
Canthigaster valentini	0.00	0.73	1.8	1.3	2.3
Abudefduf bengalensis	0.00	0.67	1.6	1.2	2.1
Acanthurus sp. 1	0.00	0.67	1.6	1.2	2.1
Siganus fuscescens	0.50	0.79	1.6	1.1	2.1
Orectolobus maculatus	0.50	0.00	1.5	0.9	2.0
Sufflamen chrysopterum	0.50	0.00	1.5	0.9	2.0
Cirrhitichthys falco	0.50	0.73	1.5	1.0	1.9
Labroides dimidiatus	0.50	0.67	1.4	0.9	1.9
Chaetodon vagabundus	0.00	0.44	1.4	0.6	1.7
Gerres subfasciatus	0.59	0.00	1.3	0.9	1.7
Diploprion bifasciatum	0.50	0.33	1.3	0.8	1.7
Gymnothorax monochrous	0.50	0.33	1.3	0.8	1.7
Microcanthus strigatus	0.50	0.33	1.2	0.9	1.6

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
	Cook Island North	Palm Beach Bait	Average dissimilarity = 91.6		
Parma unifasciata	1.26	0.00	3.2	5.3	4.5
Thalassoma lutescens	1.17	0.00	2.9	5.3	4.1
Notolabrus gymnogenis	1.13	0.00	2.9	4.4	4.0
Achoerodus viridis	1.13	0.00	2.9	4.6	4.0
Halichoeres nebulosus	1.13	0.00	2.9	4.6	4.0
Kyphosus bigibbus	1.13	0.00	2.8	5.5	4.0
Stegastes apicalis	1.13	0.00	2.8	5.5	4.0
Acanthurus sp. 1	1.11	0.00	2.8	4.3	3.9
Thalassoma nigrofasciatum	1.00	0.00	2.5	5.2	3.5
Parma oligolepis	0.77	0.00	2.0	1.2	2.7
Atypichthys strigatus	1.17	0.50	1.9	1.1	2.6
Trachurus novaezelandiae	0.00	0.84	1.8	0.9	2.5
Stethojulis interrupta	0.73	0.00	1.8	1.2	2.5
Stethojulis bandanensis	0.67	0.00	1.7	1.2	2.4
Thalassoma lunare	0.79	0.50	1.7	1.0	2.3
Halichoeres hortulanus	0.67	0.00	1.6	1.2	2.3
Morwong fuscus	0.67	0.00	1.6	1.2	2.3
Parma polylepis	0.67	0.00	1.6	1.2	2.3
Microcanthus strigatus	0.73	0.50	1.5	1.0	2.1
Diploprion bifasciatum	0.67	0.50	1.3	0.9	1.9
Labroides dimidiatus	0.67	0.50	1.3	0.9	1.9
*Acanthopagrus australis**	0.84	1.00	1.3	1.2	1.9
Plagiotremus tapeinosoma	0.67	0.50	1.3	0.9	1.8
Siganus fuscescens	0.33	0.50	1.3	0.9	1.8
Gerres subfasciatus	0.00	0.59	1.3	0.9	1.8
	Cook Island North	Palm Beach	Average dissimilarity = 69.1		
Sphyraena obtusata	0.00	1.50	2.8	4.3	4.0
Parma unifasciata	1.26	0.00	2.3	8.7	3.3
Atypichthys strigatus	1.17	0.00	2.1	4.9	3.1
Trachurus novaezelandiae	0.00	1.22	2.1	1.3	3.1
Halichoeres nebulosus	1.13	0.00	2.1	7.1	3.0
Kyphosus bigibbus	1.13	0.00	2.1	9.3	3.0
Stegastes apicalis	1.13	0.00	2.1	9.3	3.0
Orectolobus ornatus	0.00	1.00	1.8	9.4	2.7
*Acanthopagrus australis**	0.84	0.70	1.8	1.5	2.5
Schuettea scalaripinnis	0.00	1.05	1.7	0.7	2.5
Scorpis lineolata	0.33	1.23	1.7	1.7	2.4
Notolabrus gymnogenis	1.13	0.33	1.5	1.5	2.2
Achoerodus viridis	1.13	0.33	1.4	1.6	2.0
Stethojulis interrupta	0.73	0.97	1.4	1.2	2.0
Canthigaster bennetti	0.00	0.73	1.3	1.3	1.8
Cirrhitichthys falco	0.00	0.73	1.3	1.3	1.8
Canthigaster valentini	0.00	0.73	1.3	1.3	1.8
Orectolobus maculatus	0.67	0.00	1.3	1.3	1.8
Stethojulis bandanensis	0.67	0.00	1.3	1.3	1.8
Sufflamen chrysopterum	0.67	0.00	1.3	1.3	1.8
Siganus fuscescens	0.33	0.79	1.2	1.2	1.7
Diagramma pictum labiosum	0.67	0.00	1.2	1.3	1.7
Halichoeres hortulanus	0.67	0.00	1.2	1.3	1.7
Morwong fuscus	0.67	0.00	1.2	1.3	1.7
Parma polylepis	0.67	0.00	1.2	1.3	1.7

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Abudefduf bengalensis	0.00	0.67	1.2	1.3	1.7
Microcanthus strigatus	0.73	0.33	1.1	1.1	1.6
Thalassoma lunare	0.79	1.39	1.1	1.0	1.6
Acanthurus grammoptilus	0.33	0.73	1.1	1.1	1.6
Plagiotremus tapeinosoma	0.67	0.33	1.0	1.1	1.5
Diploprion bifasciatum	0.67	0.33	1.0	1.0	1.4
Thalassoma lutescens	1.17	0.80	0.9	1.1	1.3
Chaetodon vagabundus	0.00	0.44	0.9	0.7	1.3
	Cook Island South	Palm Beach Bait	Average dissimilarity = 83.2		
Diagramma pictum labiosum	0.00	1.00	6.6	1.6	7.9
Pseudolabrus guentheri	0.33	1.21	5.7	1.1	6.8
Orectolobus maculatus	0.00	0.50	4.6	0.8	5.5
Siganus fuscescens	0.00	0.50	4.6	0.8	5.5
Sufflamen chrysopterum	0.00	0.50	4.6	0.8	5.5
Rhynchobatus australiae	0.67	0.00	3.4	1.1	4.1
Thalassoma lunare	0.73	0.50	3.4	0.9	4.1
Trachurus novaezelandiae	0.00	0.84	3.4	0.9	4.0
Plagiotremus tapeinosoma	0.33	0.50	2.6	0.9	3.1
Dascyllus reticulatus	0.50	0.00	2.5	0.6	3.0
Gerres subfasciatus	0.00	0.59	2.4	0.9	2.9
Rhinoptera neglecta	0.44	0.00	2.3	0.6	2.8
Atypichthys strigatus	0.00	0.50	2.0	0.9	2.4
Chaetodon auriga	0.00	0.50	2.0	0.9	2.4
Chaetodon flavirostris	0.00	0.50	2.0	0.9	2.4
Cirrhitichthys falco	0.00	0.50	2.0	0.9	2.4
Diploprion bifasciatum	0.00	0.50	2.0	0.9	2.4
Gymnothorax monochrous	0.00	0.50	2.0	0.9	2.4
Labroides dimidiatus	0.00	0.50	2.0	0.9	2.4
	Cook Island South	Palm Beach	Average dissimilarity = 89.0		
Sphyraena obtusata	0.00	1.50	4.7	3.1	5.4
Scorpis lineolata	0.00	1.23	3.8	4.6	4.3
Trachurus novaezelandiae	0.00	1.22	3.5	1.2	3.9
Thalassoma nigrofasciatum	0.00	1.06	3.3	3.4	3.8
Stethojulis interrupta	0.00	0.97	3.3	1.3	3.7
Orectolobus ornatus	0.00	1.00	3.1	4.6	3.5
Pseudolabrus guentheri	0.33	1.23	2.8	1.6	3.2
*Acanthopagrus australis**	0.67	0.70	2.8	1.6	3.2
Schuettea scalaripinnis	0.00	1.05	2.7	0.7	3.0
Parma oligolepis	0.33	1.06	2.4	1.3	2.7
Thalassoma lutescens	0.33	0.80	2.4	1.0	2.7
Thalassoma lunare	0.73	1.39	2.3	1.0	2.6
Labroides dimidiatus	0.00	0.67	2.3	1.3	2.6
Siganus fuscescens	0.00	0.79	2.2	1.3	2.5
Acanthurus grammoptilus	0.00	0.73	2.1	1.3	2.3
Canthigaster bennetti	0.00	0.73	2.1	1.3	2.3
Cirrhitichthys falco	0.00	0.73	2.1	1.3	2.3
Canthigaster valentini	0.00	0.73	2.0	1.3	2.3
Rhynchobatus australiae	0.67	0.00	1.9	1.3	2.1
Abudefduf bengalensis	0.00	0.67	1.9	1.3	2.1

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Acanthurus sp. 1	0.00	0.67	1.9	1.3	2.1
Chaetodon vagabundus	0.00	0.44	1.6	0.7	1.9
Dascyllus reticulatus	0.50	0.00	1.4	0.7	1.6
Notolabrus gymnogenis	0.33	0.33	1.3	0.8	1.4
Plagiotremus tapeinosoma	0.33	0.33	1.3	0.8	1.4
Pomacentrus coelestis	0.33	0.33	1.3	0.8	1.4
	Cook Island North	Cook Island South	Average dissimilarity = 84.5		
Parma unifasciata	1.26	0.00	3.7	7.2	4.4
Atypichthys strigatus	1.17	0.00	3.4	4.9	4.1
Achoerodus viridis	1.13	0.00	3.3	5.6	4.0
Halichoeres nebulosus	1.13	0.00	3.3	5.6	4.0
Kyphosus bigibbus	1.13	0.00	3.3	7.6	3.9
Acanthurus sp. 1	1.11	0.00	3.3	5.2	3.9
Thalassoma nigrofasciatum	1.00	0.00	3.0	6.8	3.5
Thalassoma lutescens	1.17	0.33	2.5	1.6	3.0
Pseudolabrus guentheri	1.17	0.33	2.5	1.5	3.0
Notolabrus gymnogenis	1.13	0.33	2.4	1.5	2.9
Stegastes apicalis	1.13	0.33	2.4	1.5	2.9
Microcanthus strigatus	0.73	0.00	2.2	1.3	2.6
Stethojulis interrupta	0.73	0.00	2.1	1.3	2.4
Orectolobus maculatus	0.67	0.00	2.0	1.3	2.4
Stethojulis bandanensis	0.67	0.00	2.0	1.3	2.4
Sufflamen chrysopterum	0.67	0.00	2.0	1.3	2.4
Diploprion bifasciatum	0.67	0.00	2.0	1.3	2.4
Labroides dimidiatus	0.67	0.00	2.0	1.3	2.4
Parma oligolepis	0.77	0.33	2.0	1.1	2.3
Diagramma pictum labiosum	0.67	0.00	1.9	1.3	2.2
Halichoeres hortulanus	0.67	0.00	1.9	1.3	2.2
Morwong fuscus	0.67	0.00	1.9	1.3	2.2
	Cook Island West	Palm Beach Bait	Average dissimilarity = 81.6		
Abudefduf vaigiensis	1.46	0.00	2.8	1.2	3.5
Naso unicornis	1.39	0.00	2.8	3.7	3.4
Acanthurus grammoptilus	1.26	0.00	2.5	3.8	3.0
Halichoeres nebulosus	1.13	0.00	2.2	5.7	2.7
Kyphosus bigibbus	1.14	0.00	2.2	1.2	2.6
Thalassoma lutescens	1.06	0.00	2.1	4.8	2.6
*Acanthopagrus australis**	0.69	1.00	2.0	6.4	2.5
Scorpis lineolata	1.18	0.50	2.0	1.2	2.4
Siganus fuscescens	1.18	0.50	1.9	1.4	2.3
Parupeneus spilurus	0.98	0.00	1.8	1.2	2.3
Lutjanus fulviflamma	0.82	0.00	1.7	0.6	2.1
Stegastes apicalis	0.80	0.00	1.7	1.2	2.1
Thalassoma lunare	1.29	0.50	1.7	1.2	2.0
Monodactylus argenteus	0.78	0.00	1.7	0.6	2.0
Acanthurus sp. 1	0.84	0.00	1.6	1.3	2.0
Parma oligolepis	0.73	0.00	1.5	1.2	1.9
Pomacentrus wardi	0.73	0.00	1.5	1.2	1.9
Parma unifasciata	0.79	0.00	1.5	1.3	1.9
Stethojulis bandanensis	0.79	0.00	1.5	1.3	1.9
Diagramma pictum labiosum	0.40	1.00	1.5	1.6	1.9
Microcanthus strigatus	0.92	0.50	1.5	1.2	1.8
Trachurus novaezelandiae	0.00	0.84	1.5	0.9	1.8
Stethojulis interrupta	0.73	0.00	1.4	1.2	1.8

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Achoerodus viridis	0.73	0.00	1.4	1.3	1.7
Halichoeres hortulanus	0.67	0.00	1.4	1.3	1.7
Thalassoma trilobatum	0.67	0.00	1.4	1.3	1.7
Labroides dimidiatus	0.79	0.50	1.3	1.0	1.6
Dascyllus reticulatus	0.67	0.00	1.3	1.3	1.6
Centropyge tibicen	0.67	0.00	1.3	1.3	1.6
Morwong fuscus	0.67	0.00	1.3	1.3	1.6
Abudefduf whitleyi	0.56	0.00	1.2	0.6	1.5
Sufflamen chrysopterum	0.00	0.50	1.1	0.9	1.4
Gerres subfasciatus	0.00	0.59	1.0	0.9	1.3
Plagiotremus tapeinosoma	0.67	0.50	1.0	0.9	1.3
Atypichthys strigatus	0.33	0.50	1.0	0.9	1.2
	Cook Island West	Palm Beach	Average dissimilarity = 69.6		
Sphyraena obtusata	0.00	1.50	2.3	4.4	3.3
Naso unicornis	1.39	0.00	2.1	4.3	3.1
Abudefduf vaigiensis	1.46	0.33	2.0	1.5	2.9
Trachurus novaezelandiae	0.00	1.22	1.8	1.3	2.6
Halichoeres nebulosus	1.13	0.00	1.7	8.5	2.5
Kyphosus bigibbus	1.14	0.00	1.7	1.2	2.4
Schuettea scalaripinnis	0.00	1.05	1.5	0.7	2.1
Parupeneus spilurus	0.98	0.00	1.4	1.2	2.1
Siganus fuscescens	1.18	0.79	1.4	1.2	2.0
*Acanthopagrus australis**	0.69	0.70	1.4	0.9	1.9
Lutjanus fulviflamma	0.82	0.00	1.3	0.7	1.9
Stegastes apicalis	0.80	0.00	1.3	1.3	1.9
Monodactylus argenteus	0.78	0.00	1.3	0.7	1.8
Microcanthus strigatus	0.92	0.33	1.2	1.3	1.7
Parma unifasciata	0.79	0.00	1.2	1.3	1.7
Stethojulis bandanensis	0.79	0.00	1.2	1.3	1.7
Scorpis lineolata	1.18	1.23	1.2	1.4	1.7
Stethojulis interrupta	0.73	0.97	1.1	1.3	1.6
Thalassoma nigrofasciatum	0.33	1.06	1.1	1.4	1.6
Canthigaster bennetti	0.00	0.73	1.1	1.3	1.5
Halichoeres hortulanus	0.67	0.00	1.1	1.3	1.5
Thalassoma trilobatum	0.67	0.00	1.1	1.3	1.5
Canthigaster valentini	0.00	0.73	1.1	1.3	1.5
Dascyllus reticulatus	0.67	0.00	1.0	1.3	1.4
Orectolobus ornatus	0.33	1.00	1.0	1.3	1.4
Centropyge tibicen	0.67	0.44	1.0	1.3	1.4
Morwong fuscus	0.67	0.00	1.0	1.3	1.4
Orectolobus maculatus	0.67	0.00	1.0	1.3	1.4
Abudefduf bengalensis	0.00	0.67	1.0	1.3	1.4
Acanthurus grammoptilus	1.26	0.73	1.0	1.0	1.4
Acanthurus sp. 1	0.84	0.67	1.0	1.2	1.4
Pomacentrus wardi	0.73	0.33	0.9	1.1	1.4
Cirrhitichthys falco	0.33	0.73	0.9	1.1	1.3
Achoerodus viridis	0.73	0.33	0.9	1.1	1.3
Abudefduf whitleyi	0.56	0.00	0.9	0.7	1.3
Plagiotremus tapeinosoma	0.67	0.33	0.9	1.1	1.2
Labroides dimidiatus	0.79	0.67	0.9	1.2	1.2
Notolabrus gymnogenis	0.40	0.33	0.8	0.9	1.1
Chaetodon vagabundus	0.00	0.44	0.7	0.7	1.1
Thalassoma lutescens	1.06	0.80	0.7	1.2	1.0
Stegastes gascoynei	0.44	0.00	0.7	0.7	1.0

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Diploprion bifasciatum	0.33	0.33	0.7	0.8	1.0
	Cook Island North	Cook Island West	Average dissimilarity = 54.1		
Abudefduf vaigiensis	0.00	1.46	2.2	1.3	4.0
Naso unicornis	0.00	1.39	2.1	4.6	3.9
Scorpis lineolata	0.33	1.18	1.6	1.3	2.9
Siganus fuscescens	0.33	1.18	1.6	1.3	2.9
*Acanthopagrus australis**	0.84	0.69	1.4	1.5	2.6
Acanthurus grammoptilus	0.33	1.26	1.3	1.5	2.5
Lutjanus fulviflamma	0.00	0.82	1.3	0.7	2.4
Parupeneus spilurus	0.33	0.98	1.3	1.2	2.3
Monodactylus argenteus	0.00	0.78	1.2	0.7	2.3
Atypichthys strigatus	1.17	0.33	1.2	1.5	2.3
Pomacentrus wardi	0.00	0.73	1.1	1.3	2.1
Notolabrus gymnogenis	1.13	0.40	1.1	1.4	2.1
Kyphosus bigibbus	1.13	1.14	1.1	1.4	2.1
Thalassoma trilobatum	0.00	0.67	1.0	1.3	1.9
Sufflamen chrysopterum	0.67	0.00	1.0	1.3	1.9
Microcanthus strigatus	0.73	0.92	1.0	1.2	1.9
Dascyllus reticulatus	0.00	0.67	1.0	1.3	1.8
Thalassoma nigrofasciatum	1.00	0.33	1.0	1.3	1.8
Parma polylepis	0.67	0.00	1.0	1.3	1.8
Centropyge tibicen	0.00	0.67	1.0	1.3	1.8
Diagramma pictum labiosum	0.67	0.40	0.9	1.2	1.7
Abudefduf whitleyi	0.00	0.56	0.9	0.7	1.6
Stethojulis bandanensis	0.67	0.79	0.9	1.1	1.6
Diploprion bifasciatum	0.67	0.33	0.9	1.1	1.6
Thalassoma lunare	0.79	1.29	0.9	1.0	1.6
Labroides dimidiatus	0.67	0.79	0.9	1.1	1.6
Parma oligolepis	0.77	0.73	0.8	1.1	1.6
Stegastes gascoynei	0.33	0.44	0.8	0.9	1.6
Stethojulis interrupta	0.73	0.73	0.8	1.0	1.5
Carangoides chrysophrys	0.33	0.40	0.8	0.9	1.4
Acanthurus sp. 1	1.11	0.84	0.8	1.0	1.4
Parma unifasciata	1.26	0.79	0.7	0.8	1.4
Stegastes apicalis	1.13	0.80	0.7	1.2	1.4
Dascyllus trimaculatus	0.33	0.33	0.7	0.8	1.3
Morwong fuscus	0.67	0.67	0.7	0.8	1.3
Plagiotremus tapeinosoma	0.67	0.67	0.7	0.8	1.3
	Cook Island South	Cook Island West	Average dissimilarity = 89.0		
Abudefduf vaigiensis	0.00	1.46	3.2	1.3	3.6
Naso unicornis	0.00	1.39	3.1	4.1	3.5
Acanthurus grammoptilus	0.00	1.26	2.8	4.5	3.1
Halichoeres nebulosus	0.00	1.13	2.5	7.1	2.8
Scorpis lineolata	0.00	1.18	2.5	1.3	2.8
Siganus fuscescens	0.00	1.18	2.5	1.2	2.8
Kyphosus bigibbus	0.00	1.14	2.4	1.2	2.7
Pseudolabrus guentheri	0.33	1.31	2.3	1.7	2.5
Parupeneus spilurus	0.00	0.98	2.1	1.2	2.3
*Acanthopagrus australis**	0.67	0.69	2.0	1.6	2.3
Microcanthus strigatus	0.00	0.92	2.0	1.3	2.2
Lutjanus fulviflamma	0.00	0.82	1.9	0.7	2.2

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Labroides dimidiatus	0.00	0.79	1.9	1.3	2.1
Monodactylus argenteus	0.00	0.78	1.9	0.7	2.1
Acanthurus sp. 1	0.00	0.84	1.8	1.3	2.0
Pomacentrus wardi	0.00	0.73	1.7	1.3	2.0
Parma unifasciata	0.00	0.79	1.7	1.3	1.9
Stethojulis bandanensis	0.00	0.79	1.7	1.3	1.9
Thalassoma lutescens	0.33	1.06	1.7	1.4	1.9
Stegastes apicalis	0.33	0.80	1.6	1.1	1.8
Stethojulis interrupta	0.00	0.73	1.6	1.3	1.8
Dascyllus reticulatus	0.50	0.67	1.6	1.4	1.8
Halichoeres hortulanus	0.00	0.67	1.6	1.3	1.8
Thalassoma trilobatum	0.00	0.67	1.6	1.3	1.8
Achoerodus viridis	0.00	0.73	1.6	1.3	1.8
Parma oligolepis	0.33	0.73	1.5	1.1	1.6
Centropyge tibicen	0.00	0.67	1.5	1.3	1.6
Morwong fuscus	0.00	0.67	1.5	1.3	1.6
Orectolobus maculatus	0.00	0.67	1.5	1.3	1.6
Thalassoma lunare	0.73	1.29	1.4	1.0	1.6
Rhynchobatus australiae	0.67	0.00	1.4	1.3	1.6
Abudefduf whitleyi	0.00	0.56	1.4	0.7	1.5
Plagiotremus tapeinosoma	0.33	0.67	1.2	1.0	1.4

Appendix C Mobile Invertebrate Densities

Table C.1 Mean (± SE) density (number per photo quadrat) of mobile invertebrates among reefs (horizontal and vertical surfaces combined)

Scientific Name		KR	PBR	PBBR	CIW	CIN	CIS
Class Asteroidea (sea stars)							
Echinaster luzonicus	Mean	0.00	0.13	0.00	0.04	0.00	0.08
	S.E.	0.00	0.04	0.00	0.02	0.00	0.03
Class Crinoidea (feather stars)							
Cenolia glebosis	Mean	1.47	0.09	0.82	0.41	1.93	0.21
	S.E.	0.19	0.04	0.21	0.09	0.18	0.06
Cenolia sp.	Mean	0.54	0.00	0.33	0.32	0.28	0.02
	S.E.	0.11	0.00	0.12	0.12	0.08	0.02
Comaster nobilis	Mean	0.04	0.00	0.00	0.02	0.18	0.00
	S.E.	0.02	0.00	0.00	0.02	0.05	0.00
Oxycomanthus bennetti	Mean	0.13	0.00	0.02	0.00	0.01	0.00
	S.E.	0.05	0.00	0.02	0.00	0.01	0.00
Class Echinoidea (sea urchins)							
Diadema savignyi	Mean	0.00	0.07	0.00	0.07	0.24	0.07
	S.E.	0.00	0.03	0.00	0.03	0.06	0.03
Echinothrix calamaris	Mean	0.00	0.00	0.00	0.00	0.03	0.00
	S.E.	0.00	0.00	0.00	0.00	0.02	0.00
Heliocidaris erythrogramma	Mean	0.01	0.00	0.00	0.00	0.00	0.02
	S.E.	0.01	0.00	0.00	0.00	0.00	0.02
Phyllacanthus parvispinus	Mean	0.01	0.07	0.00	0.02	0.03	0.00
	S.E.	0.01	0.03	0.00	0.02	0.02	0.00
Tripneustes gratilla	Mean	0.00	0.00	0.00	0.03	0.04	0.00
	S.E.	0.00	0.00	0.00	0.02	0.02	0.00
Class Holothuroidea (sea cucumbers)							
Actinopyga miliaris	Mean	0.00	0.00	0.00	0.04	0.00	0.02
	S.E.	0.00	0.00	0.00	0.02	0.00	0.02
Holothuria atra	Mean	0.00	0.00	0.00	0.01	0.00	0.00
	S.E.	0.00	0.00	0.00	0.01	0.00	0.00
Class Decapoda							
Panulirus versicolor	Mean	0.00	0.00	0.00	0.00	0.00	0.01
	S.E.	0.00	0.00	0.00	0.00	0.00	0.01
Stenopus hispidus	Mean	0.00	0.00	0.00	0.01	0.00	0.00
	S.E.	0.00	0.00	0.00	0.01	0.00	0.00
Class Cephalopoda							
Octopus tetricus	Mean	0.01	0.00	0.00	0.00	0.00	0.00
	S.E.	0.01	0.00	0.00	0.00	0.00	0.00
Class Gastropoda							
Chromodoris elisabethina	Mean	0.00	0.00	0.00	0.00	0.01	0.00
	S.E.	0.00	0.00	0.00	0.00	0.01	0.00
Chromodoris kuiteri	Mean	0.00	0.00	0.00	0.00	0.07	0.00
	S.E.	0.00	0.00	0.00	0.00	0.03	0.00
Dicathais orbita	Mean	0.00	0.00	0.00	0.00	0.01	0.00
	S.E.	0.00	0.00	0.00	0.00	0.01	0.00
Lyncina vitellus	Mean	0.00	0.00	0.00	0.01	0.00	0.00
	S.E.	0.00	0.00	0.00	0.01	0.00	0.00
Ovula ovum	Mean	0.00	0.02	0.00	0.00	0.00	0.00
	S.E.	0.00	0.02	0.00	0.00	0.00	0.00

Appendix D June 2022 Fish Species List

Table D.5.18 Fish species recorded in June 2022 survey, not recorded in previous surveys

Scientific Name	Common Name	Reef Recorded at
Balistidae		
Rhinecanthus rectangulus	wedgetail triggerfish	Cook Island West
Blenniidae		
Cirripectes alboapicalis	whitedotted blenny	Cook Island West
Salarias fasciatus	banded blenny	Palm Beach Reef
Caesionidae		
Pterocaesio digramma	double-lined fusilier	Palm Beach Reef
Carangidae		
Carangoides chrysophrys	longnose trevally	Kirra Reef, Cook Island West, Cook Island South
Carangoides ferdau	blue trevally	Kirra Reef
Labridae		
Choerodon venustus	Venus tuskfish	Kirra Reef
Halichoeres marginatus	dusky wrasse	Cook Island West
Macropharyngodon choati	Choat's wrasse	Palm Beach Reef
Thalassoma trilobatum	ladder wrasse	Cook Island West
Lutjanidae		
Lutjanus argentimaculatus	mangrove jack	Palm Beach Reef
Muraenidae		
Gymnothorax monochrous	monotone moray	Palm Beach Reef, Palm Beach Bait Reef
Pomacentridae		
Amphiprion latezonatus	wideband anemonefish	Cook Island West
Pomacentrus chrysurus	whitetail damsel	Cook Island West
Pomacentrus lepidogenys	scaly damsel	Cook Island South
Stegastes fasciolatus	Pacific gregory	Kirra Reef, Cook Island North, Cook Island South
Rhinopteridae		
Rhinoptera neglecta	Australian cownose ray	Cook Island South
Serranidae		
Cephalopholis urodeta	flagtail rockcod	Palm Beach Reef
Sillaginidae		
Sillago ciliata	sand whiting	Kirra Reef
Synodontidae		
Synodus binotatus	twospot lizardfish	Cook Island North

Table D.5.19 Fish species and Max N values at Kirra Reef, Palm Beach Reef, Palm Beach Bait Reef and Cook Island Reef (West, North and South) recorded during the 2022 survey.

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Acanthuridae									
Acanthurus dussumieri	pencil surgeonfish	H	R				4		
Acanthurus grammoptilus	inshore surgeonfish	H	R	11	2		10	1	
Acanthurus sp. 1[16]	dusky or greyhead surgeonfish	H	R	*	1		3	3	
Acanthurus xanthopterus	yellowfin surgeonfish	O - HT	R	*					
Naso unicornis	bluespine unicornfish	H	R				8		
Prionurus microlepidotus	Australian sawtail	H	R	2	1				
Acanthuridae (unidentified)[17]	surgeonfish	H	R					1	1
Apogonidae									
Ostorhinchus cookii	Cook's cardinalfish	CA	R	1	1	1			
Ostorhinchus limenus	Sydney cardinalfish	CA	R	4		1	*		
Balistidae									
Rhinecanthus rectangulus	wedgetail triggerfish	O	R				1		
Sufflamen chrysopterum	eye-stripe triggerfish	CA	R	2		1		1	*
Sufflamen fraenatum	bridled triggerfish	CA	R	1					
Blenniidae									
Cirripectes alboapicalis	whitedotted blenny	H	R				1		
Exallias brevis	leopard blenny	O	R					*	
Plagiotremus tapeinosoma	piano fangblenny	CA	R	2	1	1	1	1	1
Salarias fasciatus	banded blenny	H	R		1				
Caesionidae									

[16] This species is either *Acanthurus nigrofuscus* (dusky surgeonfish) or *Acanthurus nigroris* (greyhead surgeonfish) however, these two species are indistinguishable using the UBRUVS method.
[17] These records are of fish swimming in the distance, in conditions of low visibility so identification beyond family was not possible.

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Pterocaesio digramma	double-lined fusilier	P	R		1				
Carangidae									
Carangoides chrysophrys	longnose trevally	CA	P	1			2	1	
Carangoides ferdau	blue trevally	CA	P/R	*					
Caranx melampygus	bluefin trevally	CA	P				*	1	
Pseudocaranx georgianus	silver trevally	CA	P	12					
Seriola lalandi	yellowtail kingfish	CA	P				1		
Trachurus novaezelandiae	yellowtail scad	P	P	1000	17	8			
Chaetodontidae									
Chaetodon auriga	threadfin butterflyfish	C	R			1	1	1	
Chaetodon citrinellus	citron butterflyfish	C	R		1		1	1	
Chaetodon flavirostris	dusky butterflyfish	C	R	1		1		1	
Chaetodon guentheri	Günther's butterflyfish	O	R				1		
Chaetodon kleinii	Klein's butterflyfish	O	R	1	1				
Chaetodon lunula	racoon butterflyfish	O	R				*		
Chaetodon vagabundus	vagabond butterflyfish	O	R		3				
Cirrhitidae									
Cirrhitichthys aprinus	blotched hawkfish	CA	R	*			*		
Cirrhitichthys falco	dwarf hawkfish	CA	R	2	2	1	1		
Dasyatidae									
Neotrygon kuhlii	bluespotted maskray	CA	R	*					
Diodontidae									
Dicotylichthys punctulatus	threebar porcupinefish	CA	R	1			*		
Diodon hystrix	spotted porcupinefish	CA	R	*		*	*		
Enoplosidae									
Enoplosus armatus	old wife	CA	R					*	
Gerreidae									

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Gerres subfasciatus	common silverbiddy	CA	P	2		2			
Haemulidae									
Diagramma pictum labiosum	painted sweetlips	CA	P/R	1	*	1	2	1	
Plectorhinchus flavomaculatus	goldspotted sweetlips	CA	P/R	1			*	*	*
Kyphosidae									
Kyphosus bigibbus	grey drummer	H	R	1			25	2	
Labridae									
Achoerodus viridis	eastern blue groper	CA	R		1		2	2	
Anampses caeruleopunctatus	diamond wrasse	CA	R				1		
Anampses neoguinaicus	blackback wrasse	CA	R					*	
Bodianus perditio	goldspot pigfish	CA	R	1					
Cheilio inermis	sharpnose wrasse	CA	R				1	1	
Choerodon graphicus	graphic tuskfish	CA	R				1	1	
Choerodon schoenleinii	blackspot tuskfish	CA	R	1					
Choerodon venustus	Venus tuskfish	CA	R	*					
Halichoeres hortulanus	checkerboard wrasse	O	R				1	1	
Halichoeres margaritaceus	pearly wrasse	CA	R	2			2		
Halichoeres marginatus	dusky wrasse	CA	R				1		
Halichoeres nebulosus	cloud wrasse	CA	R	2			2	2	
Labroides dimidiatus	common cleaner fish	CA	R	4	1	1	2	1	
Macropharyngodon choati	Choat's wrasse	CA	R		1				
Macropharyngodon meleagris	leopard wrasse	CA	R				1		
Notolabrus gymnogenis	crimsonband wrasse	CA	R	3	1		2	2	1
Pseudolabrus guentheri	Günther's wrasse	CA	R	4	3	4	4	3	1
Stethojulis bandanensis	redspot wrasse	CA	R	*			2	1	
Stethojulis interrupta	brokenline wrasse	O	R	7	5		2	2	
Thalassoma amblycephalum	bluntheaded wrasse	P	R		1				

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Thalassoma lunare	moon wrasse	CA	R	5	6	1	8	2	2
Thalassoma lutescens	green moon wrasse	CA	R	5	4	*	2	3	1
Thalassoma nigrofasciatum[18]	blackbarred wrasse	O	R	2	2	*	1	1	
Thalassoma trilobatum	ladder wrasse	CA	R				1		
Labridae (unidentified)[19]	wrasse		R	1	1		1	1	1
Latridae									
Goniistius vestitus	crested morwong	O	R				1		
Morwong fuscus	red morwong	O	R	1			1	1	
Lutjanidae									
Lutjanus argentimaculatus	mangrove jack	CA	R		1				
Lutjanus fulviflamma	blackspot snapper	CA	R	8		*	37		
Lutjanus russellii	Moses' snapper	CA	R	1			*	*	
Microcanthidae									
Atypichthys strigatus	mado	O	R	1	*	1	1	5	
Microcanthus strigatus	stripey	O	R	3	1	1	6	2	*
Monacanthidae									
Paraluteres prionurus	blacksaddle filefish	O	R				*		
Monodactylidae									
Monodactylus argenteus	silver moony	P	P				30	*	
Schuettea scalaripinnis	eastern pomfred	P	P	21	100		*	*	
Mullidae									
Parupeneus multifasciatus	banded goatfish	CA	R	1					
Parupeneus spilurus	blacksaddle goatfish	CA	R	1			14	1	
Muraenidae									

[18] There are few disguising features between *Thalassoma nigrofasciatum* and the closely related *Thalassoma jansenii*, however, based on the range, all were identified as *Thalassoma nigrofasciatum*.
[19] These records are of fish swimming in the distance, in conditions of low visibility so identification beyond family was not possible.

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Gymnothorax eurostus	stout moray	CA	R				*		*
Gymnothorax favagineus	honeycomb moray	CA	R		1				
Gymnothorax monochrous	monotone moray	CA	R		1	1			
Gymnothorax thyrsoideus	greyface moray	CA	R	1					
Gymnothorax undulatus	undulate moray	CA	R	*					
Orectolobidae									
Orectolobus maculatus	spotted wobbegong	CA	R	*		1	1	1	
Orectolobus ornatus	banded wobbegong	CA	R	1	1	*	1	*	
Ostraciidae									
Ostracion cubicum	yellow boxfish	O - HT	R				*		
Pempheridae									
Pempheris affinis	blacktip bullseye	P	R				*	*	1
Pinguipedidae									
Parapercis stricticeps	whitestreak grubfish	O	R				*		
Platycephalidae									
Platycephalus fuscus	dusky flathead	CA	R				*		
Pomacanthidae									
Centropyge tibicen	keyhole angelfish	O - HT	R		3		1		
Centropyge vrolikii	pearlscale angelfish	O - HT	R	1					
Pomacentridae									
Abudefduf bengalensis	Bengal sergeant	O	R	2	1				
Abudefduf vaigiensis	Indo-Pacific sergeant	O	R	1	1		25		
Abudefduf whitleyi	Whitley's sergeant	O	R				8		
Amphiprion akindynos	Barrier Reef anemonefish	O	R	*			*	*	*
Amphiprion latezonatus	wideband anemonefish	O	R				*		
Chromis margaritifer	whitetail puller	O	R				2	*	
Dascyllus aruanus	banded humbug	O	R				*		

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Dascyllus reticulatus	headband humbug	O	R				1	*	5
Dascyllus trimaculatus	threespot humbug	O	R	1			1	1	*
Parma oligolepis	bigscale scalyfin	O - HT	R	3	2		2	3	1
Parma polylepis	banded scalyfin	O - HT	R	*				1	
Parma unifasciata	girdled scalyfin	O - HT	R	2		*	2	4	
Pomacentrus chrysurus	whitetail damsel	O - HT	R				2		
Pomacentrus coelestis	neon damsel	O - HT	R	1	1				1
Pomacentrus lepidogenys	scaly damsel	P	R						1
Pomacentrus wardi	Ward's damsel	H	R	2	1		2		
Stegastes apicalis	yellowtip gregory	O - HT	R	*			4	2	1
Stegastes fasciolatus	Pacific gregory	O - HT	R	*				1	1
Stegastes gascoynei	Coral Sea damsel	O - HT	R	*			3	1	
Rhinidae									
Rhynchobatus australiae	whitespotted guitarfish	CA	R				*		1
Rhinopteridae									
Rhinoptera neglecta	Australian cownose ray	CA	P/R						3
Scorpaenidae									
Pterois volitans	common lionfish	CA	R					1	
Scorpaena jacksoniensis	eastern red scorpionfish	CA	R	*	1		*		*
Scorpididae									
Scorpis lineolata	silver sweep	P	R	23	3	1	24	1	
Serranidae									
Cephalopholis urodeta	flagtail rockcod	CA	R		1				
Diploprion bifasciatum	barred soapfish	CA	R		1	1	1	1	*
Epinephelus fasciatus	blacktip grouper	CA	R	1	1				
Epinephelus quoyanus	longfin grouper	CA	R				*		
Siganidae									

Scientific Name	Common Name	Functional Group	Habitat	Kirra Reef	Palm Beach Reef	Palm Beach Bait Reef	Cook Island West	Cook Island North	Cook Island South
Siganus fuscescens	black rabbitfish	H	R	14	2	1	31	1	
Siganus spinus	scribbled rabbitfish	H	R	1			3		
Sillaginidae									
Sillago ciliata	sand whiting	CA	P	*					
Sparidae									
Acanthopagrus australis[20]	yellowfin bream	CA	P/R	13	20	1	18	3	1
Sphyraenidae									
Sphyraena obtusata	striped barracuda	CA	P/R	18	8				
Synodontidae									
Synodus binotatus	twospot lizardfish	CA	R					*	
Tetraodontidae									
Arothron hispidus	stars-and-stripes puffer	O	R	1		*		*	
Arothron stellatus	starry puffer	O	R	1			1		
Arothron spp. (unidentified)	puffer	O	R					1	
Canthigaster bennetti	blackspot toby	O - HT	R		2				
Canthigaster valentini	blacksaddle toby	O - HT	R		2			*	*
Unidentified species[21]					2	5	1		4

Key to Functional group abbreviations: Functional Group: H = herbivore, P = planktivore, CA = carnivore, C = corallivore, O = omnivore, O - HT = omnivore with herbivorous tendencies, D = Detritivore.

Key to Habitat abbreviations: P = Pelagic, R = Reef, P/R = Pelagic and Reef

* Species only observed on ROV or diver footage, not recorded on UBRUVS footage and, therefore, no comparable Max N value derived

[20] This species is either *Acanthopagrus australis* (yellowfin bream) or *Rhabdosargus sarba* (tarwhine). Using the UBRUVS method, confidently distinguishing between these two species is not possible.

[21] Individuals swimming in the distance, in conditions of low visibility or with only part of their body visible on camera so identification was not possible.