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Reef Biota Monitoring 2023
Final Report

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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.

Table of Contents

EXECUTIVE SUMMARY **I**

1 INTRODUCTION **1**

1.1 Background **1**

1.2 Scope of Works **4**

2 METHODS **5**

2.1 Reef Extent **5**

2.1.1 Aerial Imagery 5

2.1.2 Bathymetric Surveys 5

2.2 Field Survey **5**

2.2.1 Reef Locations 5

2.2.2 Timing 5

2.2.3 Benthic Communities 8

2.2.4 Fish Communities 13

2.2.5 Quality Assurance and Control 14

2.3 Threatened and Invasive Species **15**

2.4 Abiotic Conditions **15**

2.4.1 Water Quality 15

2.4.2 Wave Conditions 15

3 RESULTS **16**

3.1 Kirra Reef Extent **16**

3.1.1 Aerial Imagery 16

3.1.2 Bathymetric Surveys 19

3.2 Benthic Communities **21**

3.2.1 Composition of Benthic Communities 21

3.2.2 Algal Assemblages 26

3.2.3 Sessile Invertebrate Assemblages 29

3.2.4 Historic Comparison of Benthic Communities 31

3.2.5 Mobile Invertebrate Assemblages 34

3.3 Fish Assemblages **37**

3.3.1 Species Richness of Fish Assemblages 40

3.3.2 Relative Abundance of Fish Assemblages 41

3.3.3 Trophic Composition and Habitat Preference 43

3.4 Threatened and Invasive Species **45**

3.4.1 Species of Conservation Significance 45

3.4.2 Introduced Species 46

3.5 Abiotic Conditions **47**

3.5.1 Water Quality 47

3.5.2 Wave Conditions 48

4 DISCUSSION AND CONCLUSIONS 1

4.1 Changes in Reef Area at Kirra Reef 1

4.2 Benthic Communities 2

4.2.1 Algal Assemblages 2

4.2.2 Sessile Invertebrate Assemblages 3

4.2.3 Mobile Invertebrate Assemblages 4

4.3 Fish Assemblages 4

4.3.1 Recommendations for Ongoing Monitoring 5

5 REFERENCES 7

APPENDIX A AREAL EXTENT A-1

APPENDIX B DETAILED STATISTICAL ANALYSES B-1

APPENDIX C MOBILE INVERTEBRATE DENSITIES C-1

APPENDIX D MAY 2023 FISH SPECIES LIST D-1

List of Figures

Figure 1.1 Fixed sand bypassing system (TSB, 2023) 1

Figure 1.2 Current approved placement areas for disposing dredged sand (top) and nominated placement areas for the 2023 dredging campaign (bottom) (TSB 2023) 3

Figure 2.1 Reef locations for Biota Monitoring in 2023 7

Figure 2.2 Location of transects surveyed in 2023 at Kirra Reef 9

Figure 2.3 Location of transects surveyed in 2023 at the three reef locations around Cook Island 10

Figure 2.4 Location of transects surveyed in 2023 at Palm Beach Reef and Palm Beach Bait Reef 11

Figure 2.5 Survey methods used included b) UBRUVS; and a) ROV deployed at each reef location 14

Figure 3.1 Estimated surface area (m^2) at Kirra Reef and total annual and dredging and pumping volumes (m^3) between 2000 and 2023 (data for 2023 includes sand volumes up to end of May) (pumping and dredging volumes sourced from TSB 2023) 17

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) 2022; and, (f) 2023 with sand delivery of the TSB now matching natural longshore drift of sand 18

Figure 3.3 Areal extent (left) and changes in depth (light green indicating shallower and blue indicating deeper water) from May 2021 to June 2022 (top right); and June 2022 to April 2023 (bottom right) 19

Figure 3.4	Oblique aerial photographs of Kirra Reef taken in 2023 (images provided by TSB)	20
Figure 3.5	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	22
Figure 3.6	Example benthic assemblages at a) Kirra Reef and b) Palm Beach Reef	23
Figure 3.7	Example benthic assemblages at a) Cook Island North and b) Cook Island West	24
Figure 3.8	Seagrass *Halophila ovalis* at Cook Island West in a) 2021 b) 2022 and c) 2023	25
Figure 3.9	Average coverage (% ± S.E.) of bare (sand & rubble) habitat between surface orientations, among reefs in (a) 2022 and (b) 2023	26
Figure 3.10	Average coverage (% ± SE) of foliose macroalgae, turf algae and coralline algae on vertical and horizontal surfaces, among reefs in 2023	27
Figure 3.11	Algal communities at a) Kirra Reef northern section and b) a band of recently exhumed reef section rapidly colonised by foliose macroalgae	28
Figure 3.12	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 2023 (Blue – Horizontal; Green – Vertical)	30
Figure 3.13	Hard and soft coral at a) Cook Island South and b) Cook Island North	31
Figure 3.14	nMDS ordination of the difference in the composition of benthic assemblages on horizontal surfaces between Kirra and Palm Beach Reefs between 2016 and 2023 (KC = Kingscliff Reef – only surveyed in 2016 & 2019)	33
Figure 3.15	Density (number of individuals per photo quadrat; mean ± SE) of a) feather stars, b) sea stars c) sea urchins and d) sea cucumber at each reef in 2023	35
Figure 3.16	Mobile invertebrates recorded on reefs in 2023 including a) vermillion sea stars, b) blue sea star c) long-spined sea urchin d) slate pencil urchin e) spotted egg cowrie and f) chromodorid nudibranch	36
Figure 3.17	nMDS ordination of the differences in the composition of fish assemblage among reefs in May 2023	38
Figure 3.18	a) whitespotted guitarfish in May 2023 b) Eastern blue grouper recorded in 2022	39
Figure 3.19	Average species richness (± SE) of fish assemblages among reefs	41
Figure 3.20	Schools of a) yellowtail scad at Kirra Reef in June 2023 and b) silver sweep at Cook Island North Reef	42
Figure 3.21	Fish species commonly seen at most reefs in 2022 including a) Günther’s wrasse, b) green moon wrasse, and c) crimsonband wrasse and common cleaner fish.	43
Figure 3.22	Trophic level composition of fish communities (% of species) recorded at each reef (based on UBRUVS, ROV and diver recordings)	44
Figure 3.23	Green turtle (*Chelonia mydas*) at Cook Island West in 2023	46
Figure 3.24	Vertical profiles of physicochemical water quality parameters among sites	47
Figure 3.25	Wave data collected at Tweed Heads, Bilinga and Palm Beach wave rider buoys between 2 May 2022 and 1 May 2023, showing a) relative percent frequency of wave direction and; b) relative precent frequency of wave height	48
Figure 3.26	Wave height and direction between 2 May 2022 and 1 May 2023 at a) Tweed Heads wave rider buoy; b) Bilinga wave rider buoy and; c) Palm Beach wave rider buoy	1

List of Tables

Table 2.1 Location of transects (sites) at each reef location (Datum: GDA2020 UTM Zone 56J) 8
Table 2.2 Wave ruder buoys water depth (m) and location (Datum: GDA2020 UTM Zone 56J) (Queensland Government 2023) 15
Table 3.1 Total species richness and abundance among the reefs in 2022 40
Table A.5.1 Approximate areal extent of Kirra Reef, Palm Beach Reef and Cook Island Reef (data not available in all years)[1] A-1
Table B.5.2 PERMANOVA of the difference in the composition of benthic communities among reefs in 2023 B-1
Table B.5.3 SIMPER of the difference in the composition of benthic communities between horizontal and vertical surfaces on Kirra Reef in 2023 B-2
Table B.5.4 PERMANOVA of the difference in the composition of algal assemblages among reefs in 2023 B-3
Table B.5.5 PERMANOVA of the difference in the coverage of algae among reefs in 2023 B-4
Table B.5.6 SIMPER of the differences in the average coverage of algae among pairs of reefs B-5
Table B.5.7 PERMANOVA of the difference in the composition of sessile invertebrate assemblages among reefs in 2023 B-6
Table B.5.8 SIMPER of the differences in the average coverage of sessile invertebrate taxonomic groups among pairs of reefs on horizontal surfaces B-7
Table B.5.9 SIMPER of the differences in the average coverage of taxonomic groups among pairs of reefs on vertical surfaces B-9
Table B.5.10 PERMANOVA of the difference in the taxonomic richness of sessile invertebrates among reefs in 2023 B-12
Table B.5.11 Comparisons of sessile assemblages on **Horizontal** surfaces among reefs and survey periods (2016 to 2023) B-13
Table B.5.12 Comparisons of sessile assemblages on **Vertical** surfaces among reefs and survey periods (2016 to 2023) B-14
Table B.5.13 SIMPER differences in sessile assemblages at Kirra Reef among survey periods (2016 to 2023) B-15
Table B.5.14 SIMPER differences in sessile assemblages at Cook Island North Reef among survey periods (2016 to 2023) B-16
Table B.5.15 SIMPER differences in sessile assemblages at Cook Island South Reef among survey periods (2020 to 2023) B-17
Table B.5.16 SIMPER differences in sessile assemblages at Cook Island West Reef among survey periods (2017 to 2023) B-18
Table B.5.17 SIMPER differences in sessile assemblages at Palm Beach Reef among survey periods (2016 to 2023) B-19
Table B.5.18 PERMANOVA of the difference in the fish assemblages among reefs in 2023 B-20
Table B.5.19 SIMPER of the differences in the fish assemblages B-21
Table B.5.20 PERMANOVA of the difference in the fish species richness among reefs in 2023 B-23
Table D.5.21 Fish species recorded in May 2023 survey, not recorded in previous surveys D-1
Table D.5.22 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 2023 survey. D-1

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 TSB operations.

Changes in the extent of Kirra Reef were assessed using bathymetric survey data as well as aerial and satellite imagery, and compared with historical changes in the areal extent. Field surveys were completed to assess changes in the composition of benthic communities (algae, sessile invertebrates and mobile invertebrates) and fish assemblages among reefs. Six reef locations were surveyed in April and June 2023: Kirra Reef (previously impacted reef); Cook Island West and South reefs (potentially impacted reefs); 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 eight years since 2016.

There have been substantial changes in the areal extent of Kirra Reef 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). The reef was completely buried in 2007 and 2008, then uncovered and has been increasing in extent since 2009 from 1,009 m^2 to the current extent. Historically there have been 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 periodically uncovered. The areal extent of Kirra Reef increased over the past year from 3,014 m^2 in May 2022 to 3,492 m^2 in April 2023. The change in reef area is not substantially different to the relatively stable reef extent that has been observed consistently since 2012. The inner western and eastern sections of Kirra Reef were not uncovered in 2023. These inner reef sections have a low profile (or relief) and are normally subject to increased frequency of physical 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 diverse community of reef dwelling organisms on these inner reef sections.

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 other reef communities in the Gold Coast and Tweed Coast Region. In the past eight years (since 2016), the composition of benthic communities on all reefs assessed has differed. However, in recent years the monitoring program has shown succession slowing, generally demonstrating consistent differences in the composition of benthic assemblages on Kirra Reef relative to those at other reef locations. In 2023, the biodiversity of benthic assemblage living on Kirra Reef was consistent with that occurring on several of the other reefs in the area, although the 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 stable physical conditions to establish and grow to a point where they dominate the benthic assemblages. It is not uncommon for benthic communities to differ on a range of spatial scales with the communities around Cook Island differing in composition despite their close proximity (i.e. hundreds of metres). This small-scale spatial variation among reef locations may be related to different physical conditions (e.g. nutrient availability and wave energy), disturbance regimes and other ecological interactions occurring around the island. This degree of variability highlights the importance of sampling numerous comparative locations to build a comprehensive and representative understanding of the variety of reef habitats and variation in benthic assemblages in the local region, which provides confidence in attributing any changes detected to TSB operations.

In 2023, the average cover of foliose macroalgae (predominantly *Sargassum* spp.) had increased considerably at Kirra Reef compared with the previous two years, which correlates with the availability of bare rock habitat recently exhumed and improvement in water clarity following floods in 2022. In particular, kelp (*Ecklonia radiata*) was recorded at Kirra Reef in 2023, which has not been present for many years. Turf forming algae continues to dominate the benthic assemblages at Kirra Reef and elsewhere, accounting for 18% to 58% of the total coverage of the benthic assemblage on the reefs. Other groups, such as foliose macroalgae (e.g. *Dictyota* sp. and *Padina* sp.), crustose coralline algae and articulate coralline algae (e.g. *Jania* sp.) were also present at the reefs.

In 2023, the sessile invertebrate assemblages on Kirra Reef were more similar to surrounding reefs both in terms of the overall coverage and average number of species. In 2023, ascidians and sponges remain the dominant sessile invertebrates on Kirra Reef. There continues to be a lack of abundant hard coral species on Kirra Reef, although the coverage of soft corals has remained relatively stable since 2020. 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. In contrast, the reefs around Cook Island generally had a good coverage of long-lived hard corals (such as those from the genus *Paragoniastrea, Turbinaria* and encrusting *Porites*), particularly at Cook Island North and Cook Island South reefs.

A variety of feather stars and sea stars dominated the mobile invertebrates observed on the reefs in 2023, with Cook Island North and Kirra Reef having the highest density and all Cook Island reefs and Palm Beach Reef having the highest diversity. Several sea urchin, sea cucumber, cowrie, nudibranch, squid and crayfish species were also observed at the reefs.

A total of 91 bony and cartilaginous fish species from 38 families were recorded across all reefs in 2023. Most fish species recorded were common to the region; however, six species were observed among the reefs that had not been recorded in previous surveys. Fish communities at Cook Island North were more diverse and abundant than all other reef locations in 2023; although, the overall composition of the community was generally similar among reefs. The trophic composition of fish communities did not differ substantially among most reefs, with carnivorous and omnivores groups dominating the assemblages.

Despite differences in the composition, the benthic community at Kirra Reef is considered to be representative of a mature assemblage of both algae and sessile invertebrates as well as mobile invertebrates and fish, reflective of the ecology of the reef community, and comparable in diversity to that found on other reefs with similar exposure and depth characteristics. Understanding the natural variability among reefs not exposed to disturbance from TSB is essential when assessing the impact and attributing 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 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 among reefs (e.g. recreational fishing through the conservation reserve around Cook Island).

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 continue but that it is timed to be 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 2023), 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, 2023)

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 2022). 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 TSB operations. Sand was placed at Fingal in 2019, 2020 and 2021, and sand was placed at Dreamtime in 2022. 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).

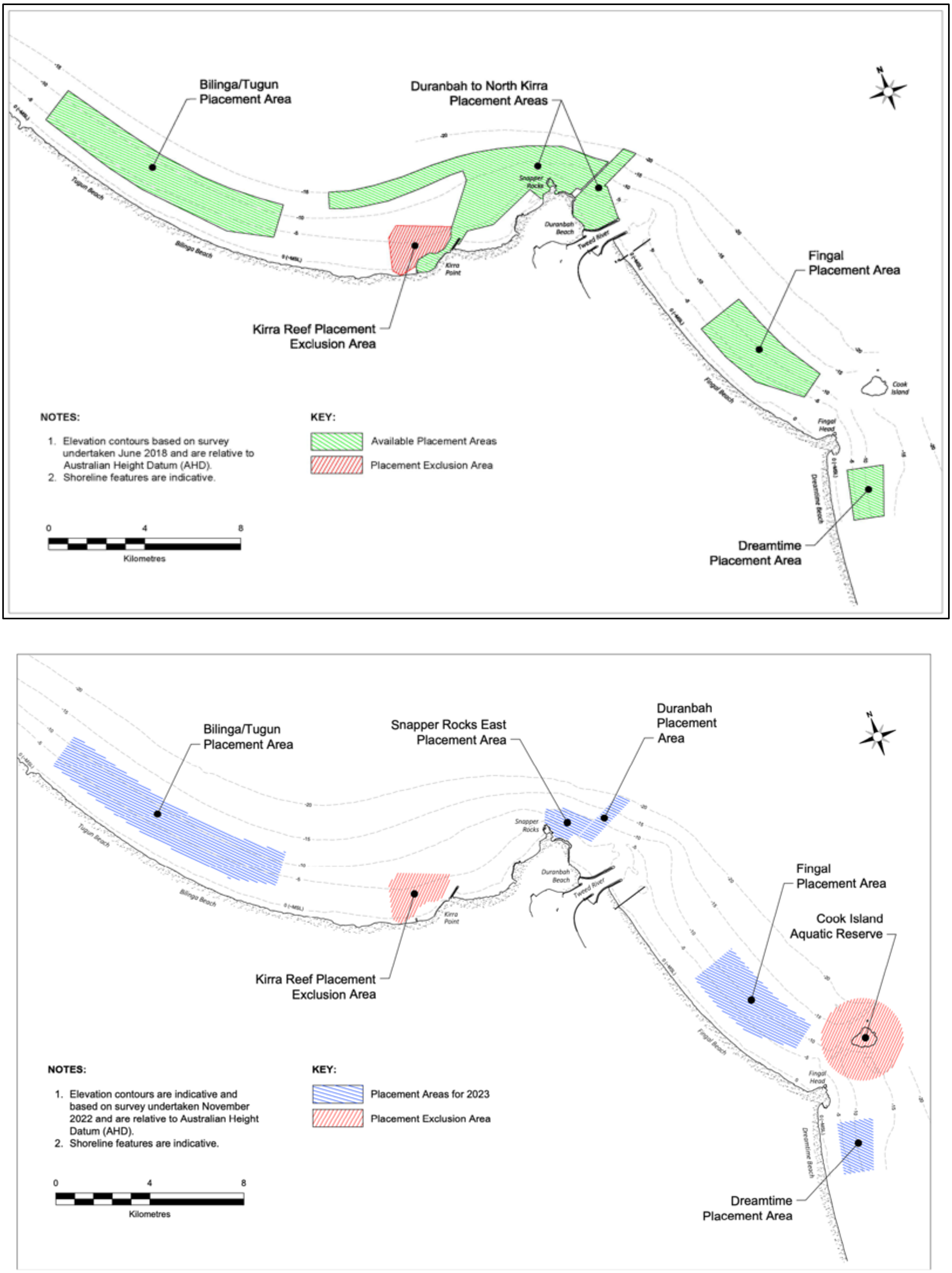

Figure 1.2 Current approved placement areas for disposing dredged sand (top) and nominated placement areas for the 2023 dredging campaign (bottom) (TSB 2023)

1.2 Scope of Works

The overall objective of the reef biota monitoring program in 2023 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 NearMap for April 2023 (NearMap 2023) and aerial mosaic for June 2023 (as provided by TSB), 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, 2022 and 2023. 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 2023 and change in depth were then mapped between 2021 and 2022, and 2022 and 2023.

2.2 Field Survey

2.2.1 Reef Locations

Six reef locations were surveyed in 2023 (Figure 2.1) based on a review of reefs previously surveyed (ESP 2023), 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 the previously and potentially impacted reefs. 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 on 2 and 3 May 2023. However, there was very poor visibility during this survey at some sites (particularly Palm Beach Bait Reef) and some images collected were of poor quality, which limited the ability to detect flora and fauna and increased the chance of type I error (i.e. false positive, detecting an impact from TSB when no impact occurred) and Type II error (i.e. false negative, detecting no impact from TSB when an impact occurred). As such, reefs were surveyed again on 8 June 2023 to supplement the benthic image data collected. Both surveys aligned with previous surveys, which have historically occurred between April and July.

During the May 2023 survey, sea conditions were moderate, with north-north-easterly swell, and significant wave heights in sets at times. Winds were east to north-easterly (approximately 5 knots) and water clarity was poor (approximately 3 to 5 m). There were significant swells (approximately 3 to 4 m) in the few weeks leading up to the survey. Rainfall leading up to the survey was lower than the average, with 84.4 mm recorded in March 2023 (monthly average for March is 199.7 mm) and 51.6 mm recorded in April 2023 (monthly average for April is 155.1 mm) (Coolangatta station 40717; BOM 2023).

Maximum wave heights were 1.8 m at Tweed Heads, 1.4 m at Bilinga and 2.5 m at Palm Beach wave rider buoys, and maximum significant wave heights were 3.1 m at Tweed Heads, 2.7 m at Bilinga and 1.5 m at Palm Beach wave rider buoys between 2 and 3 May 2023. In the two weeks prior to this, maximum wave heights were 2.9 m at Tweed Heads, 2.1 m at Bilinga and 5.2 m at Palm Beach wave rider buoys, and maximum significant wave heights were 5.5 m at Tweed Heads, 4.4 m at Bilinga and 2.6 m at Palm Beach wave rider buoys (Queensland Government 2023).

During the June 2023 survey, sea conditions were favourable with low swell and west-south-westerly to northerly winds (5–10 knots). Water clarity was good, with excellent visibility. There was high rainfall in the month leading up to the survey, with 144.2 mm recorded in May 2023 (and an average rainfall of 129.7 mm for May), but only 22.8 mm in the two weeks prior to the survey and light rainfall (0.2 mm) during the survey (Coolangatta station 40717; BOM 2023).

Maximum wave heights were 1.2 m at Tweed Heads, 0.9 m at Bilinga and 2.0 m at Palm Beach wave rider buoys, and maximum significant wave heights were 2.3 m at Tweed Heads, 1.9 m at Bilinga and 1.1 m at Palm Beach wave rider buoys on 8 June 2023. In the two weeks prior to this, maximum wave heights were 2.0 m at Tweed Heads, 1.4 m at Bilinga and 3.3 m at Palm Beach wave rider buoys, and maximum significant wave heights were 3.7 m at Tweed Heads, 2.6 m at Bilinga and 1.8 m at Palm Beach wave rider buoys (Queensland Government 2023).

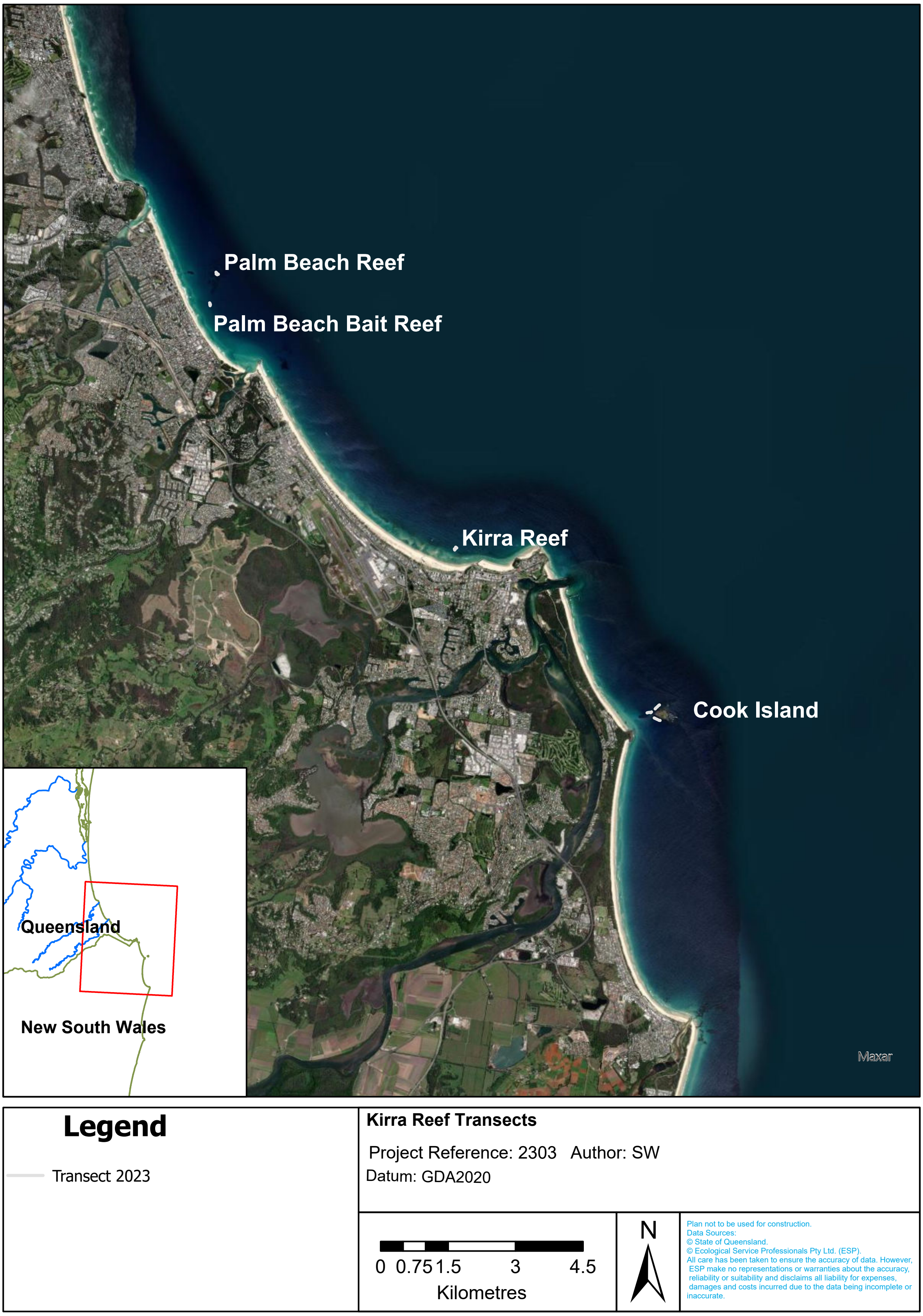

Figure 2.1 Reef locations for Biota Monitoring in 2023

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, however water clarity did not improve sufficiently to allow for suitable image collection at this site. 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. Due to poor quality of imagery collected during the diver survey (i.e. visibility was 1-2 m), data was recollect at reefs using ROV in June 2023 once water clarity had improved sufficiently to allow for suitable quantification of the benthic assemblages. The ROV was operated at 1 m above the bottom to be consistent with diver surveys and footage was georeferenced for each transect using a surface float with a BadElf GNSS GPS (± 1 m accuracy) attached. The start and end of each transect was marked prior to completing the ROV survey to provide a visual marker to orient the survey transects at reach reef location.

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 (Datum: GDA2020 UTM Zone 56J)

Reef Location	Transect (Sites)	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

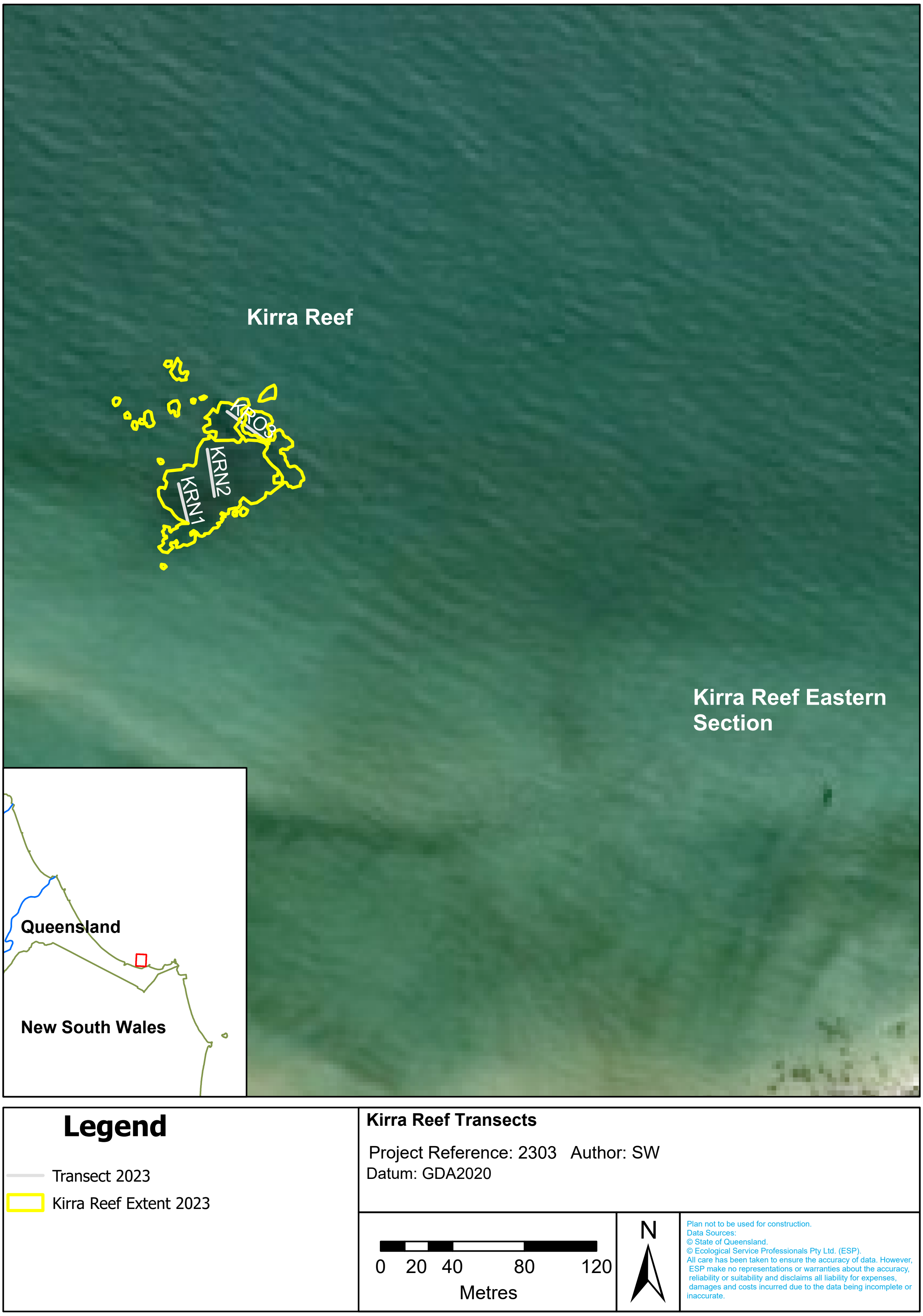

Figure 2.2 Location of transects surveyed in 2023 at Kirra Reef

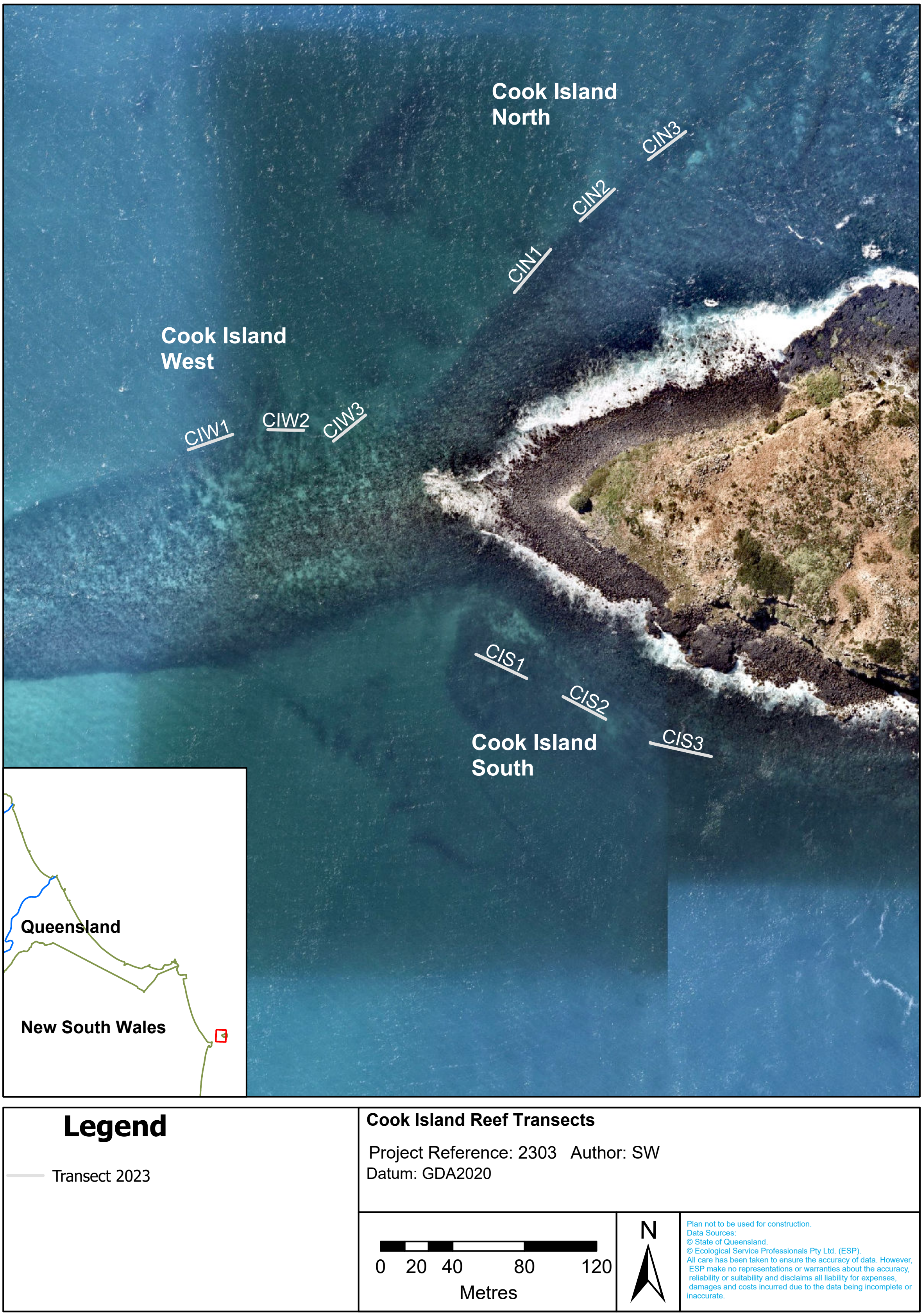

Figure 2.3 Location of transects surveyed in 2023 at the three reef locations around Cook Island

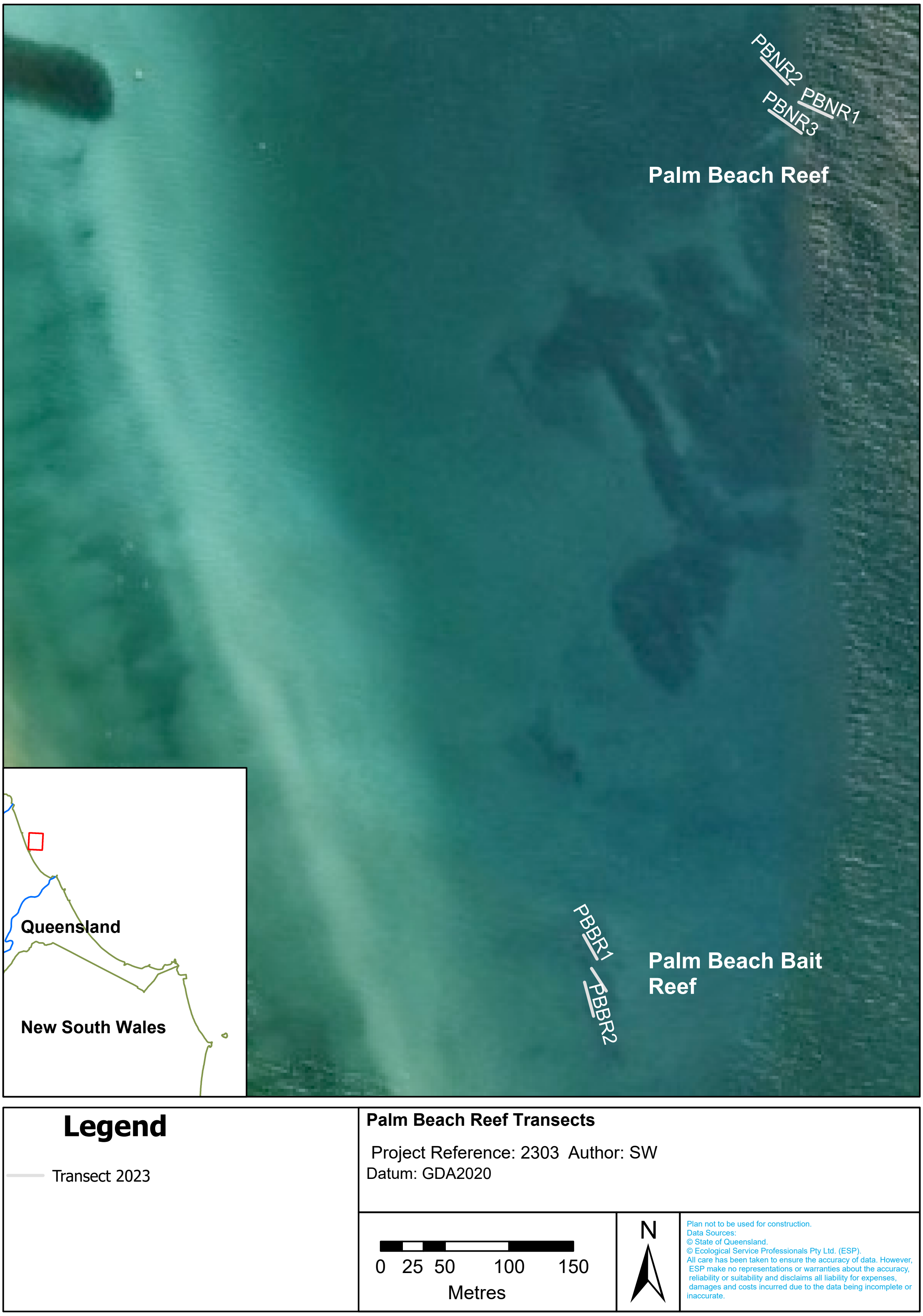

Figure 2.4 Location of transects surveyed in 2023 at Palm Beach Reef and Palm Beach Bait Reef

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 2023, 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

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[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 eight years (between 2016 and 2023), 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 two-factor PERMANOVA based on untransformed data, with survey year and location as the fixed factors separately for vertical and horizontal surfaces. Differences in the composition of the benthic assemblages among locations through time were visualised using nMDS ordinations. Sites were aggregated within each reef locations as in 2018 and 2019 there was no differentiation provided for sites within reefs.

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, Cook Island and Palm Beach reefs (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.

Two UBRUVS at Palm Beach Bait Reef were excluded from analyses, as one failed to record, and another had no species level identifications recorded due to very low visibility and the station being flipped upside down early in the recording. The number of species for each transect from UBRUVS were transformed by fourth 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 UBRUVS 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 Climate Change, Energy, the Environment and Water (DCCEEW) Protected Matters Search Tool (PMST) for a 2 km buffer of the coastline between Cook Island and Palm Beach (DCCEEW 2023) and National Introduced Marine Pest Information System (NIMPIS 2023). Additional 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.

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 2023) for the Tweed Heads (representative of conditions at Cook Island reefs), Bilinga (representative of conditions at Kirra Reef) and Palm Beach (representative of conditions at Palm Beach and Palm Beach Bait reefs) wave rider buoys (Table 2.2). Data available for the year prior to the survey (2 May 2022 to 1 May 2023) were graphed to provide a record of physical conditions preceding monitoring and compared to previous assessments of abiotic conditions of the region.

Table 2.2 Wave ruder buoys water depth (m) and location (Datum: GDA2020 UTM Zone 56J) (Queensland Government 2023)

Wave Rider Buoy	Depth (m)	Location	
		Easting	Northing
Tweed Heads	22	556596.8	6882991.1
Bilinga	18	550154.9	6886848.1
Palm Beach	23	547676.0	6893147.9

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 3.2b). 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 April 2023, Kirra Reef had an estimated total aerial extent of 3,492 m^2 measured from visual interpretation of aerial and satellite imagery, which only comprised of reef in the northern section, with no inner or eastern sections of reef. This was approximately 16% larger than the total extent measured in June 2022 (total area of 3,014 m^2, including 204 m^2 of reef in the eastern section and the remainder in the northern section; ESP 2022), and 15% smaller than the extent measured in 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; ESP 2021). 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 as well as between 2022 and 2023. 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 Duranbah). Despite this recent changes, 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 (Figure 3.1). 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 (Figure 3.1), 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, and was not present in 2023. 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 (ESP 2022). 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.

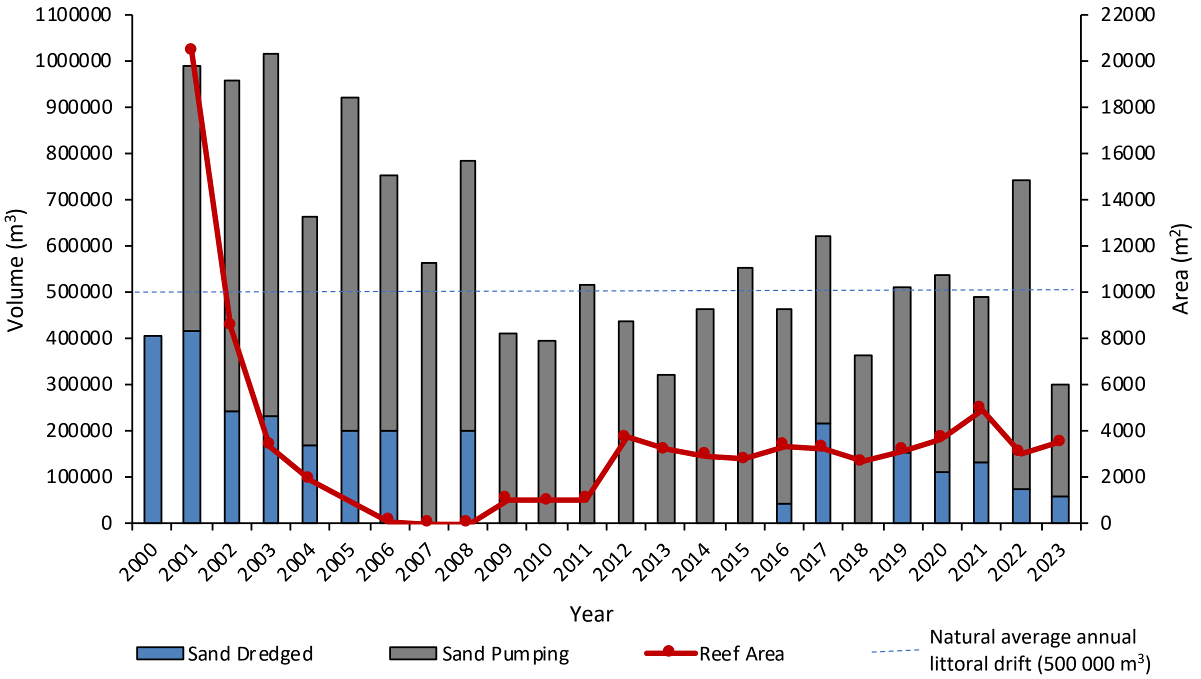


Figure 3.1 Estimated surface area (m^2) at Kirra Reef and total annual and dredging and pumping volumes (m^3) between 2000 and 2023 (data for 2023 includes sand volumes up to end of May) (pumping and dredging volumes sourced from TSB 2023)

a) 1956

Source: Queensland Government 2021a

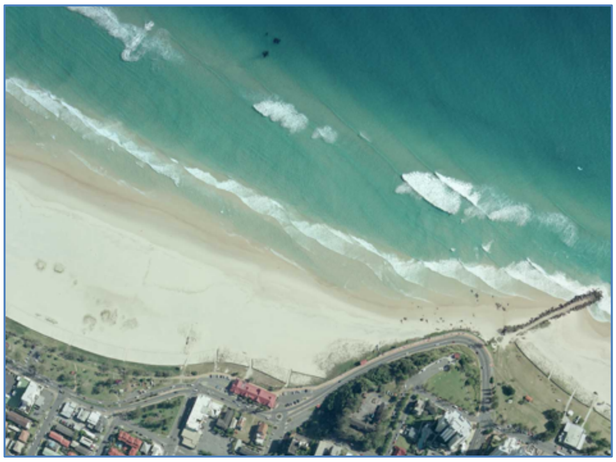
b) 1982

Source: WorleyParsons 2009

c) 1995

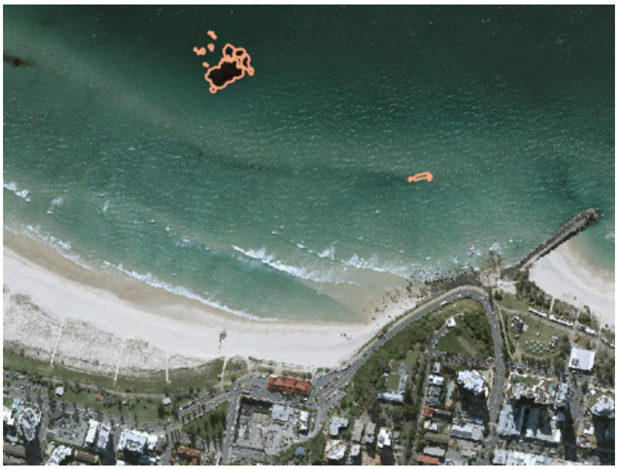
Source: Queensland Government 2021a

d) 2007



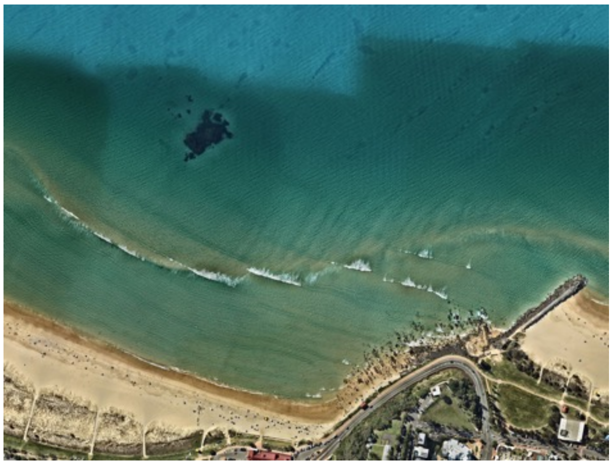
Source: Queensland Government 2021b

e) 2022



Source: NearMaps 2022

f) 2023



Source: TSB

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) 2022; and, (f) 2023 with sand delivery of the TSB now matching natural longshore drift of sand

3.1.2 Bathymetric Surveys

The depth around Kirra Reef decreased 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 reef section (Figure 3.3; as shown by the light green colours). Depth increased by 0.2 to 0.8 m near some of the outcrops to the west and north of the northern reef section (Figure 3.3; as shown by the darker blue colours). In contrast, between 2022 and 2023, there was generally an increase in depth around Kirra Reef of up to 0.8 and 1.7 m (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 or 2023, with a different and smaller area exposed to the southeast, and landwards the offshore sandbar in 2022 (Figure 3.4). This small rock outcrop was covered by the shoreward migration of the offshore sandbar (as shown by the dark blue colour in Figure 3.3). The migration of the sandbar has increased the extent of reef around the main northern reef section, which had many recently exhumed areas of bare rock. Changes in reef depth were largely related to the movement of the offshore bar along Kirra Beach, with a seaward movement in 2022 and landward movement in 2023 (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 decrease and increase in depth between May 2021 and May 2023 have been more substantial than observed in recent years (i.e. ± 0.2 m change between July 2019 and May 2020 and ± 0.2 to 1.0 m change between May 2020 and May 2021), when depth around much of the reef had either increased or stayed relatively similar (ESP 2020; ESP 2021).

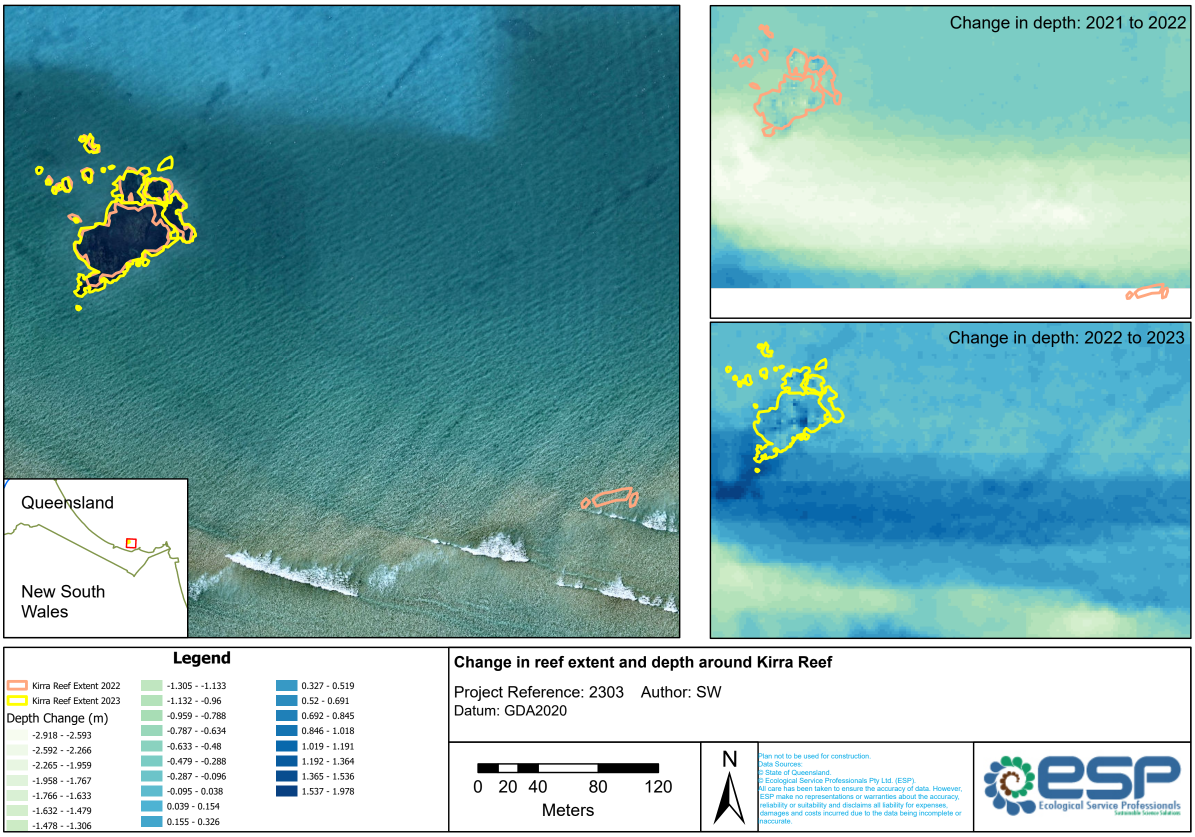


Figure 3.3 Areal extent (left) and changes in depth (light green indicating shallower and blue indicating deeper water) from May 2021 to June 2022 (top right); and June 2022 to April 2023 (bottom right)

Figure 3.4 Oblique aerial photographs of Kirra Reef taken in 2023 (images provided by TSB)

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 Reef and the comparative Palm Beach Reef on both horizontal and vertical surfaces [5] (Figure 3.6, Figure 3.7 and Figure 3.5a; PERMANOVA, Appendix B, Table B.5.2). However, benthic communities at the comparative Palm Beach Reef also differed from all Cook Island reefs on both horizontal and vertical surface. The composition of benthic communities at Kirra Reef also difference to Cook Island South, but only on vertical surfaces. The composition of benthic communities among Cook Reef reefs, which are separated by only a few hundred metres, were typically similar, except communities at Cook Island West and Cook Island North, which differed on horizontal surfaces only (Appendix B, Table B.5.2). The differences in benthic communities between Kirra and the other reefs in the area was typically due to the coverage of turf forming algae, lower coverage of coralline algae and higher coverage of some sessile invertebrates such as solitary and colonial 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 (such as wave action), settlement and recruitment of sessile species, water quality (including nutrient availability and high rainfall), and / or possible variation in the abundance of herbivorous fauna among reefs.

[5] Benthic communities PERMANOVA Orientation vs Site interaction MS = 78 pseudo-$F_{4,10}$ = 3.88, p = 0.032; Pairwise tests for differences among reefs for horizontal surfaces: KR≠PBR≠CIS=CIN≠CIW and vertical surfaces: CIS≠KR≠PBR≠CIS=CIN=CIW ≠PBNR *p(MC)* < 0.05

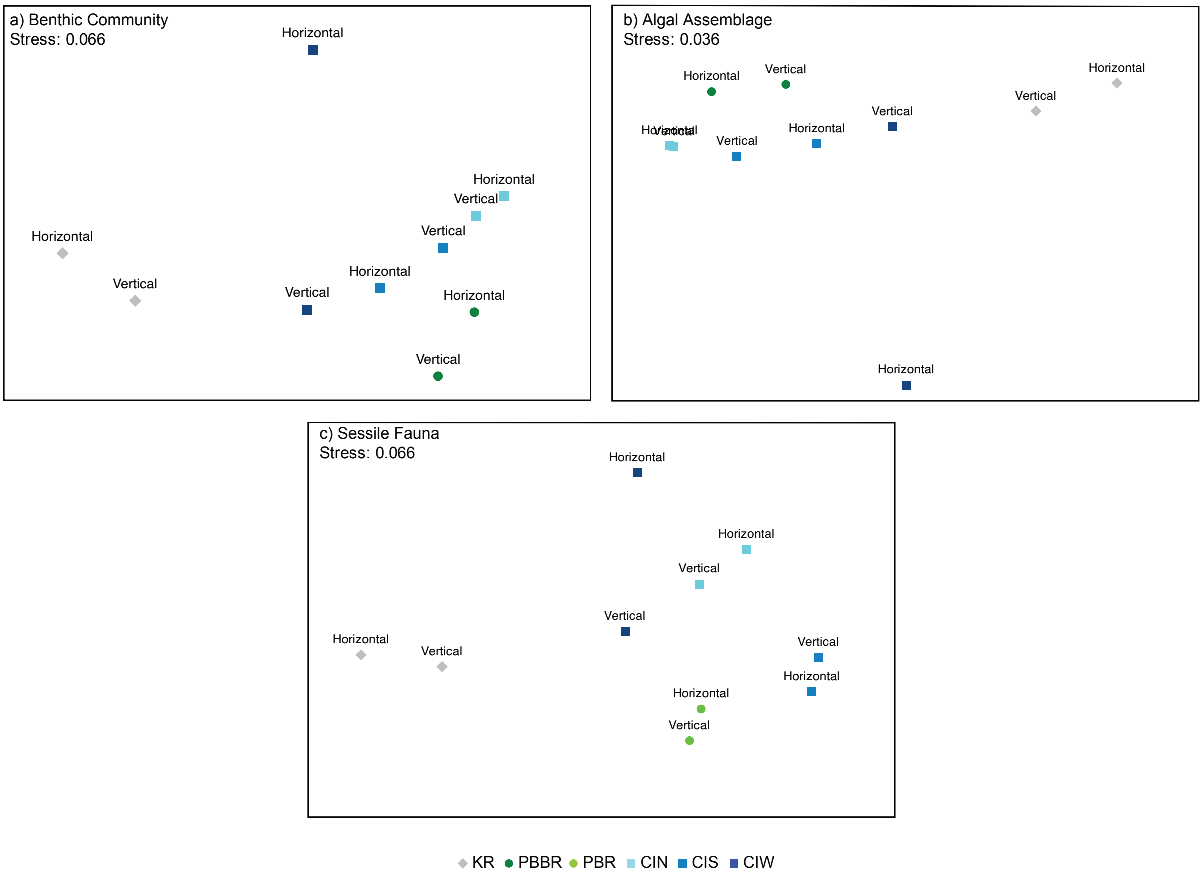


Figure 3.5 nMDS ordination showing difference in the composition of benthic assemblages between surface orientations and reefs for (a) the sessile community, (b) algal assemblages, and (c) sessile invertebrate assemblages [6]

The differences in the composition of benthic communities between horizontal and vertical surfaces were less pronounced in 2023 than in previous years (Appendix B, Table B.5.2). In 2023, there was no difference in the overall composition of the benthic communities between horizontal and vertical surfaces on Kirra Reef (SIMPER Appendix B, Table B.5.3).

The moderately dense patch of seagrass recorded between 2020 and 2022 near Cook Island West was present in 2023, although the coverage of seagrass had declined to less than 10%, likely due to prolonged recovery following flood impacts, such as 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 3.8). Marine vegetation, including seagrass, are protected under the *NSW Fisheries Management Act 1995*.

Bare sand and rubble habitat cover was higher on horizontal surfaces compared to vertical surfaces at all reefs in 2023. Kirra Reef had the highest coverage of bare sand and rubble on

[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.

horizontal surfaces (26%), which was higher than measured at this reef in 2022 (Figure 3.9). However, bare sand and rubble habitat coverage also increased between 2022 and 2023 at Palm Beach Reef (Figure 3.9).

a)

b)

Figure 3.6 Example benthic assemblages at a) Kirra Reef and b) Palm Beach Reef

a)

b)

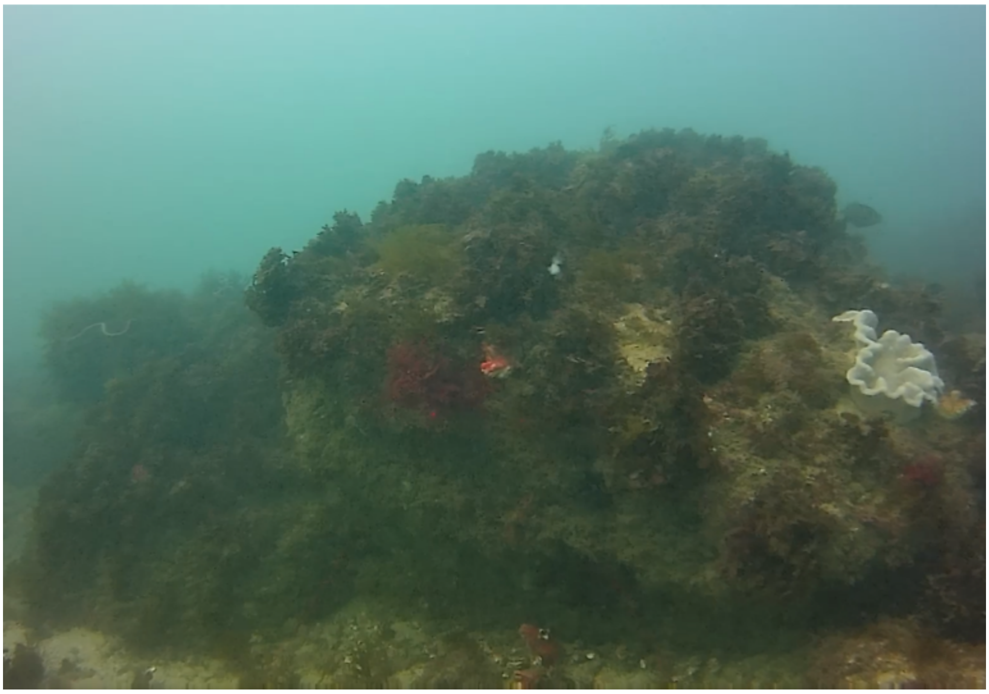
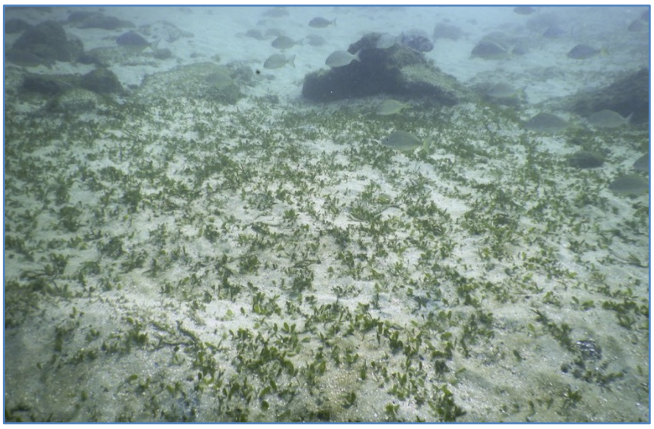
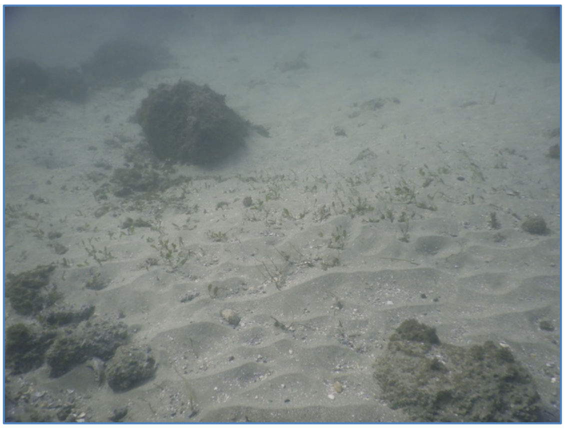


Figure 3.7 Example benthic assemblages at a) Cook Island North and b) Cook Island West

a)



b)



c)

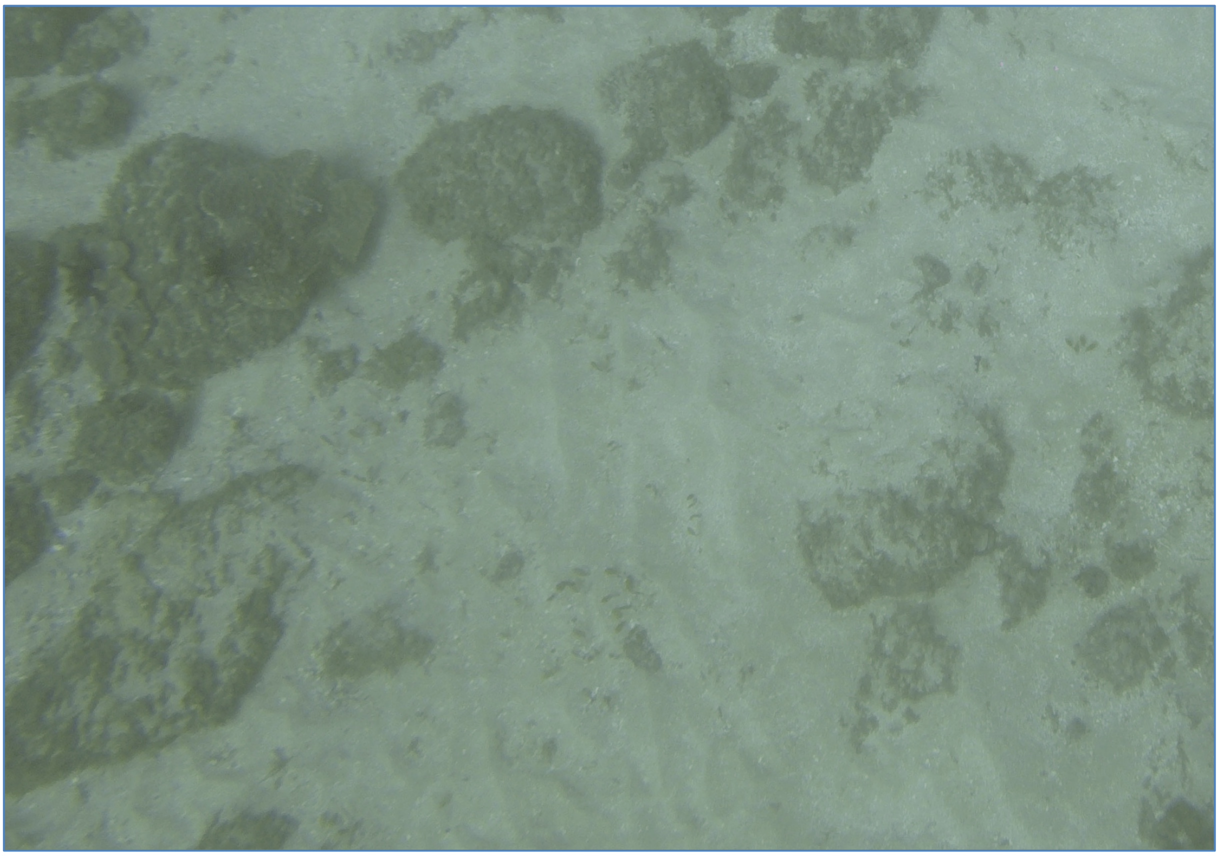


Figure 3.8 Seagrass *Halophila ovalis* at Cook Island West in a) 2021 b) 2022 and c) 2023

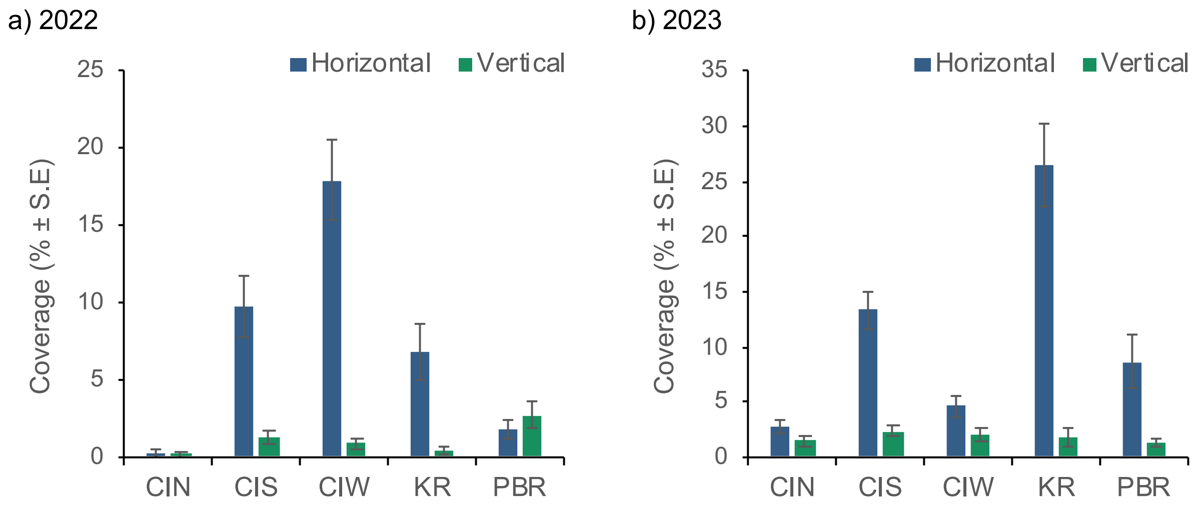


Figure 3.9 Average coverage (% ± S.E.) of bare (sand & rubble) habitat between surface orientations, among reefs in (a) 2022 and (b) 2023

3.2.2 Algal Assemblages

The algal assemblages on all reefs were dominated by turf forming algae, which covered on average more than 27% of the reef areas on vertical surfaces and more than 13% on horizontal surfaces. 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 among reefs on both horizontal and vertical surfaces[7] (Figure 3.5b; Figure 3.11; PERMANOVA, Appendix B, Table B.5.4). There were differences in the composition of algal assemblages among the reefs, particularly among horizontal surfaces (Figure 3.5b & c; PERMANOVA pairwise comparisons, Appendix B, Table B.5.4; SIMPER Table B.5.6).

The average coverage of foliose macroalgae was similar between the surface orientations on each reef (Figure 3.10a; PERMANOVA Appendix B Table B.5.5a). The coverage of foliose macroalgae was greatest at Cook Island West and lowest at Palm Beach Reef (Figure 3.10a). The reduced coverage of foliose algae at Palm Beach may be a result of past flood conditions causing prolonged poor water quality and reduced light penetration. The coverage of macroalgae on Kirra Reef was dominated by *Sargassum* spp. and was relatively high compared with that recorded on most of the other reefs, except horizontal surfaces at Cook Island West, which were covered by dense stands of *Dictyota* sp. (Figure 3.10a). The coverage of foliose macroalgae on Kirra Reef has increased relative to that recorded in 2021 and 2022 (Figure 3.10a; ESP 2021; ESP 2022), which is likely due to the increased area of bare rock recently exhumed and more favourable water quality conditions. Foliose macroalgae covered on average 29% of horizontal and 17% of vertical surfaces at Kirra Reef (Figure 3.10a; Figure 3.11), compared with 18% in 2020, 14% in 2021 and 6% in 2022 of both horizontal and vertical surfaces (ESP 2021; ESP 2022). *Sargassum* spp. was largely absent at the other reefs surveyed, with differences among reefs often largely due to variation in the coverage of turf forming algae (SIMPER; Appendix B, Table B.5.6).

[7] Algal assemblages PERMANOVA Reef x Orientation interaction effect $MS_{4,10}$ = 9816, pseudo-F = 2.24, p = 0.03; Pairwise tests for differences among reefs: Table B.5.4

The eastern section of Kirra Reef was buried by sand in 2023. When this low relief reef section of Kirra Reef was exhumed in 2022 (while not quantitatively assessed), the rock surface was dominated by a moderate coverage of foliose macroalgae, in particular *Sargassum, Padina* and *Ulva*. These species colonise rocky reefs quickly, particularly where reef surfaces are available for colonisation during winter months when algae are known to spawn (Kennelly 1987). Foliose macroalgae including kelp (*Ecklonia radiata*) has also established on recently exhumed rock on the northern section of Kirra Reef.

The coverage of turf forming algae was highest on both vertical and horizontal surfaces at Cook Island North (>50%) and was lowest on vertical surfaces at Kirra Reef (<27%) (Figure 3.10b; PERMANOVA Appendix B Table B.5.5b). Differences in the coverage of turf forming algae at Kirra reef relative to that measured on the other reefs contributed more than 84% of the difference in algal assemblages among reefs (SIMPER Appendix B, Table B.5.6).

The coverage of articulate and crustose coralline algae has remained relatively consisted through time, covering less than 13% of the surface area on any one reef (Figure 3.10c). In 2023, the coverage of coralline algae differed among the reefs and was highest on horizontal and vertical surfaces at Cook Island North (Figure 3.10c; PERMANOVA Appendix B Table B.5.5c).

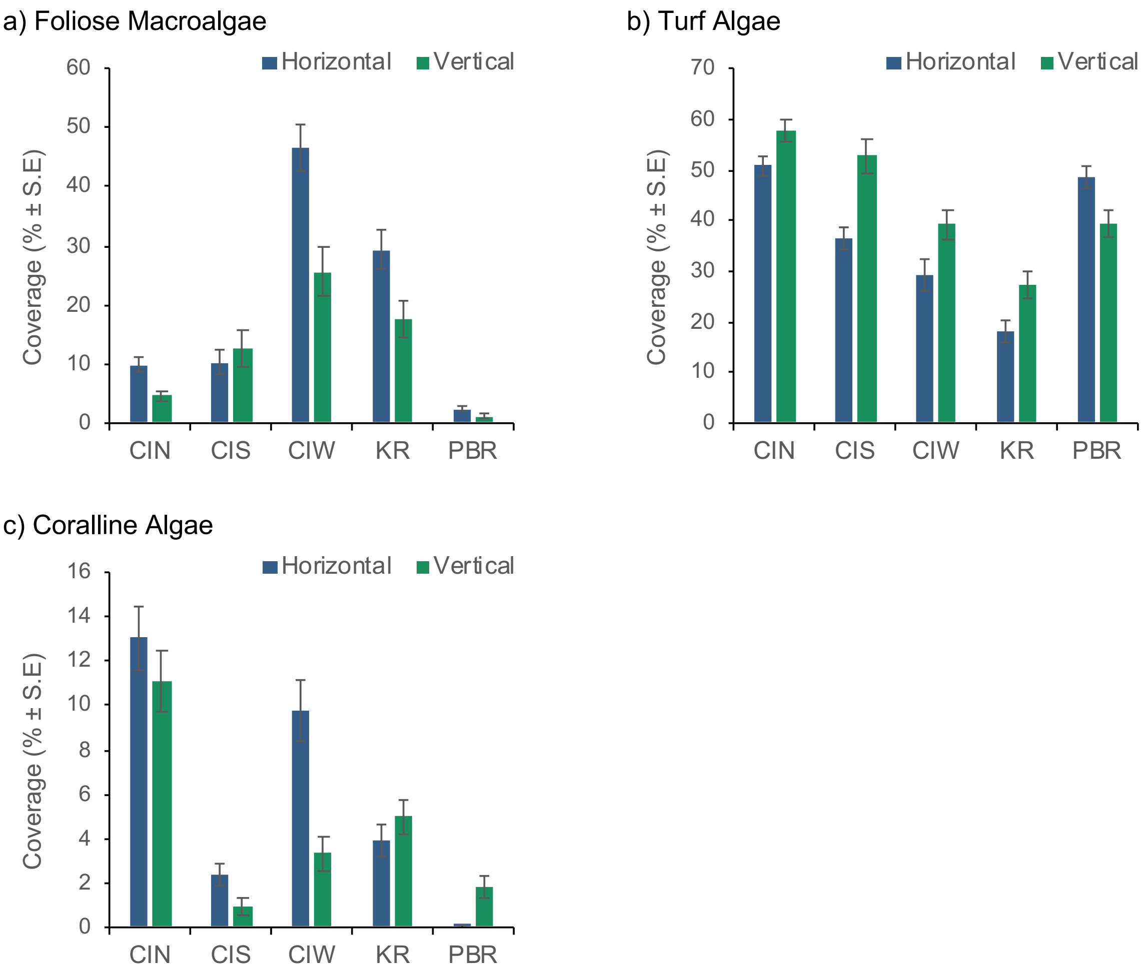


Figure 3.10 Average coverage (% ± SE) of foliose macroalgae, turf algae and coralline algae on vertical and horizontal surfaces, among reefs in 2023

a)

b)

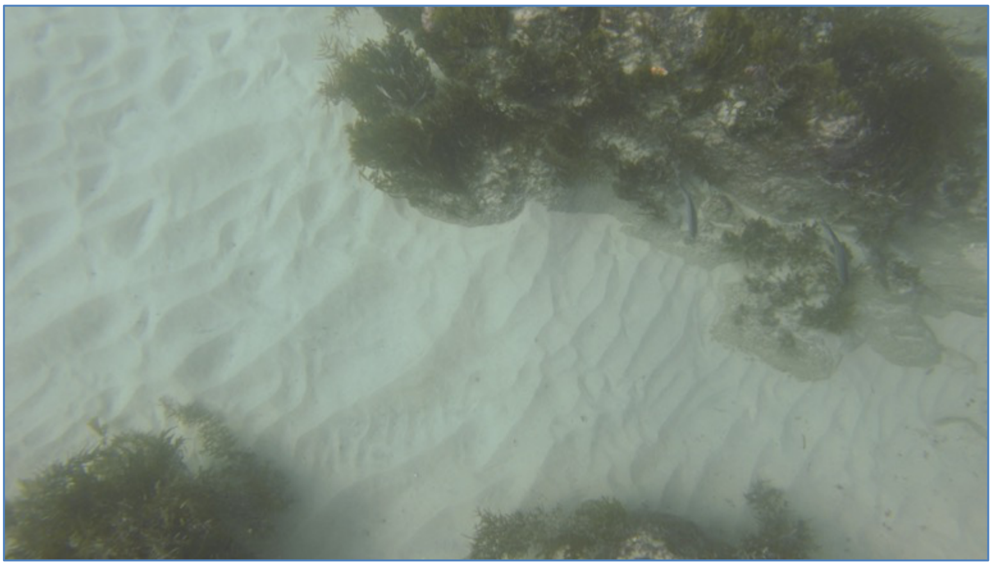


Figure 3.11 Algal communities at a) Kirra Reef northern section and b) a band of recently exhumed reef section rapidly colonised by foliose macroalgae

3.2.3 Sessile Invertebrate Assemblages

In 2023, a total of 80 taxa were recorded across all vertical surfaces and 73 taxa recorded across all horizontal surfaces on the reefs assessed. The fewest taxa were recorded on horizontal surfaces at Cook Island West Reef (19 taxa); however, 45 taxa were recorded on vertical surfaces at the same reef. The greatest number of taxa were recorded on vertical surfaces at Palm Beach Reef (59 taxa). A total of 31 taxa were recorded on vertical surfaces and 23 taxa on horizontal surfaces at Kirra Reef. In 2022 there was a higher number of taxa recorded on Kirra Reef, with a total of 46 taxa recorded on vertical surfaces and 25 taxa on horizontal surfaces. 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.

In 2023, 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 3.5d; PERMANOVA Orientation x Reef pairwise comparisons Table B.5.7). The average coverage of the dominant ascidians *Polycarpa procera* and *Cnemidocarpa stolonifera*, was typically higher on horizontal surfaces at Kirra Reef than at the other reefs and contributed 20 to 39% of the difference in assemblage composition (SIMPER Appendix B, Table B.5.8). The lack of hard corals (i.e. from genus *Paragoniastrea, Turbinaria* and encrusting *Porites*) and low coverage of soft corals at Kirra Reef also contributed to differences in the composition of assemblages among reefs, particular with those assemblages surrounding Cook Island (SIMPER Appendix B, Table B.5.8 & Table B.5.9). On vertical surfaces, the higher coverage of ascidians *Polycarpa procera*, *Pyura stolonifera* and *Herdmania momus,* and differences in the coverage of several 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 often did not differ between Kirra Reef and the comparative reefs surveyed in 2023, except at Palm Beach Reef, which was significantly higher for both average coverage and taxonomic richness[9] (Figure 3.12a,b; PERMANOVA Appendix B, Table B.5.10a,b). On most reefs, the average coverage of sessile fauna was consistently higher on vertical than horizontal surfaces[10] (Figure 3.12a,b; PERMANOVA Appendix B, Table B.5.10b). This was expected as horizontal surfaces such as those on Kirra Reef typically had a greater coverage of foliose and turf forming algae (Figure 3.10), which can outcompete sessile invertebrates and cause physical disturbance preventing settlement. There was also a higher coverage of sand and rubble on horizontal than vertical surfaces (Figure 3.9), which can increase physical disturbance from sand scour and burial creating conditions that are unsuitable for sessile invertebrate recruitment and growth.

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[8] Sessile Invertebrates - PERMANOVA Orientation vs Reef interaction $MS_{4,10}$ = 80763, pseudo-F = 11.78, 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 Orientation x Reef Interaction $MS_{4,10}$ = 78, pseudo-F = 3.88, p = 0.032, Pairwise tests for differences among reefs: CIN>CIS=CIW *p(MC)* < 0.05; Coverage of Sessile Invertebrates PERMANOVA Reef Main effect $MS_{4,10}$ = 11039, pseudo-F = 9.93, p = 0.0.004; Orientation Main effect $MS_{1,10}$ = 14149, pseudo-F = 8.45, p = 0.0.016.

[10] Coverage of Sessile Invertebrates PERMANOVA Orientation Main effect $MS_{1,10}$ = 14149, pseudo-F = 8.45, p = 0.0.016.

At both Cook Island and Palm Beach reefs, longer lived species such as hard and soft corals covered a greater proportion of both vertical and horizontal surfaces than on Kirra Reef (Figure 3.12c,d and Figure 3.13). In 2023, there was no evidence of the higher incidence of diseased corals recorded on reefs around Cook Island and Palm Beach reefs in 2022; although some hard corals may have died and become covered in turfing algae.

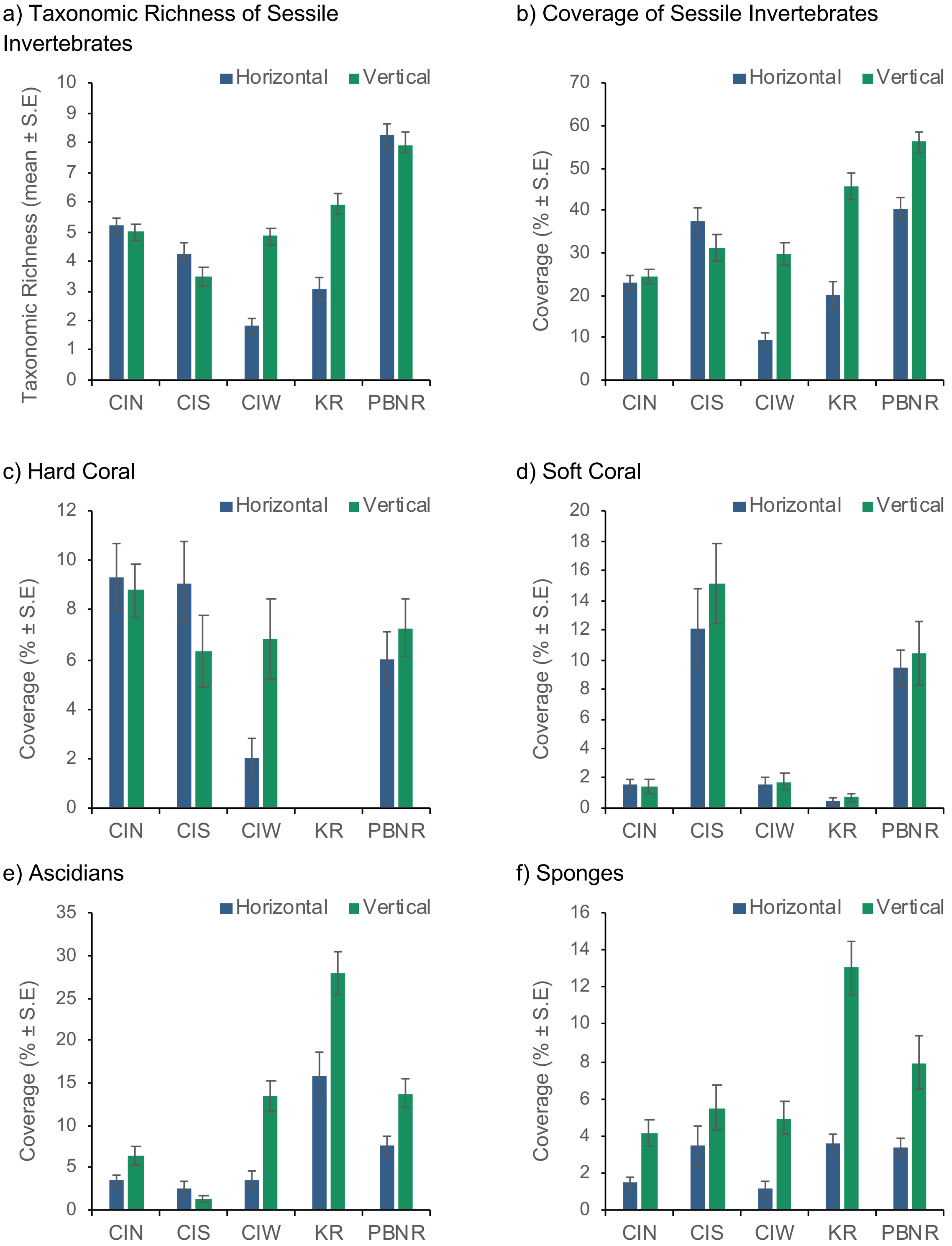
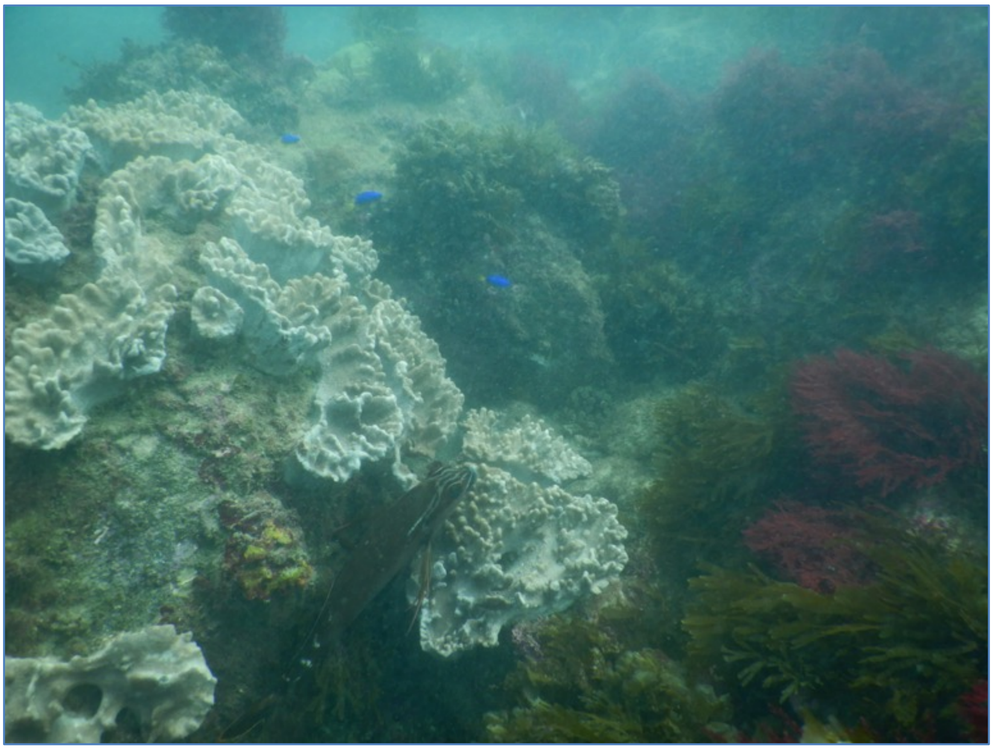


Figure 3.12 Average taxonomic richness and coverage (% ± SE) of all sessile invertebrates and average coverage of dominant sessile invertebrates categories on vertical and horizontal surfaces, among reefs in 2023 (Blue – Horizontal; Green – Vertical)

a)



b)

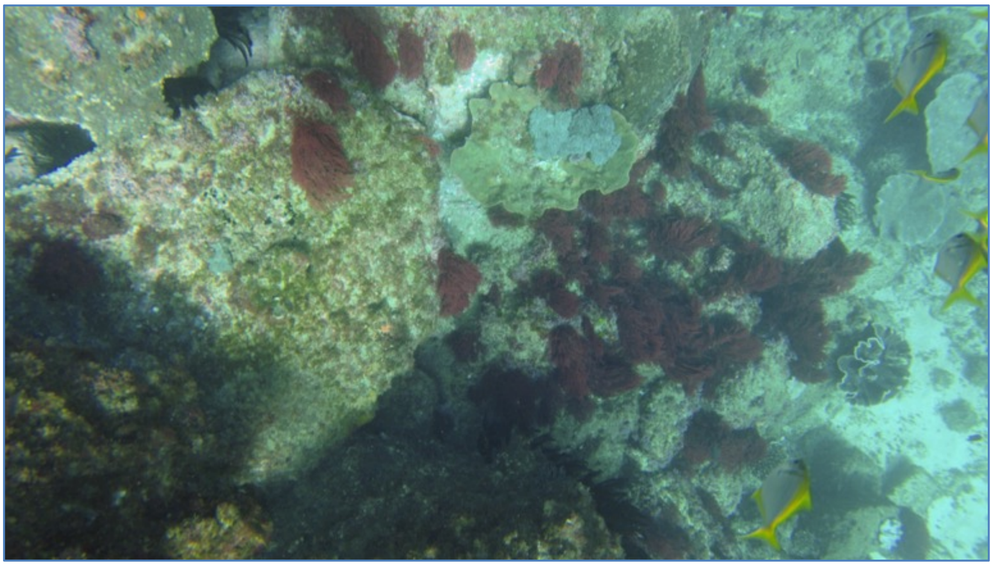


Figure 3.13 Hard and soft coral at a) Cook Island South and b) Cook Island North

3.2.4 Historic Comparison of Benthic Communities

The composition of benthic communities (algae and sessile invertebrates identified to a broad taxonomic level) continue to differ between Kirra and Palm Beach reefs (most commonly surveyed) and amoung the other reefs assessed over time[11] (Figure 3.14;

[11] Benthic Communities over time - PERMANOVA **Horizontal Surfaces** - Survey x Reef interaction $MS_{24,1698}$ = 12897 pseudo-F = 13.3, p = 0.001; **Vertical Surfaces** - Survey x Reef interaction

PERMANOVA Survey x Reef Interaction for both horizontal and vertical surfaces; pairwise comparisons Appendix B, Table B.5.11). In the past eight years (since 2016), the composition of benthic communities on all reefs assessed has differed between successive years (where surveys were completed), with the interannual variation in the composition of benthic communities largely driven by changes in the coverage of macroalgae and turf forming algae relative to the coverage of sessile invertebrates such hard corals, which have remained more stable (PERMANOVA pairwise comparisons, Table B.5.11g). Although, note that there have been some differences in the methods of data collection among surveys, particularly between 2017 and 2019, which may limit the interpretation of temporal changes. Despite these methodological differences, the composition of benthic assemblages at Kirra Reef in 2023 were more similar to that recorded in the 2017 and 2018 surveys (Figure 3.14), likely due to the recent increases in the coverage of foliose and decline in turf forming macroalgae.

On Kirra Reef, the differences in composition between successive surveys were due primarily to changes in the average coverage of foliose macroalgae, turf forming algae and ascidians, which combined accounted 68% to 84% of the difference between successive surveys on that reef (SIMPER Table B.5.13). Between 2022 and 2023, there has been a decrease in the coverage of turf forming algae and sponges contributing 41% of the difference, and an increase in the coverage of macroalgae, coralline algae and ascidians, which contributed 49% of the difference in composition between surveys (Table B.5.13). Hard corals were also not recorded in the benthic community on Kirra Reef in 2023, despite covering 2% of the area in 2020. An increase in the coverage of hard and soft corals would increase the similarity with those benthic assemblages 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, with occasional declines in sessile fauna such as sponges (SIMPER Table B.5.14 to Table B.5.17). In 2023, the coverage of hard coral at Cook Island North declined by 4% relative to the previous survey in 2022 (SIMPER Table B.5.14). The average coverage of hard corals also declined at Cook Island West from an average of 8.5% in 2022, to only 4.4% in 2023 (SIMPER Table B.5.15). While the coverage of hard and soft corals at Cook Island South remained consistent between 2022 and 2023 (SIMPER Table B.5.16).

At Palm Beach Reef there was a large increase in the coverage of bivalves (predominantly the hairy mussel (*Trichomya hirsuta*) from an average of 2.6% in 2022 to 12.4% in 2023 (SIMPER Table B.5.17). The coverage of soft corals and ascidians also increased, while other sessile organisms remained consistent over time (SIMPER Table B.5.17).

$MS_{14,1136}$ = 11623 pseudo-F = 16.3, p = 0.001; Pairwise tests for differences among reefs over time are provided in Appendix B Table B.5.11.

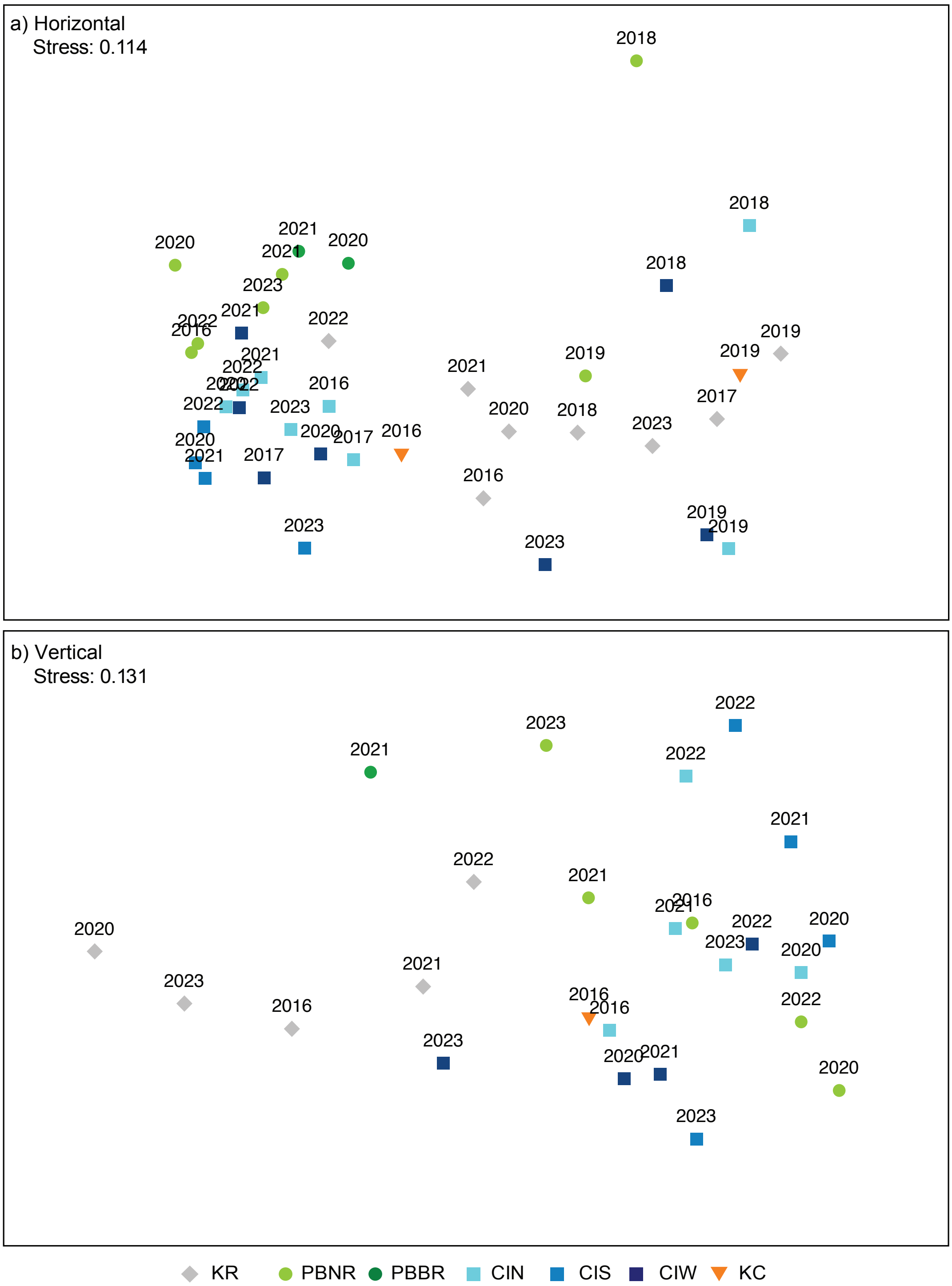


Figure 3.14 nMDS ordination of the difference in the composition of benthic assemblages on horizontal surfaces between Kirra and Palm Beach Reefs between 2016 and 2023 (KC = Kingscliff Reef – only surveyed in 2016 & 2019) [12]

[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.

3.2.5 Mobile Invertebrate Assemblages

In 2023, the average density of mobile invertebrate assemblages was highest at Cook Island North and Kirra Reef; although reefs around Cook Island and Palm Beach Reef had the greatest diversity, with six species of mobile invertebrates recorded from photo quadrats (Appendix C). Feather stars had the highest density of mobile invertebrates at all reefs, except at Cook Island South, where sea stars were higher (Figure 3.15; Figure 3.16b). This differed from recent years (2020, 2021 and 2022), when sea urchins dominated mobile invertebrate assemblages (ESP 2020; ESP 2021; ESP 2022) (Figure 3.15; Appendix C). In addition to mobile invertebrates recorded from photo quadrats, several species were also observed on ROV, UBRUVS or SCUBA diver footage in May and June 2023. Specifically:

- black feather star (*Cenolia glebosus*) at Cook Island North, Cook Island South, Kirra Reef and Palm Beach Bait Reef
- sea star, including luzon sea star (*Echinaster luzonicus*) at Cook Island North and Cook Island South; vermillion sea star (*Pentagonaster duebeni;* Figure 3.16a) at Palm Beach Reef and Cook Island South; blue sea star (*Linckia laevigata* Figure 3.16b) at Cook Island North, Cook Island South and Palm Beach Reef; and, dusky sea star (*Pseudonepanthia nigrobrunnea*) at Cook Island South
- sea urchins, including long-spined sea urchin (*Diadema savignyi;* Figure 3.16c) at all Cook Island reefs, Kirra Reef and Palm Beach Reef; rock-boring sea urchin (*Echinometra mathaei*) at Cook Island North and Cook Island South; banded sea urchin (*Echinothrix calamaris*; Figure 3.16d) at Cook Island South; slate pencil urchin (*Phyllacanthus parvispinus*) at Cook Island North, Cook Island South and Kirra Reef; and, lamington sea urchin (*Tripneustes gratilla*) at Cook Island North
- molluscs, including black spotted egg cowrie (*Calpurnus verrucosus;* Figure 3.16e) at Cook Island South; chromodorid nudibranch (*Chromodoris elisabethina*; Figure 3.16f) at all Cook Island reefs; a large nudibranch (*Marionia pustulosa*) at Cook Island South and an unidentified squid at Cook Island North and Cook Island South, and
- painted crayfish (*Panulirus versicolor*) at Cook Island North and Cook Island South.

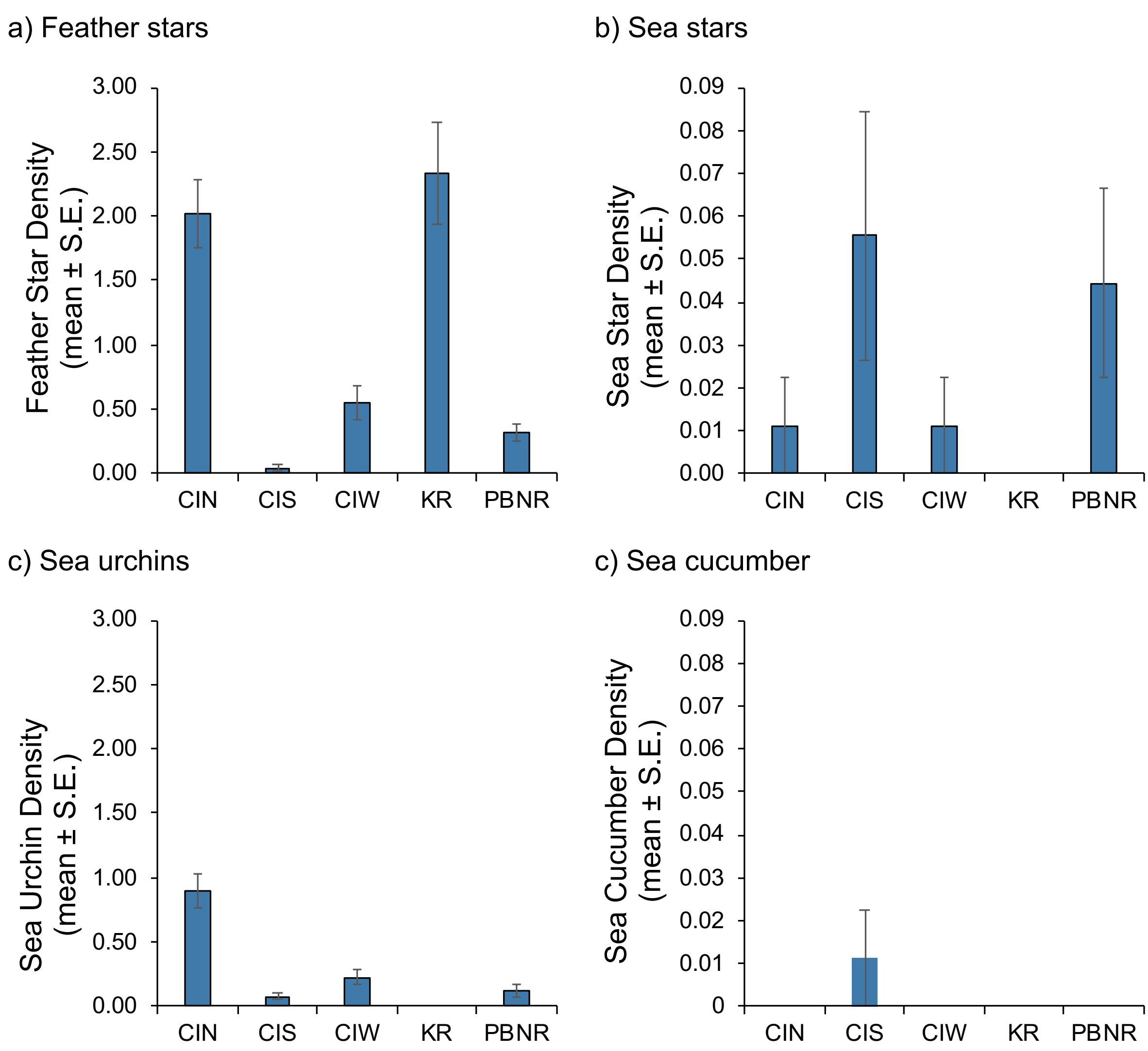


Figure 3.15 Density (number of individuals per photo quadrat; mean ± SE) of a) feather stars, b) sea stars c) sea urchins and d) sea cucumber at each reef in 2023

a) b) c) d) e) f)

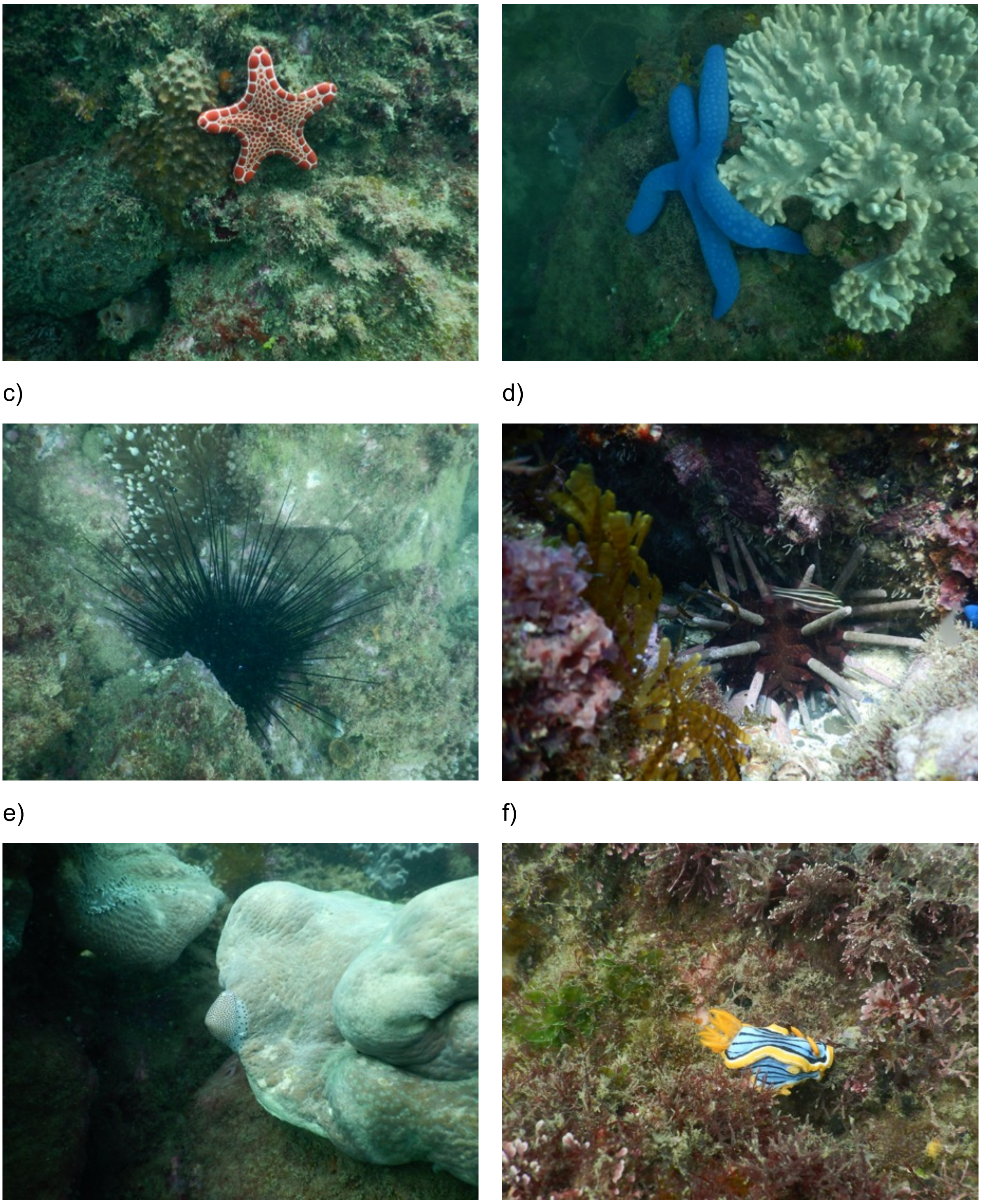


Figure 3.16 Mobile invertebrates recorded on reefs in 2023 including a) vermillion sea stars, b) blue sea star c) long-spined sea urchin d) slate pencil urchin e) spotted egg cowrie and f) chromodorid nudibranch

3.3 Fish Assemblages

A total of 91 bony and cartilaginous fish species, from 38 families were recorded across all reefs in the May 2023 survey (Appendix D), which is lower than recent years. In 2022 there were 126 species from 40 families, in 2021 there were 129 species from 44 families and in 2020 there were 116 species from 34 families recorded. The lower fish diversity was likely related to the poor visibility at the time of sampling using the BRUVS during the May 2023 survey limiting detection of more cryptic fish species. Consistent with 2020, 2021 and 2022, Labridae (wrasses) and Pomacentridae (damselfishes) were the most diverse families. These families had 16 and 14 species, respectively, in May 2023. An additional six fish species were observed that have not been recorded in previous surveys (Appendix D). Cartilaginous fish recorded in May 2023 included:

- banded wobbegong (*Orectolobus ornatus*) at Palm Beach Reef
- spotted wobbegong (*Orectolobus maculatus*) at all reefs except for Palm Beach Reef and Palm Beach Bait Reef
- whitespotted guitarfish (*Rhynchobatus australiae*) at Cook Island South (Figure 3.18a), and
- bluespotted maskray (*Neotrygon kuhlii*) at Kirra Reef.

The composition of fish assemblages differed among reefs [13], specifically between assemblages at Cook Island North 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; PERMANOVA Appendix B, Table B.5.18). Differences in fish assemblages at Cook Island North compared to Cook Island South and Palm Beach Reef were attributed to variation in the abundance of a broad range of species, with no individual species contributing more than 4% of the dissimilarity (SIMPER Appendix B, Table B.5.19). Differences in fish assemblages at Cook Island North and Cook Island South were due to higher abundances of some species at Cook Island North, including Whitley's sergeant (*Abudefduf whitleyi*), silver sweep (*Scorpis lineolata*), and Indo-Pacific sergeant (*Abudefduf vaigiensis*); absence of some species at Cook Island South, including bluespine unicornfish (*Naso unicornis*), blackbarred wrasse (*Thalassoma nigrofasciatum*), girdled scalyfin (*Parma unifasciata*), and moon wrasse (*Thalassoma lunare*); and absence of some species at Cook Island North, including blacksaddle goatfish (*Parupeneus spilurus*) and inshore surgeonfish (*Acanthurus grammoptilus*). Differences in fish assemblages at Palm Beach Reef and Cook Island North were primarily due to the absence of several species at Palm Beach Reef, including Whitley's sergeant, green moon wrasse (*Thalassoma lutescens*), yellowfin bream or tarwhine (*Acanthopagrus australis* or *Rhabdosargus sarba*), Indo-Pacific sergeant, bluespine unicornfish, pencil surgeonfish (*Acanthurus dussumieri*), blackbarred wrasse, and girdled scalyfin. Differences in the habitat complexity, benthic composition (refer to Section 3.2), availability of prey or other ecological interactions (e.g. predator abundance) likely contributed to differences in fish assemblages at these reefs. Differences may also be due to

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[13] PERMANOVA for differences in fish assemblages among reefs $F_{5,10} = 2.29$, $p = 0.001$; Pairwise comparisons among reefs CIN≠CIS; CIN≠PBR; CIN=CIW=KR=PBBR; CIS=CIW=KR=PBBR=PBR at p=0.05.

the quality of footage during the survey in May 2023, for example, there was very poor visibility at Palm Beach Reef relative to most other reefs due to highly turbid water.

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 North and Cook Island West (Figure 3.18b). No invasive fish species were recorded.

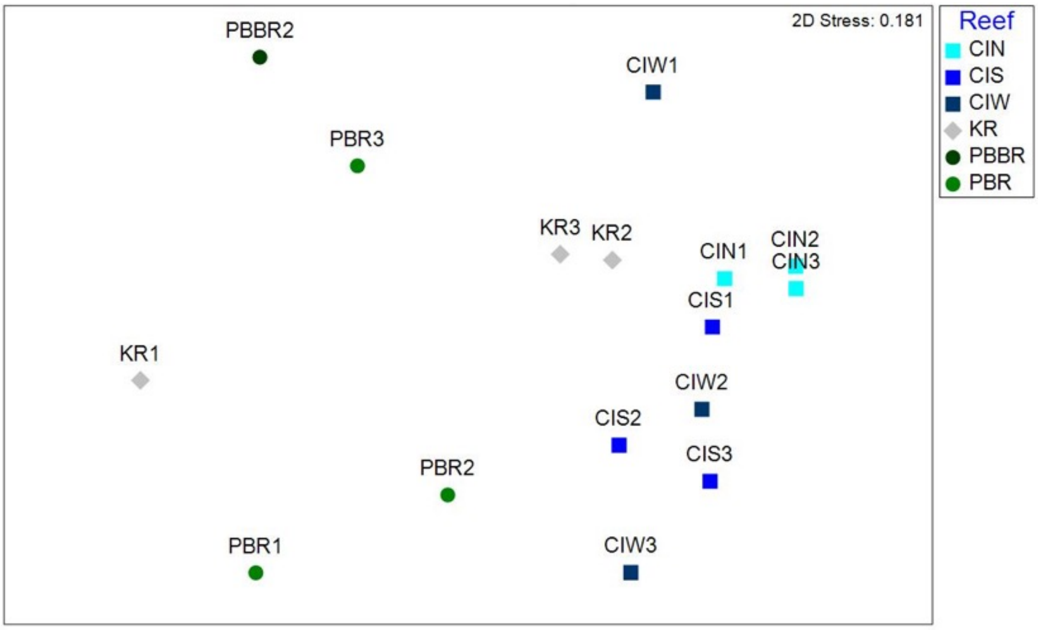
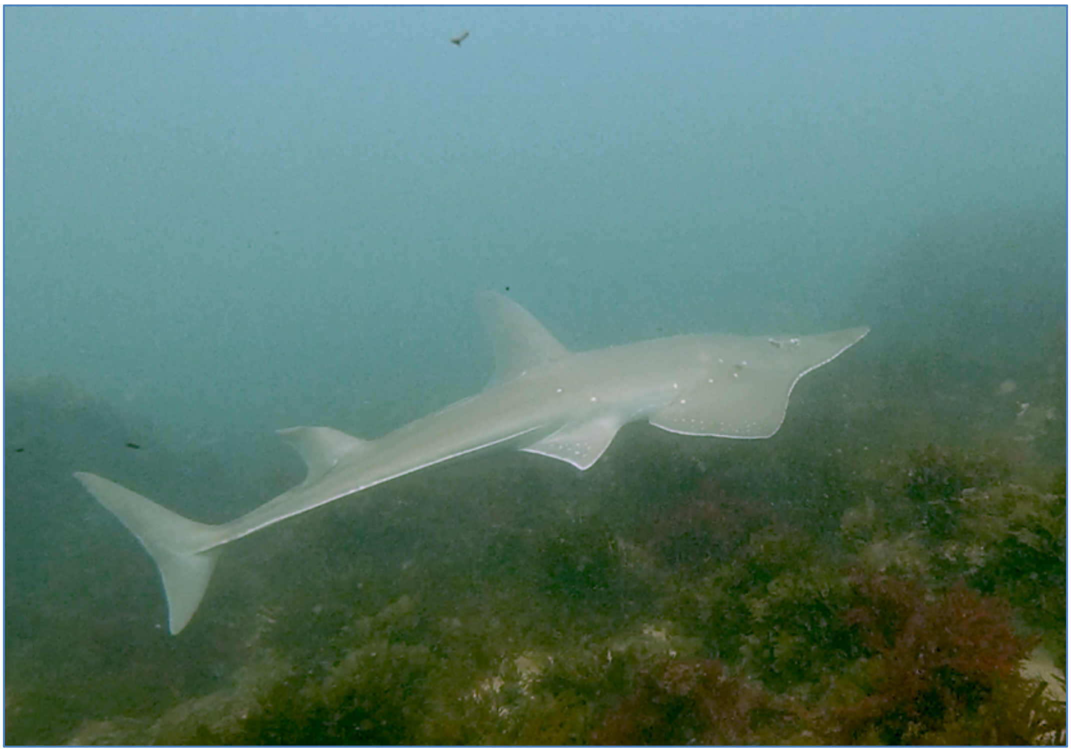


Figure 3.17 nMDS ordination of the differences in the composition of fish assemblage among reefs in May 2023 [14]

[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.

a)



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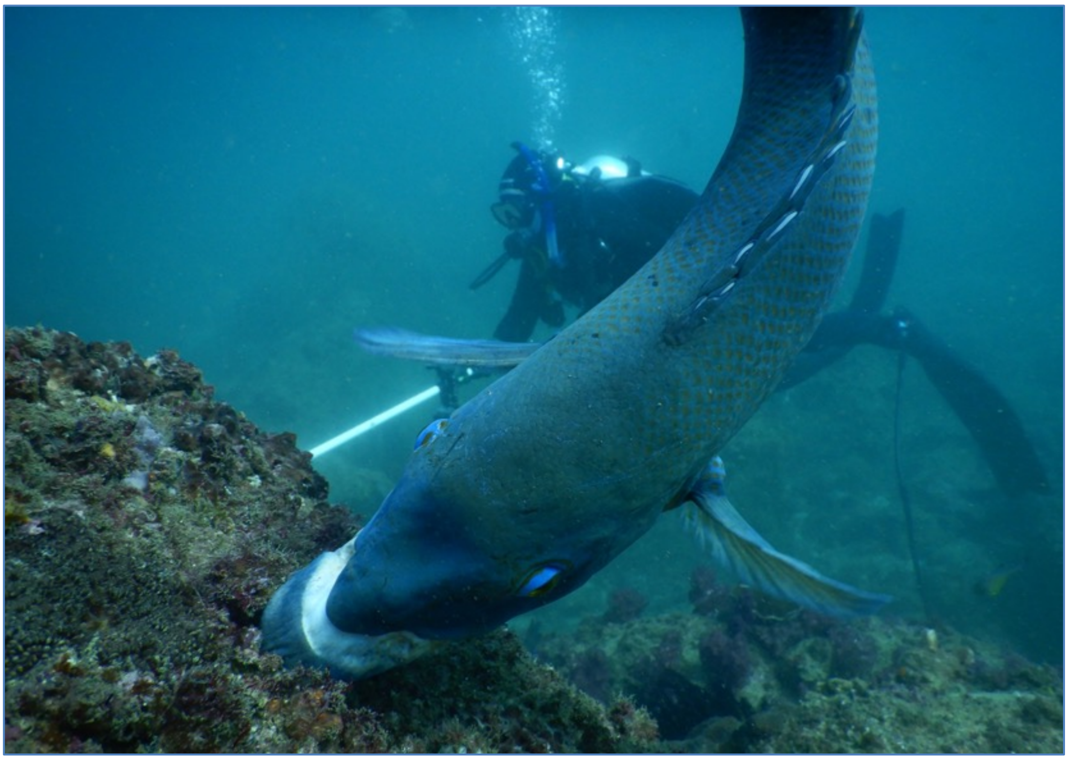


Figure 3.18 a) whitespotted guitarfish in May 2023 b) Eastern blue grouper recorded in 2022

3.3.1 Species Richness of Fish Assemblages

In May 2023, the total species richness varied among reefs, with the highest number of species recorded at Cook Island North (70 species) and the fewest species recorded at Palm Beach Bait Reef (9 species) (Table 3.1; Appendix D). This is inconsistent with results from 2022, with the highest number of species recorded at Cook Island West (81 species) and the fewest species recorded at Cook Island South (24 species). Temporal differences in the species richness during this period may be related to differences in sampling techniques, conditions while sampling (e.g. water clarity) and the timing of monitoring events.

In May 2023, the average species richness differed among reefs[15] (PERMANOVA Appendix B, Table B.5.20), with the lowest average species richness recorded at Palm Beach Reef and the highest average richness recorded at Cook Island North (Figure 3.19). In 2022 and 2023, the assemblages at Kirra and Palm Beach reefs differed, with a higher average species richness recorded at Kirra Reef. The species richness is often similar between Kirra and Palm Beach reefs among surveys, potentially due similar availability of primary food sources or providing relatively similar structural habitat in an otherwise featureless sandy bottom coastline (ESP 2020). In 2023, there was poor visibility at Palm Beach Reef and Palm Beach Bait Reef during the survey, which reduced the quality of footage collected and only one of three recordings at Palm Beach Bait Reef was available for analysis, which likely reduced the number of fish detected there.

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

	Total Species Richness*	Total Abundance (Pooled Max N)^
Kirra Reef	45	152
Palm Beach Reef	19	14
Palm Beach Bait Reef	9	44
Cook Island West	47	117
Cook Island North	70	234
Cook Island South	55	113

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

^ Total Abundance calculated from UBRUVS recordings only

[15] PERMANOVA for differences in species richness among reefs $F_{5,10} = 4.29$, $p = 0.020$; Pairwise comparisons among reefs CIN=CIS; CIN≠CIW; CIN≠KR; CIN≠PBBR; CIN≠PBR; CIS=CIW=KR=PBR=PBBR at $p = 0.05$.

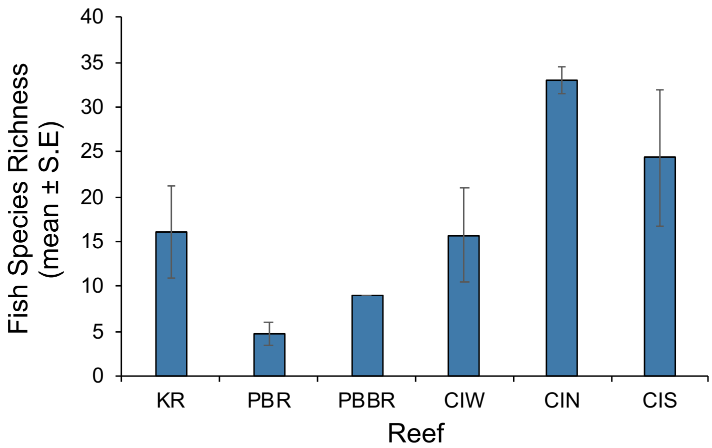


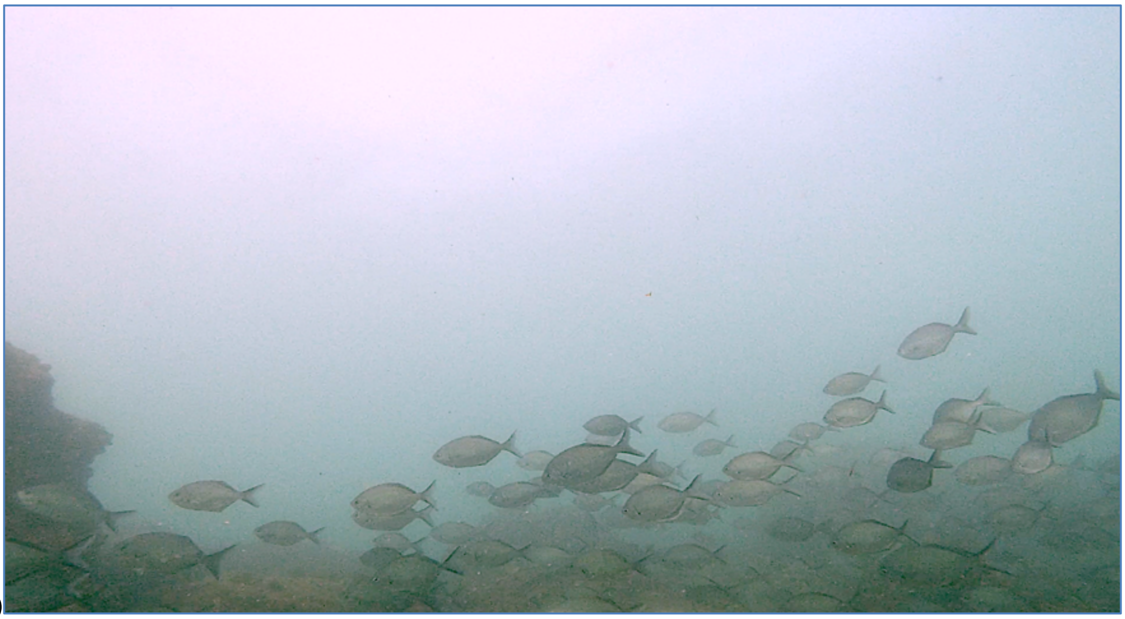
Figure 3.19 Average species richness (± SE) of fish assemblages among reefs

3.3.2 Relative Abundance of Fish Assemblages

The total abundance of fish, measured as the pooled Max N from UBRUVS, was highest at Cook Island North (234 individuals) and the lowest at Palm Beach Bait Reef (9 individuals) (Table 3.1). Kirra Reef often has the highest total abundance of fish with 1,206 individuals recorded in 2022, 1,132 individuals in 2021, and 496 individuals in 2020 (ESP 2021, ESP 2022). In 2023, Kirra Reef had the second highest abundance of 152 individuals recorded. The abundance was generally lower than previous years at all reefs, which may be due to poor visibility at inshore sites during the time of sampling. High abundance is primarily driven by schooling fish at some reefs. For example, schools (approximately more than 70 individuals) of yellowtail scad (*Trachurus novaezelandiae*) dominated fish assemblages at Kirra Reef (Figure 3.20a) and schools (approximately 100 individuals) of silver sweep dominated fish assemblages at Cook Island North (Figure 3.20b). Schools (approximately 55 individuals) of swallowtail dart (*Trachinotus coppingeri*) were recorded at Cook Island West. At Palm Beach Bait Reef, schooling species included double-lined fusilier (*Pterocaesio digramma*) and trevally (*Caranx* sp.) (Figure 3.21a), though schools were always < 50 individuals. No schooling fish were detected on UBRUVS at Palm Beach Reef in May 2023.

Species that commonly occurred among all reefs included several wrasse species (such as Günther's wrasse, *Pseudolabrus guentheri*; green moon wrasse and *Thalassoma lutescens*; crimsonband wrasse, *Notolabrus gymnogenis),* common cleaner fish (*Labroides dimidiatus*) banded goatfish (*Parupeneus multifasciatus*), blacksaddle goatfish, neon damsel (*Pomacentrus coelestis*) and silver sweep (Figure 3.21; Appendix D).

a)



c)

Figure 3.20 Schools of a) yellowtail scad at Kirra Reef in June 2023 and b) silver sweep at Cook Island North Reef

a) b) c)

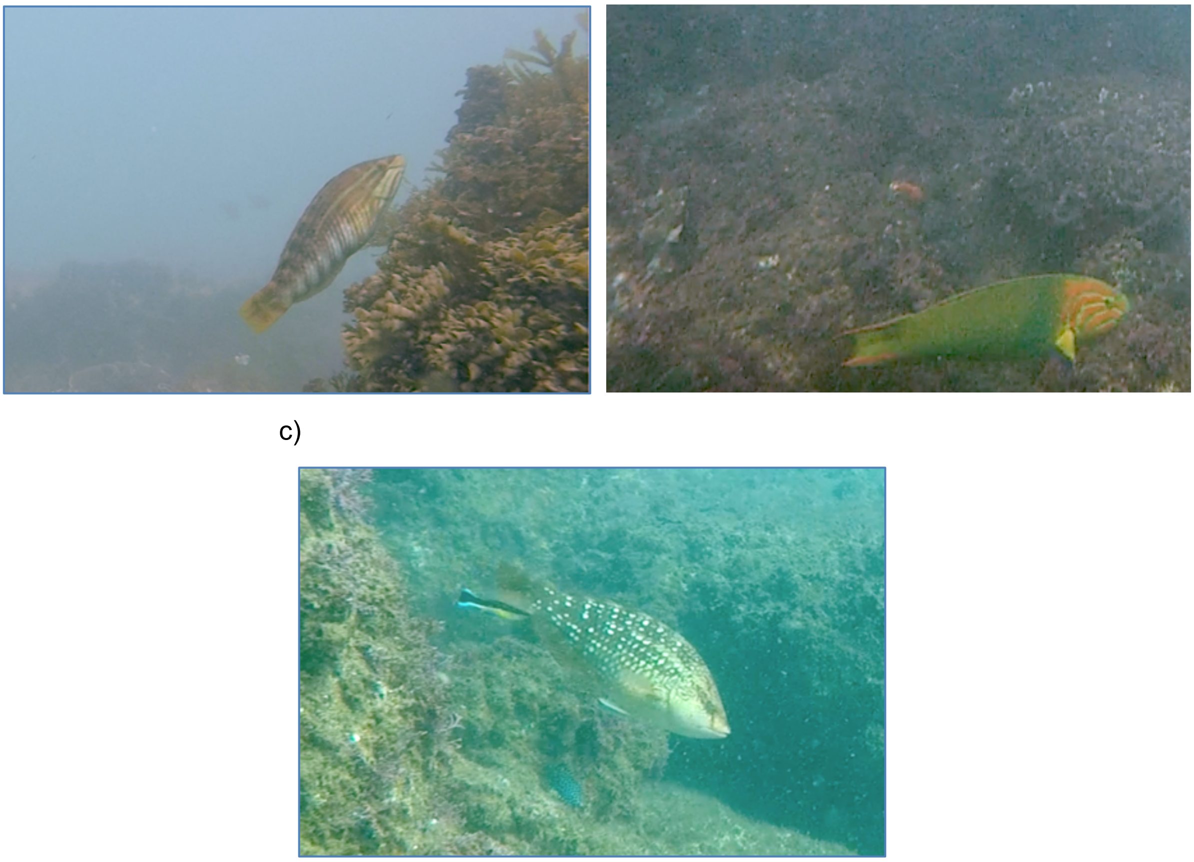


Figure 3.21 Fish species commonly seen at most reefs in 2022 including a) Günther's wrasse, b) green moon wrasse, and c) crimsonband wrasse and common cleaner fish.

3.3.3 Trophic Composition and Habitat Preference

The contribution of different trophic levels to the diversity of fish assemblages (trophic composition) did not differ substantially among most reefs (Figure 3.22). Carnivorous species were the most diverse group at all reefs (40 to 58% of species, excluding Palm Beach Bait Reef, which had limited data), with omnivores generally the next most diverse group (21 to 22% of species), except at Palm Beach Reef (10%) and Palm Beach Bait Reef (which had limited data). While there was some variation in the proportion of herbivores, omnivores with herbivorous tendencies and planktivores among reefs, these groups each contributed ≤ 20% to the trophic composition of fish assemblages at each reef. In May 2023, corallivores were generally the least diverse group and along with herbivores and omnivores were absent from the fish assemblage recorded at Palm Beach Bait Reef (Figure 3.22).

In the May 2023 survey, 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).

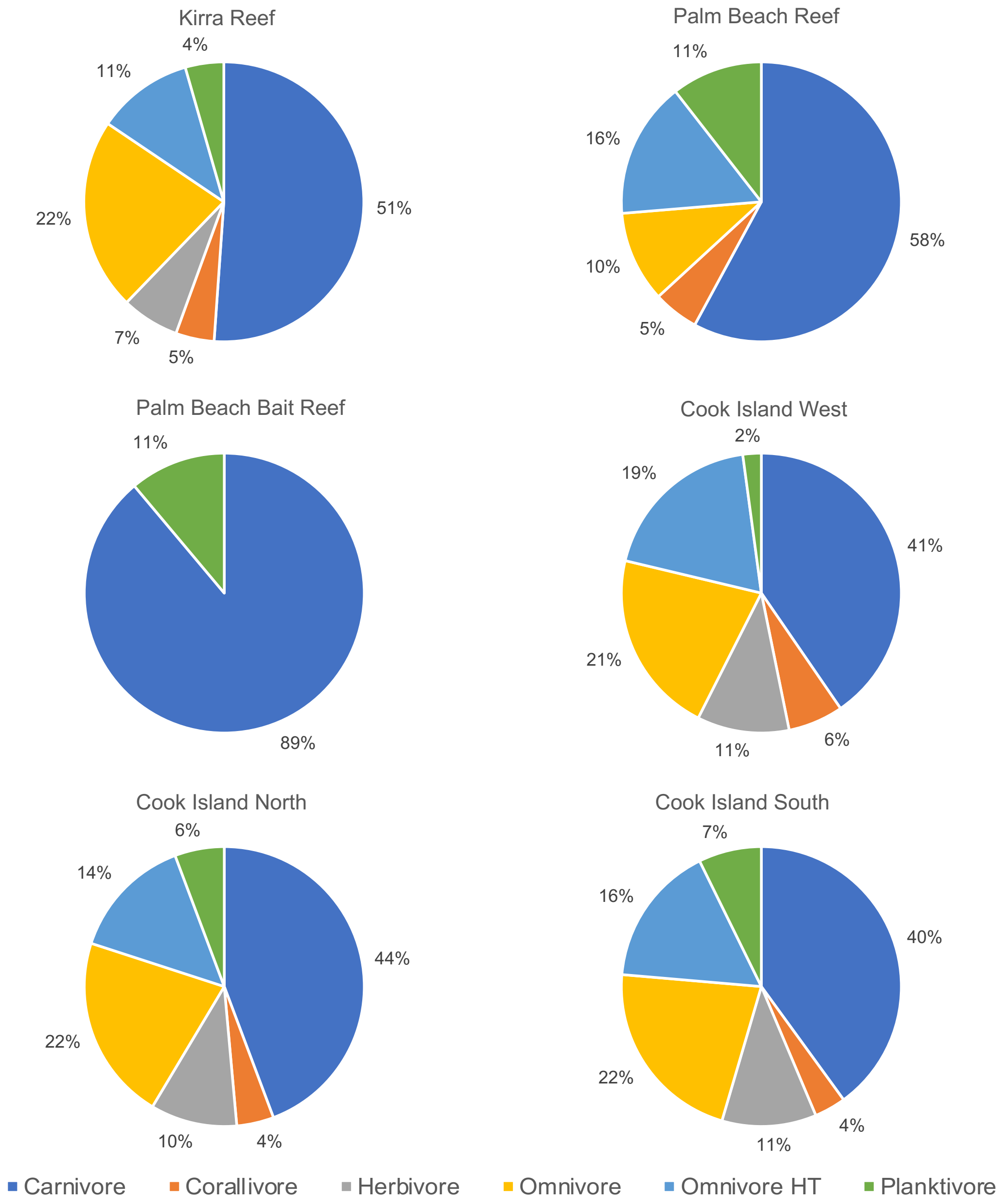


Figure 3.22 Trophic level composition of fish communities (% of species) recorded at each reef (based on UBRUVS, ROV and diver recordings)

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 (DCCEEW 2023), 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.
- southern right whale (*Eubalaena australis*), listed as endangered and migratory
- olive ridley turtle (*Lepidochelys olivacea*) listed as endangered and migratory, and
- green sawfish (*Pristis zijsron*) listed as vulnerable 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 3.23), which were recorded at all Cook Island reefs.

Figure 3.23 Green turtle (*Chelonia mydas*) at Cook Island West in 2023

3.4.2 Introduced Species

There are over 200 marine pests reported in Australian waters (DES 2023). 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) (NIMPIS 2023).

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, pH and salinity were relatively consistent across sites and with depth, although all Cook Island sites had slightly cooler temperatures than Palm Beach Bait Reef, Palm Beach Reef and Kirra Reef (Figure 3.24). The concentration of dissolved oxygen varied among sites, and was variable in the surface waters at Cook Island North and Cook Island West reefs (Figure 3.24). Turbidity was variable among sites and increased with depth at some sites (Figure 3.24).

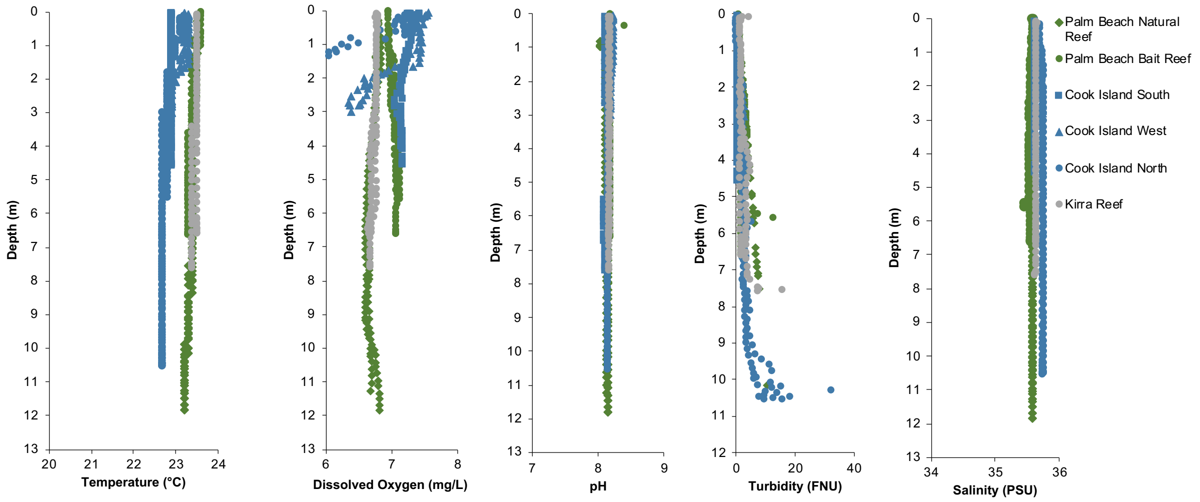
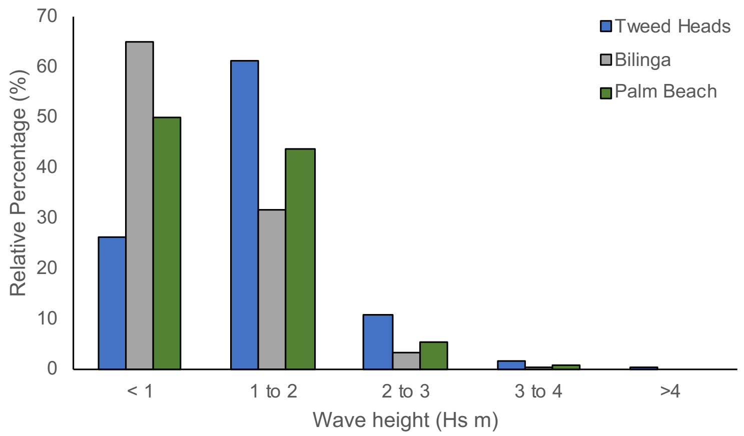


Figure 3.24 Vertical profiles of physicochemical water quality parameters among sites

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 2 May 2022 and 1 May 2023, swell direction was predominantly from the northeast and east at Tweed Heads and northeast at Bilinga and Palm Beach wave rider buoys (Figure 3.25 and Figure 3.26). Most waves were <1 m or 1 to 2 m, with <1 m waves most common at Bilinga and 1 to 2 m waves most common at Tweed Heads (Figure 3.25 and Figure 3.26Figure 3.26). During the period assessed, significant wave heights (>3 m) were rare (<2%) and predominantly from the north-east (Figure 3.25 and Figure 3.26). 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 (2 May 2022 and 1 May 2023) was typical of the region, with significant wave events unlikely to cause major changes to sand movements in the region.

a)



b)

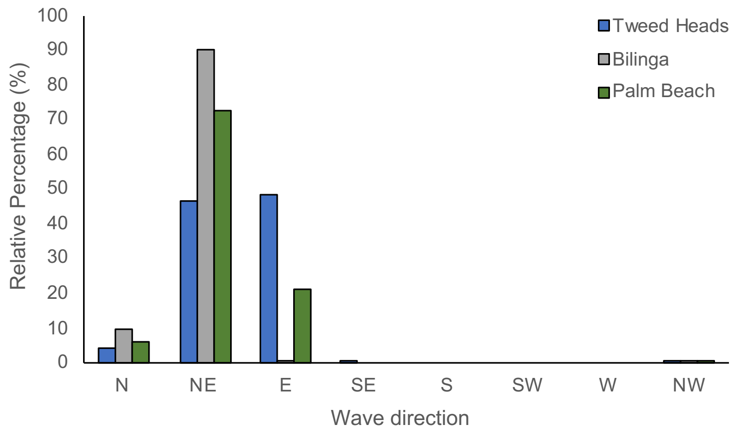


Figure 3.25 Wave data collected at Tweed Heads, Bilinga and Palm Beach wave rider buoys between 2 May 2022 and 1 May 2023, showing a) relative percent frequency of wave direction and; b) relative precent frequency of wave height

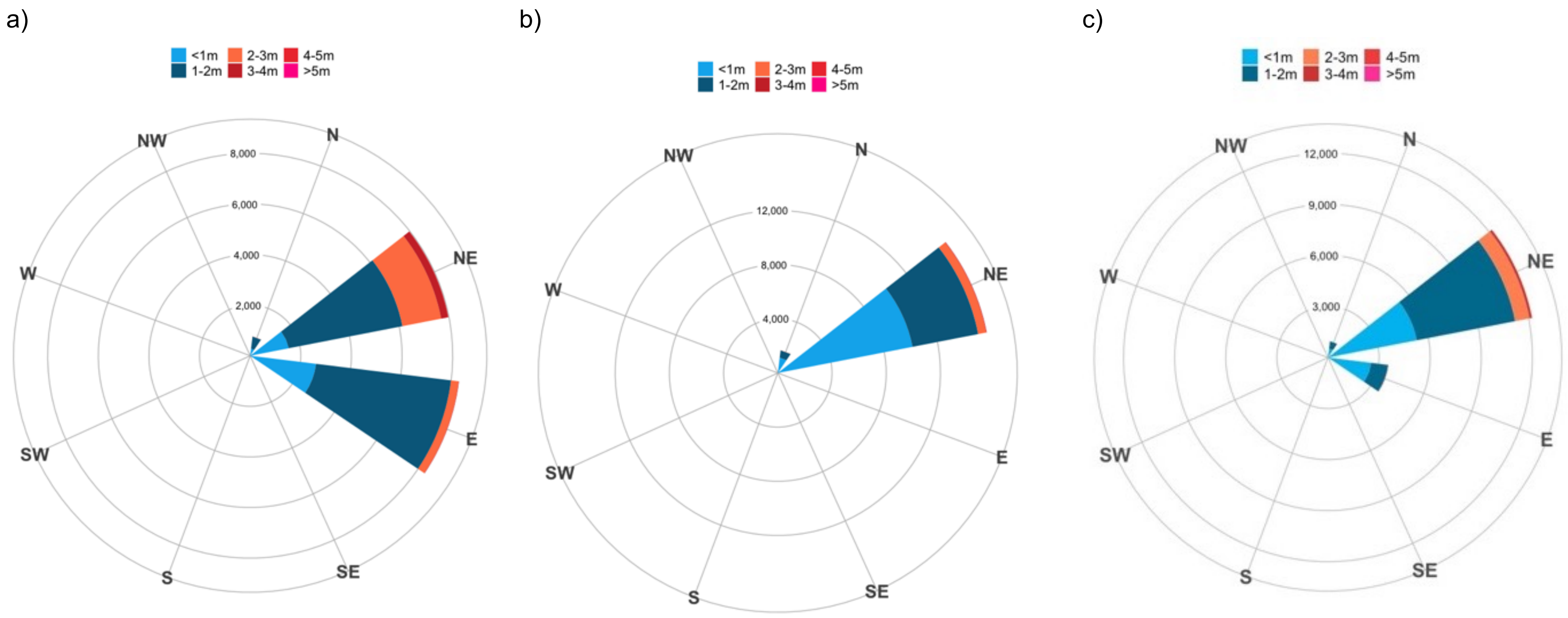


Figure 3.26 Wave height and direction between 2 May 2022 and 1 May 2023 at a) Tweed Heads wave rider buoy; b) Bilinga wave rider buoy and; c) Palm Beach wave rider buoy

4 Discussion and Conclusions

4.1 Changes in Reef Area at Kirra Reef

There have been large temporal changes in the area of exposed rock at Kirra Reef, with periods of sand burial and exhumation, resulting in changes to the benthic community growing on Kirra Reef. Prior to major artificial changes in sand movement (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 and increase in area in 2023, 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 April 2023, and changes in depth (based on 2019, 2020, 2021, 2022 and 2023 hydrographic surveys) indicated the reef area has not change significantly in recent years (it was 16% larger than 2022 and 15% smaller than 2021), and the water depth was generally deeper compared to recent years. The estimated areal extent of Kirra Reef was 3,492 m^2, comprised only of reef in the northern section. While the extent was larger in 2023 than 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 a balanced 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 biodiversity of the benthic community to increase, with the increased coverage of sessile invertebrates displacing early colonising species in some sections of the reef.

4.2 Benthic Communities

The benthic faunal and floral assemblages on Kirra Reef have undergone a process of ecological succession following exhumation in 2009, starting with the recruitment of pioneer species such as turf forming algae and foliose macroalgae. The benthic assemblages at Kirra Reef tend to be dominated by foliose and / or turf forming macroalgae and ascidians, with a low coverage of soft and hard corals. In 2023, the benthic communities on Kirra Reef remained different to those on nearby reefs. The composition of benthic assemblages has gradually become more similar in composition to reefs in the Gold Coast and Tweed Coast Region. In recent years the monitoring program has shown succession slowing with generally consistent differences in the composition of benthic assemblages on Kirra Reef and those at other reef locations indicative to the influence of prevailing environmental conditions. 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. The diverse benthic assemblage living on Kirra Reef 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 stable physical conditions to establish and grow to a point where they dominate the benthic assemblages.

4.2.1 Algal Assemblages

In 2023, the average coverage of foliose macroalgae (predominantly *Sargassum* spp.) had increased considerably on Kirra Reef compared with the previous two years, which correlates with the availability of bare rock habitat recently exhumed. In particular kelp (*Ecklonia radiata*) was recorded at Kirra Reef in 2023. Turf algae continues to dominate the benthic assemblages at Kirra Reef and elsewhere, accounting for 18% to 58% of the total coverage of the benthic assemblage at all reefs. The coverage of macroalgae prior to 2020 was very high compared with recent years (possibly due to spatial differences of locations through time or different sampling techniques). Between 2020 and 2022, the average coverage of macroalgae declined, which may be indicative of 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. The recent exhumation of rock at Kirra Reef has resulted in an increased coverage of foliose macroalgae at Kirra Reef with coverage similar to that observed prior to 2020.

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 2023 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 section of Kirra Reef is currently dominated by macroalgae including *Sargassum*. There was a relatively high proportion of bare habitat on horizontal surfaces at Kirra Reef in 2023 (indicative of sedimentation), and 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) may still occur around the reef fringe.

Of note, in May 2023 the patch of seagrass (dominated by *Halophila ovalis)* adjacent to the Cook Island West location had declined in coverage and extent relative to that observed in previous surveys. 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 2023, the sessile invertebrate assemblages on Kirra Reef were more similar to surrounding reefs both in terms of the overall coverage and average number of species. Ascidians and sponges remained the dominant sessile invertebrates on Kirra Reef, and while there continues to be a lack of abundant hard coral species on Kirra Reef, the coverage of soft corals has remained relatively stable since 2020. 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 benthic assemblages at Cook Island and Palm Beach reefs. The lack of hard and soft coral recruits may indicate a lack of larval supply or bottleneck to successful recruitment and survival on Kirra Reef. Generally, many of sessile invertebrates (including corals) growing on Kirra Reef are susceptible to impacts from smothering and sand scouring. The occurrence of a diverse group of sessile invertebrates on Kirra Reef in 2023, is indicative of assemblages continuing to recover from past impacts due to smothering of the entire reef. In contrast, the reefs around Cook Island generally had a moderate coverage of long-lived hard corals (such as those from the genus *Paragoniastrea, Turbinaria* and encrusting *Porites*) compared with other reefs in the region. Despite the higher proportion of hard corals around Cook Island, 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.

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 impacts from wave action. Reefs around cook Island are likely to have greater nutrient availability due to the large bird colonies in the area fertilising the water from their 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 this section of 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 diverse and more similar to reefs in the area.

4.2.3 Mobile Invertebrate Assemblages

In 2023, the density of mobile invertebrates was highest at Cook Island North and Kirra Reef, which was similar to 2022 (ESP 2022). Kirra Reef has previously had the highest density of mobile macroinvertebrates in 2020 and 2021, due to dense aggregations of feather stars (ESP 2020; ESP 2021). In previous years (2020, 2021 and 2022) echinoderms have dominated the assemblages; however, in 2023 feather stars had the highest density at all reefs, except Cook Island South, where sea stars had the highest density. In 2023, assemblages were most diverse at the Cook Island reefs and Palm Beach Reef, and least diverse at Kirra Reef.

4.3 Fish Assemblages

A total of 91 bony and cartilaginous fish species from 38 families were recorded among all reefs in May 2023. Similar to the 2020 and 2021 surveys (ESP 2020; ESP 2021), Labridae (wrasses) and Pomacentridae (damselfishes) were the most diverse families. Fish species recorded were generally common to the region, with most having been recorded during previous surveys; however, in the May 2023 survey, an additional six species were observed that had not been recorded in previous surveys.

In May 2023, the fish communities at Cook Island North were more diverse than recorded at all other reef locations; although, the overall composition of the community was generally similar among reefs (except for Cook Island North Reef compared to Cook Island South and Palm Beach reefs). Differences in fish assemblages among the reef locations may be related to poor water clarity limiting detection of cryptic species particularly at reefs closer to the shore. It may also be related to differences in the habitat complexity, benthic composition, availability of prey or other ecological interactions (e.g. predator abundance).

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 2023 survey. The eastern blue grouper (*Achoerodus viridis*) was recorded at Cook Island West and Cook Island North, 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 2023.

The species richness and total abundance of fish assemblages was highest at Cook Island North, and lowest at Palm Beach Reef and Palm Beach Bait Reef (with the latter site having limited data due to poor visibility in May 2023). There were several schools of fish dominating assemblages, including schools of yellowtail scad at Kirra Reef and silver sweep at Cook Island North. Carnivorous species dominated the fish assemblage on all reefs, and omnivorous fish were also common at most reefs, which is consistent with past surveys from 2020, 2021 and 2022 (ESP 2020; ESP 2021; ESP 2022). 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 periodically linked to the position of an offshore bar running along the beach.
- Benthic communities at Kirra Reef continue to be dominated by macroalgae and ascidians, with generally low coverage of soft and hard corals relative to other reefs. However, the benthic community on Kirra Reef displays good resilience to changes as evidenced by the increased coverage of macroalgae following exhumation of reef sections between 2022 and 2023, as the offshore bar along the beach moved further landwards.
- 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 and availability of recruits to colonise the reef habitat. Despite the apparent differences, the community on Kirra Reef has a diverse assemblage 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. Where possible event-based monitoring should be completed around June to allow for comparisons with existing data sets.

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		
April 2023	3,492	0	0	3,492	-	-
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 2023

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Orientation	1	94	4.66	**0.06**
Reef	4	311	37.26	0.003
Site (Reef)	10	8	1.99	**0.031**
Orientation x Reef	4	78	3.88	**0.032**
Orientation x Site (Reef)	10	20	4.77	**0.001**
Error	419	4		
Pairwise Comparisons	b) Horizontal		c) Vertical	
	t Value	P (MC)	t Value	P (MC)
KR vs PBR	5.68	**0.005**	4.95	**0.005**
KR vs CIW	1.23	0.271	1.82	0.139
KR vs CIS	0.93	0.396	5.42	**0.003**
KR vs CIN	2.48	0.063	1.65	0.193
CIW vs CIN	4.90	**0.010**	0.17	0.865
CIW vs CIS	2.10	0.092	2.01	0.111
CIW vs PBR	8.40	**0.001**	4.73	**0.011**
CIN vs CIS	0.91	0.408	2.25	0.091
CIN vs PBR	6.37	**0.002**	4.63	**0.013**
CIS vs PBR	3.78	**0.020**	8.46	**0.002**
d) Horizontal vs Vertical	t Value	P (MC)		
KR	2.79	0.11		
PBR	0.49	0.68		
CIW	2.93	0.09		
CIN	0.33	0.78		
CIS	0.63	0.56		

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 in 2023

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
	Horizontal	Vertical	Average dissimilarity = 59.6		
Sargassum spp	26.6	20.2	13.6	1.12	22.8
Polycarpa procera	11.5	21.4	12.0	1.20	20.0
Turf forming algae	18.2	22.4	10.6	1.19	17.7
Cribrochalina sp. 3	2.2	4.4	2.6	0.81	4.4
Jania sp	3.7	2.9	2.5	1.00	4.3
Herdmania momus	0.5	3.5	2.2	0.63	3.7

Table B.5.4 PERMANOVA of the difference in the composition of algal assemblages among reefs in 2023

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Orientation	1	7652	1.75	0.174
Reef	4	54829	12.37	**0.001**
Site (Reef)	10	4432	6.15	**0.001**
Orientation x Reef	4	9816	2.24	**0.030**
Orientation x Site (Reef)	10	4376	6.07	**0.001**
Error	419	720		
Pairwise Tests	b) Horizontal		c) Vertical	
	t Value	P (MC)	t Value	P (MC)
KR vs PBNR	7.56	**0.001**	5.24	**0.001**
KR vs CIW	2.69	**0.010**	1.21	0.261
KR vs CIS	5.10	**0.001**	3.36	**0.001**
KR vs CIN	8.35	**0.001**	4.90	**0.001**
CIW vs CIN	2.59	**0.017**	1.58	0.111
CIW vs CIS	2.22	**0.028**	1.09	0.336
CIW vs PBNR	2.70	**0.024**	1.45	0.162
CIN vs CIS	3.96	**0.001**	1.28	0.204
CIN vs PBNR	4.30	**0.005**	2.88	**0.014**
CIS vs PBNR	2.46	**0.011**	1.67	0.062

Table B.5.5 PERMANOVA of the difference in the coverage of algae among reefs in 2023

Source	df	a) Macroalgae MS	Pseudo-F	P (perm)	(d) Turfing Algae MS	Pseudo-F	P (perm)	(f) Coralline Algae MS	Pseudo-F	P (perm)
Orientation	1	27005	3.87	0.018	3591	3.31	0.101	163	1.19	0.296
Reef	4	107720	11.85	0.001	14874	8.82	**0.008**	1788	37.65	**0.001**
Site (Reef)	10	9093	6.13	0.001	1687	7.10	**0.001**	47	1.33	0.215
Orientation x Reef	4	14292	2.05	0.019	1973	1.82	0.202	259	1.89	0.200
Orientation x Site (Reef)	10	6974	4.70	0.001	1083	4.56	**0.001**	137	3.83	**0.001**
Error	419	1482			238			36		
Pairwise Tests	b) Horizontal		(c) Vertical		(e) Reef			(g) Reef		
	t-value	P(MC)	t-value	P(MC)	t-value	P(MC)		t-value	P(MC)	
KR vs PBNR	6.34	**0.001**	7.03	**0.001**	12.57	**0.002**		25.91	**0.001**	
KR vs CIW	2.96	**0.004**	0.93	0.486	1.82	0.148		2.70	0.055	
KR vs CIS	4.14	**0.001**	2.69	**0.003**	4.76	**0.008**		6.91	**0.005**	
KR vs CIN	10.13	**0.001**	5.22	**0.001**	10.31	**0.001**		4.98	**0.008**	
CIW vs CIN	3.73	**0.001**	1.61	0.125	2.45	0.064		3.56	**0.013**	
CIW vs CIS	2.61	**0.003**	0.97	0.455	1.13	0.326		6.48	**0.006**	
CIW vs PBNR	3.38	**0.003**	1.74	0.082	1.24	0.273		9.27	**0.003**	
CIN vs CIS	2.73	**0.005**	1.19	0.279	1.71	0.177		6.89	**0.005**	
CIN vs PBNR	3.29	**0.010**	2.04	0.067	3.26	**0.028**		7.73	**0.002**	
CIS vs PBNR	1.60	0.102	1.76	0.061	0.13	0.908		1.64	0.174	

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 = 61.7		
Turf	20.3	43.9	28.54	1.46	46.7
Sargassum	23.4	0.0	22.81	1.32	37.3
Jania	3.3	0.0	3.19	0.79	5.2
Coralline Algae	1.6	0.9	2.35	0.58	3.8
Turf	20.3	43.9	28.54	1.46	46.7
	Kirra	Cook Is. West	Average dissimilarity = 62.6		
Turf	20.3	34.3	19.45	1.2	31.1
Dictyota	1.9	24.1	17.31	0.88	27.7
Sargassum	23.4	10.7	16.91	1.25	27.0
Coralline Algae	1.6	3.8	3.32	0.64	5.3
	Kirra	Cook Is. North	Average dissimilarity = 65.2x		
Turf	20.3	54.4	29.21	1.71	44.8
Sargassum	23.4	0.0	17.62	1.3	27.0
Coralline Algae	1.6	10.0	7.86	0.95	12.1
Laurencia	0.4	7.1	5.77	0.93	8.9
	Kirra	Cook Is. South	Average dissimilarity = 60.3		
Turf	20.3	44.6	26.99	1.42	44.7
Sargassum	23.4	2.8	19.3	1.2	32.0
Laurencia	0.4	4.8	4.21	0.56	7.0
Dictyota	1.9	3.0	3.62	0.54	6.0
Jania	3.3	0.7	3.08	0.84	5.1
	Cook Is. West	Cook Is. North	Average dissimilarity = 53.7		
Turf	34.3	54.4	17.32	1.54	32.3
Dictyota	24.1	0.1	14.86	0.87	27.7
Sargassum	10.7	0.0	7.09	0.65	13.2
Coralline Algae	3.8	10.0	6.57	0.99	12.3
Laurencia	0.8	7.1	4.68	0.95	8.7
	Cook Is. West	Cook Is. South	Average dissimilarity = 53.8		
Turf	34.3	44.6	18.43	1.42	34.3
Dictyota	24.1	3.0	16.86	0.89	31.4
Sargassum	10.7	2.8	8.58	0.73	16.0
Laurencia	0.8	4.8	3.52	0.58	6.6
Coralline Algae	3.8	0.9	2.96	0.6	5.5
	Cook Is. North	Cook Is. South	Average dissimilarity = 38.0		
Turf	54.4	44.6	17.52	1.31	46.2
Coralline Algae	10.0	0.9	7.6	0.97	20.0
Laurencia	7.1	4.8	6.17	0.92	16.3
Sargassum	0.0	2.8	2.07	0.55	5.5
Dictyota	0.1	3.0	2.05	0.37	5.4
	Cook Is. West	Palm Beach	Average dissimilarity = 52.8		
Turf	34.3	43.9	18.39	1.46	34.9
Dictyota	24.1	0.0	18.06	0.87	34.2
Sargassum	10.7	0.0	8.75	0.65	16.6
Coralline Algae	3.8	0.9	3.26	0.61	6.2
	Cook Is. North	Palm Beach	Average dissimilarity = 33.0		
Turf	54.4	43.9	17.12	1.25	51.9
Coralline Algae	10.0	0.9	8.24	0.98	25.0
Laurencia	7.1	1.7	5.78	0.97	17.5
	Cook Is. South	Palm Beach	Average dissimilarity = 34.6		

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
Turf	44.6	43.9	21.23	1.31	61.3
Laurencia	4.8	1.7	4.74	0.64	13.7
Sargassum	2.8	0.0	2.65	0.55	7.7
Dictyota	3.0	0.0	2.51	0.36	7.3
Coralline Algae	0.9	0.9	1.69	0.51	4.9

Table B.5.7 PERMANOVA of the difference in the composition of sessile invertebrate assemblages among reefs in 2023

a) PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Orientation	1	32217	2.8713	0.018
Reef	4	80763	11.778	0.001
Site (Reef)	10	6857	2.4683	0.001
Orientation x Reef	4	13961	1.2443	0.215
Orientation x Site (Reef)	10	11221	4.0391	0.001
Error	419	2778		
Pairwise Tests	b) Reef			
	t Value	P (MC)		
PBNR vs KR	5.05	**0.001**		
CIN vs KR	5.01	**0.001**		
CIS vs KR	4.07	**0.001**		
CIW vs KR	3.70	**0.001**		
CIN vs CIS	2.62	**0.001**		
CIN vs CIW	2.53	**0.001**		
CIS vs CIW	2.44	**0.001**		
PBNR vs CIN	3.63	**0.001**		
PBNR vs CIS	2.73	**0.001**		
PBNR vs CIW	3.09	**0.001**		

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%
a)	**Kirra Reef**	**Palm Beach**	**Average dissimilarity = 95.5**		
Trichomya hirsuta	0	10.31	16.77	1.15	17.57
Polycarpa procera	11.53	0.84	15.35	0.9	16.08
Pyura stolonifera	0.4	3.69	6.8	0.75	7.12
Heteractis sp.	0.09	2.44	4.69	0.64	4.92
Dendronephtya sp. 2	0.4	2.8	4.57	0.72	4.79
Lobophyton sp. 2	0	2.13	4.4	0.59	4.61
Porites sp. 1	0	2.36	3.95	0.41	4.13
Cnemidocarpa stolonifera	2.09	0.49	3.81	0.73	3.99
Cribrochalina sp. 3	2.18	0.36	3.79	0.76	3.97
Cladiella sp. 1	0	1.82	2.83	0.45	2.96
b)	**Kirra Reef**	**Cook Is. West**	**Average dissimilarity = 98.5**		
Polycarpa procera	11.53	0.14	28.59	1.03	29.02
Herdmania momus	0.53	1.91	9.5	0.51	9.64
Cnemidocarpa stolonifera	2.09	0.05	9.37	0.62	9.51
Cribrochalina sp. 3	2.18	0	9.13	0.67	9.27
Zenia sp. 2	0.04	1.36	7.44	0.46	7.55
Pyura stolonifera	0.4	1.28	5.53	0.43	5.61
c)	**Kirra Reef**	**Cook Is. North**	**Average dissimilarity = 97.8**		
Polycarpa procera	11.53	0	19.32	0.93	19.75
Amphibalanus sp.	0	3.22	10.04	0.63	10.27
Porites sp. 1	0	2.37	5.65	0.57	5.78
Cnemidocarpa stolonifera	2.09	0.63	5.23	0.85	5.35
Turbinaria mesenterina	0	1.88	5.16	0.5	5.28
Cribrochalina sp. 3	2.18	0	5.07	0.8	5.18
Heteractis sp.	0.09	1.71	4.12	0.41	4.21
Entacmaea sp. 2	0.09	1.54	4.03	0.43	4.13
Herdmania momus	0.53	1.11	3.73	0.44	3.82
Didemnum membranaceum	0.13	1.26	3.02	0.38	3.09
Acropora sp. 1	0	1.12	2.78	0.41	2.84
Paragoniastrea australensis	0	0.73	2.07	0.41	2.11
d)	**Kirra Reef**	**Cook Is. South**	**Average dissimilarity = 98.9**		
Polycarpa procera	11.53	0.18	16.72	0.86	16.91
Lobophyton sp. 2	0	5.91	10.46	0.44	10.58
Cladiella sp. 1	0	4.71	8.78	0.51	8.88
Discosoma rhodostoma	0	6.36	8.12	0.45	8.21
Trichomya hirsuta	0	3.07	5.99	0.54	6.06
Porites sp. 1	0	3.47	5.95	0.44	6.02
encrusting porifera sp. 2	0	2.67	4.47	0.38	4.52
Cribrochalina sp. 3	2.18	0	4.36	0.65	4.41
Cnemidocarpa stolonifera	2.09	0.18	4.25	0.62	4.3
Paragoniastrea australensis	0	1.91	2.98	0.28	3.02
e)	**Cook Is. North**	**Cook Is. West**	**Average dissimilarity = 96.4**		
Amphibalanus sp.	3.22	0	12.24	0.67	12.7
Herdmania momus	1.11	1.91	8.05	0.65	8.36
Porites sp. 1	2.37	0.53	7.29	0.64	7.57
Turbinaria mesenterina	1.88	0	6.23	0.53	6.47
Heteractis sp.	1.71	0.73	6.11	0.53	6.34
Zenia sp. 2	0.36	1.36	5.12	0.6	5.32
Entacmaea sp. 2	1.54	0	4.62	0.43	4.8
Acropora sp. 1	1.12	0.09	3.44	0.45	3.57
Didemnum membranaceum	1.26	0	3.33	0.36	3.46
Pocillopora damicornis	0.67	0.64	3.29	0.51	3.42
Pyura stolonifera	0	1.28	2.89	0.38	2.99
Mycale sp.	0	1.09	2.82	0.37	2.93
Paragoniastrea australensis	0.73	0.15	2.65	0.45	2.75

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
f)	Cook Is. South	Cook Is. West	Average dissimilarity = 97.5		
Lobophyton sp. 2	5.91	0	12.24	0.47	12.55
Cladiella sp. 1	4.71	0.14	10.42	0.54	10.69
Discosoma rhodostoma	6.36	0	9.08	0.46	9.31
Porites sp. 1	3.47	0.53	7.39	0.49	7.58
Trichomya hirsuta	3.07	0.36	7.32	0.58	7.51
Herdmania momus	1.16	1.91	6.2	0.59	6.36
encrusting porifera sp. 2	2.67	0	5.11	0.4	5.24
Zenia sp. 2	0.04	1.36	3.89	0.44	3.99
Paragoniastrea australensis	1.91	0.15	3.53	0.3	3.62
Pocillopora damicornis	0.58	0.64	3.12	0.46	3.2
g)	**Cook Is. North**	**Cook Is. South**	**Average dissimilarity = 95.0**		
Lobophyton sp. 2	0.18	5.91	8.83	0.46	9.3
Cladiella sp. 1	0.41	4.71	7.91	0.56	8.33
Porites sp. 1	2.37	3.47	7.68	0.67	8.08
Discosoma rhodostoma	0	6.36	7.47	0.45	7.87
Amphibalanus sp.	3.22	0	6.53	0.64	6.87
Trichomya hirsuta	0.14	3.07	5.33	0.59	5.61
encrusting porifera sp. 2	0.18	2.67	4.19	0.41	4.41
Paragoniastrea australensis	0.73	1.91	3.9	0.41	4.11
Turbinaria mesenterina	1.88	0.09	3.59	0.49	3.78
Entacmaea sp. 2	1.54	0.58	3.53	0.46	3.72
Herdmania momus	1.11	1.16	3.43	0.57	3.62
Heteractis sp.	1.71	0.13	3.01	0.4	3.17
Platygyra lamellina	0.67	0.89	2.35	0.48	2.48
h)	**Palm Beach**	**Cook Is. West**	**Average dissimilarity = 95.3**		
Trichomya hirsuta	10.31	0.36	19.06	1.21	20.01
Pyura stolonifera	3.69	1.28	8.64	0.81	9.07
Heteractis sp.	2.44	0.73	5.96	0.72	6.26
Lobophyton sp. 2	2.13	0	5.21	0.62	5.47
Dendronephtya sp. 2	2.8	0.15	5.11	0.73	5.37
Porites sp. 1	2.36	0.53	5.03	0.47	5.28
Herdmania momus	0.44	1.91	4.47	0.55	4.69
Zenia sp. 2	0.53	1.36	3.55	0.54	3.73
Cladiella sp. 1	1.82	0.14	3.45	0.48	3.62
Turbinaria mesenterina	1.24	0	3.16	0.47	3.32
Lobophyton sp. 1	0.98	0	2.84	0.36	2.99
Sarcophyton sp. 1	1.02	0	2.11	0.53	2.21
i)	**Palm Beach**	**Cook Is. North**	**Average dissimilarity = 92.6**		
Trichomya hirsuta	10.31	0.14	15.01	1.2	16.22
Amphibalanus sp.	0.44	3.22	5.97	0.71	6.45
Porites sp. 1	2.36	2.37	5.94	0.64	6.41
Pyura stolonifera	3.69	0	5.91	0.79	6.38
Heteractis sp.	2.44	1.71	5.43	0.72	5.86
Turbinaria mesenterina	1.24	1.88	4.13	0.65	4.46
Dendronephtya sp. 2	2.8	0	4.03	0.72	4.35
Lobophyton sp. 2	2.13	0.18	3.54	0.7	3.83
Cladiella sp. 1	1.82	0.41	2.93	0.51	3.16
Entacmaea sp. 2	0	1.54	2.49	0.42	2.69
Herdmania momus	0.44	1.11	2.38	0.49	2.57
Acropora sp. 1	0.49	1.12	2.2	0.51	2.37
Lobophyton sp. 1	0.98	0.09	2.07	0.39	2.24
Didemnum membranaceum	0	1.26	1.86	0.35	2.01
Sarcophyton sp. 1	1.02	0.18	1.73	0.58	1.87
j)	**Cook Is. South**	**Palm Beach**	**Average dissimilarity = 93.4**		
Cladiella sp. 2	5.91	0.58	9.96	0.52	10.66
Cladiella sp. 1	3.16	0.67	6.56	0.47	7.02
Turbinaria mesenterina	1.82	2.4	6.43	0.64	6.88
Porites sp. 1	2.4	1.38	5.77	0.45	6.17
Trichomya hirsuta	0.22	2.71	5.42	0.75	5.81

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
Lobophyton sp. 1	3.11	0.27	5.11	0.42	5.47
Heteractis sp.	0.22	2.36	4.82	0.65	5.16
Pocillopora damicornis	1.82	0.58	3.96	0.68	4.24
Iotrochota sp. 1	0.84	1.07	3.08	0.7	3.3
Paragoniastrea australensis	0.62	0.8	2.92	0.37	3.13
Pyura stolonifera	0.62	0.89	2.68	0.6	2.87
Spheciospongia confoederata	0.18	1.07	2.32	0.44	2.48
Pseudodistoma inflatum	0.27	1.07	2.29	0.68	2.45
Polycarpa procera	0.49	0.76	2.07	0.53	2.22
Spheciospongia sp. 4	0.89	0.09	1.89	0.29	2.02
Amphibalanus sp.	0	0.89	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%
a)	**Kirra Reef**	**Palm Beach**	**Average dissimilarity = 92.1**		
Polycarpa procera	21.36	0.68	19.49	1.41	21.16
Trichomya hirsuta	1.94	14.4	13.13	1.16	14.26
Pyura stolonifera	0.68	9.47	9.39	0.93	10.2
Cribrochalina sp. 3	4.35	0.41	4.33	0.74	4.7
Herdmania momus	3.48	0.58	3.32	0.65	3.61
Heteractis sp.	0.48	2.27	2.63	0.63	2.85
Cladiella sp. 1	0	2.51	2.57	0.51	2.79
Callyspongia sp3	2.37	0.1	2.33	0.64	2.53
Spheciospongia confoederata	0.64	1.78	2.22	0.61	2.41
Cnemidocarpa stolonifera	1.98	0.71	2.18	0.95	2.36
encrusting porifera sp. 2	1.75	0.64	2.14	0.51	2.33
Lobophyton sp. 2	0	1.89	1.89	0.4	2.05
b)	**Kirra Reef**	**Cook Is. West**	**Average dissimilarity = 89.5**		
Polycarpa procera	21.36	1.68	26.3	1.44	29.39
Pyura stolonifera	0.68	7	9.6	0.88	10.73
Herdmania momus	3.48	3.17	6.43	0.78	7.18
Cribrochalina sp. 3	4.35	0.19	6.06	0.72	6.77
encrusting porifera sp. 2	1.75	1.81	3.94	0.61	4.4
Trichomya hirsuta	1.94	1.07	3.31	0.77	3.7
Cnemidocarpa stolonifera	1.98	0.84	3.22	0.76	3.6
Callyspongia sp3	2.37	0.11	3.18	0.62	3.56
Turbinaria mesenterina	0	1.95	2.4	0.32	2.69
c)	**Kirra Reef**	**Cook Is. North**	**Average dissimilarity = 95.2**		
Polycarpa procera	21.36	0.13	28.01	1.53	29.44
Herdmania momus	3.48	3.11	6.85	0.78	7.2
Cribrochalina sp. 3	4.35	0	6.33	0.74	6.65
Turbinaria mesenterina	0	3.04	4.77	0.62	5.02
Pyura stolonifera	0.68	2.43	4.05	0.62	4.26
encrusting porifera sp. 2	1.75	1.29	3.74	0.58	3.93
Callyspongia sp3	2.37	0.04	3.28	0.63	3.45
Cnemidocarpa stolonifera	1.98	0.14	3.12	0.89	3.27
Trichomya hirsuta	1.94	0.04	2.87	0.7	3.02
Porites sp. 1	0	1.67	2.62	0.53	2.75
Spheciospongia confoederata	0.64	1.25	2.48	0.55	2.61
d)	**Kirra Reef**	**Cook Is. South**	**Average dissimilarity = 97.0**		
Polycarpa procera	21.36	0	27.57	1.41	28.42
Cladiella sp. 1	0	9.2	10.57	0.73	10.89
encrusting porifera sp. 2	1.75	4.58	7.02	0.69	7.24
Cribrochalina sp. 3	4.35	0	6.18	0.7	6.38
Herdmania momus	3.48	0.06	4.39	0.61	4.53
Lobophyton sp. 2	0	2.92	3.91	0.53	4.03

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
Trichomya hirsuta	1.94	1.18	3.83	0.67	3.95
Callyspongia sp3	2.37	0.05	3.23	0.6	3.33
Cnemidocarpa stolonifera	1.98	0.27	3.18	0.78	3.28
e)	**Cook Is. North**	**Cook Is. West**	**Average dissimilarity = 87.6**		
Pyura stolonifera	2.43	7	12.12	0.99	13.84
Herdmania momus	3.11	3.17	8.52	0.91	9.73
Turbinaria mesenterina	3.04	1.95	7.61	0.68	8.69
encrusting porifera sp. 2	1.29	1.81	4.49	0.69	5.13
Porites sp. 1	1.67	0.66	4.09	0.59	4.68
Spheciospongia confoederata	1.25	0.86	3.55	0.56	4.06
Amphibalanus sp.	1.34	0.05	2.95	0.4	3.37
Polycarpa procera	0.13	1.68	2.91	0.38	3.33
Heteractis sp.	1.17	0.52	2.87	0.4	3.28
Echinopora sp.	0.04	1.7	2.53	0.25	2.89
Entacmaea sp. 2	1.09	0.09	2.32	0.37	2.65
Cnemidocarpa stolonifera	0.14	0.84	2.16	0.56	2.46
Acropora sp. 1	0.8	0.32	1.99	0.55	2.27
Dysidea sp. 5	0.76	0.12	1.98	0.31	2.26
Dendronephtya sp. 2	0.18	1.06	1.94	0.34	2.22
f)	**Cook Is. South**	**Cook Is. West**	**Average dissimilarity = 94.7**		
Cladiella sp. 1	9.2	0.09	12.72	0.76	13.44
Pyura stolonifera	0.63	7	12.19	0.89	12.87
encrusting porifera sp. 2	4.58	1.81	8.47	0.73	8.95
Herdmania momus	0.06	3.17	6.34	0.63	6.69
Lobophyton sp. 2	2.92	0	4.83	0.55	5.1
Turbinaria mesenterina	1.16	1.95	4.44	0.44	4.69
Trichomya hirsuta	1.18	1.07	3.66	0.55	3.87
Echinopora sp.	0.38	1.7	2.9	0.28	3.06
Polycarpa procera	0	1.68	2.73	0.34	2.89
Cnemidocarpa stolonifera	0.27	0.84	2.59	0.41	2.74
Acanthastrea sp. 2	0.78	0.74	2.28	0.31	2.41
Porites sp. 1	0.77	0.66	2.22	0.35	2.34
Spheciospongia confoederata	0.38	0.86	1.98	0.36	2.09
g)	**Cook Is. North**	**Cook Is. South**	**Average dissimilarity = 94.6**		
Cladiella sp. 1	0.23	9.2	13.3	0.8	14.07
encrusting porifera sp. 2	1.29	4.58	8.55	0.73	9.04
Turbinaria mesenterina	3.04	1.16	7.15	0.68	7.56
Herdmania momus	3.11	0.06	6.07	0.6	6.42
Lobophyton sp. 2	0.58	2.92	5.88	0.59	6.22
Pyura stolonifera	2.43	0.63	5.2	0.63	5.5
Porites sp. 1	1.67	0.77	4.25	0.61	4.49
Spheciospongia confoederata	1.25	0.38	3.11	0.49	3.29
Amphibalanus sp.	1.34	0	3.09	0.37	3.27
Trichomya hirsuta	0.04	1.18	2.61	0.43	2.76
Paragoniastrea australensis	0.91	0.65	2.51	0.49	2.65
Entacmaea sp. 2	1.09	0.12	2.36	0.35	2.5
Heteractis sp.	1.17	0.05	2.29	0.31	2.42
h)	**Palm Beach**	**Cook Is. West**	**Average dissimilarity = 86.2**		
Trichomya hirsuta	14.4	1.07	15.97	1.22	18.52
Pyura stolonifera	9.47	7	10.98	0.99	12.74
Herdmania momus	0.58	3.17	3.84	0.8	4.45
Heteractis sp.	2.27	0.52	3.06	0.65	3.55
Cladiella sp. 1	2.51	0.09	3.05	0.53	3.54
Turbinaria mesenterina	0.96	1.95	2.89	0.43	3.35
Spheciospongia confoederata	1.78	0.86	2.87	0.61	3.33
Porites sp. 1	1.54	0.66	2.48	0.51	2.88
encrusting porifera sp. 2	0.64	1.81	2.41	0.64	2.79
Dendronephtya sp. 2	1.33	1.06	2.4	0.52	2.78
Polycarpa procera	0.68	1.68	2.4	0.43	2.78
Lobophyton sp. 2	1.89	0	2.21	0.41	2.57
Cladiella sp. 2	1.85	0	2.17	0.2	2.51

Taxonomic Group	Average Abundance		Average Dissimilarity	Diss/SD	Contrib%
Tedania sp.	1.85	0	2	0.24	2.32
Echinopora sp.	0.14	1.7	1.87	0.26	2.16
i)	**Palm Beach**	**Cook Is. North**	**Average dissimilarity = 91.6**		
Trichomya hirsuta	14.4	0.04	17.27	1.3	18.86
Pyura stolonifera	9.47	2.43	10.92	0.97	11.93
Turbinaria mesenterina	0.96	3.04	4.27	0.73	4.67
Herdmania momus	0.58	3.11	3.98	0.68	4.35
Heteractis sp.	2.27	1.17	3.77	0.64	4.12
Porites sp. 1	1.54	1.67	3.35	0.72	3.65
Cladiella sp. 1	2.51	0.23	3.24	0.56	3.54
Spheciospongia confoederata	1.78	1.25	3.19	0.71	3.48
Lobophyton sp. 2	1.89	0.58	2.87	0.46	3.14
Cladiella sp. 2	1.85	0.04	2.3	0.21	2.52
encrusting porifera sp. 2	0.64	1.29	2.11	0.58	2.31
Tedania sp.	1.85	0	2.07	0.24	2.26
Amphibalanus sp.	0	1.34	1.78	0.44	1.95
Dendronephtya sp. 2	1.33	0.18	1.76	0.48	1.92
Porites lutea	1.29	0	1.54	0.28	1.69
j)	**Cook Is. South**	**Palm Beach**	**Average dissimilarity = 91.5**		
Trichomya hirsuta	1.18	14.4	16.01	1.2	17.51
Pyura stolonifera	0.63	9.47	10.94	0.93	11.96
Cladiella sp. 1	9.2	2.51	9.85	0.88	10.77
encrusting porifera sp. 2	4.58	0.64	5.21	0.66	5.7
Lobophyton sp. 2	2.92	1.89	4.57	0.69	4.99
Heteractis sp.	0.05	2.27	2.9	0.59	3.17
Spheciospongia confoederata	0.38	1.78	2.6	0.55	2.85
Porites sp. 1	0.77	1.54	2.54	0.54	2.78
Turbinaria mesenterina	1.16	0.96	2.21	0.48	2.42
Cladiella sp. 2	0	1.85	2.18	0.2	2.38
Porites lutea	0.75	1.29	2.16	0.36	2.37
Tedania sp.	0	1.85	2	0.23	2.19
Lobophyton sp. 3	1.09	0.38	1.59	0.33	1.74

Table B.5.10 PERMANOVA of the difference in the taxonomic richness of sessile invertebrates among reefs in 2023

a) PERMANOVA Source		(a) Taxonomic Richness				(b) % Coverage		
	df	MS	Pseudo-F	P(perm)		MS	Pseudo-F	P(perm)
Orientation	1	94	4.66	0.06	1414 9	8.45	0.016	94
Reef	4	311	37.26	0.003	1103 9	9.93	0.004	311
Site (Reef)	10	8	1.99	0.031	1111	4.34	0.001	8
Orientation x Reef	4	78	3.88	0.032	3842	2.29	0.138	78
Orientation x Site (Reef)	10	20	4.77	0.001	1675	6.54	0.001	20
Error	419	4			256			4
	(c) Horizontal		(d) Vertical			(e) Reef		
Pairwise Tests	t Value	P (MC)	t Value	P (MC)		t Value	P (MC)	
PBNR vs KR	5.68	0.005	4.95	0.005		7.61	0.001	
CIN vs KR	2.48	0.063	1.65	0.176		5.02	0.005	
CIS vs KR	0.93	0.396	5.42	0.008		0.26	0.815	
CIW vs KR	1.23	0.271	1.82	0.136		3.05	0.035	
CIN vs CIS	0.91	0.408	2.25	0.075		1.64	0.195	
CIN vs CIW	4.90	0.010	0.17	0.858		0.99	0.374	
CIS vs CIW	2.10	0.092	2.01	0.101		1.94	0.127	
PBNR vs CIN	6.37	0.002	4.63	0.015		16.2 0	0.001	
PBNR vs CIS	3.78	0.020	8.46	0.002		2.12	0.082	
PBNR vs CIW	8.40	0.001	4.73	0.011		6.93	0.003	

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 2023)

PERMANOVA Source	**df**	**(a) Horizontal MS**	**Pseudo-F**	**P(perm)**				
Survey	6	61145	63.1	**0.001**				
Reef	7	107120	110.5	**0.001**				
Survey x Reef	24	12897	13.3	**0.001**				
Error	1698	970						
Pairwise Tests	b) 2016	c) 2017	d) 2018	e) 2019	f) 2020	g)2021	h)2022	i)2023
	t Value	t Value	t Value	t Value	t Value	t Value	t Value	t Value
KR vs PBNR	10.4**		6.2**	4.8**	8.6**	7.1**	4.1**	7.7**
KR vs PBBR					5.4**	6.5**		
KR vs CIW		5.7**	3.5**	4.6**	8.2**	7.6**	3.0**	3.2**
KR vs CIS					10.5**	8.3**	4.0**	5.1**
KR vs CIN	5.4**	4.6**	4.6**	4.5**	10.6**	7.6**	3.7**	6.8**
CIW vs CIN		2.2**	1.7*	1.2	5.8**	6.3**	2.6**	6.5**
CIW vs CIS					6.2**	7.3**	2.1**	5.1**
CIW vs PBNR			3.5**	5.3**	10.6**	6.9**	2.9**	8.4**
CIN vs CIS					3.2**	4.3**	3.0**	3.6**
CIN vs PBNR			4.1**	5.7**	8.6**	5.1**	4.7**	5.5**
CIS vs PBNR					9.2**	6.8**	4.0**	3.1**
KR vs KC	4.2**			2.0*				
PBNR vs KC	8.0**			4.7**				
KC vs CIN	3.6**							
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****			
2022 vs 2023	**6.06****	**4.72****	**3.41****	**7.33****	**3.18****			

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

Table B.5.12 Comparisons of sessile assemblages on **Vertical** surfaces among reefs and survey periods (2016 to 2023)

		(a) Vertical			
PERMANOVA Source	**df**	**MS**	**Pseudo-F**	**P(perm)**	
Survey	6	52791	73.8	0.001	
Reef	7	18320	25.6	0.001	
Survey x Reef	24	11623	16.3	0.001	
Error	1698	715			
Pairwise Tests	b) 2016	c) 2020	d)2021	e)2022	f)2023
	t Value	t Value	t Value	t Value	t Value
KR vs PBNR	7.0**	13.3**	4.9**	5.9**	6.1**
KR vs CIW		9.7**	5.0**	4.3**	3.8**
KR vs CIS		11.2**	6.2**	4.2**	6.7**
KR vs CIN	5.8**	11.5**	5.1**	4.8**	7.9**
CIW vs CIN		5.0**	3.9**	3.6**	4.4**
CIW vs CIS		4.9**	5.3**	3.4**	3.6**
CIW vs PBNR		9.1**	5.2**	3.0**	4.2**
CIN vs CIS		1.6*	3.2**	2.5**	3.9**
CIN vs PBNR	3.5**	6.1**	3.7**	6.3**	5.3**
CIS vs PBNR		6.4**	5.1**	5.0**	4.2**
KR vs KC	6.0**				
PBNR vs KC	3.2**				
KC vs CIN	1.6*				
KC vs CIW					
g) Pairwise comparison within reefs over time	Kirra	Palm Beach	Cook Island North	Cook Island West	Cook Island South
2016 vs 2020	**4.4****	**5.8****	**5.3****		
2020 vs 2021	**5.3****	**7.4****	**3.2****	**3.6****	**2.9****
2021 vs 2022	**3.3****	**4.8****	**3.7****	**4.1****	**2.5****
2022 vs 2023	**5.1****	**5.5****	**3.9****	**4.8****	**3.7****

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

Table B.5.13 SIMPER differences in sessile assemblages at Kirra Reef among survey periods (2016 to 2023)

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
	2022	2023	Average dissimilarity = 57.88		
Turf Algae	48.9	20.3	18.8	1.4	32.5
MACROALGAE	3.8	26.0	14.0	1.2	24.2
Ascidian	17.5	22.6	11.6	1.2	20.0
Sponge	9.7	8.0	5.3	1.0	9.2
Coralline Algae	3.3	4.9	2.9	1.0	5.0

Table B.5.14 SIMPER differences in sessile assemblages at Cook Island North Reef among survey periods (2016 to 2023)

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
	2022	2023	Average dissimilarity = 38.9		
Turf Algae	45.8	54.4	9.2	1.4	23.7
Coralline Algae	14.6	12.1	6.1	1.2	15.8
Hard coral	13.3	9.1	5.9	1.1	15.2
Sponge	11.2	2.8	5.0	1.0	13.0
Ascidian	7.8	4.9	4.0	1.0	10.3
Macroalgae	0.0	7.2	3.7	0.9	9.6
Barnacle	2.3	2.3	1.8	0.8	4.6

Table B.5.15 SIMPER differences in sessile assemblages at Cook Island South Reef among survey periods (2020 to 2023)

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
	2022	2023	Average dissimilarity = 52.0		
Turf Algae	45.5	44.6	11.9	1.3	22.9
Soft Coral	13.2	13.6	10.1	1.0	19.4
Macroalgae	0.1	11.6	6.3	0.6	12.2
Hard coral	9.4	7.7	6.1	0.9	11.7
Sponge	10.4	4.5	6.1	0.8	11.6
Coralline Algae	11.1	1.7	5.6	1.0	10.7
Zoanthid	0.2	3.9	2.1	0.3	4.1

Table B.5.16 SIMPER differences in sessile assemblages at Cook Island West Reef among survey periods (2017 to 2023)

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
	2022	2023	Average dissimilarity = 57.7		
Macroalgae	0.6	36.0	19.3	1.2	33.5
Turf Algae	56.5	34.3	15.9	1.5	27.5
Coralline Algae	9.2	6.5	5.6	0.9	9.7
Hard coral	8.5	4.4	5.4	0.7	9.4
Ascidian	4.8	8.5	4.2	0.8	7.2
Sponge	5.0	3.1	3.0	1.0	5.1

Table B.5.17 SIMPER differences in sessile assemblages at Palm Beach Reef among survey periods (2016 to 2023)

Taxonomic Group	Average Abundance		Average Dissimilarity	Dissimilarity/SD	Contribution%
	2016	2018	Average dissimilarity = 77.4		
Ascidian	5.7	65.1	30.7	1.9	39.7
Turf Algae	62.0	17.5	25.8	1.9	33.3
Sponge	11.4	0.1	5.9	1.2	7.6
Hard coral	5.5	4.3	4.3	0.6	5.5
Coralline Algae	8.3	0.9	4.1	1.2	5.3
	2018	2019	Average dissimilarity = 69.4		
Ascidian	65.1	19.7	26.8	1.8	38.7
Turf Algae	17.5	28.5	15.5	1.9	22.3
Macroalgae	3.8	22.2	10.8	1.3	15.5
Soft Coral	1.5	10.2	5.4	0.8	7.9
Anemone	2.2	6.9	4.1	0.8	5.8
	2019	2020	Average dissimilarity = 64.4		
Turf Algae	28.5	80.2	27.0	3.4	42.0
Macroalgae	22.2	0.3	11.5	1.4	17.9
Ascidian	19.7	2.9	9.1	1.1	14.1
Soft Coral	10.2	1.6	5.4	0.8	8.4
Sponge	2.0	7.8	3.8	1.2	5.9
Anemone	6.9	1.1	3.6	0.8	5.5
	2020	2021	Average dissimilarity = 36.4		
Turf Algae	80.2	56.7	12.6	1.6	34.7
Ascidian	2.9	15.6	7.0	1.2	19.2
Bivalves	0.0	12.4	6.4	0.9	17.6
Sponge	7.8	3.3	3.5	1.2	9.6
Hard coral	0.8	3.3	1.9	0.6	5.3
Coralline Algae	0.8	3.0	1.7	0.6	4.6
	2021	2022	Average dissimilarity = 35.4		
Turf Algae	56.7	68.3	9.0	1.4	25.4
Ascidian	15.6	3.8	6.7	1.2	18.9
Bivalves	12.4	2.6	6.0	0.9	16.9
Hard coral	3.3	7.4	4.0	0.9	11.3
Sponge	3.3	5.2	2.7	1.1	7.5
Coralline Algae	3.0	2.4	2.1	0.7	6.0
Soft Coral	1.4	4.1	2.1	0.8	5.9
	2022	2023	Average dissimilarity = 42.1		
Turf Algae	68.3	43.9	14.0	1.5	33.2
Bivalves	2.6	12.4	5.8	1.1	13.8
Soft Coral	4.1	9.9	4.8	0.8	11.3
Ascidian	3.8	10.7	4.7	1.0	11.1
Hard coral	7.4	6.7	4.4	1.0	10.5
Sponge	5.2	5.6	3.3	0.9	7.7
Anemone	2.1	2.4	1.7	0.9	4.0

Table B.5.18 PERMANOVA of the difference in the fish assemblages among reefs in 2023

PERMANOVA Source	df	MS	Pseudo-F	P(perm)
Reef	5	4810.6	2.2923	**0.001**
Error	10	2098.5		
Pairwise Tests	t Value	P (MC)		
CIN, CIS	1.87	**0.049**		
CIN, CIW	1.48	0.126		
CIN, KR	1.78	0.058		
CIN, PBBR	2.61	0.057		
CIN, PBR	1.99	**0.035**		
CIS, CIW	1.09	0.340		
CIS, KR	1.57	0.105		
CIS, PBBR	1.72	0.151		
CIS, PBR	1.60	0.078		
CIW, KR	1.34	0.170		
CIW, PBBR	1.34	0.242		
CIW, PBR	1.29	0.194		
KR, PBBR	1.37	0.251		
KR, PBR	1.34	0.198		
PBBR, PBR	1.15	0.370		

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.5.19 SIMPER of the differences in the fish assemblages

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
	Cook Island North	Cook Island South	Average dissimilarity = 67.8		
Abudefduf whitleyi	1.59	0.33	2.1	2.0	3.1
Naso unicornis	1.27	0.00	2.0	3.3	3.0
Scorpis lineolata	1.39	0.33	1.9	1.0	2.8
Thalassoma nigrofasciatum	1.23	0.00	1.9	5.6	2.8
Parma unifasciata	1.11	0.00	1.7	4.0	2.5
Parupeneus spilurus	0.00	1.06	1.7	3.8	2.5
Acanthurus grammoptilus	0.00	0.97	1.7	1.3	2.5
Thalassoma lunare	1.06	0.00	1.7	4.6	2.4
Abudefduf vaigiensis	1.31	0.50	1.6	1.5	2.3
Thalassoma lutescens	1.32	0.40	1.6	1.5	2.3
Pomacentrus coelestis	1.13	0.40	1.6	1.2	2.3
Rhynchobatus australiae	0.00	1.00	1.6	5.2	2.3
Acanthurus dussumieri	1.24	0.40	1.5	1.5	2.2
Stethojulis bandanensis	1.06	0.44	1.3	1.7	2.0
Scomberomorus commerson	0.88	0.00	1.3	1.2	2.0
Prionurus microlepidotus	0.47	0.86	1.3	1.1	2.0
Plagiotremus tapeinosoma	0.83	0.00	1.3	1.2	1.9
Fistularia commersonii	0.67	1.02	1.2	1.5	1.8
Parupeneus multifasciatus	0.40	0.94	1.2	1.2	1.8
Plectroglyphidodon dickii	0.73	0.00	1.2	1.3	1.8
Sufflamen chrysopterum	1.00	0.33	1.2	1.3	1.7
Morwong fuscus	0.00	0.73	1.1	1.2	1.7
Acanthurus sp. 1	0.33	0.88	1.1	1.3	1.7
Parma oligolepis	0.00	0.77	1.1	1.2	1.7
Atypichthys strigatus	0.73	0.00	1.1	1.3	1.6
Zanclus cornutus	0.67	0.00	1.1	1.3	1.6
Paracaesio xanthura	0.00	0.77	1.1	1.3	1.6
Kyphosus bigibbus	0.79	0.33	1.1	1.1	1.6
Achoerodus viridis	0.67	0.00	1.0	1.3	1.5
Halichoeres hortulanus	0.67	0.00	1.0	1.3	1.5
Orectolobus maculatus	0.33	1.00	1.0	1.3	1.5
Canthigaster bennetti	0.33	0.79	1.0	1.2	1.5
Cirrhitichthys falco	0.33	0.73	1.0	1.1	1.5
Lutjanus russellii	0.67	0.00	1.0	1.3	1.5
Anampses caeruleopunctatus	0.67	0.33	0.9	1.0	1.4
Dascyllus trimaculatus	0.00	0.56	0.9	0.7	1.4
	Cook Island North	Palm Beach Reef	Average dissimilarity = 91.7		
Abudefduf whitleyi	1.59	0.00	3.7	7.3	4.1
Thalassoma lutescens	1.32	0.00	3.1	8.7	3.4
*Acanthopagrus australis**	1.35	0.00	3.1	5.4	3.4
Abudefduf vaigiensis	1.31	0.00	3.1	6.4	3.4
Naso unicornis	1.27	0.00	3.0	3.7	3.3
Acanthurus dussumieri	1.24	0.00	2.9	6.3	3.2
Thalassoma nigrofasciatum	1.23	0.00	2.9	12.8	3.1
Parma unifasciata	1.11	0.00	2.6	5.2	2.8
Scorpis lineolata	1.39	0.67	2.5	1.1	2.8
Stethojulis bandanensis	1.06	0.00	2.5	6.6	2.7
Thalassoma lunare	1.06	0.00	2.5	6.6	2.7
Sufflamen chrysopterum	1.00	0.00	2.3	8.7	2.6
Plectroglyphidodon fasciolatus	1.00	0.00	2.3	8.7	2.6
Plectroglyphidodon gascoynei	1.00	0.00	2.3	8.7	2.6
Pomacentrus coelestis	1.13	0.33	2.3	1.4	2.5
Notolabrus gymnogenis	1.19	0.33	2.0	1.7	2.2

Species	Average MaxN (4th Root Transformed)		Average Dissimilarity	Dissimilarity/ SD	Contribution %
Scomberomorus commerson	0.88	0.00	2.0	1.3	2.2
Pseudolabrus guentheri	1.17	0.40	2.0	1.4	2.1
Plagiotremus tapeinosoma	0.83	0.00	1.9	1.2	2.1
Plectroglyphidodon dickii	0.73	0.00	1.8	1.3	2.0
Kyphosus bigibbus	0.79	0.00	1.8	1.3	1.9
Anampses caeruleopunctatus	0.67	0.00	1.7	1.3	1.8
Zanclus cornutus	0.67	0.00	1.7	1.3	1.8
Atypichthys strigatus	0.73	0.00	1.6	1.3	1.8
Achoerodus viridis	0.67	0.00	1.5	1.3	1.7
Halichoeres hortulanus	0.67	0.00	1.5	1.3	1.7
Siganus fuscescens	0.67	0.00	1.5	1.3	1.7
Fistularia commersonii	0.67	0.00	1.5	1.3	1.7
Chaetodon auriga	0.67	0.00	1.5	1.3	1.6

Table B.5.20 PERMANOVA of the difference in the fish species richness among reefs in 2023

a) PERMANOVA Source	(a) Max N			
	df	MS	Pseudo-F	P(perm)
Reef	5	289.73	4.2902	**0.020**
Error	10	67.53		
Pairwise Tests	t Value	P (MC)		
CIN, CIS	1.13	0.330		
CIN, CIW	3.42	**0.034**		
CIN, KR	3.18	**0.039**		
CIN, PBBR	7.86	**0.022**		
CIN, PBR	13.97	**0.001**		
CIS, CIW	1.03	0.370		
CIS, KR	0.91	0.420		
CIS, PBBR	1.02	0.388		
CIS, PBR	2.57	0.061		
CIW, KR	0.14	0.910		
CIW, PBBR	0.60	0.595		
CIW, PBR	1.98	0.127		
KR, PBBR	0.68	0.586		
KR, PBR	2.14	0.111		
PBBR, PBR	1.63	0.241		

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).

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	CIN	CIS	CIW
Class Asteroidea (sea stars)						
Pentagonaster dubeni	Mean	0.000	0.000	0.000	0.011	0.000
	S.E.	0.000	0.000	0.000	0.011	0.000
Linckia laevigata	Mean	0.000	0.000	0.000	0.011	0.011
	S.E.	0.000	0.000	0.000	0.011	0.011
Echinaster luzonicus	Mean	0.000	0.044	0.011	0.033	0.000
	S.E.	0.000	0.022	0.011	0.025	0.000
Class Crinoidea (feather stars)						
Cenolia glebosis	Mean	2.078	0.311	2.022	0.044	0.344
	S.E.	0.385	0.070	0.266	0.022	0.082
Oxycomanthus bennetti	Mean	0.256	0.011	0.000	0.000	0.200
	S.E.	0.112	0.011	0.000	0.000	0.098
Class Echinoidea (sea urchins)						
Diadema savignyi	Mean	0.000	0.033	0.789	0.078	0.133
	S.E.	0.000	0.025	0.122	0.028	0.042
Echinothrix calamaris	Mean	0.000	0.000	0.044	0.000	0.000
	S.E.	0.000	0.000	0.022	0.000	0.000
Heliocidaris erythrogramma	Mean	0.000	0.044	0.022	0.000	0.067
	S.E.	0.000	0.027	0.016	0.000	0.031
Phyllacanthus parvispinus	Mean	0.000	0.044	0.044	0.000	0.022
	S.E.	0.000	0.027	0.022	0.000	0.016
Class Holothuroidea (sea cucumbers)						
Actinopyga sp.	0.000	0.000	0.000	0.011	0.000	0.000
	0.000	0.000	0.000	0.011	0.000	0.000

Appendix D May 2023 Fish Species List

Table D.5.21 Fish species recorded in May 2023 survey, not recorded in previous surveys

Scientific Name	Common Name	Reef Recorded at
Balistidae		
Sufflamen bursa	pallid triggerfish	Cook Island North
Carangidae		
Trachinotus coppingeri	swallowtail dart	Cook Island West
Lutjanidae		
Paracaesio xanthura	false fusilier	Cook Island South
Lutjanus gibbus	paddletail	Palm Beach Bait Reef
Pomacanthidae		
Centropyge flavissima	lemonpeel angelfish	Cook Island North
Priacanthidae		
Priacanthus hamrur	lunartail bigeye	Cook Island West

Table D.5.22 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 2023 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	1				4	2
Acanthurus grammoptilus	inshore surgeonfish	H	R				6		9
Acanthurus sp. 1[16]	dusky or greyhead surgeonfish	H	R	*			1	1	3
Naso unicornis	bluespine unicornfish	H	R					5	
Prionurus microlepidotus	Australian sawtail	H	R				*	4	6
Apogonidae									
Ostorhinchus limenus	Sydney cardinalfish	CA	R		1				*
Balistidae									
Sufflamen bursa	pallid triggerfish	CA	R					1	
Sufflamen chrysopterum	eye-stripe triggerfish	CA	R	1	*			1	1
Blenniidae									
Plagiotremus tapeinosoma	piano fangblenny	CA	R					5	
Caesionidae									
Pterocaesio digramma	double-lined fusilier	P	R			25			
Carangidae									
Carangoides ferdau	blue trevally	CA	P/R	1					
Caranx sp.	unknown trevally	CA	P/R			18			
Scomberoides lysan	lesser queenfish	CA	P/R					1	

[16] This species is either *Acanthurus nigrofuscus* (dusky surgeonfish) or *Acanthurus nigroris* (greyhead surgeonfish) however, these two species are indistinguishable using the UBRUVS method.

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
Trachinotus coppingeri	swallowtail dart	CA	P/R				55		
Trachurus novaezelandiae	yellowtail scad	P	P	70	*				10
Chaetodontidae									
Chaetodon auriga	threadfin butterflyfish	C	R				1	1	1
Chaetodon citrinellus	citron butterflyfish	C	R	2			*	1	1
Chaetodon flavirostris	dusky butterflyfish	C	R	1	*		*	1	
Chaetodon guentheri	Günther's butterflyfish	O	R	*					
Chaetodon kleinii	Klein's butterflyfish	O	R	1					1
Chaetodon vagabundus	vagabond butterflyfish	O	R					*	1
Cirrhitidae									
Cirrhitichthys falco	dwarf hawkfish	CA	R		1		1	1	2
Paracirrhites forsteri	freckled hawkfish	CA	R					1	
Cirrhitichthys aprinus	blotched hawkfish	CA	R			1			
Dasyatidae									
Neotrygon kuhlii	bluespotted maskray	CA	R	1					
Dasyatidae (unidentified)	ray	CA	R	1					
Diodontidae									
Dicotylichthys punctulatus	threebar porcupinefish	CA	R		1	1		1	
Diodon hystrix	spotted porcupinefish	CA	R	1					
Echeneidae									
Echeneis naucrates	Australian remora	CA	P/R				1		
Enoplosidae									
Enoplosus armatus	old wife	CA	R						*
Ephippidae									
Platax teira	roundface batfish	O	R					3	

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
Fistulariidae									
Fistularia commersonii	smooth flutemouth	CA	R	1			1	1	6
Gerreidae									
Gerres subfasciatus	common silverbiddy	CA	P	2					
Haemulidae									
Diagramma pictum labiosum	painted sweetlips	CA	P/R	1			1	1	1
Plectorhinchus flavomaculatus	goldspotted sweetlips	CA	P/R					*	*
Kyphosidae									
Kyphosus bigibbus	grey drummer	H	R	1			3	2	1
Labridae									
Achoerodus viridis	eastern blue groper	CA	R				1	1	
Anampses caeruleopunctatus	diamond wrasse	CA	R	*			1	1	1
Bodianus axillaris	goldspot pigfish	CA	R	*					
Cheilio inermis	sharpnose wrasse	CA	R	1					1
Choerodon graphicus	graphic tuskfish	CA	R					1	
Choerodon schoenleinii	blackspot tuskfish	CA	R					1	
Coris dorsomacula	pinklined wrasse	O	R				1		
Halichoeres hortulanus	checkerboard wrasse	O	R					1	
Halichoeres marginatus	dusky wrasse	CA	R					1	
Halichoeres nebulosus	cloud wrasse	CA	R			1		1	3
Hemigymnus fasciatus	fiveband wrasse	O	R					*	
Labroides dimidiatus	common cleaner fish	CA	R	1	1		1	2	4
Notolabrus gymnogenis	crimsonband wrasse	CA	R	1	1		2	2	2
Pseudolabrus guentheri	Günther's wrasse	CA	R	5	2		5	3	2
Stethojulis bandanensis	redspot wrasse	CA	R					2	3

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	4			4	2	
Thalassoma lutescens	green moon wrasse	CA	R	1	*		1	3	2
Thalassoma nigrofasciatum[17]	blackbarred wrasse	O	R	1				3	
Labridae (unidentified)[17]	wrasse		R		1			1	1
Latridae									
Goniistius vestitus	crested morwong	O	R	1			1	1	1
Morwong fuscus	red morwong	O	R						2
Lutjanidae									
Lutjanus fulviflamma	blackspot snapper	CA	R			2		*	
Lutjanus russellii	Moses' snapper	CA	R	1				1	
Paracaesio xanthura	false fusilier	P	R						3
Lutjanus gibbus	paddletail	CA	R			1			
Microcanthidae									
Atypichthys strigatus	mado	O	R	3			*	2	
Microcanthus strigatus	stripey	O	R	2				*	*
Monodactylidae									
Monodactylus argenteus	silver moony	P	P					13	
Schuettea scalaripinnis	eastern pomfred	P	P				*	*	*
Mullidae									
Parupeneus multifasciatus	banded goatfish	CA	R	1		1	3	2	5
Parupeneus spilurus	blacksaddle goatfish	CA	R	3		11	1		2
Muraenidae									

[17] 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*.
[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
Gymnothorax thyrsoideus	greyface moray	CA	R	1					
Myliobatidae									
Aetobatus ocellatus	whitespotted eagle ray	CA	P/R	*					
Nemipteridae									
Scolopsis monogramma	rainbow monacle bream	CA	R			1			
Orectolobidae									
Orectolobus maculatus	spotted wobbegong	CA	R	1			1	1	1
Orectolobus ornatus	banded wobbegong	CA	R		1				
Ostraciidae									
Ostracion cubicum	yellow boxfish	O - HT	R						1
Pempheridae									
Pempheris affinis	blacktip bullseye	P	R					*	
Platycephalidae									
Platycephalus fuscus	dusky flathead	CA	R	1					
Pomacanthidae									
Centropyge bicolor	bicolour angelfish	O	R				*		
Centropyge flavissima	lemonpeel angelfish	H	R					*	
Centropyge tibicen	keyhole angelfish	O - HT	R	1			1	*	1
Centropyge vrolikii	pearlscale angelfish	O - HT	R					*	
Pomacentridae									
Abudefduf bengalensis	Bengal sergeant	O	R				3		
Abudefduf vaigiensis	Indo-Pacific sergeant	O	R	1			3	4	5
Abudefduf whitleyi	Whitley's sergeant	O	R					8	1
Amphiprion akindynos	Barrier Reef anemonefish	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
Amphiprion latezonatus	wideband anemonefish	O	R	*	1				*
Chromis margaritifer	whitetail puller	O	R	*			*	*	
Dascyllus reticulatus	headband humbug	O	R				*	*	
Dascyllus trimaculatus	threespot humbug	O	R	9	1			*	8
Parma oligolepis	bigscale scalyfin	O - HT	R		1		1		3
Parma polylepis	banded scalyfin	O - HT	R	*			2		
Parma unifasciata	girdled scalyfin	O - HT	R				1	3	
Plectroglyphidodon apicalis	yellowtip gregory	O - HT	R				*	2	*
Plectroglyphidodon dickii	Dick's damsel	O - HT	R					2	
Plectroglyphidodon fasciolatus	Pacific gregory	O - HT	R	1				1	1
Plectroglyphidodon gascoynei	Coral Sea gregory	O - HT	R	*				1	1
Pomacentrus chrysurus	whitetail damsel	O - HT	R				1		
Pomacentrus coelestis	neon damsel	O - HT	R	3	1		5	10	2
Priacanthidae									
Priacanthus hamrur	lunartail bigeye	CA	R				*		
Rhinidae									
Rhynchobatus australiae	whitespotted guitarfish	CA	R						1
Scombridae									
Scomberomorus commerson	Spanish mackerel	CA	P					7	
Scorpaenidae									
Pterois volitans	common lionfish	CA	R				*	1	
Scorpaena jacksoniensis	eastern red scorpionfish	CA	R						*
Scorpididae									
Scorpis lineolata	silver sweep	P	R	25	1			100	1
Serranidae									

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
Diploprion bifasciatum	barred soapfish	CA	R				*		
Siganidae									
Siganus fuscescens	black rabbitfish	H	R				3	1	1
Sparidae									
*Acanthopagrus australis**[19]	yellowfin bream*	CA	P/R				1	12	4
Sphyraenidae									
Sphyraena obtusata	striped barracuda	CA	P/R		*				
Synodontidae									
Synodus binotatus	twospot lizardfish	CA	R					*	1
Tetraodontidae									
Arothron hispidus	stars-and-stripes puffer	O	R				1		1
Arothron nigropuncatus	blackspotted puffer	O	R						1
Arothron stellatus	starry puffer	O	R					*	
Canthigaster bennetti	blackspot toby	O - HT	R				1	1	2
Canthigaster valentini	blacksaddle toby	O - HT	R		1		2	1	1
Zanclidae									
Zanclus cornutus	moorish idol	CA	R	*	*			1	
Unidentified species[20]					1				

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

[19] 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.

[20] 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.