Monitoring of Biota at Kirra Reef: 2019

Tweed River Entrance Sand Bypassing Project

Prepared for:

Coastal Infrastructure Unit
NSW Department of Industry – Crown Lands

frc environmental

PO Box 2363, Wellington Point QLD 4160
Telephone: + 61 3286 3850
Facsimile: + 61 3821 7936

frc reference: 181203

freshwater estuarine marine

Document Control Summary

Project No.:	181203
Status:	Final
Project Director:	Dr John Thorogood
Project Manager:	Lachlan Webster
Title:	Monitoring of Biota at Kirra Reef: 2019
Project Team:	Deya Angulo, Carol Conacher, Alex Munro, John Thorogood and Lachlan Webster.
Client:	Coastal Infrastructure Unit, NSW Department of Industry – Crown Lands
Client Contact:	Tui Williams / Matthew Harry
Date:	7 November 2019
Edition:	181203
Checked by:	Carol Conacher
Issued by:	John Thorogood

Distribution Record

Coastal Infrastructure Unit, NSW Department of Industry – Crown Lands: as pdf.

Contents

Tables

Figures

Maps

Summary

Kirra Reef has intrinsic ecological and conservation value and, is both a highly visible and iconic fishing and diving site on the southern Gold Coast. The extent and biodiversity of Kirra Reef varies naturally with the northerly longshore transport of sand and episodic storm events. Over the last 6 decades, Kirra Reef has been subject to changes in the rate of longshore drift and the intensity of wave action resulting from coastal management strategies, including the extension of the Tweed River training walls, installation of groynes, beach nourishment and the Tweed River Entrance Sand Bypassing Project (TRESBP). Rapid population growth and urban development have also increased pressure on reef ecosystems in the region, through sediment and nutrient runoff, habitat loss, boating and anchoring impacts, waste disposal, overfishing, aquarium trade collection and climate change.

The TRESBP was established in 1995 as a joint initiative of the New South Wales and Queensland Governments to improve and maintain navigation conditions at the Tweed River entrance and to provide a continuing supply of sand to the southern Gold Coast beaches consistent with the natural rate of longshore drift. Ongoing monitoring of Kirra Reef is required under *the Environmental Management System (EMS) Sub-Plan B14 Kirra Reef Management Plan*, prepared by the TRESBP in January 2010. This report discusses the results of ecological monitoring of benthic and fish communities at Kirra Reef in May 2019, and compares the results to previous monitoring in 1995, 1996, 2001, 2003, 2004, 2005, 2010, 2012, 2014, 2015, 2016, 2017 and 2018. In 2016, 2017 and 2018. Communities at Kirra Reef were compared to communities at Palm Beach, Cook Island North and Cook Island West (although none of these reefs are essentially similar in characteristics to Kirra Reef). In 2019, the floral and faunal communities of Kirra Reef were also compared to those of Kingscliff Reef. In the earliest surveys, communities at Kirra Reef were only compared to communities at Palm Beach Reef.

Benthic Communities

There are clear differences in benthic communities at Kirra Reef and Palm Beach, Kingscliff, Cook Island West and Cook Island North. Kirra Reef had a higher cover of the large brown alga *Sargassum* sp. and ascidians, and a lower cover of turf algae and hard corals (nil) than the other reefs.

While the benthic community at Kirra Reef has varied over time, macroalgae has remained dominant. Following the commencement of stage 2 of the TRESBP in 2001, the cover of macroalgae dramatically decreased, likely a result of the direct and indirect effects of 'catch-up' sand delivery. Most of Kirra Reef was buried by sand between 2006 and 2008. Since

2008, sand volumes delivered by the TRESBP have been consistent with the natural rate of longshore drift, and the cover of macroalgae increased between 2010 and 2016. The cover of macroalgae decreased from 2016 to 2017. This may have been a result of strong storms prior to sampling in 2017. Since 2017 the cover of macroalgae has again increased, and it is now at its highest since the commencement of stage 2 of the TRESBP in 2001.

The cover of soft and hard coral at Kirra Reef is naturally low and characteristic of shallow inshore reefs. Since the emergence of a large area of reef from sand burial in 2009, there has been little (<0.2% cover) or no soft coral and hard coral on the Kirra Reef. This may indicate the community is subject to frequent disturbance from shifting sands and wave action preventing recruitment and / or growth.

Fish Communities

As in previous years the fish community at Kirra Reef was dominated by large schools of yellowtail along with mado in lower abundance. Reef associated species present at Kingscliff and Cook Island, such as Indo-Pacific sergeant and Whitley's sergeant, along with the large schools of yellowtail present at Kirra Reef largely contributed to the differences in fish communities between reefs. These differences in fish communities are likely to be due to a combination of factors, including differences in topography, benthic communities influencing food availability, and fishing activity at Kirra Reef, Kingscliff and Palm Beach compared to the protected Cook Island reefs.

Reef Area

The greatest change to the ecological condition of Kirra Reef since the commencement of the TRESBP has been the burial of large areas of hard substrate that support benthic flora and fauna. In particular, the delivery of large volumes of sand during the stage 1 TRESBP (1995 to 1998), and the initial operation of the sand bypass system (2001 to 2008), resulted in a significant increase in the beach width at Kirra, with wave action and tidal currents redistributing sand over Kirra Reef, reducing its overall extent. This was predicted in the project's Environmental Impact Statement (EIS) in 1997, and in 2001 the EMS predicted that the extent of Kirra Reef would return to conditions prior to 1962 when the extension of the Tweed River training walls depleted sand supplies to the area. Overall, the extent of Kirra Reef has remained relatively constant for the last six years. Over this period the delivery of sand by the TRESBP has mimicked natural rates of longshore drift, and storm activity has been moderate. While a period of increased storm activity may result in an increase in the exposed area of Kirra Reef in the short-term, over the long-term it is unlikely the reef will significantly increase in area.

Future Monitoring

While the number of comparative sites has increased, and now includes reefs around Cook Island, none of the comparative sites provide an ‘ideal match’ for Kirra Reef. Kirra Reef is unique in the region, being completely surrounded by mobile sand. It is likely that the ‘rocks’ off the north-eastern tip of Stradbroke Island (such as Manta Bommie) may serve as a better comparative site for future monitoring.

Glossary

AHD	Australian Height Datum
ANOSIM	Analysis of Similarities
BRUVS	Baited Remote Underwater Video Station
CPCe	Coral Point Cover with Excel extensions
df	Degrees of Freedom
DO	Dissolved Oxygen
EC	Electrical Conductivity
EIS	Environmental Impact Statement
EMS	Environmental Management System
EPBC	Environment Protection and Biodiversity Conservation
F	F- ratio, the statistic used to test whether means are statistically different
GIS	Geographic Information Software
IPO	Interdecadal Pacific Oscillation
maxN	Maximum Number of individuals in a given timeframe
MS effect	Mean Square value, calculated by dividing sum-of-squares by degrees of freedom
nMDS	non-Metric Multidimensional Scaling
NSW	New South Wales
NTU	Nephelometric Turbidity Units
p	p value, the calculated probability of a statistically significant difference
PERMANOVA	Permutational Multivariate Analysis Of Variance
ROV	Remotely Operated Vehicle
SE	Standard Error
SIMPER	Similarity Percentage
SST	Sea Surface Temperature
STDev	Standard Deviation
t	t-statistic, the ratio of departure of the hypothesized value from its standard error
TRESBP	Tweed River Entrance Sand Bypassing Project

1 Introduction

1.1 The Kirra Reef Biota Monitoring Program

Kirra Reef is the collective name given to the complex of rocky outcrops a few hundred metres offshore of Kirra Beach on the southern Gold Coast, at approximately −5 m Australian Height Datum (AHD). The reef is naturally subject to shifting sands and storm events that intermittently cover and uncover parts of the reef (TRESBP 2015). The extent of exposure of Kirra Reef has also varied due to anthropogenic changes to the coastal environment that have included the extension of the Tweed River training walls in 1964 and the commencement of the Tweed River Entrance Sand Bypassing Project (TRESBP) in 2001 (WorleyParsons 2009). Rapid population growth and urban development have contributed to elevated sediment and nutrient runoff from the catchment, anchoring impacts, and to litter and overfishing (including for the aquarium trade) (Loder et al. 2013).

Ongoing monitoring of Kirra Reef is required under *the Environmental Management System (EMS) Sub-Plan B14 Kirra Reef Management Plan*, prepared by the TRESBP in January 2010. Under *EMS Sub-Plan B14 Kirra Reef Management Plan*, if the area of exposed reef on aerial photography is smaller than the range of areas shown on aerial photographs from 1962 to 1965, then monitoring of marine biota of Kirra Reef is triggered.

Kirra Reef has intrinsic ecological and conservation value, and is a highly visible and iconic fishing and diving site on the southern Gold Coast. The Kirra Reef Biota Monitoring Program contributes to an understanding of how the sand bypassing system directly impacts Kirra Reef, and also how the placement of sand interacts with a range of natural factors that influence the physical extent of the reef, its biodiversity, and the abundances of its biota.

1.2 History of the Tweed River Entrance Sand Bypassing Project

The TRESBP was established in 1995 as a joint initiative of the New South Wales (NSW) and Queensland Governments to improve and maintain navigation conditions at the Tweed River entrance and to provide a continuing supply of sand to the southern Gold Coast beaches that is consistent with the natural rate of longshore drift. The project has two stages:

- Stage 1: Initial dredging and nourishment works (April 1995 to May 1998), and
- Stage 2: Implementation of a sand bypassing system to maintain the improvements achieved during Stage 1 (from May 2001 onwards).

During Stage 1, approximately three million cubic metres (m^3) of clean marine sand (with less than 3% fines) were dredged from the Tweed River entrance. Most of the sand was delivered to −10 m mean water depth extended between Point Danger and North Kirra, with approximately 600 000 m^3 of sand placed on the upper beaches from Rainbow Bay to North Kirra. Between April 2000 and February 2001, there was additional dredging to maintain a clear navigation channel at the Tweed River entrance. Prior to the establishment of the permanent sand bypassing system, a further 480 000 m^3 of clean marine sand was placed in near-shore areas from Point Danger to Coolangatta Beach.

Stage 2 commissioning trials commenced in March 2001 and full-scale operation of the sand bypassing system commenced in May 2001. Since then, approximately 9.09 million m^3 of pumped sand and 2.3 million m^3 of dredged sand (derived from dredging of the Tweed River mouth) have been deposited along the southern Gold Coast beaches. Most of the sand delivered through pumping and dredging has been deposited in the primary placement area, south-east of Snapper Rocks. Sand from the pumping system is also periodically discharged from outlets at Duranbah Beach, and occasionally at Snapper Rocks West, Greenmount and Kirra. The outlet at Kirra Beach has not been used since December 2003. A placement exclusion zone was established around Kirra Reef extending a minimum of 100 m from the reef edge (1995 extent) to prevent sand being placed close to the reef (Lawson et al. 2001).

During the early years (from 2001 to 2008) of stage 2 of the TRESBP, relatively high quantities of sand were delivered to the southern Gold Coast beaches to:

- nourish those beaches that had been severely eroded
- improve the Tweed Entrance Bar, and
- clear a sand-trap in the vicinity of the pumping jetty to improve the efficiency of the sand bypass system.

These objectives were achieved, and since 2008 the quantity of sand delivered has decreased and been more consistent with the natural movement of sand along the coast (average natural northerly net longshore sand drift is estimated to be 500 000 m^3 per year). In 2017, a total of 405 524 m^3 of sand was delivered north from Duranbah and Snapper Rocks East. During 2018 a total of 361 247 m^3 of sand has been delivered to Snapper Rocks East. The volume of sand pumped this calendar year (up until May 2019) has been 165 050 m^3 with the entire volume again delivered to Snapper Rocks East.

The Tweed River entrance is also dredged to maintain a navigable entrance channel, with dredged sand supplementing the sand bypassing system. Dredging campaigns typically remove between 100 000 m^3 and 200 000 m^3 of sand from the Tweed River channel and mouth. Sand from these campaigns is usually placed between Duranbah and Snapper

Rocks to provide nearshore nourishment. Between 2008 and 2015, there was only one small dredging campaign (200 m^3 in 2011). However, in 2016, 41 943 m^3 of sand was dredged and placed at Duranbah, and between January and April 2017, 57 125 m^3 of sand was dredged and placed at Snapper Rocks East and Duranbah. To date there has not been any dredging in within the Tweed River mouth since April 2017 (TRSBP 2019).

1.3 Past Monitoring – Events and Insights

frc environmental completed a baseline assessment of Kirra Reef in April and June 1995 (Fisheries Research Consultants 1995a), with subsequent ecological monitoring of the reef on behalf of TRESBP in February 1996, January 2001 (frc environmental 2001), May 2003 (frc environmental 2003), March 2004 (frc environmental 2004), February 2005 (frc environmental 2005), February 2010 (frc environmental 2010), July 2012 (frc environmental 2012), April 2014 (frc environmental 2014), March 2015, July 2016 (Ecosure 2016) May 2017 (frc environmental 2017) and May 2018 (frc environmental 2018). The current survey was completed in May 2019.

Comparison with Predictions Made in the Project's EIS

The current extent of Kirra Reef is broadly in accordance with predictions made in the EIS. Initial 'catch-up' bypassing and dredge placement of sand (between 2001 and 2008) resulted in the burial of Kirra Reef. Sand delivery since 2008 has more closely reflected natural patterns of longshore sand transport, allowing the reef to gradually re-emerge.

Since monitoring commenced, the greatest change to the floral and faunal communities of Kirra Reef has been due to the burial of rocky substrate. The coincident shallowing of the waters surrounding the reef and consequent increase in wave action (and likely sediment suspension) and energy has also influenced community structure.

The diversity of fishes associated with Kirra Reef has remained broadly similar to that recorded prior to the commencement of sand bypassing in 1995.

Kirra Reef therefore continues to provide habitat for a range of flora and fauna, and provides important marine ecological functions and services in the region.

The Influence of Storm-driven Waves

The extent of the Kirra Reef has been relatively stable since 2013. While there are signs of ongoing ecological stress (e.g. typically low percent cover of hard and soft corals) in the benthic assemblage of Kirra Reef due storm-driven waves, physical abrasion and burial by sand, this is both natural and characteristic of shallow, wave exposed inshore reefs surrounded by sand.

1.4 This Report

This report presents results of the survey of benthic macrophytes, benthic macroinvertebrates and fishes at Kirra Reef and at comparative sites at Palm Beach Reef, Kingscliff Reef and Cook Island, in May 2019.

In 2019 monitoring focused on:

- the quantitative description of the benthic community at Kirra Reef
- the description of biodiversity at Kirra Reef, through species lists of macroalgae, benthic invertebrates and fishes
- comparing observed changes in biodiversity, cover and abundance with abiotic factors including water temperature and wave conditions, and
- assessing the impacts of sand placement through the comparison of data acquired from Kirra Reef with that acquired from reefs at Palm Beach, Kingscliff and Cook Island.

2 Scope of the 2019 Monitoring Event and Methods Used

2.1 Scope

The scope of the 2019 monitoring event was to:

- update the understanding of the influence of abiotic environmental factors, recreational fishing and diving activity at Kirra Reef, and species of conservation significance and invasive species
- acquire fresh data from a single monitoring event at Kirra Reef and comparative sites, and
- develop a report that complies with the requirements of the Environmental Management System.

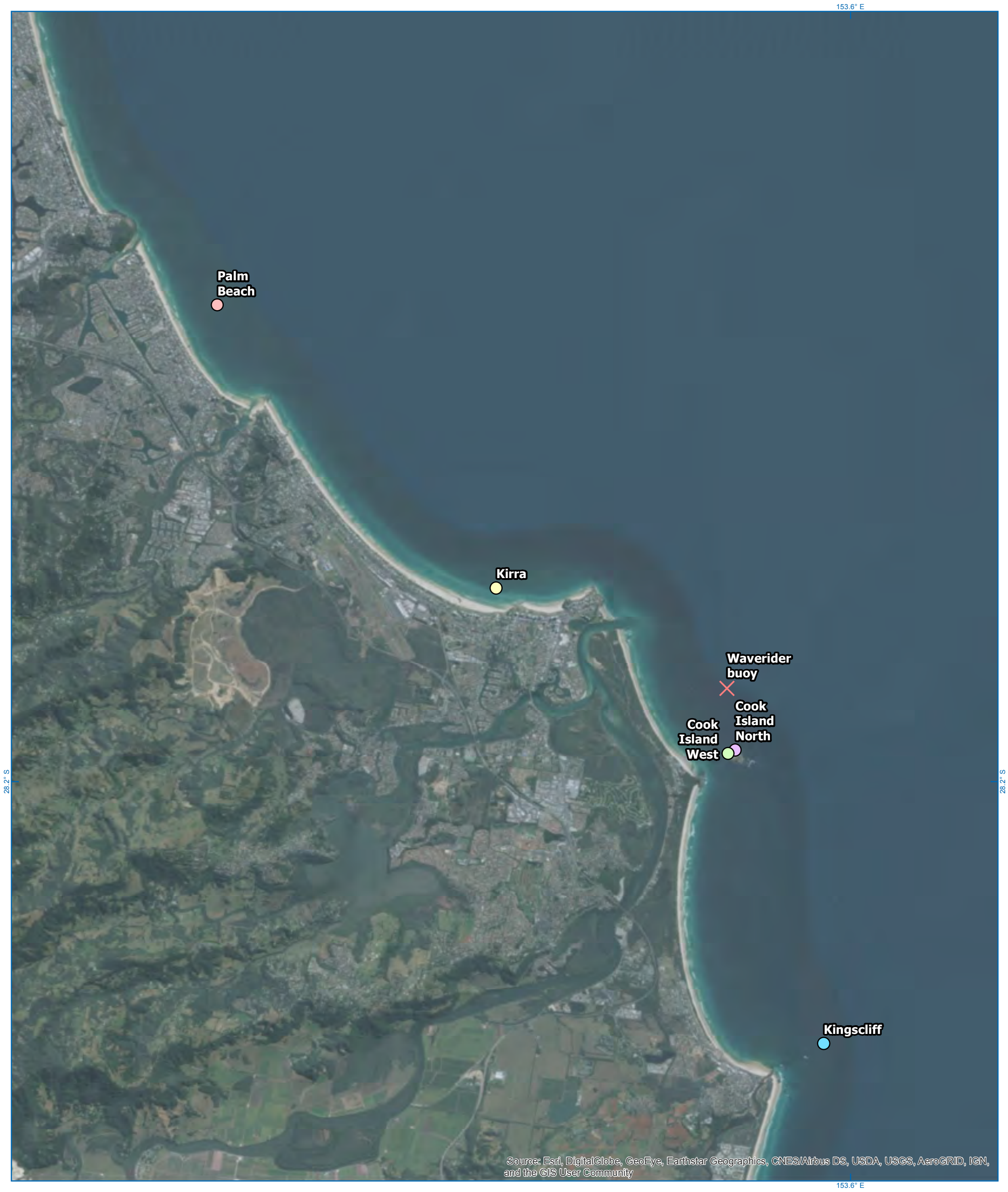
2.2 Experimental Design

The experimental design for monitoring in 2019 comprised surveys of:

- benthic biota
  - at five sites: Kirra Reef and reefs at Kingscliff, Cook Island North, Cook Island West and Palm Beach Reef (Map A1),
  - in forty-five randomly placed 0.5 m by 0.5 m quadrats at each site [1], supplemented by focused diver searches.
- fishes
  - at five sites: Kirra Reef and reefs at Kingscliff, Cook Island North, Cook Island West and Palm Beach Reef, with
  - three baited remote underwater video stations (BRUVS) at each site, supplemented by video transects and diver observations / searches.

The reefs were monitored in May 2019, after a relatively dry period. Visibility at each site was approximately 15-20 m during the survey period.

[1] In the experimental design, an additional 15 randomly placed quadrats were to be assessed in recently uncovered areas of Kirra Reef. However, sand is currently accreting around Kirra Reef, and no recently uncovered reef was recorded, despite a thorough search of the reef by divers.



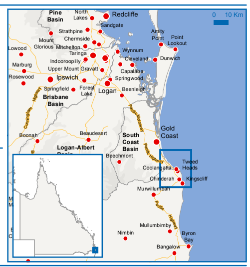
Moitoring of Biota at Kirra Reef - 2019

Map 1: Survey sites and waverider buoy

LEGEND

Survey sites and Waverider buoy

- Cook Island North
- Cook Island West
- Kingscliff
- Kirra Reef
- Palm Beach
- Waverider buoy



frc environmental
AQUATIC ECOLOGISTS
deep thinking. science.

PO Box 2363
Wellington Point
Q 4160 Australia

P 07 3286 3850
E info@frcenv.com.au
www.frcenv.com.au

SOURCES

DATE	DRAWN BY	VERSION	PROJECTION
2019-06-19	LW	01	Coordinate System: GCS GDA 1994 Datum: GDA 1994 Units: Degree

Document Path: Z:\Utility\Mappings\Mappings\2018\181203_NSW_Kirra reef\Workspaces\181203_Map1_19-06-18_LW.mxd

N

SCALE

0 2 4

Kilometres

Scale: 1:75,876 @ A3

2.3 Collection of Data

Benthic Biota

In May 2019, benthic biota was surveyed using accredited scientific divers who focused on (Figure 2.1 and Figure 2.2):

- collecting photo quadrats
- identification of species in situ, and
- searching for cryptic and invasive species.

Fishes

Three baited remote underwater video stations (BRUVS) and diver searches at each reef, were used to develop an understanding of fish community structure and relative abundances.

Figure 2.1

Setting a BRUV in place, Cook Island North.

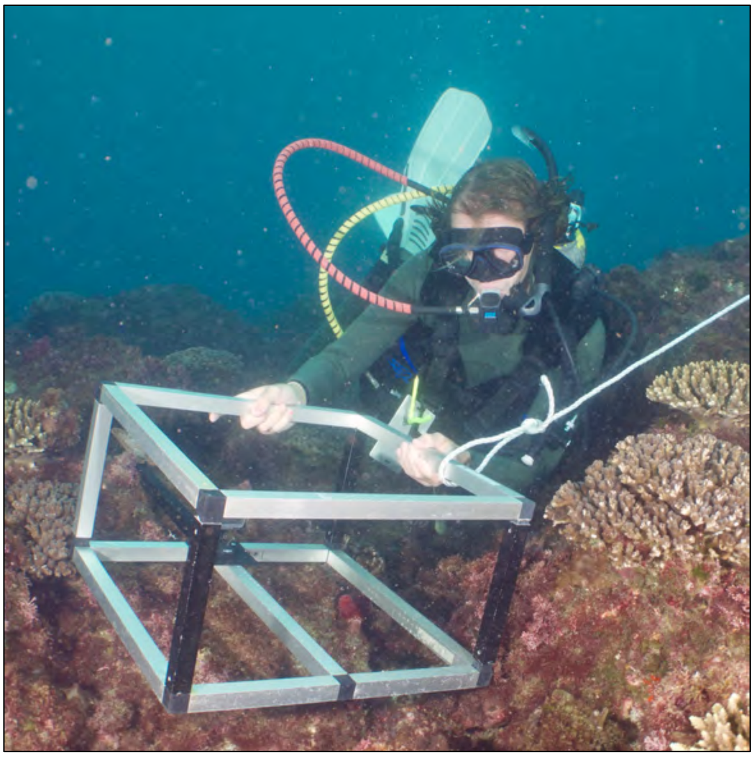


Figure 2.2

Capturing a photo quadrat at Palm Beach Reef.

Abiotic Factors

Sea condition, wind strength and direction and temperature were recorded at each site. Wave height, wave direction and sea surface temperature data were sourced from the Tweed Heads Waverider Buoy data base (DSITI 2019), to provide a record of physical conditions preceding and during monitoring.

2.4 Data Management and Analyses

Benthic Biota

Coral Point Count with Excel extensions (CPCe) (Kohler & Gill 2006) was used to generate a matrix of 50[2] randomly distributed points for each 0.5 m by 0.5 m quadrat. The substrate type, and identity of macroalgae and invertebrate fauna were determined by an experienced reef ecologist for each point (referencing the species list compiled from *in-situ* observations

[2] 50 points were considered statistically appropriate considering the typically small size of sessile fauna encountered.

and collected specimens). Percentage cover/abundance of key taxa was calculated for each reef.

A one factor permutational multivariate analysis of variance (PERMANOVA) was used to examine differences in the composition of benthic communities, with sites (Cook Island North, Cook Island West, Kirra Reef, Kingscliff and Palm Beach Reef) as the factor (fixed). To examine differences in benthic communities at Kirra Reef (only) through time, a one factor PERMANOVA was used, with time as the factor. For temporal comparisons at Kirra Reef, data was transformed to a Euclidean distance matrix and aggregated into the taxonomic categories used prior to 2017 (frc environmental 2015).

Prior to analyses, data was square-root transformed to down-weight the dominance of highly abundant species, converted to a Bray Curtis distance matrix, and tested for significance using 9999 permutations, where possible. Non-metric multidimensional scaling (nMDS) ordinations were used to visually represent the variation in the composition of communities between reefs, for each survey. Taxa that contributed to the differences in communities between sites were identified using the similarity percentages (SIMPER) routine. Post-hoc pairwise tests were used on significant terms to determine the source and magnitude of differences. The magnitude of difference between reefs was assessed using pairwise tests following analyses of similarity (ANOSIM), where differences were greater where the *R* value is closer to 1.

Average data for each reef was used to generate K-dominance curves and used to examine the difference in diversity (richness and evenness) of benthic communities between reefs.

Fishes

All digital imagery from the BRUVS was analysed by the same observer and the maxN was recorded for each species, with maxN defined as the highest number of individuals of a given species recorded within a single video frame throughout each 60-minute deployment (Pearson & Stevens 2015).

One-way PERMANOVA were used to assess similarities between sites in 2019 (with the factor being sites), with the differences visually displayed as nMDS ordinations. SIMPER was used to identify taxa contributing to dissimilarities between reefs. Post-hoc pairwise tests were used on significant terms to determine the source and magnitude of differences. Prior to analyses, data was square-root transformed to down-weight the dominance of highly abundant species, converted to a Bray Curtis distance matrix, and tested for significance using 9999 permutations, where possible.

Abiotic Factors

The historical dataset of biota on the reef was analysed with respect to other historical datasets relating to:

- wave height
- satellite imagery
- weather data including wind strength and direction, and
- sand release.

Temporal Changes in the Extent of Exposed Reef

Historical data on the extent of Kirra Reef was sourced from previous Kirra Reef Biota Monitoring program reports (frc environmental 2015; Ecosure 2016) and other available literature. As in previous years the extent of exposed reef in 2019 was calculated from a rectified aerial image (nearmap 2017) using Geographic Information Software (ESRI 2014).

3 Results

3.1 Benthic Communities in 2019

The composition of benthic fauna and flora differed when comparing reefs during 2019 sampling (Table 3.1; Table 3.2; and Figure 3.1). When comparing the degree in separation of benthic communities at each reef Cook Island West and Cook Island North showed the least difference and were not significantly different (ANOSIM; R- 0.075, p- 0.17, Table 3.3). Benthic community assemblage of all reefs was significantly different to that of Kirra Reef during 2019.

Kirra Reef had (SIMPER analyses; Appendix A):

- more brown macroalgae (Phaeophyta) of the genus *Sargassum* than the other sites (Figure 3.3).
- more red algae (Rhodophyta) of the family *Galaxauraceae* than all sites with the exception of Cook Island West.
- less turf algae cover than all other sites (Figure 3.9)
- less hard (nil) and soft coral than the other reefs (Figure 3.4 and Figure 3.5); and
- more ascidians than the other reefs (Figure 3.6).

In general, abundance of benthic flora and fauna at Cook Island North and West were the most even of the sites surveyed in 2019 (that is, the abundance of different species present was relatively similar). This is illustrated by a steeper gradient, and more elevated k-dominance curve (Figure 3.2; Rice 2000). Kirra Reef shows the least evenly distributed benthic community with the shallowest gradient of the five sites surveyed. This supports our observation that Kirra Reef is dominated by fewer benthic taxa.

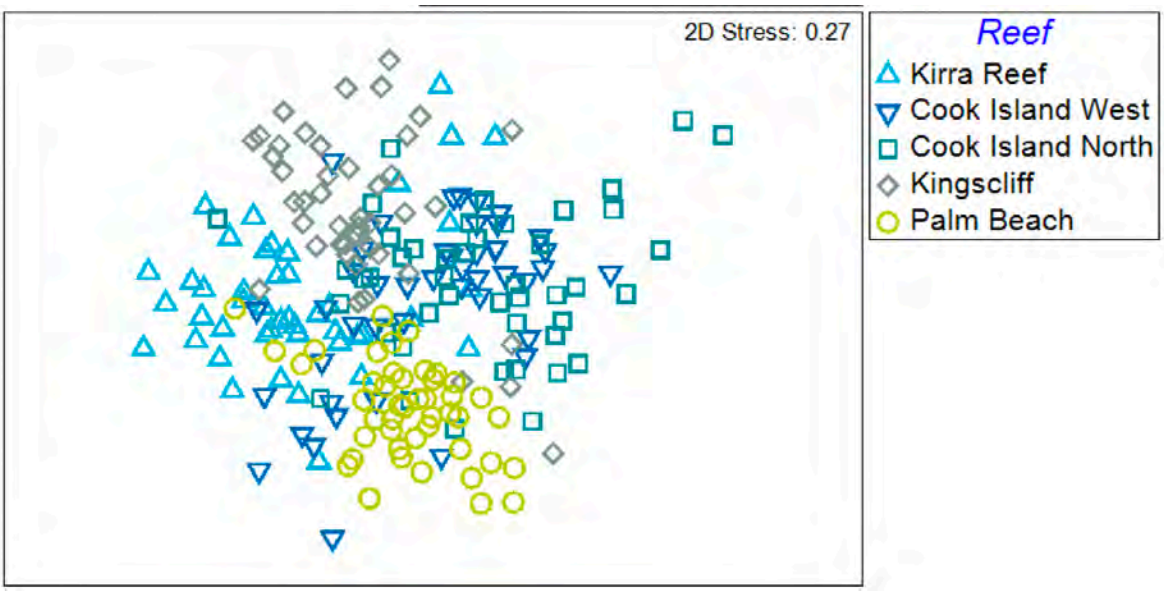


Figure 3.1 nMDS plot of benthic invertebrate communities at Kirra, Cook Island West, Cook Island North, Kingscliff and Palm Beach reefs during the 2019 survey.

Table 3.1 PERMANOVA results for differences in the composition of benthic communities between reefs.

Factor	df	MS effect	Pseudo-F	p (MC)[a]
Main test				
Reef	4	19668	20.794	**0.0001**
Residual	220	946		

[a] p values based on Monte Carlo simulations. Bold p values denote significance at p<0.05.

Table 3.2 Results of pairwise comparisons between reefs following PERMANOVA.

Groups	t	p (perm)	Unique permutations	p (MC)[a]
Cook Island North, Cook Island West	1.9744	**0.0013**	9948	**0.0017**
Cook Island North, Palm Beach	4.7218	**0.0001**	9937	**0.0001**
Cook Island North, Kirra	4.3664	**0.0001**	9939	**0.0001**
Cook Island West, Palm Beach	4.5126	**0.0001**	9942	**0.0001**
Cook Island West, Kirra	4.2209	**0.0001**	9948	**0.0001**
Palm Beach, Kirra	5.0608	**0.0001**	9955	**0.0001**
Kingscliff, Kirra Reef	4.6916	**0.0001**	9955	**0.0001**
Cook Island West, Kingscliff	4.3053	**0.0001**	9946	**0.0001**
Cook Island North, Kingscliff	4.9702	**0.0001**	9941	**0.0001**
Palm Beach, Kingscliff	6.2462	**0.0001**	9937	**0.0001**

[a] p values based on Monte Carlo simulations. Bold p values denote significance at p<0.05.

Table 3.3 Results of pairwise comparisons between reefs following ANOSIM analyses.

Groups	R value[a]	Significance Level	Actual permutations
Cook Island North, Cook Island West	0.075	0.1	9999
Cook Island North, Palm Beach	0.429	**0.01**	9999
Cook Island North, Kirra	0.383	**0.01**	9999
Cook Island West, Palm Beach	0.471	**0.01**	9999
Cook Island West, Kirra	0.382	**0.01**	9999
Palm Beach, Kirra	0.517	**0.01**	9999
Kingscliff, Kirra Reef	0.435	**0.01**	9999
Cook Island West, Kingscliff	0.363	**0.01**	9999
Cook Island North, Kingscliff	0.425	**0.01**	9999
Palm Beach, Kingscliff	0.651	**0.01**	9999

[a] (Global R = 0.232; p = 0.001). R-values closer to 1 are more different, with R-values of 0 indicating no difference. Bold p values denote significance at p<0.05.

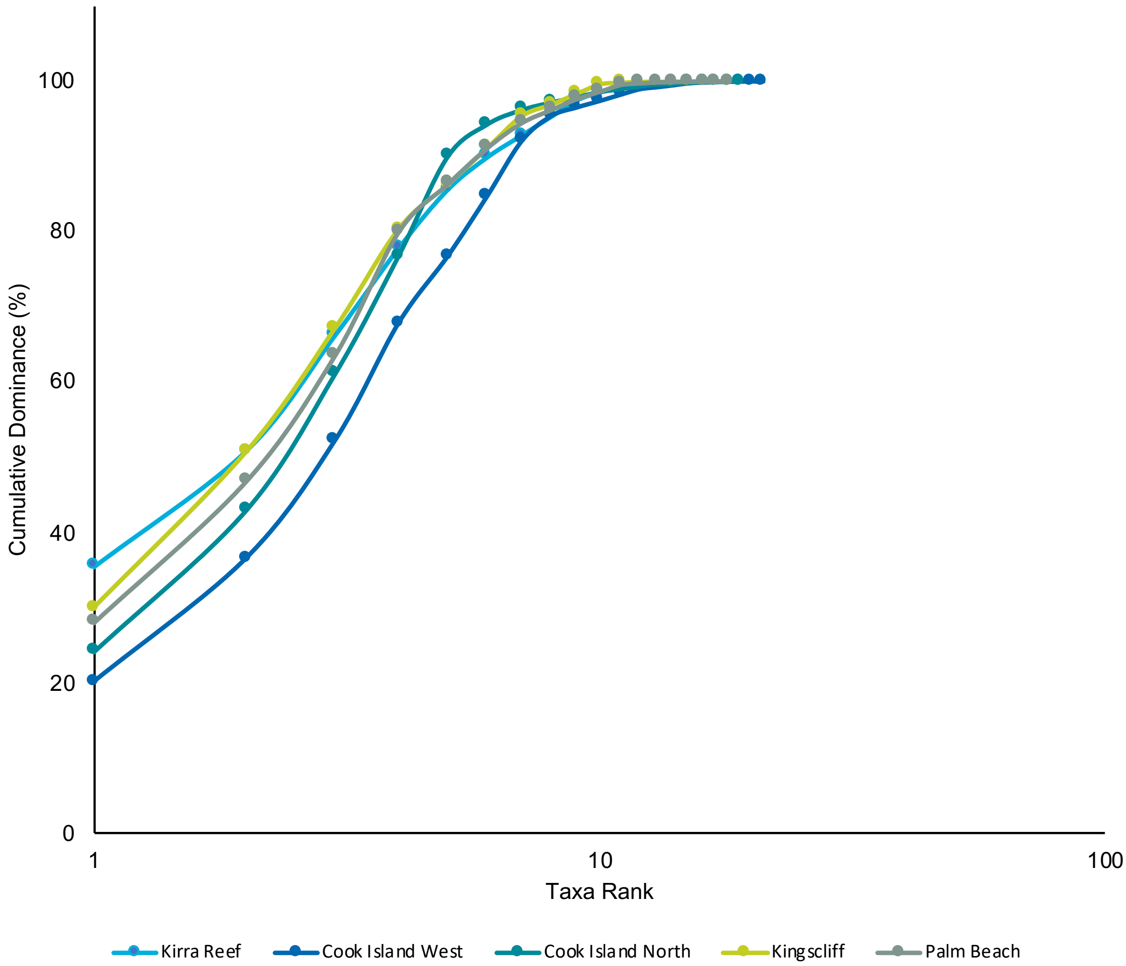


Figure 3.2 k-dominance of benthic communities at each reef in 2019.

Figure 3.3

The brown alga, *Zonaria* sp. at Cook Island North.

Figure 3.4

Turbinaria sp. Colony at Kingscliff Reef.

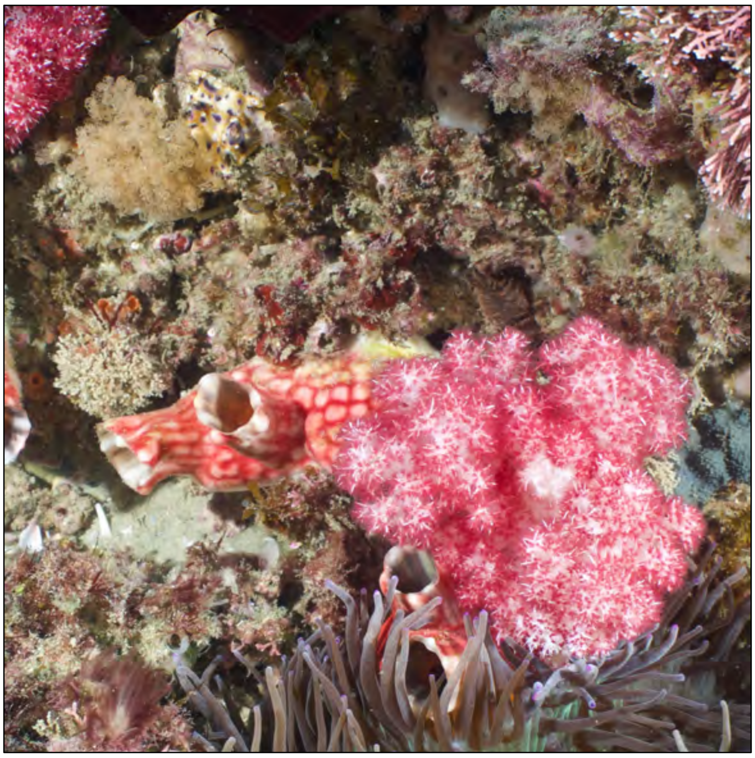


Figure 3.5

Soft coral (*Dendronepthya* sp. and ascidian (*Pyura* sp.) at Kirra Reef.

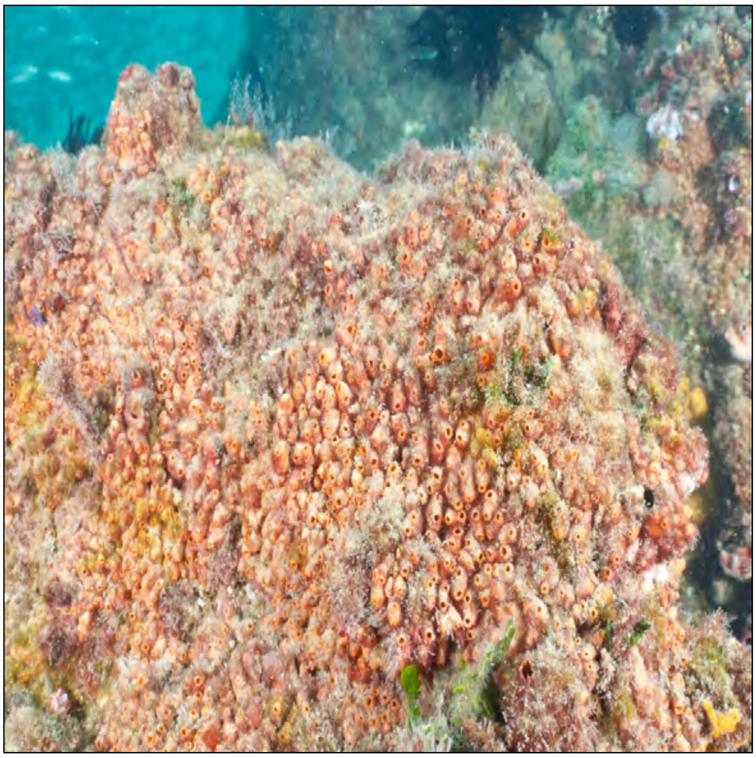


Figure 3.6

Community of ascidians at Kirra Reef.

Turf and Macroalgae

As in previous years, Kirra Reef was dominated by macroalgae (Sargassaceae, Galaxauraceae, Rhodomelaceae) and turf algae. In contrast to 2018 (frc environmental 2018) where brown algae of the family Dictyotaceae (including *Zonaria* sp., *Lobophora variegata*, and *Glossophora* sp.) were more dominant, algae of the order Rhodophyta (*Laurencia* sp., *Amphiroa* sp.) were the most dominant at Kirra Reef, Cook Island North and West during 2019 surveys (Figure 3.7 and Figure 3.8, Appendix A).

Red algae in the family Corallinaceae (predominantly *Amphiroa* sp.) had a higher cover at Kirra and Cook Island North and West than any other red algae, and had a significantly higher cover at Kirra Reef than at all other reefs. The cover of red algae was low at Palm Beach Reef. The cover of red algae of the family Rhodomelaceae (*Laurencia* sp.) was significantly higher at Cook Island North and Palm Beach reef than at all other reefs.

The cover of green algae (Chlorophyta) at each reef was typically low for all reefs surveyed, with the exception of Kingscliff and Cook Island West where *Ulva* sp. (family Ulvaceae) was relatively abundant (Figure 3.7; Appendix A). Green algae were present in small isolated patches at all sites, and included *Caulerpa spp., Chlorodesmis* sp., *Halimeda discoidea* and *Ulva* sp.

All reefs had a moderate to high cover of turf algae relative to other benthic cover (Appendix A).

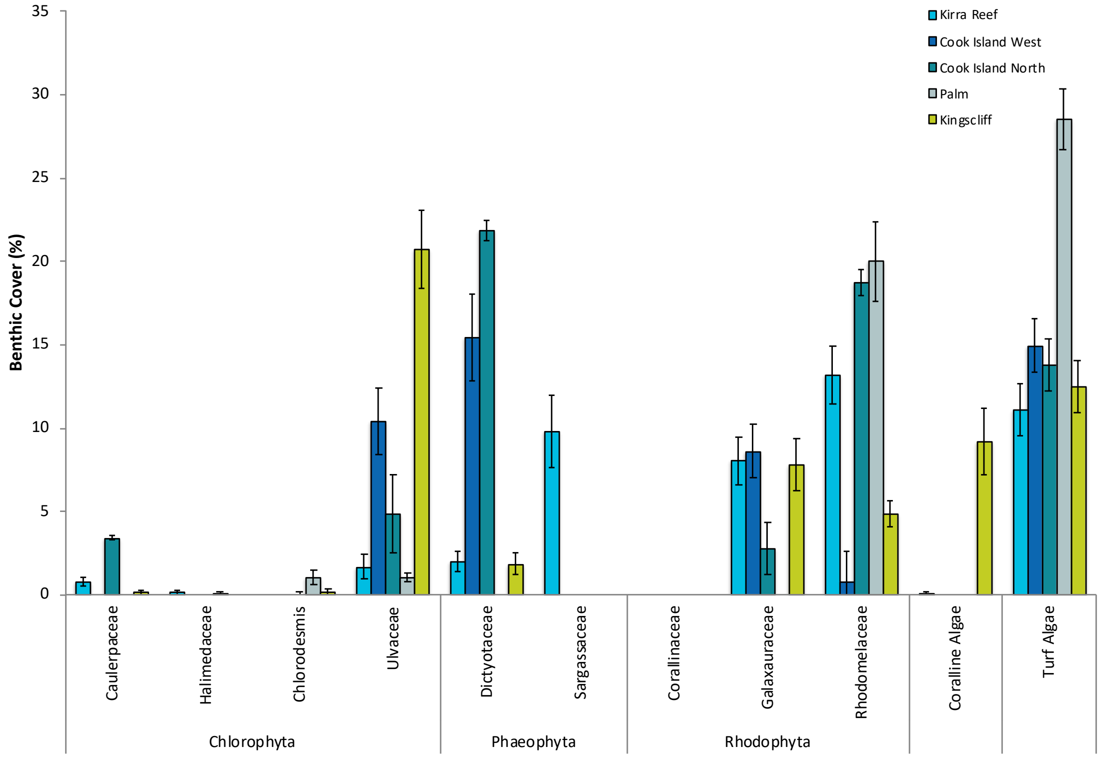


Figure 3.7 Mean percent cover of turf algae and macroalgae in 2019 (± standard error).

Figure 3.8

Macroalgae dominate the substrate at Cook Island North.

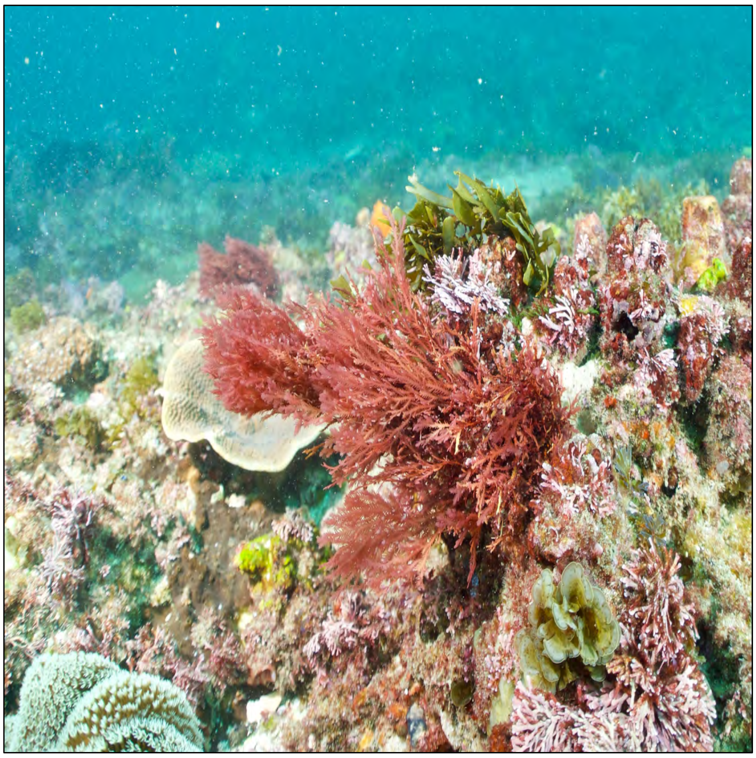


Figure 3.9

A nudibranch (*Chromodoris kuiteri*) browses amongst turf algae at Kirra Reef.

Benthic Invertebrates: Ascidians, Corals, Sponges and Crinoids

All sites had a high percentage cover of ascidians with comparatively low cover of anemones, sponges and soft corals (Figure 3.10, Figure 3.11 and Figure 3.10). The abundance of ascidians was higher at Kirra Reef (41%) and Kingscliff (36%) than at the other reefs, where percentage cover was less than 20% (Appendix A).

Hard corals have not been recorded at Kirra Reef since 2015 (frc environmental 2015; Figure 3.12 and Figure 3.13). Percentage cover was highest at Cook Island West (5%) followed by Cook Island North (1.3%) and Palm Beach (0.96%). The apparent significant reduction in hard coral cover at North and West Cook Island since 2018, is considered likely to be an artefact of survey.

Soft Coral had the lowest percentage cover at Kirra Reef (0.14%) similar to that recorded in 2018. The percentage cover of soft coral at Cook Island West, Cook Island North and Kingscliff reefs was similar, with the highest percentage cover recorded at Palm Beach Reef (10%) (Appendix A).

The cover of sponges was low (<3%) and not significantly different at all reefs.

The percentage cover of anemones was significantly higher at Kirra Reef (4%) than at Cook Cook Island North and Kingscliff reefs (Figure 3.16). There was no significant difference in percentage cover of anemones when comparing Cook Island West and Palm Beach Reef (Figure 3.12).

Other groups such as molluscs (Figure 3.8), echinoderms (Figure 3.19), polychaetes and hydroids (Figure 3.18) were typically sparse at all sites (Figure 3.10 and Appendix A).

At each reef a diverse range of less common invertebrate taxa was recorded, including sea urchins (Figure 3.15) and nudibranchs (Figure 3.9). Painted cray (*Panulirus versicolor*) were observed at Kirra Reef and Cook Island West, while banded coral shrimp (*Stenopus hispidus*) were recorded from both Cook Island West and North.

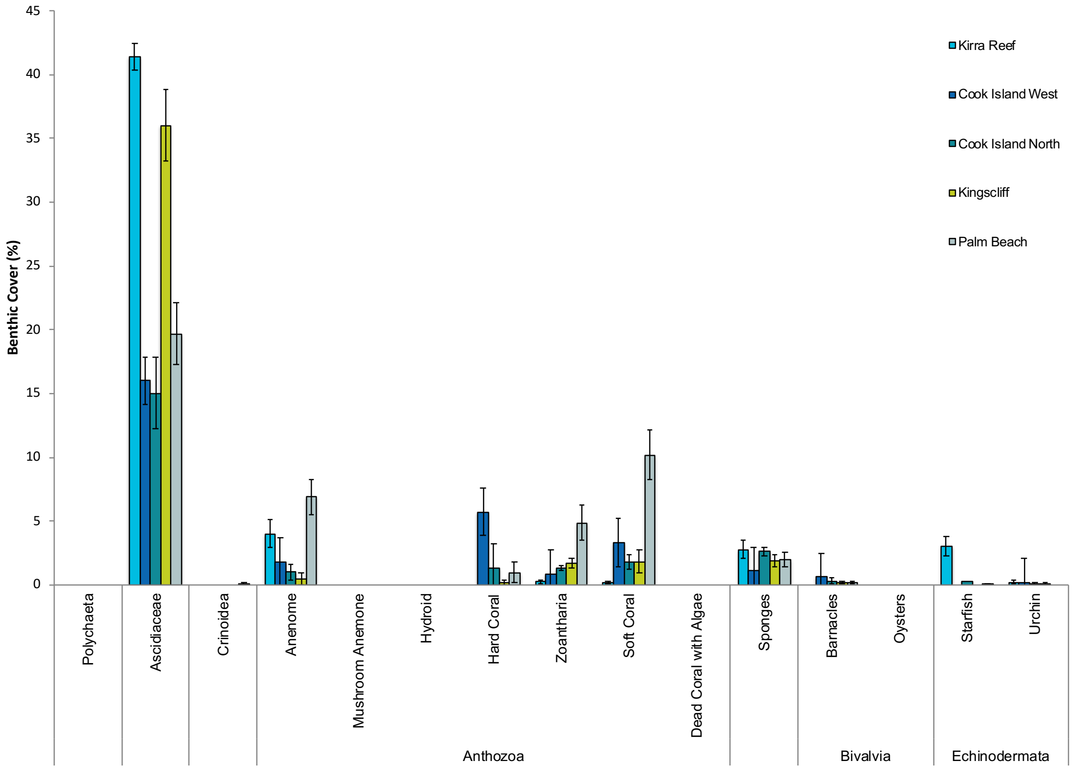


Figure 3.10 Percent cover of benthic communities other than macroalgae in 2019 (± standard error).

Figure 3.11

Benthic community dominated by ascidians, sponges and algae at Cook Island North.

Figure 3.12

An encrusting hard coral (Faviidae) at Cook Island.

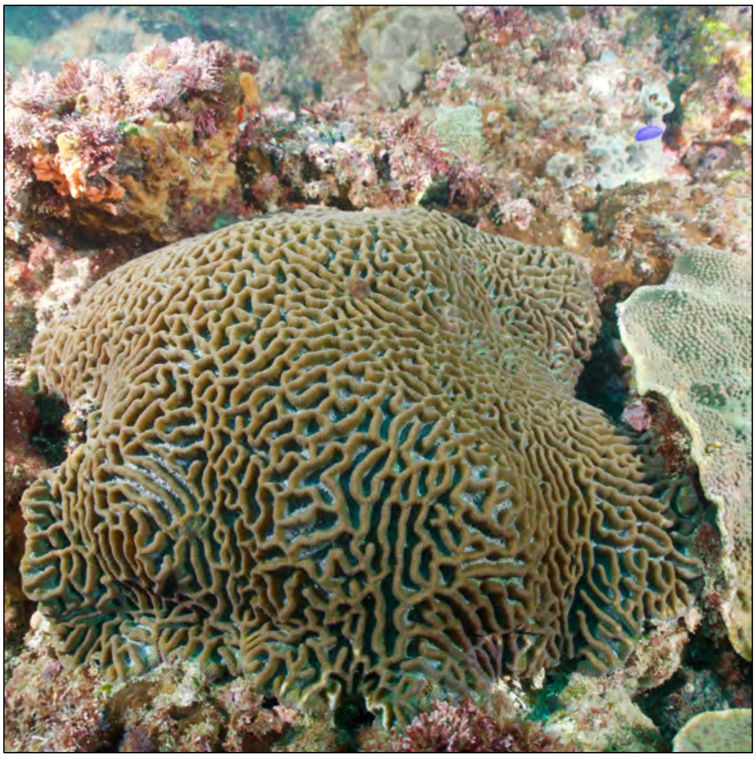


Figure 3.13

Turbinaria sp. at Cook Island.

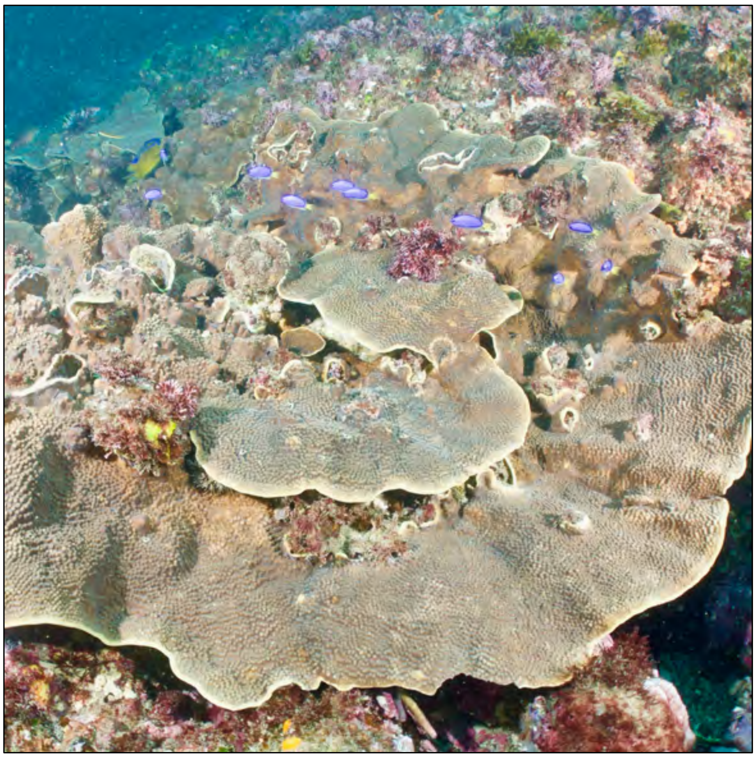


Figure 3.14

Community of ascidians at Kirra Reef.

Figure 3.15

Sea urchin and soft corals at Kirra Reef.

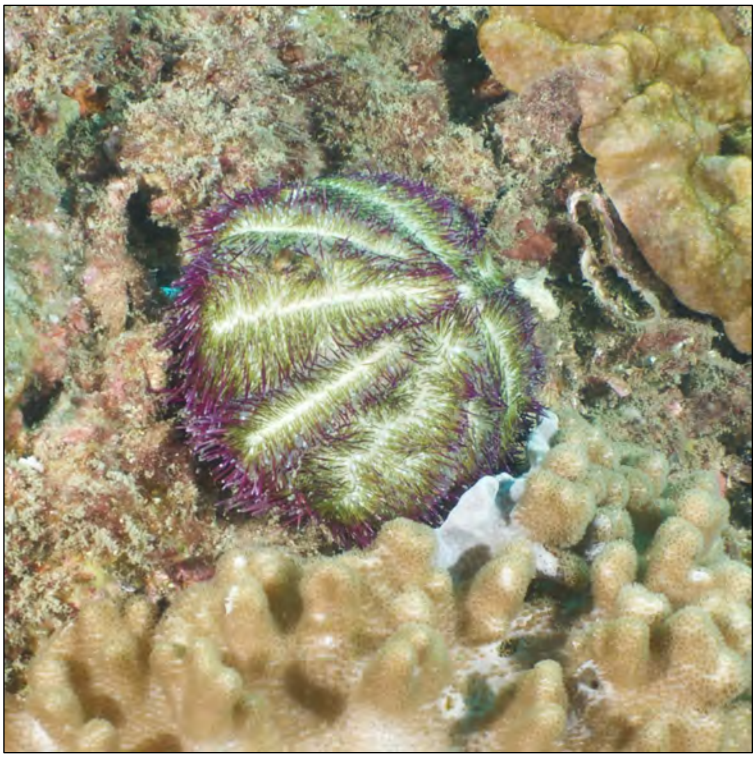


Figure 3.16

Anemone (*Radianthus crispa*) at Kirra Reef.

Figure 3.17

Seastar, *Echinaster luzonicus* at Palm Beach Reef.

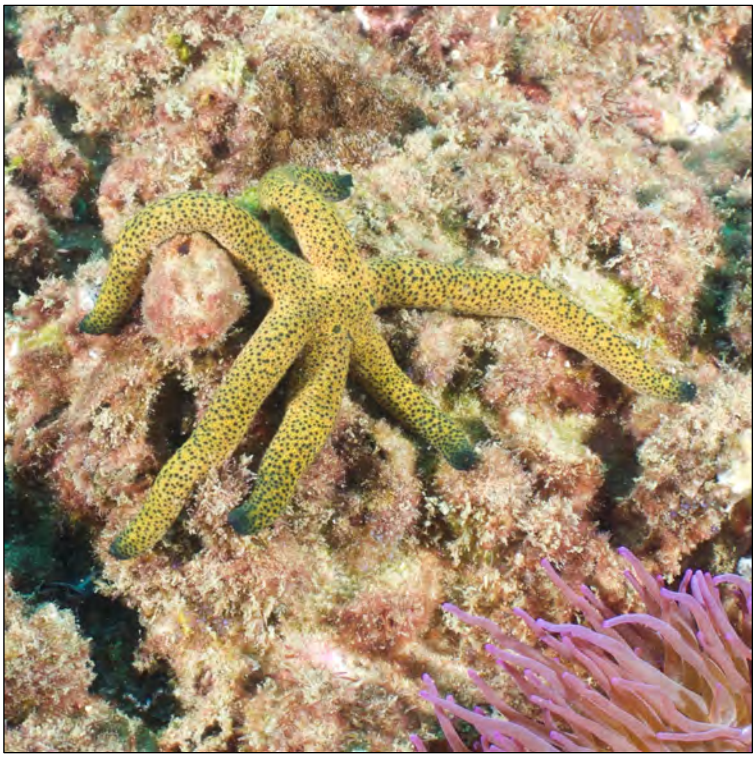
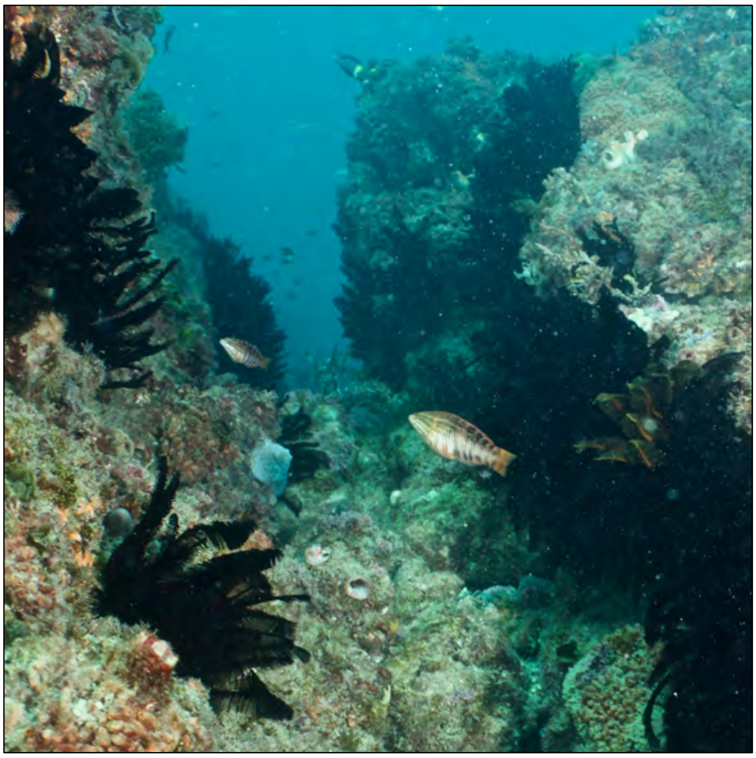


Figure 3.18

Black feather stars (*Cenolia* sp., Order Crinoidea) at Kirra Reef.



3.2 Changes in Benthic Communities at Kirra Reef Over Time

Benthic communities were similar over time at Kirra Reef (Figure 3.19) with macroalgae, turf algae, and ascidians the more dominant taxa. There were however, significant differences between years, with post-hoc tests indicating most years were different to each other (Table 3.4; Appendix A). Differences between years were largely due to changes in the cover of macroalgae, turf algae, ascidians, and hard coral (SIMPER, Appendix A).

Table 3.4 One-way PERMANOVA Results for the comparison of benthic communities at Kirra Reef over all surveys.

Factor	**df**	**MS effect**	**Pseudo-F**	**p (perm)***
	Main test			
Years	14	30982	38.037	**0.0001**
Residual	671	814.53		

* Bold p values indicate significance at p <0.05.

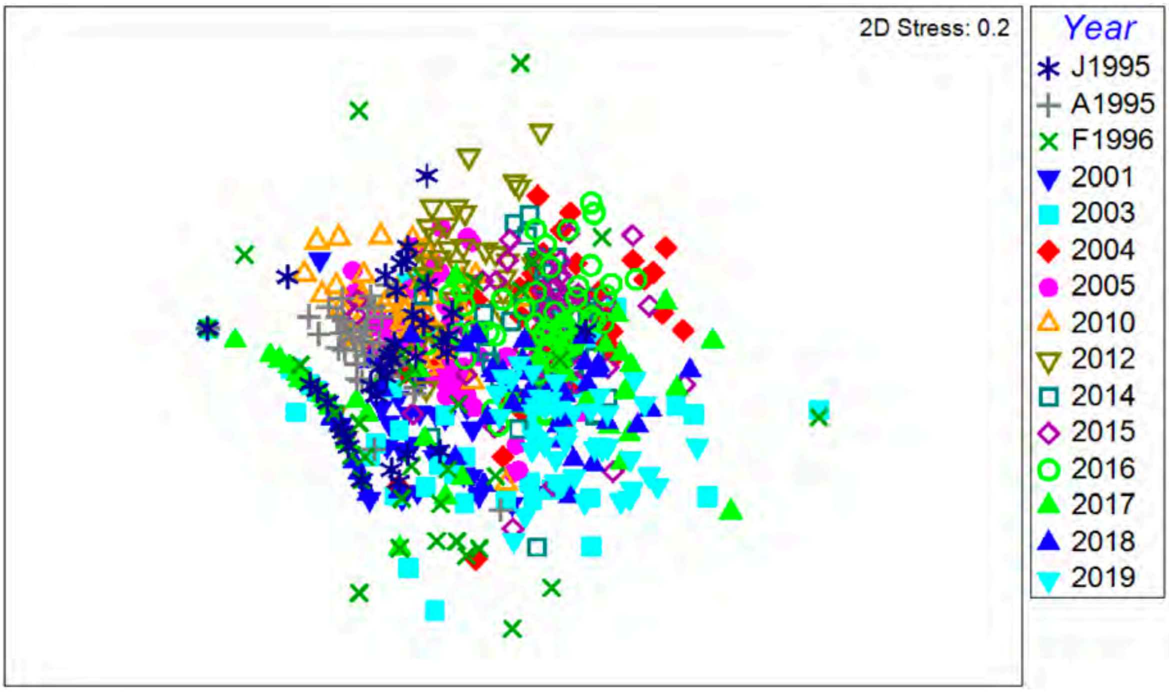


Figure 3.19 Multi-dimensional scale plot of benthic cover at Kirra Reef in all surveys.

Turf and Macroalgae

The cover of macroalgae at Kirra Reef was highest in 2001, and decreased from 2001 to 2003 (Figure 3.21, Appendix A). This decrease was likely to be a result of the large volume of sand placed during stage 2 of the TRESBP, which resulted in an almost complete burial of Kirra Reef by sand. Since 2008, the volume of sand placed by the TRESBP has been lower, and more consistent with natural sand supply rates. This resulted in the emergence of Kirra Reef between 2006 and 2009, with an increase in the cover of macroalgae between 2010 and 2018. In 2017, macroalgae cover was significantly lower than in 2016 (frc environmental, pers. obs.) (Appendix A). The cover of macroalgae and turf algae has not changed significantly between 2018 and 2019 at Kirra Reef (Figure 3.20 and Figure 3.21).

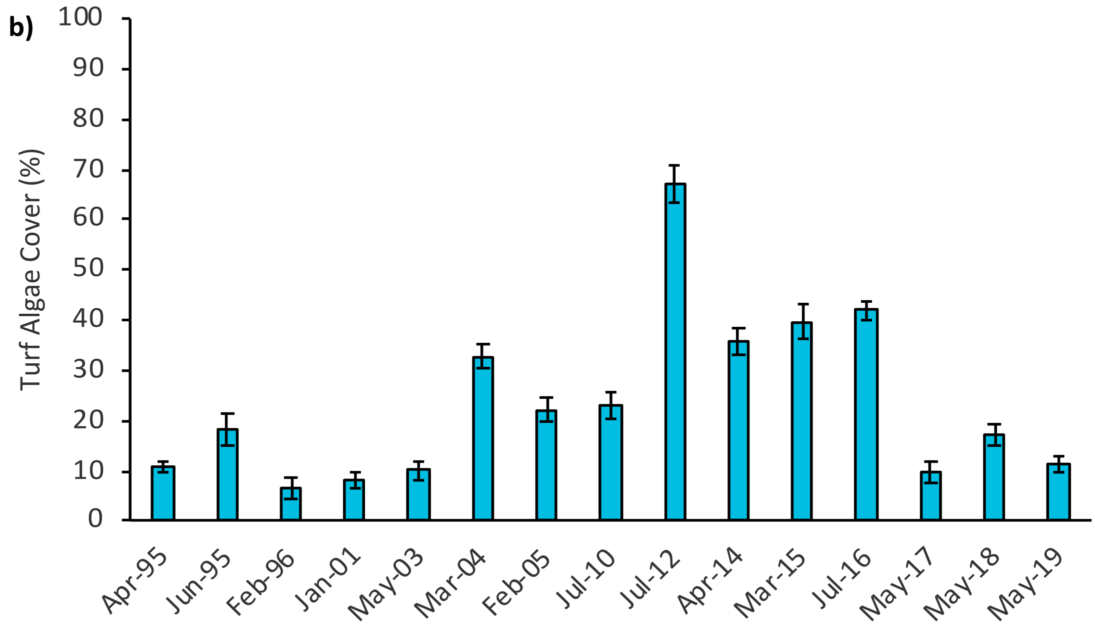


Figure 3.20 Mean cover of turf algae (± standard error) at Kirra Reef.

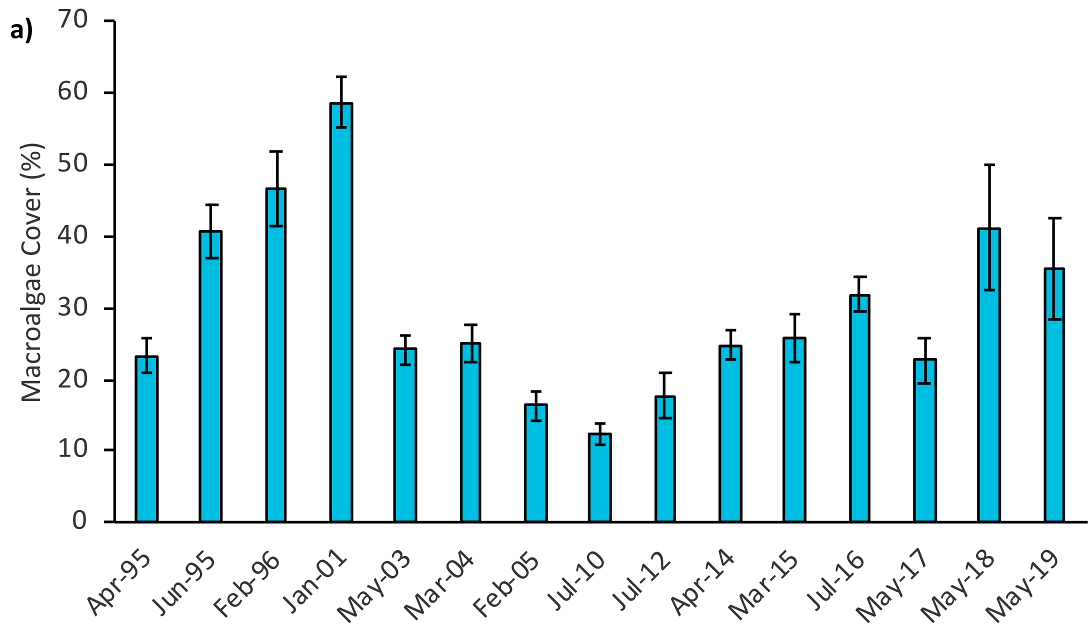


Figure 3.21 Mean cover of macroalgae (± standard error) at Kirra Reef.

Benthic Invertebrates: Corals, Sponges and Ascidians

In 1995 and 1996, prior to and during stage 1 of the TRESBP, the cover of soft coral at Kirra Reef was between 0.7% and 9.7%, and cover of hard coral was between 0% and 2.3%. In 2001, at the start of stage 2 of the TRESBP, no soft or hard coral was recorded at Kirra Reef.

Between 2003 and 2005, the cover of soft coral was between 0.6% and 5.8%, and the cover of hard coral cover was between 0% and 1.7%. Between 2006 and 2009 the reef was largely buried in sand. Since surveys recommenced in 2010, there has been very little soft coral or hard coral (<0.2%) recorded at Kirra Reef, which is likely to be a result of frequent disturbance due to prolonged periods of elevated turbidity associated with shifting sands and wave action inhibiting both recruitment and growth. During 2019 hard coral was not recorded at Kirra Reef and percentage cover of soft coral was similar to previous years (<1%)

The cover of sponges at Kirra Reef has varied significantly among years, being relatively high in 1996, 2003 and 2004, and lowest in 1995, 2001, 2010, 2012 and 2018 (Figure 3.22; Appendix A). Since 2012, the cover of sponges has varied but has always been statistically higher than in 2010 and lower than in 1996, 2003 and 2004 (Table 3.1; Appendix A). However, in 2018, sponge cover was only slightly higher than in 2010, and significantly lower than in 2012-2017 (Figure 3.22 & Appendix A). In 2019 a moderate cover of sponge was recorded. As filter-feeders, sponges are likely to be significantly influenced by wave-induced suspended sediment (Figure 3.23).

The cover of ascidians has also varied significantly among years, with percent cover steadily increasing since 2016 with the highest cover recorded in 2019, and the lowest in 1995, 1996 and in 2012.

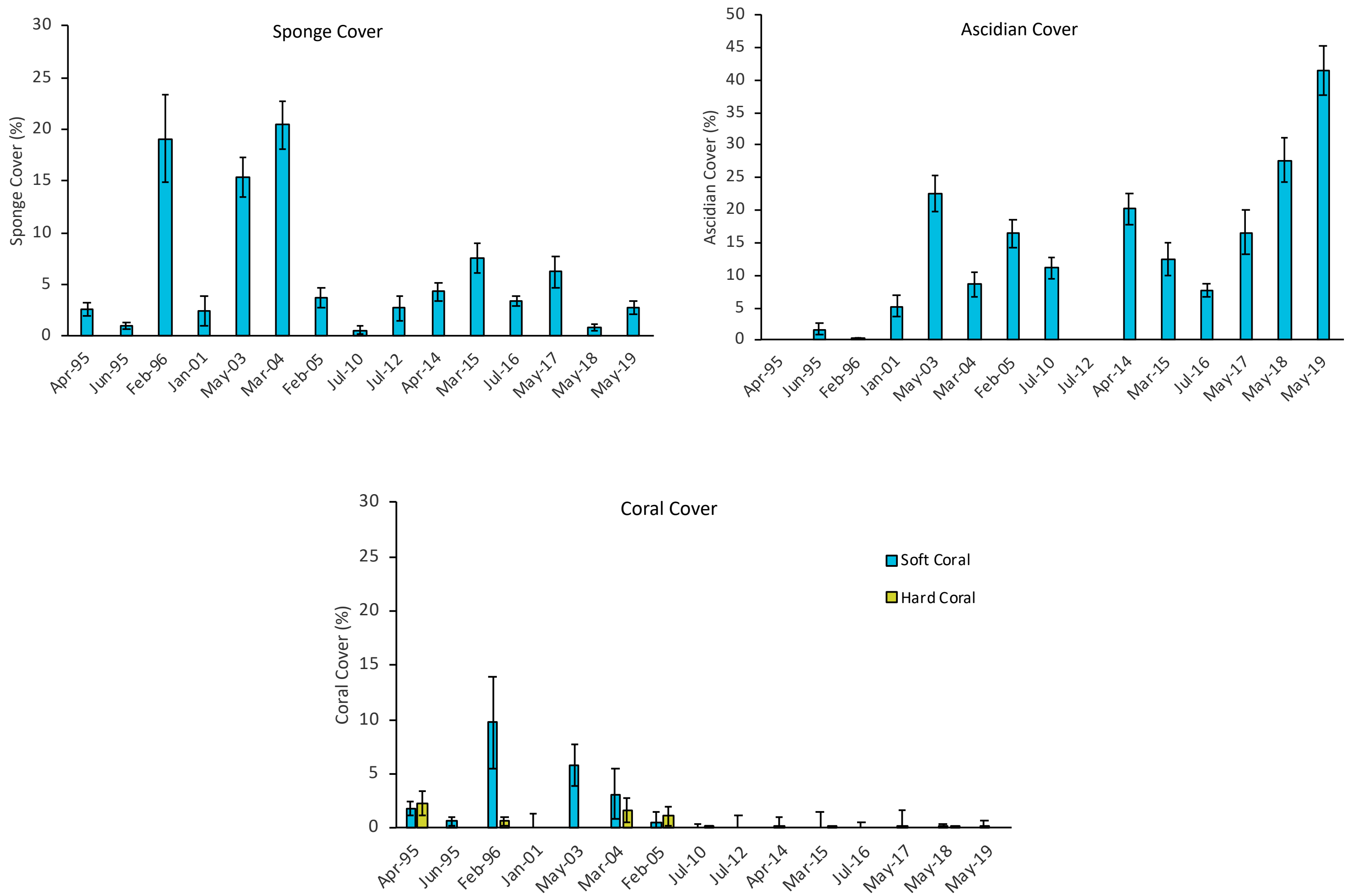


Figure 3.22 Temporal mean cover of sponge, ascidians, soft and hard coral (± standard error) at Kirra Reef.

Table 3.5 One-way PERMANOVA results for the differences in the cover of benthic taxa at Kirra Reef between 1995 and 2019.

Benthic Taxa	Factor	df	MS effect	Pseudo-F	p (perm)*
Macroalgae	Survey	14	3986.2	7.4194	0.0001
	residual	671	537.26		
Turf Algae	Survey	14	19287	30.751	0.0001
	residual	671	627.19		
Soft Coral	Survey	14	1705.2	6.9125	0.0001
	residual	671	246.68		
Hard Coral	Survey	14	1705.2	6.9125	0.0001
	residual	671	246.68		
Sponges	Survey	14	10791	14.408	0.0001
	residual	671	748.99		
Ascidians	Survey	14	24794	35.113	0.0001
	residual	671	706.12		

* Bold p values indicate significance at p <0.05.

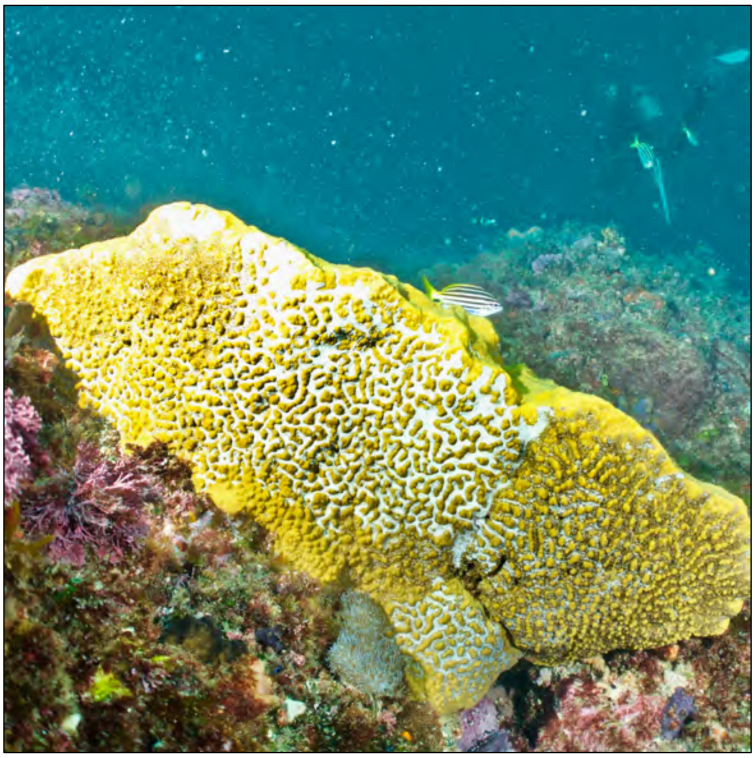


Figure 3.23

Sponges grow to considerable size at Palm Beach Reef.

3.3 Fish Communities in 2019

Species Richness and Evenness

In the May 2019 survey, 107 species of fish were observed in aggregate at Kirra, Palm Beach, Kingscliff and the Cook Islands reefs (Appendix B). These 107 species represented 41 families with Pomacentridae (13 species), Labridae (16 species) and Chaetodontidae (9 species) the most speciose. There were three species of cartilaginous fish recorded during the May 2019 survey. These included spotted wobbegong (Kirra, Kingscliff and Cook Island North and West), ornate wobbegong (Cook Island North and West) and white-spotted eagle ray (Kirra Reef). There were similar numbers of fish species recorded across all sites with the exception of Kingscliff Reef which displayed the lowest species richness (Table 3.6) of the five sites.

Figure 3.24

Barrier reef anemonefish (*Amphiprion akindynos*) at Cook Island West.

Fourteen new species were recorded in May 2019, all being reef-associated species (Table 3.7).

Table 3.6 Number of fish species observed at Kirra, Palm Beach, Kingscliff and Cook Island Reefs in 2019 and their characteristic range and habitat.

	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef	Kingscliff
Range[a]					
Temperate	11	8	11	6	8
Tropical	19	20	27	20	9
Tropical/Temperate	24	26	25	31	21
Total	**54**	**54**	**63**	**57**	**38**
Habitat[b]					
Pelagic	2	1	3	1	3
Reef associated	51	53	60	56	35
Reef/Pelagic	1	0	0	0	0
Total	**54**	**54**	**63**	**57**	**38**

[a] Ranges have been derived from the Australian Museum's OZCAM mapping, https://australianmuseum.net.au/ and Johnson, J. W. "Annotated checklist of the fishes of Moreton Bay, Queensland, Australia." Memoirs Queensland Museum 43.2 (1999): 709-762.

[b] Life styles and substrate associations were sourced from fishbase.org

Across all sites surveyed in May 2019 approximately half of all species recorded at each reef had tropical / temperate ranges (Table 3.6), and it is suggested that these species would not be at the extent of their range. However, the remaining species typically have either temperate or tropical ranges indicating that they are likely to be at, or approaching the northern or southern extent of their range. Stressors induced by climate or environment are likely to have a significant impact on the occurrence of these species.

As in previous years, reef-associated fish species were dominant at all sites surveyed. Between 92 and 98% of fish species recorded during 2019 were reef-associated species (e.g. barrier reef anemonefish Figure 3.24, blacktip bullseye Figure 3.26). Pelagic species were recorded at all sites, with the maximum number recorded at Cook Island West and Kingscliff (3), and only one species classed as reef / pelagic recorded at Kirra Reef.

The lowest species richness was recorded at Kingscliff; however, the species distribution was more even than that of Kirra Reef (Figure 3.28). As in previous years the species abundance recorded at Kirra Reef was dominated by a single species (yellowtail). As in previous years Kirra Reef had similar species' abundance to that of Palm Beach, Cook Island North and Cook Island West, however the abundance of fishes at these reefs was more evenly distributed.

Blue groper (*Achoerodus viridis,* Figure 3.25), recorded within the Cook Island Aquatic Reserve at both North and West sites, is partially protected under NSW legislation. Blue groper can only be taken by line, and not fished commercially or be taken by spear fishing. 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 survey.

Table 3.7 Fish recorded in May 2019, not recorded in previous surveys.

Scientific Name	Common Name	Reef Recorded at
Chaetodontidae		
Chaetodon ephippium	saddle butterflyfish	Cook Island West
Chaetodon lunula	racoon butterflyfish	Cook Island West
Gerreidae		
Gerres subfasciatus	silver biddy	Kirra Reef
Gobiidae		
Ptereleotris evides	arrow dartfish	Cook Island West
Haemulidae		
Plectorhinchus lineatus	oblique-banded sweetlip	Cook Island West
Monocanthidae		
Cantherhines fronticinctus	spectacled leatherjacket	Palm Beach Reef
Mullidae		
Parupeneus ciliatus	diamondscale goatfish	Palm Beach Reef
Muraenidae		
Gymnothorax meleagris	whitemouth moray	Palm Beach Reef
Plotosidae		
Plotosus lineatus	striped catfish	Kingscliff
Scorpaendiae		
Pterois antennata	spotfin lionfish	Cook Island North and West
Serranidae		
Epinephelus undulatostriatus	maori rockcod	Palm Beach Reef
Siganidae		
Siganus punctatus	spotted rabbitfish	Kirra Reef
Solenostomidae		
Solenostomus cyanopterus	robust ghost pipefish	Kirra Reef
Tetraodontidae		
Torquigener pleurogramma	weeping toadfish	Kirra Reef

Figure 3.25

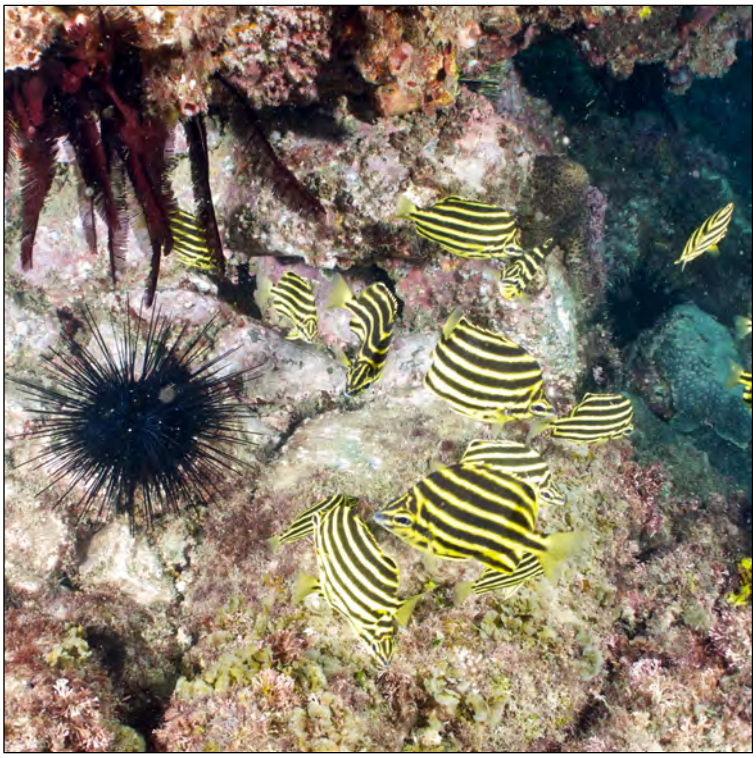
Blue groper (*Achoerodus viridis)* at Cook Island West.

Figure 3.26

Blacktip bullseye (*Pemphris affinis*) at Cook Island West

Figure 3.27

Schooling stripeys (*Microcanthus strigatus*) at Kirra Reef.



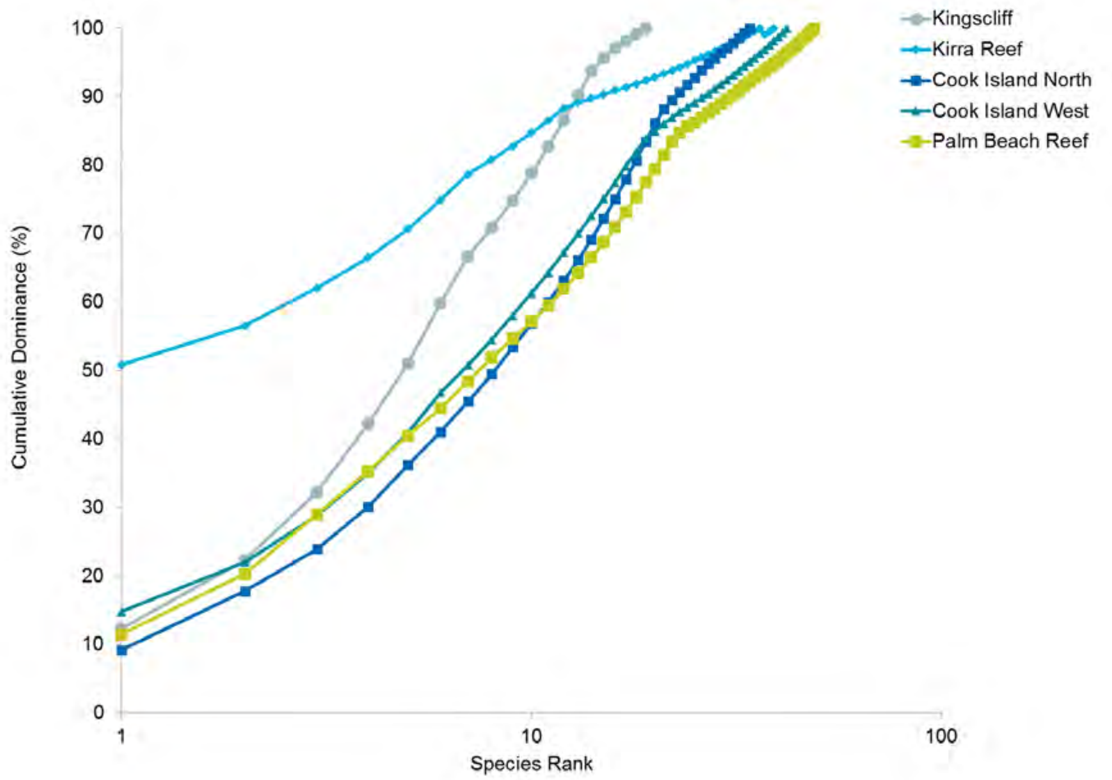


Figure 3.28 k-dominance curve for fish communities at Kirra, Kingscliff, Cook Island North and West and Palm Beach Reefs.

Abundance and Trophic Levels

Based on BRUVS derived-data, in May 2019, Kirra Reef had the highest total abundance (sum of MaxN values) of fish (401) followed by Palm Beach reef (358), Cook Island West (121), Cook Island North (97) then Kingscliff (63). Kirra Reef and Palm Beach had the highest abundances of carnivorous species (e.g. striped catfish Figure 3.29 & spotfin lionfish Figure 3.30) when comparing the five locations in 2019 (Figure 3.34). Fish abundance at Kingscliff, Cook Island North and Cook Island West were all dominated by omnivorous species (Figure 3.32). The abundance of herbivorous, omnivorous–herbivorous tendencies and planktivorous fish was relatively similar between all sites. The abundance of corallivorous fish was low at Kirra Reef and Kingscliff but similar to that of other trophic groups at the remaining sites.

Figure 3.29

Striped catfish (*Plotosus lineatus*) at Kingscliff Reef.

Figure 3.30

Spotfin lionfish (*Pterois antennata*) at Cook Island West.

Figure 3.31

Red morwong (*Cheliodactylus fuscus*) at Cook Island West.

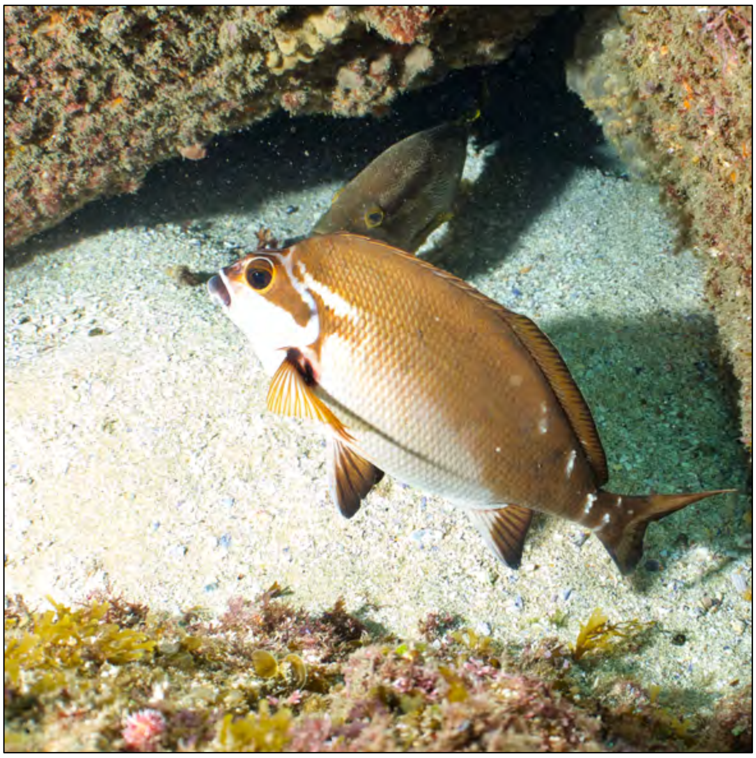


Figure 3.32

Tallfin batfish (*Platax teira*) at Cook Island North.

Figure 3.33

A sub-adult green turtle (*Chelonia mydas*) at Cook Island North.

Green turtles were recorded at Cook Island North and Cook Island West (Figure 3.33).

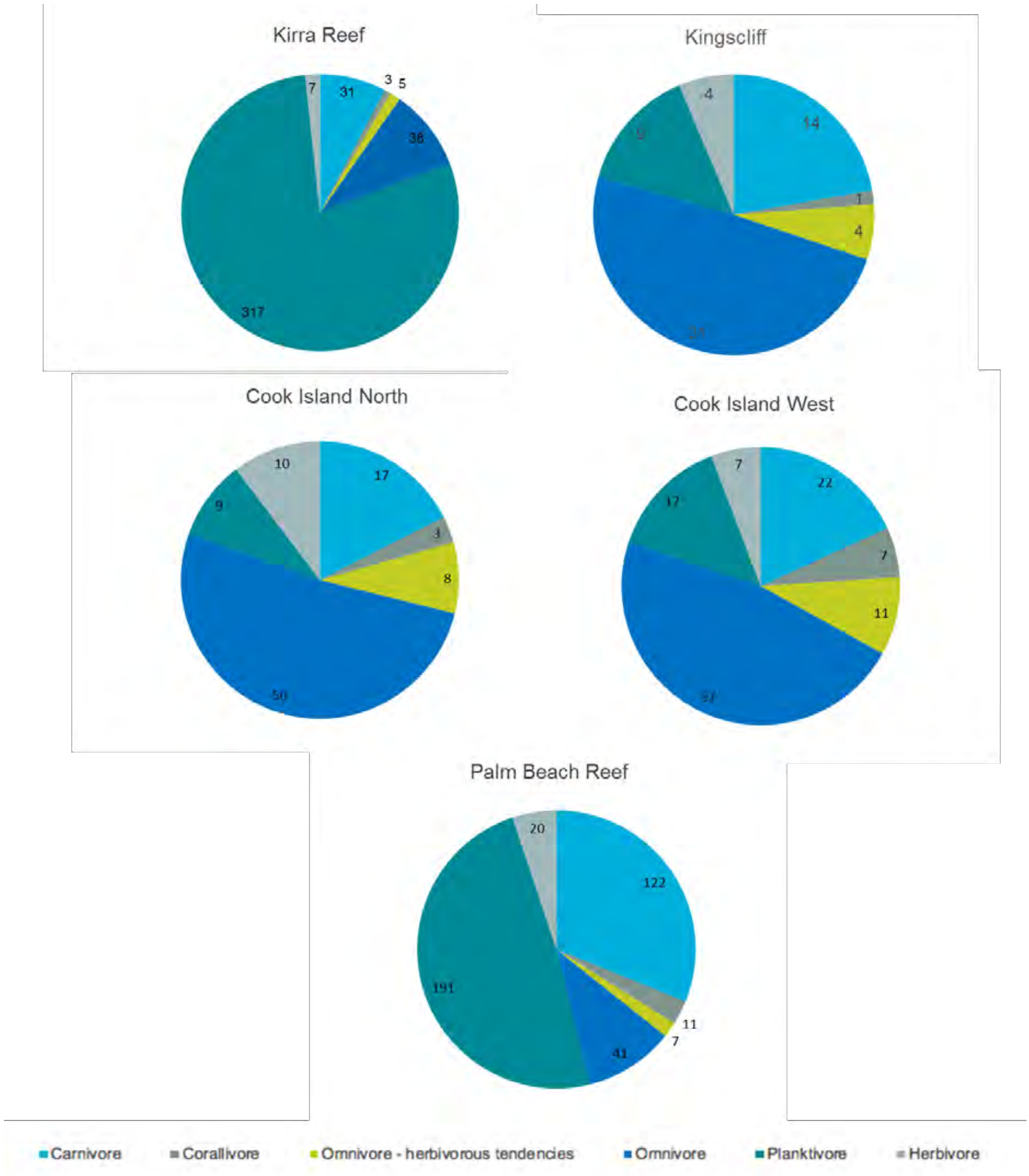


Figure 3.34 Abundance of fish of different trophic levels using summed maxN values at each reef.

The species richness for each trophic level did not differ greatly between the five sites during the May 2019 survey. Carnivores and omnivores were the two most speciose trophic groups at all five sites. The species richness of the remaining trophic groups again was relatively evenly represented across all sites (Figure 3.35).

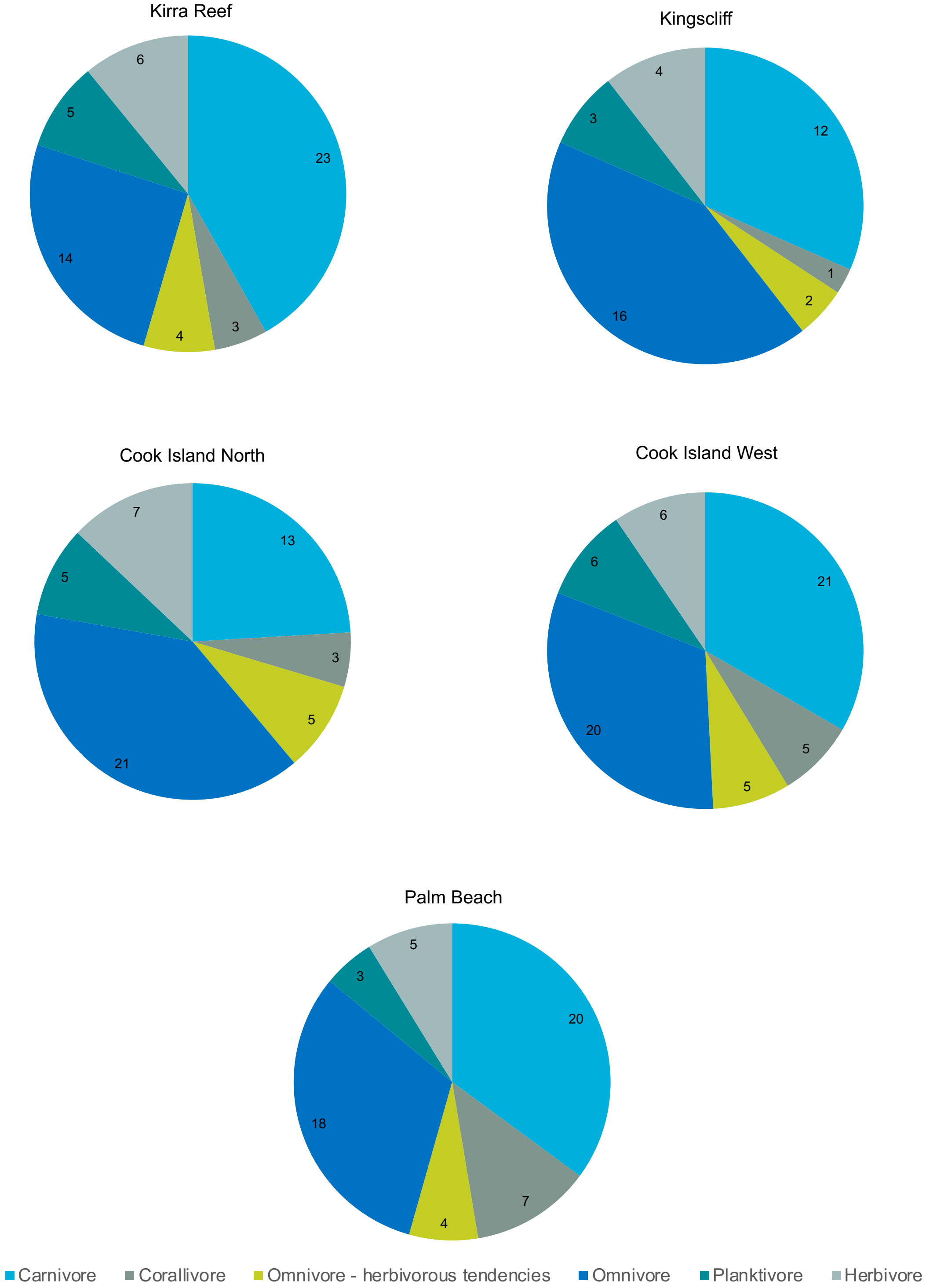


Figure 3.35 Species richness of different trophic levels at each reef.

Fish Communities at Kirra, Palm Beach, Kingscliff and Cook Island Reefs

Fish communities recorded at Kirra Reef were significantly different to those recorded at Kingscliff, Palm Beach, Cook Island North and Cook Island West (Table 3.8, Table 3.9, Table 3.10; Figure 3.36). Significant differences in fish communities were also seen between Palm Beach and reefs at Kingscliff, Cook Island West and Cook Island North. Fish communities recorded at Kingscliff, Cook Island North and West were not significantly different from one another (Table 3.8 & Table 3.9).

Species contributing to differences between Kirra Reef and Kingscliff, Cook Island North and West sites included yellowtail (*Trachurus novazelandiae,* Figure 3.37), silver sweep (*Scorpis lineolata*), Indo-Pacific sergeant (*Abudefduf vaigiensis*), brassy drummer (*Kyphosus vaigiensis*) and Whitley's sergeant (*Abudefduf whitleyi*) (SIMPER, Appendix A).

Similar to previous monitoring events, large schools of yellowtail (*Trachurus novaezelandiae*) present at Kirra Reef were the principal species contributing to differences in community assemblage. Reef-associated species (e.g. barrier reef anemonefish, Figure 3.38 and yellow moon wrasse, Figure 3.39) were typically most abundant at Kingscliff and Cook Island West and North.

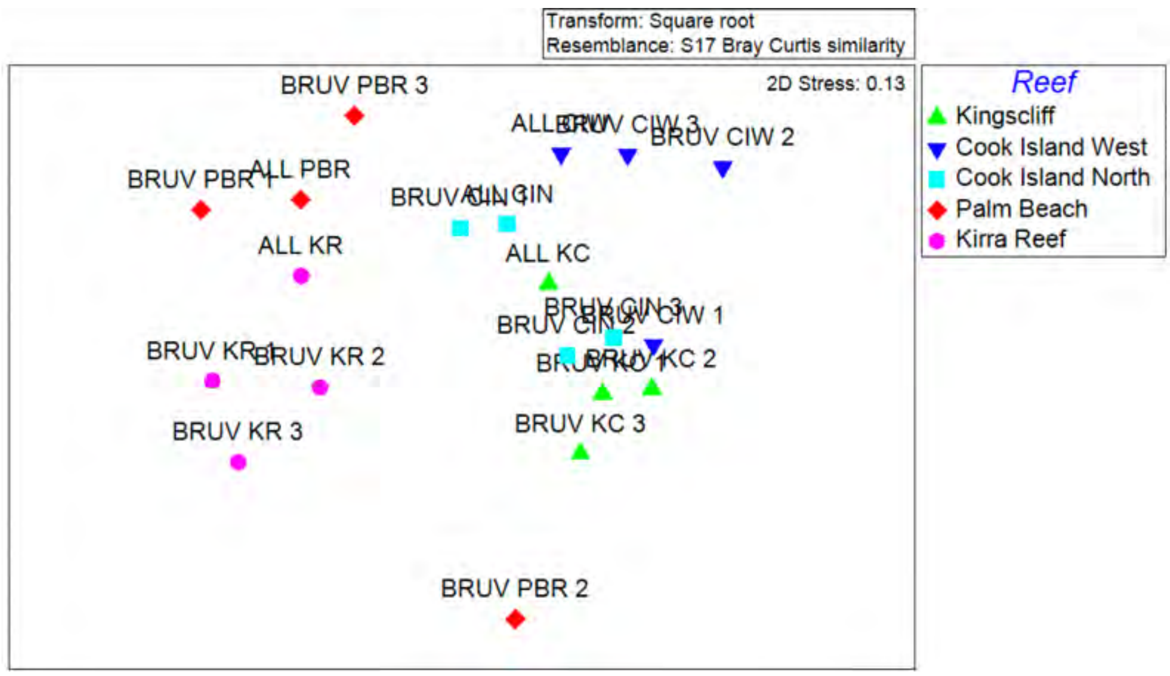


Figure 3.36 Multi-dimensional scale plot of fish communities at each Reef in May 2019.

Table 3.8 PERMANOVA results for differences in the composition of fish communities between reefs.

Factor	**df**	**MS effect**	**Pseudo-F**	**p (MC)[a]**
	Main test			
Reef	4	5975.6	4.1307	**0.0001**
Residual	15	1446.6		

[a] p values based on Monte Carlo simulations, bold values indicate significance at p <0.05.

Table 3.9 Results of pairwise comparisons between reefs following PERMANOVA.

Groups	**t**	**Unique permutations**	**p (MC)[a]**
Kingscliff, Cook Island West	1.6753	35	0.055
Kingscliff, Cook Island North	1.3903	35	0.114
Kingscliff, Palm Beach	2.1322	35	**0.015**
Kingscliff, Kirra Reef	2.7979	35	**0.003**
Cook Island West, Cook Island North	1.4635	35	0.084
Cook Island West, Palm Beach	1.962	35	**0.024**
Cook Island West, Kirra Reef	2.6587	35	**0.002**
Cook Island North, Palm Beach	1.8127	35	**0.028**
Cook Island North, Kirra Reef	2.5035	35	**0.001**
Palm Beach, Kirra Reef	1.7249	35	**0.04**

[a] p values based on Monte Carlo simulations, bold values indicate significance at p <0.05.

Table 3.10 One-way analysis of similarities (ANOSIM) of fish communities at all reefs.

Group	Test statistic (R)	Significance (*p*)[a]	Possible permutations
Main Test			
Between Reefs	0.643	0.1	9999
Pairwise			
Kingscliff, Cook Island West	0.438	0.057	35
Kingscliff, Cook Island North	0.281	0.057	35
Kingscliff, Palm Beach	0.656	0.057	35
Kingscliff, Kirra Reef	0.990	**0.029**	35
Cook Island West, Cook Island North	0.427	**0.029**	35
Cook Island West, Palm Beach	0.635	**0.029**	35
Cook Island West, Kirra Reef	0.969	**0.029**	35
Cook Island North, Palm Beach	0.510	0.057	35
Cook Island North, Kirra Reef	0.969	**0.029**	35
Palm Beach, Kirra Reef	0.458	**0.029**	35

[a] Bold values indicate significance at $p < 0.05$.

Figure 3.37

Yellowtail (*Trachurus novazealandiae*) schooling at Kirra Reef.

Figure 3.38

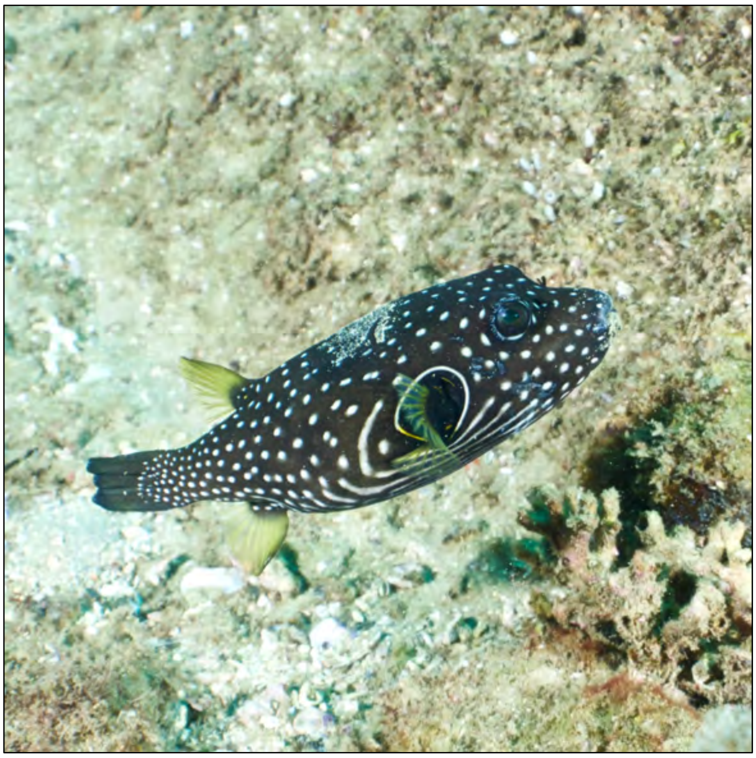
Barrier reef anemonefish (*Amphiprion akindynos*) at Kirra Reef.

Figure 3.39

Yellow moon wrasse (*Thalasoma lutescens*) at Cook Island North.

Figure 3.40

Stars and stripes puffer (*Arothron hispidus*) at Palm Beach Reef.



3.4 Abiotic Factors

Weather Conditions

Water conditions during the May 2019 survey were typical of shallow coastal seas on the Australian east coast during Autumn (Table 3.11). Visibility was 10+ m at all sites surveyed. Water temperature varied between 21 and 22°C – within the typical range for the time of year. The wind strength and direction during the survey was also typical of the time of year, with prevailing light winds from the south and east.

Table 3.11 Abiotic conditions during the surveys at each reef in May 2019.

	Kingscliff	Cook Island West	Cook Island North	Palm Beach	Kirra Reef
	22-May-19	22-May-19	22-May-19	24-May-19	24-May-19
Sea conditions	seas to 1.3m	seas to 1.3m	seas to 1.3m	seas below 1m	seas below 1m
Temperature (°C at 0.5m)	22.4	22.4	22.4	21.8	21.8
Wind strength (km/h)	7	7	7	4	4
Wind direction	SE	SE	SE	SSE	ESE

Wave Height and Direction

As in previous surveys, in the 12 months preceding the 2019 monitoring program, wave height and direction followed these general trends (Figure 3.41):

- Waves predominantly occurred from the E to SE with waves from the ENE the next most frequent
- Wave heights were most frequent between 0.5-1.5 m, and
- Waves larger than 2.5 m were rare.

Between June 2018 and April 2019 the mean wave height at the Waverider buoy was 0.91 m and slightly from the east-south-east (97°) (Table 3.12). The standard deviation of wave direction varied throughout the twelve months preceding monitoring from 12 to 33 degrees.

Wave heights exceeded 4 m in October 2018 (east) and February 2019 (north-east). Other than this, the 12 months preceding May 2019 were relatively calm with waves less than 3 m and commonly less than 1m (Figure 3.42).

The calmest month (i.e. lowest average monthly wave height) was November 2018 with an average wave height of 0.84 m (Table 3.12).

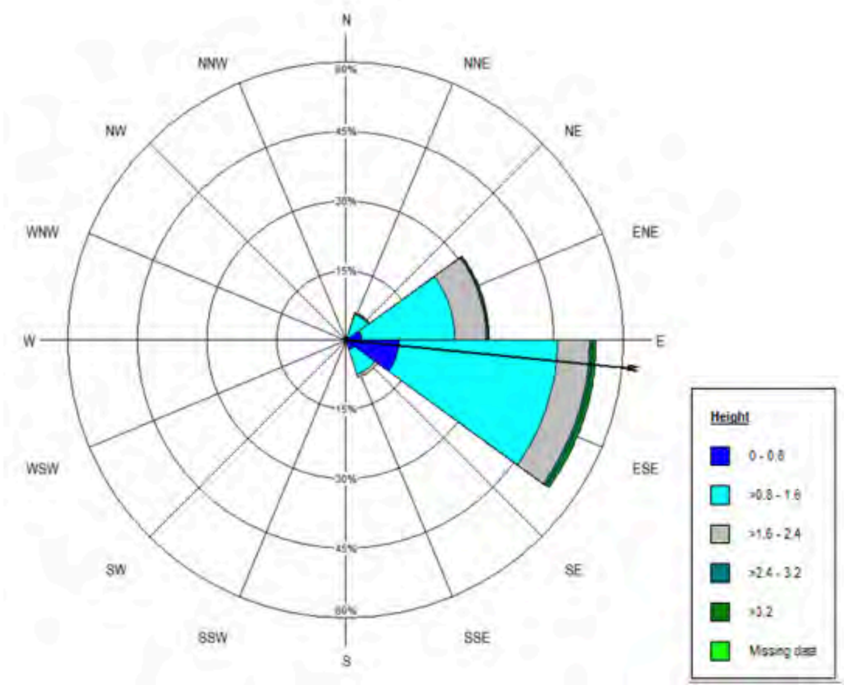


Figure 3.41 Rose plot showing the height in metres and cardinal direction of waves between June 2018 and April 2019.

Table 3.12 Wave height, direction and circular variation

Year	Season	Month	Mean Wave Direction	Mean Wave Height	Circular StDev
2018	Winter	June	110.435°	0.959	16.666°
		July	105.439°	0.886	28.161°
		August	103.691°	0.908	25.126°
	Spring	September	101.061°	0.884	28.409°
		October	100.621°	0.959	16.573°
		November	93.128°	0.842	33.653°
	Summer	December	88.632°	0.904	25.763°
2019		January	80.996°	0.977	12.343°
		February	89.623°	0.967	14.932°
	Autumn	March	91.964°	0.940	20.091°
		April	91.632°	0.960	16.301°
		Overall	96.019°	0.916	21.638°

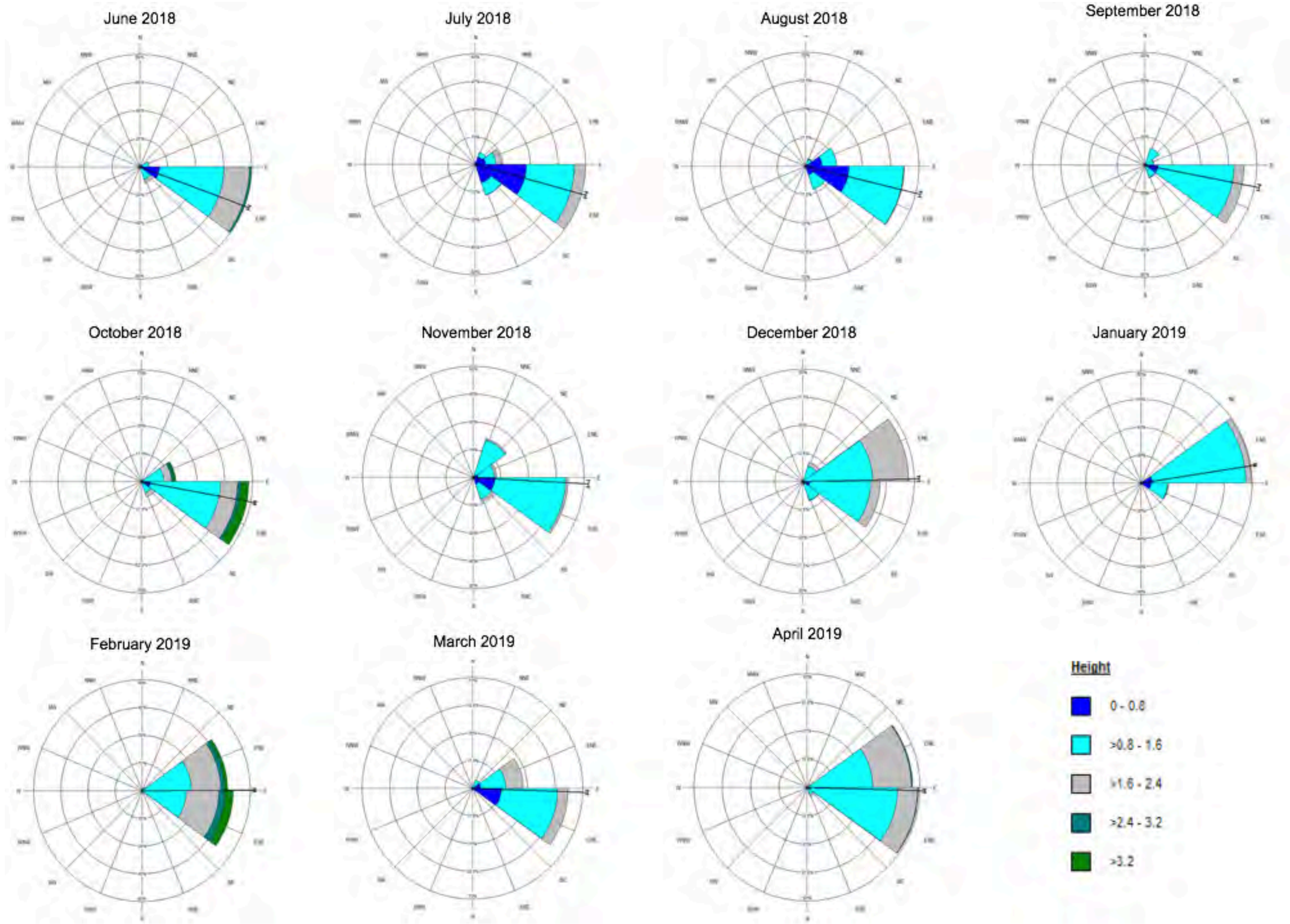


Figure 3.42 Rose plots of wave height and cardinal directions of waves measured at the Tweed Heads Waverider Buoy between June 2018 and April 2019.

Sea Surface Temperature

There has been little change in sea surface temperature over the last 15 years, with the exception of a notable increase in 2010 and decrease in 2013 (Ecosure 2016). During the 11 months preceding the 2019 monitoring event, sea surface temperature followed typical trends with highest temperatures in February and March and the lowest around August (Figure 3.43). Sea surface temperatures ranged from 19.0°C in August and 25.9°C in March.

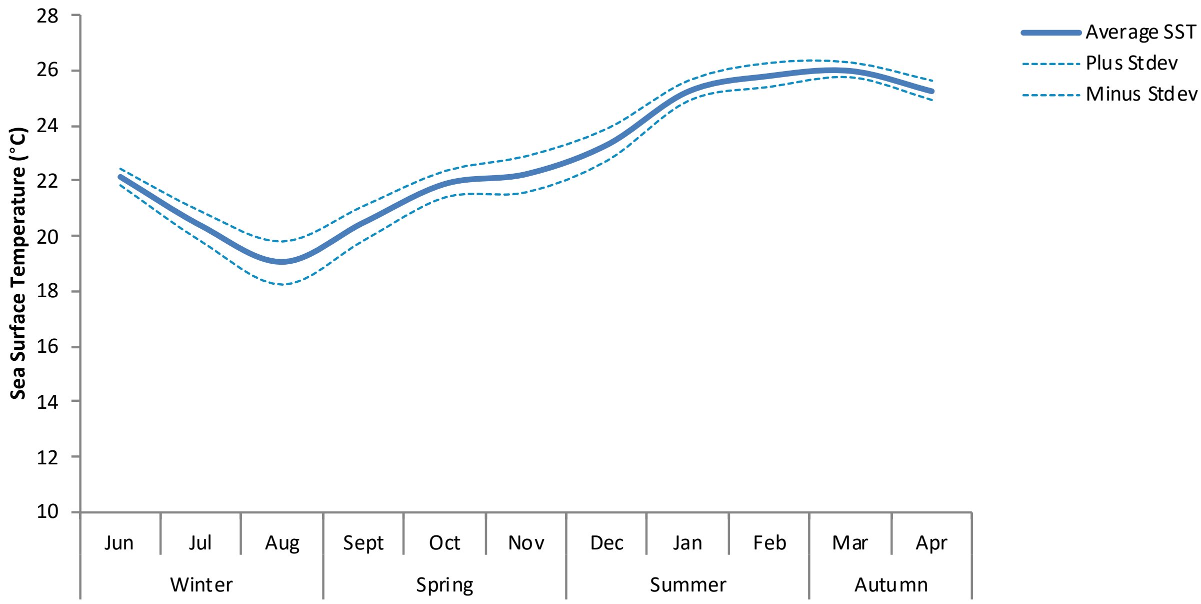


Figure 3.43 Sea surface temperature at the Tweed Heads Waverider Buoy between June 2018 and April 2019. Note Sea surface temperature for May 2019 was not available at time of reporting.

3.5 Temporal Changes in the Extent of Exposed Area on Kirra Reef

The area of exposed reef has changed substantively over the course of the last 9 decades, since aerial images of the reef first became available (Figure 3.48). Three major outcrops of reef (north, south and east) have been exposed and covered with sand at various times as a result of sand movement in the area.

Natural Sand Movement Pre-1960s

Prior to 1960 (Figure 3.44), Kirra Reef was partially covered by sand, which varied naturally with the longshore drift of sand and wave energy. Partial cover of the reef by sand was normal under natural sand supply rates, with the movement of large sand shoals likely to have covered the eastern and southern reefs at times (WorleyParsons 2009). Sand supply in the area during this time was largely uninterrupted and sand movements were episodic, with large amounts of sand transported during major storm events.

Major storm events on the Gold Coast correlate with the Interdecadal Pacific Oscillation (IPO). Between the 1920s and 1940s, the IPO was positive, indicating calmer, drier periods with less frequent and less extreme cyclones. The IPO was negative in the late 1940s and 1950s, indicating stormy periods during this time, although relatively few tropical cyclones and east coast lows were recorded during this time (Callaghan & Helman 2008). The only major coastal structure in the area pre-1960 was the original Tweed River training walls built in 1891 and they were not of sufficient length to substantially interrupt sand supply (WorleyParsons 2009).

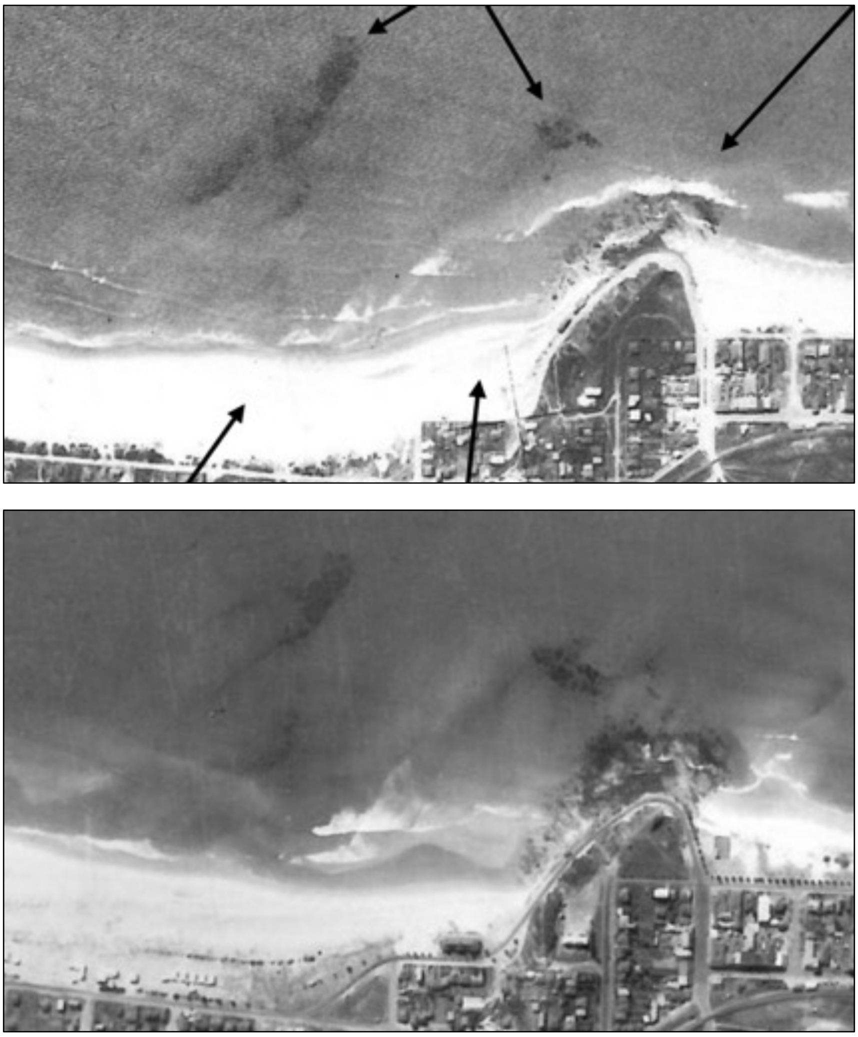


Figure 3.44 Aerial photos for Kirra Reef in 1930 (top) and 1946 (bottom). Source TRESBP 2017.

Sand Depletion - 1960s to Mid-1980s

Following the extension of the Tweed River training walls by 380 m between 1962 and 1965, Kirra Reef became increasingly exposed due to a depleted sand supply. It was also a period of negative IPO, and in 1967 there was a series of successive high intensity east coast lows and cyclones. Kirra Beach suffered major beach erosion and as a consequence hard groyne structures were installed, including Kirra Point groyne in 1972 and Miles Street groyne in 1974. Kirra Beach was also nourished with extra sand (0.765 Mm^3) in 1974-75. However, the lack of sand supply resulted in Kirra Reef being perennially exposed during this period (Figure 3.45).

Figure 3.45 Aerial photos of Kirra Reef in 1965 (top), 1977 (middle) and 1982 (bottom). Source TRESBP 2015 (top) and WorleyParsons 2009 (middle and bottom).

Sand Accretion - Mid-1980s to 2001

Beach nourishment works in the mid to late 1980s (Figure 3.46), along with the commencement of stage 1 of the TRESBP in 1995, resulted in an accumulation of sand. There were relatively few major storms events, with the IPO positive since the 1980s. The area of Kirra Reef that was exposed decreased as sand accumulated around it, but nevertheless, a relatively large area remained uncovered. Kirra Point and Miles Street groynes were both shortened by 30 m in 1996.

Figure 3.46 Aerial photos of Kirra Reef in 1987 (top) and 1999 (bottom). Source TRESBP 2015.

Sand Excess - 2001 to 2008

During the early years of stage 2 of the TRESBP (from 2001 to 2008), relatively high quantities of sand were delivered to the southern Gold Coast beaches as a 'catch-up'. As predicted in the EIS, an inherent result of TRESBP was the reduction in area of Kirra Reef (Figure 3.47). This decrease in the area of exposed reef continued, and by early 2006, the area of exposed reef was <100 m^2, and it was almost completely covered in 2007 and 2008. The remaining reef was in the northern section, with the southern and eastern sections covered. As a consequence of the extensive burial of the reef, there were only simple visual inspections of the reef between 2006 and 2010, rather than full ecological surveys[3].

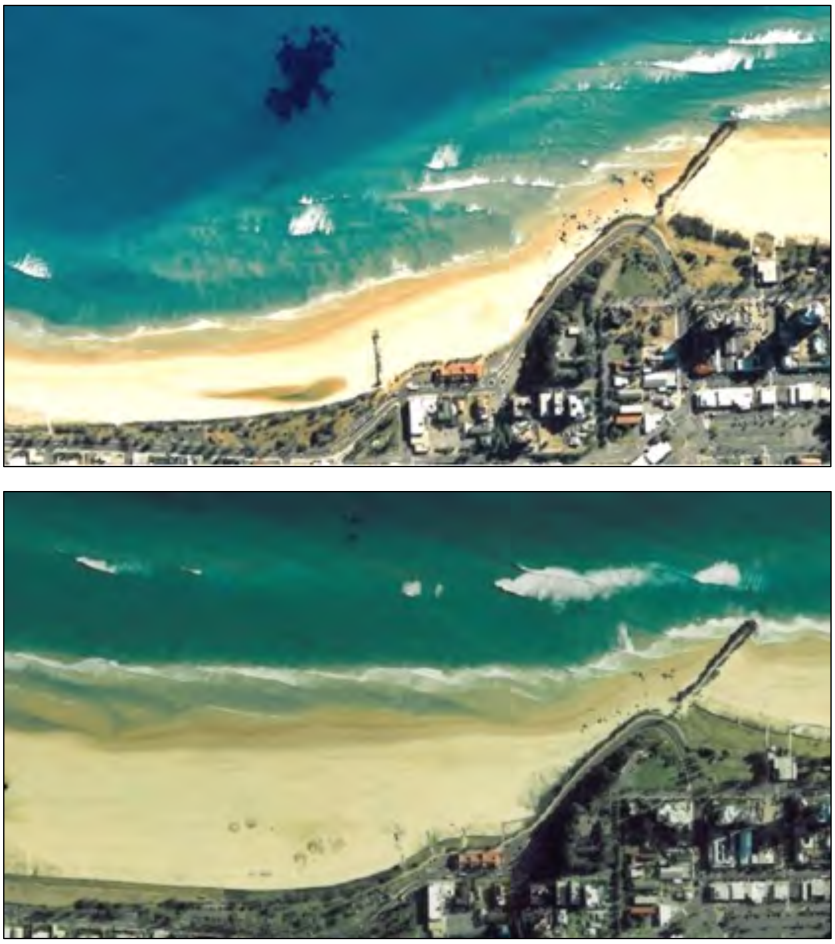


Figure 3.47 Aerial photos for Kirra Reef in 2002 (top) and 2008 (bottom). Source TRESBP 2015.

[3] Underwater visual inspections were completed by Gilbert Diving and Gold Coast City Council from 2006 to 2010.

Mimicking Natural Sand Supply - 2008 to 2019

Since 2008, sand delivery through the TRESBP has been more consistent with the natural movement of sand along the coast. There was a substantial lag between the reduction in sand delivery and transport of the sand further north, due to a period of calmer than usual conditions with reduced storm activity from the north-east. As a consequence, the dispersion of sand from Kirra Beach and the reduction in the sand levels around the reef was slower than predicted. In May 2009, a series of storms moved approximately 200 000 m^3 of sand from Kirra Beach to the north. This, along with the removal of approximately 140 000 m^3 of sand from the Kirra Beach intertidal zone, resulted in the uncovering of parts of Kirra Reef (TRESBP 2015).

Between February 2010 and July 2012, there was a large (50%) increase in the area of exposed rock in the northern section of Kirra Reef. In late 2013, Kirra Point groyne was extended by 30 m, and while this was done with the expectation that the beach bar would move seaward, it has had little effect on reef exposure. The reef has been relatively stable since 2012, with relatively[4] minor changes (<25%) in reef area.

The width of Kirra Beach generally correlates with the exposure of Kirra Beach, with a wide width corresponding to low reefal area and the eastern and southern section's becoming buried (Hyder Consulting 1997). The southern section of the reef has not been exposed for more than fifteen years, and while the eastern section had several instances of being exposed by shifting sand, it has also remained mostly covered. In May 2018 the area of, Kirra Reef was approximately 2 659 m^2. This has increased slightly to 3 161 m^2 in May 2019 (Map 2, Table 3.13) and is currently similar to the extent of reef observed in 2016 and 2017 surveys (Ecosure 2016; frc environmental 2017).

The increase in areal extent of reef is likely due to offshore sand movement caused by Cyclone Oma in late February 2019. Overall, the extent of Kirra Reef has remained relatively constant for the last six years during a period in which sand bypass rates have mimicked the rate of natural sand transport and storm conditions have been moderate.

[4] A 25% change in reef area is considered relatively minor given the error associated with accurately calculating the area from aerial images and given Kirra Reef is in an area of active sand movement and transportation and thus is naturally subject to large changes reef area from shifting sands.

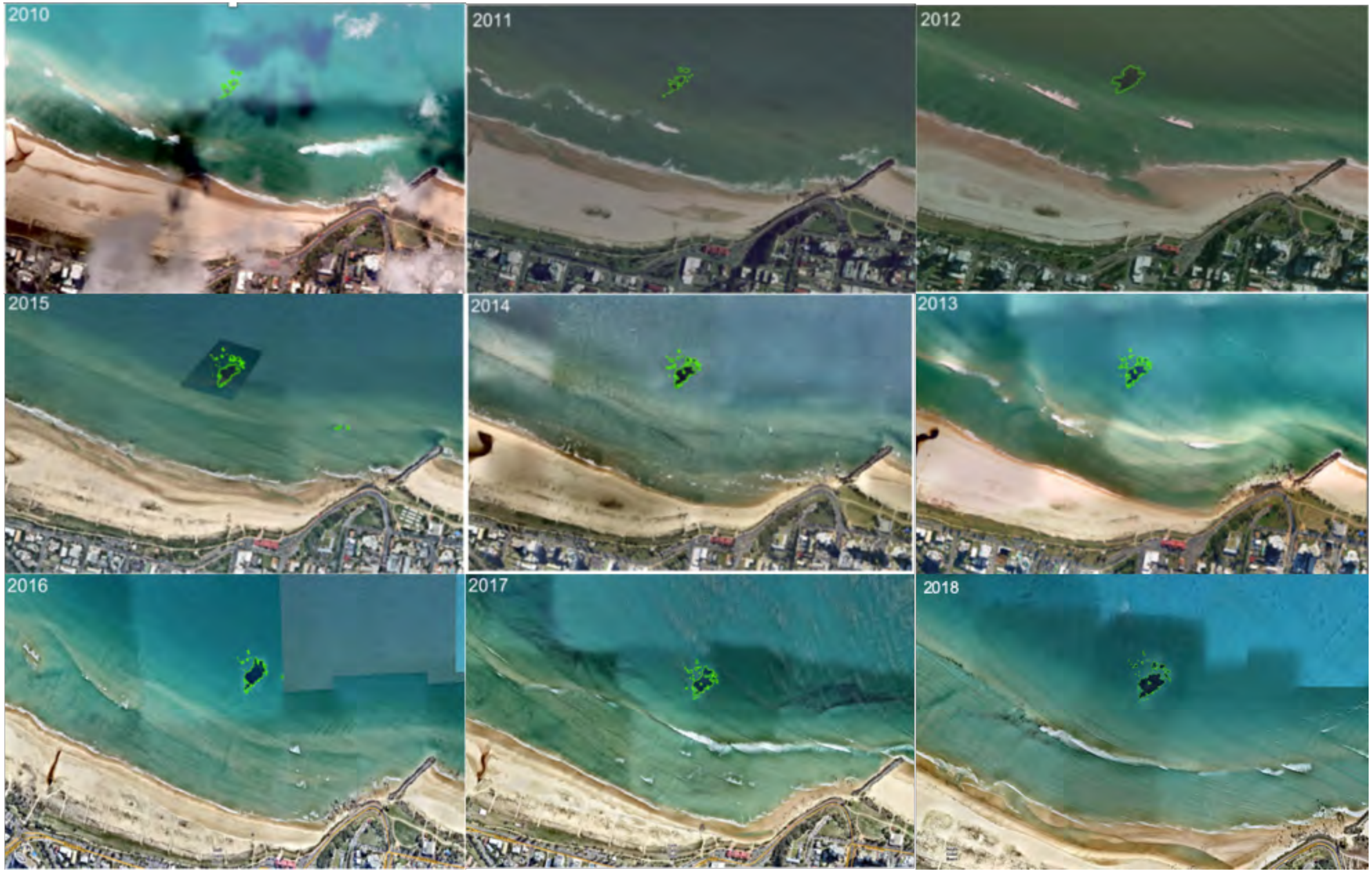


Figure 3.48 Extent of Kirra Reef between 2010 to 2018.

Table 3.13 Approximate extent of Kirra Reef since 1930 (some years are missing as data is not available).

Date		Area (m^2)				Source of Image
		Northern Section	Southern Section	Eastern Section	Total	
May	2019	3 161	0	0	3 161	Nearmap
May	2018	2 659	0	0	2 659	Nearmap
Feb	2017	3 263	0	0	3 263	Nearmap
May	2016	3 326	0	0	3 326	Nearmap[4]
Mar	2015	2 672	0	116	2 788	Rectified image, NSW Trade & Investment
Apr	2014	2 920	0	0	2 920	Nearmap
Jun	2013	2 801	0	0	2 801	Nearmap
May	2013	3 539	0	0	3 539	Nearmap
Aug	2012	3 700	0	0	3 700	Nearmap
Nov	2011	1 044	0	0	1 044	NSW DPI, Catchment and Land Division
May	2010	965	0	0	965	Nearmap
Nov	2009	868	0	141	1 009	Nearmap
Apr	2004	1 578	0	273	1 851	Department of Land and Water Conservation
Nov	2003	3 369	0	0	3 369	Department of Land and Water Conservation
Aug	2002	8 442	0	73	8 515	Department of Infrastructure Planning & Natural Resources
Feb	2001	11 194	2 156	7 048	20 398	Department of Infrastructure Planning & Natural Resources
Oct	1996	3 435	3 491	8 959	15 885	Rectified image from Boswood and Murray 1997[2]
	1995	9 090	11 998	19 725	40 813	NSW DPI, Catchment and Land Division
Nov	1989	9 528	6 660	20 077	36 265	Rectified image, Boswood and Murray 1997[2]
Nov	1974	6 078	-	-	> 6 078	Rectified image, Boswood and Murray 1997[2]
Feb	1972	5 480	0	16 631	22 111	Rectified image, Boswood and Murray 1997[2]
Oct	1962[1]	-	3 841	742	> 4 583	Rectified image, Boswood and Murray 1997[2]
Nov	1935	1694	-	1 656	> 3 350	Rectified image, Boswood and Murray 1997[2]
Sep	1930	5016[3]	-	1 047	> 6 063	Rectified image, Boswood and Murray 1997[2]

[1] Area of Kirra Reef between 1962 and 1965 ranged from 4 850 to 7 800 in the northern reef; 0 to 4 900 in the southern reef; and 600 to 2 150 in the eastern reef, with a total range between 7 000 and 13 300 (Department of Land and Water Conservation, photogrammetric analysis).

[2] Area of reef extent is the outside limit of major clusters of reef as viewed from the 1:6 000 and 1:12 000 photographs. It does not exactly correspond to the area of exposed rocky reef outcrop and indeed may overestimates it as it includes sandy areas between rock outcrops and may also include areas of sand near the rocky reef covered by debris, seaweed or shadow.

[3] Owing to flight height and clarity, the actual area for 1930 may be much less than this figure.

[4] Area from 2016 Ecosure report

- Images not clear enough to calculate extent.

frc environmental
AQUATIC ECOLOGISTS
deep thinking. science.

PO Box 2363
Wellington Point
Q 4160 Australia

P 07 3286 3850
E info@frcenv.com.au
www.frcenv.com.au

Kirra Reef Biota Monitoring 2019

Map 3.51: Extent of Kirra Reef in May 2019

SOURCES

Document Path: Z:\Utility\Mappings\Mappings\2018\181203_NSW_Kirra reef\Workspaces\181203_Map3.51_19-06-19.mxd

LEGEND

Reef Extent

May 2019

N

SCALE

0 0.05 0.1
Kilometres

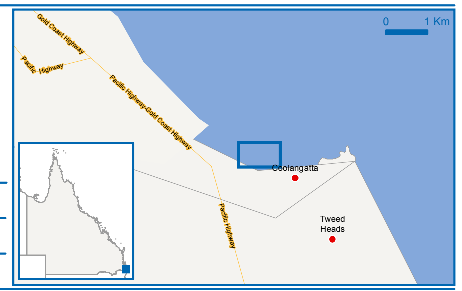
Scale: 1:2,500 @ A3

PROJECTION
Coordinate System: GCS GDA 1994
Datum: GDA 1994
Units: Degree

DATE
2019-06-20

DRAWN BY
LW

VERSION
01



4 Discussion

The benthic assemblage of Kirra Reef continues to be characterised by a high cover of macroalgae and a moderate cover of sessile benthic invertebrates dominated by ascidians, sponge and soft corals. The benthic assemblage at Kirra Reef has experienced significant change over time, due to storms and changes in sand supply impacting the extent of rocky substrate, wave energy, suspended sediments and sediment deposition.

4.1 Changes in Biodiversity and Cover at Kirra Reef

Turf and Macroalgae

In previous years macroalgae cover has dominated the benthic community at Kirra Reef, with a higher cover of *Sargassum* sp. compared to other reefs, with 2019 being no exception. The abundance of *Sargassum* sp. is likely to be indirectly influenced by sand supply, with elevated seabed levels contributing to increased wave energy, surge and abrasive suspended sand particles: conditions favouring *Sargassum* sp. over other macroalgae species.

Following the commencement of stage 2 of the TRESBP in 2001, the cover of macroalgae dramatically decreased, likely a result of the 'catch-up' sand delivery and the burial of reef habitat. Since 2008, sand volumes have been more consistent with natural sand supply rates, and macroalgae cover increased between 2010 and 2016. In 2017, macroalgae cover was lower than in 2016, which may have been a result of storm activity in 2017 (frc environmental, pers. obs.).

Under physically harsh conditions, macroalgae can often out-compete many forms of benthic fauna (frc environmental 2005; Harris 2015), but also experience seasonal changes due to abiotic conditions (Clifton & Clifton 1999), disturbances and propagule supply and recruitment (Vroom et al. 2003). Grazing by fish has also been linked to reduced macroalgae cover and can be seasonal with grazing peaking in the warmer months (Duran et al. 2016). The cover of macroalgae has varied between less than 15% to greater than 55% over the past 15 years, likely in response to a combination of these factors. The cover of macroalgae in 2018 was the highest since 2003, and significantly higher than in the 1995 baseline monitoring (23%). Cover of macroalgae in 2019 was slightly lower than that recorded in 2018. The cover of turf algae is remains near its lowest level since 2004, which may be attributed to an increase competition with larger macroalgae species.

Benthic Invertebrates

The cover of sponges and ascidians was significantly higher than recorded in 2018. The higher cover of sessile benthic organisms is also likely assisted due to the lower cover of turf algae.

The cover of both hard and soft coral at Kirra Reef continues to be very low. Small colonies of hard coral were recorded in 2016 (Ecosure 2016); but not in 2017. Small isolated corals (recruits) were again recorded in 2018; but not in 2019. Soft coral colonies at Kirra Reef are also typically smaller than at both Cook Island sites and Palm Beach Reef, indicating that Kirra Reef is subject to more severe disturbance.

Overall, sites at Cook Island, Kingscliff and Palm Beach Reef had a more evenly distributed benthic community than Kirra Reef. This is likely due to frequent disruptions (e.g. wave action and sand coverage) that prevent the establishment of less resilient taxa. At Kirra Reef, taxa such as ascidians and macroalgae that are able to rapidly colonise recently uncovered and disturbed substrate, (McCook et al. 2001; Mumby 2009) are more common than longer lived taxa such as soft and hard corals.

Fishes

The species richness of each trophic guild was comparable between reefs with carnivorous and omnivorous species the most common at each reef. The number of species belonging to other trophic guilds, i.e. planktivores, corallivores and omnivores with herbivorous tendances were relatively even when comparing across all reefs, however their abundance was notably less. Abundance of yellowtail (*Trachurus novaezelandiae*) was greatest at Kirra Reef and Palm Beach, contributing largely to the significant difference in fish assemblage between these sites and the remaining three reefs. This is consistent with previous surveys (Ecosure 2016; frc environmental 2017; 2018).

Kirra Reef, Palm Beach, Kingscliff and Cook Island Aquatic Reserve are in the northern extent of the Temperate East bioregion defined under the *EPBC Conservation Act 1999*. Being a transitional zone explains the prevalence of species with tropical / temperate distribution at all sites (21-30 species). Species with tropical ranges were the next most specieos (9-27 species) followed by temperate species (6-11). Considering a globally warming climate, this disparity could be expected to increase.

The number of species observed at Kirra Reef during 2019 was greater than that of Kingscliff and Cook Island North, while slightly lower than that of Palm Beach and Cook Island West. All four of the comparative reefs (Palm Beach, Cook Island North and West and Kingscliff) surveyed during 2019 offer varying degrees of habitat type and quality. It is expected that these factors along with shelter from wave energy and legislative protection (Cook Island North and West) have a more notable influence on species abundances between these sites.

The Cook Island Marine Sanctuary and Kirra Reef

The Cook Island Marine Sanctuary includes 78 hectares extending from the mean high water mark out to a 500 m radius from the survey marker on Cook Island (NSW DPI 2017). The area around Cook Island is considered to be a ‘no take’ zone where fishing by all methods is prohibited (although this is likely to be occasionally breached). Studies have shown that ‘no take’ zones can be effective in increasing herbivore density and diversity (Gilby & Stevens 2014; McClanahan 2014), which can lead to increased macroalgae herbivory and the potential for coral growth (Stockwell et al. 2009; Rasher et al. 2013). Analyses from the 2017 monitoring event indicate that the ‘no take’ zone has no obvious impact on the species richness of herbivorous fish, this is reflected by low species abundance again during the 2018 monitoring. During 2019 monitoring there was a slight increase in the species richness of herbivores across the two Cook Island reference sites though a more robust survey method would be necessary to determine significant impacts of the no take zone on herbivorous species. Studies from the Great Barrier Reef demonstrate the importance of no-take zones for the recruitment of large predatory species (Harrison et al. 2012). Larger carnivorous species were notably less abundant within the Cook Island reserve during 2019 than in previous years, with the exception of blue groper (*Achoerodus viridis*) and red bass (*Lutjanus bohar*) which were recorded at both Cook Island sites.

Discarded fishing line and litter was noted at Kirra Reef, whilst no such impact was observed at the reefs at Cook Island, where line fishing is prohibited. Some broken and overturned coral was noted at Palm Beach and Cook Island Reefs, possibly a result of small craft anchoring.

No comparative site used to date in this monitoring program has provided an ‘ideal match’. Palm Beach Reef is representative of a deeper and more offshore environment; Kingscliff Reef is subject to more frequent strong swell than Kirra Reef; and the reefs of Cook Island are more sheltered from wave action than Kirra Reef. Kirra Reef is unique in the region, being completely surrounded by mobile sand. It is likely that the rocky outcrops (such as Manta Bommie) off the north-eastern tip of Stradbroke Island would serve as better comparative sites.

4.2 The Influence of the Sand Bypassing Program

The greatest change to the ecological condition of Kirra Reef since the commencement of TRESBP has been the burial of large areas of hard substrate that support benthic flora and fauna. In particular, the delivery of large sand volumes during the stage 1 TRESBP (1995 to 1998) and the initial operation of the sand bypass system (2001 to 2008) resulted in a significant increase in the beach width at Kirra, with wave action and tidal currents redistributing sand over Kirra Reef. This was predicted in the projects EIS.

It has been predicted that the extent of Kirra Reef will return to conditions similar to those recorded prior to 1962 when the Tweed River training walls were extended. Overall, the areal extent of Kirra Reef has remained relatively constant for the last five years during a time of natural sand transportation rate via the TRESBP and relatively calm storm conditions.

4.3 The Influence of Storms and Wave Action

Exposure to wave action, sand scouring and smothering are important factors influencing the distribution and abundance of sessile species on rocky reefs (Kay & Keough 1981; McGuinness 1987). Change in the height of sand levels around the base of Kirra Reef appears to be the major factor influencing the abundance (cover) of benthic flora and fauna, periodically resulting in bare stratum. Outcrops on the eastern section of the reef, where wave action and likely sand abrasion are greatest, have historically supported a lower abundance of benthic fauna than outcrops on the northern section (Fisheries Research Consultants 1995c; b; 1996; frc environmental 2003; 2004; 2005; 2010). During 2019 monitoring, no freshly exposed rock was observed despite the minor increase in extent determined from satellite imagery.

4.4 Species of Conservation Significance

Fourteen threatened (critically endangered, endangered or vulnerable) and twenty-one migratory fish, marine reptiles or marine mammals protected by the Commonwealth Environmental Protection and Biodiversity Conservation Act were listed as potentially occurring at Kirra Reef using the Protected Matters Search Tool (Appendix E). Threatened species that may occur from time to time in the vicinity of Kirra Reef include:

- black rockcod, listed as vulnerable[5]

5 Although there are very few records from Queensland

- humpback whale and southern right whale, listed as threatened and migratory
- green turtle, loggerhead turtle and hawksbill turtle, listed as threatened and migratory marine
- grey nurse shark, listed as critically endangered
- great white shark, listed as vulnerable and migratory
- Indo-Pacific humpback dolphin, listed as migratory
- reef manta ray, listed as migratory, and
- giant manta ray, listed as migratory.

Of these, the black rock cod, and green and hawksbill turtles are most likely to occur from time to time at Kirra Reef. However, the (potential) extent of Kirra Reef is such that it does not represent critical habitat for these species.

4.5 Invasive Species

Three pest species have previously been recorded within the Brisbane, Gold Coast and Northern NSW region:

- marine pill bug (*Sphaeroma walkeri*)
- hydroid (*Halecium delicatulum*), and
- hydroid (*Obelia dichotoma*).

Over 200 marine pests have been recorded from Australian waters, with 27 marine pests identified in Queensland.

No marine pest species were observed during monitoring in May 2019. However, the highly disturbed nature of Kirra Reef makes the reef vulnerable to colonisation by invasive species.

5 Conclusion

Kirra Reef is a rocky outcrop with locally unique characteristics. The extent of rocky substrate fluctuates with the rate of sand pumping, longshore sand drift, and storm activity.

Brown macroalgae continue to be the dominant epi-flora, whilst a diverse assemblage of temperate and tropical epi-fauna remains in a near-constant flux, with ascidians currently the most dominant of these. Hard and soft coral cover is typically very low.

Large schools of yellowtail dominate the reef's fish communities, with sweep, mado and yellowfin bream also common.

The commencement of the TRESBP resulted in the burial of large areas of rocky substrate. However, much of the reef has re-emerged and the extent of Kirra Reef has remained relatively unchanged for the last seven years, during a period where the delivery of sand by the TRESBP has mimicked natural rates of longshore drift, and in which storm activity has been moderate.

6 References

Callaghan, J. & Helman, P., 2008, 'Severe storms on the east coast of Australia 1770–2008', *Griffith Centre for Coastal Management, Griffith University, Southport, Australia*.

Clifton, K.E. & Clifton, L.M., 1999, 'The phenology of sexual reproduction by green algae (Bryopsidales) on Caribbean coral reefs', *Journal of Phycology* 35: 24-34.

Commonwealth of Australia, 2012, *Marine bioregional plan for the Temperate East Marine Region*, report prepared for and under the Environment Protection and Biodiversity Conservation Act 1999.

DoTE, 2014, EPBC Protected Matters Search Tool, http://www.environment.gov.au/arcgis-framework/apps/pmst/pmst-coordinate.jsf, updated.

DSITI, 2019, Coastal Data System - Waves (Tweed Heads), https://data.qld.gov.au/dataset/coastal-data-system-waves-tweed-heads/resource/f0947711-5fc5-4f88-8365-f8765d4ad571, updated.

Duran, A., Collado-Vides, L. & Burkepile, D.E., 2016, 'Seasonal regulation of herbivory and nutrient effects on macroalgal recruitment and succession in a Florida coral reef', *PeerJ* 4: e2643.

Ecosure, 2016, *Tweed River Entrance Sand Bypassing Project - Kirra Reef biota Monitoring 2016*, report prepared for New South Wales Department of Industry.

ESRI, 2014. ArcGIS Desktop: Release 10.3. Environmental Systems Research Institute, Redlands, CA.

Fisheries Research Consultants, 1995a, *Tweed River Entrance Bypassing Project Monitoring Study of the Impacts of Stage 1 (A) Nourishment on Kirra Reef: Results of the First Scheduled Monitoring Event*.

Fisheries Research Consultants, 1995b, *Tweed River Entrance Sand Bypassing Project Monitoring Study of the Impacts of Stage 1 (A) Nourishment on Kirra Reef, June 1995*, report prepared for Tweed River Entrance Sand Bypassing Project, New South Wales Public Works.

Fisheries Research Consultants, 1995c, *Tweed River Entrance Sand Bypassing Project Monitoring Study of the Impacts of Stage 1 (A) Nourishment on Kirra Reef, May,* *1995*, report prepared for Tweed River Entrance Sand Bypassing Project, New South Wales Public Works.

Fisheries Research Consultants, 1996, *Tweed River Entrance Sand Bypassing Project, Monitoring Study of the Impacts of Stage 1(A) Nourishment on Kirra Reef*, report prepared for Tweed River Entrance Sand Bypassing Project, New South Wales Public Works.

frc environmental, 2001, *Tweed River Entrance Sand Bypassing Project, Monitoring of Kirra Reef, January 2001*, report prepared for Brown and Root.

frc environmental, 2003, *Tweed River Entrance Sand Bypassing Project, Kirra Reef Ecological Monitoring 2003*, report prepared for Department of Infrastructure Planning & Natural Resources (unpublished).

frc environmental, 2004, *Tweed River Entrance Sand Bypassing Project, Kirra Reef Ecological Monitoring 2004*, report prepared for Department of Infrastructure Planning & Natural Resources (unpublished).

frc environmental, 2005, *Tweed River Entrance Sand Bypassing Project, Kirra Reef Ecological Monitoring 2005*, report prepared for Department of Lands.

frc environmental, 2010, *Tweed River Entrance Sand Bypassing Project, Kirra Reef Ecological Monitoring 2010*, report prepared for NSW Land & Property Management Authority and the QLD Department of Environment and Resource Management.

frc environmental, 2012, *Tweed River Entrance Sand Bypassing Project, Kirra Reef Marine Biota Monitoring 2012*, report prepared for NSW Department of Primary Industries, Catchment and Land Division.

frc environmental, 2014, *TRESBP Kirra Reef Marine Biota Monitoring 2014*, report prepared for NSW Department of Trade and Investment, Crown Lands.

frc environmental, 2015, *TRESBP Kirra Reef Marine Biota Monitoring 2015*, report prepared for The New South Wales Department of Primary Industries, Lands and the Queensland Department of Science, Information Technology and Innovation.

frc environmental, 2017, *TRESBP Kirra Reef Biota Monitoring 2017*, report prepared for The New South Wales Department of Primary Industries, Lands and the Queensland Department of Science, Information Technology and Innovation.

frc environmental, 2018, *TRESBP Kirra Reef Biota Monitoring 2018*, report prepared for The New South Wales Department of Primary Industries, Lands and the Queensland Department of Science, Information Technology and Innovation.

Gilby, B.L. & Stevens, T., 2014, 'Meta-analysis indicates habitat-specific alterations to primary producer and herbivore communities in marine protected areas', *Global Ecology and Conservation* 2: 289-299.

Harris, J.L., 2015, 'Quantifying scales of spatial variability in algal turf assemblages on coral reefs', *Marine Ecology Progress Series* 532.

Harrison, H.B., Williamson, D.H., Evans, R.D., Almany, G.R., Thorrold, S.R., Russ, G.R., Feldheim, K.A., Van Herwerden, L., Planes, S. & Srinivasan, M., 2012, 'Larval export from marine reserves and the recruitment benefit for fish and fisheries', *Current biology* 22: 1023-1028.

Hyder Consulting, 1997, *Tweed River Entrance Sand Bypassing Project Permanent Bypassing System. Environmental Impact Statement / Impact Assessment Study, report prepared for New South Wales Department of Land and Water Conservation.*

Kay, A.M. & Keough, M.J., 1981, 'Occupation of patches in the epifaunal communities on pier pilings and the bivalve Pinna bicolor at Edithburgh, South Australia', *Oecologia* 48: 123-130.

Kohler, K.E. & Gill, S.M., 2006, 'Coral Point Count with Excel extensions (CPCe): A Visual Basic program for the determination of coral and substrate coverage using random point count methodology', *Computers & Geosciences* 32: 1259-1269.

Lawson, S., McMahon, J. & Boswood, P., 2001 'Environmental management of the construction and operation of a sand bypassing system at the Tweed River entrance', In: Coasts & Ports 2001: Proceedings of the 15th Australasian Coastal and Ocean Engineering Conference, the 8th Australasian Port and Harbour Conference, Institution of Engineers, Australia: 322.

Loder, J., Byrne, C., Grealy, K. & Trim, K., 2013, 'Reef Check Australia South East Queensland Season Summary Report 2012'.

McClanahan, T.R., 2014, 'Recovery of functional groups and trophic relationships in tropical fisheries closures', *Marine Ecology Progress Series* 497: 13-23.

McCook, L., Jompa, J. & Diaz-Pulido, G., 2001, 'Competition between corals and algae on coral reefs: a review of evidence and mechanisms', *Coral reefs* 19: 400-417.

McGuinness, K.A., 1987, 'Disturbance and organisms on boulders .1. patterns in the environment and the community', *Oecologia* 71: 409-419.

Mumby, P.J., 2009, 'Phase shifts and the stability of macroalgal communities on Caribbean coral reefs', *Coral Reefs* 28: 761-773.

nearmap, 2017, http://www.nearmap.com.au/, updated.

NSW DPI, 2017, http://www.dpi.nsw.gov.au/content/fisheries/marine-protected-areas/aquatic-reserves/cook-island-aquatic-reserve, updated.

Pearson, R. & Stevens, T., 2015, 'Distinct cross-shelf gradient in mesophotic reef fish assemblages in subtropical eastern Australia', *Marine Ecology Progress Series* 532: 185-196.

Rasher, D.B., Hoey, A.S. & Hay, M.E., 2013, 'Consumer diversity interacts with prey defenses to drive ecosystem function', *Ecology* 94: 1347-1358.

Stockwell, B., Jadloc, C.R.L., Abesamis, R.A., Alcala, A.C. & Russ, G.R., 2009, 'Trophic and benthic responses to no-take marine reserve protection in the Philippines', *Marine Ecology Progress Series* 389: 1-15.

TRESBP, 2015, *Tweed Sand Bypassing: Restoring Coastal Sand Drift, Improving Boating Access – Technical information*.

Vroom, P.S., Smith, C.M., Coyer, J.A., Walters, L.J., Hunter, C.L., Beach, K.S. & Smith, J.E., 2003, 'Field biology of Halimeda tuna (Bryopsidales, Chlorophyta) across a depth gradient: comparative growth, survivorship, recruitment, and reproduction', *Hydrobiologia* 501: 149-166.

WorleyParsons, 2009, *TRESBP Kirra Groyne Effects Study*.

Appendix A Detailed Statistical Analyses

Benthic Communities at Kirra Reef, Palm Beach Reef and Cook Island in 2019

Table A.1 Similarity percentage analysis (SIMPER) of dissimilarity of benthic communities at Kirra Reef, Palm Beach, Kingscliff and Cook Island reefs. Benthic taxa contributing up to and including 90% cumulative dissimilarity are shown. Data for SIMPER analysis has been derived from square-root transformed abundance (percent cover) data.

Genus	Average Abundance		Contrib%	Cum.%
	Kirra Reef	Cook Island West		
Kirra Reef versus Cook Island West, Average Dissimilarity = 52.21				
Ascidian (ASC)	6.05	3.54	12.31	12.31
Dictyotaceae (DIC)	0.73	2.93	10.52	22.83
Ulva (UL)	0.45	2.39	8.88	31.71
Turf Algae (TA)	2.76	3.52	7.95	39.65
Corallinaceae (RCO)	2.19	2.32	7.71	47.36
Rhodomelaceae (RRH)	3.17	4.06	7.55	54.91
Sargassaceae (SAR)	1.95	0	7.06	61.97
Anemone (ANE)	1.15	0.67	5.02	66.99
Soft Coral (SCR)	0.08	1.26	4.67	71.66
Sponges (SPG)	1.1	0.52	4.31	75.97
Hard (CH)	0	1.1	4.1	80.07
Tape, shadow (TS)	2.74	2.97	4.07	84.14
Starfish (STA)	1.08	0.15	4.02	88.15
Zoanthids (ZOA)	0.14	0.5	2.08	90.23

Genus	Average Abundance		Contrib%	Cum.%
	Kirra Reef	Cook Island North		
Kirra Reef versus Cook Island North, Average dissimilarity = 53.89				
Ascidian (ASC)	6.05	3.16	14.14	14.14
Dictyotaceae (DIC)	0.73	3.69	13.06	27.2
Rhodomelaceae (RRH)	3.17	4.59	10.26	37.46
Turf Algae (TA)	2.76	3.36	7.86	45.32
Corallinaceae (RCO)	2.19	0.95	7.49	52.81
Sargassaceae (SAR)	1.95	0	7.09	59.9
Ulva (UL)	0.45	1.5	5.91	65.81
Sponges (SPG)	1.1	0.7	4.89	70.7
Anemone (ANE)	1.15	0.3	4.62	75.32
Tape, shadow (TS)	2.74	3.01	4.33	79.65
Starfish (STA)	1.08	0.17	4.02	83.68
Caulerpaceae (CAL)	0.4	0.76	3.83	87.51
Rubble (RUB)	0.33	0.43	2.31	89.82
Zoanthids (ZOA)	0.14	0.52	2.2	92.02

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island West	Cook Island North		
Cook Island West versus Cook Island North, Average dissimilarity = 45.78				
Dictyotaceae (DIC)	2.93	3.69	13.57	13.57
Ascidian (ASC)	3.54	3.16	10.33	23.9
Rhodomelaceae (RRH)	4.06	4.59	9.95	33.84
Ulva (UL)	2.39	1.5	9.34	43.19
Corallinaceae (RCO)	2.32	0.95	8.74	51.93
Turf Algae (TA)	3.52	3.36	7.69	59.62
Soft Coral (SCR)	1.26	0.51	5.77	65.39
Hard (CH)	1.1	0.36	5.45	70.84
Tape, shadow (TS)	2.97	3.01	4.18	75.02
Sponges (SPG)	0.52	0.7	3.92	78.94
Caulerpaceae (CAL)	0.19	0.76	3.64	82.58
Anemone (ANE)	0.67	0.3	3.49	86.07
Zoanthids (ZOA)	0.5	0.52	3.29	89.36
Rubble (RUB)	0.34	0.43	2.65	92.01

Genus	Average Abundance		Contrib%	Cum.%
	Kirra Reef	Kingscliff		
Kirra Reef versus Kingscliff, Average dissimilarity = 51.09				
Ulva (UL)	0.45	4.21	15.41	15.41
Ascidian (ASC)	6.05	5.68	9.36	24.77
Rhodomelaceae (RRH)	3.17	1.73	8.56	33.33
Corallinaceae (RCO)	2.19	1.91	8.55	41.88
Turf Algae (TA)	2.76	3.07	8.32	50.2
Coralline Algae (CA)	0.05	1.9	7.49	57.69
Sargassaceae (SAR)	1.95	0	7.38	65.07
Sponges (SPG)	1.1	0.79	4.85	69.92
Tape, shadow (TS)	2.74	3.09	4.43	74.35
Anemone (ANE)	1.15	0.03	4.37	78.72
Dictyotaceae (DIC)	0.73	0.74	4.22	82.95
Starfish (STA)	1.08	0	4.1	87.05
Zoanthids (ZOA)	0.14	0.76	3.11	90.16

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island West	Kingscliff		
Cook Island West versus Kingscliff, Average dissimilarity = 48.47				
Ascidian (ASC)	3.54	5.68	11.44	11.44
Dictyotaceae (DIC)	2.93	0.74	10.91	22.36
Ulva (UL)	2.39	4.21	10.82	33.18
Rhodomelaceae (RRH)	4.06	1.73	10.23	43.4
Corallinaceae (RCO)	2.32	1.91	8.66	52.06
Turf Algae (TA)	3.52	3.07	7.61	59.67
Coralline Algae (CA)	0	1.9	7.43	67.1
Soft Coral (SCR)	1.26	0.45	5.49	72.59
Hard (CH)	1.1	0.07	4.42	77.01
Tape, shadow (TS)	2.97	3.09	3.86	80.87
Sponges (SPG)	0.52	0.79	3.77	84.63
Zoanthids (ZOA)	0.5	0.76	3.51	88.14
Anemone (ANE)	0.67	0.03	2.62	90.77

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island North	Kingscliff		
Cook Island North versus Kingscliff, Average dissimilarity = 53.01				
Dictyotaceae (DIC)	3.69	0.74	13.01	13.01
Ascidian (ASC)	3.16	5.68	12.76	25.77
Rhodomelaceae (RRH)	4.59	1.73	12.63	38.4
Ulva (UL)	1.5	4.21	11.75	50.15
Corallinaceae (RCO)	0.95	1.91	7.39	57.53
Turf Algae (TA)	3.36	3.07	7.33	64.86
Coralline Algae (CA)	0	1.9	7.19	72.06
Sponges (SPG)	0.7	0.79	4.23	76.29
Tape, shadow (TS)	3.01	3.09	3.96	80.25
Zoanthids (ZOA)	0.52	0.76	3.64	83.89
Soft Coral (SCR)	0.51	0.45	3.12	87.01
Caulerpaceae (CAL)	0.76	0.06	2.98	89.99
Rubble (RUB)	0.43	0.23	2.09	92.08

Genus	Average Abundance		Contrib%	Cum.%
	Kirra Reef	Palm Beach		
Kirra Reef versus Palm Beach, Average dissimilarity = 51.62				
Ascidian (ASC)	6.05	4.05	11.25	11.25
Turf Algae (TA)	2.76	5.21	10.74	21.99
Rhodomelaceae (RRH)	3.17	3.98	8.85	30.84
Soft Coral (SCR)	0.08	2.31	8.71	39.55
Corallinaceae (RCO)	2.19	0	8.12	47.67
Anemone (ANE)	1.15	1.85	7.39	55.05
Sargassaceae (SAR)	1.95	0	7.2	62.26
Zoanthids (ZOA)	0.14	1.42	5.44	67.7
Sponges (SPG)	1.1	0.86	4.71	72.41
Starfish (STA)	1.08	0.03	4.02	76.43
Tape, shadow (TS)	2.74	3.04	3.92	80.34
Rubble (RUB)	0.33	0.84	3.49	83.83
Ulva (UL)	0.45	0.59	3.29	87.12
Sand (SND)	0.29	0.68	3.04	90.16

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island West	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 51.62				
Dictyotaceae (DIC)	2.93	0	11.27	11.27
Corallinaceae (RCO)	2.32	0	8.92	20.19
Ulva (UL)	2.39	0.59	8.53	28.72
Ascidian (ASC)	3.54	4.05	8.36	37.08
Soft Coral (SCR)	1.26	2.31	8.22	45.3
Turf Algae (TA)	3.52	5.21	8.15	53.44
Rhodomelaceae (RRH)	4.06	3.98	8	61.44
Anemone (ANE)	0.67	1.85	6.99	68.43
Zoanthids (ZOA)	0.5	1.42	5.42	73.85
Hard (CH)	1.1	0.23	4.75	78.6
Sponges (SPG)	0.52	0.86	3.7	82.3
Rubble (RUB)	0.34	0.84	3.55	85.85
Tape, shadow (TS)	2.97	3.04	3.32	89.18
Sand (SND)	0.08	0.68	2.68	91.85

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island North	Palm Beach		
Cook Island North versus Palm Beach, Average dissimilarity = 51.41				
Dictyotaceae (DIC)	3.69	0	14.46	14.46
Rhodomelaceae (RRH)	4.59	3.98	10.32	24.78
Ascidian (ASC)	3.16	4.05	9.79	34.57
Turf Algae (TA)	3.36	5.21	8.87	43.44
Soft Coral (SCR)	0.51	2.31	8.77	52.21
Anemone (ANE)	0.3	1.85	7.14	59.34
Zoanthids (ZOA)	0.52	1.42	5.7	65.04
Ulva (UL)	1.5	0.59	5.59	70.63
Sponges (SPG)	0.7	0.86	4.28	74.91
Rubble (RUB)	0.43	0.84	3.77	78.68
Tape, shadow (TS)	3.01	3.04	3.58	82.26
Corallinaceae (RCO)	0.95	0	3.52	85.77
Caulerpaceae (CAL)	0.76	0	2.88	88.66
Sand (SND)	0.11	0.68	2.77	91.42

Genus	Average Abundance		Contrib%	Cum.%
	Kingscliff	Palm Beach		
KIngscliff versus Palm Beach, Average dissimilarity = 52.85				
Ulva (UL)	4.21	0.59	13.64	13.64
Rhodomelaceae (RRH)	1.73	3.98	10.24	23.88
Ascidian (ASC)	5.68	4.05	9.57	33.45
Turf Algae (TA)	3.07	5.21	9.18	42.63
Soft Coral (SCR)	0.45	2.31	8.53	51.16
Corallinaceae (RCO)	1.91	0	7.03	58.19
Coralline Algae (CA)	1.9	0	7.01	65.2
Anemone (ANE)	0.03	1.85	6.75	71.96
Zoanthids (ZOA)	0.76	1.42	5.45	77.41
Sponges (SPG)	0.79	0.86	4.05	81.47
Tape, shadow (TS)	3.09	3.04	3.37	84.84
Rubble (RUB)	0.23	0.84	3.29	88.13
Dictyotaceae (DIC)	0.74	0	2.7	90.83

Temporal Comparisons of Benthic Groups at Kirra Reef

Table A.2 Results of pairwise comparisons for macroalgae over time at Kirra Reef following PERMANOVA.

Groups	t	P(perm)	Unique permutations
2001, 2003	4.2003	**0.0001**	9968
2001, 2004	8.1174	**0.0001**	9959
2001, 2005	6.6647	**0.0001**	9963
2001, 2010	7.7699	**0.0001**	9964
2001, 2012	8.7492	**0.0001**	9957
2001, 2014	7.864	**0.0001**	9955
2001, 2015	8.0611	**0.0001**	9963
2001, 2016	9.7949	**0.0001**	9953
2001, 2017	3.6398	**0.0001**	9962
2001, 2018	5.2656	**0.0001**	9952
2001, 2019	9.2512	**0.0001**	9942
2001, A1995	6.285	**0.0001**	9951
2001, F1996	3.2527	**0.0001**	9960
2001, J1995	2.8276	**0.0006**	9951
2003, 2004	4.1089	**0.0001**	9957
2003, 2005	3.6399	**0.0001**	9960
2003, 2010	5.215	**0.0001**	9966
2003, 2012	6.6416	**0.0001**	9967
2003, 2014	4.4873	**0.0001**	9958
2003, 2015	4.7487	**0.0001**	9957
2003, 2016	6.4041	**0.0001**	9951
2003, 2017	2.0595	**0.0133**	9962
2003, 2018	3.6318	**0.0001**	9965
2003, 2019	5.0313	**0.0001**	9969
2003, A1995	5.3407	**0.0001**	9958
2003, F1996	2.8212	**0.0001**	9940
2003, J1995	4.4845	**0.0001**	9962
2004, 2005	6.8785	**0.0001**	9966
2004, 2010	8.6424	**0.0001**	9954

Groups	t	P(perm)	Unique permutations
2004, 2012	6.7103	**0.0001**	9960
2004, 2014	4.0816	**0.0001**	9952
2004, 2015	3.5143	**0.0001**	9944
2004, 2016	5.3103	**0.0001**	9952
2004, 2017	5.1615	**0.0001**	9957
2004, 2018	5.4176	**0.0001**	9956
2004, 2019	7.3094	**0.0001**	9963
2004, A1995	9.3959	**0.0001**	9959
2004, F1996	4.9876	**0.0001**	9960
2004, J1995	8.0901	**0.0001**	9954
2005, 2010	3.7106	**0.0001**	9960
2005, 2012	7.9576	**0.0001**	9957
2005, 2014	6.1704	**0.0001**	9947
2005, 2015	6.7985	**0.0001**	9962
2005, 2016	9.0252	**0.0001**	9955
2005, 2017	2.5267	**0.0026**	9959
2005, 2018	5.5004	**0.0001**	9957
2005, 2019	9.2788	**0.0001**	9950
2005, A1995	6.0906	**0.0001**	9955
2005, F1996	6.007	**0.0001**	9945
2005, J1995	5.1889	**0.0001**	9957
2010, 2012	8.481	**0.0001**	9960
2010, 2014	7.6995	**0.0001**	9949
2010, 2015	8.4684	**0.0001**	9950
2010, 2016	10.794	**0.0001**	9957
2010, 2017	3.8323	**0.0001**	9962
2010, 2018	7.0577	**0.0001**	9954
2010, 2019	11.211	**0.0001**	9957
2010, A1995	6.5491	**0.0001**	9960
2010, F1996	6.9055	**0.0001**	9953
2010, J1995	5.8782	**0.0001**	9944
2012, 2014	7.0618	**0.0001**	9972

Groups	t	P(perm)	Unique permutations
2012, 2015	6.6808	**0.0001**	9960
2012, 2016	8.0032	**0.0001**	9950
2012, 2017	6.2015	**0.0001**	9957
2012, 2018	7.8298	**0.0001**	9958
2012, 2019	12.17	**0.0001**	9956
2012, A1995	9.1806	**0.0001**	9964
2012, F1996	6.6785	**0.0001**	9965
2012, J1995	7.1072	**0.0001**	9950
2014, 2015	1.739	**0.0211**	9954
2014, 2016	3.7425	**0.0001**	9942
2014, 2017	4.5916	**0.0001**	9953
2014, 2018	3.97	**0.0001**	9953
2014, 2019	6.3035	**0.0001**	9953
2014, A1995	10.195	**0.0001**	9951
2014, F1996	6.2265	**0.0001**	9937
2014, J1995	8.0693	**0.0001**	9952
2015, 2016	2.9618	**0.0001**	9969
2015, 2017	4.8603	**0.0001**	9958
2015, 2018	4.9886	**0.0001**	9954
2015, 2019	7.0645	**0.0001**	9958
2015, A1995	9.8789	**0.0001**	9961
2015, F1996	5.8178	**0.0001**	9960
2015, J1995	8.1146	**0.0001**	9954
2016, 2017	5.6588	**0.0001**	9949
2016, 2018	5.5422	**0.0001**	9961
2016, 2019	7.4236	**0.0001**	9959
2016, A1995	12.659	**0.0001**	9953
2016, F1996	7.2244	**0.0001**	9951
2016, J1995	9.7992	**0.0001**	9955
2017, 2018	3.4481	**0.0002**	9949
2017, 2019	4.6904	**0.0001**	9956
2017, A1995	3.8056	**0.0002**	9952

Groups	t	P(perm)	Unique permutations
2017, F1996	3.4061	**0.0001**	9947
2017, J1995	3.5094	**0.0001**	9948
2018, 2019	3.4338	**0.0001**	9949
2018, A1995	8.4897	**0.0001**	9955
2018, F1996	5.1934	**0.0001**	9961
2018, J1995	6.3545	**0.0001**	9962
2019, A1995	13.288	**0.0001**	9955
2019, F1996	6.9906	**0.0001**	9962
2019, J1995	10.336	**0.0001**	9958
A1995, F1996	4.9933	**0.0001**	9962
A1995, J1995	3.4759	**0.0001**	9960
F1996, J1995	3.8639	**0.0001**	9964

Table A.3 Results of pairwise comparisons for turf algae over time at Kirra Reef following PERMANOVA.

Groups	t	P(perm)[a]	Unique permutations
2017, 2001	5.0867	**0.0001**	9943
2017, 2003	0.43632	0.777	9936
2017, 2004	0.61084	0.6098	9951
2017, 2005	0.89265	0.4018	9944
2017, A1995	1.6466	0.0784	9927
2017, F1996	2.0428	**0.0283**	9940
2017, J1995	2.4179	**0.0094**	9948
2017, 2010	1.635	0.083	9943
2017, 2012	1.2089	0.2211	9944
2017, 2014	2.1081	**0.0233**	9946
2017, 2015	1.4375	0.1389	9943
2017, 2016	2.23	**0.0169**	9946
2017, 2018	3.2084	**0.0004**	9941
2017, 2019	2.6727	**0.0036**	9939
2001, 2003	4.5232	**0.0001**	9930
2001, 2004	4.4511	**0.0001**	9943
2001, 2005	6.3794	**0.0001**	9927
2001, A1995	5.9719	**0.0001**	9938
2001, F1996	2.569	**0.0053**	9927
2001, J1995	2.5537	**0.0034**	9953
2001, 2010	7.9816	**0.0001**	9945
2001, 2012	6.3733	**0.0001**	9926
2001, 2014	5.5648	**0.0001**	9935
2001, 2015	4.7568	**0.0001**	9944
2001, 2016	3.7387	**0.0001**	9941
2001, 2018	2.5679	**0.0041**	9943
2001, 2019	3.3482	**0.0003**	9960
2003, 2004	0.48703	0.713	9910

Groups	t	P(perm)[a]	Unique permutations
2003, 2005	1.2196	0.2168	9874
2003, A1995	1.7542	0.0677	9911
2003, F1996	1.6577	0.0854	9935
2003, J1995	2.0947	**0.0314**	9912
2003, 2010	1.9853	**0.0377**	9938
2003, 2012	1.4209	0.1462	9933
2003, 2014	2.07	0.0291	9916
2003, 2015	1.4009	0.1533	9914
2003, 2016	1.9971	**0.0364**	9939
2003, 2018	2.8622	**0.0019**	9943
2003, 2019	2.4079	**0.01**	9941
2004, 2005	1.519	0.1172	9866
2004, A1995	1.314	0.1849	9923
2004, F1996	1.6139	0.0994	9933
2004, J1995	1.8225	0.0548	9939
2004, 2010	2.2877	**0.0154**	9947
2004, 2012	1.819	0.057	9909
2004, 2014	1.6006	0.0949	9854
2004, 2015	0.91873	0.3798	9927
2004, 2016	1.5591	0.0986	9955
2004, 2018	2.5628	0.0056	9933
2004, 2019	2.037	**0.026**	9941
2005, A1995	2.4314	**0.0077**	9871
2005, F1996	2.8868	**0.002**	9933
2005, J1995	3.4265	**0.0002**	9936
2005, 2010	0.74951	0.5153	9941
2005, 2012	0.51977	0.7335	9699
2005, 2014	3.0467	**0.0009**	9733
2005, 2015	2.3418	**0.0132**	9884
2005, 2016	3.3065	**0.0006**	9951

Groups	t	P(perm)[a]	Unique permutations
2005, 2018	4.3377	**0.0001**	9930
2005, 2019	3.7495	**0.0002**	9929
A1995, F1996	2.5318	**0.0042**	9956
A1995, J1995	2.351	**0.0097**	9950
A1995, 2010	3.202	**0.0001**	9949
A1995, 2012	2.8573	**0.0013**	9915
A1995, 2014	0.81357	0.5249	9898
A1995, 2015	0.67758	0.6297	9928
A1995, 2016	1.6929	0.0699	9950
A1995, 2018	3.049	**0.0009**	9951
A1995, 2019	2.2298	**0.0152**	9942
F1996, J1995	0.99897	0.3375	9953
F1996, 2010	3.7141	**0.0001**	9940
F1996, 2012	2.9765	**0.0014**	9964
F1996, 2014	2.4119	**0.0079**	9929
F1996, 2015	1.9365	**0.0388**	9940
F1996, 2016	1.5997	0.0944	9944
F1996, 2018	1.69	0.0717	9949
F1996, 2019	1.6754	0.0787	9936
J1995, 2010	4.3871	**0.0001**	9942
J1995, 2012	3.624	**0.0001**	9955
J1995, 2014	1.9911	**0.0251**	9952
J1995, 2015	1.6869	0.0737	9940
J1995, 2016	0.86364	0.4318	9933
J1995, 2018	0.77586	0.4953	9949
J1995, 2019	0.75163	0.5247	9949
2010, 2012	0.86128	0.4291	9939
2010, 2014	3.983	**0.0001**	9955
2010, 2015	3.1549	**0.0003**	9949
2010, 2016	4.2767	**0.0001**	9953

Groups	t	P(perm)[a]	Unique permutations
2010, 2018	5.5158	**0.0001**	9947
2010, 2019	4.8198	**0.0001**	9948
2012, 2014	3.4278	**0.0001**	9923
2012, 2015	2.7145	**0.0038**	9936
2012, 2016	3.6233	**0.0002**	9940
2012, 2018	4.5313	**0.0001**	9955
2012, 2019	4.0008	**0.0001**	9954
2014, 2015	0.70804	0.6082	9894
2014, 2016	1.2291	0.2199	9944
2014, 2018	2.5118	**0.004**	9945
2014, 2019	1.6747	0.0666	9935
2015, 2016	1.0447	0.3166	9950
2015, 2018	2.297	**0.0069**	9950
2015, 2019	1.5878	0.0936	9942
2016, 2018	1.3059	0.1839	9951
2016, 2019	0.62949	0.6378	9951
2018, 2019	0.75915	0.5536	9943

[a] Bold p values denote significance at $p<0.05$

Table A.4 Results of pairwise comparisons for hard coral over time at Kirra Reef following PERMANOVA.

Groups	t	P(perm)	Unique permutations
2017, 2001	Denominator is 0		
2017, 2003	Denominator is 0		
2017, 2004	1.7118	0.2409	4
2017, 2005	1.4005	0.4873	2
2017, A1995	3.1993	0.0035	28
2017, F1996	1.7728	0.2349	2
2017, J1995	Denominator is 0		
2017, 2010	1	1	1
2017, 2012	Denominator is 0		
2017, 2014	Denominator is 0		
2017, 2015	1	1	1
2017, 2016	Denominator is 0		
2017, 2018	1	1	1
2017, 2019	Denominator is 0		
2001, 2003	Denominator is 0		
2001, 2004	1.7118	0.2416	4
2001, 2005	1.4005	0.4952	2
2001, A1995	3.1993	**0.003**	28
2001, F1996	1.7728	0.2445	2
2001, J1995	Denominator is 0		
2001, 2010	1	1	1
2001, 2012	Denominator is 0		
2001, 2014	Denominator is 0		
2001, 2015	1	1	1
2001, 2016	Denominator is 0		
2001, 2018	1	1	1
2001, 2019	Denominator is 0		
2003, 2004	1.7118	0.2435	4

Groups	t	P(perm)	Unique permutations
2003, 2005	1.4005	0.5021	2
2003, A1995	3.1993	**0.0026**	28
2003, F1996	1.7728	0.2438	2
2003, J1995	Denominator is 0		
2003, 2010	1	1	1
2003, 2012	Denominator is 0		
2003, 2014	Denominator is 0		
2003, 2015	1	1	1
2003, 2016	Denominator is 0		
2003, 2018	1	1	1
2003, 2019	Denominator is 0		
2004, 2005	0.41558	0.8109	12
2004, A1995	1.6324	0.1097	124
2004, F1996	0.25067	0.809	16
2004, J1995	1.7118	0.2355	4
2004, 2010	1.1739	0.3624	6
2004, 2012	1.7118	0.2393	4
2004, 2014	1.7118	0.2371	4
2004, 2015	1.3289	0.2391	8
2004, 2016	1.9119	0.0832	8
2004, 2018	1.3122	0.2423	8
2004, 2019	1.7118	0.2438	4
2005, A1995	2.0419	**0.0469**	84
2005, F1996	0.40231	1	5
2005, J1995	1.4005	0.4987	2
2005, 2010	0.79401	0.4967	4
2005, 2012	1.4005	0.4998	2
2005, 2014	1.4005	0.4954	2
2005, 2015	0.96585	0.4928	4
2005, 2016	1.5643	0.1952	4

Groups	t	P(perm)	Unique permutations
2005, 2018	0.94723	0.4928	4
2005, 2019	1.4005	0.4899	2
A1995, F1996	1.7286	0.116	70
A1995, J1995	3.1993	**0.0027**	28
A1995, 2010	2.7305	**0.0111**	32
A1995, 2012	3.1993	**0.0027**	28
A1995, 2014	3.1993	**0.0026**	28
A1995, 2015	2.8621	**0.0019**	56
A1995, 2016	3.5733	**0.0004**	56
A1995, 2018	2.8477	**0.0024**	56
A1995, 2019	3.1993	**0.0026**	28
F1996, J1995	1.7728	0.2404	2
F1996, 2010	1.1343	0.2442	4
F1996, 2012	1.7728	0.2435	2
F1996, 2014	1.7728	0.2408	2
F1996, 2015	1.3044	0.2456	4
F1996, 2016	1.9801	0.0878	4
F1996, 2018	1.2854	0.2408	4
F1996, 2019	1.7728	0.2411	2
J1995, 2010	1	1	1
J1995, 2012	Denominator is 0		
J1995, 2014	Denominator is 0		
J1995, 2015	1	1	1
J1995, 2016	Denominator is 0		
J1995, 2018	1	1	1
J1995, 2019	Denominator is 0		
2010, 2012	1	1	1
2010, 2014	1	1	1
2010, 2015	0.21678	1	2
2010, 2016	1.1169	0.4418	2

Groups	t	P(perm)	Unique permutations
2010, 2018	0.19193	1	2
2010, 2019	1	1	1
2012, 2014	Denominator is 0		
2012, 2015	1	1	1
2012, 2016	Denominator is 0		
2012, 2018	1	1	1
2012, 2019	Denominator is 0		
2014, 2015	1	1	1
2014, 2016	Denominator is 0		
2014, 2018	1	1	1
2014, 2019	Denominator is 0		
2015, 2016	1.1169	0.4501	2
2015, 2018	2.60E-02	1	2
2015, 2019	1	1	1
2016, 2018	1.1169	0.449	2
2016, 2019	Denominator is 0		
2018, 2019	1	1	1

[a] Bold p values denotes significance at p<0.05.

Table A.5 Results of pairwise comparisons for soft coral over time at Kirra Reef following PERMANOVA.

Groups	t	P(perm)[a]	Unique permutations
2017, 2001	1	1	1
2017, 2003	2.6141	**0.006**	108
2017, 2004	3.0031	**0.0036**	84
2017, 2005	1.0471	0.3711	6
2017, A1995	2.7386	**0.0109**	48
2017, F1996	3.4328	**0.0005**	946
2017, J1995	1.0238	0.4961	6
2017, 2010	1	1	1
2017, 2012	1	1	1
2017, 2014	5.59E-02	1	2
2017, 2015	1	1	1
2017, 2016	1.1169	0.4531	2
2017, 2018	8.34E-02	1	2
2017, 2019	0.45007	1	4
2001, 2003	3.0099	**0.0062**	54
2001, 2004	3.4609	**0.0013**	42
2001, 2005	1.7631	0.2413	3
2001, A1995	3.2571	**0.0019**	24
2001, F1996	3.7915	**0.0005**	484
2001, J1995	1.7321	0.2378	3
2001, 2010	Denominator is 0		
2001, 2012	Denominator is 0		
2001, 2014	1	1	1
2001, 2015	Denominator is 0		
2001, 2016	Denominator is 0		
2001, 2018	1	1	1
2001, 2019	1.4215	0.4836	2
2003, 2004	0.50246	0.6373	972

Groups	t	P(perm)[a]	Unique permutations
2003, 2005	1.8759	0.0569	180
2003, A1995	0.66151	0.5827	1017
2003, F1996	0.89239	0.3907	5412
2003, J1995	1.8781	0.0559	216
2003, 2010	3.0099	**0.0065**	54
2003, 2012	3.0099	**0.006**	54
2003, 2014	2.6457	**0.005**	108
2003, 2015	3.0099	**0.005**	54
2003, 2016	3.3618	**0.0012**	107
2003, 2018	2.661	**0.0051**	108
2003, 2019	2.4351	**0.0173**	216
2004, 2005	2.1618	**0.0403**	68
2004, A1995	0.46313	0.6568	250
2004, F1996	0.88481	0.391	2118
2004, J1995	2.1698	**0.0252**	105
2004, 2010	3.4609	**0.0008**	42
2004, 2012	3.4609	**0.0012**	42
2004, 2014	3.0366	**0.0039**	56
2004, 2015	3.4609	**0.0015**	42
2004, 2016	3.8655	**0.0003**	83
2004, 2018	3.053	**0.002**	84
2004, 2019	2.7807	**0.0032**	166
2005, A1995	1.8217	0.0978	42
2005, F1996	2.7394	**0.0045**	982
2005, J1995	3.47E-02	1	12
2005, 2010	1.7631	0.2359	3
2005, 2012	1.7631	0.2461	3
2005, 2014	1.0907	0.3662	5
2005, 2015	1.7631	0.2495	3
2005, 2016	1.9693	0.0856	6

Groups	t	P(perm)[a]	Unique permutations
2005, 2018	1.1127	0.2426	6
2005, 2019	0.72898	0.4301	12
A1995, F1996	1.3196	0.1778	2567
A1995, J1995	1.8329	0.0764	63
A1995, 2010	3.2571	**0.0035**	24
A1995, 2012	3.2571	**0.0027**	24
A1995, 2014	2.7745	**0.0111**	28
A1995, 2015	3.2571	**0.0029**	24
A1995, 2016	3.638	**0.0004**	48
A1995, 2018	2.7922	**0.0028**	48
A1995, 2019	2.4826	**0.0083**	96
F1996, J1995	2.7417	**0.0055**	972
F1996, 2010	3.7915	**0.0003**	486
F1996, 2012	3.7915	**0.0002**	484
F1996, 2014	3.4618	**0.0004**	642
F1996, 2015	3.7915	**0.0004**	486
F1996, 2016	4.2349	**0.0001**	940
F1996, 2018	3.4758	**0.0003**	954
F1996, 2019	3.2666	**0.0011**	1790
J1995, 2010	1.7321	0.2447	3
J1995, 2012	1.7321	0.2403	3
J1995, 2014	1.0674	0.4877	4
J1995, 2015	1.7321	0.2386	3
J1995, 2016	1.9347	0.0815	6
J1995, 2018	1.0894	0.242	6
J1995, 2019	0.71223	0.4308	12
2010, 2012	Denominator is 0		
2010, 2014	1	1	1
2010, 2015	Denominator is 0		
2010, 2016	Denominator is 0		

Groups	t	P(perm)[a]	Unique permutations
2010, 2018	1	1	1
2010, 2019	1.4215	0.493	2
2012, 2014	1	1	1
2012, 2015	Denominator is 0		
2012, 2016	Denominator is 0		
2012, 2018	1	1	1
2012, 2019	1.4215	0.4923	2
2014, 2015	1	1	1
2014, 2016	1.1169	0.4395	2
2014, 2018	2.76E-02	1	2
2014, 2019	0.48371	1	4
2015, 2016	Denominator is 0		
2015, 2018	1	1	1
2015, 2019	1.4215	0.4915	2
2016, 2018	1.1169	0.4421	2
2016, 2019	1.5877	0.1933	4
2018, 2019	0.5032	1	4

a Bold p values denotes significance at $p<0.05$.

Table A.6 Results of pairwise comparisons for sponges over time at Kirra Reef following PERMANOVA.

Groups	t	P(perm)[a]	Unique permutations
2017, 2001	3.2045	**0.0016**	9855
2017, 2003	1.5814	0.1094	9916
2017, 2004	4.8567	**0.0001**	9934
2017, 2005	1.1005	0.2722	9913
2017, A1995	1.4535	0.1445	9881
2017, F1996	1.6541	0.0932	9946
2017, J1995	3.4886	**0.0008**	9793
2017, 2010	4.6645	**0.0001**	9771
2017, 2012	2.9547	**0.0037**	9902
2017, 2014	0.33022	0.8101	9914
2017, 2015	2.0318	**0.0393**	9918
2017, 2016	1.6972	0.0848	9947
2017, 2018	3.1752	**0.002**	9933
2017, 2019	0.85215	0.4063	9932
2001, 2003	4.2439	**0.0002**	8295
2001, 2004	9.0001	**0.0001**	8824
2001, 2005	2.095	0.0434	692
2001, A1995	1.8262	0.0799	229
2001, F1996	4.4134	0.0001	8727
2001, J1995	0.33665	0.8184	55
2001, 2010	1.373	0.1561	80
2001, 2012	0.23274	0.9373	646
2001, 2014	2.9464	**0.0035**	998
2001, 2015	5.6959	**0.0001**	3251
2001, 2016	5.5019	**0.0001**	9907
2001, 2018	0.63036	0.5851	5472
2001, 2019	2.9795	**0.0028**	9883
2003, 2004	3.0633	**0.0022**	9672

Groups	t	P(perm)[a]	Unique permutations
2003, 2005	2.4561	**0.0157**	9089
2003, A1995	2.8131	**0.0063**	8987
2003, F1996	0.23103	0.9108	9888
2003, J1995	4.5685	**0.0001**	8246
2003, 2010	5.5601	**0.0001**	8018
2003, 2012	4.0084	**0.0003**	9164
2003, 2014	1.8693	0.0588	9454
2003, 2015	1.5357	0.1274	9853
2003, 2016	2.4962	**0.0083**	9931
2003, 2018	4.3685	**0.0001**	9923
2003, 2019	2.4467	**0.0152**	9928
2004, 2005	6.1901	**0.0001**	9137
2004, A1995	6.7311	**0.0001**	9130
2004, F1996	2.8956	**0.0039**	9895
2004, J1995	9.6283	**0.0001**	8664
2004, 2010	11.497	**0.0001**	9041
2004, 2012	8.5986	**0.0001**	9476
2004, 2014	5.2805	**0.0001**	9480
2004, 2015	3.1702	**0.0011**	9826
2004, 2016	5.3498	**0.0001**	9951
2004, 2018	9.3218	**0.0001**	9935
2004, 2019	6.0661	**0.0001**	9956
2005, A1995	0.35343	0.7405	692
2005, F1996	2.5788	**0.0088**	9298
2005, J1995	2.3433	**0.0189**	380
2005, 2010	3.5084	**0.0007**	636
2005, 2012	1.8573	0.0638	2581
2005, 2014	0.81306	0.4264	1965
2005, 2015	3.2349	**0.0017**	4831
2005, 2016	2.7996	**0.0047**	9928

Groups	t	P(perm)[a]	Unique permutations
2005, 2018	2.0222	**0.0396**	9179
2005, 2019	0.83884	0.4057	9918
A1995, F1996	2.9395	**0.0024**	9240
A1995, J1995	2.0523	**0.0473**	120
A1995, 2010	3.2605	**0.0021**	202
A1995, 2012	1.592	0.1149	981
A1995, 2014	1.1563	0.2451	1023
A1995, 2015	3.6489	**0.0002**	3375
A1995, 2016	3.1706	**0.0019**	9907
A1995, 2018	1.7001	0.0849	7667
A1995, 2019	1.0604	0.2889	9903
F1996, J1995	4.7386	**0.0001**	7907
F1996, 2010	5.7526	**0.0001**	9085
F1996, 2012	4.1744	**0.0002**	9685
F1996, 2014	1.9582	**0.0435**	9610
F1996, 2015	1.3924	0.1598	9820
F1996, 2016	2.4181	**0.0127**	9946
F1996, 2018	4.5247	**0.0001**	9925
F1996, 2019	2.5145	0.0092	9932
J1995, 2010	1.2688	0.2726	42
J1995, 2012	0.52718	0.6177	285
J1995, 2014	3.2192	**0.0023**	609
J1995, 2015	6.0981	**0.0001**	2105
J1995, 2016	5.8791	**0.0001**	9905
J1995, 2018	0.55269	0.601	4032
J1995, 2019	3.2319	0.0024	9841
2010, 2012	1.5947	0.1081	180
2010, 2014	4.4183	**0.0001**	1039
2010, 2015	7.5971	**0.0001**	3857
2010, 2016	7.613	**0.0001**	9919

Groups	t	P(perm)[a]	Unique permutations
2010, 2018	1.8405	0.0712	2852
2010, 2019	4.5906	**0.0001**	9811
2012, 2014	2.698	**0.0069**	3700
2012, 2015	5.3837	**0.0001**	7665
2012, 2016	5.1675	**0.0001**	9921
2012, 2018	0.61334	0.5621	7475
2012, 2019	2.7226	**0.0079**	9920
2014, 2015	2.3601	**0.0192**	6034
2014, 2016	1.9144	0.0536	9921
2014, 2018	2.8923	**0.0056**	9382
2014, 2019	0.60655	0.5688	9929
2015, 2016	1.6614	0.0923	9941
2015, 2018	5.7466	**0.0001**	9846
2015, 2019	2.8175	**0.0051**	9936
2016, 2018	5.4003	**0.0001**	9904
2016, 2019	2.0264	0.0424	9927
2018, 2019	2.8181	**0.0064**	9905

[a] Bold p values denotes significance at $p<0.05$.

Table A.7 Results of pairwise comparisons for ascidians over time at Kirra Reef following PERMANOVA.[a]

Groups	t	P(perm)[a]	Unique permutations
2017, 2001	2.6605	**0.0082**	9932
2017, 2003	0.58772	0.5805	9913
2017, 2004	0.88595	0.3829	9931
2017, 2005	3.2942	**0.0003**	9918
2017, A1995	6.9466	**0.0001**	9899
2017, F1996	5.6632	**0.0001**	9920
2017, J1995	4.7863	**0.0001**	9918
2017, 2010	1.3104	0.1808	9945
2017, 2012	6.9466	**0.0001**	9886
2017, 2014	3.116	**0.0017**	9941
2017, 2015	1.1048	0.2668	9940
2017, 2016	1.8183	0.0651	9941
2017, 2018	2.6973	**0.0073**	9937
2017, 2019	5.6984	**0.0001**	9937
2001, 2003	2.9481	**0.003**	9837
2001, 2004	2.0095	**0.042**	3287
2001, 2005	6.8743	**0.0001**	9066
2001, A1995	4.2752	**0.0001**	364
2001, F1996	2.8758	**0.0033**	3473
2001, J1995	2.0775	**0.036**	1731
2001, 2010	3.9593	**0.0001**	9945
2001, 2012	4.2752	**0.0002**	363
2001, 2014	6.5864	**0.0001**	9603
2001, 2015	3.6476	**0.0003**	8846
2001, 2016	4.3329	**0.0002**	9928
2001, 2018	5.8273	**0.0001**	9920
2001, 2019	10.208	**0.0001**	9926

Groups	t	P(perm)[a]	Unique permutations
2003, 2004	1.4213	0.1447	9873
2003, 2005	3.1933	**0.0015**	9914
2003, A1995	6.9261	**0.0001**	8228
2003, F1996	5.7839	**0.0001**	9789
2003, J1995	4.938	**0.0001**	9756
2003, 2010	1.6301	0.0996	9933
2003, 2012	6.9261	**0.0001**	8244
2003, 2014	2.9185	**0.0035**	9909
2003, 2015	1.4833	0.1313	9932
2003, 2016	2.2958	**0.017**	9935
2003, 2018	2.3284	**0.0198**	9914
2003, 2019	5.0833	**0.0001**	9925
2004, 2005	4.1836	**0.0002**	9202
2004, A1995	6.5628	**0.0001**	629
2004, F1996	5.1203	**0.0001**	4340
2004, J1995	4.2271	**0.0002**	2373
2004, 2010	1.7593	0.0713	9921
2004, 2012	6.5628	**0.0001**	632
2004, 2014	4.0623	**0.0001**	9578
2004, 2015	1.5018	0.1303	9057
2004, 2016	1.9832	**0.0445**	9927
2004, 2018	3.6875	**0.0004**	9915
2004, 2019	7.1394	**0.0001**	9940
2005, A1995	17.132	**0.0001**	7757
2005, F1996	13.226	**0.0001**	9700
2005, J1995	10.876	**0.0001**	9082
2005, 2010	2.3971	**0.0122**	9945
2005, 2012	17.132	**0.0001**	7774
2005, 2014	0.68916	0.5699	9883
2005, 2015	2.6263	**0.0067**	9885

Groups	t	P(perm)[a]	Unique permutations
2005, 2016	3.0747	**0.0011**	9932
2005, 2018	1.7874	**0.0644**	9956
2005, 2019	4.4246	**0.0001**	9945
A1995, F1996	2.5725	**0.0253**	10
A1995, J1995	2.5227	**0.0249**	16
A1995, 2010	9.8323	**0.0001**	9895
A1995, 2012	Denominator is 0		
A1995, 2014	15.113	**0.0001**	9131
A1995, 2015	9.1834	**0.0001**	7208
A1995, 2016	10.85	**0.0001**	9911
A1995, 2018	11.947	**0.0001**	9920
A1995, 2019	27.963	**0.0001**	9917
F1996, J1995	0.86422	0.4164	320
F1996, 2010	7.8795	**0.0001**	9943
F1996, 2012	2.5725	0.0288	10
F1996, 2014	12.106	**0.0001**	9836
F1996, 2015	7.3656	**0.0001**	9303
F1996, 2016	8.6277	**0.0001**	9930
F1996, 2018	10.032	**0.0001**	9926
F1996, 2019	20.081	**0.0001**	9934
J1995, 2010	6.6604	**0.0001**	9918
J1995, 2012	2.5227	**0.0292**	16
J1995, 2014	10.159	**0.0001**	9610
J1995, 2015	6.2322	**0.0001**	9097
J1995, 2016	7.3104	**0.0001**	9920
J1995, 2018	8.6534	**0.0001**	9922
J1995, 2019	15.828	**0.0001**	9939
2010, 2012	9.8323	**0.0001**	9905
2010, 2014	2.4368	**0.0121**	9944
2010, 2015	0.26562	0.8971	9925

Groups	t	P(perm)[a]	Unique permutations
2010, 2016	0.70083	0.5303	9939
2010, 2018	2.4961	**0.0089**	9930
2010, 2019	5.778	**0.0001**	9933
2012, 2014	15.113	**0.0001**	9053
2012, 2015	9.1834	**0.0001**	7174
2012, 2016	10.85	**0.0001**	9899
2012, 2018	11.947	**0.0001**	9928
2012, 2019	27.963	**0.0001**	9923
2014, 2015	2.6337	**0.0054**	9908
2014, 2016	3.2307	**0.0015**	9953
2014, 2018	1.1515	0.2491	9949
2014, 2019	3.4974	**0.0004**	9953
2015, 2016	0.70877	0.5245	9930
2015, 2018	2.6076	**0.0078**	9938
2015, 2019	5.8728	**0.0001**	9924
2016, 2018	3.4044	**0.0005**	9938
2016, 2019	7.1263	**0.0001**	9951
2018, 2019	2.7242	**0.0035**	9931

[a] Bold p values denotes significance at $p<0.05$.

Table A.8 Similarity percentage analysis (SIMPER) of dissimilarity of fish communities at Kirra, Palm Beach, Kingscliff and Cook Island reefs. The relative contribution (Contrib.%) of fish species up to 50% cumulative dissimilarity (Cum.%) is shown. Data for SIMPER analysis has been derived from square-root transformed maxN values (combined for all survey methods).

Species	Common name	Average Abundance		Contrib%	Cum.%
		Kingscliff	Cook Island West		
Kirra Reef versus Cook Island North, Average dissimilarity = 59.98					
Abedefduf vaigensis	sergent major	0.96	3.7	7.25	7.25
Parupeneus spilurus	black saddle goatfish	0.71	1.58	4.08	11.34
Stethojulis bandanensis	redspot wrasse	0.96	1.98	3.96	15.3
Schuettea scalaripinnis	Eastern pomfret	1.12	1.41	3.83	19.13
Labroides dimidiatus	cleaner wrasse	0.25	1.47	3.49	22.62
Monodactylus argenteus	silver batfish	1.66	0.75	3.45	26.07
Thalssoma lutecens	yellow moon wrasse	1.57	0.5	3.07	29.14
Chelio inermis	cigar wrasse	0.5	1.06	2.4	31.54
Scorpis lineolata	sweep	0	0.96	2.38	33.93
Parma oligolepis	big-scale parma	1.31	0.6	2.29	36.22
Amphiprion akindynos	barrier reef anemonefish	0.25	0.87	2.15	38.37
Abudefduf sexfasciatus	scissortail sergent	0.5	1.21	2.03	40.4
Acanthopargus australis	yellowfin bream	1.21	0.5	2.02	42.42
Haliochoeres hortulanus	checkerboard wrasse	0.5	1.21	2.01	44.43
Thalssoma lunare	moon wrasse	0.96	0.5	2	46.42

Species	Common name	Average Abundance		Contrib%	Cum.%
		Kingscliff	Cook Island West		
Kirra Reef versus Cook Island North, Average dissimilarity = 59.98					
Orectolobus maculatus	spotted wobbegong	0.75	1.06	1.98	48.41
Thalassoma jansenii	Jansens wrasse	0.75	1.12	1.96	50.37

Species	Common name	Average Abundance		Contrib%	Cum.%
		Kingscliff	Cook Island North		
Kingscliff versus Cook Island North, Average dissimilarity = 52.98					
Monodactylus argenteus	silver batfish	1.66	1.66	4.61	4.61
Abudefduf sexfasciatus	scissortail sergent	0.5	1.41	4.44	9.05
Acanthopargus australis	yellowfin bream	0	1.25	4.09	13.14
Schuettea scalaripinnis	Eastern pomfred	1.12	0	3.23	16.38
Platax teira	tallfin batfish	0	0.96	3.14	19.52
Chromis margaritifer	whitetail puller	1.12	0.87	3.11	22.63
Achoerodus viridis	blue groper	0.25	0.96	2.97	25.6
Abudefduf whitelyi	Whitley's sergent	1.31	1.47	2.93	28.53
Scorpis lineolata	sweep	0	0.87	2.72	31.25
Naso unicornis	bluespine unicornfish	0	0.75	2.59	33.84
Diploprion bifasciatum	barred soapfish	0	0.75	2.59	36.44
Parupeneus spilurus	black saddle goatfish	0.71	1	2.59	39.03
Haliochoeres hortulanus	checkerboard wrasse	0.5	0.96	2.46	41.49
Acanthopargus australis	yellowfin bream	1.21	1.8	2.4	43.89
Amphiprion akindynos	barrier reef anemonefish	0.25	0.71	2.25	46.14
Thalssoma lutecens	yellow moon wrasse	0	0.71	2.22	48.36
Naso unicornis	bluespine unicornfish	0	0.71	2.22	50.58

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island West	Cook Island North		
Kingscliff versus Cook Island North, Average dissimilarity = 59.94					
Abedefduf vaigensis	sergent major	3.7	0.96	6.15	6.15
Parupeneus spilurus	black saddle goatfish	1.58	1	3.56	9.7
Abudefduf sexfasciatus	scissortail sergent	1.21	1.41	3.26	12.96
Acanthopargus australis	yellowfin bream	0.5	1.8	3.08	16.03
Schuettea scalaripinnis	Eastern pomfred	1.41	0	3.04	19.07
Stethojulis bandanensis	redspot wrasse	1.98	1	3.03	22.1
Monodactylus argenteus	silver batfish	0.75	1.66	2.82	24.92
Acanthopargus australis	yellowfin bream	0	1.25	2.75	27.67
Labroides dimidiatus	cleaner wrasse	1.47	0.5	2.71	30.38
Chelio inermis	cigar wrasse	1.06	0	2.48	32.86
Thalssoma lutecens	yellow moon wrasse	0.5	1.3	2.45	35.31
Abudefduf whitelyi	Whitley's sergent	0.96	1.47	2.33	37.64
Chromis margitifer	whitetail puller	1.47	0.87	2.21	39.85
Stegastes gascoynei	coral sea gregory	1.83	1.06	2.05	41.9
Scorpis lineolata	sweep	0.96	0.87	2.03	43.93
Amphiprion akindynos	barrier reef anemonefish	0.87	0.71	1.96	45.89
Chromis margitifer	whitetail puller	0.83	0.5	1.9	47.79
Diploprion bifasciatum	barred soapfish	0	0.75	1.73	49.52
Chaetodon flavirostris	dusky butterflyfish	0.87	0.25	1.7	51.22

Species	Common name	Average Abundance		Contrib%	Cum.%
		Kingscifff	Palm Beach		
Kingscliff versus Cook Island North, Average dissimilarity = 77.78					
Trachurus novaezelandiae	yellowtail	0.25	6.12	7.74	7.74
Abudefduf whitelyi	Whitley's sergent	0	5	6.22	13.96
Scorpis lineolata	sweep	0	1.83	4.03	17.99
Monodactylus argenteus	silver batfish	1.66	0	3.5	21.49
Thalssoma lunare	moon wrasse	0.96	2.86	3.41	24.9
Abudefduf whitelyi	Whitley's sergent	1.31	0.25	2.77	27.66
Stegastes gascoynei	coral sea gregory	1.21	0	2.75	30.41
Acanthopargus australis	yellowfin bream	0	1.85	2.72	33.14
Acanthopargus australis	yellowfin bream	1.21	0.25	2.47	35.61
Chaetodon flavirostris	dusky butterflyfish	0	1.5	2.36	37.96
Parma oligolepis	big-scale parma	1.31	0.5	2.22	40.18
Chromis margitifer	whitetail puller	1.12	0.25	2.2	42.38
Schuettea scalaripinnis	Eastern pomfred	1.12	0	2.07	44.45
Notolabrus gymnogenis	crimsonband wrasse	0.96	0	2.04	46.49
Stethojulis bandanensis	redspot wrasse	0.96	0.5	1.75	48.24
Labroides dimidiatus	cleaner wrasse	0.25	1.25	1.73	49.97
Acanthurus blochii	dark surgeonfish	0	1.32	1.65	51.61

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island West	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 79.56					
Trachurus novaezelandiae	yellowtail	0	6.12	6.36	6.36
Abudefduf whitelyi	Whitley's sergent	0	5	5.19	11.55
Abedefduf vaigensis	sergent major	3.7	0.75	4.42	15.97
Thalssoma lunare	moon wrasse	0.5	2.86	3.32	19.29
Stegastes gascoynei	coral sea gregory	1.83	0	2.83	22.12
Stethojulis bandanensis	redspot wrasse	1.98	0.5	2.58	24.71
Parupeneus spilurus	black saddle goatfish	1.58	0.96	2.42	27.12
Acanthopargus australis	yellowfin bream	0	1.85	2.2	29.32
Schuettea scalaripinnis	Eastern pomfred	1.41	0	2.14	31.46
Chromis margitifer	whitetail puller	1.47	0.25	2.13	33.59
Abudefduf sexfasciatus	scissortail sergent	1.21	0	1.97	35.56
Thalssoma lutecens	yellow moon wrasse	0.5	1.71	1.97	37.53
Labroides dimidiatus	cleaner wrasse	1.47	1.25	1.85	39.38
Chelio inermis	cigar wrasse	1.06	0	1.75	41.13
Haliochoeres hortulanus	checkerboard wrasse	1.21	0.25	1.72	42.86
Orectolobus maculatus	spotted wobbegong	1.06	0	1.67	44.52
Chaetodon flavirostris	dusky butterflyfish	0.87	1.5	1.64	46.16
Acanthurus blochii	dark surgeonfish	0.5	1.32	1.58	47.75

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island West	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 79.56					
Chromis margitifer	whatetail puller	0.83	0.96	1.57	49.32
Notolabrus gymnogenis	crimsonband wrasse	0.96	0	1.55	50.87

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island North	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 73.74					
Trachurus novaezelandiae	yellowtail	0	6.12	7.25	7.25
Abudefduf whitelyi	Whitley's sergent	0	5	5.92	13.18
Thalssoma lunare	moon wrasse	0.75	2.86	3.39	16.57
Acanthopargus australis	yellowfin bream	1.8	0.25	3.21	19.78
Monodactylus argenteus	silver batfish	1.66	0	2.93	22.71
Abudefduf whitelyi	Whitley's sergent	1.47	0.25	2.58	25.28
Acanthopargus australis	yellowfin bream	1.25	1.85	2.37	27.66
Abudefduf sexfasciatus	scissortail srgent	1.41	0	2.37	30.02
Scorpis lineolata	sweep	0.87	1.83	2.23	32.25
Chaetodon flavirostris	dusky butterflyfish	0.25	1.5	2.09	34.34
Stegastes gascoynei	coral sea gregory	1.06	0	2	36.34
Achoerodus viridis	blue groper	0.96	0	1.81	38.15
Platax teira	tallfin batfish	0.96	0	1.76	39.91
Notolabrus gymnogenis	crimsonband wrassse	0.96	0	1.76	41.67
Acanthurus blochii	dark surgeonfish	0.25	1.32	1.65	43.32
Haliochoeres hortulanus	checkerboard wrasse	0.96	0.25	1.64	44.96
Pseudolabrus guntheri	Gunther's wrasse	1.71	1.12	1.59	46.55
Labroides dimidiatus	cleaner wrasse	0.5	1.25	1.56	48.11

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island North	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 73.74					
Thalssoma lutecens	yellow moon wrasse	0.71	1.12	1.54	49.65
Chromis margitifer	whitetail puller	0.87	0.25	1.47	51.12

Species	Common name	Average Abundance		Contrib%	Cum.%
		Kingscliff	Kirra Reef		
Kingscliff versus Kirra Reef, Average dissimilarity = 76.41					
Trachurus novaezelandiae	yellowtail	0.25	15.02	29.18	29.18
Scorpis lineolata	sweep	0	2.41	4.48	33.66
Kyphosus vaigensis	Northern drummer	0.25	2.9	4.35	38
Chaetodon citrinellus	citron butterflyfish	0	2.29	3.31	41.31
Monodactylus argenteus	silver batfish	1.66	0	3.19	44.5
Abudefduf whitelyi	Whiteley's sergent	1.31	0	2.71	47.21
Stegastes gascoynei	coral sea gregory	1.21	0.25	2.16	49.38
Chromis margitifer	whitetail puller	1.12	0.25	1.99	51.37

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island West	Kirra Reef		
Cook Island West versus Kirra Reef, Average dissimilarity = 81.26					
Trachurus novaezelandiae	yellowtail	0	15.02	21.64	21.64
Abedefduf vaigensis	sergent major	3.7	0	5.33	26.98
Kyphosus vaigensis	Northern drummer	0	2.9	3.46	30.44
Chaetodon citrinellus	citron butterflyfish	0	2.29	2.6	33.04
Stethojulis bandanensis	redspot wrasse	1.98	0.25	2.51	35.55
Stegastes gascoynei	coral sea gregory	1.83	0.25	2.37	37.92
Scorpis lineolata	sweep	0.96	2.41	2.18	40.11
Parupeneus spilurus	black saddle goatfish	1.58	0.5	2.17	42.28
Schuettea scalaripinnis	Eastern pomfred	1.41	0	1.97	44.25
Chromis margitifer	whitetail puller	1.47	0.25	1.93	46.18
Labroides dimidiatus	cleaner wrasse	1.47	0.25	1.93	48.1
Abudefduf sexfasciatus	scissortail sergent	1.21	0	1.8	49.91
Haliochoeres hortulanus	checkerboard wrasse	1.21	0	1.79	51.7

Species	Common name	Average Abundance		Contrib%	Cum.%
		Cook Island North	Kirra Reef		
Cook Island North versus Kirra Reef, Average dissimilarity = 74.66					
Trachurus novaezelandiae	yellowtail	0	15.02	25.56	25.56
Kyphosus vaigensis	Northern drummer	0	2.9	4.02	29.58
Scorpis lineolata	sweep	0.87	2.41	3.05	32.63
Chaetodon citrinellus	citron butterflyfish	0	2.29	3.01	35.64
Monodactylus argenteus	silve batfish	1.66	0	2.71	38.34
Abudefduf whitelyi	Whitley's sergent	1.47	0	2.48	40.82
Abudefduf sexfasciatus	scissortail sergent	1.41	0	2.2	43.02
Stegastes gascoynei	coral sea gregory	1.06	0.25	1.7	44.72
Achoerodus viridis	blue groper	0.96	0	1.66	46.38
Haliochoeres hortulanus	checkerboard wrasse	0.96	0	1.62	47.99
Platax teira	tallfin batfish	0.96	0	1.62	49.61
Abedefduf vaigensis	sergent major	0.96	0	1.61	51.22

Species	Common name	Average Abundance		Contrib%	Cum.%
		Palm Beach	Kirra Reef		
Palm Beach versus Kirra Reef, Average dissimilarity = 68.90					
Trachurus novaezelandiae	yellowtail	6.12	15.02	19.35	19.35
Abudefduf whitelyi	Whitley's sergent	5	0.5	5.94	25.3
Kyphosus vaigensis	Northern drummer	0	2.9	4.03	29.32
thalssoma lunare	moon wrasse	2.86	0.96	3.06	32.39
Chaetodon citrinellus	citron butterflyfish	0	2.29	3.01	35.4
Acanthopargus australis	yellowfin bream	0.25	1.5	2.23	37.63
Acanthopargus australis	yellowfin bream	1.85	0.96	2.19	39.82
Orectolobus maculatus	spotted wobbegong	0	1.21	2.1	41.92
Chaetodon flavirostris	dusky butterflyfish	1.5	0	2.08	44
Scorpis lineolata	sweep	1.83	2.41	2.02	46.02
Acanthurus blochii	dark surgeonfish	1.32	0.25	1.59	47.6
Labroides dimidiatus	cleaner wrasse	1.25	0.25	1.53	49.13
Abedefduf vaigensis	Indo-Pacific sergent	0.75	0	1.52	50.65

Appendix B Abundance of Fishes at Kirra Reef, Palm Beach, Kingscliff and Cook Island in 2019

Table B.1 Fish species at Kirra, Palm Beach, Kingscliff and Cook Island Reef recorded during the 2019 survey. Key to abbreviations: Trophic Level: **H** = herbivore, **P** = planktivore, **CA** = carnivore, **C** = Corallivore, **O** = omnivore, **O-HT** = omnivore with herbivorous tendencies; Reef/Pelagic: **R** = reef associated or benthic, **P** = pelagic, **R/P** = bentho-pelagic; Range: **TR** = found generally in tropical and subtropical waters, Kirra and Cook Island Reefs at south end of range, **TE** = found generally in temperate and subtropical waters, Kirra and Cook Island Reefs at north end of range; **TR/TE** = found throughout tropic and temperate waters, Kirra, Palm Beach and Cook Island Reefs are not in extreme range.

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN					Relative abundance				
					Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef
Acanthuridae														
Acanthurus blochii	dark surgeonfish	H	R	TR	1	0	1	1	7	*		*	*	**
Prionurus microlepidotus	Australian sawtail	H	R	TR	0	1	1	1	0		*	*	*	
Acanthurus nigricans	Whitecheek Surgeonfish		R	TR	0	0	1	0	0			*		
Acanthurus nigrofuscus	dusky surgeonfish	H	R	TR	2	0	4	0	8	*		*		**
Acnathurus pyroferus	mimic surgeonfish	H	R	TR/TE	0	1	1	0	1		*	*		*
Naso unicornis	bluespine unicornfish	P	R	TR	1	0	1	1	0	*		*	*	
Aplodactylidae														
Aplodactylus lophodon	rock cale	H	R	TR	1	0	0	0	0	*				
Apogonidae														
Ostorhinchus limenus	sydney cardinalfish	CA	R	TR/TE	1	1	1	1	0	*	*	*	*	
Aulostomidae														
Aulostomus chinensis	trumpetfish	CA	R	TR	0	0	0	1	0				*	
Balistidae														
Sufflamen chrysopterus	half-moon triggerfish	CA	R	TR/TE	1	1	0	0	1	*	*			*
Blenniidae														
Exallias brevis	Leopard Blenny	CA	R	TR	0	0	0	1	0				*	
Blennidae sp.		CA	R	TR/TE	0	1	1	0	1		*	*		
Carangidae														
Pseudocaranx sp.	dentex'	CA	P	TR	1	0	0	1	0	*			*	
Trachinotus blochii	dart	CA	R	TR/TE	0	0	0	0	1					*
Trachurus novaezelandie	yellowtail	CA	P	TE	300	1	0	0	150	****	*			****
Chaetodontidae														
Chaetodon auriga	threadfin butterflyfish	C	R	TR/TE	1	0	0	1	1	*			*	*
Chaetodon citrinellus	citron butterflyfish	C	R	TR	0	1	1	1	1		*	*	*	*
Chaetodon ephippium	saddle butterflyfish	C	R	TR	0	0	0	1	0				*	
Chaetodon flavirostris	dusky butterflyfish	C	R	TR/TE	0	0	1	3	4			*	*	*
Chaetodon lineolatus	lined butterflyfish	C	R	TR/TE	0	0	0	0	1					1
Chaetodon lunula	racoon butterflyfish	C	R	TR	0	0	0	1	0				*	
Chaetodon kleinii	brown butterflyfish	C	R	TR/TE	1	0	0	0	2	*				*

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN					Relative abundance				
					Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef
Chaetodon trifascialis	chevroned Butterflyfish	C	R	TR	1	0	1	0	1	*		*		*
Chaetodon unimaculatus	teardrop butterflyfish	C	R	TR	0	0	0	0	1					*
Cheilodactylidae														
Cheilodactylus fuscus	red morwong	CA	R	TE	1	1	0	1	0	*			*	
Cheilodactylus vestitus	crested morwong	CA	R	TE	1	0	0	1	1	*			*	*
Chironemidae														
Chironemus marmoratus	kelpfish	CA	R	TR/TE	1	0	0	0	0	*				
Cirrhitidae														
Cirrhitichthys falco	dwarf hawkfish	CA	R	TR/TE	1	1	1	1	1	*	*	*	*	*
Diodontidae														
Diodon hystrix	black-spotted porcupine fish	CA	R	TR/TE	1	0	0	1	0	*			*	
Ephippidae														
Platax teira	tall-fin Batfish	O	R	TR/TE	0	0	2	1	0			*	*	
Enoplosidae														
Enoplosus armatus	old wife	CA	R	TE	1	0	0	1	0	*			*	
Gerreidae														
Gerres subfasciatus	silver biddy	CA	R	TR	1	0	0	0	0	*				
Gobiidae														
Ptereleotris evides	arrow dartfish	P	R	TR	0	0	0	2	0				*	
Haemulidae														
Plectorhincus flavomaculatus	gold-spotted sweetlip	CA	R	TR/TE	2	0	0	1	1	*		*	*	
Plectorhinchus lineatus	oblique-banded sweetlip	CA	R	TR	0	0	0	1	0				*	
Kyphosidae														
Kyphosus sydenyanus	Northern drummer	H	R	TE	0	0	0	2	0				*	
Labridae														
Achoerodus viridis	blue groper	O	R	TE	0	1	2	1	0		*	*	*	
Anampses neoguinaicus	black backed wrasse	O	R	TR	0	0	0	0	1					1
Bodianus axillaris	coral pigfish	O	R	TR/TE	0	0	1	0	0			*		
Cheilio inermis	cigar wrasse	O	R	TR/TE	1	1	0	2	0	*	*		*	
Choerodon graphicus	graphic tuskfish	CA	R	TR	0	0	0	1	0				*	
Gomphosus varius	bird wrasse	O	R	TR	0	0	1	1	0			*	*	
Halichoeres hortulanus	checerboard wrasse	O	R	TR/TE	0	1	2	2	1		*	*	*	*
Labroides dimidiatus	cleaner wrasse	O	R	TR/TE	1	1	1	6	4	*	*	*	**	*

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN					Relative abundance				
					Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef
Macrophayngodon meleagris	Eastern leopard wrasse	O	R	TR/TE	0	0	1	0	0			*	*	
Notolabrus gymnogensis	crimson-banded wrasse	O	R	TE	1	2	2	2	0	*	*	*	*	
pseudolabrus guentheri	Gunther's wrasse	O	R	TR	2	3	3	1	4	*	*	*	*	*
Thalassoma amblycephalum	two tone wrasse	O	R	TR/TE	1	0	0	0	1	*				*
Thalasoma jansenii	Jansen's wrasse	O	R	TR	1	2	1	3	3	*	*	*	*	*
Thalassoma lunare	moon wrasse	O	R	TR	2	2	1	1	13	*	*	*	*	**
Thalassoma lutescens	yellow moon wrasse	O	R	TR/TE	2	3	3	1	4	*	*	*	*	
Stethojulis bandanensis	Redspot Wrasse	O	R	TR/TE	1	2	1	2	1	*	*	*	*	*
Lutjanidae														
Lutjanus bohar	red bass	CA	R	TR	0	0	1	1	0			*	*	
Lutjanus fluviflamma	black-spot Snapper	CA	R	TR	0	0	0	0	1					*
Lutjanus kasmira	bluestripe snapper	CA	R	TR	1	0	0	0	0	*				
Microcanthidae														
Atpichthys strigatus	mado	O	R	TE	21	0	0	0	0	***				
Microcanthus strigatus	stripey	O	R	TE	2	1	1	1	1	*	*	*	*	*
Monocanthidae														
Cantherines dumerilii	barred filefish	O	R	TR	0	0	0	1	1				*	*
Cantherhines fronticinctus	spectacled leatherjacket	O	R	TR	0	0	0	0	1					*
Paraluteres prionurus	mimic filefish	O	R	TR	1	0	2	1	1	*		*	*	*
Monodactylidae														
Monodactylus argenteus	silver batfish	O	P	TR/TE	0	6	8	1	0		**	**	*	
Schuettea scalaripinnis	eastern pomfred	P	P	TE	0	5	0	8	0		*		**	
Mullidae														
Parupeneus ciliatus	diamonscale goatfish	CA	R	TR/TE	0	0	0	0	2					*
Parupeneus multifasciatus	banded goatfish	CA	R	TR/TE	0	0	1	1	2			*	*	*
Parupeneus spilurus	black spot goat fish	CA	R	TR/TE	1	2	1	1	2	*	*	*	*	*
Muraenidae														
Gymnothorax meleagris	whitemouth moray	CA	R	TE	0	0	0	0	1					*
Gymnothorax thyrsoidea	greyface moray	CA	R	TR	0	0	0	0	1					*
Gymnothorax pseudothyrsoideus	highfin moray	CA	R	TR	1	0	1	0	1	*		*		*
Myliobatididae														
Aetobatus ocelleatus	white-spotted eagle ray	CA	R/P	TR/TE	1	0	0	0	0	*				
Orectolobidae														

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN					Relative abundance				
					Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef
Orectolobus ornatus	ornate wobbegong	CA	R	TR/TE	0	0	1	1	0			*	*	*
Orectolobus maculatus	spotted wobbegong	CA	R	TE	2	1	1	2	0	*	*	*	*	
Ostraciidae														
Ostracion cubicus	yellow boxfish	O	R	TR/TE	0	0	1	0	1			*		*
Pempheridae														
Pempheris affinis	Blacktip Bullseye	P	R	TE	1	1	1	0	0	*	*	*		
Plotosidae														
Plotosus lineatus	striped catfish	CA	R	TR	0	1	0	0	0		*			
Pomacanthidae														
Centropyge tibicen	keyhole angelfish	H	R	TR/TE	1	1	1	0	3	*	*	*		*
Centropyge bispinosus	coral beauty	H	R	TR/TE	0	1	0	1	0		*		*	
Centropyge vrolikii	pearly-scaled angelfish	H	R	TR	0	0	1	1	0			*	*	
Pomacentridae														
Abudefduf vaigiensis	Indo-Pacific sergent	O	R	TR/TE	0	2	2	23	1		*	*	***	*
Abudefduf sexfasciatus	scissortail sergent	O	R	TR/TE	0	1	8	2	0		*	**	*	
Abedefduf whitleyi	Whitley's sergent	O	R	TR	0	2	5	2	1		*	*	*	*
Amphiprion akindynos	barrier reef anemonefish	O	R	TR/TE	1	1	2	3	0	*	*	*	*	
Chromis margaritifer	Whitetail puller	P	R	TR	1	3	3	3	1	*	*	*	*	*
Dascyllus trimaculatus	domino puller	P	R	TR/TE	1	0	1	1	1	*		*	*	*
Parma oligolepis	large-scaled parma	O-HT	R	TR/TE	2	2	1	2	1	*	*	*	*	*
Parma unifasciata	girdled scalyfin	O-HT	R	TE	1	0	2	1	0	*		*	*	
Plectroglyphidodon dickii	Dick's damsel	O-HT	R	TR	0	0	0	1	0				*	
Pomacentrus bankanensis	speckeled damsel	O-HT	R	TR	0	0	1	0	2			*		*
Pomacentrus coelestis	neon damsel	O-HT	R	TR/TE	1	0	2	1	3	*		*	*	*
Stegastes gascoynei	coral sea gregory	O-HT	R	TR/TE	1	2	2	6	0	*	*	*	**	
Stegastes apicalis	Australian gregory	O-HT	R	TR/TE	0	0	0	0	1					*
Scorpaendiae														
Scorpaena cardinalis	red scorpionfish	CA	R	TR/TE	0	0	1	1	0			*	*	
Pterois antennata	spotfin lionfish	CA	R	TR	0	0	1	1	0			*	*	
Scorpididae														
Scorpis lineolatus	sweep	P	R	TE	13	0	3	2	5	**		*	*	*
Serranidae														
Epinephelus fasciatus	black-tipped cod	CA	R	TR/TE	0	1	0	0	1		*			*
Epinephelus undulatostriatus	maori rockcod	CA	R	TE	0	0	0	0	1					*

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN					Relative abundance				
					Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Kingscliff	Cook Island North	Cook Island West	Palm Beach Reef
Diploprion bifasciatum	barred soapfish	CA	R	TR	1	0	1	1	2	*		*	*	*
Pseudoantias squampinnis	orange basslet	CA	R	TR/TE	1	0	0	0	0	*				
Siganidae														
Siganus spinus	scribbled rabbitfish	H	R	TR	1	0	0	1	1	*			*	*
Siganus punctatus	spotted rabbitfish	H	R	TR	1	0	0	0	0	*				
Solenostomidae														
Solenostomus cyanopterus	robust ghost pipefish	CA	R	TR	2	0	0	0	0	*				
Sparidae														
Acanthopagrus australis	yellow fin bream	CA	R	TR	4	2	5	1	1	*	*	*	*	*
Sphyraenidae														
Sphyraena obtusa	striped barracuda	CA	R	TR/TE	1	0	0	0	100	*				***
Tetraodontidae														
Arothron hispidus	stars and stripes pufferfish	O	R	TR/TE	0	0	0	0	1					*
Arothron nigropunctatus	blackspotted pufferfish	O	R	TR/TE	1	0	0	0	1	*				*
Torquigener pleurogramma	weeping toadfish	CA	R	TR/TE	4	0	0	0	0					
Zanclidae														
Zanclus cornutus	moorish idol	CA	R	TR/TE	0	1	0	0	1		*			*

References for trophic levels, benthic/pelagic lifestyles and range:

OZCAM mapping from https://australianmuseum.net.au/ fishbase.org

Johnson, J. W. "Annotated checklist of the fishes of Moreton Bay, Queensland, Australia." MEMOIRS-QUEENSLAND MUSEUM 43.2 (1999): 709-762.

Appendix C Cover of Benthic Communities at Kirra Reef and Cook Island 2019

Table C.1 Percentage cover of benthic communities using CPCe.

Taxa		Kirra Reef		Cook Island North		Cook Island West		Palm Beach		Kingscliff	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Polychaeta		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ascidiaceae		41.47	3.88	15.24	2.56	15.98	2.35	19.68	2.43	35.86	2.84
Anthozoa	**Anemone**	4.01	1.07	1.00	0.57	1.79	0.63	6.88	1.41	0.05	0.05
	Mushroom Anemone	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hydroid	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hard Coral	0.00	0.00	1.30	0.70	4.50	1.75	0.96	0.81	0.20	0.20
	Zoantharia	0.23	0.12	1.26	0.82	0.84	0.20	4.83	1.38	1.65	0.38
	Soft Coral	0.14	0.10	1.80	0.80	0.84	0.20	10.18	1.92	1.84	0.91
	Dead Coral with Algae	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sponges		2.77	0.61	2.64	1.51	1.05	0.34	1.96	0.53	1.86	0.47
Bivalvia	**Barnacles**	0.00	0.00	0.30	0.17	0.63	0.25	0.15	0.08	0.15	0.08
	Oysters	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.06	0.00	0.00
Echinodermata	**Starfish**	3.02	0.74	0.25	0.11	0.28	0.16	0.05	0.05	0.00	0.00
	Feather stars	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.00	0.00
	Urchins	0.20	0.12	0.05	0.05	0.20	0.10	0.00	0.00	0.09	0.06
Chlorophyta	**Caulerpaceae**	0.77	0.27	3.41	1.36	0.35	0.16	0.00	0.00	0.14	0.14
	Halimedaceae	0.16	0.12	0.00	0.00	0.00	0.00	0.10	0.07	0.11	0.07
	Chlorodesmis	0.00	0.00	0.00	0.00	0.15	0.08	1.01	0.43	0.19	0.15
	Ulvaceae	1.67	0.75	4.80	1.00	10.41	1.99	1.09	0.26	20.73	2.34
Ochrophyta	**Dictyotaceae**	2.01	0.60	21.80	3.60	15.46	2.60	0.00	0.00	1.85	0.63
	Alariaceae	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Sargassaceae	9.81	2.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rhodophyta	**Corallinaceae**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Galaxauraceae	8.06	1.43	2.70	1.36	8.61	1.59	0.00	0.00	7.78	1.57
	Rhodomelaceae	13.16	1.74	26.80	3.70	18.73	1.85	20.00	2.37	4.88	0.80
Coralline Algae		0.09	0.09	0.00	0.00	0.00	0.00	0.00	0.00	9.20	1.96
Turf Algae		11.13	1.57	13.70	1.07	14.96	1.64	28.52	1.81	12.52	1.56
Other	**Fish**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.07
	Unidentified Fauna	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09
	Bare Ground	0.00	0.00	0.14	0.08	0.45	0.15	0.35	0.14	0.05	0.05
	Rock	0.00	0.00	1.00	0.81	0.23	0.19	0.25	0.13	0.18	0.13
	Rubble	0.63	0.24	1.06	0.38	0.69	0.27	2.09	0.66	0.48	0.23
	Sand	0.59	0.24	0.29	0.21	0.15	0.12	1.73	0.51	0.00	0.00

Appendix D Protected Matters Search

The Protected Matters Search Tool was used to assist in determining whether any marine MNES were likely to occur within 1 km of Kirra Reef. This search area was considered to include all marine areas that are within the likely extent of potential impact of the TRESBP, in order to adequately identify all marine MNES that could potentially be impacted by the TRESBP.

The following MNES relevant to marine ecology[2] were listed in this search:

- World Heritage Properties – none
- National Heritage Places – none
- Wetlands of International Importance – none
- Great Barrier Reef Marine Park – none
- Commonwealth Marine Areas – none
- Listed Threatened Ecological Communities – none
- Listed Threatened Species – 14
- Listed Migratory Species – 21

Other matters listed in the search results included 109 listed marine species and 14 whales and other cetaceans. The EPBC Act only protects these species in Commonwealth Marine Areas. The closest Commonwealth Marine Area is three nautical miles offshore. The TRESBP will not have a significant impact on Commonwealth Marine Areas and thus species listed only as ‘marine species’ or ‘whales and other cetaceans’ are not considered further in this report. However, species that are also listed as ‘migratory’ or ‘threatened’ are also protected in state waters (i.e. coastal waters to three nautical miles and other waters under Queensland jurisdiction) under the EPBC Act.

There are no World Heritage Properties, National Heritage Places, Wetlands of International Importance, listed threatened ecological communities, Commonwealth Lands, Commonwealth Heritage Places, Commonwealth Reserves or critical habitats in the vicinity of Kirra Reef. Likewise, the Great Barrier Reef Marine Park is approximately 400 km north of the proposed project and will not be affected. The Temperate East Marine Bioregional

[2] 46 threatened species (25 birds, 2 frog, 4 terrestrial mammals, 1 snail, 11 plants 1 insect and 2 snakes); 35 migratory species (10 migratory wetland birds, 19 migratory marine birds and 6 terrestrial birds) and 44 marine species (all birds) were also listed in the Protected Matters Search Tools and are not assessed in this report.

Plan (Commonwealth of Australia 2012) has been prepared under section 176 of the EPBC Act for Commonwealth Marine Area (which extend from 3 to 200 nautical miles from the coastline). The Commonwealth Marine Area is approximately 5 km east of Kirra Reef, and will not be affected by TRESBP.

Listed Threatened Marine Species

Fourteen threatened (critically endangered, endangered or vulnerable) fish, marine reptiles or marine mammals were listed as potentially occurring within 1 km of Kirra Reef. The likelihood that these species are present in the area of Kirra Reef was assessed using the criteria in Table D.1. The list of species is shown in Table D.2.

Table D.1 Criteria used to assess the likelihood of occurrence of species.

Likelihood of Occurrence	**Definition**
low	The species is considered to have a low likelihood of occurring in the area potentially impacted by the proposed action, or occurrence is infrequent and transient. Existing database records are considered historic, invalid or based on predictive habitat modelling. The habitat does not exist for the species, or the species is considered locally extinct. Despite a low likelihood based on the above criteria, the species cannot be totally ruled out of occurring in the potentially impacted area.
moderate	There is habitat for the species; however, it is either marginal or not particularly abundant. The species is known from the wider region.
high	The species is known to occur in the potentially impacted area, and there is core habitat in this area.

Table D.2 Threatened marine species listed on the protected matters search tool as potentially occurring within 1 km of Kirra Reef, and their likelihood of occurrence in this area.

Species	Common Name	EPBC Act Threatened Status	Likelihood of Occurrence
Mammals			
Balaenoptera musculus	blue whale	E	low
Eubalaena australis	southern right whale	E	low
Megaptera novaeangliae	humpback whale	V	moderate to high
Reptiles			
Caretta caretta	loggerhead turtle	E	moderate to high
Chelonia mydas	green turtle	V	moderate to high
Dermochelys coriacea	leatherback turtle	E	low
Eretmochelys imbricata	hawksbill turtle	V	moderate
Lepidochelys olivacea	olive Ridley turtle	E	low
Natator depressus	flatback turtle	V	low
Fish and Sharks			
Epinephelus daemelii	black rockcod	V	low
Carcharias taurus	grey nurse shark	CE	moderate
Carcharodon carcharias	great white shark	V	moderate
Pristis zijsron	green sawfish	V	low
Rhincodon typus	whale shark	V	low

CE Critically Endangered
E endangered
V vulnerable

Listed Migratory Marine Species

Twenty-one migratory marine species were listed as potentially occurring within 1 km of Kirra Reef using the Protected Matters Search Tool. Of these, 12 species are also listed as threatened species.

The likelihood of occurrence of each listed marine migratory species near Kirra Reef is shown in Table D.3.

Table D.3 Migratory marine species listed as potentially occurring within 1 km of Kirra Reef on the protected matters search tool, and their likelihood of occurrence in the area.

Species	Common Name	EPBC Act Threatened Status	Likelihood of Occurrence
Mammals			
Balaenoptera edeni	Bryde's whale	–	low
Balaenoptera musculus	blue whale	E	low
Eubalaena australis	southern right whale	E	low
Megaptera novaeangliae	humpback whale	V	moderate
Orcaella heinsohni (previously known as *Orcaella brevirostris)*	Australian snubfin dolphin	–	low
Sousa chinensis	Indo-Pacific humpback dolphin	–	moderate
Dugong dugon	dugong	–	low
Lagenorhynchus obscurus	dusky dolphin	–	low
Orcinus orca	killer whale	–	low
Reptiles			
Caretta caretta	loggerhead turtle	E	moderate to high
Chelonia mydas	green turtle	V	moderate to high
Dermochelys coriacea	leatherback turtle	E	low
Eretmochelys imbricata	hawksbill turtle	V	moderate
Lepidochelys olivacea	olive Ridley turtle	E	low
Natator depressus	flatback turtle	V	low
Fish and Sharks			
Pristis zijsron	green sawfish	V	low
Rhincodon typus	whale shark	V	low
Carcharodon carcharias	great white shark	V	moderate
Lamna nasus	mackerel shark	–	low

Species	Common Name	EPBC Act Threatened Status	Likelihood of Occurrence
Rays			
Manta birostris	giant manta ray	–	low
Manta alfredi	reef manta ray		moderate

Source: (DoTE 2014)

E endangered

V vulnerable