Monitoring of Biota at Kirra Reef: 2018

Tweed River Entrance Sand Bypassing Project

Prepared for:

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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 55 years, 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 2018, and compares the results to previous monitoring in 1995, 1996, 2001, 2003, 2004, 2005, 2010, 2012, 2014, 2015, 2016 and 2017. In 2016, 2017 and 2018, communities at Kirra Reef were compared to communities at Palm Beach, Cook Island East and Cook Island West. In the earlier surveys communities at Kirra Reef were only compared to communities at Palm Beach.

Benthic Communities

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

While the benthic community at Kirra Reef has varied over time, macroalgae was always 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 increased, and it is now more than in 2016.

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

Kirra and Palm Beach Reefs had the most similar fish communities, with large schools of yellowtail dominating both reefs, and stripey and cleaner wrasse more abundant at Palm Beach Reef. As in previous years, there were large schools of yellowtail at Kirra Reef, however schools of mado and striped sea pike while present were lower in abundance. These species were on average more abundant at Kirra Reef than at the Cook Island reefs (Kirra Reef appears to have a concentrating effect). In contrast, sergeant major and stripey were more common at the Cook Island West Reef and dart and silver batfish at Cook Island North than at Kirra. Differences in fish communities between reefs 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 compared to Palm Beach and 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 five 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 be 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' (such as Manta Bommie) off the north-eastern tip of Stradbroke Island may serve as a better comparative site.

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 extened 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 pumped through the system to Snapper Rocks East (371 818 m^3) and Duranbah (33 706 m^3). In 2018 (Jan - May) 163 870 m^3 of sand has been 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 2018.

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) and May 2017 (frc environmental 2017). The current survey was completed in May 2018.

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) 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 and Cook Island, in May 2018.

In 2018 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 and Cook Island.

2 Scope of the 2018 Monitoring Event and Methods Used

2.1 Scope

The scope of the 2018 monitoring event was to:

- review previous monitoring data and confirm the monitoring design[1]
- 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

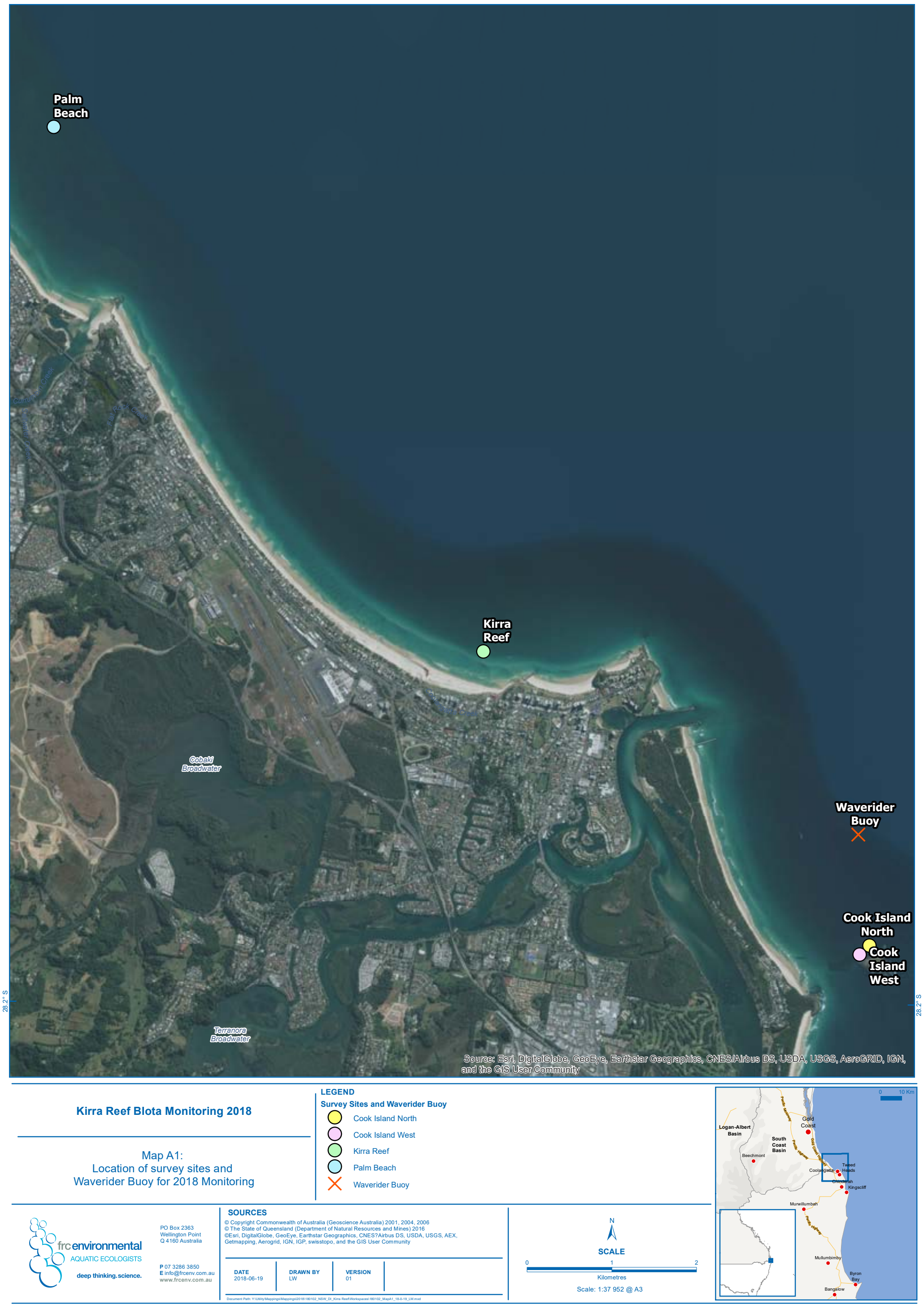
The experimental design for monitoring in 2018 comprised surveys of:

- benthic biota
  - at four sites: Kirra Reef and reefs at 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[2], supplemented by focused diver searches.
- fishes
  - at four sites: Kirra Reef and reefs at 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.

1 A review report was provided to the Department in February 2018.

2 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.

The reefs were monitored in May 2018, after a relatively dry period. Visibility at each site was approximately 10 m, with the exception of Kirra Reef, where the swell nearly continuously resuspended sediment and detritus, reducing visibility.



2.3 Collection of Data

Benthic Biota

In May 2018, 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

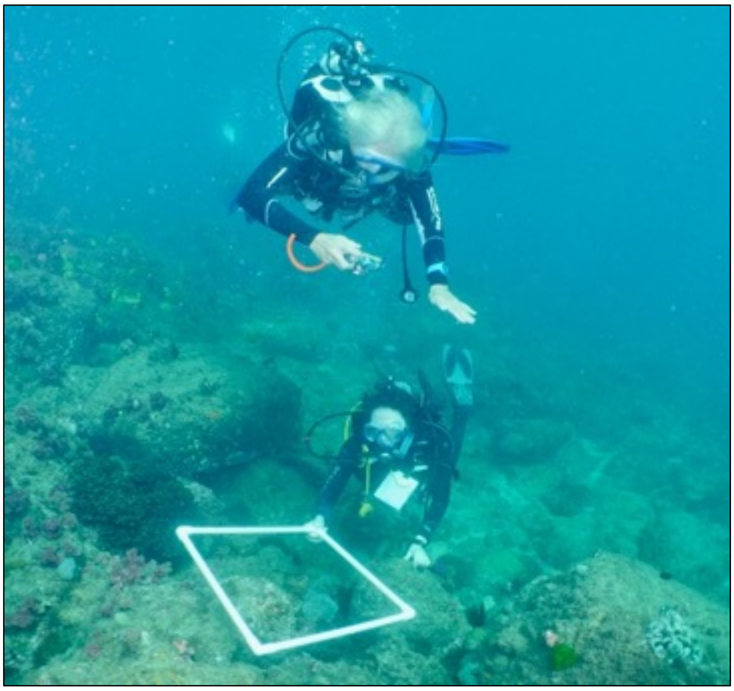
Three baited remote underwater video stations (BRUVS) and diver searches at each reef, were used to develop an understanding of fish community structure and relative abundances.

Figure 2.1

Scientific diver at Kirra Reef in 2018.

Figure 2.2

Preparing to capture a photo quadrat at Cook Island North.



Abiotic Factors

Sea condition, wind strength and direction, Secchi depth 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 2018), 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 and Gill 2006) was used to generate a matrix of 50[3] 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-*

[3] 50 points were considered statistically appropriate considering the typically small size of sessile fauna encountered.

situ observations 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 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 and Stevens 2015).

One-way PERMANOVA were used to assess similarities between sites in 2018 (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 (Ecosure 2016, frc environmental 2015) and other available literature. As in previous years the extent of exposed reef in 2018 was calculated from a rectified aerial image (nearmap 2017) using Geographic Information Software (ESRI 2014).

3 Results

3.1 Benthic Communities in 2018

The composition of benthic fauna and flora differed between reefs (Table 3.1; Table 3.2; and Figure 3.1). However, Cook Island West and Cook Island North were not significantly different to each other (Figure 3.1).

Kirra Reef had (SIMPER analyses; Appendix A):

- more brown macroalgae (Phaeophyta) of the genus *Sargassum* than the other sites (Figure 3.5)
- less red algae (Rhodophyta) cover than Cook Island North, but more than Cook Island West and Palm Beach Reef
- less hard coral than the other reefs (Figure 3.4, Figure 3.18 and Figure 3.19)
- less ascidians than the other reefs (Figure 3.7), and
- less turf algae than Cook Island West and Palm Beach Reef, but more than Cook Island North (Figure 3.8).

In general, the benthic communities at Kirra Reef had a higher evenness (that is, the abundance of different species was relatively similar) compared to the other reefs, illustrated by a steeper gradient, and more elevated k-dominance curve (Figure 3.2; Rice 2000) however both Cook Island reefs also had a relatively high level of evenness.

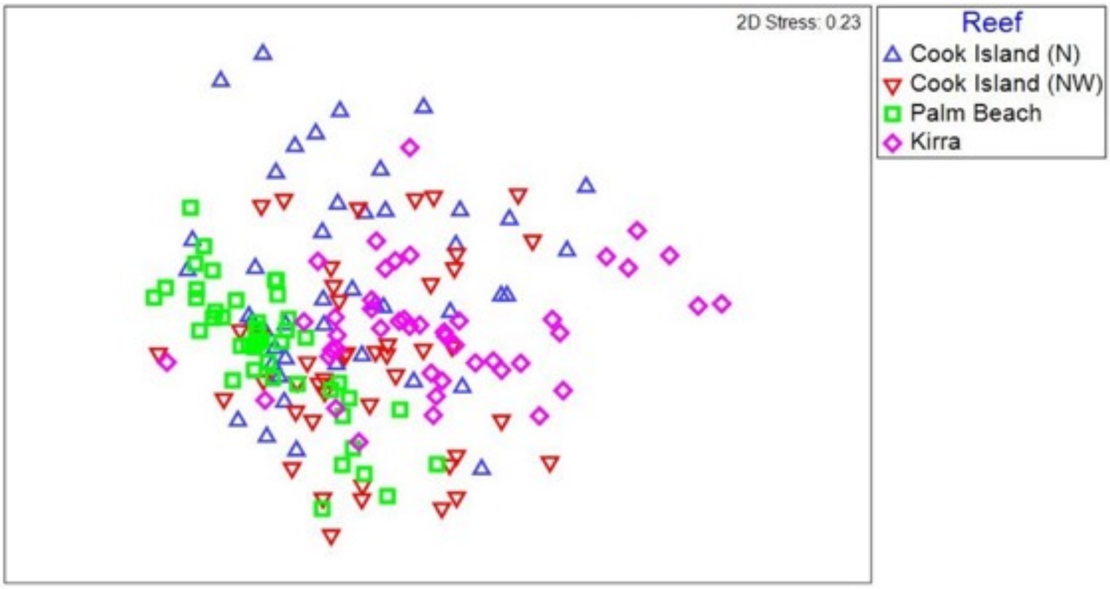


Figure 3.1 nMDS plot of benthic invertebrate communities at Kirra, Cook Island West, Cook Island North and Palm Beach reefs during the 2018 survey.

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	3	17460	13.235	**0.0001**
Residual	176	1319.2		

[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	1.7633	0.0053	9939	0.0071
Cook Island North, Palm Beach	3.3091	**0.0001**	9931	**0.0001**
Cook Island North, Kirra	3.6342	**0.0001**	9943	**0.0001**
Cook Island West, Palm Beach	3.5883	**0.0001**	9933	**0.0001**
Cook Island West, Kirra	3.592	**0.0001**	9948	**0.0001**
Palm Beach, Kirra	5.509	**0.0001**	9956	**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	0.05	0.5	9999
Cook Island North, Palm Beach	0.202	0.01	9999
Cook Island North, Kirra	0.241	0.01	9999
Cook Island West, Palm Beach	0.227	0.01	9999
Cook Island West, Kirra	0.239	0.01	9999
Palm Beach, Kirra	0.431	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.

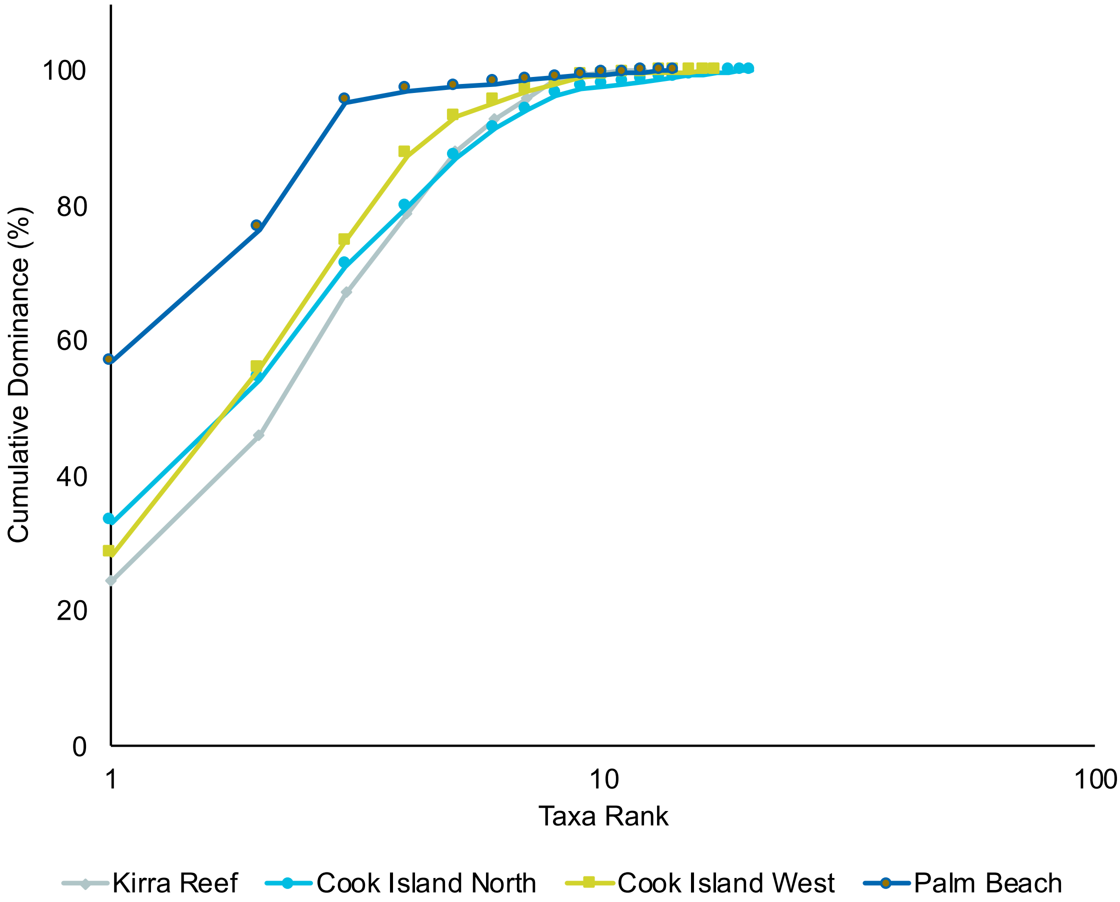


Figure 3.2 k-dominance of benthic communities at each reef in 2018.

Figure 3.3

An assemblage of hard and soft coral, the brown algae *Glossophora* sp. and tunicates at Cook Island North.

Figure 3.4

A colony of hard coral (*Turbinaria peltata*) at Cook Island North.

Figure 3.5

Hard coral (*Pocillopora damicornis*), turf algae, sponge, tunicates and the sea star *Echinaster luzonicus*.

Figure 3.6

A nudibranch (*Chromodoris kuiteri*) at Cook Island North.

Figure 3.7

A Gunthers wrasse above a benthic community of turf algae with soft coral (*Dendronephthya* sp.) behind.

Figure 3.8

An allied cowrie (*Ovula ovum*), feeding on soft coral at Cook Island West.

Turf and Macroalgae

In previous surveys, the brown macroalgae, *Sargassum* sp. (Figure 3.12), dominated benthic communities at Kirra Reef, and had significantly higher cover at Kirra Reef than at either of the Cook Island reefs (Ecosure 2016, frc environmental 2015). However, in 2018, while there was still significant cover of *Sargassum* sp. at Kirra, there was significantly more brown algae from the family Dictyotaceae (including *Zonaria* sp., *Lobophora* sp., and *Glossophora* sp.). Brown algae from the family Dictyotaceae was also dominant at both Cook Island reefs, but not at Palm Beach Reef (Figure 3.11; Appendix A). In 2018 there was no *Sargassum* sp. at Palm Beach Reef, or at the Cook Island sites.

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 family, and had a significantly higher cover at Kirra Reef than at the other reefs (Figure 3.11). The cover of red algae was low at Palm Beach Reef. The cover of the red algae of the family Plocamiaceae (predominantly *Plocamium microcladioides)*, was significantly higher at Cook Island North than at the other reefs.

The cover of green algae (Chlorophyta) at each reef was low, with a similar cover at each reef ($p > 0.05$; Figure 3.9; Appendix A). Green algae was present in small isolated patches, and included *Chlorodesmis* sp. (Figure 3.11), *Halimeda discoidea* (Figure 3.12) and *Ulva* sp.

All reefs had a similarly high cover of turf algae relative to other benthic cover (Figure 3.9; Appendix A).

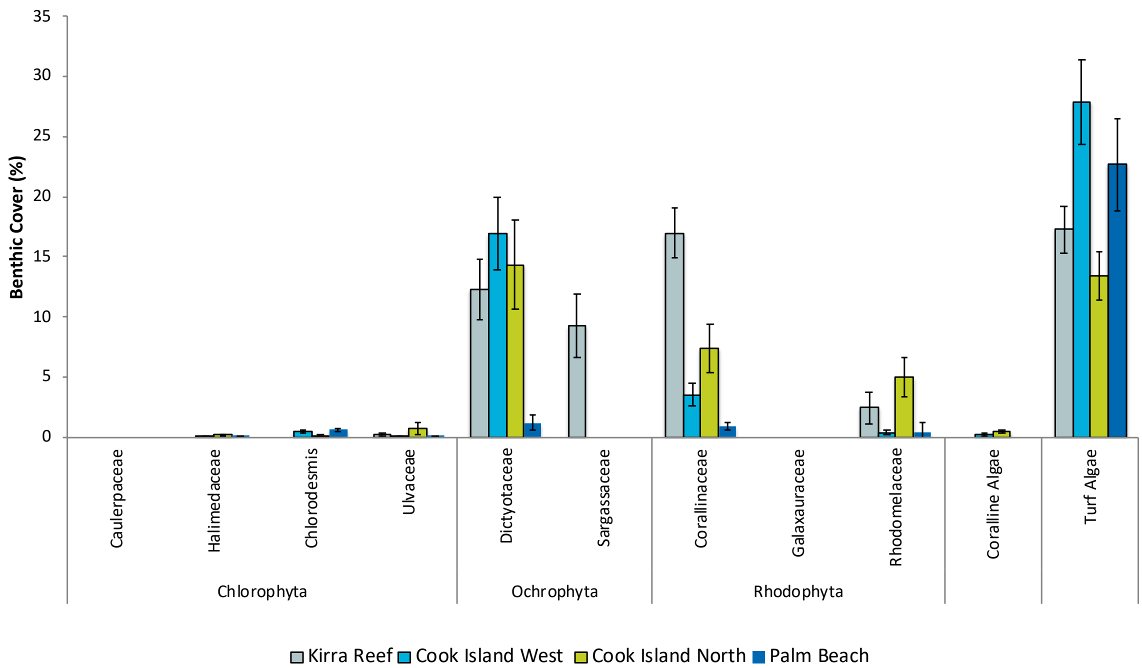


Figure 3.9 Mean percent cover of turf algae and macroalgae in 2018 (± standard error).

Figure 3.10

The brown algae *Sargassum* sp. at Kirra Reef.

Figure 3.11

The green algae *Chlorodesmis* sp. at Cook Island North.

Figure 3.12

The green algae *Halimeda discoidea* in an assemblage of red algae and hard coral at Cook Island North.

Figure 3.13

Brown algae of the family Dictyotaceae among ascidians at Cook Island.

Benthic Invertebrates: Ascidians, Corals, Sponges and Crinoids

The abundance and cover of several benthic groups were very different between Kirra and Palm Beach reefs, while the Cook Island reefs were similar. The abundance of ascidians (mean cover 62%) was significantly higher at Palm Beach (Figure 3.15) than at the other reefs. The abundance of ascidians at the other reefs were similar to each other and less than 30% (Figure 3.14; Appendix A).

Hard corals were not recorded at Kirra Reef since 2015 (frc environmental 2015) with only 0.49% cover recorded in 2018 (Figure 3.16). Hard corals had a significantly higher cover at the Cook Island Reefs (11.34% at Cook Island West and 19.59% at Cook Island North) than at Kirra or Palm Beach Reefs (4.88% cover) (Figure 3.16).

There was a significantly lower cover of soft coral at Kirra Reef (0.09%) than at the other reefs (Figure 3.17, Figure 3.22), with soft coral colonies very uncommon on Kirra Reef. The abundance of soft coral was also low at Cook Island North (1.2%) and Palm Beach reefs (1.3%). The highest abundance of soft coral was recorded at Cook Island West (3.49%) (Figure 3.16, Appendix A).

The cover of sponges was low at all reefs (<1.5%) (Figure 3.16).

The cover of feather stars (Crinoidea) was highest at Kirra Reef, with the cover statistically higher than at Cook Island North and Palm Beach, but not statistically different to Cook Island West (Figure 3.16, Figure 3.21).

The cover of anemones (0.53%) was significantly lower at Kirra than at the other reefs (Figure 3.16), which had a similar cover (2.48% at Cook Island West, 4.15% at Cook Island North, and 1.93% at Palm Beach).

Other groups such as molluscs (Figure 3.8), echinoderms (Figure 3.19), polychaetes and hydroids (Figure 3.23) were very sparse and not statistically different between reefs (Figure 3.14 and Appendix A).

At each reef a diverse range of less common invertebrate taxa was recorded, including sea urchins (Figure 3.20) and nudibranchs (Figure 3.22). Painted cray (*Panulirus versicolor*) were abundant at Cook Island West, while banded coral shrimp (*Stenopus hispidus*) were recorded from both Cook Island West and Palm Beach Reef.

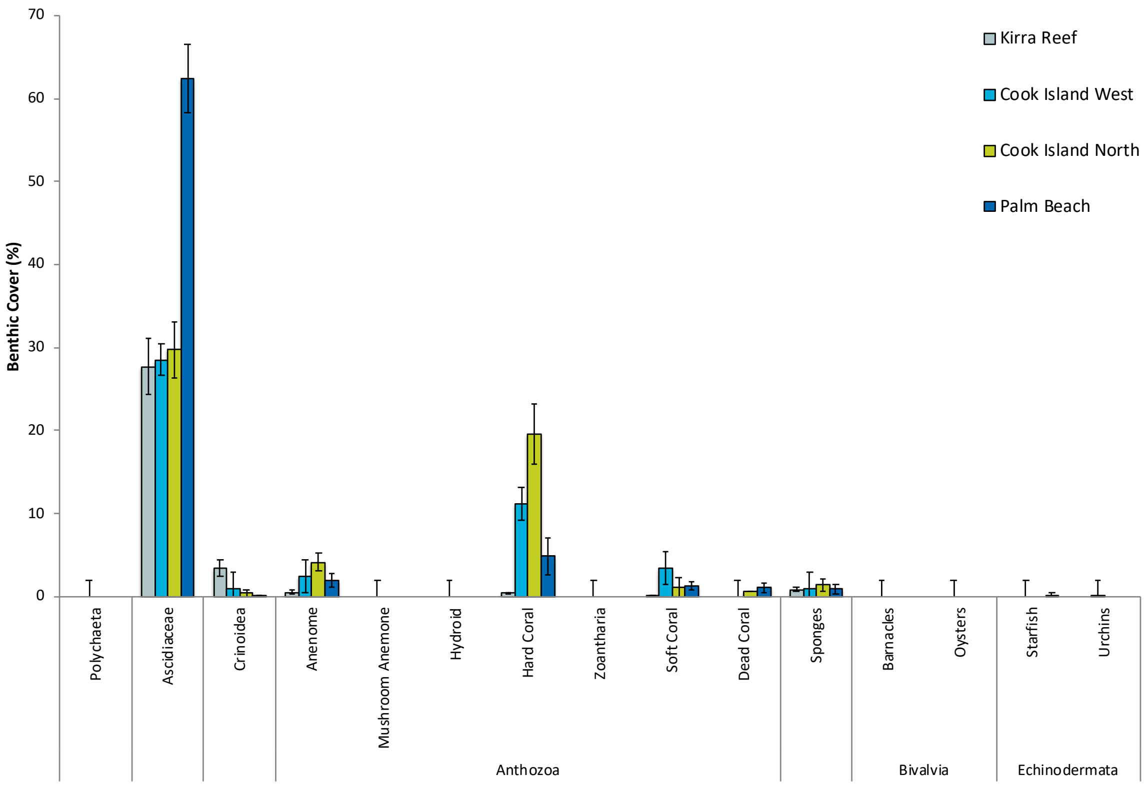


Figure 3.14 Percent cover of benthic communities other than macroalgae in 2018 (± standard error).

Figure 3.15

Benthic community dominated by ascidians, sponges and the soft coral *Dendronepthya* sp. at Kirra Reef.

Figure 3.16

An encrusting hard coral (*Goniastrea* sp.) at Cook Island.

Figure 3.17

The branching hard coral *Acropora* sp. at Cook Island.

Figure 3.18

A sponge (Order Demospongiae) at Kirra Reef.

Figure 3.19

A black feather star (*Cenolia* sp., Order Crinoidea) on the hard coral *Turbinara* sp. at Cook Island North Reef.

Figure 3.20

Sea urchin, soft coral and ascidians covered in turf algae amongst surge-suspended sand at Kirra Reef.

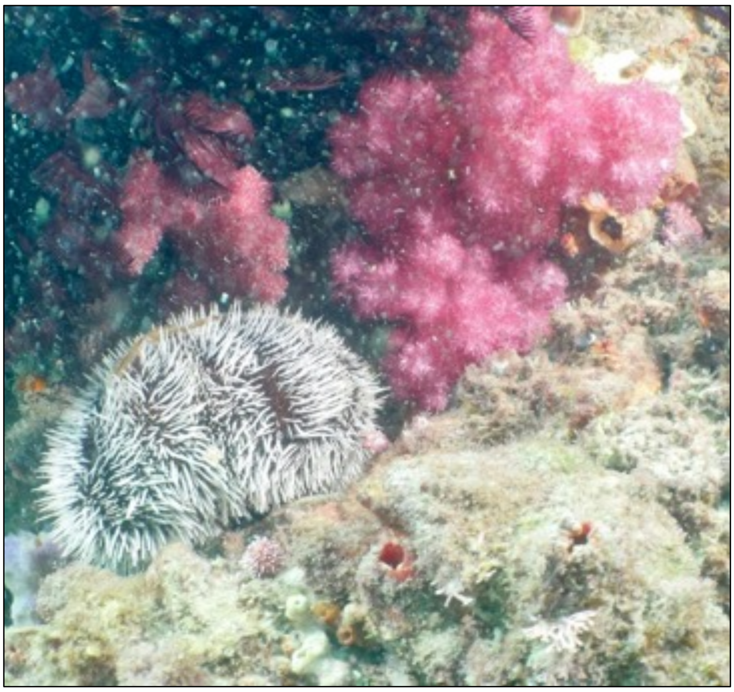


Figure 3.21

Anemone (*Entacmeae quadricolour*) with turf algae and ascidians at Cook Island West.

Figure 3.22

An octopus (*Octopus tetricus*) and surge-suspended sand at Kirra Reef.

Figure 3.23

The stinging hydroid *Macrorhynchia philippina* at Kirra Reef.

3.2 Changes in Benthic Communities at Kirra Reef Over Time

Benthic communities were similar over time at Kirra Reef (Figure 3.24); nevertheless, there were 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	13	39415	41.087	**0.0001**
Residual	762	959.31		

* Bold p values indicate significance at p <0.05.

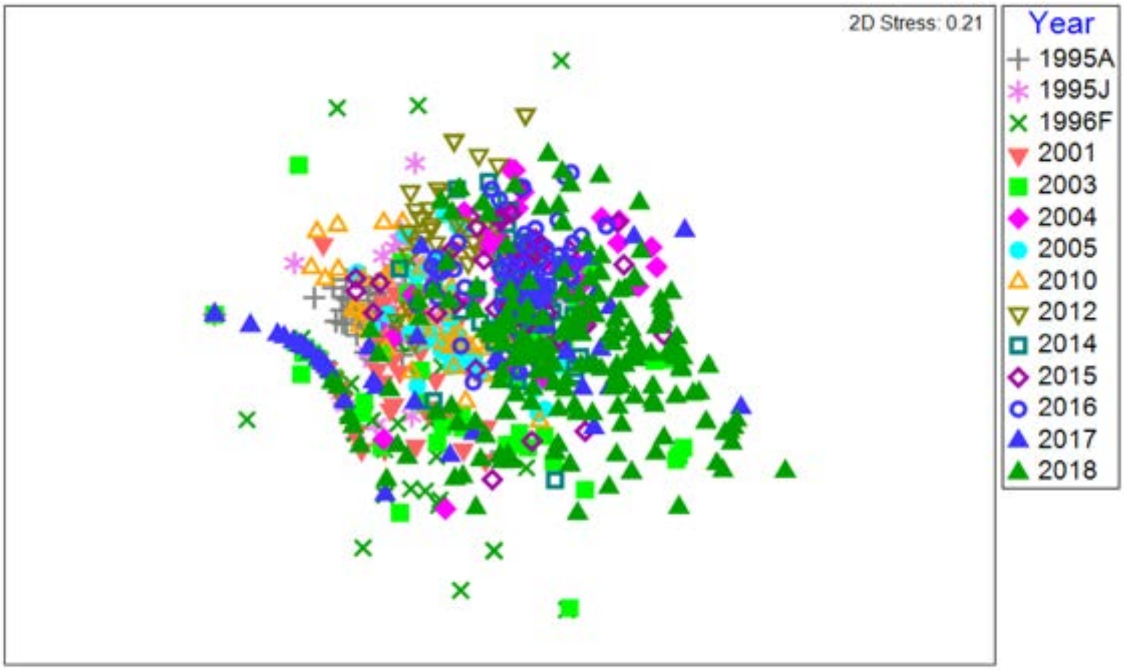


Figure 3.24 Multi-dimensional scale plot of benthic cover at Kirra Reef in all surveys.

Turf and Macroalgae

The cover of macroalgae at Kirra Reef was highest in 2001, and decreased from 2001 to 2003 (Figure 3.26) (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 2016. In 2017, macroalgae cover was significantly lower than in 2016 (frc environmental, pers. obs.) (Figure 3.26; Appendix A). The cover of macroalgae increased significantly from 2017 to 2018 (Figure 3.25).

The cover of turf algae in 2018 was significantly higher than in 2017, similar to April 1995, but significantly lower than in 2004 to 2016 (Figure 3.26; Appendix A).

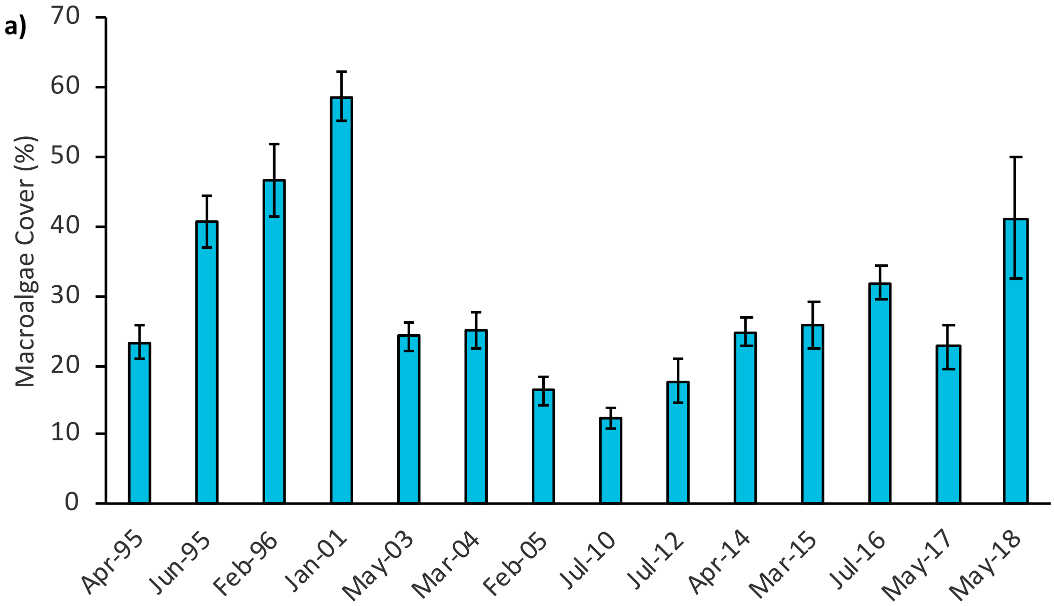


Figure 3.25 Mean cover of turf algae (± standard error) at Kirra Reef in each survey.

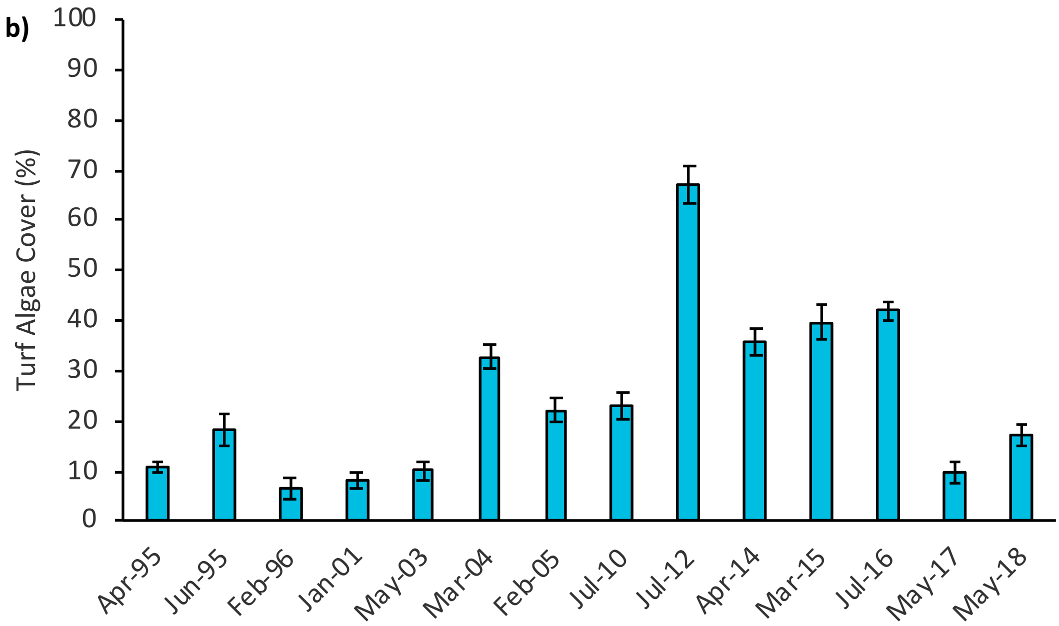


Figure 3.26 Mean cover of macroalgae (± standard error) at Kirra Reef in each survey.

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%), which is likely to be a result of frequent disturbance and prolonged periods of elevated turbidity associated with shifting sands and wave action inhibiting both recruitment and growth.

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 and 2012 (Figure 3.27; Appendix A). Since 2012, the cover of sponges has varied but has always been statistically significantly higher than in 2010 and lower than in 1996, 2003 and 2004 (Figure 3.27; Appendix A). However, in 2018, sponge cover was only slightly higher than in 2010, and significantly lower than in 2012-2017 (Figure 30). As filter-feeders, sponges are likely to be significantly influenced by wave-induced suspended sediment.

The cover of ascidians has also varied significantly among years, with the highest cover recorded in 2018, and the lowest in 1995, 1996 and in 2012.

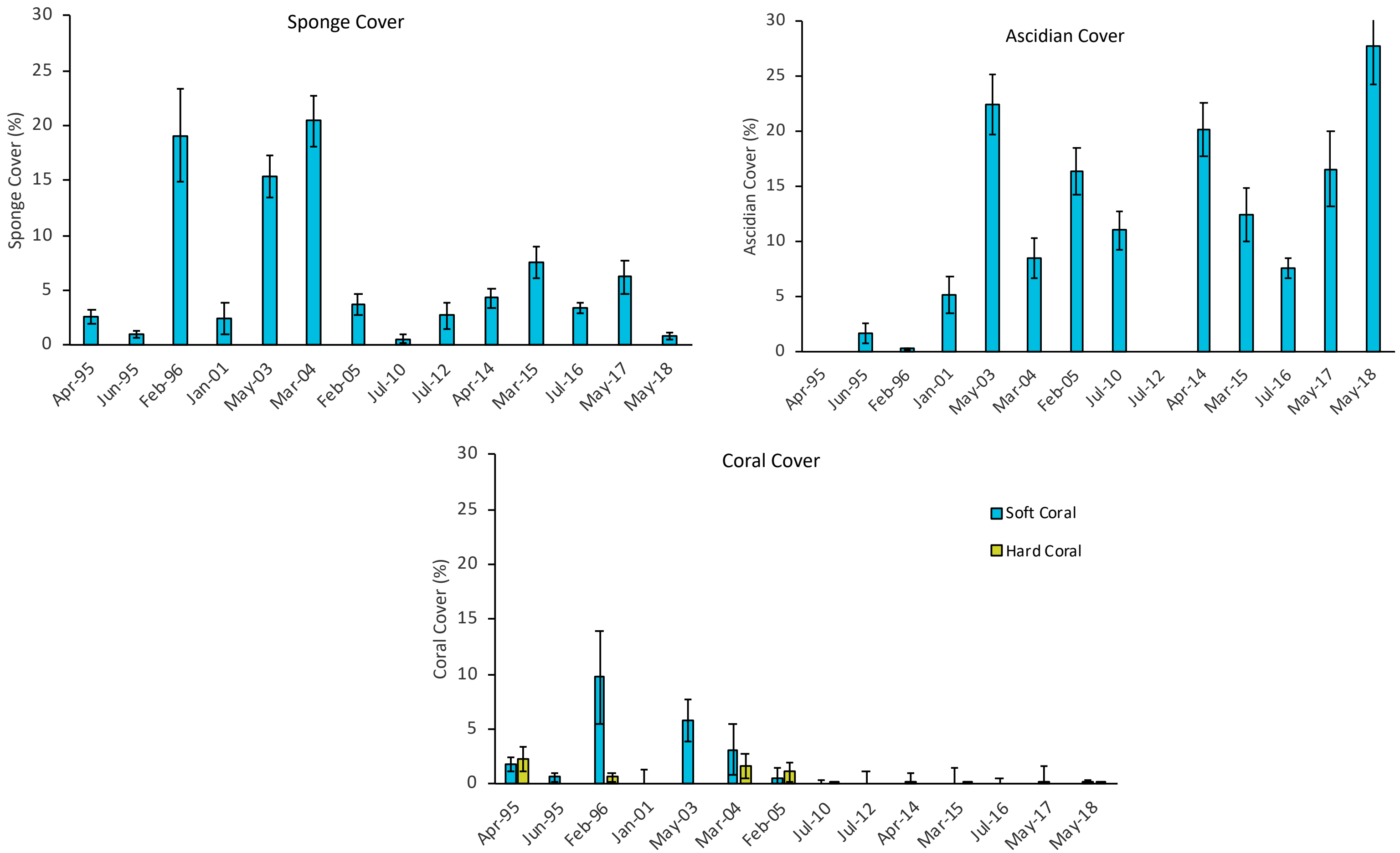


Figure 3.27 Mean cover of sponge, ascidians, soft and hard coral (± standard error) at Kirra Reef in each survey.

Table 3.5 One-way PERMANOVA results for the differences in the cover of benthic taxa at Kirra Reef between 1995 and 2018.

Benthic Taxa	Factor	df	MS effect	Pseudo-F	p (perm)*
Macroalgae	Survey	13	67.091	11.499	**0.001**
	error	762	5.8347		
Turf Algae	Survey	13	183.37	38.881	**0.001**
	error	762	7.4762		
Soft Coral	Survey	13	9.4872	6.8983	**0.001**
	error	762	1.3753		
Hard Coral	Survey	13	28.525	16.478	**0.001**
	error	762	1.7311		
Sponges	Survey	13	68.491	24.434	**0.001**
	error	762	2.8022		
Ascidians	Survey	13	209.9	42.807	**0.001**
	error	762	4.9035		

* Bold p values indicate significance at $p < 0.05$.

3.3 Fish Communities in 2018

Species Richness and Evenness

In the May 2018 survey, 116 species of fish were observed at Kirra, Palm Beach and the Cook Islands reefs (Appendix B). These 116 species represented 40 families with Pomacentridae (18 species), Labridae (21 species) and Chaetodontidae (9 species) the most speciose. Three species of cartilaginous fish were recorded of which 2 were recorded at Palm Beach Reef (ornate wobbegong and white-spotted eagle ray) and 1 (spotted wobbegong), at Kirra Cook Island North and West. There were a similar number of species at Kirra Reef (43) to Palm Beach Reef (45) and Cook Island North (48), while at Cook Island West 60 species were recorded.

Figure 3.28

Bennetts toby (*Canthigaster bennetti*) at Cook Island West.

Forty new species were recorded in May 2018, including eleven Labrids and three pelagic species (bluefin and thicklip trevally, and yellowtail kingfish (Table 3.6).

Table 3.6 Fish recorded in the survey in May 2018 that were not recorded in previous surveys.

Scientific Name	Common Name	Reef Recorded at
Acanthuridae		
Acanthurus nigricans	whitecheek surgeonfish	Cook Island North
Acanthurus pyroferus	mimic surgeonfish	Palm Beach
Paracanthus hepatus	blue tang	Kirra and Cook Island West
Blennidae		
Exallias brevis	leopard blenny	Cook Island North and Palm Beach
Petroscitirtes breviceps	shorthead sabretooth blenny	Palm Beach
Carangidae		
Carangoides orthogrammas	thicklip trevally	Cook Island West
Seirola lalandi	yellowtail kingfish	Cook Island North and West
Chaetodontidae		
Chaetodon trifascialis	cheveroned butterflyfish	Cook Island West
Chaetodon unimaculatus	teardrop butterflyfish	Cook Island North and West
Focipiger flavissimus	long-nosed butterflyfish	Cook Island West
Haemulidae		
Diagramma pictum	painted sweetlip	Cook Island West
Kyphosidae		
Kyphosus vaigiensis	silver drummer	Cook Island North
Labridae		
Anampses caeruleopinctatus	diamond wrasse	Cook Island North
Anampses geographicus	scribbled wrasse	Cook Island North and West
Anampses neoguinaicus	black backed wrasse	Cook Island West and Palm Beach
Bodianus axillaris	coral pigfish	Cook Island West
Coris gaimard	clown wrasse	Cook Island North and West
Halichoeres hortulanus	checkerboard wrasse	Cook Island West and Palm Beach
Hemigymnus melapterus	half and half wrasse	Cook Island North

Scientific Name	Common Name	Reef Recorded at
Marcophayngodon melegaris	eastern leopard wrasse	Cook Island West
Thalassoma amblycephalum	two tone wrasse	Palm Beach
Thalassoma hardwicke	six banded wrasse	Cook Island North
Stethojulis bandanensis	red spot wrasse	All reefs
Lutjanidae		
Lutjanus bohar	red bass	Cook Island West
Monocanthidae		
Catherhines dumerilii	barred filefish	Cook Island West and Palm Beach
Paraluteres prionuurus	mimic filefish	Kirra and Cook Island North and West
Monocentridae		
Cleidopus gloriamris	pineapplefish	Kirra
Mullidae		
Parapeneus multifasciatus	banded goatfish	Cook Island North and West
Muraenidae		
Enchelycore ramosa	mosaic moray	Kirra and Cook Island North
Pomacanthidae		
Centropyge bispinosus	coral beauty	Cook Island North
Pomacentridae		
Abedefduf sexfasciatus	scissortail sergeant	Cook Island West and Palm Beach
Abedefduf whitleyi	Whitley's sergeant	Cook Island West
Chromis margitifer	whitetail puller	Kirra and Cook Island North and West
Plectroglyphodidon johnstonianus	Johnston's damsel	Cook Island North and West
Plectroglyphodidon lacrymatus	jewel damsel	Palm Beach
Pomacentrus bankanensis	fire damsel	Cook Island North
Scombridae		
Grammatorcynus bicarinatus	shark mackeral	Palm Beach
Serrenidae		
Pseudoantias squampinnis	orange basslet	Kirra

Scientific Name	Common Name	Reef Recorded at
Tertradontidae		
Arothron nigropunctatus	blockspotted pufferfish	Cook Island North and West
Canthisgaster bennetii	blackspot toby	Kirra and Cook Island West

Approximately half of the species at each reef had tropical/temperate ranges (Table 3.7), and would not be at either extreme of their distribution across. However, the remaining species typically have either temperate or tropical ranges, indicating they are likely 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.

Between 91and 97% of fish species recorded during 2018 were reef-associated species (e.g. blue groper, Figure 3.30, yellowtail, Figure 3.31, Table 3.7). The maximum number of pelagic species recorded was 4 at Cook Island West with only 1 species classed as reef/pelagic at Palm Beach.

In May 2018, the lowest number of species was recorded at Kirra Reef, with a few dominant species (e.g. yellow-tail) indicated by a shallower k-dominance curve (Figure 3.33). Although Cook Island North and Palm Beach had similar species abundance to Kirra, the abundance of species was more evenly distributed.

Blue groper (*Achoerodus viridis*), 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 Number of fish species observed at Kirra, Palm Beach and Cook Island Reefs in 2018 and their typical range and life style.

	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Range[a]				
Temperate	11	3	7	6
Tropical	14	20	27	17
Tropical/Temperate	18	22	30	25
Total	**43**	**45**	**64**	**48**
Life style[b]				
Pelagic	1	2	4	3
Reef associated	42	43	60	44
Reef/Pelagic	0	0	0	1
Total	**43**	**45**	**64**	**48**

[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

Figure 3.29

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

Figure 3.30

Scientific diver setting a BRUV at Cook Island North.

Figure 3.31

Schooling yellowtail (*Trachurus novaezelandiae)* at Kirra Reef

Figure 3.32

Schooling stripeys (*Microcanthus strigatus*) at Cook Island West

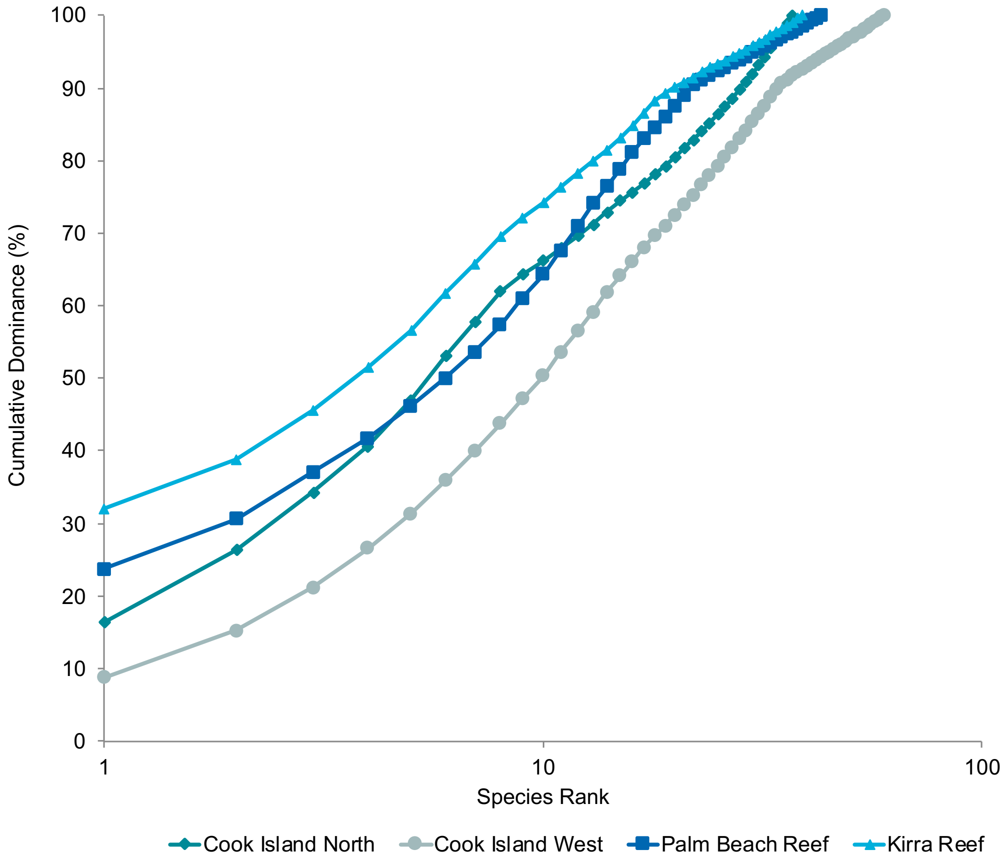


Figure 3.33 k-dominance curve for fish communities at Kirra, Cook Island North and West and Palm Beach Reefs.

Abundance and Trophic Levels

In May 2018, Kirra Reef had the highest total abundance (sum of MaxN values) of fish (355) followed by Palm Beach reef (235), Cook Island North (189) then Cook Island West (130). Kirra and Palm Beach had the highest abundances of planktivorous fish when comparing the four locations. While Cook Island North reefs were dominated by carnivorous fish (e.g. spotted wobbegong, Figure 3.34) while Cook Island west had a higher abundance of omnivorous fish (Figure 3.35). The occurrence of fish having herbivorous, omnivorous-herbivorous tendencies and planktivorous fish were similar between Kirra and the Cook Island reef sites. The abundance of corallivorous species was low at all sites.

Figure 3.34

Spotted wobbegong (*Orectolobus maculatus)* at Kirra Reef.

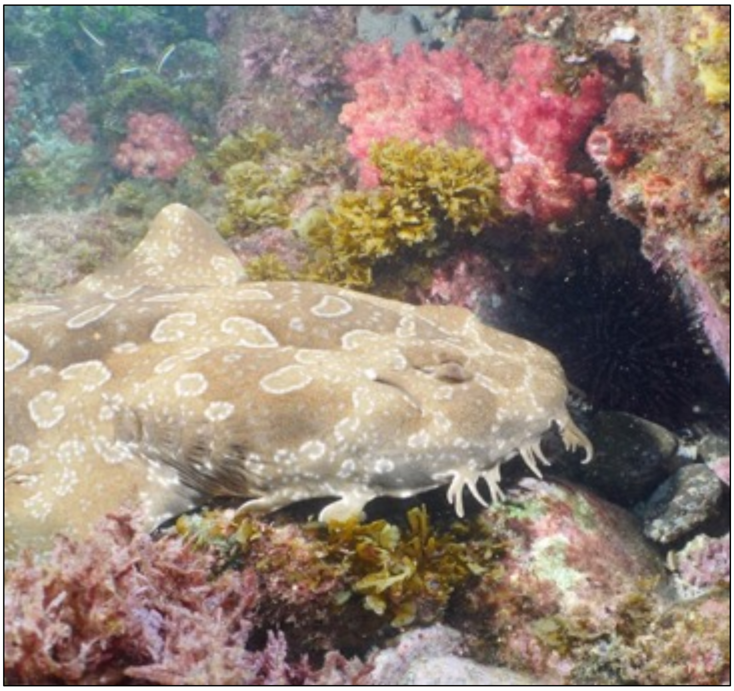


Figure 3.35

Barrier Reef anemonefish *(Amphiprion akindynos)* at Cook Island West

Figure 3.36

Bigscale scalyfin (*Parma oligolepsis*) defending its territory at Cook Island North.

Figure 3.37

Gunthers wrasse (*Pseudolabrus guentheri*) at Kirra Reef.

Figure 3.38

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

Figure 3.39

Adult male green turtle (*Chelonia mydas*) at Cook Island North.

Green turtles were recorded at Cook Island North and Cook Island West (Figure 3.39).

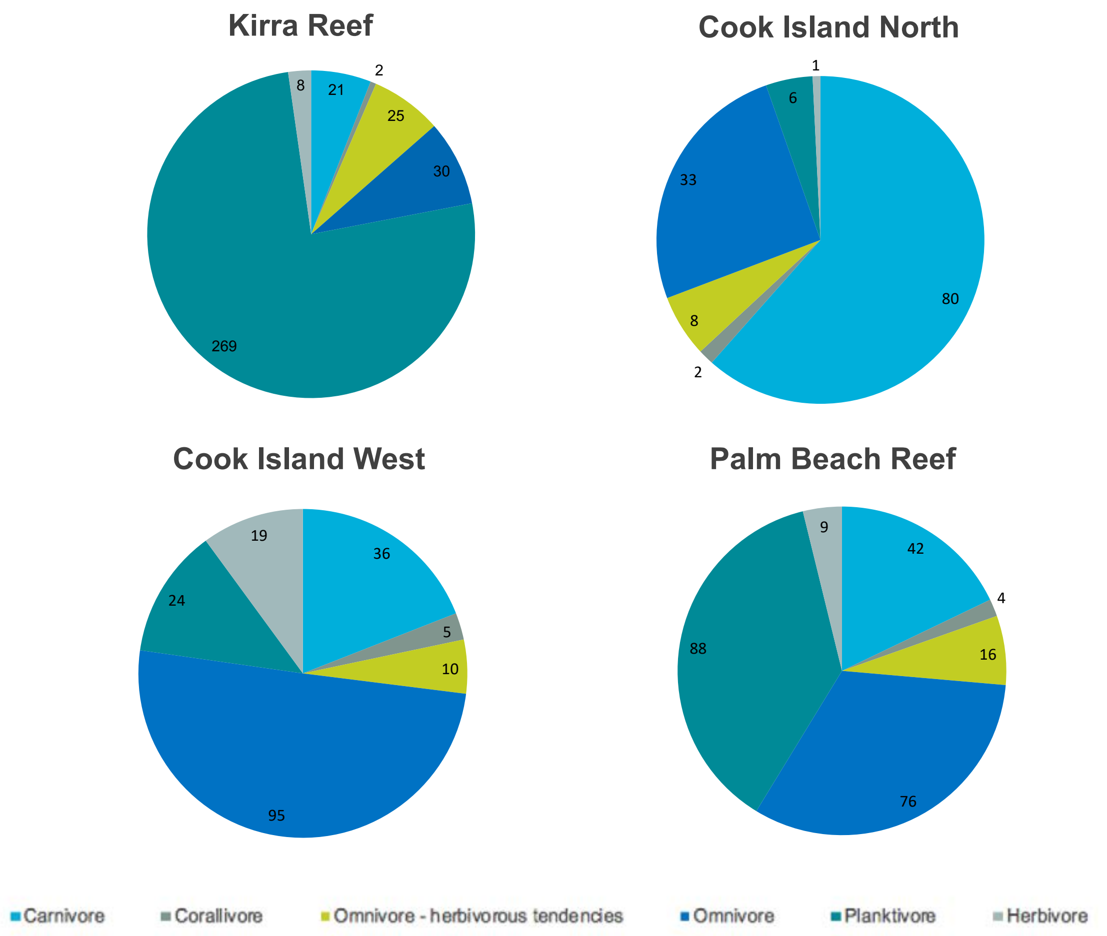


Figure 3.40 Abundance of fish of different trophic levels using summed maxN values at each Reef.

The representation of each trophic level did not differ greatly between the 4 sites, with carnivores and omnivores dominating. Most omnivorous species were recorded at Cook Island West while most carnivorous species were recorded at Palm Beach Reef (Figure 3.36).

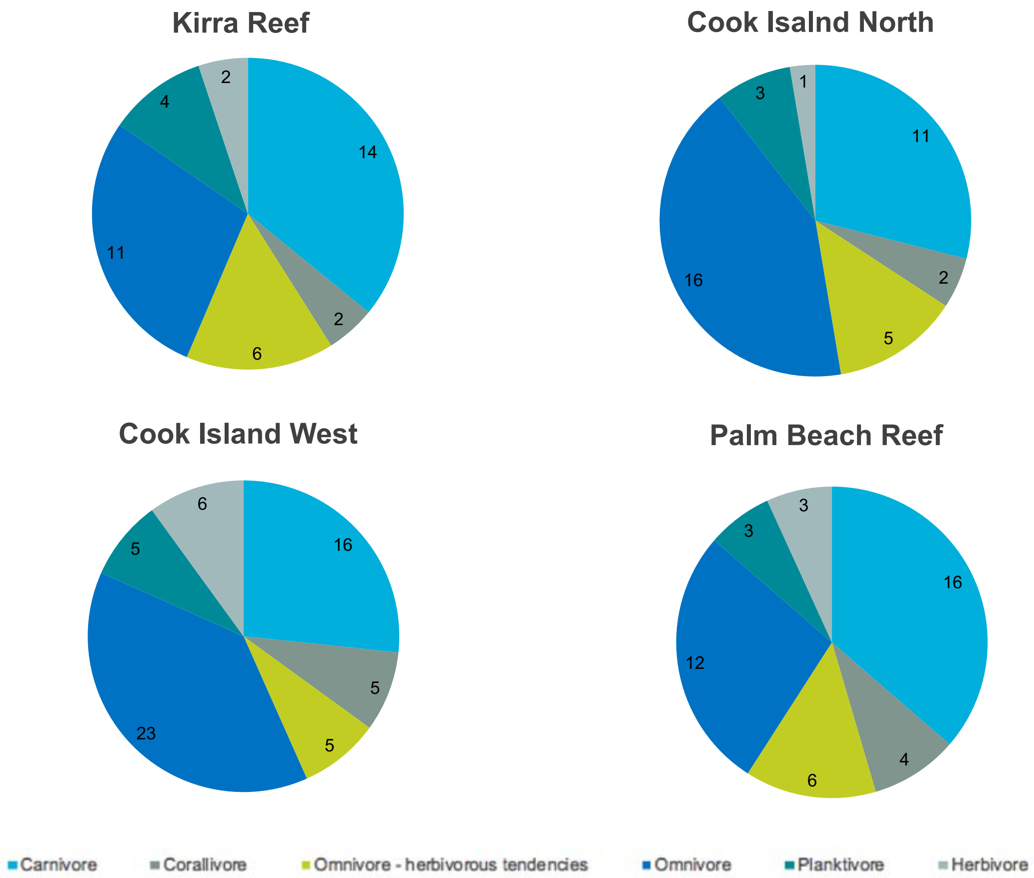


Figure 3.41 Fish species of different trophic levels at each Reef.

Fish Communities at Kirra, Palm Beach and Cook Island Reefs

Fish communities recorded at Kirra Reef were significantly different to those recorded at Palm Beach, Cook Island North and Cook Island West (Table 3.8, Table 3.9, Table 3.10; Figure 3.42). Fish communities recorded at Cook Island North and West were not significantly different from one another (Table 3.8 & Table 3.9).

Species contributing to differences between Kirra and Cook Island sites included yellowtail (*Trachurus novazelandiae*), dart (*Trachinotus blochii*), silver batfish (*Monodactylus argenteus*), sergeant major (*Abedefduf vaigiensis*) and neon damselfish (*Pomacentrus coelestis*) (SIMPER, Appendix A).

As in 2017, yellowtail (*Trachurus novaezelandiae*) and neon damselfish were abundant at Kirra Reef, while silver batfish (*Monodactylus argenteus*), dart (*Trachinotus blochii*) and sweetlip (*Diagramma pictum*) were more abundant at Cook Island North. When comparing Kirra and Palm Beach reefs, again the large schools of yellowtail (*Trachurus novazelandiae*) were more abundant at Kirra Reef.

Silver batfish (*Monodactylus argenteus*), cleaner wrasse (*Labroides dimidiatus*) and yellowfin bream (*Acanthopagrus australis*) were more abundant at Palm Beach Reef.

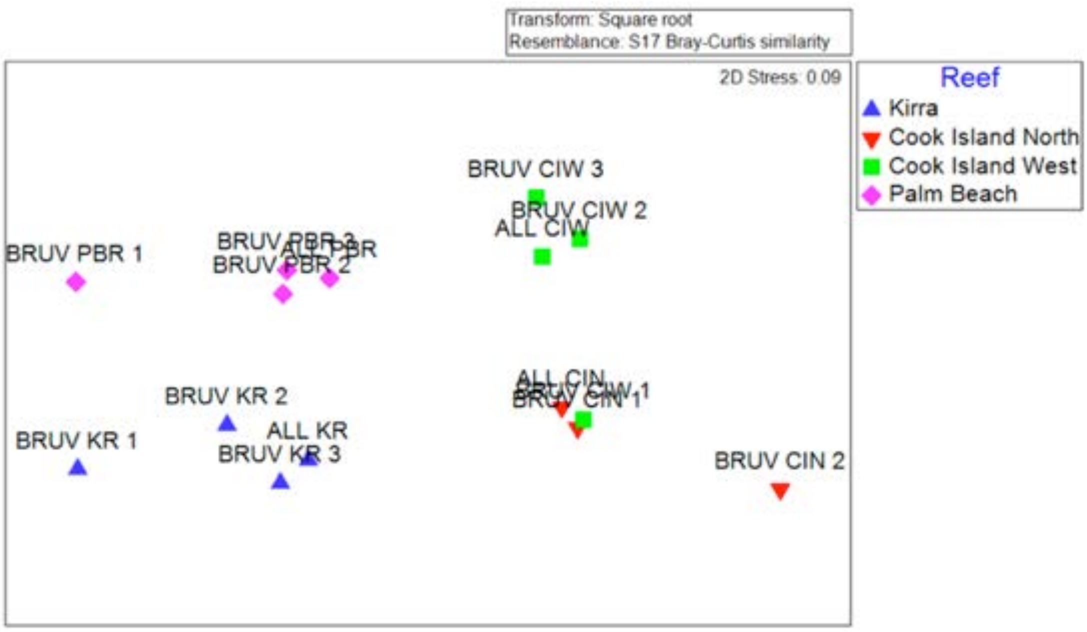


Figure 3.42 Multi-dimensional scale plot of fish communities at each Reef in May 2018.

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	3	5640.4	5.845	**0.0001**
Residual	11	965		

[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	p (perm)	Unique permutations	p (MC)[a]
Kirra, Cook Island North	2.5917	**0.0283**	35	**0.0086**
Kirra, Cook Island West	2.8803	**0.0281**	35	**0.0018**
Kirra, Palm Beach	1.712	**0.0286**	35	**0.0441**
Cook Island North, Cook Island West	1.6661	0.0603	35	0.0884
Cook Island North, Palm Beach	2.6115	**0.0282**	35	**0.0081**
Cook Island West, Palm Beach	2.7262	**0.0305**	35	**0.0032**

[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.

	Test statistic (R)	Significance (*p*)[a]	Possible permutations
Main Test			
Between Reefs	0.814	**0.0001**	2627625
Pairwise			
Kirra, Cook Island North	0.963	**0.029**	35
Kirra, Cook Island West	0.99	**0.029**	35
Kirra, Palm Beach	0.563	**0.029**	35
Cook Island North, Cook Island West	0.444	0.057	35
Cook Island North, Palm Beach	0.944	**0.029**	35
Cook Island West, Palm Beach	0.969	**0.029**	35

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

Figure 3.43

Painted sweetlip (*Diagramma pictum*) taking shelter at Cook Island North.

Figure 3.44

Black-tip bullseye (*Pemphris affinis*) schooling at Cook Island North.

Figure 3.45

Crimson banded wrasse (*Notolabrus gymnogenis*, foreground) and blue groper (*A. viridis*) at Cook Island North.

Figure 3.46

A school of old wives (*Enoplosus armatus*) at Kirra Reef.

3.4 Abiotic Factors

Weather Conditions

Water conditions in the May 2018 survey were typical of shallow coastal seas on the Australian east coast during Autumn (Table 3.11). Visibility was 10+ m at all sites except Kirra which had reduced visibility due to suspended sediment and detritus. At each site, Secchi depth equalled water depth. 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 2018.

	Cook Island West	Cook Island North	Palm Beach	Kirra Reef
	10 May 2018	**10 May 2018**	**29 May 2018**	**29 May 2018**
Sea conditions	seas below 1 m	seas below 1 m	seas up to 1.3 m	seas up to 1.3 m
Temperature (°C at 0.5m)	22.0	22.0	21.9	21.8
Wind strength (km/h)	2	5	2	10
Wind direction	NW	NW	SSE	ESE
Secchi Depth (m)	10+	10+	8+	6+

Wave Height and Direction

As in previous surveys, in the 12 months preceding the 2018 monitoring program, wave height and direction followed these general trends (Figure 3.47):

- 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 April 2017 and March 2018 the mean wave height at the Waverider buoy was 0.95 m and slightly from the east-south-east (97°) (Table 3.11). The standard deviation of wave direction varied throughout the twelve months preceding monitoring from 12 to 42 degrees.

Wave heights exceeded 3 m in October 2017 (east) and February 2018 (north east). Other than this, the 12 months preceding May 2018 were relatively calm with waves always less than 3 m (Figure 3.48).

Overall, the conditions, relating to wave height, experienced between April 2017 and March 2018 were relatively calm, with seas rarely over 2 m and typically under 1 m. The calmest month (i.e. lowest average monthly wave height) was December 2017 with an average wave height of 0.76 m (Table 3.11).

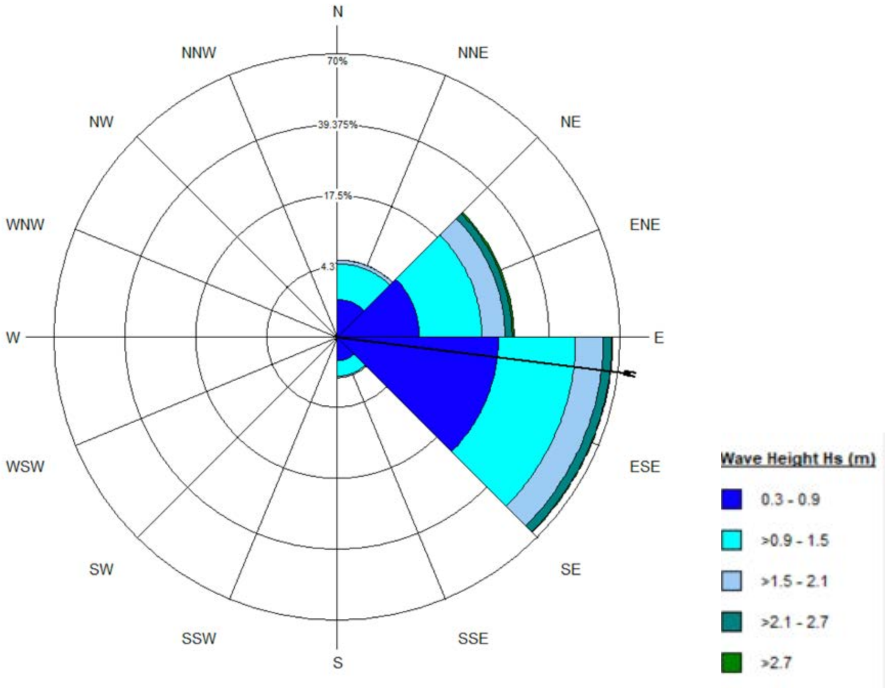


Figure 3.47 Rose plot showing the height in metres and cardinal direction of waves between April 2017 and March 2018.

Table 3.12 Wave height, direction and circular variation

Year	Season	Month	Mean Wave Direction	Mean Wave Height	Circular StDev
2017	Autumn	April	97.712°	0.910	24.812°
		May	91.779°	0.942	19.718°
	Winter	June	104.183°	0.958	16.798°
		July	103.441°	0.963	15.637°
		August	109.243°	0.951	18.098°
	Spring	September	96.393°	0.975	12.862°
		October	88.356°	0.926	22.486°
		November	97.609°	0.902	25.992°
	Summer	December	88.778°	0.756	42.89°
2018		January	98.743°	0.862	31.259°
		February	93.543°	0.968	14.67°
	Autumn	March	95.537°	0.938	20.515°
		Overall	**97.112°**	**0.947**	**18.823°**

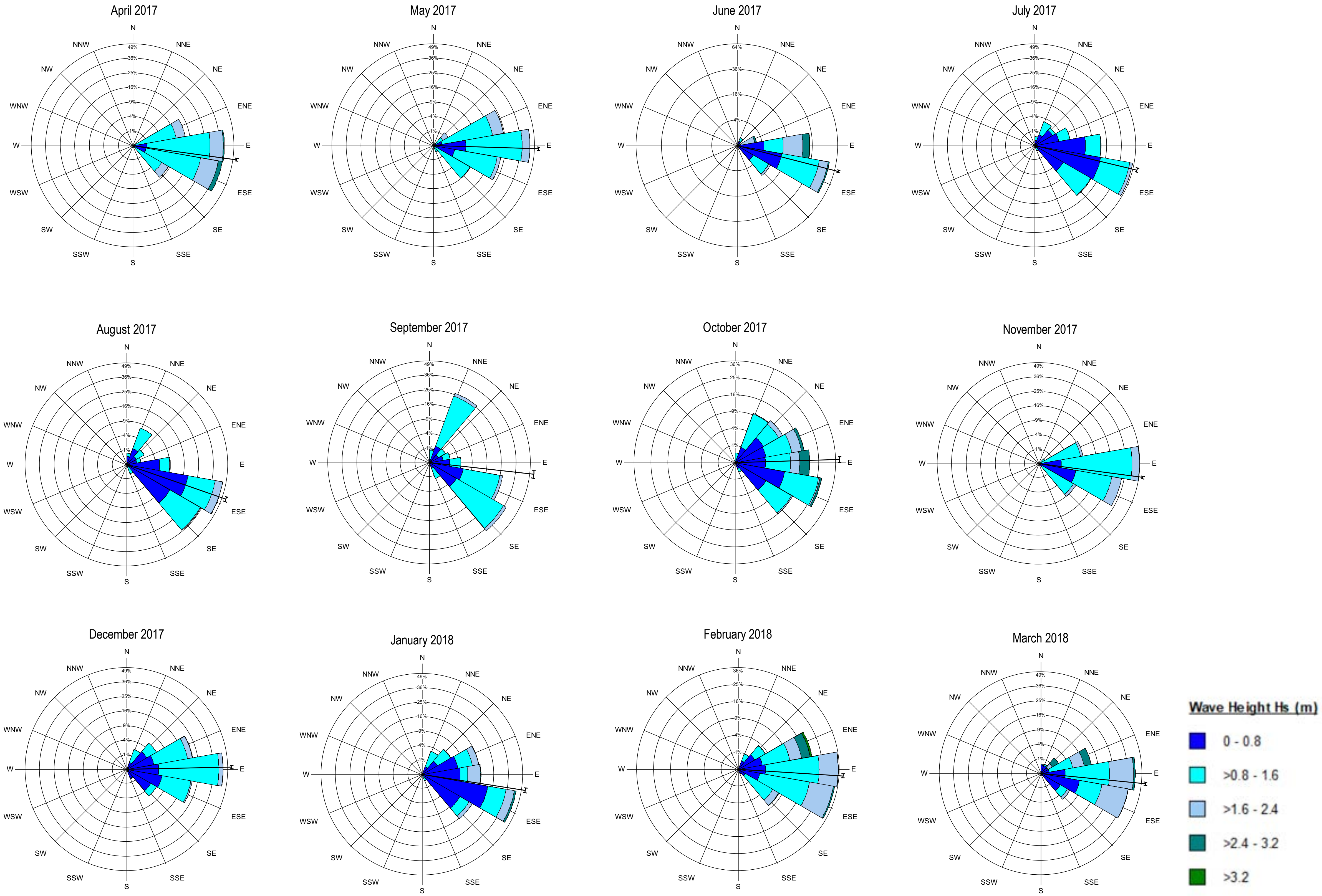


Figure 3.48 Rose plots of wave height and cardinal directions of waves measured at the Tweed Heads Waverider Buoy between April 2017 and March 2018.

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 12 months preceding the 2018 monitoring event, sea surface temperature followed typical trends with highest temperatures in February and March and the lowest around August (Figure 3.49). Sea surface temperature ranged between 18.0 and 27.8 °C between April 2017 and March 2018 (Figure 3.49).

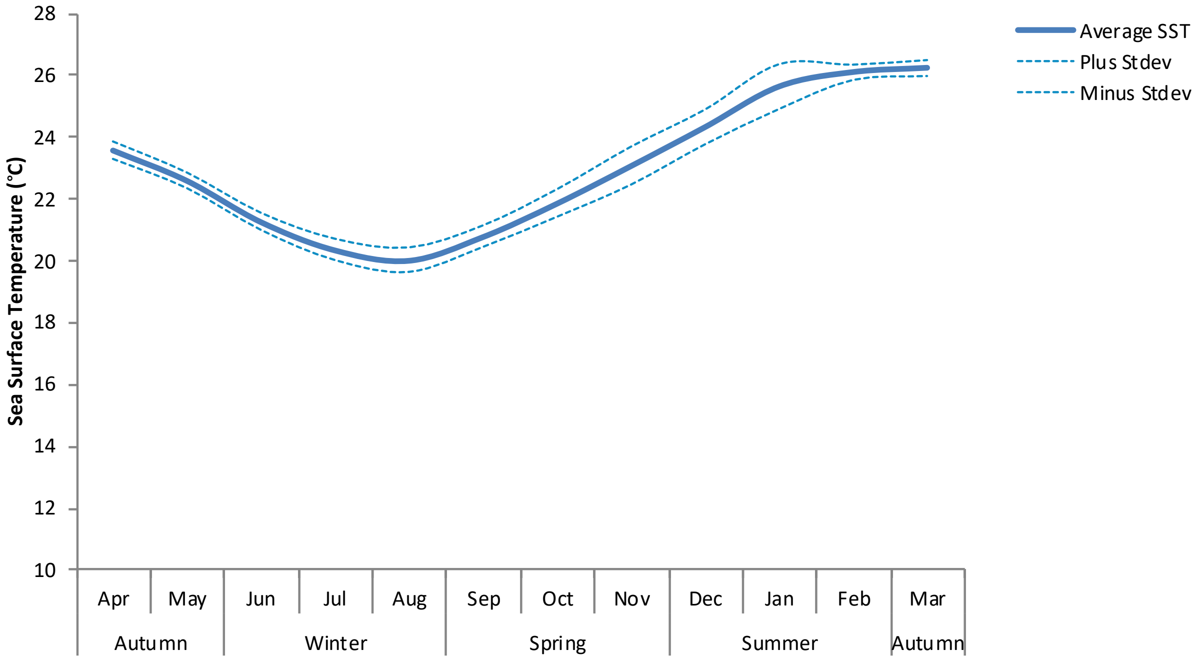


Figure 3.49 Sea surface temperature at the Tweed Heads Waverider Buoy between April 2017 and March 2018.

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 3.54). Three major outcrops of reef (north, south and east) have been exposed and covered with sand at various times as a result of sand movements in the area.

Natural Sand Movement Pre-1960s

Prior to 1960 (Figure 3.50), 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 and 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).

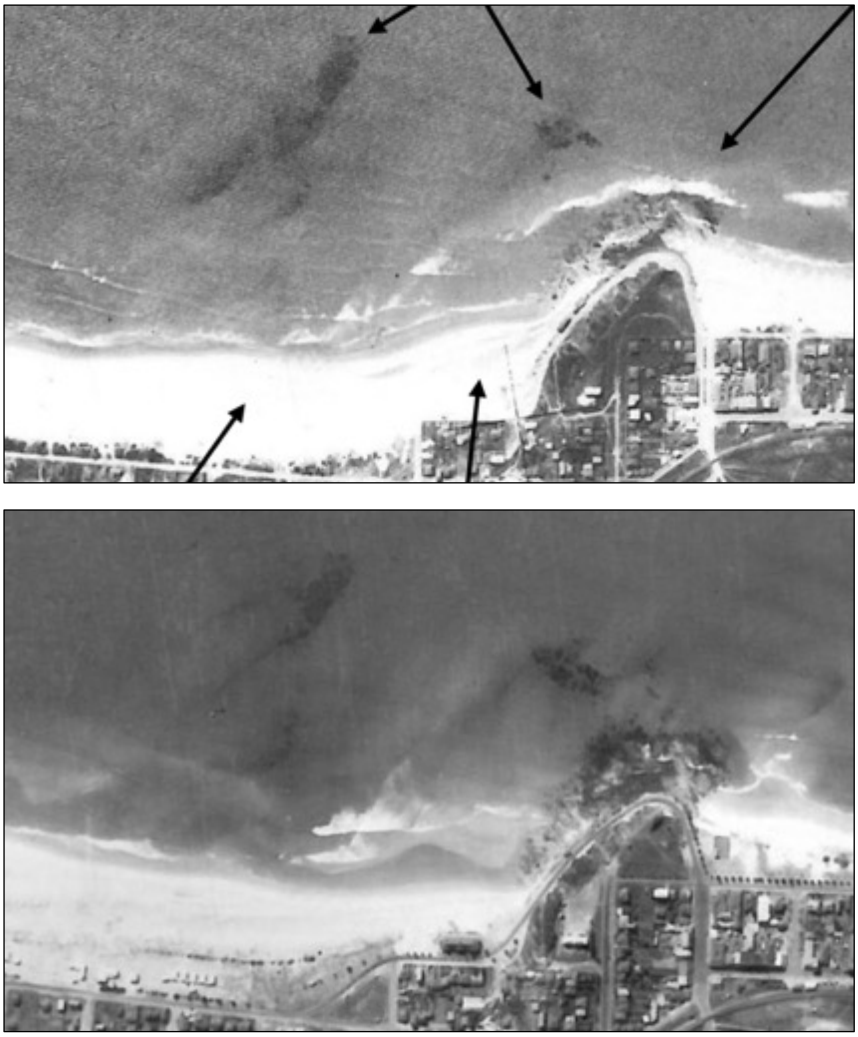


Figure 3.50 Aerial photos for Kirra Reef in 1930 (top) and 1946 (bottom). Source TRESBP 2017.

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 3.51).

Figure 3.51 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 3.52), 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 3.52 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 3.53). 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[4].

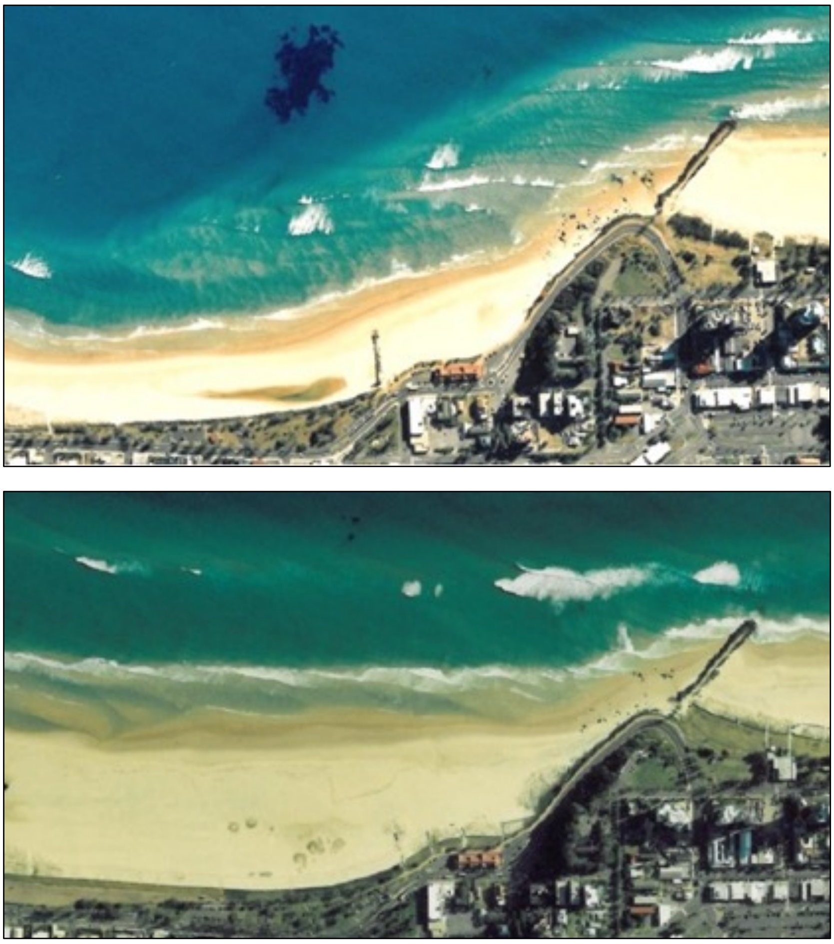


Figure 3.53 Aerial photos for Kirra Reef in 2002 (top) and 2008 (bottom). Source TRESBP 2015.

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

Mimicking Natural Sand Supply - 2008 to 2018

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[5] 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 (Map 1, Table 3.13), marginally smaller (604 m^2) than 12 months earlier (Ecosure 2016).

The aerial extent of reef increased slightly in the months preceding 2017 monitoring possibly from sand movement due to Cyclone Debbie in March 2017. The current decrease in reef extent is likely due to lack of recent storm activity and the consequent uninterrupted accretion of sand in the vicinity of the reef.

Overall, the extent of Kirra Reef has remained relatively constant for the last five years during a period in which sand bypass rates have mimicked the rate of natural sand transport and storm conditions have been moderate.

---

[5] 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.

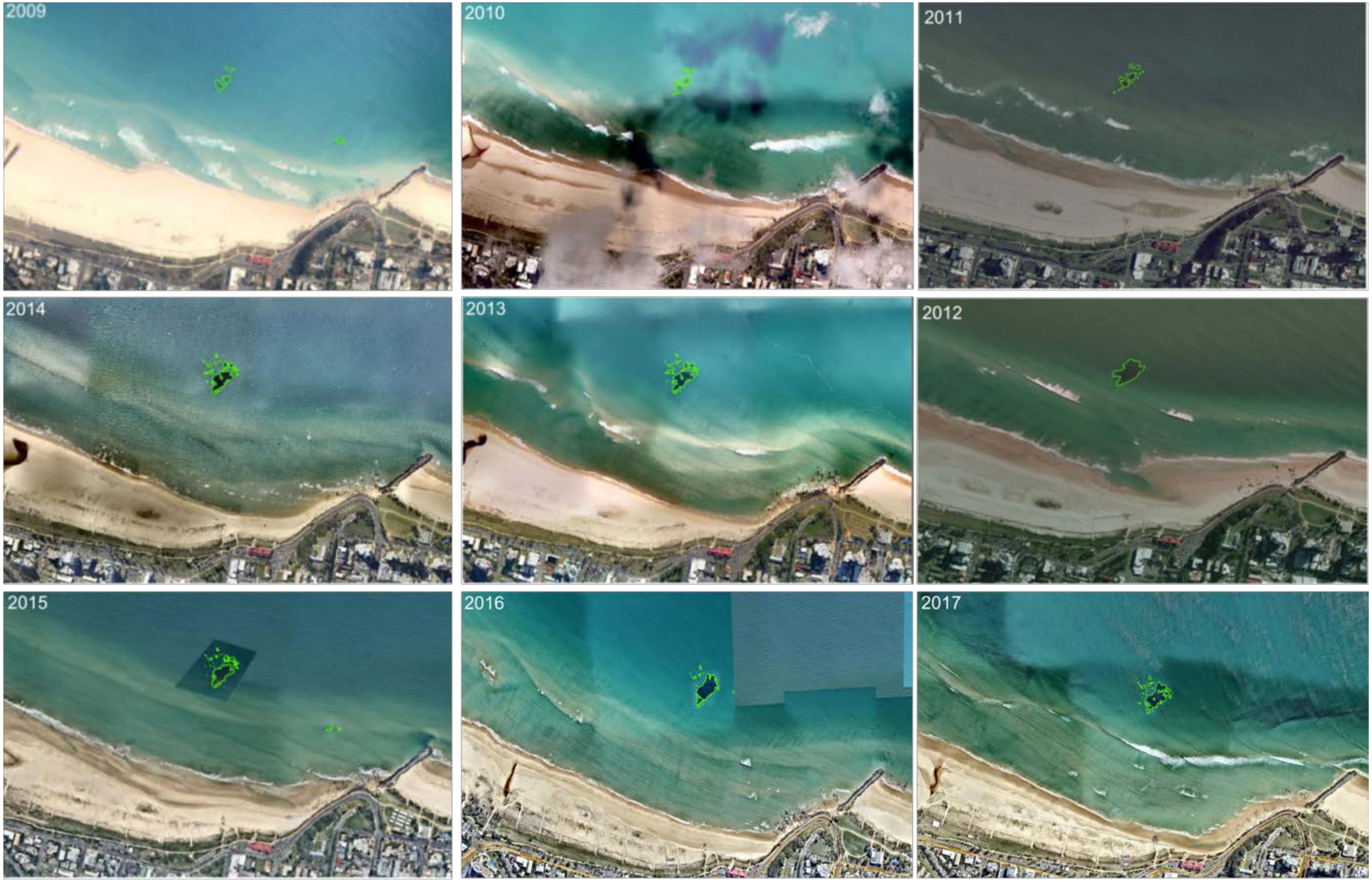


Figure 3.54 Extent of Kirra Reef between 2009 to 2017.

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	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]

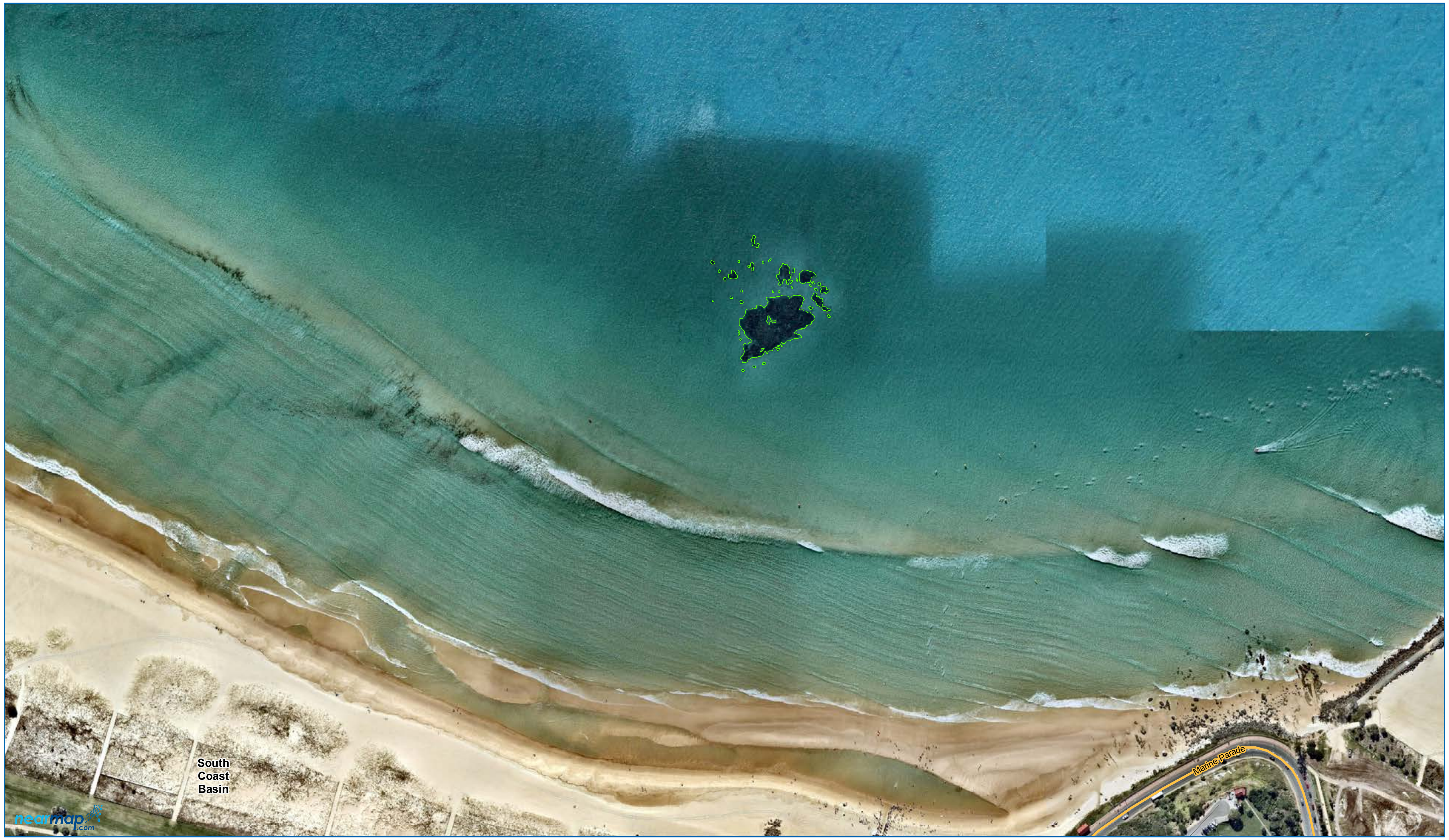
[1] Area of Kirra Reef between 1962 and 1965 ranged from 4 850 to 7 800 in the northern reef; 0 to 4 900 in the southern reef; and 600 to 2 150 in the eastern reef, with a total range between 7 000 and 13 300 (Department of Land and Water Conservation, photogrammetric analysis).

[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.



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Kirra Reef Biota Monitoring 2018

Map 1 Extent of Kirra Reef in May 2018

SOURCES
© Copyright Commonwealth of Australia (Geoscience Australia) 2001, 2004, 2006, 2017
© Nearmap 2017

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LEGEND

Reef Extent
May 2018

Road Network
Highway
Local Road

N

SCALE
0 0.075 0.15
Kilometres
Scale: 1:3 000 @ A3

PROJECTION
Coordinate System: GDA 1994 Zone 56
Datum: GDA 1994
Units: Degree

DATE
2018-06-19

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4 Discussion

The benthic assemblage of Kirra Reef is characterised by a high cover of macroalgae and a moderate cover of sessile benthic invertebrates, at times including a few small soft and hard corals (Edwards and Smith 2005). The benthic assemblage at Kirra Reef has experienced significant change over time, due to storms and changes in sand supply.

4.1 Changes in Biodiversity and Cover at Kirra Reef

Turf and Macroalgae

Macroalgae cover continues to dominate communities at Kirra Reef, with a higher cover of *Sargassum* sp. compared to other reefs. 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. These conditions favour *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 2018, macroalgae cover was lower than in 2017, which may have been a result of storm activity in 2017 (frc environmental, pers. obs.).

Turf algae can out-compete other taxa, often thriving under harsh conditions (nutrient pollution, sedimentation and ocean acidification) (frc environmental 2005, Harris 2015). However, the cover of turf algae commonly varies with time (Mumby 2009). Macroalgal communities are also known to have a competitive advantage following disturbance, but also experience seasonal changes due to abiotic conditions (Clifton and Clifton 1999), disturbances and propagule supply and recruitment (Vroom et al. 2003). Grazing by fish has also been linked to reduced macroalgal cover and can be seasonal with grazing peaking in the warmer months (Duran et al. 2016). The cover of macroalgae has varied between 18 and 32% 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%). The cover of turf algae was also lower in 2018 than in the previous survey.

Benthic Invertebrates

There was lower cover of sponges, but a higher cover of ascidians recorded in 2018 than in 2017. The higher cover of sessile benthic organisms is likely related to the lower cover of macroalgae and turf algae, which can affect recruitment and survival due to fronds 'sweeping' the substrate with wave action, killing new recruits (McCook et al. 2001).

The percent cover of hard and soft corals at Kirra Reef continues to be very low. Small colonies of hard coral were recorded in 2016 (Ecosure 2016); but not observed in 2017 and this may have been a result of sediment deposition. However, small isolated colonies were recorded in the current survey. 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 frequent disturbance.

Overall, the sites at Cook Island and Palm Beach Reef are dominated by fewer taxa of benthic invertebrates than at Kirra Reef. More diverse communities are indicative of disruptions (e.g. wave disturbance and sand coverage) that prevent the establishment of a few dominant groups (frc environmental 2015). 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. Although Palm Beach Reef had twice the coverage of ascidians and more turf algae coverage than Kirra Reef, it also was able to maintain significantly more anemone, hard coral and soft coral than Kirra Reef.

Fishes

The number of species from different trophic guilds was similar 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 across all reefs however their abundance was notably less. Abundances of planktivores at Kirra Reef were greatest in 2018, as has been the case in previous surveys (Ecosure 2016, frc environmental 2017). Large schools of yellowtail (*Trachurus novaezelandiae*) contributed to the disparity between trophic guilds.

Kirra Reef, Palm Beach 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 (18-30 species). Species with tropical ranges were the next most specieos (14-27 species) followed by temperate species (3-11). Considering a globally warming climate this disparity could be expected to increase over future monitoring events.

Overall, the number of species at Kirra Reef was only slightly lower than at Palm Beach Reef, however these reefs offer varying types and qualities of habitat and aren't a direct comparison. Species abundances at Cook Island North was notably higher, but again can't be directly compared due to protection of this site in the Reserve, different habitat type and quality, and shelter from wave energy afforded at this site.

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 and Stevens 2014, McClanahan 2014), which can lead to increased macroalgae herbivory and the potential for coral growth (Rasher et al. 2013, Stockwell et al. 2009). Analyses from the 2017 monitoring event indicate that the 'no take' zone has no obvious impact on the species richness of herbivorous fish, and this is reflected by low species abundance again during the 2018 monitoring. Studies from the Great Barrier Reef demonstrate the importance of no-take zones for the recruitment of large predatory species (Harrison et al. 2012). As in previous years, fish species commonly targeted by recreational anglers, along with other carnivorous species, were notably more abundant at the Cook Island reefs compared to Kirra Reef (Table B1). These included:

- black spot snapper (*Lutjanus fulviflamma*)
- yellowtail kingfish (*Seriola lalandi*)
- red bass (*Lutjanus bohar*)
- queenfish (*Scomberoides* sp.)
- blue groper (*Achoerodus viridis*)
- thicklip trevally (*Carangoides orthogrammus*), and
- yellow-fin bream (*Acanthopagrus australis*).

Discarded fishing line and litter is present 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 greater wave intensity than Kirra Reef; and the reefs of Cook Island are more sheltered from wave action than Kirra Reef and sheltered by the island. 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 and 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 1995b, Fisheries Research Consultants 1995c, Fisheries Research Consultants 1996, frc environmental 2003, frc environmental 2004, frc environmental 2005, frc environmental 2010). During 2018 monitoring, no freshly exposed rock was observed. This is likely due to relatively calm weather conditions experienced since May 2017.

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[6]
- 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.

[6] Although there are very few records from Queensland

No marine pest species were observed during the monitoring in May 2018. 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 remain in a near-constant flux. Hard and soft coral cover is typically very low.

Large schools of yellowtail dominate the reef's fish communities, with striped sea pike, mado and neon damselfish also relatively 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 six 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.

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Appendix A Detailed Statistical Analyses

Benthic Communities at Kirra Reef, Palm Beach Reef and Cook Island in 2018

Table A.1 Similarity percentage analysis (SIMPER) of dissimilarity of benthic communities at Kirra 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.%
	Cook Island West	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 51.46				
Ascidian	4.57	7.57	18.25	18.25
Turf Algae	4.61	3.82	15.99	34.24
Dictyotaceae	2.99	0.32	14.15	48.39
Branching coral	1.79	1.03	9.61	58.00
Soft coral	2.74	2.91	6.15	64.16
Corallinaceae	0.98	0.47	5.60	69.76
Anemone	1.03	0.40	5.41	75.16
Sand	0.68	0.52	4.82	79.99
Encrusting coral	0.74	0.43	4.60	84.58
Sponges	0.48	0.09	2.45	87.04
Rhodomelaceae	0.23	0.27	2.15	89.19

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island North	Kirra		
Cook Island North versus Kirra, Average dissimilarity = 59.31				
Ascidian	4.83	4.42	11.88	11.88
Dictyotaceae	2.34	2.62	11.48	23.35
Corallinaceae	1.60	3.61	11.45	34.80
Turf algae	3.01	3.62	9.34	44.14
Branching coral	2.18	0.00	8.18	52.33
Sand	0.33	1.74	6.78	59.11
Sargassaceae	0.00	1.51	5.81	64.92
Rhodomelaceae	1.21	0.48	5.36	70.27
Crinoid	0.17	1.12	4.33	79.93
Anemone	1.02	0.28	4.26	84.19
Encrusting coral	0.85	0.03	3.27	87.46
Sponges	0.39	0.42	2.65	90.11

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island West	Kirra		
Cook Island West versus Kirra, Average dissimilarity = 56.12				
Ascidian	4.57	4.42	12.92	12.92
Corallinaceae	1.03	3.61	12.37	25.29
Dictyotaceae	2.99	2.62	12.07	37.36
Turf algae	4.61	3.62	11.84	49.20
Sand	0.74	1.74	7.94	57.14
Branching coral	1.79	0.00	7.08	64.22
Sargassaceae	0.00	1.51	6.25	76.85
Crinoid	0.30	1.12	4.88	81.73
Soft coral	0.98	0.05	3.96	85.69
Anemone	0.68	0.28	3.34	89.03

Genus	Average Abundance		Contrib%	Cum.%
	Palm Beach	Kirra		
Palm Beach versus Kirra, Average dissimilarity = 58.14				
Ascidian	7.57	4.42	16.93	16.93
Corallinaceae	0.40	3.61	14.01	30.94
Turf algae	3.82	3.62	12.34	43.28
Dictyotaceae	0.32	2.62	11.18	54.46
Sand	0.43	1.74	7.62	62.08
Sargassaceae	0.00	1.51	6.50	75.60
Crinoid	0.03	1.12	4.67	80.26
Branching coral	1.03	0.00	4.24	84.50
Anemone	0.52	0.28	2.93	87.43
Rhodomelaceae	0.25	0.48	2.76	90.19

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island North	Palm Beach		
Cook Island North versus Palm Beach, Average dissimilarity = 53.61				
Ascidian	4.83	7.57	16.14	16.14
Turf algae	3.01	3.82	13.31	29.45
Dictyotaceae	2.34	0.32	10.70	40.14
Branching coral	2.18	1.03	10.43	50.57
Corallinaceae	1.60	0.40	7.31	57.87
Anemone	1.02	0.52	5.81	63.68
Rhodomelaceae	1.21	0.25	5.51	69.19
Encrusting coral	0.85	0.09	4.07	78.40
Soft coral	0.38	0.47	3.23	81.63
Sand	0.33	0.43	2.81	84.44
Foliose coral	0.59	0.00	2.76	87.19
Sponges	0.39	0.27	2.66	89.85

Genus	Average Abundance		Contrib%	Cum.%
	Cook Island North	Cook Island West		
Cook Island West versus Cook Island North, Average dissimilarity = 54.13				
Dictyotaceae	2.34	2.99	13.42	13.42
Turf algae	3.01	4.61	13.06	26.48
Ascidian	4.83	4.57	12.49	38.97
Branching coral	2.18	1.79	9.92	48.89
Corallinaceae	1.60	1.03	7.67	56.56
Anemone	1.02	0.68	5.64	62.20
Rhodomelaceae	1.21	0.18	5.02	67.22
Encrusting coral	0.85	0.48	4.73	71.95
Soft coral	0.38	0.98	4.70	76.64
Sand	0.33	0.74	3.79	85.12
Foliose coral	0.59	0.25	3.36	88.48
Sponges	0.39	0.23	2.33	90.81

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)[g]	Unique permutations
2017, 2001	7.1853	**0.0001**	0.0001
2017, 2003	0.29616	0.7675	0.7695
2017, 2004	0.67547	0.4994	0.4967
2017, 2005	1.3033	0.1905	0.1991
2017, 1995A	0.92561	0.3547	0.358
2017, 1996F	3.0143	**0.0052**	0.0038
2017, 1995J	3.3524	**0.0016**	0.0017
2017, 2010	2.306	**0.0233**	0.0219
2017, 2012	1.3173	0.1965	0.1891
2017, 2014	1.5415	0.1241	0.1299
2017, 2015	1.2555	0.2154	0.2141
2017, 2016	2.6332	**0.0102**	0.01
2017, 2018	0.69456	0.4876	0.4835
2001, 2003	6.7448	**0.0001**	0.0001
2001, 2004	6.6434	**0.0001**	0.0001
2001, 2005	9.3437	**0.0001**	0.0001
2001, 1995A	7.5411	**0.0001**	0.0001
2001, 1996F	2.4938	**0.0118**	0.0157
2001, 1995J	3.2719	**0.001**	0.0016
2001, 2010	11.551	**0.0001**	0.0001
2001, 2012	8.5421	**0.0001**	0.0001
2001, 2014	7.3465	**0.0001**	0.0001
2001, 2015	6.6868	**0.0001**	0.0001
2001, 2016	5.3875	**0.0001**	0.0001
2001, 2018	7.6542	**0.0001**	0.0001
2003, 2004	0.36308	0.7207	0.7169
2003, 2005	1.6018	0.1058	0.1196
2003, 1995A	0.56876	0.5679	0.5776

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

Groups	t	P(perm)[g]	Unique permutations
2003, 1996F	2.7432	**0.0077**	0.0071
2003, 1995J	3.0222	**0.0027**	0.0039
2003, 2010	2.6121	0.0103	0.0099
2003, 2012	1.5932	0.1156	0.1094
2003, 2014	1.1558	0.2481	0.2467
2003, 2015	0.90971	0.3634	0.3624
2003, 2016	2.2561	**0.0275**	0.0272
2003, 2018	1.0022	0.3207	0.3142
2004, 2005	2.0706	0.0427	0.0431
2004, 1995A	0.1688	0.8661	0.8655
2004, 1996F	2.5117	**0.0165**	0.0127
2004, 1995J	2.7712	**0.0063**	0.006
2004, 2010	3.1918	**0.002**	0.0026
2004, 2012	2.0157	**0.0503**	0.0473
2004, 2014	0.76969	0.4415	0.4462
2004, 2015	0.54332	0.5923	0.5779
2004, 2016	1.9218	**0.0581**	0.0571
2004, 2018	1.3874	0.1692	0.1696
2005, 1995A	2.5744	**0.0113**	0.0127
2005, 1996F	4.2083	**0.0002**	0.0001
2005, 1995J	4.8588	**0.0001**	0.0001
2005, 2010	0.97534	0.3244	0.3319
2005, 2012	0.13084	0.8942	0.898
2005, 2014	3.3677	**0.0018**	0.002
2005, 2015	2.8409	**0.0062**	0.0062
2005, 2016	4.3574	**0.0001**	0.0001
2005, 2018	0.56883	0.5657	0.5682
1995A, 1996F	2.5836	**0.0113**	0.0115
1995A, 1995J	2.9432	**0.0049**	0.0051
1995A, 2010	4.0432	**0.0001**	0.0002
1995A, 2012	2.4288	**0.0198**	0.0181
1995A, 2014	0.71824	0.4905	0.4681

Groups	t	P(perm)[g]	Unique permutations
1995A, 2015	0.44562	0.6509	0.6558
1995A, 2016	1.9959	**0.0489**	0.0504
1995A, 2018	1.5792	0.1141	0.1114
1996F, 1995J	0.18023	0.8561	0.8592
1996F, 2010	5.1325	**0.0001**	0.0001
1996F, 2012	4.0768	**0.0002**	0.0001
1996F, 2014	2.2174	**0.0299**	0.0283
1996F, 2015	2.2158	**0.027**	0.0309
1996F, 2016	1.2907	0.2006	0.1997
1996F, 2018	4.2424	**0.0003**	0.0001
1995J, 2010	6.1421	**0.0001**	0.0001
1995J, 2012	4.5997	**0.0002**	0.0001
1995J, 2014	2.5212	0.0136	0.0143
1995J, 2015	2.4598	**0.0158**	0.0186
1995J, 2016	1.2906	0.2035	0.2054
1995J, 2018	4.242	**0.0001**	0.0001
2010, 2012	0.71749	0.4773	0.4686
2010, 2014	5.1185	**0.0001**	0.0001
2010, 2015	4.2175	**0.0002**	9813
2010, 2016	5.8376	**0.0001**	9833
2010, 2018	1.3754	0.1673	9810
2012, 2014	3.1034	0.0029	9566
2012, 2015	2.6884	**0.0091**	9760
2012, 2016	4.1165	**0.0003**	9831
2012, 2018	0.68349	0.4992	9824
2014, 2015	0.19099	0.855	9701
2014, 2016	1.4309	0.151	9815
2014, 2018	2.1075	0.0368	9836
2015, 2016	1.4688	0.1433	9856
2015, 2018	1.9217	**0.0589**	9824
2016, 2018	3.4536	**0.001**	9839

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

Groups	t	P(perm)[h]	Unique perms
2017, 2001	0.12606	0.8958	9814
2017, 2003	0.31942	0.7522	9832
2017, 2004	7.7145	**0.0001**	9827
2017, 2005	5.8055	**0.0001**	9841
2017, 1995A	2.9185	**0.0051**	9792
2017, 1996F	1.2778	0.2027	9815
2017, 1995J	2.0285	0.0433	9820
2017, 2010	5.7666	**0.0001**	9831
2017, 2012	12.186	**0.0001**	9806
2017, 2014	8.0749	**0.0001**	9825
2017, 2015	7.8022	**0.0001**	9823
2017, 2016	11.996	**0.0001**	9828
2017, 2018	4.2607	**0.0001**	9841
2001, 2003	0.46419	0.6463	3169
2001, 2004	8.4607	**0.0001**	7771
2001, 2005	6.4033	**0.0001**	8385
2001, 1995A	3.2089	**0.0023**	1708
2001, 1996F	1.5311	0.1284	1956
2001, 1995J	2.0532	0.0435	7073
2001, 2010	6.3111	**0.0001**	9831
2001, 2012	13.225	**0.0001**	9803
2001, 2014	8.8177	**0.0001**	9842
2001, 2015	8.382	**0.0001**	9769
2001, 2016	13.542	**0.0001**	9847
2001, 2018	4.2383	**0.0001**	9856
2003, 2004	7.6711	**0.0001**	8969
2003, 2005	5.8498	**0.0001**	9209
2003, 1995A	3.1296	**0.0033**	3978
2003, 1996F	0.8882	0.3744	4678

[h] Bold p values denotes significance at p<0.05

Groups	t	P(perm)[h]	Unique perms
2003, 1995J	2.2505	0.0283	8475
2003, 2010	5.8213	**0.0001**	9855
2003, 2012	11.97	**0.0001**	9836
2003, 2014	8.0228	**0.0001**	9819
2003, 2015	7.7937	**0.0001**	9811
2003, 2016	11.69	**0.0001**	9834
2003, 2018	4.596	**0.0001**	9850
2004, 2005	2.8227	**0.0048**	9657
2004, 1995A	7.6177	**0.0001**	8325
2004, 1996F	9.6755	**0.0001**	9075
2004, 1995J	4.4968	**0.0001**	9431
2004, 2010	2.5221	0.0115	9825
2004, 2012	5.8999	**0.0001**	9837
2004, 2014	0.63897	0.5227	9823
2004, 2015	0.98349	0.3294	9792
2004, 2016	3.2272	0.0015	9828
2004, 2018	4.2073	**0.0001**	9837
2005, 1995A	4.9151	**0.0001**	7472
2005, 1996F	7.7725	**0.0001**	9415
2005, 1995J	2.6822	0.0092	9582
2005, 2010	0.18445	0.8512	9846
2005, 2012	8.7298	**0.0001**	9812
2005, 2014	3.4007	**0.0014**	9822
2005, 2015	3.4333	**0.0011**	9846
2005, 2016	7.2666	**0.0001**	9842
2005, 2018	1.7799	0.0789	9857
1995A, 1996F	4.8876	**0.0001**	2479
1995A, 1995J	0.019351	0.9842	6200
1995A, 2010	4.774	**0.0001**	9811
1995A, 2012	13.394	**0.0001**	9813
1995A, 2014	8.0253	**0.0001**	9821
1995A, 2015	7.3455	**0.0001**	9822

Groups	t	P(perm)[h]	Unique perms
1995A, 2016	14.987	**0.0001**	9825
1995A, 2018	1.6482	0.1009	9805
1996F, 1995J	3.2442	0.0018	8213
1996F, 2010	7.6493	**0.0001**	9806
1996F, 2012	14.177	**0.0001**	9815
1996F, 2014	9.9957	**0.0001**	9815
1996F, 2015	9.5085	**0.0001**	9816
1996F, 2016	14.742	**0.0001**	9826
1996F, 2018	5.8555	**0.0001**	9839
1995J, 2010	2.7422	0.0079	9816
1995J, 2012	8.7348	**0.0001**	9831
1995J, 2014	4.8895	**0.0001**	9844
1995J, 2015	4.9058	**0.0001**	9790
1995J, 2016	7.5664	**0.0001**	9854
1995J, 2018	1.4338	0.151	9827
2010, 2012	8.2615	**0.0001**	9836
2010, 2014	3.09	**0.0032**	9837
2010, 2015	3.1703	**0.0022**	9828
2010, 2016	6.5948	**0.0001**	9823
2010, 2018	1.9199	**0.057**	9805
2012, 2014	5.1697	**0.0001**	9810
2012, 2015	4.3358	**0.0001**	9848
2012, 2016	4.5364	**0.0001**	9844
2012, 2018	10.098	**0.0001**	9840
2014, 2015	0.40185	0.6922	9826
2014, 2016	2.2799	0.0222	9841
2014, 2018	4.7888	**0.0001**	9854
2015, 2016	1.4737	0.1459	9849
2015, 2018	5.0881	**0.0001**	9801
2016, 2018	7.5137	**0.0001**	9836

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

Groups	t	P(perm)[i]	Unique permutations
2017, 2001	0		
2017, 2003	0		
2017, 2004	1.6518	0.236	4
2017, 2005	1.354	0.49	2
2017, 1995A	2.9428	**0.004**	18
2017, 1996F	1.7728	0.222	2
2017, 1995J	0		
2017, 2010	1	1	1
2017, 2012	0		
2017, 2014	0		
2017, 2015	1	1	1
2017, 2016	0		
2017, 2018	4.6471	**0.001**	997
2001, 2003	0		
2001, 2004	1.6518	0.222	4
2001, 2005	1.354	0.488	2
2001, 1995A	2.9428	**0.006**	18
2001, 1996F	1.7728	0.254	2
2001, 1995J	0		
2001, 2010	1	1	1
2001, 2012	0		
2001, 2014	0		
2001, 2015	1	1	1
2001, 2016	0		
2001, 2018	4.6471	**0.001**	996
2003, 2004	1.6518	0.246	4
2003, 2005	1.354	0.485	2
2003, 1995A	2.9428	**0.001**	17
2003, 1996F	1.7728	0.241	2

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

Groups	t	P(perm)[i]	Unique permutations
2003, 1995J	0		
2003, 2010	1	1	1
2003, 2012	0		
2003, 2014	0		
2003, 2015	1	1	1
2003, 2016	0		
2003, 2018	4.6471	**0.001**	997
2004, 2005	0.41319	0.801	12
2004, 1995A	1.072	0.273	67
2004, 1996F	0.45315	0.747	12
2004, 1995J	1.6518	0.261	4
2004, 2010	1.343	0.385	6
2004, 2012	1.6518	0.225	4
2004, 2014	1.6518	0.254	4
2004, 2015	1.4652	0.222	8
2004, 2016	1.8449	0.092	8
2004, 2018	3.678	**0.001**	996
2005, 1995A	1.5476	0.118	42
2005, 1996F	0		
2005, 1995J	1.354	0.507	2
2005, 2010	0.98587	0.483	4
2005, 2012	1.354	0.489	2
2005, 2014	1.354	0.516	2
2005, 2015	1.1294	0.513	4
2005, 2016	1.5123	0.21	4
2005, 2018	3.9846	**0.001**	997
1995A, 1996F	1.6778	0.082	40
1995A, 1995J	2.9428	**0.005**	18
1995A, 2010	2.6307	**0.013**	20
1995A, 2012	2.9428	**0.002**	18
1995A, 2014	2.9428	**0.005**	18
1995A, 2015	2.7608	**0.003**	36

Groups	t	P(perm)[i]	Unique permutations
1995A, 2016	3.2868	**0.002**	34
1995A, 2018	2.8622	**0.003**	995
1996F, 1995J	1.7728	0.221	2
1996F, 2010	1.2502	0.256	4
1996F, 2012	1.7728	0.249	2
1996F, 2014	1.7728	0.261	2
1996F, 2015	1.4585	0.268	4
1996F, 2016	1.9801	0.108	4
1996F, 2018	4.0204	**0.001**	998
1995J, 2010	1	1	1
1995J, 2012	0		
1995J, 2014	0		
1995J, 2015	1	1	1
1995J, 2016	0		
1995J, 2018	4.6471	**0.001**	996
2010, 2012	1	1	1
2010, 2014	1	1	1
2010, 2014	3.09	**0.0032**	9837
2010, 2015	3.1703	**0.0022**	9828
2010, 2016	6.5948	**0.0001**	9823
2010, 2018	1.9199	**0.057**	9805
2012, 2014	5.1697	**0.0001**	9810
2012, 2015	4.3358	**0.0001**	9848
2012, 2016	4.5364	**0.0001**	9844
2012, 2018	10.098	**0.0001**	9840
2014, 2015	0.40185	0.6922	9826
2014, 2016	2.2799	0.0222	9841
2014, 2018	4.7888	**0.0001**	9854
2015, 2016	1.4737	0.1459	9849
2015, 2018	5.0881	**0.0001**	9801
2016, 2018	7.5137	**0.0001**	9836

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

Groups	t	P(perm)[j]	Unique perms
2017, 2001	1	1	1
2017, 2003	2.6605	**0.005**	90
2017, 2004	2.9421	**0.0018**	70
2017, 2005	1.0965	0.3648	6
2017, 1995A	2.7042	**0.0095**	48
2017, 1996F	3.3314	**0.0006**	741
2017, 1995J	1.081	0.49	5
2017, 2010	1	1	1
2017, 2012	1	1	1
2017, 2014	0.08607	1	2
2017, 2015	1	1	1
2017, 2016	1.1169	0.4388	2
2017, 2018	2.3381	**0.0202**	9595
2001, 2003	2.8669	**0.0061**	45
2001, 2004	3.2577	**0.0013**	35
2001, 2005	1.751	0.2464	3
2001, 1995A	3.1394	**0.0026**	24
2001, 1996F	3.4966	**0.0003**	377
2001, 1995J	1.6648	0.2453	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	2.6888	**0.0087**	9483
2003, 2004	0.43014	0.6662	551
2003, 2005	2.1816	**0.031**	150
2003, 1995A	1.0112	0.3165	449
2003, 1996F	0.94083	0.3559	3394

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

Groups	**t**	**P(perm)[j]**	**Unique perms**
2003, 1995J	2.136	**0.0375**	117
2003, 2010	2.8669	**0.0053**	45
2003, 2012	2.8669	**0.0046**	45
2003, 2014	2.6877	**0.0056**	90
2003, 2015	2.8669	**0.0063**	45
2003, 2016	3.2021	**0.0009**	90
2003, 2018	2.0111	**0.0432**	9823
2004, 2005	2.2395	**0.0331**	53
2004, 1995A	0.69059	0.4959	160
2004, 1996F	1.412	0.1655	896
2004, 1995J	2.1687	0.0336	60
2004, 2010	3.2577	**0.0013**	35
2004, 2012	3.2577	**0.0016**	35
2004, 2014	2.9855	**0.0028**	42
2004, 2015	3.2577	**0.0007**	35
2004, 2016	3.6386	**0.0003**	70
2004, 2018	1.4563	0.1396	9795
2005, 1995A	1.7957	0.0861	42
2005, 1996F	2.9407	**0.0025**	508
2005, 1995J	0.052815	1	9
2005, 2010	1.751	0.2449	3
2005, 2012	1.751	0.2407	3
2005, 2014	1.1764	0.3669	5
2005, 2015	1.751	0.2384	3
2005, 2016	1.9557	0.0843	6
2005, 2018	1.5293	0.1289	9685
1995A, 1996F	1.948	**0.0563**	1129
1995A, 1995J	1.7094	0.099	40
1995A, 2010	3.1394	**0.002**	24
1995A, 2012	3.1394	**0.003**	24
1995A, 2014	2.7644	**0.0097**	28
1995A, 2015	3.1394	**0.0036**	24

Groups	t	P(perm)[j]	Unique perms
1995A, 2016	3.5064	**0.0006**	48
1995A, 2018	0.51044	0.6116	9771
1996F, 1995J	2.9017	**0.0037**	543
1996F, 2010	3.4966	**0.0004**	377
1996F, 2012	3.4966	**0.0003**	378
1996F, 2014	3.3533	**0.0004**	426
1996F, 2015	3.4966	**0.0001**	377
1996F, 2016	3.9054	**0.0001**	727
1996F, 2018	3.6389	**0.0008**	9846
1995J, 2010	1.6648	0.2431	3
1995J, 2012	1.6648	0.2444	3
1995J, 2014	1.1528	0.4934	3
1995J, 2015	1.6648	0.2487	3
1995J, 2016	1.8595	0.0818	5
1995J, 2018	1.4694	0.14	9656
2010, 2012	Denominator is 0		
2010, 2014	1	1	1
2010, 2015	Denominator is 0		
2010, 2016	Denominator is 0		
2010, 2018	2.6888	**0.0088**	9481
2012, 2014	1	1	1
2012, 2015	Denominator is 0		
2012, 2016	Denominator is 0		
2012, 2018	2.6888	**0.0092**	9493
2014, 2015	1	1	1
2014, 2016	1.1169	0.4517	2
2014, 2018	2.3809	**0.018**	9560
2015, 2016	Denominator is 0		
2015, 2018	2.6888	**0.0088**	9467
2016, 2018	3.0002	**0.0027**	9732

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

Groups	t	P(perm)[k]	Unique perms
2017, 2001	2.8024	**0.006**	9714
2017, 2003	2.2341	**0.0296**	9827
2017, 2004	5.4884	**0.0001**	9849
2017, 2005	1.2904	0.1966	9806
2017, 1995A	1.8462	0.0727	9781
2017, 1996F	2.424	**0.0208**	9824
2017, 1995J	3.6778	**0.0006**	9566
2017, 2010	4.4439	**0.0001**	9654
2017, 2012	2.5548	**0.0118**	9782
2017, 2014	0.61686	0.533	9811
2017, 2015	1.5135	0.134	9826
2017, 2016	0.30241	0.7523	9816
2017, 2018	6.0987	**0.0001**	9822
2001, 2003	4.5527	**0.0001**	5040
2001, 2004	8.7146	**0.0001**	5681
2001, 2005	1.6673	0.0984	379
2001, 1995A	1.2284	0.2342	191
2001, 1996F	4.4982	**0.0001**	4830
2001, 1995J	0.62785	0.562	55
2001, 2010	1.4683	0.1356	80
2001, 2012	0.24116	0.8249	465
2001, 2014	2.4256	**0.0165**	474
2001, 2015	4.7839	**0.0001**	2257
2001, 2016	3.6008	**0.0005**	9850
2001, 2018	1.2381	0.2112	9249
2003, 2004	2.3371	**0.0216**	7785
2003, 2005	3.3668	**0.002**	5122
2003, 1995A	3.8432	**0.0005**	4931
2003, 1996F	0.34675	0.7324	8977

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

Groups	t	P(perm)[k]	Unique perms
2003, 1995J	5.2439	**0.0001**	4516
2003, 2010	5.7924	**0.0001**	5979
2003, 2012	4.354	**0.0001**	7213
2003, 2014	2.8377	**0.007**	6621
2003, 2015	1.1395	0.2617	8759
2003, 2016	2.9992	**0.0031**	9826
2003, 2018	9.3913	**0.0001**	9835
2004, 2005	7.1656	**0.0001**	5738
2004, 1995A	7.967	**0.0001**	5670
2004, 1996F	1.7541	0.0857	9103
2004, 1995J	10.147	**0.0001**	5316
2004, 2010	11.022	**0.0001**	6792
2004, 2012	8.4109	**0.0001**	7642
2004, 2014	6.5052	**0.0001**	7115
2004, 2015	4.3872	**0.0001**	8971
2004, 2016	7.4247	**0.0001**	9836
2004, 2018	16.815	**0.0001**	9833
2005, 1995A	0.54883	0.5973	449
2005, 1996F	3.4398	**0.0012**	6022
2005, 1995J	2.5601	**0.015**	237
2005, 2010	3.4468	**0.0008**	405
2005, 2012	1.4038	0.1682	1323
2005, 2014	0.74555	0.4605	964
2005, 2015	3.0796	**0.0026**	3092
2005, 2016	1.449	0.1449	9831
2005, 2018	4.0956	**0.0006**	9696
1995A, 1996F	3.8568	**0.0002**	5701
1995A, 1995J	2.1609	**0.0407**	126
1995A, 2010	3.1556	**0.0021**	194
1995A, 2012	0.95167	0.3425	686
1995A, 2014	1.3436	0.1805	525
1995A, 2015	3.8146	**0.0005**	2325

Groups	t	P(perm)[k]	Unique perms
1995A, 2016	2.2781	**0.0237**	9814
1995A, 2018	3.3593	**0.0014**	9564
1996F, 1995J	5.0742	**0.0001**	3372
1996F, 2010	5.5445	**0.0001**	6240
1996F, 2012	4.324	**0.0002**	8205
1996F, 2014	2.9648	**0.0042**	7226
1996F, 2015	1.4353	0.1478	8390
1996F, 2016	3.1503	**0.0022**	9832
1996F, 2018	9.3258	**0.0001**	9829
1995J, 2010	1.1184	0.2727	42
1995J, 2012	0.89628	0.3875	247
1995J, 2014	3.438	**0.0007**	311
1995J, 2015	6.1199	**0.0001**	1389
1995J, 2016	5.257	**0.0001**	9784
1995J, 2018	0.38169	0.71	9075
2010, 2012	1.7235	0.0894	180
2010, 2014	4.355	**0.0002**	594
2010, 2015	7.1068	**0.0001**	2693
2010, 2016	6.6556	**0.0001**	9803
2010, 2018	0.8873	0.3881	8706
2012, 2014	2.1505	0.0342	1642
2012, 2015	4.4778	**0.0001**	5294
2012, 2016	3.2277	**0.0017**	9844
2012, 2018	1.6362	0.1012	9429
2014, 2015	2.3391	**0.0228**	3966
2014, 2016	0.51182	0.6026	9817
2014, 2018	5.4119	**0.0001**	9727
2015, 2016	2.4058	**0.0174**	9850
2015, 2018	9.5473	**0.0001**	9800
2016, 2018	7.4995	**0.0001**	9847

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

Groups	t	P(perm)	Unique perms
2017, 2001	3.0706	**0.0027**	9834
2017, 2003	0.79666	0.4381	9829
2017, 2004	1.4982	0.138	9825
2017, 2005	1.5427	0.1222	9846
2017, 1995A	6.3352	**0.0001**	9767
2017, 1996F	5.8185	**0.0001**	9795
2017, 1995J	4.9305	**0.0001**	9828
2017, 2010	0.30911	0.7546	9836
2017, 2012	6.3352	**0.0001**	9739
2017, 2014	2.1004	0.0387	9819
2017, 2015	0.27697	0.7838	9838
2017, 2016	1.1614	0.25	9837
2017, 2018	5.333	**0.0001**	9830
2001, 2003	3.717	**0.0005**	9296
2001, 2004	1.8633	0.0646	1163
2001, 2005	6.0567	**0.0001**	6205
2001, 1995A	3.9849	**0.0002**	140
2001, 1996F	3.2292	**0.001**	1846
2001, 1995J	2.1105	0.0352	619
2001, 2010	3.4764	**0.0009**	9843
2001, 2012	3.9849	**0.0002**	140
2001, 2014	6.4096	**0.0001**	7582
2001, 2015	3.2292	**0.0022**	4403
2001, 2016	3.1169	**0.0027**	9839
2001, 2018	9.3004	**0.0001**	9826
2003, 2004	2.2673	0.0277	9424
2003, 2005	0.47038	0.6441	9666
2003, 1995A	6.637	**0.0001**	7566
2003, 1996F	6.1868	**0.0001**	9596

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

Groups	t	P(perm)	Unique perms
2003, 1995J	5.4101	**0.0001**	9321
2003, 2010	1.192	0.2336	9826
2003, 2012	6.637	**0.0001**	7602
2003, 2014	1.0269	0.3103	9814
2003, 2015	1.1264	0.256	9701
2003, 2016	2.1053	**0.038**	9811
2003, 2018	4.0961	**0.0001**	9826
2004, 2005	3.8408	**0.0005**	6470
2004, 1995A	6.17	**0.0001**	383
2004, 1996F	5.4272	**0.0001**	3189
2004, 1995J	4.1657	**0.0001**	1229
2004, 2010	1.482	0.1436	9818
2004, 2012	6.17	**0.0001**	377
2004, 2014	4.3434	**0.0001**	7486
2004, 2015	1.3965	0.1637	5273
2004, 2016	0.76954	0.4493	9823
2004, 2018	7.4211	**0.0001**	9815
2005, 1995A	13.163	**0.0001**	4473
2005, 1996F	12.018	**0.0001**	9007
2005, 1995J	9.5832	**0.0001**	6462
2005, 2010	2.3747	**0.0228**	9851
2005, 2012	13.163	**0.0001**	4522
2005, 2014	0.81373	0.4129	9220
2005, 2015	2.1594	0.0352	9175
2005, 2016	3.9469	**0.0003**	9828
2005, 2018	3.9206	**0.0003**	9825
1995A, 1996F	2.5426	**0.0269**	10
1995A, 1995J	2.3728	**0.0298**	16
1995A, 2010	8.7297	**0.0001**	9793
1995A, 2012	Denominator is 0		
1995A, 2014	12.418	**0.0001**	6499
1995A, 2015	7.572	**0.0001**	2611

Groups	t	P(perm)	Unique perms
1995A, 2016	9.711	**0.0001**	9835
1995A, 2018	12.584	**0.0001**	9852
1996F, 1995J	1.2379	0.2317	318
1996F, 2010	7.8552	**0.0001**	9815
1996F, 2012	2.5426	0.0272	10
1996F, 2014	11.497	**0.0001**	9234
1996F, 2015	6.8664	**0.0001**	5868
1996F, 2016	8.5423	**0.0001**	9833
1996F, 2018	12.088	**0.0001**	9834
1995J, 2010	6.2075	**0.0001**	9815
1995J, 2012	2.3728	**0.0262**	16
1995J, 2014	9.5411	**0.0001**	7859
1995J, 2015	5.584	**0.0001**	5795
1995J, 2016	6.3918	**0.0001**	9826
1995J, 2018	11.294	**0.0001**	9854
2010, 2012	8.7297	**0.0001**	9769
2010, 2014	2.9869	**0.003**	9796
2010, 2015	0.020421	0.9835	9837
2010, 2016	1.031	0.312	9830
2010, 2018	6.0269	**0.0001**	9826
2012, 2014	12.418	**0.0001**	6547
2012, 2015	7.572	**0.0001**	2633
2012, 2016	9.711	**0.0001**	9807
2012, 2018	12.584	**0.0001**	9829
2014, 2015	2.7524	**0.0077**	9391
2014, 2016	4.5582	**0.0001**	9844
2014, 2018	3.1072	**0.0025**	9842
2015, 2016	0.96773	0.3327	9837
2015, 2018	5.8968	**0.0001**	9834
2016, 2018	7.7449	**0.0001**	9835

Table A.8 Similarity percentage analysis (SIMPER) of dissimilarity of fish communities at Kirra, Palm Beach 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).

Trophic level	**Species**	**Common name**	**Average Abundance**		**Contrib%**	**Cum.%**
			Kirra Reef	**Cook Island North**		
Kirra Reef versus Cook Island North, Average dissimilarity = 74.78%						
CA	*Trachurus novaezelandiae*	yellowtail	11.49	0	17.03	17.03
CA	*Trachinotus blochii*	dart	0	6.08	8.93	25.96
O	*Monodactylus argenteus*	silver batfish	0	2.51	3.78	29.74
O-HT	*Pomacentrus coelestis*	neon damsel	2.24	0.94	3.06	32.8
O	*Thalassoma lutescens*	yellow moon wrasse	0.25	2.07	2.85	35.65
CA	*Sphyraena obtusata*	striped sea pike	1.93	0	2.79	38.44
P	*Scorpis lineolatus*	sweep	2.59	0.67	2.78	41.22
O	*Microcanthus strigatus*	stripey	1.97	0.33	2.51	43.73
O	*Atpichthys strigatus*	mado	1.47	0	2.13	45.86
CA	*Parupeneus multifasciatus*	banded goatfish	0	1.28	1.9	47.76
O	*Abudefduf vaigiensis*	sergeant major	0	1.33	1.85	49.61
H	*Acanthurus nigrofuscus*	whitecheek surgeonfish	1.83	0.67	1.78	51.39

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Kirra Reef	Cook Island West		
Kirra Reef versus Cook Island West, Average dissimilarity = 72.73%						
CA	*Trachurus novaezelandiae*	yellowtail	11.49	0	14.49	14.49
O	*Abedefduf vaigiensis*	sergeant major	0	4.25	5.19	19.69
O	*Monodactylus argenteus*	stripey	0	3.86	4.58	24.27
P	*Naso unicornis*	bluespine unicornfish	0	2.44	3.08	27.34
O-HT	*Pomacentrus coelestis*	neon damselfish	2.24	0.71	2.62	29.97
P	*Scorpis lineolatus*	sweep	2.59	0.5	2.54	32.51
CA	*Sphyraena obtusata*	striped sea pike	1.93	0	2.39	34.89
CA	*Acanthopagrus australis*	yellowfin bream	0.75	2.51	2.17	37.07
O	*Thalassoma lutescens*	yellow moon wrasse	0.25	1.87	2.14	39.21
P	*Chromis margaritifer*	whitetail puller	0.71	2.26	2.04	41.25
O	*Atpichthys strigatus*	mado	1.47	0	1.82	43.07
O	*Amphiprion akindynos*	Barrier Reef anemonefish	0.71	2.08	1.78	44.85
H	*Prionurus microlepidotus*	sawtail surgeon	0	1.58	1.69	46.54
CA	*Seriola lalandi*	yellowtail kingfish	0	1.31	1.69	48.23
CA	*Parupeneus multifasciatus*	banded goatfish	0	1.21	1.55	49.78
O	*Microcanthus strigatus*	stripey	1.97	0.96	1.49	51.27

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Cook Island North	Cook Island West		
Cook Island West versus Cook Island North, Average dissimilarity = 51.92%						
CA	*Trachinotus blochii*	dart	6.08	1.12	8.91	8.91
O	*Abudefduf vaigiensis*	sergeant major	1.33	4.25	5.19	14.1
P	*Naso unicornis*	bluespine unicornfish	0	2.44	4.43	18.53
O	*Monodactylus argenteus*	stripey	2.51	3.86	3.02	21.55
P	*Chromis margaritifer*	whitetail puller	0.67	2.26	2.73	24.28
H	*Prionurus microlepidotus*	sawtail surgeon	0.33	1.58	2.49	26.76
CA	*Acanthopagrus australis*	yellowfin bream	1.15	2.51	2.46	29.22
H	*Dascyllus trimaculatus*	three-spot dascyllus	0.33	1.5	2.33	31.55
P	*Amphiprion akindynos*	Barrier Reef anemonefish	0.94	2.08	2.08	33.63
O	*Abedefduf whitleyi*	Whitley's sergeant	0	1.25	2.02	35.66
H	*Acanthurus nigrofuscus*	sawtail surgeon	0.67	1.3	1.76	37.41
O	*Halichoeres hortulanus*	yellow moon wrasse	0	0.96	1.59	39
CA	*Enchelycore ramosa*	cleaner wrasse	0.94	0.25	1.58	40.58
H	*Acanthurus blochii*	black-spot snapper	0.67	1.12	1.48	42.06
O	*Anampses geographicus*	scribbled wrasse	0.94	0.5	1.45	43.51
O	*Microcanthus strigatus*	stripey	0.33	0.96	1.39	44.9
O-HT	*Pomacentrus coelestis*	neon damselfish	0.94	0.71	1.32	46.22

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Cook Island North	Cook Island West		
C	*Chaetodon flavirostris*	dusky butterflyfish	0	0.75	1.26	47.47
H	*Kyphosus sydenyanus*	silver drummer	0	0.75	1.26	48.73
CA	*Parupeneus spilurus*	black spot goatfish	0	0.75	1.26	49.99
H	*Centropyge vrolikii*	pearly-scaled angelfish	0	0.75	1.26	51.24

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Kirra Reef	Palm Beach		
Kirra Reef versus Palm Beach Reef, Average dissimilarity = 52.70%						
CA	*Trachurus novaezelandiae*	yellowtail	11.49	8.5	8.59	8.59
O	*Monodactylus argenteus*	stripey	0	3.4	5.75	14.34
O	*Labroides dimidiatus*	cleaner wrasse	0.75	2.72	4.11	18.45
P	*Pomacentrus coelestis*	neon damselfish	2.24	1.77	4.1	22.55
O-HT	*Acanthopagrus australis*	yellowfin bream	0.75	2.8	3.84	26.39
P	*Thalassoma lunare*	moon wrasse	0.87	2.32	2.89	29.29
CA	*Atpichthys strigatus*	mado	1.47	0	2.75	32.04
CA	*Scorpis lineolatus*	sweep	2.59	1.21	2.69	34.73
O	*Sphyraena obtusata*	striped sea pike	1.93	1.83	2.49	37.22
P	*Siderea thyrsoidea*	white-eyed moray	0	1.21	2.29	39.51
O	*Acanthurus nigrofuscus*	dusky surgeonfish	1.83	1.43	1.98	41.49
O	*Dascyllus trimaculatus*	three-spot dascyllus	1.12	0.5	1.97	43.46
H	*Abudefduf bengalensis*	Bengal sergeant	0.71	1.12	1.7	45.15
CA	*Stethojulis bandanensis*	red spot wrasse	0.5	1.31	1.65	46.8
CA	*Parupeneus multifasciatus*	banded goatfish	0	0.96	1.63	48.43
O	*Plagiotremus tapeinosoma*	hit and run blenny	0.75	0.87	1.62	50.05

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Cook Island North	Palm Beach		
Cook Island North versus Palm Beach Reef, Average dissimilarity = 72.21%						
CA	*Trachurus novaezelandiae*	yellowtail	0	8.5	12.11	12.11
O	*Trachinotus blochii*	dart	6.08	0	8.66	20.77
O	*Labroides dimidiatus*	cleaner wrasse	0.67	2.72	3.13	23.9
P	*Monodactylus argenteus*	silver batfish	2.51	3.4	3.12	27.02
O-HT	*Thalassoma lutescens*	yellow moon wrasse	2.07	0.25	2.76	29.78
P	*Thalassoma lunare*	moon wrasse	0.67	2.32	2.43	32.21
CA	*Sphyraena obtusata*	striped sea pike	0	1.83	2.42	34.63
CA	*Acanthopagrus australis*	yellowfin bream	1.15	2.8	2.37	37
O	*Stegastes gascoynei*	coral sea gregory	1.63	0.25	2.11	39.11
P	*Microcanthus strigatus*	stripey	0.33	1.57	1.95	41.06
O	*Parupeneus spilurus*	black spot goatfish	0	1.31	1.87	42.92
O	*Pomacentrus coelestis*	neon damsel	0.94	1.77	1.8	44.73
H	*Abudefduf vaigiensis*	sergeant major	1.33	0	1.8	46.52
CA	*Siderea thyrsoidea*	white-eyed moray	0	1.21	1.72	48.25
CA	*Abudefduf bengalensis*	Bengal sergeant	0	1.12	1.56	49.81
O	*Acanthurus nigrofuscus*	dusky surgeonfish	0.67	1.43	1.54	51.35

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Cook Island West	Palm Beach		
Cook Island West versus Palm Beach, Average dissimilarity = 67.10%						
CA	*Trachurus novaezelandiae*	yellowtail	0	8.5	10.91	10.91
O	*Abudefduf vaigiensis*	sergeant major	4.25	0	5.32	16.23
P	*Monodactylus argenteus*	silver batfish	3.86	3.4	3.22	19.46
O	*Naso unicornis*	bluespine unicornfish	2.44	0	3.15	22.61
P	*Labroides dimidiatus*	cleaner wrasse	1	2.72	2.69	25.3
H	*Amphiprion akindynos*	Barrier Reef anemonefish	2.08	0	2.63	27.93
CA	*Chromis margaritifer*	whitetail puller	2.26	0.25	2.52	30.46
H	*Sphyraena obtusata*	striped sea pike	0	1.83	2.2	32.66
P	*Thalassoma lutescens*	yellow moon wrasse	1.87	0.25	2.19	34.85
O	*Prionurus microlepidotus*	sawtail sergeant	1.58	0.71	1.86	36.71
H	*Pomacentrus coelestis*	neon damselfish	0.71	1.77	1.73	38.44
O	*Seriola lalandi*	yellowtail kingfish	1.31	0	1.73	40.17
CA	*Stegastes gascoynei*	coral sea gregory	1.47	0.25	1.69	41.86
H	*Thalassoma lunare*	moon wrasse	1	2.32	1.68	43.54
O	*Dascyllus trimaculatus*	three-spot dascyllus	1.5	0.5	1.58	45.12
O	*Siderea thyrsoidea*	white-eyed moray	0	1.21	1.55	46.67

Trophic level	Species	Common name	Average Abundance		Contrib%	Cum.%
			Cook Island West	Palm Beach		
O-HT	*Trachinotus blochii*	dart	1.12	0	1.45	48.12
C	*Abedefduf whitleyi*	Whitley's sergeant	1.25	0	1.45	49.57
H	*Abudefduf bengalensis*	sergeant major	0	1.12	1.41	50.98

Appendix B Abundance of Fishes at Kirra Reef, Palm Beach Reef and Cook Island in 2018

Table B.1 Fish species at Kirra and Cook Island Reef recorded during the 2018 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	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Acanthuridae												
Acanthurus blochii	ring-tailed surgeon	H	R	TR	2	1	3	3	*	*	*	*
Acanthurus nigricans	whitecheek surgeonfish	H	R	TR	0	1	0	0		*		
Acanthurus nigrofuscus	dusky surgeonfish	H	R	TR	6	0	3	4	**		*	*
Acanthurus pyroferus	mimic surgeonfish	H	R	TR/TE	0	0	0	1				*
Naso unicornis	bluespine unicornfish	P	R	TR	0	4	7	0		*	**	*
Paracanthus hepatus	blue tang	H	R	TR	1	0	1	0	*		*	
Prionurus microlepidotus	sawtail surgeon	H	R	TR	0	0	10	2			**	*
Apogonidae												
Ostorhinchus limenus[x]	Sydney cardinalfish	CA	R	TR/TE	1	1	0	1	*	*		*
Balistidae												
Sufflamen chrysopterus	half-moon triggerfish	CA	R	TR/TE	1	0	0	1	*			*
Blenniidae												
Exallias brevis	leopard blenny	CA	R	TR	0	1	0	1		*		*
Petroscitirtes breviceps	shorthead sabretooth benny	CA	R	TR	1	1	1	0	*	*	*	
Plagiotremus tapeinosoma	hit and run blenny	CA	R	TR/TE	1	2	3	3	*	*	*	*
Carangidae												
Caranx melampygus	bluefin trevally	CA	P	TR/TE	0	0	1	0			*	
Carangoides orthogrammus	thicklip trevally	CA	P	TR/TE	0	0	1	0			*	
Seriola lalandi	yellowtail kingfish	CA	P	TR/TE	0	2	2	0		*	*	
Scomberoides sp.		CA	P	TR/TE	0	8						
Trachinotus blochii	dart	CA	R	TR/TE	0	64	5	0		***	*	
Trachurus novaezelandiae	yellowtail	CA	P	TE	250	0	0	85	****			***
Chaetodontidae												
Chaetodon auriga[x]	threadfin butterflyfish	C	R	TR/TE	1	1	1	1	*	*	*	*
Chaetodon citrinellus	citron butterflyfish	C	R	TR	0	0	1	2			*	*
Chaetodon flavirostris	dusky butterflyfish	C	R	TR/TE	1	0	1	2	*		*	*
Chaetodon lineolatus	lined butterflyfish	C	R	TR/TE	0	1	0	0		*		

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN				Relative abundance			
					Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Chaetodon guentheri	Gunther's butterflyfish	C	R	TE	1	0	0	0	*			
Chaetodon kleinii[x]	brown butterflyfish	C	R	TR/TE	0	0	0	1				*
Chaetodon trifascialis	chevroned Butterflyfish	C	R	TR	0	0	1	0			*	
Chaetodon unimaculatus	teardrop butterflyfish	C	R	TR	0	1	1	0		*	*	
Forcipiger falvissimus	long nosed butterflyfish	C	R	TR	0	0	1	0			*	
Cheilodactylidae												
Cheilodactylus fuscus	red morwong	CA	R	TE	1	0	2	0	*		*	
Cheilodactylus vestitus	crested morwong	CA	R	TE	2	0	0	1	*			*
Cirrhitidae												
Cirrhitichthys oxycephalus	coral hawkfish	CA	R	TR/TE	0	0	0	1				*
Diodontidae												
Diodon hystrix	black-spotted porcupine fish	CA	R	TR/TE	1	0	0	1	*			*
Ephippidae												
Platax teira	tall-fin batfish	O	R	TR/TE	0	0	1	0			*	
Enoplosidae												
Enoplosus armatus[x]	old wife	CA	R	TE	0	1	0	0		*		
Fistularidae												
Fistularia commersonii	smooth flutemouth	CA	R	TR/TE	0	0	0	1				*
Haemulidae												
Diagramma pictum[x]	painted sweetlip	CA	R	TR	0	0	1	0			*	
Plectorhyncus flavomaculatus	gold-spotted sweetlip	CA	R	TR/TE	1	1	2	0	*	*	*	
Hemiscylliidae												
Chiloscyllium punctatum[x]	brownbanded bamboo shark	CA	R	TR	0	0	0	1				*
Kyphosidae												
Kyphosus sydenyanus	silver drummer	H	R	TE	0	0	1	0				*
Labridae												
Achoerodus viridis	blue groper	O	R	TE	0	1	1	0		*	*	
Anampses caeruleopunctatus	diamond wrasse	O	R	TR	0	1	0	0		*		
Anampses geographicus	scribbled wrasse	O	R	TR	0	2	1	0		*	*	

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN				Relative abundance			
					Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Anampses neoguinaicus	black backed wrasse	O	R	TR	0	0	2	2			*	*
Bodianus axillaris	coral pigfish	O	R	TR/TE	0	0	1	0			*	
Cheilio inermis	cigar wrasse	O	R	TR/TE	0	1	1	1		*	*	*
Coris gaimard[x]	clown wrasse	O	R	TR	0	1	1	0		*	*	
Diproctacanthus xanthurus	yellowtail tubelip	O	R	TR	0	0	1	0			*	
Gomphosus varius	bird wrasse	O	R	TR	0	1	0	0		*		
Halichoeres hortulanus	checkerboard wrasse	O	R	TR/TE	0	0	2	0			*	
Hemigymnus melapterus	half and half wrasse	O	R	TR	0	1	0	0		*		
Labroides dimidiatus	cleaner wrasse	O	R	TR/TE	1	1	1	2	*	*	*	*
Macrophayngodon meleagris[x]	eastern leopard wrasse	O	R	TR/TE	0	0	1	0			*	
Notolabrus gymnogensis	crimson-banded wrasse	O	R	TE	2	0	1	1	*		*	*
Pseudolabrus guentheri	Gunthers wrasse	O	R	TR	5	3	2	2	*	*	*	*
Thalassoma amblycephalum	two tone wrasse	O	R	TR/TE	0	0	0	2				*
Thalassoma hardwicke	six-banded wrasse	O	R	TR	0	1	0	0		*		
Thalassoma jansenii	Jansen's wrasse	O	R	TR	1	0	0	2	*			*
Thalassoma lunare	moon wrasse	O	R	TR	3	1	1	7	*	*	*	**
Thalassoma lutescens	yellow moon wrasse	O	R	TR/TE	0	5	4	0		*	*	
Stethojulis bandanensis	redspot wrasse	O	R	TR/TE	1	1	2	2	*	*	*	*
Lutjanidae												
Lutjanus bohar	red bass	CA	R	TR	0	0	2	0			*	
Lutjanus fulviflamma	black-spot snapper	CA	R	TR	0	0	1	1			*	*
Microcanthidae												
Atpichthys strigatus	mado	O	R	TE	6	0	0	0	**			
Microcanthus strigatus	stripey	O	R	TE	6	0	2	3	**		*	*
Monocanthidae												
Cantherines dumerilii	barred filefish	O	R	TR	0	0	1	1			*	*
Paraluteres prionurus	mimic filefish	O	R	TR	1	1	1	0	*	*	*	
Monocentridae												
Cleidopus gloriamaris[x]	pineapplefish	CA	R	TR/TE	1	0	0	0	*			
Monodactylidae												
Monodactylus argenteus	silver batfish	O	P	TR/TE	0	7	33	30		**	***	***

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN				Relative abundance			
					Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Schuettea scalaripinnis	eastern pomfred	P	P	TE	0	1	0	0		*		
Mullidae												
Parupeneus multifasciatus	banded goatfish	CA	R	TR/TE	0	2	2	2		*	*	*
Parupeneus spilurus	black spot goatfish	CA	R	TR/TE	1	0	1	2	*		*	*
Muraenidae												
Enchelycore ramosa	mosaic moray	CA	R	TE	1	2	0	0	*	*		
Gymnothorax thyrsoidea	white-eyed moray	CA	R	TR	0	0	0	2				*
Myliobatididae												
Aetobatus ocelleatus	white-spotted eagle ray	CA	R/P	TR/TE	0	0	0	2				*
Orectolobidae												
Orectolobus ornatus	ornate wobbegong	CA	R	TR/TE	0	1	1	1		*	*	*
Orectolobus maculatus[x]	spotted wobbegong	CA	R	TE	1	0	0	0	*			
Ostraciidae												
Ostracion cubicus[x]	yellow boxfish	O	R	TR/TE	0	1	0	0		*		
Pempheridae												
Pempheris affinis	blacktip bullseye	P	R	TE	0	0	2	0			*	
Pomacanthidae												
Centropyge tibicen	keyhole angelfish	H	R	TR/TE	0	0	1	0			*	
Pomacanthus semicirculatus	blue angelfish	H	R	TR/TE	0	1	0	0		*		
Centropyge bispinosus[x]	coral beauty	H	R	TR/TE	0	1	0	0		*		
Centropyge vrolikii	pearly-scaled angelfish	H	R	TR	0	0	1	0			*	
Pomacentridae												
Abudefduf bengalensis	Bengal sergeant	O	R	TR	2	0	0	3	*			*
Abudefduf vaigiensis	sergeant major	O	R	TR/TE	0	4	25	0		*	***	
Abudefduf sexfasciatus	scissortail sergeant	O	R	TR/TE	0	0	1	0			*	
Abedefduf whitleyi	Whitley's sergeant	O	R	TR	0	0	4	0			*	
Amphiprion akindynos	Barrier Reef anemonefish	O	R	TR/TE	2	2	6	0	*	*	**	
Chromis margaritifer	whitetail puller	P	R	TR	2	1	10	0	*	*	**	
Dascyllus trimaculatus	domino puller	P	R	TR/TE	5	0	4	1	*		*	*
Neopomacentrus bankieri	half moon damsel	O-HT	R	TR	0	0	0	1				*
Parma oligolepis	large-scaled parma	O-HT	R	TR/TE	1	1	3	2	*	*	*	*

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN				Relative abundance			
					Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Parma unifasciata	girdled scalyfin	O-HT	R	TE	1	0	0	1	*			*
Plectroglyphidodon johnstonianus	Johnston's damsel	O-HT	R	TR	0	1	1	0		*	*	
Plectroglyphidodon lacrymatus	jewel damsel	O-HT	R	TR	0	0	0	3				*
Plectroglyphidodon leucozonus	whiteband damsel	O-HT	R	TR	1	0	0	0	*			
Pomacentrus australis	Australian damsel	O-HT	R	TR/TE	0	0	0	1				*
Pomacentrus bankanensis[x]	fire damsel	O-HT	R	TR	0	1	0	0		*		
Pomacentrus coelestis	neon damsel	O-HT	R	TR/TE	20	2	2	8	**	*	*	**
Stegastes gascoynei	coral sea gregory	O-HT	R	TR/TE	1	3	3	0	*	*	*	
Stegastes apicalis	Australian gregory	O-HT	R	TR/TE	0	1	1	0		*	*	
Scorpaenidae												
Scorpaena cardinalis	red scorpionfish	CA	R	TR/TE	0	0	0	1				*
Scombridae												
Grammatorcynus bicarinatus	shark mackeral	CA	P	TR	0	0	0	1				*
Scorpididae												
Scorpis lineolatus	sweep	P	R	TE	12	1	1	2	**	*	*	*
Serranidae												
Epinephelus fasciatus	black-tipped cod	CA	R	TR/TE	0	0	0	1				*
Diploprion bifasciatum	barred soapfish	CA	R	TR	1	1	1	0	*	*	*	
Pseudoantias squampinnis	orange basslet	CA	R	TR/TE	1	0	0	0	*			
Siganidae												
Siganus sp.			R	TR/TE	0	0	0	1	*			
Sparidae												
Acanthopagrus australis	yellow-fin bream	CA	R	TR	1	3	10	13	*	*	**	**
Sphyraenidae												
Sphyraena obtusata	striped sea pike	CA	R	TR/TE	7	0	0	10	**			**
Synodontidae												
Synodus dermatogenys[x]	two-spot lizardfish	CA	R	TR/TE	0	0	1	0			*	
Tertradontidae												
Arothron hispidus	stars and stripes pufferfish	O	R	TR/TE	0	0	0	1	*			

Scientific name	Common name	Trophic	Reef/Pelagic	Range	MaxN				Relative abundance			
					Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef	Kirra Reef	Cook Island North	Cook Island West	Palm Beach Reef
Arothron nigropunctatus	blackspotted pufferfish	O	R	TR/TE	0	1	1	0		*	*	
Arothron stellatus[x]	starry toadfish	O	R	TR/TE	1	0	0	1	*			*
Canthigaster bennetii	blackspot toby	O-HT	R	TR/TE	1	0	0	0	*			
Canthigaster valentini[x]	black-saddled toby	O-HT	R	TR/TE	0	1	0	0		*		
Zanclidae												
Zanclus cornutus	Moorish idol	CA	R	TR/TE	0	1	1	1		*	*	*

x Fish species only observed by scientific diver

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 2018

Table C.1 Percentage cover of benthic communities using CPCe

Taxa		Kirra Reef		Cook Island North		Cook Island West		Palm Beach	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
Polychaeta		0.0	0.00	0.0	0.00	0.0	0.00	0.00	0.00
Ascidiaceae		27.71	3.4	29.77	3.45	28.54	3.37	62.42	4.15
Crinoidea		3.4	0.98	0.41	0.28	0.92	0.46	0.05	0.04
Anthozoa	**Anemone**	0.53	0.23	4.15	1.50	2.48	1.03	1.94	0.81
	Mushroom Anemone	0.0	0.00	0.0	0.00	0.0	0.00	0.00	0.00
	Hydroid	0.00	0.00	0.0	0.00	0.0	0.00	0.00	0.00
	Hard Coral	0.05	0.05	19.56	6.55	11.13	3.68	4.88	2.19
	Zoantharia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Soft Coral	0.1	0.09	1.2	0.58	3.49	1.16	1.30	0.47
	Dead Coral with Algae	0.0	0.00	0.0	0.00	0.00	0.00	0.00	0.00
Sponges		0.84	0.26	1.41	0.77	0.99	0.73	0.93	0.57
Bivalvia	**Barnacles**	0.84	0.84	0.00	0.00	0.0	0.00	0.00	0.00
	Oysters	0.0	0.00	0.0	0.00	0.0	0.00	0.00	0.00
Echinodermata	**Starfish**	0.0	0.00	0.0	0.00	0.0	0.0	0.04	0.04
	Feather stars	3.4	0.98	0.41	0.28	0.92	0.46	0.05	0.04
	Urchins	0.0	0.00	0.0	0.00	0.05	0.05	0.00	0.00
Chlorophyta	**Caulerpaceae**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Halimedaceae	0.0	0.00	0.19	0.09	0.10	0.06	0.05	0.05
	Chlorodesmis	0.0	0.00	0.10	0.07	0.43	0.13	0.62	0.11
	Ulvaceae	0.18	0.14	0.76	0.48	0.05	0.04	0.05	0.04
Ochrophyta	**Dictyotaceae**	12.31	2.48	14.34	3.71	16.97	3.01	1.20	0.60
	Alariaceae	0.0	0.00	0.0	0.00	0.00	0.00	0.00	0.00
	Sargassaceae	9.28	2.69	0.0	0.00	0.00	0.00	0.00	0.00
Rhodophyta	**Corallinaceae**	16.99	2.07	7.38	2.00	3.54	0.96	0.86	0.30
	Galaxauraceae	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Rhodomelaceae	2.42	1.25	5.03	1.66	0.39	0.21	0.47	0.19
Coralline Algae		0.00	0.00	0.48	0.18	14.34	1.79	0.00	0.00
Turf Algae		17.25	1.95	13.69	2.01	27.81	3.52	22.65	3.88
Other	**Fish**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Unidentified Fauna	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bare Ground	0.0	0.00	0.0	0.00	0.0	0.00	0.00	0.00
	Rock	0.05	0.04	0.00	0.00	0.00	0.00	0.50	0.44
	Rubble	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00
	Sand	8.38	2.39	0.82	0.38	2.90	1.33	0.96	0.33

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[13] 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

[13] 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