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NSW GOVERNMENT

Environmental values of the Lord Howe Island Marine Park

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Executive summary

The Lord Howe Island Marine Park (LHIMP) covers 480 km² of the NSW marine estate and is located 600 km from the coast of New South Wales. The LHIMP was declared on 26 February 1999, with management rules commencing in December 2004.

A new management plan is being prepared for the LHIMP following the development of a draft Network Management Plan for the five mainland marine parks in NSW. Under the *Marine Estate Management Act 2014*, these new management plans aim to conserve environmental, social, cultural and economic values of the marine park, and to manage priority threats to those values.

In line with these requirements, **this report aims to summarise the current environmental values for the LHIMP**, including the physical environment, biological communities, ecological relationships, and threatened and protected species. The review includes all ecosystems represented in the LHIMP marine park boundary, from estuarine to shelf slope and from pelagic to benthic. It also describes knowledge gaps to inform future environmental research priorities in the area. We include threats (e.g. climate change, pollution) to the LHIMP as they broadly relate to specific environmental values, but a detailed summary and assessment of threats to these values will be covered elsewhere.

Physical values

The physical values of the LHIMP include its **humid and sub-tropical climate** which is subject to cyclone activity and frequent storms. The LHIMP is also renowned for its **excellent water visibility** linked to high water quality. Oceanography includes the **eastward flow of the Eastern Australian Current** coinciding with the Tasman Front, which separates the subtropical and subantarctic surface water masses in the region and contributes to the combination of temperate and sub-tropical species found in the LHIMP. The geological processes in the region have produced **diverse and unique geomorphology**, with the earliest evidence of coral reef growth occurring around LHI 120,000 years ago.

Subsequent phases of coral reef accretion have continued up to the present day, where an active coral reef fringes the western coast of the LHI. This present-day fringing reef, as well as the evidence of fossil coral reef growth, are among the **southernmost records of coral reef distribution** in the world.

The physical environmental values of the LHIMP do not operate in isolation and can instead have complex relationships with each other. Importantly, the physical values of the LHIMP support the unique and representative ecological and biological values of the region.

Ecological and biological values

The LHIMP includes **numerous ecosystems spanning a wide range of habitats and biological communities**: three estuarine ecosystems along the island, lagoon ecosystems including the modern fringing reef, intertidal and shallow subtidal ecosystems, shelf ecosystems including mesophotic coral communities, slope ecosystems much of which occurs outside the LHIMP boundary, and pelagic ecosystems with communities similar to that found in the larger Lord Howe Rise region.

Highly isolated from other reefs in the region, **corals** of the LHIMP include at least 100 scleractinian (i.e. hard coral) species. Despite recent coral bleaching events in 1998, 2010, 2011 and 2019, coral cover in the lagoons has remained relatively stable in the LHIMP over the past few decades. The LHIMP also supports relatively diverse **mesophotic coral reefs** which have the potential to act as deep reef refugia under a changing climate.

The LHIMP supports a highly **diverse fish assemblage**, with 537 species identified to occur in the waters of the LHIMP. The majority of fish species are tropical with broad distributional ranges; however, temperate species dominate the total biomass. The LHIMP support several commercially important fish species including the yellowtail kingfish (*Seriola lalandi*), which accounts for over half of the total LHI fishery catch. Demersal fish assemblages were structured by benthic habitats, while mid-water fish assemblages are likely driven by ocean current speed. Monitoring programs have identified no clear changes in the total abundance and diversity of fishes from 2006 to 2018, although declines in some species were noted (e.g. bluefish, doubleheader wrasse, black rockcod).

Macrophytes are common in the LHIMP, including diverse macroalgal assemblages with some species at their southernmost distribution, two species of seagrass (*Zostera muelleri* subspecies *capricorni*, *Holophilas ovalis*) that form meadows in the lagoon, and two species of mangrove (*Avicennia marina* subsp. *australasica, Aegiceris corniculatum*). The LHIMP also contains small patches of coastal saltmarsh which is floristically equivalent to the endangered saltmarsh communities along mainland NSW.

Non-coral marine invertebrates have a high level of diversity (216 intertidal species) and endemism (11% of intertidal species, 75% of chitons). On subtidal reef communities, invertebrate species richness has remained relatively consistent from 2006 to 2018 and shows no significant difference between sanctuary and habitat protection zones. In 2008, a sea urchin (*Tripneustes gratilla*) outbreak in northern LHI contributed to loss of macroalgal cover. Shelf sediments seem to support low numbers of macrofaunal species, but these represent a high proportion of rare, new and endemic species.

The LHIMP supports several **threatened and protected species**:

- The black rockcod (*Epinephelus daemelii*) is listed as 'Vulnerable' under the *NSW Fisheries Management Act 1994*. This species is territorial and lives in caves and overhangs. There is a some concern that numbers dropped from 2011 to 2019 surveys, potentially due to incidental captures.
- The Ballina angelfish (*Chaetodontoplus ballinae*) is a protected species in NSW, found in depths of 25–125 m predominately around Balls Pyramid.
- The elegant wrasse (*Anampses elegans*) is a protected species in NSW, occurring within the LHI lagoon and on coral and rocky reefs to 35 m depth. Juveniles will often form large aggregations in shallow waters and are generally found around coral and algae habitats.
- Bluefish (*Girella cyanea*) are protected from fishing in all NSW waters, other than the waters of LHIMP in which there is a bag limit of 5 fish per person per day. The species is fast growing, living up to 41 years.
- At least 8 Syngnathid species are known to occur within the LHIMP (seahorses, pipefish, pipehorses), all of which are protected in NSW, but no information exists on the population status of these species within the LHIMP due to infrequent sightings.
- Marine mammals occur within the LHIMP with bottlenose (*Tursiops truncatus*) and common dolphins (*Dephinus delphis*) often observed in deeper waters. The humpback whale (*Megaptera novaengliae*) is the most frequent whale species observed in the LHIMP as they make both their northwards and southwards migrations. Other marine mammals (fur seals, leopard seals, beaked whales) are infrequently sighted in the LHIMP.
- The green turtle (*Chelonia mydas*) is the most common marine reptile to occur in the LHIMP, often encountered within the lagoon. The hawksbill turtle (*Eretmochelys imbricate*) is also a resident, while the leatherback and loggerhead turtles are considered migratory species in the LHIMP. Sea snakes occasionally turn up in the waters of the LHIMP but are not considered to be resident to the local waters.
- The Lord Howe Island Group (LHIG) includes breeding sites for 14 species of seabirds made up of seven 'tubenose' Procellarids, five terns, a Sulid (masked booby), and a phaethontid (red-tailed tropicbird). None of the breeding populations of these seabirds reside year-round on islands in the LHIG, although some like grey ternlet and masked booby, have individuals that remain throughout the year.

The LHIMP also supports **other significant species** – those that are iconic or play keystone ecological roles:

- The Galapagos shark (*Carcharhinus galapagensis*) is an abundant predator in the region and is a key indicator species of pelagic ecosystem health for the management of the marine parks surrounding LHI due to its local abundance and top-level trophic influence.
- The doubleheader wrasse (*Coris bulbifrons*) shows no obvious trends of increasing or decreasing abundance, but there is limited research about its life history and population dynamics to assist in understanding the species biology for LHIMP.

- The McCulloch's anemonefish (*Amphiprion mccullochi*) is endemic to LHI and Middleton and Elizabeth Reefs, and the LHI lagoon seems to be the remaining stronghold for this species. Over the past decade, it is estimated that the LHI population has declined by over 50% due to loss of essential habitat (anemone) from heat stress and is currently being considered for listing as a threatened species under Commonwealth and NSW legislation.
- The Lord Howe Island abalone (*Haliotis rubiginosa*) is endemic to LHIMP, restricted to carbonate reefs at low abundances. It was listed as 'Critically Endangered' under the IUCN Redlist in 2020 and is currently being considered for listing as a threatened species under Commonwealth and NSW legislation.

Threats

Threats to environmental values were previously identified and managed under current arrangements in the LHIMP and include those associated with climate change, vessel use (commercial shipping activities, visiting vessels, port use and navigation channels, vessel-sourced pollution, aquatic biosecurity, personal water craft), urban development (works, motor vehicle use, land-based pollution, marine debris, dogs, fires), fishing operations (fishing, fish cleaning, recreational and aquarium collecting, aquaculture), other tourism activities (fish feeding, photography and filming, public events and recreational activities), and biological threats (urchins, crown-of-thorns starfish).

These threats should be included in any future threat and risk assessment for the LHIMP, noting the above is not a comprehensive list and will be examined further via a threat and risk assessment process for LHIMP as part of the management planning process.

Knowledge Gaps

The knowledge gaps listed below were compiled from published research cited in this report, the authors' expert knowledge, and priorities identified by LHIMP managers:

- Assessment and monitoring of coastal processes and threats;
- Impacts of fishing and marine park zoning efficacy on bony fish;
- Movement patterns of commercially important and iconic fish;
- Resource use and at-sea movements of seabirds;
- Impacts of marine park users on turtles and associated near-shore behaviour of turtles;
- Understanding of mesophotic coral reefs as potential refugia against different climate change scenarios;
- Baseline information on small macrofaunal, infaunal, meiofaunal, and microbial communities;
- Understanding of the relationships between urchin densities, macroalgal beds, herbivorous fish, urchin predators, and climate change stressors to predict future changes in urchin densities;
- Continued impacts of climate change and associated stressors on the unique species, communities and habitats of the LHIMP;
- Impacts of multiple and cumulative stressors on LHIMP ecosystems, communities, and key species; and
- Identification of the complex relationships between environment, social, cultural and economic values and threats.

1 Introduction

1.1 Regional description

The Lord Howe Island Marine Park (LHIMP) is located in the Tasman Sea along the Lord Howe Rise, approximately 600 km from the coast of New South Wales (Figure 1).

The region consists of flat deep-sea plains and plateaus, interspersed with volcanic cones, seamounts, reefs, and offshore islands such as Balls Pyramid and Lord Howe Island (LHI) which provide habitat complexity across the seafloor and the terrestrial environments in the region.

Ocean circulation patterns in this region are strongly influenced by the East Australian Current (EAC) which flows south and eastward, at times colliding with the Tasman Front, a shifting separation of subtropical and subantarctic surface water. This high temporal and spatial variability influence the physical and chemical composition of the water and nutrients around the seamounts, reefs, and islands. These currents in turn drive food resources and recruitment, hence influencing the composition of marine communities within the region.

Due to the multiple ways in which the region's high geomorphological diversity and oceanographic processes have affected marine species distributions, the Lord Howe Rise region has highly structured local patterns in biogeography (Przeslawski *et al*., 2011). LHIMP is located within this region in a transition zone between temperate and tropical ecosystems and supports the world's southernmost coral reef ecosystem. It is a rare example of how dominant habitat-forming species transition from tropical coral reefs to macroalgal beds in higher latitudes. Elizabeth and Middleton Reefs are the nearest analogous habitats to LHIMP at almost 100 km away (Figure 1).

The Lord Howe Island Group (LHIG) was inscribed on the UNESCO World Heritage List in 1982 in recognition of its superlative natural landscapes and scenery, its rich terrestrial and marine biodiversity, and as an outstanding example of an island ecosystem developed from submarine volcanic activity (Lord Howe Island Board, 2010). These natural values confer international, national, and state interest in the management of this area. The World Heritage area includes approximately 1450 km² of marine environment including the LHIMP, which is the only marine park in NSW waters that falls within a World Heritage area.

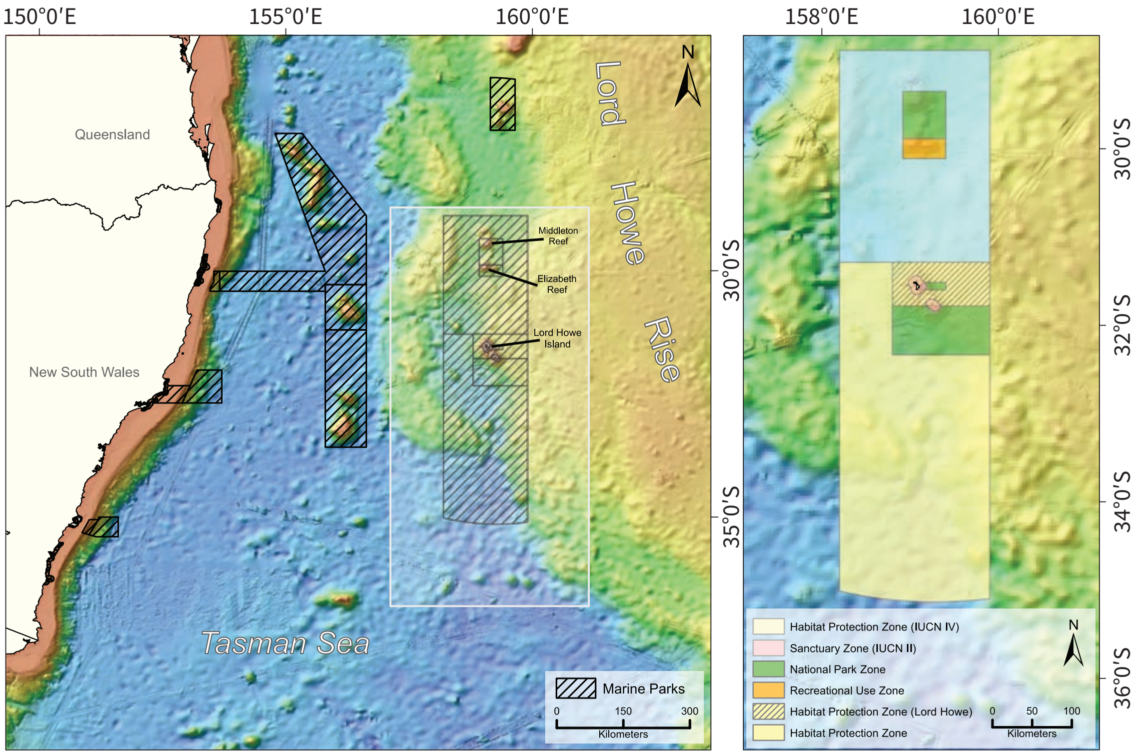


Figure 1: Map of NSW Lord Howe Island Marine Park and Commonwealth Lord Howe Marine Park, [left] regional scale and [right] marine park scale.

1.2 NSW Lord Howe Island Marine Park

The NSW LHIMP covers approximately 480 km² of the NSW marine estate. This includes all the seabed and waters extending to three nautical miles from the mean high-water mark surrounding LHI, Balls Pyramid, and their adjacent rocks and islands.

Unlike coastal areas of the NSW marine estate, the waters surrounding LHI are virtually inaccessible to people other than residents (approximately 350), guests of on-island accommodation (capped at 400 beds), and from visiting vessels. Tourism provides the major income for the island community, with up to 16,000 people visiting annually. As a consequence, management arrangements for the LHIMP are of particular relevance to the local community, both in terms of environmental, social, cultural and economic values, as well as threats to those values.

The LHIMP was declared on 26 February 1999. Mining is prohibited throughout LHIMP by the Act, and development assessment and other park management provisions apply.

The primary purpose of LHIMP is to conserve biological diversity and maintain ecosystem integrity and ecosystem function of the Lord Howe bioregion, while providing for a range of ecologically sustainable uses that deliver social, cultural and economic benefits. Management rules, including zones and other regulations, for the LHIMP commenced in December 2004 and are specified in the *Marine Estate Management (Management Rules) Regulation 1999*. The management rules for LHIMP were developed to protect the important environmental, cultural, economic and social values of LHIMP while maintaining a range of recreational commercial activities.

The management rules include three types of zones:

- Sanctuary Zones provide the highest level of protection by prohibiting or regulating activities that harm marine life, such as fishing, collecting and anchoring, while permitting activities that do not harm plants, animals and habitats. The major habitats of the LHIMP are represented in a network of sanctuary zones across the entire Marine Park;

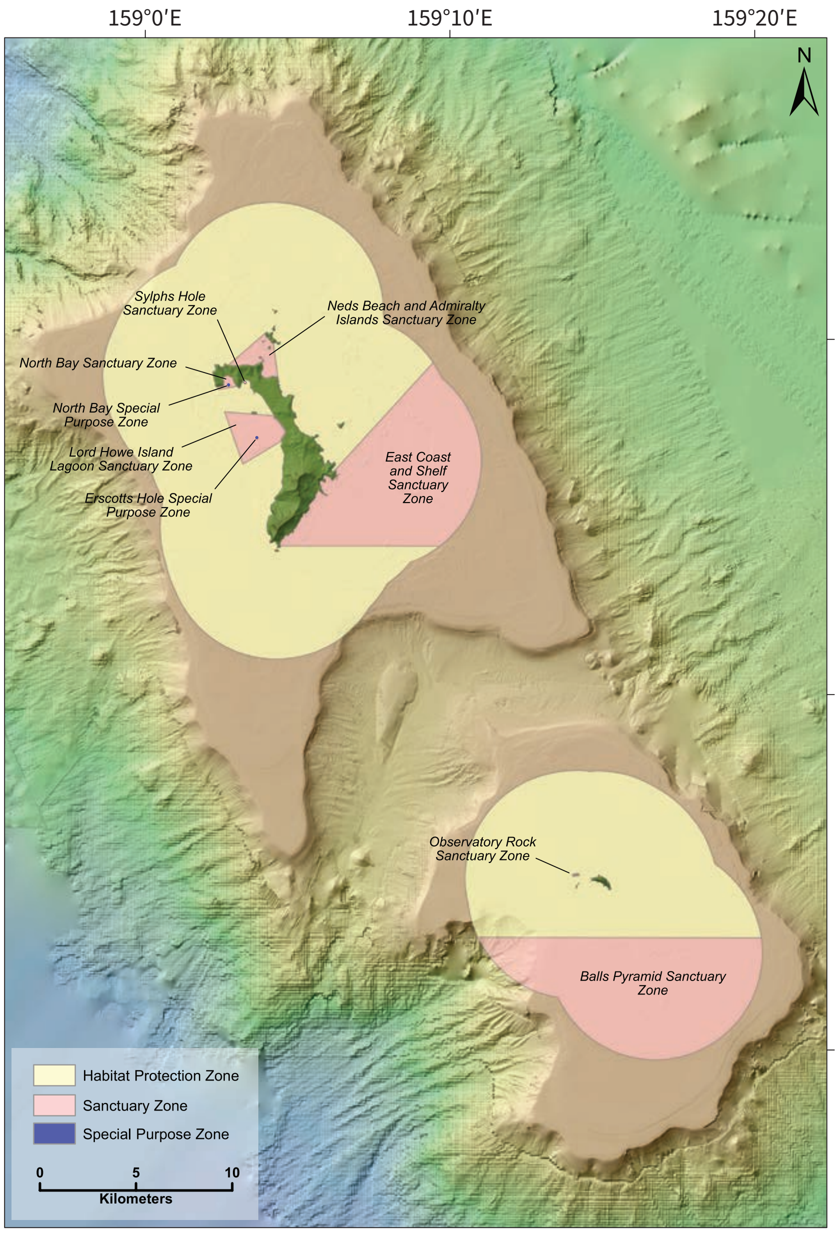


Figure 2: Zoning plan map for the Lord Howe Island Marine Park

- Habitat Protection Zones, which include the largest area of the LHIMP (Figure 2) protect biotic and abiotic habitats by limiting damaging activities. Recreational fishing and charter boat fishing are permitted in these areas; and
- Special Purpose Zones include several sites requiring special management arrangements such as fish feeding at Neds Beach, North Bay and Erscotts Hole.

A range of management programs complement the management rules and include compliance and community education programs; infrastructure programs such as provision of vessel moorings; research and monitoring; assessment of permits for a range of activities; development and planning assessment and input; protection of cultural heritage; pollution control and incident management; managing threats to aquatic biosecurity; complementary management with other agencies; and additional actions to facilitate conservation and sustainable use.

The LHIMP sits nested within the larger regional Commonwealth Lord Howe Marine Park (LHMP) which was declared in 2000 and extends out from the state waters covering a total area of 110,126 km² (Figure 1). It was proclaimed under the *Environment Protection and Biodiversity Conservation Act 1999* on 14 December 2013 and renamed on 9 October 2017. The Commonwealth LHMP includes large sections of the Lord Howe Rise, such as Elizabeth and Middleton Reefs, Lord Howe seamount chain and the Tasman Front. The updated zoning and rules for the LHMP are provided in the Temperate East Marine Parks Network Management Plan 2018.

Management arrangements for the LHIMP have been developed to compliment the conservation of adjacent protected areas through the connection of Permanent Park Preserve managed by the Lord Howe Island Board (LHIB), LHIMP sanctuary zones and Commonwealth National Park zones, capturing a complete cross section of the island, shelf, and seamount bathyal plain.

Locations of interest mentioned in this review are indicated in Figure 3.

Figure 3: Map showing locations around Lord Howe Island that are referred to in this report.

1.3 Purpose of the review

A new management plan is being prepared for LHIMP following the development of a draft Network Management Plan for the five mainland marine parks in NSW. These new management plans aim to conserve environmental, social, cultural and economic values of marine parks, and manage priority threats to those values.

Under the *Marine Estate Management Act 2014* (s. 48), these new management plans must:

- state the environmental, economic and social values to be conserved by the marine park;
- identify threats to those values;
- state the management objectives of the marine park in relation to those values and threats;
- specify actions to achieve those management objectives, based on a consideration of risks; and
- set out the programs to be implemented for managing the marine park.

In line with these requirements, this report aims to summarise the current environmental values for the LHIMP, including the physical environment, biological communities, ecological relationships, and threatened and protected species. The compiled literature and associated synthesis of environmental values will also be broadly useful to scientists working in this region and others interested in the values of the LHIMP.

Studies of the environmental values in the LHI region have typically focused on the shallow lagoon and coral reef habitats, but research in the past decade indicates that the mesophotic zone of the relict reefs supports highly diverse communities (Linklater *et al.*, 2018b), thereby extending the zone of LHIMP environmental values beyond the coast and shallow reefs.

This review includes all ecosystems represented in the LHIMP marine park boundary, from estuarine to shelf slope and from pelagic to benthic. We also identify knowledge gaps to inform future environmental research priorities in the area. We focus on the marine area within the LHIMP and the immediate areas of the Commonwealth LHMP immediately adjacent to it (Figure 1), and we limit our consideration of the wider offshore area only to provide relevant regional context. We include threats (e.g. climate change, pollution) to the LHIMP as they broadly relate to specific environmental values, but a detailed summary and assessment of threats to these values will be comprehensively addressed in a separate threat and risk assessment process for LHIMP.

Previous reports have identified the natural values of the NSW (NSW Marine Parks Authority, 2010a) and Australian (Director of National Parks, 2018) Marine Parks around LHI, but there have been many marine environmental studies in the region since these were written. This report aims to build on these previous reports with current findings specific to the LHIMP.

The following topics are outside the scope of the current report and have been considered elsewhere: social, cultural and economic values of the LHIMP (BDO, 2022) and species inventories (e.g. Atlas of Living Australia, Ocean Biodiversity Information System). Although we do include some information on marine park zoning effectiveness, particularly for fishes due to the comparatively large amount of information available for this group, a comprehensive review of marine park efficacy is outside the scope of this review (see Edgar *et al.*, 2020).

2 Physical natural values

The physical environmental values of the LHIMP do not operate in isolation and can instead have complex relationships with each other.

For example, it is well known that climate influences ocean currents, and ocean currents and geomorphology can affect sediment transport (Haskoning 2004). In this section, we review these natural values separately, noting that any assessment of threats related to these natural values should consider their interdependencies.

2.1 Climate

The maritime climate of the LHIMP reflects its small land area (14.5 km²) and its isolation from any major continent (located some 600 km to the east of mainland Australia). The climate is described as humid and sub-tropical with mean monthly maximum temperatures range from 19°C in the Austral winter to 26°C in the summer, whereas mean monthly minimum temperatures range from 13°C in winter to 21°C in summer (Table 1). Mean monthly rainfall is greatest from late autumn to early winter, with a maximum monthly mean of 167 mm in June, and monthly means exceeding 100 mm in every month (Table 1). Monthly mean wind speeds are similar throughout the year with afternoon wind speeds only marginally greater than morning wind speeds (Table 1). There is, however, a seasonal variation in the wind direction. In summer and autumn, the wind is most commonly from the northeast and east. The strongest winds also arise from those directions, as well as the southwest in autumn (Figure 4). In winter and spring, the wind is most commonly from the southwest, and the strongest winds are mostly from that direction also but can occasionally arrive from the northeast and east. The region is also subject to major storms and cyclone activity, with storms being frequent and occurring throughout the year (Woodroffe *et al*., 2005).

Month	Mean max. temp. (°C)	Mean min. temp. (°C)	Mean monthly rainfall (mm)	Mean 9am wind speed (km/h)	Mean 3pm wind speed (km/h)
Jan	25.5	20.8	107.2	21.3	22.4
Feb	25.8	21.1	105.0	22.0	23.3
Mar	24.9	20.1	129.6	21.6	22.5
Apr	23.4	18.2	137.7	20.2	20.9
May	21.6	16.4	150.0	21.0	21.7
Jun	19.9	14.8	167.3	21.9	22.5
Jul	19.1	13.9	142.6	21.8	23.9
Aug	19.1	13.5	111.8	21.5	23
Sep	20.0	14.6	111.8	21.0	22.4
Oct	21.1	15.8	101.4	20.4	20.6
Nov	22.4	17.5	112.1	19.9	20.9
Dec	24.1	19.3	100.8	20.0	21.4
Annual	22.2	17.2	1467.4	21.0	22.1

Table 1: Climate summary derived from meteorological data collected at Lord Howe Island Airport (Station 200839) for the period 1988 to 2021. Temperature and rainfall information represents the full 33 years, whereas wind information represents the most recent 22 years. Information obtained from the Australian Bureau of Meteorology.

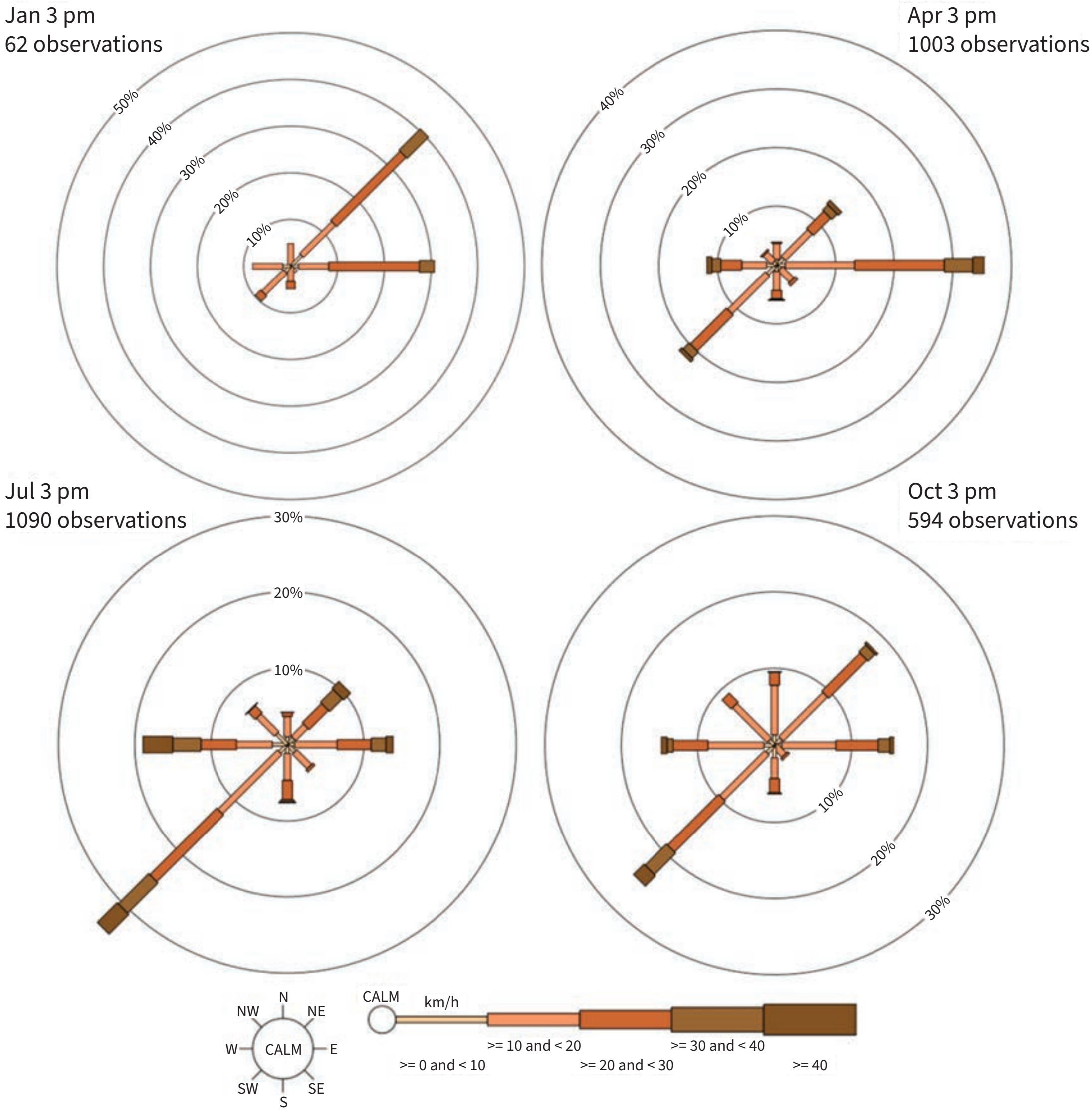


Figure 4: Seasonal wind roses for 3 pm derived from meteorological data collected at Lord Howe Island Airport (Station 200839) for the period 2000 to present. Information obtained from the Australian Bureau of Meteorology.

2.2 Water quality

The LHIMP is renowned for its high ocean water quality (Environment Australia, 2002), and its exceptional water clarity has been noted in satellite imagery (Linklater *et al*., 2018a) and underwater video (Heagney *et al*., 2007). Water visibility is closely associated with depth and wave exposure in the LHIMP (Edgar *et al*., 2010). Data on water visibility is available from Reef Life Survey for shallow depths (Edgar *et al*., 2020), but quantitative data is lacking for deeper waters in the LHIMP.

Despite the low turbidity, water quality in the LHIMP may be affected by contaminated groundwater through increased nutrient levels in adjacent lagoons (Davis 2022a, b). Nonetheless, no eutrophication events or other impacts on ecosystems have yet been clearly linked to poor groundwater quality (see Section 4).

2.3 Oceanography

The coastal waters around LHI experience a mixed semi-diurnal tide, meaning there are two high and two low tides of different size each day. The mean spring tide range is 1.51 m, and the mean neap range is 0.81 m, indicating a microtidal regime (Haskoning 2004). Table 2 shows indicative tidal ranges. Variation from predicted tide levels can occur at LHI outside astronomical predictions, known locally as tide anomalies that can be either positive or negative. These anomalies have been suggested to occur due to effects of the East Australian Current (Modra, 2013).

Monthly-average total significant wave heights vary between 1.9 m and 2.7 m. The largest wave heights occur during the winter months, when both swell and sea are at their greatest. The swell direction is persistently from the south-southwest to southeast sector throughout the year, driven by the passage of low-pressure systems across the southern Tasman Sea (Table 3). The sea direction, however, varies seasonally with the local wind conditions. Sea arrives from the east-northeast to southeast sector during summer and autumn, and from the west-southwest to southeast sector during winter and spring. Swell periods are typically around 9 s and sea periods are 3-4 s (Table 3).

Harmonic amplitudes		Indicative tidal ranges	
K1	0.149 m	Mean spring range	1.51 m
O1	0.082 m	Mean neap range	0.81 m
M2	0.581 m	Mean range	1.16 m
S2	0.175 m	Maximum range	2.08 m

Table 2: Indicative tidal ranges calculated from harmonic amplitudes of four key tidal constituents for the period 2009-2021, obtained from the Lord Howe Island tide gauge (Station 240402) maintained by Manly Hydraulics Laboratory.

Month	Total			Swell			Sea		
	Hsig	Tm	WDm	Hsig	Tm	WDm	Hsig	Tm	WDm
Jan	1.98	5.9	140	1.70	9.1	158	0.78	3.6	73
Feb	2.13	6.0	134	1.84	9.2	144	0.85	3.8	91
Mar	2.15	6.2	141	1.90	9.5	151	0.79	3.7	91
Apr	2.24	6.3	163	1.96	9.7	167	0.84	3.8	121
May	2.51	6.6	183	2.16	9.9	177	0.97	4.0	176
Jun	2.72	6.6	179	2.21	9.9	174	1.25	4.4	188
Jul	2.62	6.5	197	2.18	9.9	183	1.16	4.3	225
Aug	2.52	6.4	205	2.06	9.7	194	1.12	4.2	231
Sep	2.39	6.2	203	2.00	9.6	194	1.02	4.1	229
Oct	2.21	6.3	192	1.90	9.6	185	0.82	3.7	144
Nov	2.03	5.8	185	1.73	9.0	179	0.83	3.7	140
Dec	1.95	5.8	141	1.67	8.8	155	0.79	3.7	66

Table 3: Summary of wave climate data for LHI, based on a decade of reanalysis data (2011-2020). Wave climate statistics obtained from the European Centre for Medium-Range Weather Forecasting's ERA5 Reanalysis data set covering the decade 2011-2020. Significant wave height, Hsig, is in metres; mean wave period, Tm, is in seconds; and mean wave direction (WDm) is in degrees relative to north. Data represents a 0.25° grid cell centred on 31.5°S 159.0°E.

The East Australian Current (EAC) travels southward along the shelf edge up to 30-40^{0}S before turning eastward towards the Lord Howe Rise. The mean annual flow of the EAC at 30^{0}S is 15 Sv (Tomcczak and Godfrey, 1994), but with high temporal and spatial variability. This eastward flow of the EAC coincides with the Tasman Front, which separates the subtropical and subantarctic surface water masses in the latitudinal zone 31-37^{0}S (Figure 5; Mulhearn, 1987). Annual mean temperatures range between 26^{0}C in the subtropical water mass to the north and 16^{0}C in the subantarctic water mass to the south (CSIRO, 2009).

Westward propagating Rossby waves along the Tasman Front are frequently associated with the formation of anticyclonic (warm-core) eddies in the EAC that continue to travel south as far as Tasmania (Figure 5; Nilsson and Cresswell, 1980). However, recent research indicates that continuous, zonal, eastward flow across the Tasman Sea is less common than previously accepted, and there has been a recommendation to instead refer to the Tasman Front as a 'southern extension of the EAC' (Oke *et al*., 2019).

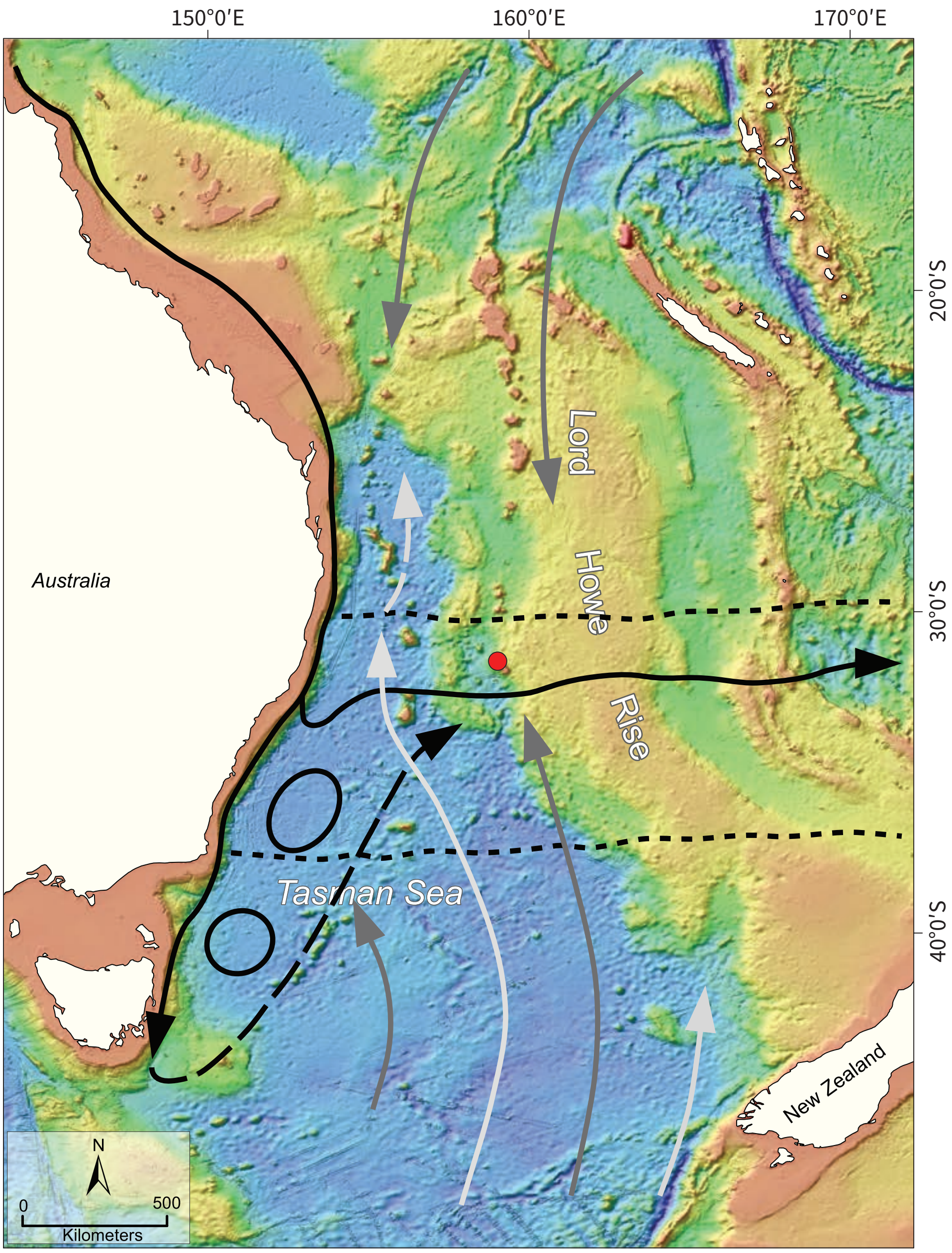


Figure 5: Schematic of the Tasman Sea regional oceanography influencing the waters around LHIMP (located at the red dot). Black lines indicate surface circulation: the southward and eastward arrows represents the Eastern Australian Current; the black circles represent warm-core eddies. Dark grey lines represent circulation of intermediate waters. Light grey lines represent circulation of bottom waters. Dotted lines indicate the northern and southern limits of the seasonally migrating Tasman Front. Image modified from Przeslawski *et al*. (2011).

LHIMP monthly average sea surface temperature ranges from 19.2^{0}C in August to 24.5^{0}C in February (Table 4). Dissolved oxygen varies inversely with temperature, ranging between a minimum of 211.2 µmole kg^{-1} in March and a maximum of 225.6 µmole kg^{-1} in August (Table 4). Salinity is persistently 35.6-35.7 PSU. The nutrients nitrogen, phosphorus and silica are variable throughout the year (Table 4), probably reflecting the large temporal variability in EAC flow.

Although outside the depths of the LHIMP, intermediate and bottom ocean currents may affect dispersal patterns and migratory movements of some species. Intermediate-depth (700-1500 m) circulation on the Lord Howe Rise is primarily driven by Antarctic Intermediate Water, which arrives at the Lord Howe Rise as a northward directed flow from the polar front immediately to the south of the region, and as a southward directed flow having been entrained by the subtropical gyre in the south-eastern Pacific and completing nearly one lap around the gyre (Figure 5). The abyssal waters of the Tasman Sea are primarily Antarctic Bottom Water (AABW), generated in the Ross Sea and flowing northward at water depths >3000 m (Przeslawski *et al*., 2011). AABW flow is sluggish, consequently the water is over 500 years old and dissolved oxygen levels are about 4.48 ml l-1 by the time it reaches the Lord Howe Rise (Craig *et al*., 1981, Reid, 1997, Tomcczak and Godfrey, 1994).

Month	Temp	Salinity	DO	Nitrogen	Phosphorus	Silica
Jan	23.7	35.6	215.5	0.224	0.272	0.970
Feb	24.5	35.6	211.9	0.186	0.216	0.936
Mar	24.4	35.6	211.2	0.030	0.152	1.006
Apr	23.6	35.6	213.5	0.006	0.123	1.177
May	22.1	35.6	218.0	0.313	0.150	1.360
Jun	20.6	35.6	222.4	0.924	0.204	1.380
Jul	19.6	35.6	224.9	1.377	0.229	1.189
Aug	19.2	35.7	225.6	1.324	0.209	0.933
Sep	19.4	35.7	225.4	0.863	0.179	0.804
Oct	20.1	35.7	224.7	0.283	0.182	0.833
Nov	21.3	35.6	223.0	0.010	0.227	0.946
Dec	22.5	35.6	219.9	0.078	0.271	1.001

Table 4: Monthly-average sea surface temperature (^{0}C); salinity (PSU); dissolved oxygen (DO; µmole kg^{-1}); and nutrients nitrogen, phosphorus, and silica (µmol kg^{-1}) for surface waters surrounding Lord Howe Island. Data represents a 0.5° grid cell centred on 31.5°S 159.0°E. Information obtained from the CSIRO Atlas of Regional Seas 2009.

2.4 Geology and geomorphology

Lord Howe Island and Balls Pyramid formed as shield volcanoes from hotspot volcanism 6 to 7 million years ago as part of a chain of islands and seamounts along the Lord Howe Rise, which also includes Elizabeth Reef and Middleton Reef to the north (McDougall *et al*., 1981). Plate tectonic motion carried the volcanoes in a northward direction away from the magma source, and over time the volcanoes eroded to a fraction of their original size, with LHI estimated to comprise 3% of its original area (Dickson, 2004). Erosion heavily truncated the volcanoes to form broad platforms, with both LHI and Balls Pyramid surrounded by near-horizontal shelves, now submerged in 30-60 m water depth (Dickson, 2004, Linklater *et al*., 2018a, Woodroffe *et al*., 2010). As plate tectonics gradually moved the islands north into warmer waters (6 cm/year, Quilty, 1993), and over multiple phases of sea level fluctuations, the formative volcanic basalt deposits were overlain by eolianite sequences (Brooke *et al*., 2003), and eventually entered waters warm enough to accrete coral reefs (Kennedy and Woodroffe, 2000, Woodroffe *et al*., 2010, Woodroffe *et al*., 2006). The earliest evidence of coral reef growth around LHI occurred 120,000 years BP during the Pleistocene, and subsequent phases of coral reef accretion have continued up to the present day, where a modern, active coral reef fringes the western coast (Kennedy and Woodroffe, 2000) (Section 3.2). This present-day fringing reef, as well as the evidence of fossil coral reef growth, are among the southernmost records of coral reef distribution in the world.

During times of higher sea level coinciding with periods between glacial cycles, coral reefs accreted on the island's shelves. Following the end of the last glacial period approximately 19,000 years BP, when sea level began to rise, the shelves surrounding the islands were inundated and substantial coral reefs accreted from 10,000 to 7,000 years BP (Linklater, 2016, Woodroffe *et al*., 2010). From 6,500 years BP, the sea level began to stabilise close to its present level and the modern fringing reef initiated at LHI, (Kennedy and Woodroffe, 2000). The shelf reefs, submerged by approximately 30 m of water, largely 'gave up' significant reef accretion during this time and form the shelf around the Island (Figure 6). Nonetheless, some coral growth continued to occur on the submerged reefs at reduced capacity, with a phase of coral reef accretion recorded on the LHI fossil reef around 2,000 BP years (Woodroffe *et al*., 2010), and evidence of live modern corals encrusting the fossil reef surfaces of both shelves today (Linklater *et al*., 2016, Linklater *et al*., 2018b).

On the LHI shelf, a large fossil barrier reef (155 km²) comprises approximately one third of the 504 km² shelf (Figure 6). This fossil reef encircles the mid shelf in 25-50 m water depth, with a typical relief of 20 m (Linklater *et al*., 2018a). Drill cores extracted from the reef surface demonstrate the upper portion of the reef is Holocene (9,000 to 2,400 years BP), likely forming a capping of several metres over older reef sequences and other deposits (Woodroffe *et al*., 2010). Sedimentary basins occur on the mid and inner shelf in 30 to 60 m water depth, infilled with up to 25 m of carbonate sediment (Brooke *et al*., 2010b) (Figure 6). These basins may have functioned as lagoons during times of lower sea level. Patchy inner shelf reefs comprising fossil reef and bedrock outcrops surround the island, with the modern coral reef (6 km in length, 6.5 km²) forming along the island's western coast (Linklater *et al*., 2018a). The lagoon inshore of the fringing reef is infilled with Holocene carbonate sediment 5 to 20 m thick (Kennedy and Woodroffe, 2000).

The Balls Pyramid shelf, which is a smaller shelf (261 km²) compared to the LHI shelf, is similarly dominated by a large mid-shelf reef (87 km²) occurring in 30-60 m depth (Linklater *et al.*, 2015, Linklater *et al*., 2018a) (Figure 6). The mid-shelf reef surrounding Balls Pyramid exhibits a platform-type morphology, with a typical relief of 15 m. Basin development is more restricted on the inner and mid shelf and have accumulated up to 16 m of sediment. Surrounding the mid-shelf reefs of both shelves are outer shelf platforms, which appear to be limestone surfaces veneered with carbonate sands. The outer shelf edges are marked by sequences of terraces occurring in 65 to 100 m water depth, formed as erosional and depositional features during periods of lower sea level (Linklater *et al*., 2015, Linklater *et al*., 2018a).

LHI originated as a larger volcano compared to Balls Pyramid, and thus had a greater amount of material remaining following erosion and truncation of the shelf. The greater availability of inner shelf bedrock and reef outcrops in shallow waters around LHI provided opportunities for corals to keep pace with rising sea level and form shallow coral communities, including the modern fringing reef. Balls Pyramid, on the other hand, was more heavily eroded to form a steep monolith structure, with little shallow substrate available for corals to colonise with rising sea level. The fossil reef surrounding Balls Pyramid therefore appears to have largely stopped growing as sea level rose to present levels (Linklater *et al*., 2018a), whereas coral growth around LHI was able to backstep toward the land and continue to accrete to the present day (Kennedy and Woodroffe, 2000, Linklater *et al*., 2018a, Woodroffe *et al*., 2010).

Despite LHI being at the latitudinal limits for the growth of coral reefs, the region demonstrates a substantial capacity for carbonate production. Such carbonate production is evident in the form of accreting fossil coral reefs, which occurred concurrent with sea level rise, as well as carbonate sediments infilling basins and veneering the outer shelf (Linklater *et al*., 2018a, Woodroffe *et al*., 2006). Nevertheless, Davis *et al*. (2020) estimated that modern rates of calcification at LHI are lower than those of other high-latitude coral reefs.

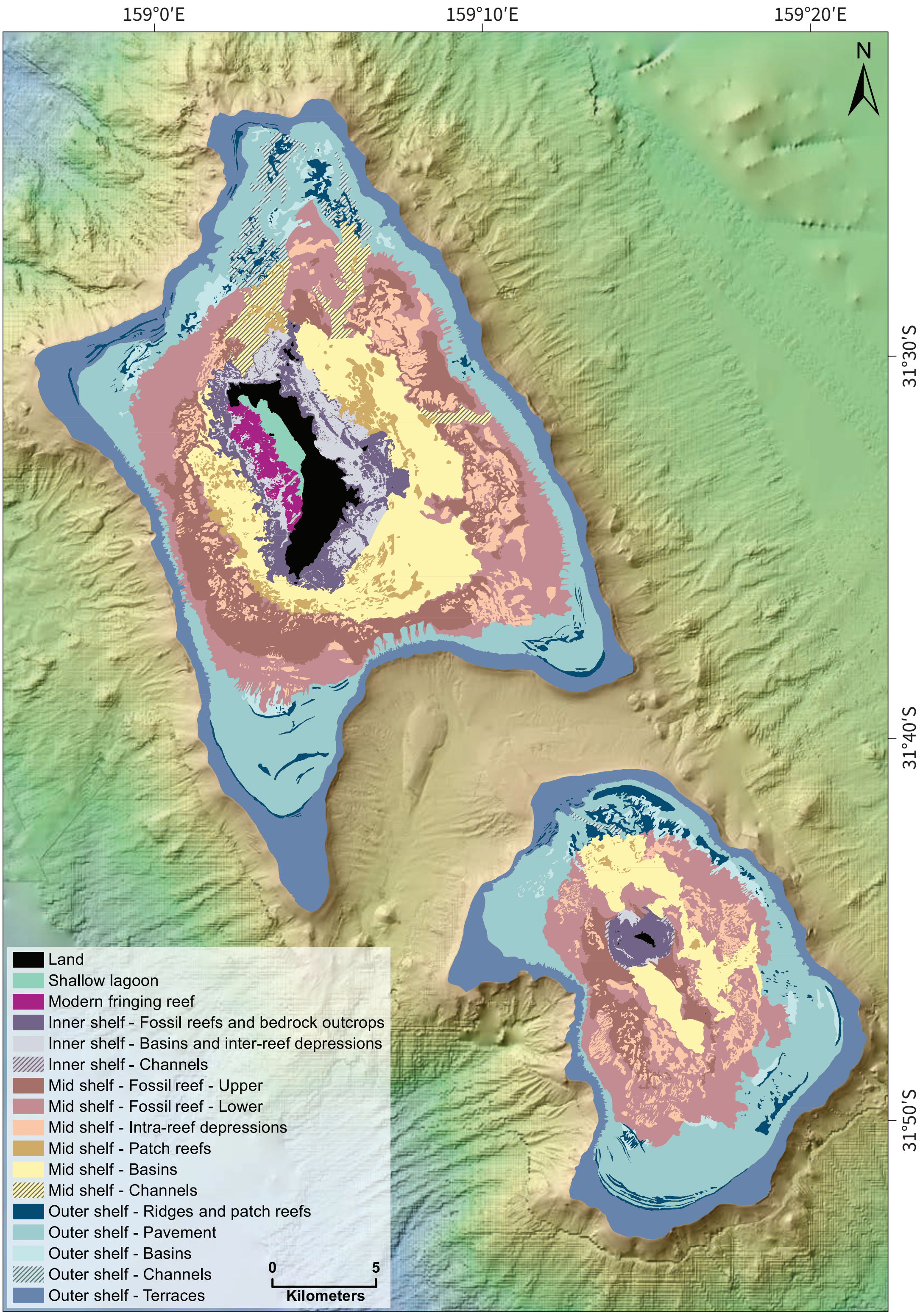


Figure 6: Geomorphic classification of Lord Howe Island Marine Park based on bathymetric and geological data.

3 Ecological and biological values

3.1 Ecosystems

In this section, we briefly describe the wide range of habitats and biological communities in each ecosystem. Ecosystems are categorised differently to those in the LHIMP Natural Values Report (Marine Parks Authority, 2010a) and are based on their horizontal (distance to shore) and vertical (depth) zonations.

These categories better incorporate recent geomorphological classifications (Section 2.3) and more clearly delineate physical parameters. Table 5 maps the links between the ecosystem schema used in this report and that from Marine Parks Authority (2010a).

Some biological communities (e.g. corals, seagrasses, mangroves) are described in further detail in their own sections below, but for lists of individual species supported by each ecosystem, refer to Marine Parks Authority (2010a).

2010 Report (MPA 2010a)	Description	Current report
OCEAN ECOSYSTEMS	Benthic coastal, shelf, and slope	
> Subtidal reef	Benthic subtidal rocky or coral reefs	
– Lagoon reefs	Discontinuous 6-km fringing reef along western margin of LHI lagoon, and isolated reefs within LHI lagoon	Lagoon ecosystems
– Open coastal fringing reefs	Reefs outside LHI lagoon on inner shelf (0-30 m depth)	Intertidal and shallow subtidal ecosystems, shelf ecosystems
– Mid-outer shelf reefs	Reefs 30-100 m depth	Shelf ecosystems
– Seamount slope	Reefs > 100 m depth	Slope ecosystems
> Subtidal soft sediment	Unconsolidated sediment, excluding seagrasses	Intertidal and shallow subtidal ecosystems
> Intertidal reef	Marine and terrestrial transition zone with rocky reef	Intertidal and shallow subtidal ecosystems
> Ocean and lagoon beaches	Marine and terrestrial transition zone with unconsolidated sediments	Lagoon ecosystems
> Seagrasses	Unconsolidated sediments dominated by seagrass meadows	Lagoon ecosystems
PELAGIC ECOSYSTEMS	Open ocean, water column	Pelagic ecosystems
ESTUARINE ECOSYSTEMS	Estuaries and brackish creeks	Estuarine ecosystems

Table 5: Ecosystem and habitat categories from 2010 LHIMP natural values report mapped to ecosystem categories used in the current natural values report.

Estuarine ecosystems

LHIMP includes only three estuaries, all bordering the lagoon and all intermittently closed to the sea (ICOLLs, Intermittently Closed and Open Lakes and Lagoons):

- Soldiers Creek is the largest estuary with regular flushing via tidal inundation, but may be closed to the sea during summer and other dry periods;
- Cobbys Creek is north of Soldiers Creek, small, and rarely open to the sea; and
- Old Settlement Creek is north of Cobbys Creek, small, and rarely open to the sea.

Biological communities in Cobbys Creek and Old Settlement Creek are likely to be dominated by freshwater and brackish species due to the creek's extended closure to the ocean for most of the time. In contrast, Soldiers Creek is more likely to support estuarine or marine species or those species with wide ranges of salinity tolerances. Three freshwater fish species have been recorded from LHI, including in estuaries, but only two of these have been found since 1989, the longfin eel (*Anguilla reinhardtii*) and the southern shortfin eel (*Anguilla australis*) (Reader *et al*., 2018). Importantly, these estuarine ecosystems support important, but highly restricted mangrove and salt marsh habitats (see Section 3.4).

Lagoon ecosystem

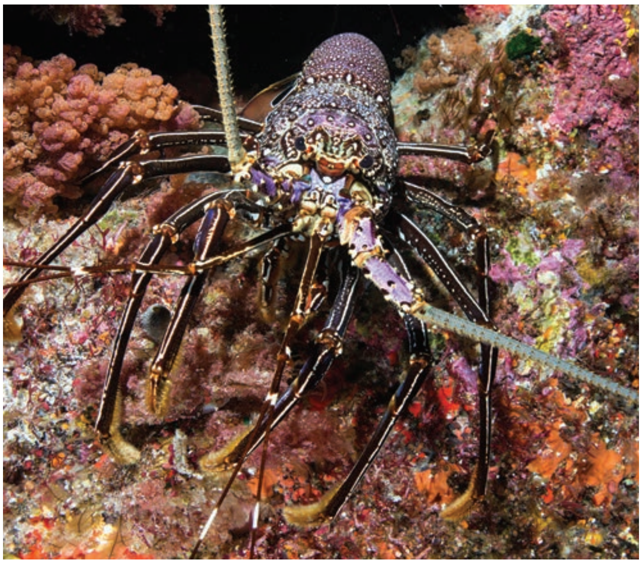
LHIMP includes lagoon reefs at depths of 10 m or less, located in the lagoon on the western side of LHI (Figure 6). The modern fringing reef here (including Comets Hole and Erscotts Hole) is the only 'true' coral reef in the LHIMP as defined by reef accretion and growth on the limestone of coral remains (see Section 3.2). Other rocky reefs also occur in the lagoon and support invertebrates, fish, encrusting algae and macroalgae.

99% of the beach and lagoon sediments in the LHIMP are composed of carbonates from skeletal remains of marine organisms (Haskoning 2004). The lagoon includes large expanses of carbonate sands, with smaller areas of black basalt sands at the southern end of the lagoon. These expanses support narrow bands of seagrass (see Section 3.4), as well as infaunal communities and scattered sessile and sedentary epifauna and macroalgae (Section 3.5). They are also important nursery and feeding grounds for fish and cephalopods (Hutton and Harrison 2004).

Intertidal and shallow subtidal ecosystems

Open coastal reefs extend from the intertidal zone to the inner shelf (0-30 m depth) around LHI and Balls Pyramid, including the fore slope of the LHI fringing reef, the Admiralty Islands, and additional smaller islands and islets (NSW Marine Parks Authority, 2010a).

There are five types of intertidal rocky shore in the LHIMP including basalt platform, basalt boulder, mixed boulder, calcium carbonate platform, and calcium carbonate boulder. Within each of these, intertidal biodiversity of solitary macro-invertebrates was assessed by Woods (2022) who found that boulder reefs generally supported highest levels of biodiversity, particularly calcium carbonate boulder and mixed boulder reefs formed by coral rubble (see Section 3.5).



The shallow subtidal ecosystems of the open coast are exposed to strong wave action, and although there are still abundant populations of scleractinian corals (Harrison *et al*., 1995), they grow directly on rock with little accretion. For shallow water benthic ecosystems, wave exposure has been identified as one of the drivers of marine fish, macro-invertebrates, and sessile organisms (Edgar *et al*., 2010). Rocky reefs also support macroalgae, encrusting algae and sessile habitat-forming invertebrates which in turn host a suite of fish and invertebrates, while unconsolidated sediments between reefs support communities of infauna, fish, scattered macroalgae, seagrass, and solitary corals, and other sedentary macrofauna.

Shelf ecosystems

Beyond the intertidal and shallow subtidal, the shelf ecosystem is predominately hard substrate, including relict reef that divides the inner and outer parts of the shelf (Kennedy *et al*., 2002, Brooke *et al*., 2010a, Linklater *et al*., 2018a) (Figure 6). This extensive relict reef supports low and sparse brown and green algae (Speare *et al*., 2004) and mesophotic corals (Linklater *et al*., 2018b). The outer shelf is predominately sand, with gorgonian communities anchoring on scattered rubble or exposed bedrock (Speare *et al*., 2004). The shelf ecosystem around Balls Pyramid included algal communities attached to the hard seafloor to a depth of 42 m, as well as numerous solitary corals (Speare *et al*., 2004). Three habitat types have been classified across the LHI shelf: coral reefs (see Section 3.2), macroalgal beds (see Section 3.4), and an offshore/open coast community (Edgar *et al*., 2010).

Slope ecosystems

Rocky reefs are common below 100 m along the outer shelf and slope ecosystems, noting that much of this ecosystem occurs outside of the LHIMP boundary. Biodiversity may be higher on the slope due to higher habitat complexity (e.g. rocky outcrops, walls, overhangs) and exposure to nutrient upwelling from ocean currents. Indeed, one of the few biological surveys along the slope revealed the most sightings of fish in the LHIMP region (Speare *et al*., 2004). Although several bathymetric surveys have comprehensively mapped the slope around LHI and Balls Pyramid (Linklater *et al*., 2018a), it remains more challenging to ecologically assess the seabed here due to difficulties sampling or imaging along steep walls or overhangs (but see Speare *et al*., 2004). Our knowledge of outer shelf and slope species and communities thus remains more limited than the other shallower ecosystems in the LHIMP area.

Pelagic ecosystems

The unique ocean circulation characteristics in the LHIMP (Section 2.2) support a mix of tropical and temperate pelagic species, including cetaceans, large fish and sharks, jellyfish, krill (*Thysanoessa gregaria*) and many other invertebrates and smaller fish (Hutton and Harrison, 2004). Pelagic communities are generally similar to those found throughout the rest of the Lord Howe Rise region and are described in more detail in NSW Marine Parks Authority (2010a). Several pelagic species are key natural values of the LHIMP and are also described more fully in the sections below.

3.2 Corals

Lagoon and open coastal fringing reefs

Coral reefs in the LHIMP are highly isolated from other reefs in the Lord Howe Rise region (Abrego *et al*., 2021). Earlier studies recorded more than 80 scleractinian coral species from the LHIMP (Harriott *et al*., 1995, Harrison, 2008, Veron and Done, 1979, Veron, 1993), and more recent collections on both fringing reefs and rocky substrate in deeper waters have increased the total number of species to ~100 (Baird and Bridge, personal communication). Following the discovery of a new species in the genus *Cyphastrea* in the LHIMP, Baird (2017) suggests that other new species might be found and that the scleractinian fauna is more distinct than previously recognized, with further taxonomic work required. The reef coral communities dominate much of the reef benthos, with positive calcification rates (Davis *et al*., 2020). They support unique associations of tropical species at their southern latitudinal distribution limits, subtropical species, that are rare or absent on tropical reefs, and some temperate coral species (Edgar *et al*., 2010, Harrison, 2008, Harrison *et al*., 2011). These high-latitude coral reefs are noteworthy for their relatively high proportion of live coral cover compared to other subtropical reefs (Dalton and Roff, 2013, Hoey *et al*., 2011) and positive (albeit slow) carbonate accretion (Harriott *et al*., 1995). Throughout the LHIMP, live coral cover has remained relatively stable over the last several decades (despite recent bleaching events, e.g., Dalton *et al*., 2020, Harrison *et al*., 2011), but there has been an almost 350% increase in coral cover between 1984 and 2017 at North Bay (Figure 7). However, some temporal shifts in dominant families (Acroporidae, Pocilloporidae and Poritidae) within coral communities inside the lagoon have been recorded (Dalton and Roff, 2013, Harriott *et al*., 1995, Hoey *et al*., 2011).

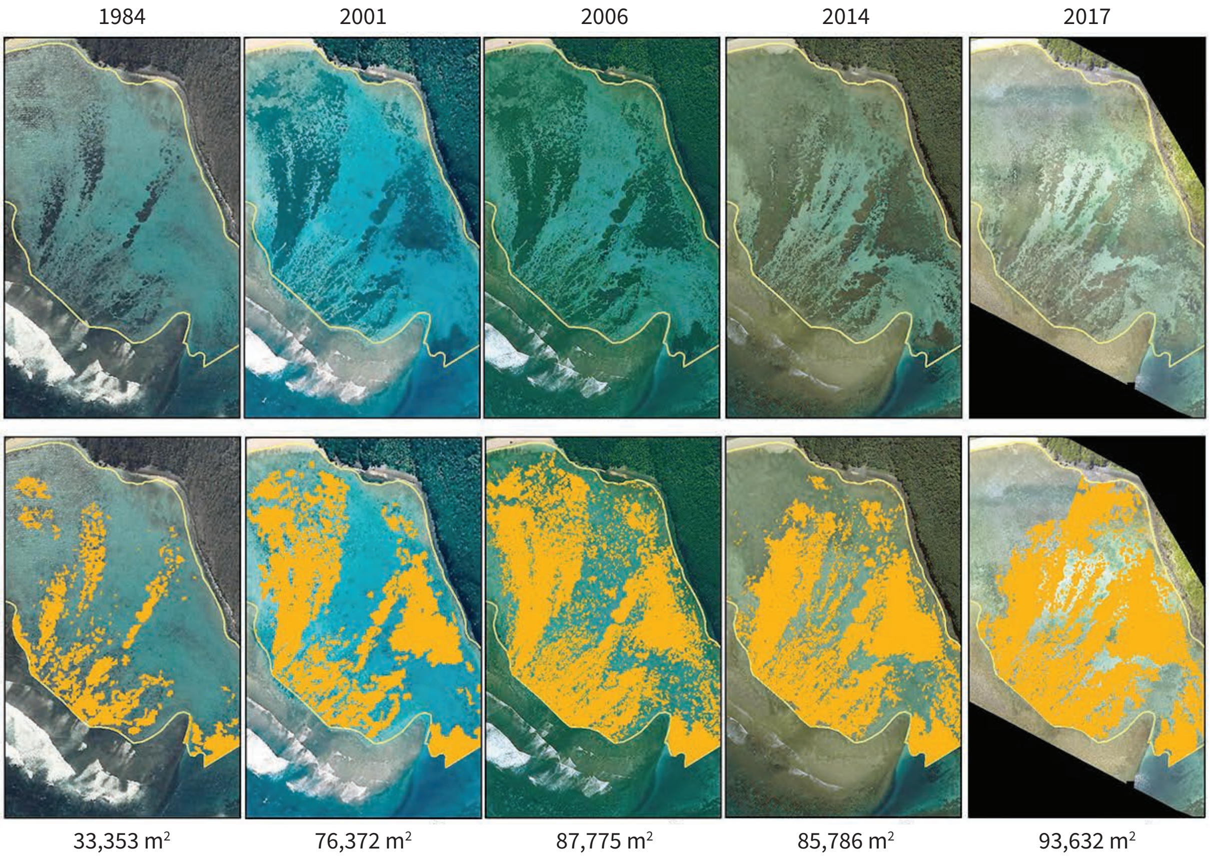


Figure 7: Coral cover in North Bay, LHI from 1984 to 2017 showing [top] aerial imagery and [bottom] automated classification area of coral cover in orange with total spatial area.
Images and data from Joe Neilson.

Coral bleaching events

Coral bleaching has been documented around LHI in 1998, 2010, 2011, and 2019. The earliest recorded coral bleaching event at LHI occurred during the 1998 austral summer when sea temperatures rose above 27°C; however, the bleaching event had limited impact on coral cover (Harrison *et al*., 2011). Following a fast phase-transition of the record-breaking 2009-10 warm-pool El Niño in the Central Pacific to a strong La Niña event in late 2010, the high-latitude coral and reef assemblages in the LHIMP were exposed to unprecedented successive marine heatwaves (Dalton *et al*., 2020). During the 2010 summer season, sea temperatures around LHI rose above 28°C (~2–3°C above normal summer maximum), with an accumulated thermal stress that exceeded 19-degree heating weeks (Dalton *et al*., 2020, Harrison *et al*., 2011). This thermal stress anomaly coincided with high light penetration and resulted in a severe coral bleaching event, with bleached coral cover exceeding 95% at the most affected sites within the lagoon (Dalton *et al*., 2020, Harrison *et al*., 2011). Species in the genera *Pocillopora, Stylophora, Seriatopora* and *Porites* were the most susceptible, while lower rates of bleaching and mortality were recorded among other coral families (e.g., Acroporidae, Dendrophyllidae, Merulinidae; Figure 8) (Dalton *et al*., 2020). Surviving corals underwent a subsequent, but much less intense, thermal anomaly in 2011 that led to a disproportionate bleaching response among susceptible taxa (Dalton *et al*., 2020).

Although live coral cover at most sites recovered to pre-bleaching levels within three years (Dalton *et al*., 2020), these events demonstrated that even the highest latitude coral reef assemblages are also susceptible to severe bleaching stressors, which could limit future reef development and predicted range shifts (e.g., Greenstein and Pandolfi, 2008). High macroalgal abundance (Hoey *et al*., 2011), low coral recruitment success (Keith *et al*., 2015) and slow growth rates (Anderson *et al*., 2015), may also restrict refugia potential under increased ocean warming. In 2019-20, coinciding with anomalously high sea surface temperatures across the reef system from January-April, LHIMP coral and reef assemblages were again exposed to a marine heatwave that resulted in severe coral bleaching, affecting up to 95% of corals in the inshore lagoon (Moriarty *et al*., 2019). Significant differences in bleaching prevalence were observed across the lagoonal coral reef, ranging from 16 to 83% across offshore and inshore reef regions and with variable onset timing. Coral mortality of up to 40% was recorded at the most severely impacted inshore region of the reef. The four most dominant species, *Stylophora pistillata, Pocillopora damicornis, Porites* spp. and *Seriatopora hystrix*, were the most susceptible to bleaching, with all coral colonies found to be bleached or dead at the most affected inshore site during and following peak heat stress (Moriarty *et al*., in reviewz). During the 2019 marine heat wave, octocorals were generally more resistant to bleaching than stony corals, although their susceptibility varied among species (Steinberg *et al*., 2022).

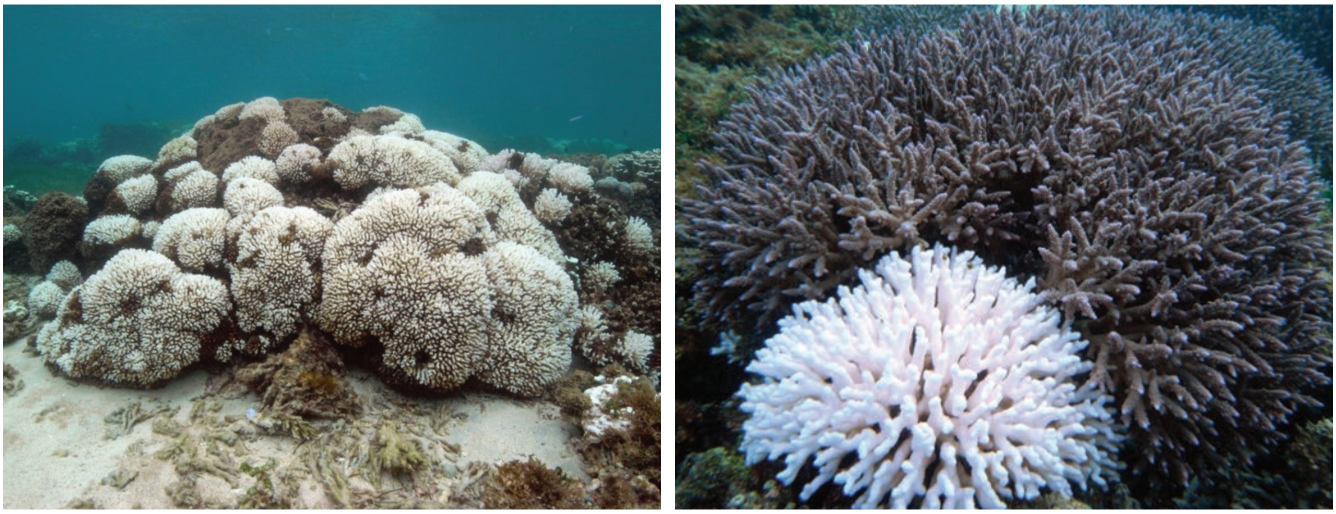


Figure 8: Coral bleaching at LHIMP during 2010 event, [left] extensive stands of bleached *Pocillopora damicornis* at North Bay and [right] severely bleached *Stylophora pistillata* coral adjacent to healthy *Acropora yongei*. Images from Steven Dalton.

Coral reproduction and recruitment patterns

Understanding coral reproduction and recruitment patterns that maintain and renew coral populations, is essential for determining the ability of corals to respond to changes in ocean temperatures and altered oceanographic conditions. Multi-species synchronous spawning events in the LHIMP occur following full moon periods during the austral summer (Keith *et al*., 2015, Woolsey *et al*., 2015), with reproductive activity of Acroporidae and brooding species highest in December and January (Baird *et al*., 2015, Harrison, 2008). These reproduction patterns are consistent with observations of settlement and recruitment activity in the LHIMP, with the greatest abundance of coral recruitment occurring during summer (Cameron and Harrison, 2016). The higher relative abundance of species that brood larvae in the LHIMP suggests that local retention of larvae is a key for population maintenance at this biogeographically and genetically isolated location (Noreen *et al*., 2009). Replenishment of coral populations is therefore likely to be dependent on local recruitment or the infrequent input of propagules from external reefs (Baird *et al*., 2015, Harrison, 2008, Keith *et al*., 2015).

Mesophotic corals on subtropical shelves

While coral research at LHI has historically focused on shallow reef communities, more recent studies have shown that the submerged shelves surrounding LHI and Balls Pyramid also include extensive fossil coral reefs and abundant extant coral communities (See Section 2.3). Mesophotic coral ecosystems (MCEs) are light-dependent benthic communities occurring in ocean depths ranging between ~30 m to the bottom of the photic zone (~100 -150 m) (Hinderstein *et al*., 2010, Kahng *et al*., 2014). MCEs have attracted growing interest in recent years, due to their unique biodiversity and potential to act as refugia for shallow coral reef taxa, subject to increased thermal stress (e.g. Turner *et al*., 2019). MCEs in Australia remain largely underexplored (Eyal *et al*., 2021, Turner *et al*., 2017), and this is particularly true for temperate, high-latitude mesophotic ecosystems. This lack of knowledge limits our ability to assess refuge potential by better understanding the link between mesophotic fish assemblages, habitat structure, benthic composition, and connectivity with shallow reefs (e.g., Williams *et al*., 2019).

The LHIMP supports relatively diverse MCEs (Figure 9), which have the potential to act as deep reef refugia under a changing climate (Linklater, 2016, Linklater *et al*., 2018b). The fossil reefs around both shelves occur at similar depths and cover approximately one-third of the shelf area (Linklater *et al*. 2019). Similar habitats occur across both shelves, with communities varying among inner-, mid- and outer-shelf zones (Section 2.3). Abundant scleractinian corals occur on the submerged reefs, extending to a maximum depth of 94 m at Balls Pyramid (Linklater *et al*. 2016). Corals are more prevalent on the south-western and eastern mid-shelf reefs around Balls Pyramid, with some locations around the LHI mid-shelf reporting similar coral cover (Linklater *et al*., 2018a). The prevalence of scleractinian reef-building corals on the submerged reef features at Balls Pyramid in particular, and the mesophotic depths to which these corals extend, highlight the significance of this subtropical island shelf as an important habitat for modern coral communities in the South Pacific Ocean (Linklater *et al*., 2016, Linklater *et al*., 2018b).

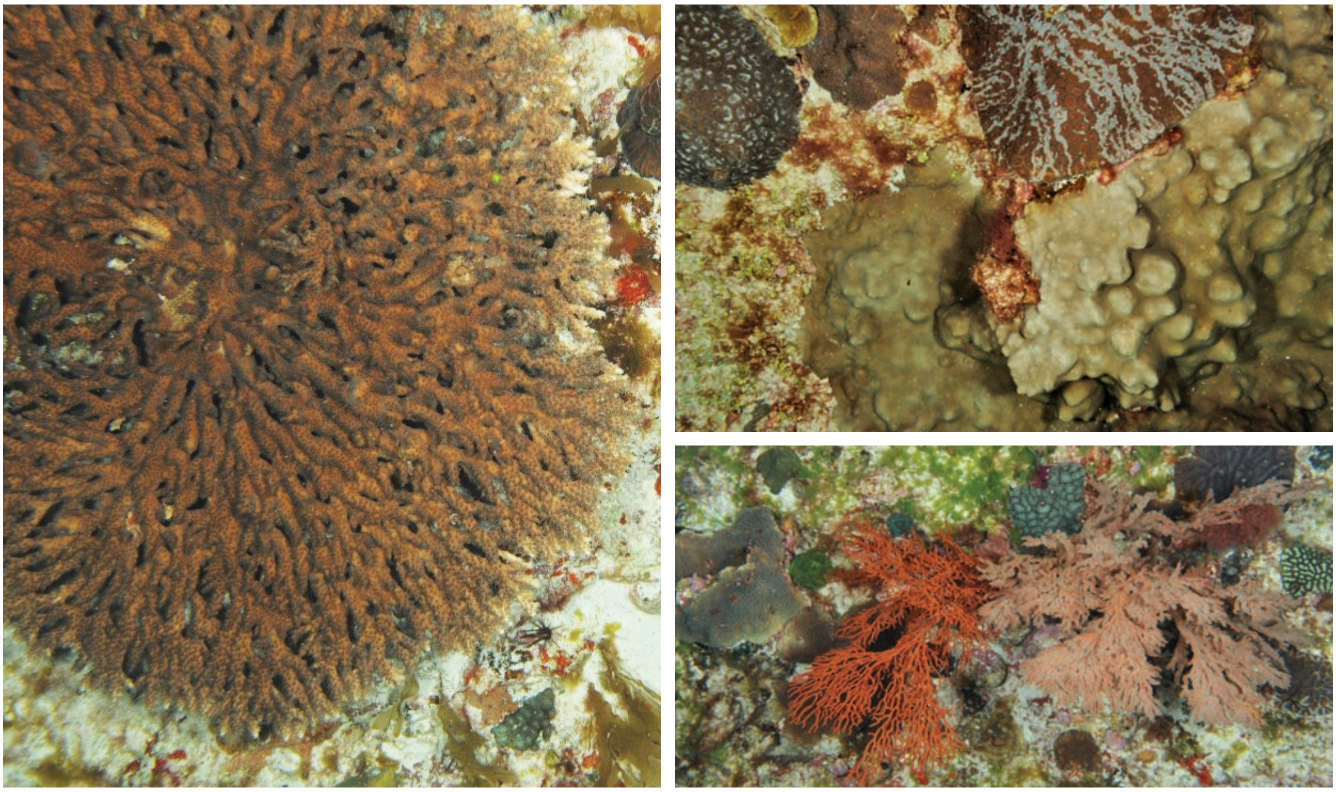


Figure 9: Mesophotic coral reefs of LHIMP, [left] tabulate *Acropora* sp. at 48 m depth, Balls Pyramid shelf, [upper right] hard coral-dominated seabed; encrusting and sub-massive scleractinian corals (e.g., *Dipsastraea* sp., *Oulophyllia* sp., *Porites* sp.) with *Halimeda* sp. and filamentous red algae, mid-shelf lower reef, 37 m depth, and [lower right] black coral and octocoral-dominated seabed; fans with encrusting scleractinian corals, encrusting green and calcareous red algae, mid-shelf upper reef, 34 m depth. Images from Geoscience Australia.

3.3 Fish

Biodiversity and biogeography

The LHIMP supports a highly diverse fish assemblage, with 537 coastal species identified to occur in the waters of the LHIMP (Francis, 2019). Given LHI's position on the Tasman front (Section 2.2), the region contains an unusual combination of tropical and temperate fishes. The majority of fish species are tropical with broad distributional ranges; however, temperate species dominate the total biomass of fishes (Edgar *et al*., 2010). Approximately 4% of the inshore fishes are endemic or near endemic to the LHI and Norfolk Island region, largely due to geographic isolation from other bioregions (Hobbs *et al*., 2009).

Larval recruitment dynamics and movement of adult fishes are likely to play key roles in structuring the LHI fish community. Between September and December, LHI is exposed to warm water pulses from the East Australian Current (Nilsson and Cresswell, 1980) (Section 2.2), transporting tropical fish larvae from the Great Barrier Reef and northern NSW. Many of these tropical species are presumed vagrants, lacking self-sustaining populations in the region (Edgar *et al*., 2010). In contrast, many warm temperate and sub-tropical fish are likely to have self-sustaining populations in the region. For example, using otolith chemical signatures, Patterson and Swearer (2008) found that approximately half of comb wrasse (*Coris picta*) individuals assessed at LHI were likely recruits from the New South Wales mainland coast, with the other half originating from LHI's waters. Larval connectivity also likely occurs from LHI to the NSW mainland coast (Edgar *et al*., 2010), as several abundant fish species in the LHI region occur in small numbers along the NSW mainland coast (Kuiter, 1993).

For fishes endemic to the LHI region, connectivity to surrounding reefs such as Elizabeth and Middleton reef (~150 – 200 km north) and Norfolk Island (~600 km east) appears limited. Genetic studies on the endemic doubleheader wrasse (*Coris bulbifrons*), three-striped butterflyfish (*Chaetodon tricinctus*) and McCulloch's anemonefish (*Amphiprion mccullochi*) have shown limited contemporary gene flow among locations and high levels of self-replenishment (van der Meer *et al*., 2015, van der Meer *et al*., 2012a, b). Similarly, a genetic study on the connectivity of wide-band anemonefish (*Amphiprion latezonatus*) populations on LHI, Norfolk Island and two coastal locations on mainland Australia found very high (>89%) self-replenishment across all locations with limited contemporary gene flow (Steinberg *et al*., 2016). Interestingly, populations of Galapagos whaler (*Carcharhinus galapagensis*), which are large and are considered to be highly mobile, from LHI are genetically distinct from the nearby Elizabeth and Middleton reefs (van Herwerden *et al*., 2008).

In contrast, analyses of otolith (earbone) chemistry of kingfish analysis indicates that although most adult kingfish from LHI likely originated from mainland spawning grounds, a relatively high portion of adults (28%) are likely to have originated from the waters of LHI and Elizabeth and Middleton Reefs (Patterson and Swearer, 2008). In a tag-recapture study of yellowtail kingfish, Gillanders *et al*. (2001) observed one individual from the mainland NSW coast recaptured at LHI.

Habitat associations

Research in shallow-water habitats (<30 m) surrounding LHI has demonstrated the importance of benthic habitats in structuring the fish assemblage and distributional patterns of key species and trophic groups (Edgar *et al*., 2010, Lindsay *et al*., 2008). Clear differences in shallow water fish assemblages have been observed among sheltered coral communities (Sylphs Hole and Comets Hole; Figure 3), macroalgal dominated communities (Algal Holes) and offshore rocky reef communities (Balls Pyramid and Admiralty Islands) (Edgar *et al*., 2010, Stuart-Smith *et al*., 2019). Herbivores were strongly associated with macroalgal habitats within the lagoon and Algal Holes site, with bluefish (*Girella cyanea*) and large spotted surgeonfish (*Prionurus maculatus*) comprising the majority of herbivore biomass. Offshore wave-exposed reef communities were dominated by planktivorous fishes, the splendid hawkfish (*Cirrhitus splendens*) and the Lord Howe Island butterflyfish (*Amphichaetodon howensis*). A range of tropical fish species were associated with coral communities and more sheltered areas, such as the lagoon (Edgar *et al*., 2010). For intertidal rock pool fishes, Davis *et al*. (2018) found a strong influence of pool volume, with larger pools having a significantly greater species richness. This result is most likely due to larger pools offering a greater range of microhabitats and higher structural complexity for fish to shelter from predation.

A number of studies have assessed the habitat associations of LHI endemic fishes, highlighting the importance of live coral cover and the lagoon for these species (Edgar *et al*., 2010, Hobbs *et al*., 2008). The density of three stripe butterflyfish (*Chaetodon tricinctus*) is greatest in the lagoon compared to outer reef habitats and positively correlated to the amount of live hard coral cover (Hobbs *et al*., 2008). Pratchett *et al*. (2014) observed larger aggregations of *C. tricinctus* on reef-sand boundaries, but generally near colonies of arborescent *Acropora*. Higher densities of doubleheader wrasse (*Coris bulbifrons*) have also been observed in the lagoon compared to outer reef sites; primarily driven by an abundance of juveniles in the lagoon (Hobbs *et al*., 2008). Similarly, higher densities of McCulloch's anemonefish (*Amphiprion mccullochi*) have been recorded in the lagoon compared to outer reef sites, and within the lagoon densities were greatest on reef edges compared to reef centres or patch reefs (Hobbs *et al*., 2008). These habitat types contain higher densities of the anemone *Entacmaea quadricolor*, the host species of McCulloch's anemonefish, and Hobbs *et al*. (2008) observed a strong positive relationship between densities of *E. quadricolor* and McCulloch's anemonefish. Likewise, in a study on the near endemic wide-band anemonefish, it was found that their abundance was positively correlated to the abundance of its host anemone (Steinberg *et al*., 2020).

In contrast to the shallow water environment, only a few studies have explored habitat associations of deep-water fishes (>30 m) surrounding LHI. As these habitats are beyond the depth limits of SCUBA, remote survey methods such as baited remote underwater video (BRUVs) and towed underwater video systems have been used (Rees *et al*., 2021, Speare *et al*., 2004) (Figure 10). Apart from one deployment in the lagoon, Speare *et al*. (2004) deployed 22 BRUVs between depths of 37 m and 66 m surrounding LHI and Balls Pyramid. They found two relatively distinct fish assemblages, one associated with algal dominated communities and the other deeper sandy seafloors. The hard-bottom algal-dominated community were characterised by silver trevally (*Pseudocaranx dentex*), blackspot pigfish (*Bodianus unimaculatus*) and comb wrasse (*Coris picta*) while the open sandy seafloors of deeper waters were dominated by Galapagos whaler sharks (*Carcharhinus galapagensis*), large stingrays (*Dasyatis brevicaudata, D. thetidis,* and *Taeniura meyeni*) and silver toadfish (*Lagocephalus sceleratus*).

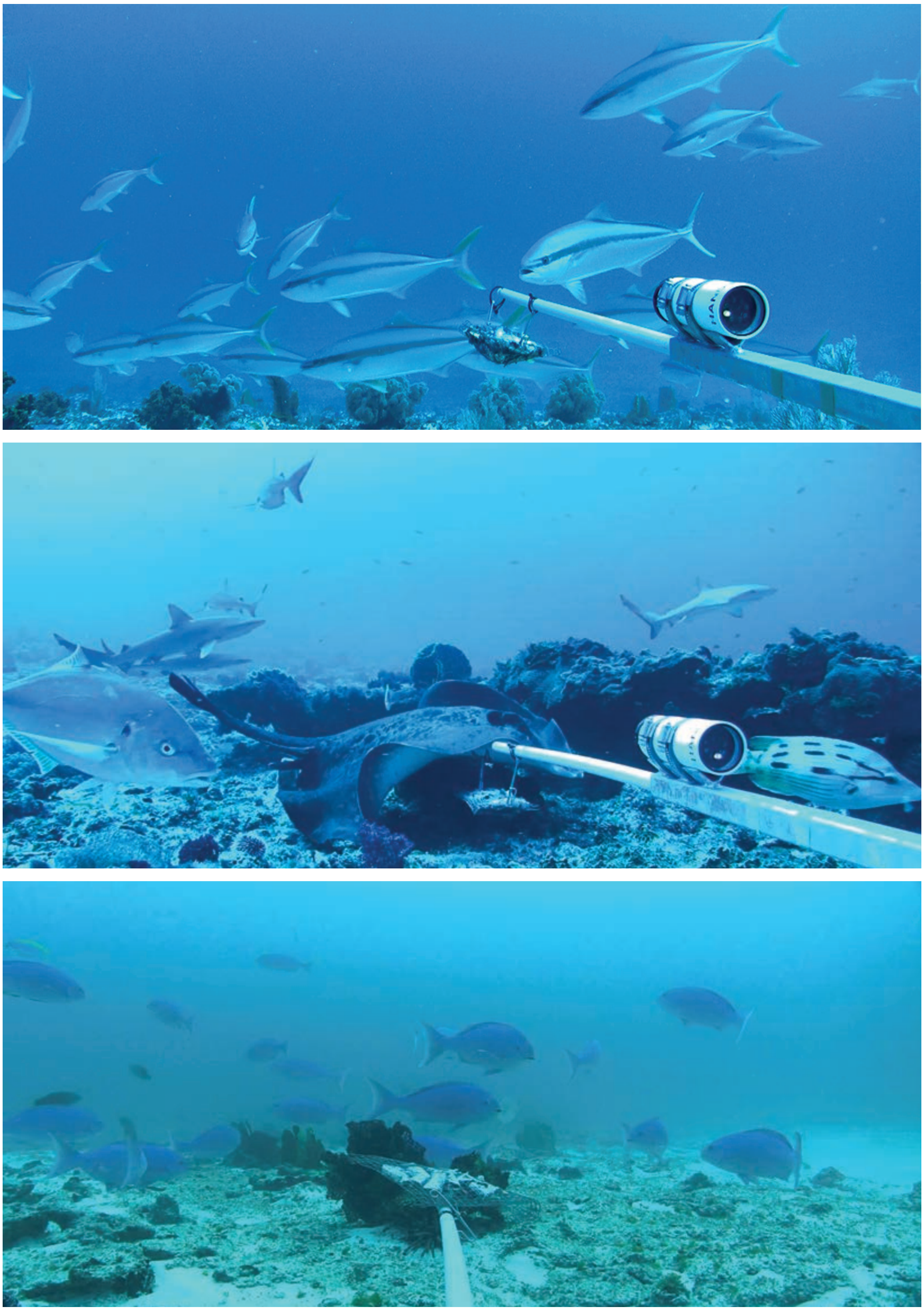


Figure 10: Footage from baited remote underwater video (BRUV) deployed in the LHIMP, [top] yellowtail kingfish from 2013, [middle] silver trevally, pigfish, blotched fantail ray and Galapagos whalers from 2013, [bottom] bluefish from 2009.

Spatial patterns in fish assemblages on the LHI and Balls Pyramid shelf (26 – 50 m) have also been assessed during NSW DPI's long-term BRUV monitoring program. Most notable is the low diversity and abundance in fish assemblages at site 1 and 2 on the Balls Pyramid shelf (Figure 11). This result is most likely due to these sites being deeper and lacking biotic cover compared to the other survey sites (Neilson *et al*., 2010). Many of the NSW DPI's long term BRUV monitoring sites have consistently high abundances of particular fish species through time. For example, bluefish (*Girella cyanea*), were recorded in relatively high abundances at site 5 and 6 (Figure 11), which is likely driven by these sites being shallower and in close proximity to LHI (Rees *et al*., 2021). Greater abundances of yellowtail kingfish (*Seriola lalandi*) have been observed on shelf habitats with greater topographic complexity (Rees *et al*., 2018). This result is likely due to seafloor habitats of greater structural complexity providing increased prey (baitfish) and favorable abiotic conditions such as high current speeds (Heagney *et al*., 2007). Similarly, more Ballina angelfish were observed at deeper sites (Rees *et al*., 2021, Speare *et al*., 2004). These results suggest that *C. ballinae* may be more common than what was previously thought. Speare *et al*. (2004) observed greater fish sightings at mesophotic depths. Interestingly, sightings included large unidentified groupers from the Epinephelinae family, large yellowtail kingfish (*Seriola lalandi*), redfish (*Centroberyx* species) and rosy jobfish (*Pristipomoides multidens*). These observations highlight the need to assess the habitat associations of fishes deeper in the mesophotic zone surrounding LHI and Balls Pyramid.

Only one study has examined spatial patterns in mid-water fish assemblages. Heagney *et al*. (2007) used pelagic BRUVs suspended in the mid-water 10 m from the surface and found Galapagos whalers (*Carcharhinus galapagensis*), amberjack (*Seriola rivoliana*) and blue mackerel (*Scomber australasicus*) were associated with low current speed environments, while yellowtail kingfish (*Seriola lalandi*) were associated with the higher flow environments.

Fisheries species

Several species of fish are important for the LHI fishery and recreational fishery. Both fisheries operate in the state and Commonwealth parks, subject to zoning and management regulations. The LHI fishery includes fishing vessels (commercial charter & smaller private vessels) based on LHI, and it has a commercial element in which retained catch is sold for consumption on LHI (Figueira and Harianto, 2022). The fishing method is hook and line, and the commercial export of fish from LHI is prohibited. The LHI fishery is managed through the LHIMP Management Rules, Fisheries Management Act regulations, and Temperate East Network Management Plan. Size and bag limits apply to all fishing activities as specified in the Fisheries Management Act and regulations with additional daily bag limits specified in the LHIMP Management Rules for: doubleheader (one fish), bluefish (five fish), spangled emperor (two fish) and scorpion fish/red rock cod/bucket head (two of any one species). Prohibited fishing methods in LHIMP include trawling, long-lining, drop-lining and dredging. Other methods restricted in these waters include all forms of nets (except dip and scooping) and spearfishing.

The available catch reporting information for the LHI fishery, for the period between 2004- 2018 indicated a diversity of fish species caught in the fishery, being either retained or released. Yellowtail kingfish accounted for over half of the total LHI fishery catch, the Galapagos whaler was the second most frequently caught species accounting for approximately a quarter of the catch and silver trevally was the third most reported caught species (Figueria and Harianto, 2022). Silver trevally are currently defined as depleted in NSW waters, and the biological stock structure of silver trevallies is uncertain (FRDC, 2022).

The primary target species in the LHI region is yellowtail kingfish, which is a large bodied predatory species belonging to the family Carangidae. Given their high abundance in the region, size and sportfish status, the LHI region is a renowned hotspot for yellowtail kingfish which attracts domestic and international fishers to the island. Yellowtail kingfish are regarded as excellent eating and the retained catch from the fishery is sold to restaurants on LHI. Most of the fishing effort for yellowtail kingfish occurs on the shelf, shelf edge and nearshore habitats of LHI and Ball's Pyramid (Figueria and Harianto, 2022; Mitchell *et al*., 2021). Estimated landings of yellowtail kingfish in the LHI fishery have ranged from 12 to 24 tons per year between 2004 and 2018 (Figueira and Harianto, 2022). As a comparison, the NSW mainland reported commercial catch was 76 tons in the 2018/19 reporting year (Hughes and Stewart, 2021).

Yellowtail kingfish in the LHI region are considered part of the eastern Australian stock (Hughes and Stewart, 2021) which extends as far as New Zealand (Miller *et al*., 2011). Other key species harvested in the fishery on shelf and shelf edge habitats include red rock cod (*Scorpaena cardinalis*), redfish (*Centroberyx* spp.), wahoo (*Acanthocybium solandri*), yellowfin tuna (*Thunnus albacares*) and silver trevally (*Pseudocaranx dentex*) (Figueira and Harianto, 2022).

The LHI lagoon and nearshore environments are other areas targeted by the LHI fishery and recreational fishers. Between 2004 and 2018, two charter boat vessels focused much of their fishing effort in the LHI lagoon, where catch typically consists of yellowtail kingfish (23%), pacific chub (17%), silver trevally (17%), doubleheader wrasse (10%) and bluefish (9%) by weight. Approximately 68% of catch in the lagoon by the LHI fishery is released (Figueira and Harianto, 2022). Similarly, the LHI lagoon is a popular area for recreational fishing, where anglers target the region's iconic species – bluefish and doubleheader wrasse. Fishers also target eastern garfish in the lagoon, which are considered good eating and an excellent bait. LHI offers excellent land-based recreational fishing opportunities for yellowtail kingfish, yellowfin tuna and other more coastal species, such as pacific chub (*Kyphosus sectatrix*) and bluefish (*Girella cyanea*).

More recently, fishers have been using jigs and electric reels to target deep-water (>150 m) demersal species, many of which are considered long-lived species with slow growth rates and late maturity. (Koslow *et al*., 2000) Species caught include flame snapper (*Etelis coruscans*), bar cod (*Epinephelus ergastularius*), blue-eye trevalla (*Hyperoglyphe antarctica* and *Schedophilus labyrinthica*), redfish (*Centroberyx* spp.), ray's bream (*Brama brama*) among others, all of which are regarded as high-value table fish.

Contemporary changes

Temporal variation in fish populations at LHI have been examined through two ongoing monitoring programs: Baited Remote Underwater Video surveys (BRUVs) conducted by NSW DPI and underwater visual census surveys (UVCs) by the Reef Life Survey (RLS) Foundation. RLS surveys were generally restricted to depths < 25 m, thereby complementing the BRUVs program which examined fish assemblages at greater depths (26–50 m) (Figure 11). Assessment of fish assemblages by BRUVs were completed on the LHI and Balls Pyramid shelf in 2009 (Neilson *et al*., 2010), 2013 (Rees, 2013) and 2017 (Davis *et al*., 2017). The primary objectives of the BRUVs surveys were to examine spatial and temporal patterns in fish assemblages for depths from 26–50 m, including the effectiveness of marine park zoning. Sampling in 2009 was conducted in November at a core set of sites (Sites 1–16, Figure 11), while sampling in 2013 was conducted in April at the core sites and an additional 5 sites (17–21, Figure 11) and sampling in 2017 was conducted from October–December at the core sites and at 2 additional sites (19 and 22, Figure 11). Analysis of the 2009–2017 BRUVs data identified no clear changes in the total abundance and diversity of fishes through time. Similarly, the abundance of common species, such as the conspicuous angelfish (*Chaetodontoplus conspicillatus*), comb wrasse (*Coris picta*), luculentus wrasse (*Pseudolabrus luculentus*), darkvent leatherjacket (*Thamnaconus analis*) and fished species, yellowtail kingfish (*Seriola lalandi*) and silver trevally (*Pseudocaranx dentex*) remained stable through time. There was a declining trend in the number of bluefish (*Girella cyanea*) and black

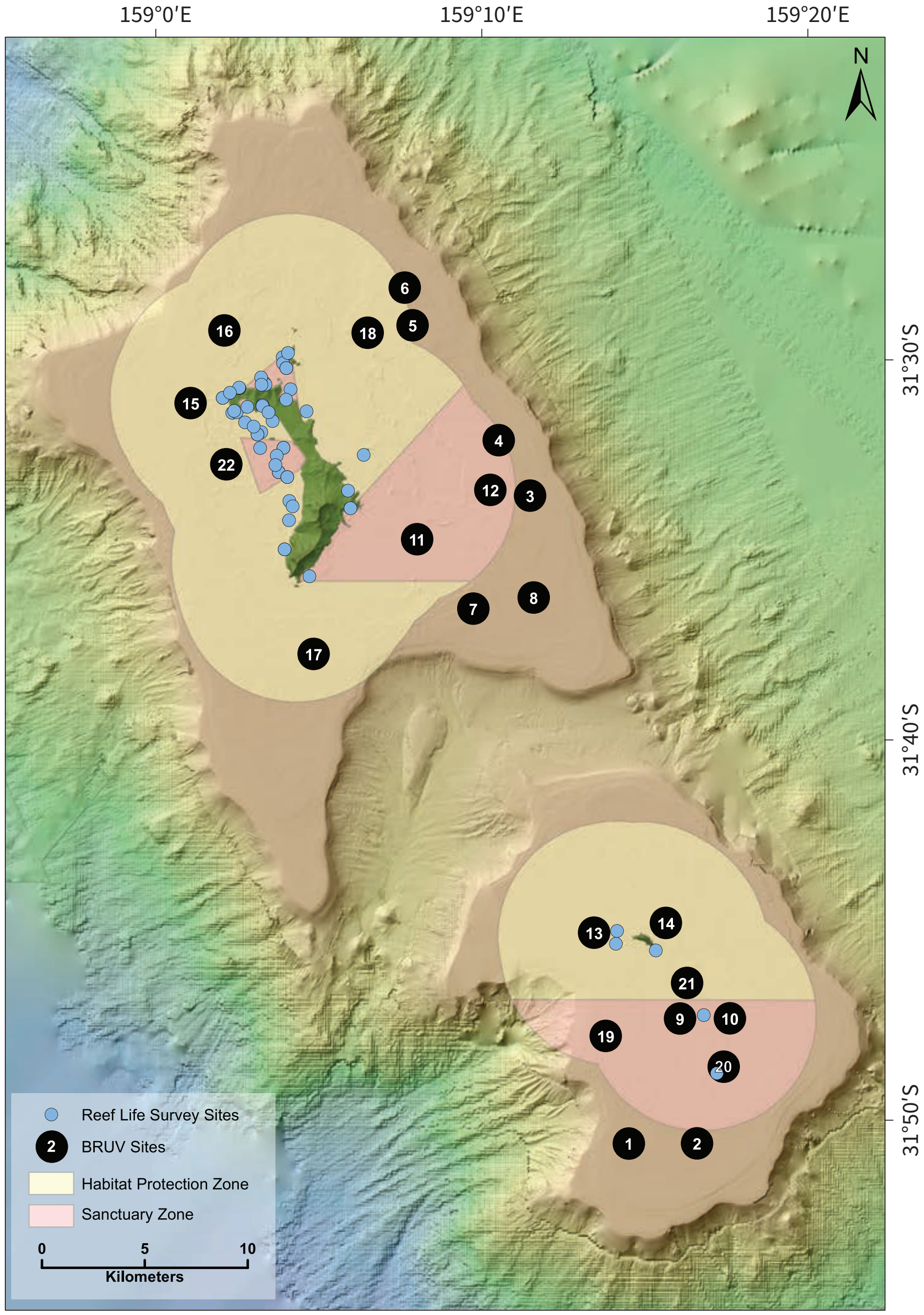


Figure 11: Map showing sites for Lord Howe Island baited video surveys of fish assemblages. Sites 1 to 16 surveyed in 2009 (Nielson *et al*., 2010), sites 1–21 in 2013 (Rees, 2013), sites 1–16, 19 and 22 in 2017 (Davis *et al*., 2017) and Reel Life Survey visual census sites (Blue circles).

rockcod (*Epinephelus daemelii*) through time. However, as these species were recorded in low numbers, a more targeted monitoring program is required to accurately assess these trends (Rees *et al*., 2021).

Underwater visual census (UVC) surveys of fish assemblages, mobile invertebrates and habitats at LHI were conducted in 2006 and 2008 by Aquenal Pty Ltd (Stuart-Smith *et al*., 2019) and continued by RLS in 2009, and every two years from 2010–2020. All UVC surveys examined fish and mobile invertebrate abundances and assemblages, and recorded benthic habitat using the standardized RLS survey methodology along 50 m belt transects (Stuart-Smith *et al*., 2019). Examination of UVC survey data and trends from 2006–2018 identified that fish community structure was generally very stable throughout all survey years (Stuart-Smith *et al*., 2019). However, significant variations in abundance were observed for some species, with low numbers of bluefish and doubleheader wrasse potentially of concern, with targeted research recommended to better understand population dynamics for these species (Stuart-Smith *et al*., 2019).

Marine Park protection

Remote oceanic islands often display disproportionally high levels of biodiversity and endemism, making them globally important locations for marine parks aimed at conserving biodiversity (Allen, 2008). As identified by Edgar *et al*. (2014) global study on marine park effectiveness, the LHIMP displays a number of key attributes shown to enhance conservation benefits for fishes. These include no-take (sanctuary) zoning, high compliance, and zones that have been established for >10 years. Although the 'Lord Howe Island Lagoon Sanctuary Zone', 'North Bay Sanctuary Zone' and the 'Neds Beach & Admiralty Islands Sanctuary Zone' are relatively small in size, the 'East Coast and Shelf Sanctuary Zone' and 'Balls Pyramid Sanctuary Zone' are adjacent to Commonwealth no-take zones and are >100 km² in area (Figure 2). Importantly, no-take zones of this size were also identified as a key feature for effective marine park protection for fishes (Edgar *et al*., 2014).

In comparison to marine parks at similar latitudes on mainland Australia (Solitary Islands and Port Stephens-Great Lakes Marine Parks), the abundance of higher order predators is much greater in the LHIMP (Malcolm *et al*., 2007, Rees *et al*., 2021). Similarly, the LHIMP has been identified as a global hotspot for carcharhinid reef sharks (MacNeil *et al*., 2020), driven by the exceptionally high abundance of Galapagos whalers.

Few studies have tested changes in fish assemblages between LHIMP's no-take sanctuary zones and partially protected habitat protection zones using either fish data from the Reef Life Survey UVC or NSW DPI's BRUV monitoring program. Stuart-Smith *et al*. (2019) provides the most recent analysis on changes in the fish assemblage between management zone types using the Reef Life Survey data collected between 2006 and 2018. Here, the authors found no significant zone type by year interaction for all fish metrics examined. That is, there was no strong evidence of increasing fish biomass, diversity and densities of trophic groups and species through time in sanctuary zones (SZ) relative to habitat protection zones (HPZs). However, effects of zoning were observed for higher-order carnivores, planktivores and spotted sawtail (*Prionurus maculatus*), where greater densities were observed in SZs compared to HPZs through time.

Analysis of the 2009–2017 data from the NSW DPI BRUV monitoring identified no clear changes in fish assemblage, diversity, total abundance and abundance of key species between SZs and HPZs within the LHIMP and Commonwealth LHMP (Rees *et al*., 2021). This lack of change was attributed to the relatively pristine environment and minimal current human threats to fish assemblages on shelf habitats in the region. However, using NSW DPI 2009 and 2013 BRUV data, (Rees *et al*., 2018) demonstrated greater abundances of yellowtail kingfish inside SZs compared to HPZs on reefs of high structural complexity. This result is most likely driven by differences in fishing pressure between SZs and HPZs, and structurally complex reef being optimal habitat for yellowtail kingfish.

3.4 Macrophytes

The marine macroalgae of LHIMP (Figure 12) is diverse and primarily tropical Indo-Pacific (Kraft, 2000) with a mix of temperate species (see www.algaebase.org), including the following:

- Brown algae (Phaeophyta) from at least 11 genera and 22 species of which two are endemic (Allender and Kraft, 1983) (see Kraft 2009 for broader brown algae catalogue including southern Great Barrier Reef);
- Green algae (Chlorophyta) from at least 32 genera and 71 species, of which 12 are endemic (Kraft, 2000) (see Kraft 2007) for broader green algae catalogue including southern Great Barrier Reef); and
- Red algae (Rhodophyta), is one of the more diverse algal groups of LHIMP, including the family Solieriaceae (Gabrielson and Kraft, 1984) (see Millar and Kraft 1993 for broader red algae catalogue including waters off mainland NSW).

As with coral and other benthic species, several species of macroalgae occur at their southernmost distribution limits at LHIMP (Burnell *et al*., 2013). The LHIMP holds the world's highest latitude populations of the genera *Neomeris, Boodlea, Valoniopsis, Ventricaria* and *Trichosolen*, and is the site of the highest latitude populations of particular species in the genera *Halimeda, Polyphysa, Caulerpa, Chaetomorpha, Chlorodesmis, Codium, Avrainvillea, Struvea* and *Dictyosphaeria* (Ceccarelli, 2010). Hoey *et al*. (2011) found that macroalgae covered 20.9% of benthic communities in lagoon depths of 1 – 10 m surpassed in this environment only by scleractinian coral (37.4%). The southernmost reef crest and slope had an extremely high cover of macroalgae dominated by *Caulerpa* (Chlorophyta), which covered over 30% of this area (Hoey *et al*., 2011).

Caulerpa, a genus of green macroalgae, had declined in all habitats by 2018 after a large increase in cover during 2010-2014 (Stuart-Smith *et al*., 2019). Macroalgae has declined at the Algal Holes sites based on results from UVC, with the risk of extinction of endemic macroalgae of concern (Stuart-Smith *et al*., 2019). Macroalgal losses have been linked to urchin outbreaks, particularly of *Tripneustes gratilla* at wave-exposed sites and *Heliocidaris tuberculata* at sheltered sites. Consequently, ongoing monitoring using UVCs has been recommended to more closely track urchin densities, algal cover and populations of key endemic fish species (Stuart-Smith *et al*., 2019).

LHIMP supports two species of seagrass (*Zostera muelleri* subspecies *capricorni* and *Holophilas ovalis*) (Figure 13) that play key ecological roles in sediment stability, foraging, and habitat provision to fish, invertebrates, seabirds, and turtles (Hutton and Harrison, 2004). Seagrass beds occur in the lagoon along western LHI, with highest densities at the northern end of the lagoon (Hunter and North Bays), as well as at more exposed eastern LHI sites including Neds Beach (NSW Marine Parks Authority, 2010a). Seagrass may be temporally variable in the

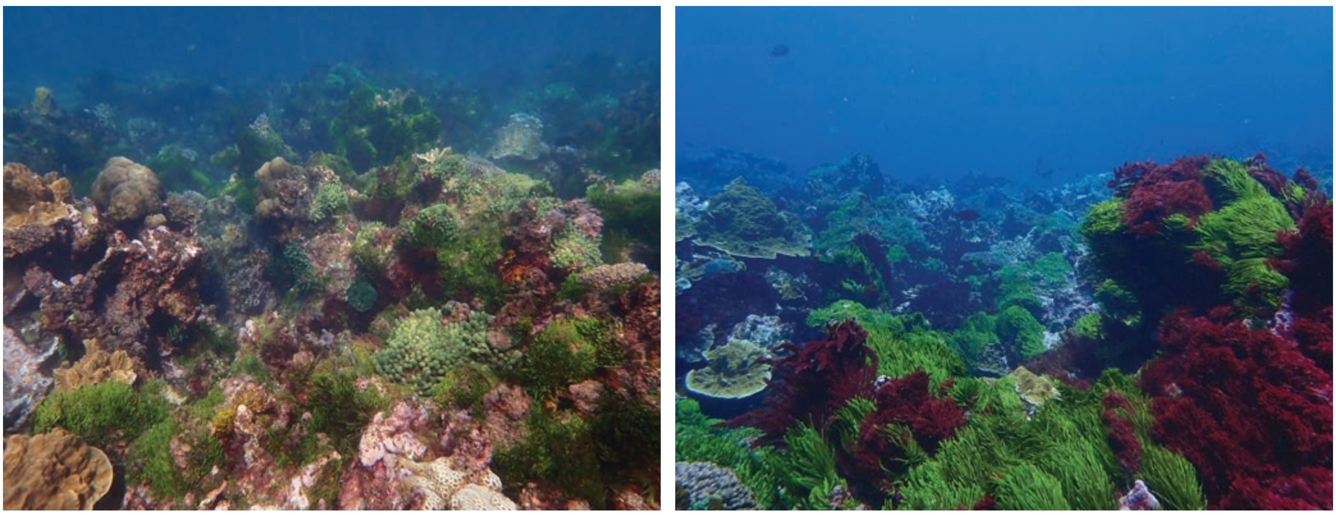


Figure 12: Macroalgal beds at Algal Holes, Lord Howe Island, showing a mix of green and red algae including *Caulerpa* species.

region due to winter dieback or other environmental stressors (NSW Marine Parks Authority, 2010a).

Two species of mangrove occur in the LHIMP, the grey mangrove (*Avicennia marina* subsp. *australasica*) and the river mangrove (*Aegiceris corniculatum*, Figure 14), which provide habitat to estuarine and marine species, stabilize sediments and riverbanks, and improve water quality. *Avicennia marina* is rarer and extremely restricted, with grey mangrove woodland identified only at the mouth of Old Settlement Creek, while *A. corniculatum* is more widespread along all three estuaries (Sheringham *et al*., 2016).

Figure 13: Seagrass of LHIMP, [left] diver over *Zostera muelleri* subspecies *capricorni* and [right] *Holophilas ovalis* and Clouded Saury (*Saurida nebulosa*).

LHIMP contains small patches of coastal saltmarsh along Old Settlement Creek (Sheringham *et al*., 2016). Coastal saltmarsh in adjacent NSW bioregions is listed as an endangered ecological community under the *Biodiversity Conservation Act 2016*. This saltmarsh is characterized by saltwater couch (*Sporobilis virginicus*) and the grey mangrove (*Avicennia marina* subsp. *australasica*) and is floristically equivalent to the endangered saltmarsh communities along mainland NSW (Sheringham *et al*., 2016).

Figure 14: River mangroves (*Aegiceris corniculatum*) in Cobbys Creek. Image from Justin Gilligan.

3.5 Marine invertebrates (non-coral)

Invertebrate communities in the LHIMP are a mix of tropical, temperate and endemic due to the unique combination of physical natural values influencing the LHIMP (Section 2). Endemism occurs across a range of taxonomic groups (e.g. echinoderms in O'Hara (2008), heterobranch sea slugs in Nimbs *et al*. (2020), Figure 15) and is particularly high for infauna (Anderson *et al*., 2013) and intertidal species (Woods, 2022). In a recent study of rocky shore macro-invertebrates in the LHIMP, 11% of all recorded species were endemic and up to 75% in some groups such as polyplacophorans (Woods, 2022). One endemic marine invertebrate, the abalone *Haliotis rubiginosa*, is listed as Critically Endangered under the IUCN Redlist (Section 3.6). Other endemic invertebrate species may also be vulnerable to extinction (Woods, 2022) however, poor overall knowledge about invertebrate taxonomy and distribution inhibits the assessment of most invertebrate species (Pippard *et al*., 2017).

On rocky shores in the LHIMP, there is high biodiversity of invertebrates, with 216 species recorded from 15,600 m2 of reef habitat (Woods, 2022). An earlier survey to sample intertidal and subtidal invertebrates yielded 113 samples from six sites (Reid *et al*., 2017). Each of the five rocky shore habitats in the LHIMP (Section 3.1) supports distinct communities or biodiversity characteristics (Woods, 2022). Less is known about intertidal biodiversity around Balls Pyramid, but basalt boulder fields and platforms at its base may also support populations of endemic species.

On subtidal reef communities, invertebrate species richness has remained relatively consistent from 2006 to 2018 and shows no significant difference between sanctuary and habitat zones (Stuart-Smith *et al*., 2019). However, fluctuations in the populations of some subtidal species have occurred, including urchins and crown-of-thorns starfish (COTS), with potential flow-on effects to benthic and other marine communities (Taylor, 2003).

Urchins are a well-known boom-and-bust group, and populations of *Tripneustes gratill*a underwent an 'explosive outbreak' in northern LHI in 2008 (Valentine and Edgar, 2010). Although very few individuals were detected in 2016 and 2018, macroalgal cover due to the outbreak remains low (Stuart-Smith *et al*., 2019). Several studies have examined the role of urchins in macroalgae and coral recruitment (Edgar *et al*., 2011, Valentine and Edgar, 2010, Hoey *et al*., 2011) which require baseline knowledge of urchin distribution and habitat preferences. The sea urchin *Tripneustes gratilla* is a dominant herbivore at wave-exposed sites while *Heliocidaris tuberculata* is a dominant herbivore at sheltered sites (Stuart-Smith *et al*., 2019) (Figure 16).

Figure 15: Sea slugs of LHIMP, [left] *Phyllodesmium* sp. and [right] *Thuridilla splendens*. Images from Matt Nimbs.

Figure 16: Sea urchins of LHIMP, [left] *Heliocidaris tuberculata* and [right] *Tripneustes gratilla*.

Reef Life Survey has been collecting data on subtidal invertebrates in the LHIMP since 2006 (Edgar *et al*., 2011, Stuart-Smith *et al*., 2015, Stuart-Smith *et al*., 2019) (see Figure 11 for sites in LHIMP), and this has been used to investigate broadscale patterns and identify new species and distributions. Intertidal lagoonal reef communities (Woods, 2022) and macroalgal communities at Algal Holes (Edgar *et al*., 2010) have a greater level of threat to biodiversity, the latter due to high susceptibility from potential impacts of global warming and urchin outbreaks (Section 4).

Our understanding of the small macrofauna of LHIMP comes from larger regional studies (Przeslawski *et al*., 2011, Anderson *et al*., 2011) and a survey undertaken in 2008 on shelf sediments of LHI that revealed overall low infaunal species richness, but a high proportion of rare, new and endemic species (Anderson *et al*., 2013). Lagoonal sediments support an impoverished assemblage with a reduced trophic structure indicative of harsh physical environments, while topographically raised sites exposed to oceanic currents support high densities of suspension feeders and the highest levels of infaunal diversity recorded in the LHIMP (Anderson *et al*., 2013). Infaunal communities in the LHIMP seem to be driven by the distribution and character of sandy substrates and local oceanographic conditions as determined by the irregular shelf morphology (Brooke *et al*., 2010a). No studies on the microbial or meiofaunal communities of the LHIMP were identified for this review.

3.6 Threatened and protected species and communities

This section relates to those LHIMP species that are listed as threatened or protected under the NSW *Fisheries Management Act 1994* and the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999*, the latter of which includes marine mammals, marine reptiles, and seabirds as listed threatened species.

Black rockcod

The black rockcod (*Epinephelus daemelii*) is a large reef dwelling cod species belonging to the family Serranidae. In Australia, the black rockcod is also known as black cod or saddled rock cod, and in New Zealand it is generally referred to as spotted black grouper. Black rockcod are somewhat similar in appearance to a number of other large *Epinephelus* sp. and the colour pattern of black rockcod is highly variable and can change quickly from a uniform dark grey-black to a blotched or distinctively banded dark and light pattern (Figure 17).

Figure 17: Black rockcod of LHIMP showing colour variation.

The black rockcod was once a widespread species along the NSW coast (Roughly, 1916). However, from the 1950s through to the late 1970s, spearfishers at various locations along this coastline heavily targeted this species (Andrewartha and Kimp, 1968). They were also caught by line-fishing and regarded as an excellent eating fish. This concentrated spearfishing effort combined with line fishing impacts led to a noticeable decline in black rockcod numbers, and NSW DPI was approached by concerned divers to protect the species in the late 1970s.

Even though there was limited information on black rockcod available at the time, it was recognised as being under threat, and the species was afforded total protection in 1983 under NSW Fisheries legislation in all NSW waters, which includes LHI. It is currently listed as 'Vulnerable' under the *NSW Fisheries Management Act 1994*. Under the Act, a maximum fine of $55,000 applies for anyone who harms, buys, sells or possesses a black rockcod. Additionally, the species is classified as 'Near Threatened' under the IUCN Red List (Pollard and Sadovy, 2018). Due to overfishing in past decades, it is now unusual to find large black rockcod in areas where they were once common across mainland NSW (Francis *et al*., 2015).

There are several key threats that have been identified in relation to black rockcod. Hook and line fishing in areas important for the survival of threatened fish species, including the black rockcod, is listed as a key threatening process under the *NSW Fisheries Management Act 1994*. It is recognised that black rockcod are very susceptible to barotrauma, particularly when caught in depths of greater than ~ 30 m (Francis *et al*., 2015). Impacts on juvenile black rockcod may also occur due to the loss or degradation of estuarine and rocky inter-tidal nursery habitats where they are known to frequent (NSW Department of Primary Industries, 2012; Harasti *et al*., 2014).

Surveys for black rockcod on reefs around LHI were undertaken in 2011 and 2019 to assess abundance and size distribution of black rockcod (Harasti *et al*., 2011). Surveys were undertaken by using timed swims on SCUBA or snorkelling. In 2011, a total of 18 sites were surveyed with 12 black rockcod observed at eight sites (Harasti *et al*., 2011). The average length of black rockcod was 49.3 cm with the largest fish estimated by diver to be 110 cm and the smallest measured at 26.3 cm using stereo-video photogrammetry. Surveys in 2019 found significantly less black rockcod, with only 6 individuals observed occurring at 6 sites (Harasti & Malcolm, unpublished data). The average length in 2019 was 62.2 cm, with the largest fish estimated by diver to be 135 cm and the smallest stereo measured at 35 cm. Black rockcod were found residing in a variety of habitats within the LHIMP with overhangs and coral reef considered to be an important habitat for black rockcod in the LHIMP. Similarly, overhangs were considered to be an important habitat for black rockcod in sites along the NSW north coast (Harasti and Malcolm, 2013).

Sampling with BRUVs undertaken in deeper waters around LHI in 2009, 2013 and 2017 recorded from 7-10 adults on the mid and outer Lord Howe shelf, resulting in the discovery that black rockcod were locally abundant in rubble dominated habitats on the eastern side of LHI (Davis *et al*., 2017). Only one individual was recorded at the Balls Pyramid shelf in 2013. For those fish encountered in deep water, they were all considered adults based on length measurements from stereo-BRUVs (Harasti *et al*., 2011; Davis *et al*., 2017). The BRUVs footage indicate that the sites where black rockcod were most abundant were dominated by low profile rubble, relict reef and sand habitats; a habitat it is not generally associated with. RLS surveys in shallow waters around LHI recorded five black rockcod on transects in 2016 and 2018 (Stuart-Smith *et al*., 2019).

Whilst only two dedicated black rockcod surveys have been undertaken to date at LHIMP, there is a concern that numbers were significantly lower in the 2019 survey compared to the initial 2011 survey. There are still concerns that the species is being incidentally caught, and even though they may be released, after suffering a barotrauma, their chances of survival are greatly reduced (Francis *et al*., 2015). In January 2020 during a compliance investigation, one charter operator told LHIMP staff that he had caught six Black rockcod over the previous six weeks and had filleted three of them. The operator suggested that this had always been common practice on the island. None of these interactions were subsequently reported on the catch returns, suggesting a level of under reporting associated with this species (Figueira and Harianto 2022).

Ballina angelfish

The Ballina angelfish (*Chaetodontoplus ballinae*, Figure 18) is a protected species in NSW under the Fisheries Management Act. This is a rare species that is infrequently encountered by scuba divers as it is found in depths of 25 – 125 m. Within the LHIMP, the species occurs predominantly in the deep waters around Balls Pyramid (Rees *et al*., 2021, Speare *et al*., 2004) and is not known to occur in the shallow waters around LHI (Hobbs *et al*., 2009). BRUVs identified 4-9 Ballina angelfish on deployments in 2009-2017 with all sightings recorded on the south side of Balls Pyramid (Davis *et al*., 2017). Given that this species is not known to be caught incidentally by fishers and occurs in the deep waters around Balls Pyramid, it is currently not considered at risk from any threats.

Figure 18: Ballina angelfish at 30 m off Balls Pyramid. Image from Justin Gilligan.

Elegant wrasse

The elegant wrasse (*Anampses elegans*, Figure 19) is a protected species in NSW under the FM Act and are commonly encountered in the shallow waters around LHI, however, are considered rare along the NSW coastline. The species also occurs at Norfolk Island and northern New Zealand. This species can be found occurring within the LHI lagoon and on coral and rocky reefs from depths of 2 to 35 m. Juveniles will often form large aggregations in shallow waters and are generally found around coral and algae habitats. This species is not known to be caught as bycatch by fishers and there are not considered to be any significant threats to the species within the LHIMP. RLS data indicated that biomass of elegant wrasse increased in 2014-2018, following a dip in 2012, rising to levels comparable to those occurring on surveys in 2006 (Stuart-Smith *et al*., 2019).

Figure 19: A male elegant wrasse (*Anampses elegans*) in LHIMP.

Bluefish

Bluefish (*Girella cyanea*) are a drummer/blackfish in the family Kyphosidae. Bluefish are found in the south-west Pacific Ocean and occur along the east coast of Australia from Flinders Reef off Cape Moreton in Queensland to Eden in southern New South Wales. Bluefish are also found at Elizabeth and Middleton Reefs, Lord Howe and Norfolk Islands, the Kermadec Islands and the North Island of New Zealand. Bluefish are protected from fishing in all NSW waters, other than the waters of LHIMP. There is a bag limit of 5 fish per person per day within the LHIMP. A study on bluefish populations in the LHIMP indicates that the species is fast growing, can live for up to 41 years and the transition to sexual maturity occurs between 2 and 5 years of age or around 20 cm (Lewis, 2012).

Being a herbivorous fish, around LHI bluefish are often observed in shallow-water macro-algae dominated habitats (Edgar *et al*., 2010). Juvenile bluefish are known to occur in rock pool habitats, with intertidal surveys using mini-BRUVs finding they were one of the most abundant species in shallow inter-tidal pools around LHI (Davis *et al*., 2018). There are local concerns that bluefish populations in areas open to fishing are in decline, and there has been a declining trend in the species abundance from BRUVs surveys over the past decade (Rees *et al*., 2021). Additionally, RLS surveys from

2006 to 2018 indicate that across the period 2014-2018 bluefish biomass was low, when compared against previous years (Stuart-Smith *et al*., 2019). Similarly, BRUV data indicates that bluefish abundance per BRUV deployment in 2013 (0.06 ± 0.03) and 2017 (0.06 ± 0.03) were lower than in 2009 (0.24 ± 0.15) (Davis *et al*., 2017).

Commercial fishery data for bluefish from 2004 to 2018 indicates that the species is not heavily targeted around LHI and is only a small portion of the commercial catch (Figueira and Harianto, 2022). However, the catch data indicates that catch numbers for this species have been gradually declining over the past two decades (Figueira and Harianto, 2022). Little data exists on the recreational catch of this species, that is subject to a bag limit of 5 with no minimum legal-size limit. Figueira and Harianto (2022) reported ninety three percent of all bluefish catch came from the Lagoon LHI and Nearshore LHI catch regions.

Syngnathids

Since 2004, all species within the families 'Syngnathidae', 'Solenostomidae' and 'Pegasidae' are protected under the Fisheries Management Act 1994. These unique and delicate groups of fish include seahorses, seadragons, pipefish, pipehorses, ghostpipefish and seamoths, known collectively as 'Syngnathiformes'. Pipehorses, seahorses and pipefishes have been recorded in the LHIMP from the shallows of the lagoon through to the deep waters of the seamount slope.

At least 8 Syngnathidae species are known to occur within the LHIMP: 3 seahorses (*Hippocampus colemani* (Figure 20), *H. kelloggi* and *H. jugumus*), 4 pipefish (*Cosmocampus howensis, Halicampus boothae, Stigmatopora nigra* and *Urocampus carinirostris*) and 1 pipehorse (*Solegnathus dunckeri*). Of particular interest is the Coleman's pygmy seahorse (*H. colemani*) discovered by naturalist Neville Coleman, which was first described from two specimens collected in the LHI lagoon, and was considered endemic to NSW (Kuiter, 2003). However, over the past two decades this species has been found occurring at numerous locations across the western Pacific and is no longer considered endemic to Australia (iNaturalist, 2022; Graham Short, personal communication). No information exists on the population status and habitat requirements of syngnathid species within the marine park, and due to very infrequent sightings, they are considered rare within the LHIMP.

Figure 20: Coleman's Pygmy Seahorse (*Hippocampus colemani*) was described from two specimens collected in the Lord Howe Island lagoon.

Marine mammals

The water of LHI are home to large numbers of dolphins, with the bottlenose dolphin (*Tursiops truncatus*) (Figure 21) the most frequently sighted. The other species to occur regularly in the waters of the LHIMP is the common dolphin (*Dephinus delphis*). Dolphins are most commonly encountered offshore, particularly in the deeper water trench between LHI and Balls Pyramid, and they occasionally can be seen inside the lagoon. There has been no targeted research to date on dolphin populations within the LHIMP.

Both the Australian fur seal (*Arctocephalus pusillus*) and the New Zealand fur seal (*Arctocephalus forsteri*) occasionally turn up in the waters of LHIMP, but they are not resident to the island. Leopard seals (*Hydrurga leptonyx*) and subantarctic fur seals (*Arctocephalus tropicalis*) are rare in the waters of LHIMP; however, both have been observed on a few occasions hauled out on beaches (NSW NPWS *unpublished data*).

The humpback whale (*Megaptera novaengliae*) is the most frequent whale species observed in the LHIMP as they make both their northwards and southwards migrations. Other whale species that have been infrequently detected in the LHIMP include species of beaked whales (such as Blainville's Beaked Whale *Mesoplodon densirostris*) and long-finned pilot whales (*Globicephala melas*), including five Beaked Whale strandings 1869, 1989, 2002, 2003, 2011) and two long-finned Pilot Whale strandings (1909, 1955) (NSW NPWS *unpublished data*).

Figure 21: Bottlenose dolphins in the deep trench between Lord Howe Island and Balls Pyramid.

Marine reptiles

Within the waters of the LHIMP, there are four species of turtles that are known to reside or transit through the marine park. Both the green turtle (*Chelonia mydas*, Figure 22) and the hawksbill turtle (*Eretmochelys imbricate*) are considered to be residents to LHI, whilst the leatherback turtle (*Dermochelys coriacea*) and loggerhead turtle (*Caretta caretta*, Figure 22) are considered to be migratory species and do not reside.

Figure 22: Turtles of LHIMP [top] green turtle (*Chelonia mydas*) and [bottom] hawksbill turtle (*Eretmochelys imbricata*).

The green turtle is the most common species to occur in the waters of the LHIMP. It is commonly encountered within the shallow lagoon where its presence is important for eco-tourism for local boating and diving operators (Manning, 2011). It also occurs offshore and can be found around the entire island and offshore at the Admiralty Islands. The green turtle predominantly feeds on algae and seagrass. Whilst not as common as the green turtle, the hawksbill turtle is also considered resident in the LHIMP. This species occurs in the shallow waters of the lagoon and also around the rocky and coral reefs of LHI. The hawksbill turtle predominantly feeds on sponges, but also consumes algae, soft corals, seagrasses and shellfish.

Over the past decade, there have been numerous incidents of sick or dead turtles washing up on LHI or turtles entangled in fishing gear. These turtle observations are recorded in a turtle database managed by Marine Parks staff (Lord Howe Island Marine Park, unpublished data). In those few situations where a turtle was encountered entangled, it was freed and released alive. There have been a few necropsies undertaken of washed-up turtles, which have attributed most turtle deaths to Spirorchiidiasis, which is a common cause of morbidity and mortality in sea turtles within Australian waters (Turner and Thompson, 2022).

Whilst turtle populations worldwide are faced with various threats, within the LHIMP there are few threats to the turtles. Turtles do face risk from vessel strikes, particularly within the shallow lagoon where turtles are most common, and potentially from land-based pollution sources or any oil/fuel spills from vessels. There were previous concerns with the feeding of turtles within the LHI lagoon by tour operators, however, this practice is no longer undertaken.

Sea snakes occasionally turn up in the waters of the LHIMP, particularly the yellow-bellied sea snake (*Pelamis platurus*) (Hutton and Harrison, 2004), however, they are not considered to be resident to the local waters.

Seabirds

The Lord Howe Island Group (LHIG) includes breeding sites for 14 species of seabirds made up of seven 'tubenose' Procellarids (Providence petrel, Kermadec petrel, black-winged petrel, white-bellied storm-petrel, Flesh-footed shearwater, wedge-tailed shearwater, little shearwater), five terns (sooty tern, common noddy, black noddy, grey ternlet and common white tern) and a single species of Sulid (masked booby) and Phaethontidae (red-tailed tropicbird) (Table 6) (Figure 23).

Seabirds have the ability to impact the quantity of targeted marine species in localized areas, when breeding in large numbers (Lewis *et al*., 2001) and similarly suffer declines in productivity when large predatory species are missing from key foraging areas away from colonies (Miller *et al*., 2018). They also have the ability to change the quality of the shallow benthic marine habitat, by the addition of distant marine derived nutrients into the local ecosystem (Graham *et al*., 2018).

None of the breeding populations of these seabirds reside year-round on islands in the LHIG, although some like grey ternlet and masked booby, have individuals that remain throughout the year. As a group, the breeding seabirds are thought to forage extensively throughout the Tasman and Coral Seas as well as in local waters while breeding in the region, but at-sea movements remain unknown for many of the species. Only the common white tern extensively utilises the LHIMP, spending 50% of their foraging within its boundaries while breeding (Carlile and O'Dwyer, in press). Following the eradication of rodents from the main island in 2019, it is expected that many seabird populations will increase in the coming decades, further elevating their influence on the LHIMP environment as well as their reliance on its protection for their continued recovery. Breeding seabirds may also have a strong influence on the marine environment around LHIMP. A recent study estimated that every additional species of seabird with significant breeding on islands can lead to a doubling of fish species within the local reefs (Benkwitt *et al*., 2022).

Seabird species	Status*	Pairs	Foraging movements
Providence Petrel	V	32,000	Broadly pelagic (Carlile & O'Dwyer in litt.)
Kermadec Petrel	V	< 100	**Unknown**
Black-winged Petrel	V	600	Broadly pelagic (O'Dwyer *et al*. In Press)
Wedge-tailed Shearwater		55,500	Broadly pelagic (Miller *et al*., 2018)
Flesh-footed Shearwater	V	22,600	Broadly pelagic (Thalmann *et al*., 2009)
Little Shearwater	V	1,300	**Unknown^**
White-bellied Storm-petrel	V	< 100	**Unknown^**
Masked Booby	V	2,600	Marine Park (Machovsky-Capuska *et al*., 2016)
Red-tailed Tropicbird	V	600	**Unknown#**
Common White	V	600	Marine Park (Carlile & O'Dwyer In Press)
Sooty Tern	V	57,000	**Unknown**
Common Noddy	Not listed	< 1,000	**Unknown#**
Black Noddy	Not listed	500	**Unknown#**
Grey Ternlet	Vu	< 500	**Unknown#**

*Status within NSW; # Likely to exclusively forage within LHIMP; ^Possibly foraging in LHIMP

Table 6: Summary information of seabirds in the Lord Howe Island Marine Park.

Figure 23: Seabirds of LHIMP [clockwise from upper left]: Providence petrel, common noddy, flesh-footed shearwater, little shearwater, common white tern, Kermadec petrel, white-bellied storm petrel. Images from Nicholas Carlile.

3.7 Other significant species

This section relates to those species that are iconic or play keystone ecological roles that are not otherwise considered in Sections 3.2 or 3.3 above.

Galapagos shark

Galapagos sharks (*Carcharhinus galapagensis*) are a large-bodied requiem (whaler) shark distributed at oceanic islands and seamounts throughout temperate and sub-tropical waters worldwide (Ebert *et al*., 2021) (Figure 24). Internationally, Galapagos sharks are considered as 'Least Concern' on the IUCN Red List of Threatened Species, although it is recognised that localised population reductions have occurred where the species has been subjected to fishing pressure (de Queiroz *et al*., 2021, Kyne *et al*., 2019, Luiz and Edwards, 2011). In Australian waters, it is similarly listed as 'Least Concern' (Simpfendorfer *et al*., 2019). However, as an abundant predator, the Galapagos shark has been identified as a key indicator species for the management of the marine parks surrounding LHI (Edgar *et al*., 2011). Two commercial marine park permit holders offer a non-intrusive snorkel encounter with Galapagos sharks within LHIMP without the need to use bait or shark attractant devices.

The waters surrounding LHI, along with Elizabeth and Middleton Reefs and Norfolk Island, are the only known locations where Galapagos sharks occur in Australian waters (Kyne *et al*., 2019). It occurs in high abundance throughout these marine parks (Davis *et al*., 2017, Heagney *et al*., 2007, Neilson *et al*., 2010, Rees *et al*., 2021). This shark species inhabits waters from 0-285 m depth (Kyne *et al*., 2019). Within LHIMP, acoustically tagged and tracked Galapagos sharks have been recorded year-round with inter-individual variation in their core (i.e. 50% of time) space use ranging from 0.28 km² to 217.65 km², increasing to a maximum of 1,342.63 km² when mapping 95% of their area utilisation (Mitchell *et al*., 2021). Core space use areas were located close to productive shelf edges. Both residency and space use were strongly influenced by the presence of fishing-related activities (Mitchell *et al*., 2021).

The large number of juveniles <1.5 m caught in the LHI fishery (Figueira and Hunt, 2017), the frequent observation of juvenile sharks on baited camera surveys (Davis *et al*., 2017, Neilson *et al*., 2010, Rees, 2013) and the capture of exclusively juvenile sharks during tagging research (Mitchell *et al*., 2021) imply that the LHIMP constitutes a possible nursery area for this species. This suggests that LHI is likely a Biologically Important Area as defined by the Commonwealth government https://atlas.parksaustralia.gov.au/amps/natural-values/biologically-important-areas.

The primary human-induced impact on this population of Galapagos sharks is through their regular interaction with fishers in the LHIMP where they consume bait and hooked fish (a process known as depredation) (Mitchell *et al*., 2018, Mitchell *et al*., 2021, Robbins *et al*., 2011). Fishers report that the frequency of depredation by Galapagos sharks has increased within the last decade. Increased depredation rates have been linked to possible changes in shark behaviour, whereby they associate boat engine noise with the availability of a food source in the form of bait, hooked fish and/or released fish that are injured and unable to escape shark predation, and discarded fish waste (Mitchell *et al*., 2018). Shark depredation causes extra mortality for targeted species, e.g. yellowtail kingfish, and costly loss of fish and gear for fishers. Such interactions are also causing a broader shark-fisher conflict in the marine park, resulting in fishers deliberately injuring and killing sharks, with some local fishers also advocating for a cull of the species (Mitchell *et al*., 2021). Large numbers of Galapagos sharks are also caught as incidental bycatch in the LHI fishery, ranging from 559 – 1,328 animals per year, and whilst >95% of sharks are released (Figueira and Hunt, 2017), post-release mortality can occur from hook injuries and stress (Butcher *et al*., 2015).

Therefore, in combination with the possible genetic localisation and high residency of this population, the presence of a potential nursing area in the LHIMP increases the vulnerability of the local shark population to declines caused by culling and high levels of bycatch. Such declines have previously been observed at Saint Paul's Rocks in the Atlantic Ocean, where the resident population of Galapagos sharks was reduced to very low levels due to large catches in longline and hand line fisheries (de Queiroz *et al*., 2021, Luiz and Edwards, 2011). Confirmation of the genetic status of the stock of Galapagos sharks within LHIMP would support ongoing attempts to ensure long-term population viability by reducing fishing-associated shark fatalities.

As the most abundant shark in the LHIMP, Galapagos sharks are likely to play an important ecological role in these waters. Large sharks occupy high trophic levels and are typically third-order consumers, which is similar to marine mammals and substantially higher than the

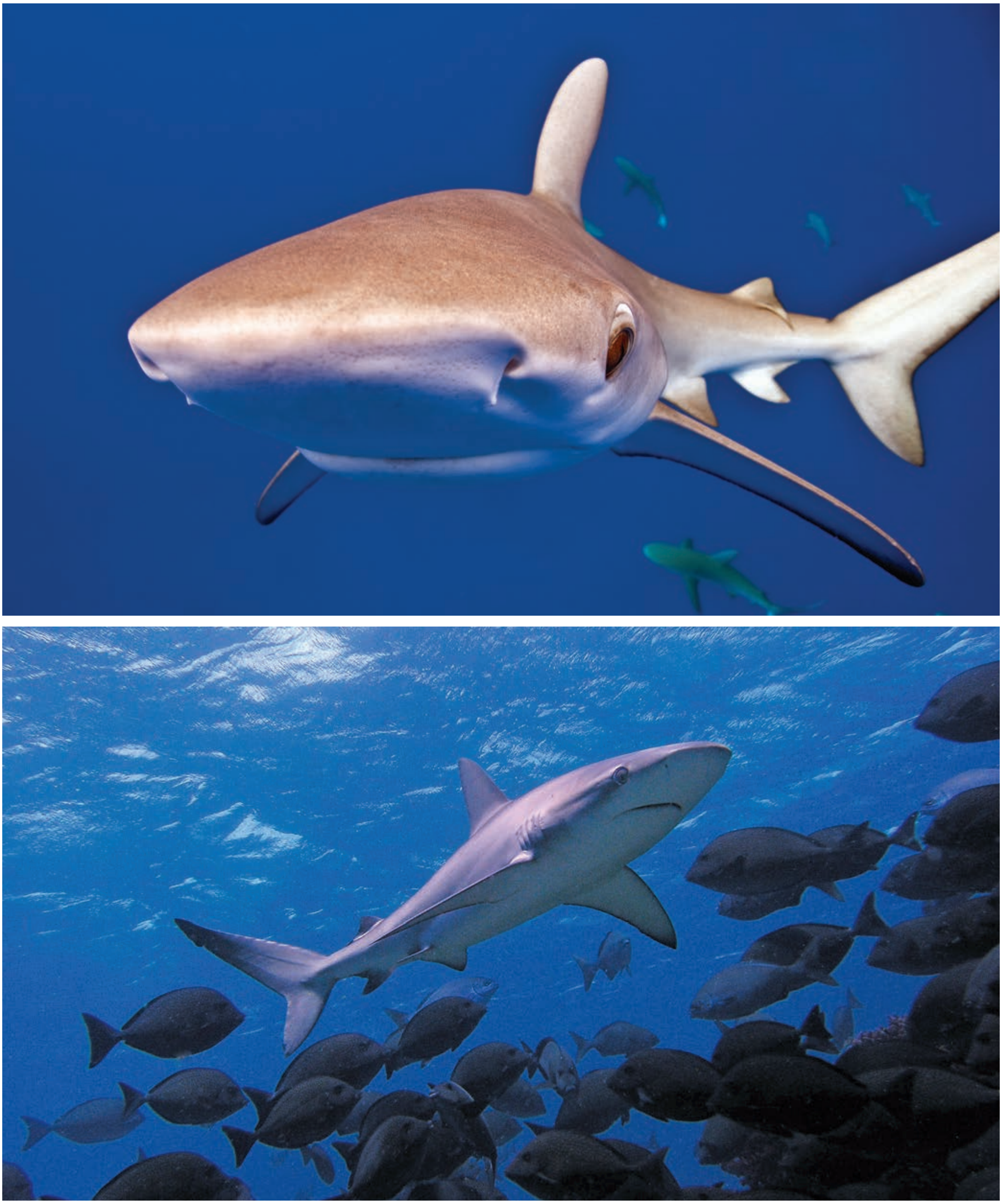


Figure 24: Galapagos sharks in LHIMP.

trophic level of seabirds (Cortés, 1999) and provide top-down control over mesopredators (Heithaus *et al*., 2010). Although there is currently no information on the diet of Galapagos sharks in east Australian waters, removal of these sharks in ecosystem modelling for the Galapagos Archipelago could disrupt trophic cascades by allowing prey species to increase in abundance (Okey *et al*., 2004). However, other studies have suggested that the impact of shark predation may be much weaker, e.g. juvenile sandbar shark diet flexibility limits their impacts on prey populations through direct predation (Ellis and Musick, 2007), highlighting the requirement to better understand the diet of the most prolific predator in the LHIMP to better determine potential ecological impacts of non-natural population perturbations.

Other sharks

Large pelagic sharks act as important regulators of lower trophic level species, playing a fundamental role in marine ecosystems through both direct (predation) and indirect (competition) ecological interactions (Heithaus *et al*., 2010) with substantial inter-specific variability in how they exert influence over food webs (Bornatowski *et al*., 2018), highlighting their divergent and trophically essential role (Li *et al*., 2016).

Other migratory shark species are occasionally found in LHIMP waters, but there is no indication that the region is of major importance to these species. Few records of the whale shark (*Rhincodon typus*) exist in LHIMP, and the area is unlikely to be a Biologically Important Area for them. Several other species of oceanic shark are transient through LHIMP waters, occurring with moderate frequency. These include the white shark (*Carcharodon carcharias*), tiger shark (*Galeocerdo cuvier*), silky shark (*Carcharhinus falciformis*), shortfin mako shark (*Isurus oxyrinchus*) and blue shark (*Prionace glauca*). Oceanic whitetip shark (*Carcharhinus longimanus*) has not been recorded in LHIMP waters.

Doubleheader wrasse

The doubleheader wrasse (*Coris bulbifrons*) is found in the waters of LHI, Middleton and Elizabeth Reefs, Norfolk Island and northern New Zealand (Figure 25). This species is a protogynous hermaphrodite where it changes sex from female to male. Juveniles are often found in shallow water habitats, including rock pools (Davis *et al*., 2018), whereas adults are generally found on coral and rocky reef habitats (Stuart-Smith *et al*., 2015, Stuart-Smith *et al*., 2019). RLS data collected regularly from 2006 to 2018 indicate that the abundance of the species varies temporally between Sanctuary Zones and Habitat Protection Zones, however, there is no obvious decline in observed abundance (Stuart-Smith *et al*., 2019). There has been no research conducted on the life history and population dynamics of the Doubleheader wrasse and this warrants further investigation to assist in understanding the species biology for LHI. Commercial fishery catch data indicate that both the numbers and length of fish caught varies from year to year, and there are no obvious trends for the species increasing or decreasing (Figueira and Harianto, 2022).

Figure 25: Doubleheader wrasse in the LHIMP showing [left] adult and [right] juvenile fish.

McCulloch's anemonefish

The McCulloch's anemonefish (*Amphiprion mccullochi*) (Figure 26) can only be found occurring at LHI and Middleton and Elizabeth Reefs. It was previously known to occur at Norfolk Island; however, it is no longer known to occur at this locality. Based on surveys of LHI and Middleton and Elizabeth Reefs, the LHI lagoon seems to be the remaining stronghold for this species (Hobbs, 2022). Recent research on this fish species at LHI has focused on assessing how environmental and social factors influence intraspecific variation in foraging and antipredator behaviour (Wong *et al*., 2022). Individuals significantly adjusted their time spent far and close to their host anemone depending on the tide, status and the presence of eggs (Wong *et al*., 2022).

Over the past decade it is estimated that the abundance at LHI has declined by over 50% (Hobbs, 2022). This is attributed to the loss of essential habitat for the anemonefish, which is driven by its habitat use of only one particular anemone species (*Entacmaea quadricolor*). As a result of elevated sea temperatures at LHI over the past decade, this anemone has declined in abundance because of mortality from heat stress leading to bleaching (Section 4.1). The ongoing risk of increased water temperatures greatly threatens the survival of the anemone, and hence the McCulloch's anemonefish that resides in it. As a result of this species' extremely limited distribution, and the ongoing threat to the species from climate change, a threatened species nomination has been prepared for this species (Hobbs, 2022) and it is currently being considered for listing as a threatened species under the EPBC and Fisheries Management Acts.

Figure 26: McCulloch's anemonefish in its host anemone.
Image from Justin Gilligan.

Lord Howe Island abalone

In 2020, the Lord Howe Island abalone (*Haliotis rubiginosa*, Figure 27) was listed as 'Critically Endangered' under the IUCN Redlist for threatened species. This small abalone species is endemic to LHIMP and grows to a maximum length of approximately 5 cm (Peters, 2021). The species is restricted to carbonate reefs around LHI, and its abundance is considered to be low (Woods, 2022). Due to its extremely limited distribution, threats to this species such as climate change (Section 4.1) or marine pollution (Section 4.2) could have devasting effects on the species abundance and survival. This species is currently being considered for listing as a threatened species under both the EPBC and FM Acts.

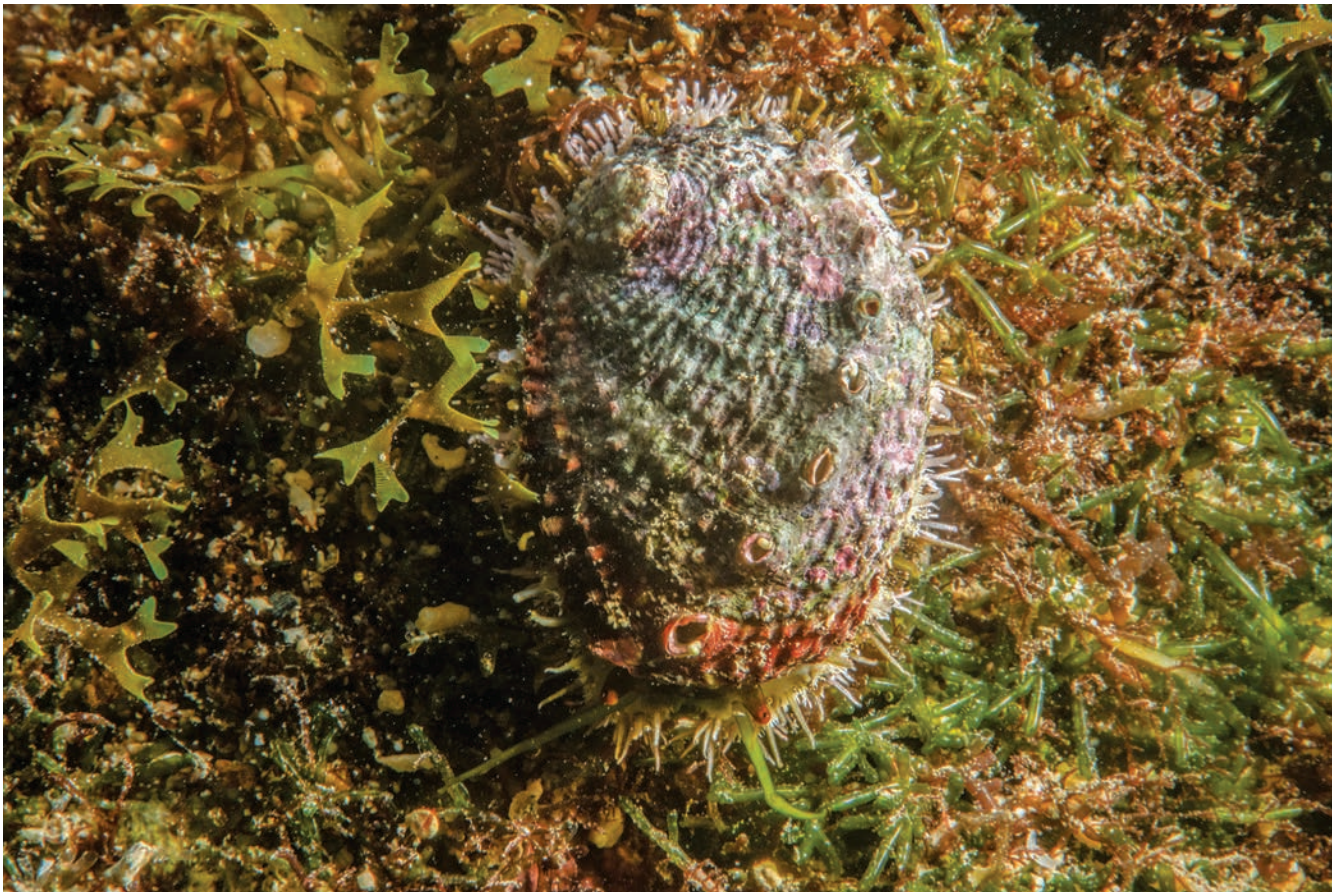


Figure 27: Lord Howe Island abalone. Image from Justin Gilligan.

4 Threats

In this section, we provide an overview and summary of the major threats identified in this review, and those threats managed by the LHIMP and LHIB, to the environmental values of the LHIMP.

The threats identified below can be used in any future threat and risk assessment for LHIMP in line with that conducted for the mainland marine parks (MEMA, 2017). If any marine species are extirpated from the island due to bleaching or other disturbances, prognosis for unaided recovery is poor due to LHI's isolation from neighboring reefs (UNESCO, 2020).

Threats to environmental values previously identified and managed under current arrangements in the LHIMP include:

> CLIMATE CHANGE

Climate change is a primary threat to the environmental values of the LHIMP. A recent World Heritage Report identifies it as the main threat to several environmental values (seabirds, coral reefs, tropical and temperate mix of marine fauna) as well as social, cultural, and economic values (CSIRO, in review). As described in Section 3.2, marine heatwaves and associated bleaching are a significant threat to the coral communities of LHIMP as well as other zooxanthellic organisms such as sponges and anemones (CSIRO, in review) and non-zooxanthellic invertebrates (Woods, 2022). As described in Section 3.2, marine heatwaves and associated bleaching are a significant threat to the coral communities of LHIMP as well as other zooxanthellic organisms such as sponges and anemones (CSIRO, in review, Steinberg *et al*., 2022) and non-zooxanthellic invertebrates (Peters, 2021). A strengthening of the East Australian Current will cause further southern shifts in the distribution of fish, invertebrates, algae and microorganisms, which will continue to impact the structure and function of marine ecosystems (Poloczanska *et al*., 2007). This may change the composition of the fish community to one dominated by tropical species rather than warm-temperate species. Increasing water temperatures will also increase the likelihood of coral bleaching events, which will have dramatic consequences for fish species that depend on live coral cover (Anderson *et al*., 2015, Woodroffe *et al*., 2010), as well as endemic species with narrow habitat requirements (e.g. McCulloch's anemonefish and LHI abalone in Section 3.6).

Climate change stressors may also interact with other anthropogenic stressors to affect marine environmental values. For example, higher coral bleaching levels at Sylphs Hole in 2019 has been attributed to interactions between high temperatures and excess nutrients due to submarine groundwater discharge (Davis 2022b) (Section 5).

> COMMERCIAL SHIPPING ACTIVITIES (INCLUDING TRADE AND CRUISE SHIPS)

One trading vessel regularly visits the Island from Port Macquarie. Commercial vessels are required to apply to the LHIB for entry and complete a biosecurity declaration. The LHIB Cruise Ship Policy provides a framework to guide the LHIB in determining applications from cruise ship operators to disembark passengers on the island. Commercial vessels are required to hold a marine park permit. Threats include introduced marine pests, which are currently managed through ballast water restrictions and biofouling requirements. Anchoring, and marine pollution from fuel and oil spills are also a threat to nearshore environments.

> VISITING VESSELS

Smaller vessels (including yachts) from the Australian mainland and other countries visit LHIMP. As above, all private and commercial vessels are required to apply to the LHIB for entry and complete a biosecurity declaration. These visiting vessels from outside the region present a threat of marine pest introduction (NSW Department of Primary Industries, 2022). However, the risk from invasive marine species seems low based on the absence of invasive fish or invertebrates found during a 5-year period (Edgar *et al*., 2011), although the status of several recorded species was flagged as unclear if native or introduced (Aquenal, 2006, NSW Department of Primary Industries, 2020).

The introduction of any non-native species poses a high level of risk to ecosystems, habitats and species within the LHIMP and its social, cultural, and economic values. As such, an interim marine pest surveillance strategy has been put in place for the LHIMP (NSW Department of Primary Industries, 2020). Marine environmental values may also be at indirect risk from terrestrial biosecurity threats. In addition to marine pests, visiting vessels can also harbour rodents, weeds, spores and seeds, or pathogens, all of which can have major impacts on threatened species such as seabirds and shorebirds (Brown and Baker, 2009). Indeed, the Rodent Eradication Program (REP) on LHI was undertaken to protect biodiversity values, including seabirds (Segal *et al*., 2022, O'Dwyer *et al*., in press). Although aerial distribution of cereal-based bait pellets may present risks to the LHIMP, the REP was highly successful at removing invasive species and protecting biodiversity values, including seabirds. Environmental benefits to the LHIMP are likely to be realised in coming decades from the REP (see section 3.6, page 40).

> PORT USE AND NAVIGATION CHANNELS

Entrances to the lagoon are narrow, flanked by ocean waves, and subject to strong currents, presenting an ongoing risk of vessel grounding and associated impacts. Vessels are required to enter the lagoon during daylight hours under the guidance of the LHI Port Operations Manager (NSW Police). Coral growth has also been identified previously by local stakeholders as impacting accessibility of some areas of the lagoon, particularly North Bay and around the public boat ramp. Historically, vessels dragging chains have been used to clear areas of coral growth in the lagoon.

> VESSEL-SOURCED POLLUTION

All visiting vessels must conduct pre-departure biosecurity actions, and meet specific biosecurity requirements through the LHIB. Vessels wishing to stay for longer than two weeks must provide a genuine reason in order to reduce levels of boat-sourced pollution. Under the *Protection of the Environment Operations Act 1997*, it's an offence to pollute any waters, unless permitted under a licence. MARPOL regulations prohibit the discharge of sewage/sullage from vessels within LHIMP. The absence of a slipway on LHI, means that some vessels are required to use the jetty for general maintenance. Oil or fuel spills from vessels transiting past or within passing by the park are also a potential threat and would have detrimental effects on flora and fauna within the park.

Vessel-sourced pollution impacts on marine biodiversity by degrading habitats and water quality or by directly smothering or killing marine species. This vessel pollution can impact on the structure and function of marine communities and alter key ecosystem processes, such as primary production. Pollutants often persist in the environment, continuing to impact marine organisms and habitats for many years after their discharge (Willis *et al*., 2017).

> ANCHORING AND MOORING

Vessel-based activity in LHI takes place over sensitive habitats, which can be particularly prone to damage from anchors and chain. Management rules that restrict anchoring are in place to limit impacts on sensitive habitats such as coral and seagrass. The LHIB have a mooring policy to guide its management of lagoon moorings. The policy identifies mooring types: private, public temporary, and public day use (managed by LHIMP) and identifies designated mooring areas.

> AQUATIC BIOSECURITY

The introduction of any non-native species poses a high level of risk to ecosystems, habitats and species in LHIMP. Visiting vessels with hull or machinery that is heavily fouled by marine organisms represent the greatest risk of the introduction of exotic animals or plants to the marine park. Management rules are in place to address this to authorize the removal of high-risk vessels. A long-term marine pest surveillance strategy and response guidelines have been developed for LHIMP. See additional comments in 'visiting vessels' above. In addition to risk of introduction of introduced marine species, there is also risk of terrestrial invasive species, such as weeds, being introduced to the island that could impact on marine habitats such as saltmarsh.

> PERSONAL WATER CRAFT (PWC)

The operation of PWC's is prohibited within the LHIMP, which have been identified to conflict with the World Heritage-based setting and have the potential to result in wildlife disturbance as PWC pose a risk through vessel strike, particularly to resident marine turtles, and noise disturbance.

> WORKS

Foreshore development and beach nourishment and emergency works have the potential to impact on nearshore intertidal and subtidal habitats directly through the construction of infrastructure, use of machinery and pollution, and indirectly through the disturbance of water and sediment flows. A marine park permit is required for any works within LHIMP. Infrastructure works on the island have contributed to ongoing erosion issues that have potential to impact on environmental values, particularly within the lagoon (Haskoning Australia, 2014). Determining authorities must have regard to marine park management plans and rules when assessing applications under the *Environmental Planning & Assessment Act 1979*.

> USE OF MOTOR VEHICLES

Emergency vehicles are permitted in all areas of LHIMP. Other vehicles are prohibited in all areas of the marine park except for the purpose of launching or retrieving vessels from the formalised boat ramp or for accessing the jetty. Vehicle access to the marine park in other areas (which includes all areas below mean high water mark) requires a permit. Permitted use of motor vehicles in LHIMP is predominantly associated with works in LHIMP. Vehicles have the potential to disturb wildlife, impact intertidal habitats including beached, and present a risk of pollution.

> LAND-BASED POLLUTION

The waters of the LHIMP are considered to be relatively pristine, however, they are still susceptible to land-based pollution sources (Aquenal, 2006, Davis 2022a). While point source discharges (such as sewage outfalls) and solid waste are easier to manage to ensure water quality guidelines are met, diffuse discharge is more problematic. The potential for land-based pollution to impact on marine biodiversity is dependent on a range of different factors including types of pollutant, size of catchment, modification of catchment, and the type and amount of industrial, urban and agricultural development. Estuarine waters adjacent to large urban populations or within highly modified agricultural catchments are particularly susceptible to diffuse pollution (Scanes *et al.*, 2007). These types of impacts can be exacerbated in intermittently closed and open creeks (Section 3.1) when they are closed to the ocean, due to limited tidal exchange or flushing of pollutants.

Besides having adverse impacts on marine biodiversity, land-based pollution can have serious implications for marine industries, in particular fisheries and tourism.

Input of excess nutrients into the marine system can also have a significant effect on the marine life of LHIMP. The estuaries of Soldiers Creek, Cobbys Creek and Old Settlement Creek environments receive nutrient rich inputs from terrestrial run off (nutrients sourced from fertilisers and septic systems) which can lead to eutrophication (Coade *et al.*, 2010, Davis, 2022a). This is enhanced by the grazing of cattle and also the disturbance caused by mechanical opening of the estuaries for flushing with the lagoon. Although nutrient excess is often considered in the context of agricultural practices (e.g. fertilisers), submarine groundwater discharge is rich in dissolved nitrogen, phosphorus, and carbon and may also be a source of nutrient input to coral reefs (McMahon and Santos 2017), including the LHI ecosystem (Davis, 2022a). Changes to land and water use can unbalance this process and negatively impact coral reefs. Increased nutrient levels have been recorded in the lagoon and it is thought that this is the cause of thick growth of cyanobacteria and increased epiphytic algal growth primarily on seagrass but also on coral.

> MARINE DEBRIS

Marine debris, in particular garbage wastes, discarded lost fishing gear and lost traps, threaten biodiversity in the LHIMP. Lost fishing gear, such as traps and nets, can continue ghost fishing for weeks, even months, and is a notable threat to fish, marine animals and birds. Seabirds have been shown to be impacted by both entanglement and ingestion of marine debris (Puskic *et al.*, 2020). On LHI, marine debris is commonly seen incorporated in the nests of some terns, found in the regurgitated boluses of shearwaters and flushed from the stomachs of several procellarid species. While several studies have shown presence of plastics in the stomachs of seabirds at LHI (Hutton *et al.*, 2008, Lavers *et al.*, 2021, Lavers *et al.*, 2014, Lavers *et al.*, 2019b), there is yet to be presented evidence that such presence has led to impacts on populations, their breeding success or adult survival. In fact, the species showing the highest rates of ingestion, the Flesh-footed Shearwater is undergoing population recovery (Carlile *et al.*, 2019, Lavers *et al.*, 2019a, Wilcox *et al.*, 2021), first indicated as being in decline for other anthropogenic causes in the early 2000s (Priddel *et al.*, 2006) and again a decade later (Reid *et al.*, 2013).

Internationally, while impacts on individuals of a species are commonly reported, the impacts of plastic ingestion on seabird populations still requires further study (Senko *et al*., 2020). Most marine debris is not originating from LHI itself, but from the high seas, and therefore is difficult to control (UNESCO, 2020). Recently, marine turtles have been susceptible to the threat of marine debris following entanglement in discarded/lost fishing gear (Turner and Thompson, 2022).

> FISHING ACTIVITIES

One of the most direct threats to fishes in any marine park, including LHIMP, is fishing activity, which occurs recreationally and through participation in a local fishery. Recreational fishing (with no on-sale of catch) occurs within the LHIMP as shore and vessel-based activity, and the surrounding LHMP as vessel-based activity. Uncertainty exists around the level of catch and numbers of participants during recreational fishing activity.

The LHI fishery also operates both in the LHIMP and LHMP. The fishery is most active on the shelf and slope of LHI and Balls Pyramid (Figueira and Hunt, 2017; Figueria and Harianto, 2022). The fishery activities include a commercial element, where fish are taken and sold for use on the island. The fishing fleet is comprised primarily of commercial charter fishing vessels in addition to smaller privately-owned vessels that are not authorised to sell catch. Vessels catch and retain fish for the purposes of sale as part of recreational fishing charters or independent fishing trips.

Since the LHIMP zoning plan came into effect in 2004, commercial charter vessels have been required to hold a commercial activity permit and submit catch and effort logs (Figueria and Harianto, 2022). A threat to the sustainability of the fishery includes the unreported fishery effort of unauthorised privately-owned vessels, the percentage and significance of this effort is largely unknown (Figueria and Harianto, 2022).

Information that is available on catch rates and catch per unit effort for the fishery provides no evidence that current activities are unsustainable (Figueria and Harianto, 2022); however, improved catch reporting across all vessels including smaller private vessels that sell catch is required to further inform the sustainability and management of the fishery (Figueira and Harianto, 2022). There is concern regarding the downward trend of yellowtail kingfish catch and the reporting uncertainty for black rockcod (see sections on yellowtail kingfish (3.3) and black rockcod (3.6)). Management actions that are in place to help sustainability, including local bag and size limits, species restrictions, no export of fish, and no take zones, help ensure the sustainable management of the fishery.

More recently, in 2019, NSW DPI and the Commonwealth implemented a new pilot reporting system associated with the Vessel Monitoring System (VMS). Further collaboration between State and Commonwealth agencies on this pilot program could help strengthen reporting and further complement reporting with other advances in technology to collect and analyse fishery dependent data.

With recent improvements in fishing gear and techniques, a growing threat in the region is increased targeting of deeper-water fishes (>150 m) using jigs and electric reels. Many of these deep-water species are common menu items in the island's restaurants. Given the lack of information on what species occur in these waters and their basic biology these populations may be vulnerable even to low levels of fishing effort. Fishing activity may indirectly affect other species through removal of predatory fish which can result in a subsequent boom of sea urchins (Cook and Vanderklift, 2011, Johansson *et al*., 2013), which is itself a different threat (see below). Continued management to ensure accuracy of catch data is crucial to assess the magnitude or likelihood of risk associated with this indirect threat.

> CLEANING OF FISH

Fish caught within the lagoon by recreational fishers (not charter fishing) may be cleaned within the lagoon. Management rules allow the cleaning of fish and the dumping of offal offshore in an area beyond the line between Dawsons Point and North Passage. The discarding of fish has the potential to impact shark behavior and increase the risk of attack risks to swimmers and tourists regarding this activity.

> FISHING GEAR RESTRICTIONS

The *Marine Estate Management Act 2014* and *Fisheries Management Act 1994* regulations determine the type of fishing methods that are currently allowed in LHIMP. The absence of a general use zone in the park means that trawling, long-lining, drop-lining, and dredging are prohibited to conserve stocks and protect sensitive benthic habitats. Other method restrictions include all forms of nets (except dip and scooping) and spearfishing.

> MANAGEMENT OF SPECIES

Some marine species are vulnerable to overexploitation due to their restricted distribution, low rates of replacement, ease of capture or other factors. To ensure that fishing and collecting remain sustainable, different levels of exploitation are appropriate for different species. Bag limits for species that may be taken from habitat protection zones for recreational purposes. Species not listed in Table A in the Management Rules and those that are prohibited from harm under the *Fisheries Management Act 1994* are considered protected species.

> COLLECTION ACTIVITIES

Recreational collecting by hand is undertaken for gathering bait, aquarium specimens, curios, seaweed wrack for gardens and food for human consumption. Bait gathering is undertaken on beaches and on rocky headlands. The collection of non-living things from the beach, rocks and reef flats also occurs. In other parts of Australia, collecting has led to severe depletion of some species and consequent ecological imbalance. There are anecdotal reports from Norfolk Island, that the once common intertidal turban shell is now uncommon due to the pressure of collection. Collecting activities may also pose a risk to endemic invertebrate species in the LHIMP, including the endemic turban snail (*Turbo cepoides*) (Woods, 2022). A list of species that may be taken from habitat protection zones for recreational purposes is provided in the Management Rules. Species not listed are considered protected species under the Management Rules, which is an effective approach given the environmental values of LHIMP.

> AQUARIUM COLLECTION

Aquarium collection activities have the potential to impact populations of fish and invertebrates including regionally endemic species, for example the McCulloch's anemonefish (Hobbs, 2022). Local aquarium activities can occur in LHIMP if authorised by a permit. Commercial aquarium collection activities are prohibited, which is also closely associated with no export of fish from LHI, although many enquiries have been received historically.

> AQUACULTURE

There is no history of aquaculture in the LHIMP. The open ocean surrounding LHI is subject to frequent heavy weather and is unlikely to be suitable for aquaculture. Given the importance of the lagoon for tourism and the relatively small area the threats to habitat from infrastructure and increased nutrients loads associated with aquaculture means it is prohibited.

> FISH FEEDING

Recreational fish feeding occurs at Neds Beach in a special purpose zone and is an embedded cultural value for LHI. Only approved fish feeding pellets are used for feeding fish in this location. A commercial operator sells the pellets and hold a permit and is required to report on the amount of food used over time. Commercial operators also are permitted to feed fish in special purpose zones in the lagoon at Erscotts Hole and North Bay. Fish feeding pellets and urchins are used to feed the fish, volumes are also associated with reporting conditions.

> COMMERCIAL ACTIVITIES

Because of the 400-bed limit on tourism accommodation, visitor numbers to the island are relatively stable. Under current arrangements, commercial operators are not operating in a growing market. A marine park permit and business license from the LHIB is required to undertake commercial activities. Some commercial activities might pose a threat to environmental values and should be assessed independently. Commercial activity reporting is required as a condition of the marine park permit. Marine park commercial activity permits have been issued for activities including: sightseeing and wildlife observation, swimming and snorkelling, scuba diving, equipment hire, fish feeding, charter fishing, passenger transfer, use of slip rails, mooring hire, non-motorised water sports, sea scooter tours, manta boarding, cruise ship operation, freight charter.

> PHOTOGRAPHY AND FILMING USING STRUCTURES

The placement of filming and photography structures has the potential to impact sensitive benthic habitats such as coral and seagrass. These activities require a marine park permit. Requests for permits not previously issued include the use of shark cage and burley, which has the potential to impact shark and fish species.

> ORGANISED PUBLIC EVENTS

A range of events and activities have been permitted in the LHIMP including nippers' events, photography events, swimming events, other aquatic sporting events and citizen science. Organised events have the potential to impact sensitive intertidal or subtidal habitats depending on their location, number of participants, and if infrastructure is required. Marine debris and pollution can also threaten wildlife and sensitive habitats.

> DOGS ON BEACHES

Dogs can have negative impacts on the environment by direct disturbance of native animals (particularly wading birds) and by depositing faeces. Under the *Companion Animals Act 1998*, the LHIB has designated areas where dogs are prohibited. Other beaches are designated as areas where dogs are either permitted on a leash or off leash. The marine park management rules prohibit domestic animals below high water in some areas without a permit.

> FIRES ON BEACHES

Lighting of fires on beaches and other parts of the foreshore can impact seabirds, and other shore-based wildlife such as crabs and can create litter and pollutants, endangering marine life. Fires may not be lit in the LHIMP, other than on vessels or through a permit through LHIMP.

> RESEARCH ACTIVITIES

Organised research activities are a popular activity in LHIMP. Some observational research activities present a minor threat, whilst other research activities including collection and manipulative research has the potential to threaten species and habitats within LHIMP. Manipulative experiments and collection activities have predominantly occurred outside of Sanctuary Zones to ensure effective controls were maintained for the range of research interests in LHIMP. All research activities require a marine park permit; collection activities require a permit under the *Fisheries Management Act 1994*.

> ORGANISED SPORT, EDUCATION AND RECREATIONAL ACTIVITIES:

Similar to organised events, organized activities have the potential to impact sensitive intertidal or subtidal habitats depending on their location, number of participants, and if infrastructure is required. Marine debris and pollution can pose a threat as a result of these activities threatening wildlife and sensitive habitats.

> EXPLORATORY INDUSTRIES

It is unlawful to prospect or mine for minerals in a marine park. The *Offshore Minerals Act 1999*, the *Mining Act 1992*, the *Petroleum (Onshore) Act 1991* and the *Petroleum (Offshore) Act 1982* do not apply in respect of any area within a marine park or an aquatic reserve. Exploratory industries in the LHIMP are not in-line with world heritage values.

> SEA URCHINS

Overgrazing by urchins can be a threat to macroalgae as observed with population surges of *Tripneustes gratilla* associated with declines in brown foliose algae (20.4% to 1.8% cover in two years) and red algae (11.2% to 2.5% cover in two years) on LHI rocky reefs. In contrast, crustose coralline algal cover increased from 2.7% to 42.6% (Valentine and Edgar, 2010). The unique and endemic macroalgal communities at the Algal Holes are fully contained within a Habitat Protection Zone (HPZ). Edgar *et al*. (2011) identified their risk due to targeted removal of predatory fishes and lobsters by fishing potentially leading to increased populations of urchin prey, with subsequent algal overgrazing by urchins (Edgar *et al*., 2011).

> CROWN-OF-THORNS STARFISH

The corallivorous crown-of-thorns starfish (COTS) (*Acanthaster plancii*) occurs in low numbers in the LHIMP, however, the species remains a potential threat to the corals and associated communities of the LHIMP (Harriott, 1996) based on its significant negative impacts in the Great Barrier Reef. From 40 sampling sites around LHIMP, a total of 193 COTS were recorded, the majority between 14-19 m depth, with the most obvious coral scarring due to feeding observed at Admiralty Islands (Taylor, 2003). The population around LHI are more genetically distinct than other populations, likely owing to limited dispersal due to geographic isolation and ocean currents (Benzie, 1999), and it remains unknown how this population will respond to warming waters and other climate change-related stressors. A small COTS control program in the LHIMP has been successful in reducing populations at selected sites (Taylor, 2003).

5 Knowledge gaps

The knowledge gaps described below were compiled from published research cited in this report, the authors' expert knowledge, and priorities identified by LHIMP managers.

Coastal processes and threats

- We have yet to understand and predict the impacts on environmental values of coastal hazards, including erosion, long-term recession, and inundation, as well as the associated impacts of management actions (including beach scraping and nourishment) and infrastructure (e.g. seawalls) on environmental values.
- Further monitoring is required to investigate potential impacts of recreational use (e.g. reef walking, boating, fishing, collecting, snorkelling/swimming) on ecological and biological natural values.

Bony fish

There is a considerable need for further research into many of the fishery and iconic fish species known to occur in the LHIMP, particularly regarding impacts from fishing and effectiveness of marine park zoning. The following are identified knowledge gaps:

- Deep-water fish assemblages (>60 m), including baseline data, monitoring trends through time, and how these assemblages respond to different management regimes (e.g. black rockcod in Figueira and Harianto, 2022). This could be undertaken using remote survey techniques, such as BRUVs;
- Habitat associations of fish assemblages on the shelf habitats. Future BRUV surveys could score benthos and relief in imagery to better resolve habitat associations of key species (as per Rees *et al*., 2018);
- Life history and population dynamics of endemic and iconic species in the LHIMP including species such as bluefish, doubleheader wrasse and elegant wrasse (Stuart-Smith *et al*., 2019);
- Impacts of barotrauma and appropriate release methods for those species that are known to be susceptible when caught in deep water (e.g. black rockcod in Figueira and Harianto (2022));
- Movement patterns of protected fish species within the LHIMP (e.g. yellowtail kingfish, silver trevally, bluefish, doubleheader wrasse) which could be undertaken using tagging and acoustic telemetry;
- Analysis of catch rates, specifically comparing yellowtail kingfish catch numbers from LHIMP with NSW mainland to identify similarities and patterns (Figueira and Harianto, 2022);
- Yellowtail kingfish demography research (including fishery independent size and age estimations) is recommended to more fully evaluate stock dynamics and connectedness of LHIMP stock with nearby populations (Figueira and Harianto, 2022);
- The unreported fishery effort of non-permitted vessels needs to be taken into account to accurately assess fishery trends on LHI in the future; the percentage and significance of this effort is largely unknown (Figueira and Harianto, 2022). Uncertainty exists around the level of catch and numbers of participants during recreational fishing activity; and
- Continued monitoring of the observed decline in McCullochs anemonefish in LHIMP is recommended. Given this species is reliant on host anemones that are subject to bleaching events, this habitat may prove a suitable candidate for a restoration program and should be investigated further (Hobbs, 2022).

Sharks

- Considering the global confirmation that pelagic sharks exert a top-down control within ecosystems, an understanding of the trophic niche occupied by Galapagos sharks is desired to understand the potential ecosystem effects of fishing-related mortalities on this species (Stuart-Smith *et al*., 2019).
- As LHIMP represents the only known distribution for Galapagos sharks in Australia, it is recommended that emphasis is placed on genetically determining their population structure and potential connectivity with other areas of known occurrence in the eastern Pacific.
- Long-term data on the movement patterns of tagged Galapagos sharks within the LHIMP would provide a better understating of movements around the island and help identify key areas that they utilise (Mitchell *et al*., 2021).

- Research has indicated a distinct overlap between shark movements and fishing vessels, possibly because of their learned behaviour of easy meals related to fishing activity. To reduce potential impact on this population of Galapagos Sharks, it is recommended that further research be conducted to develop and trial shark deterrent devices specifically designed to reduce shark interactions with fishing gear to assess whether they are effective at reducing Galapagos shark bycatch and depredation in the marine parks surrounding LHI (Figueira and Harianto, 2022, Mitchell *et al*., 2021).

Seabirds

- Information on seabird movements around LHI would help improve information on species biology, ecology and their movements in the region. At-sea movements of nine of the 14 resident breeding seabirds through Global Light Sensor and GPS tracking would be useful to determine their resource-use and reliance on the LHI Marine Park.
- Research to improve the understanding of resource use of rarer breeding seabirds in and outside the LHIMP would allow the relevance of park boundaries to be assessed for these threatened species. Key foraging areas can be the resource mismatch that perpetuates poor breeding for some species, maintaining low populations despite efforts on land to improve their status. For every additional seabird species breeding in numbers within tropical environments, fish biomass can double within surrounding reefs (Benkwitt *et al* 2022).

Marine mammals and reptiles

- Although recorded occasionally, we still have limited information on the species diversity, migratory patterns, near-shore behaviour and beaching of whales that visit and/or reside in the LHIMP.
- Further research on the migratory patterns, breeding behaviour and near-shore behaviour of turtles that reside in the LHIMP will inform assessment of where management effort may be best targeted for conservation (e.g. reducing threats at high-usage sites).
- Understanding the impacts of marine park users and any associated disturbance on marine reptiles and other species sensitive to human interaction will help marine planning and management of the LHIMP.

Coral

- Understanding the refugia potential of mesophotic coral assemblages that surround LHI and BP requires information on larval life histories and dispersal potential of coral, coupled with oceanographic models and climate scenarios that predict potential shifts in species distributions (Linklater *et al*. 2016 & 2018).
- Additional research is needed to determine success rates as well as the source, exchange and survival of coral larvae between the upper and lower mesophotic coral ecosystems (MCEs) and surrounding reef systems to assess what role these coral assemblages may play as potential refugia under a changing climate (Linklater *et al*., 2016, Linklater *et al*., 2018b).
- Recent efforts to catalogue coral disease in the LHIMP (Moriarty *et al*., in review) have provided a foundation for future research to investigate the effects of climate change stressors and potential biological interactions (e.g. macroalgae) on coral disease and mortality (see Climate Change Impacts below).

Smaller epifauna, infauna, and microbes

As with many marine parks, there is limited information available on smaller less conspicuous species, including small epifauna (< 2 cm), infauna, and microbes, as research tends to be more focused on charismatic, commercially-important, or habitat-forming species (Kenchington and Hutchings, 2018), partially owing to the significant taxonomic effort often required for the lesser-known groups (Hutchings, 2021). Infauna and small macrofauna may also be an important indicator of community change due to natural and anthropogenic stressors, and these groups underpin healthy ecosystems and can be integral to nutrient cycling, sediment irrigation, habitat provision, population regulation and contaminated sediment remediation (Aller, 1982). The following are identified knowledge gaps:

- These smaller epifauna warrant further research to understand their diversity, distribution and abundance in the LHIMP to assist with management planning (Przeslawski *et al.*, 2019); and
- Future research in the LHIMP could establish species inventories and environmental baselines using both traditional (e.g. morphology) and emerging (e.g. e-DNA) methods from which impacts on larger fauna, communities, and habitats could then be investigated.

Herbivory, coral recruitment and macroalgae

- Urchins form notoriously boom-and-bust populations, and research is required to understand the impacts of climate change on urchin densities and associated herbivory and coral recruitment in the LHIMP.
- There are also uncertainties over which fish species may assist in keeping urchin densities under control and the role of herbivorous fishes in either facilitating or grazing endemic seaweeds remains unknown (Stuart-Smith *et al*., 2019). Further research following Hoey *et al*. (2011) would help assess the complexities of urchin densities, coral recruitment, herbivorous fish, and climate change stressors. This could largely be a desktop study using the data already available through Reef Life Survey and the NSW DPI BRUVS program, although additional transects have been recommended at Algal Holes to more closely track urchin densities (Stuart-Smith *et al*., 2019).
- Additional research should also focus on other potential causes of macroalgae loss, including climate change and nutrient input (Stuart-Smith *et al*., 2019).

Climate change impacts

One of the greatest knowledge gaps remains the continued impacts of climate change and associated stressors on the unique species, communities and habitats of the LHIMP.

- Whilst it is recognized that sea temperatures are likely to increase under climate change, the actual impacts of increased water temperatures on the habitats and biodiversity of LHIMP are not known.
- Studies focusing on adaptability and resilience of those LHIMP species considered at greatest risk to increasing water temperatures (i.e corals), including endemic species (e.g. LHI abalone) would be valuable.
- We do not yet have an understanding of the impacts of sea level rise on ecological values, including how lagoon (e.g. seagrass) and coastal (e.g. saltmarsh) habitats may migrate.
- An Australian World Heritage climate change report recommends the following actions to manage climate change threats to the LHIMP (CSIRO, in review):
    - Identify environmental assets at most risk of climate change stressors;
    - Establish critical baselines;
    - Identify local long-term trends on available information to further clarify projections;
    - Implement enhanced mapping and foreshore monitoring for erosion and sea level rise impacts;
    - Develop emergency response actions for high-risk endemic species;
    - Undertake research and monitoring to fill identified knowledge gaps and assess the condition of at-risk habitats and species distributions;
    - Undertake research to investigate potential causes of macroalgae loss, especially caused by environmental factors associated with urchins and herbivorous fish;
    - Continue to monitor impacted and reference sites to assess recovery and change over time; and
    - Develop a rapid coral bleaching assessment method to quantify future quantify coral bleaching events.

Cumulative impacts and multiple stressors

- Although there is information available on the discrete threats to the environmental values of the LHIMP (Section 4), there is far less understanding of multiple stressors (two or more concurrent stressors) and cumulative impacts (one or more stressors impacting environmental values over time), particularly as related to climate change. For example, ocean warming and acidification have both been shown to increase urchin grazing in South Australia, but these effects are somewhat ameliorated with nutrient enrichment from run-off (Burnell *et al*., 2013). Another example is a potential interaction between high temperatures and groundwater-related nutrients that may have contributed to significant coral bleaching at Slyphs Hole in LHIMP in 2019 (Davis 2022b).
- To test such hypotheses in the LHIMP, research should focus on a given threat (e.g. coral disease in Moriarty *et al*., in review) in the context of other stressors, including possible synergistic interactions in which the effects of two or more stressors are greater than the sum of their individual effects (Przeslawski *et al*., 2015).

Relationships between values and threats

- This report and the companion report on socioeconomic values of the LHIMP (BDO 2022) were developed independently, but there are likely complex relationships between environment, social cultural and economic values and threats. For example, an activity that may bolster tourism could be considered an economic value, but that same activity could also have negative impacts on marine habitats and be considered an environmental threat.
- Any future threat and risk assessment (TARA) should consider these relationships (Gollan *et al*., 2019).

6 Closing

This report provides a comprehensive review of the environmental values of the LHIMP, including the physical, ecological (habitats) and biological values.

Each value is described based on available research and scientific literature, and where applicable, threats to the values have been identified in each of the relevant sections as well as summarised in the threats section. A companion review similarly reviewed the social, economic and cultural values of LHIMP, but identified challenges due to the lack of data and research directly associated with LHIMP (BDO, 2022).

Lord Howe Island Lagoon. Image from Louise Bell.

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