A Snapshot of Marine Research in Shark Bay (Gathaagudu)

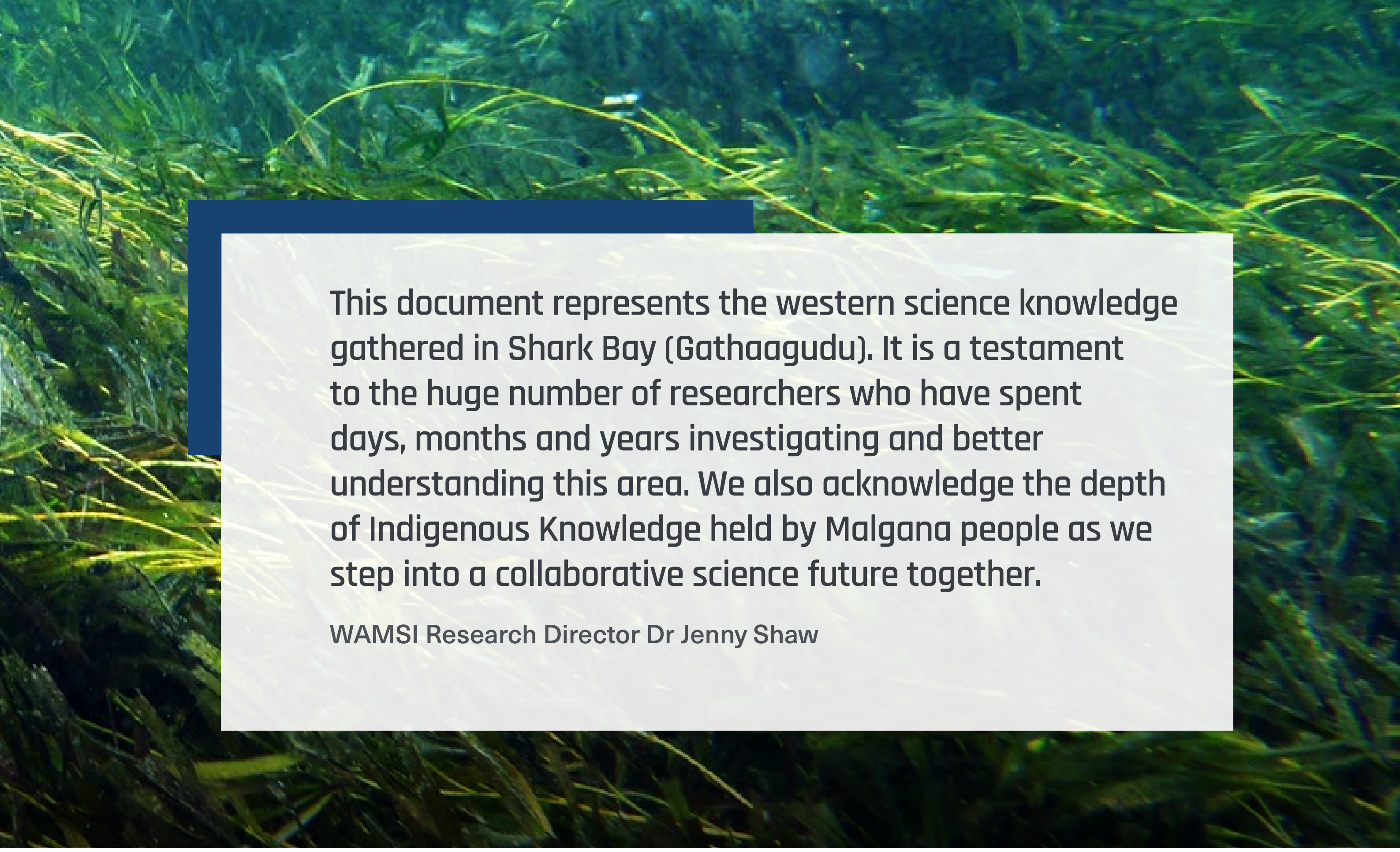
Literature Review and Metadata Collation (1949 – 2020)

WESTERN AUSTRALIAN
MARINE SCIENCE
INSTITUTION

White-spotted jellyfish (*Phyllorhiza punctata*) over wireweed seagrass (*Amphibolis antarctica*) at L'Haridon Bight, Shark Bay (Gathaagudu). (Photo: Matthew Fraser)

A Snapshot of Marine Research in Shark Bay (Gathaagudu): Literature Review and Metadata Collation (1949-2020)

This literature review and accompanying metadata synthesis describes published work on the marine environment of Shark Bay across various western science disciplines over seven decades. A total of 775 pieces of literature have been included in this document. The accompanying metadata synthesis contains 962 entries. This resource forms part of the Western Australian Marine Science Institution's (WAMSI) Shark Bay Science Plan and contributes to the regional understanding and knowledge of the Shark Bay marine environment.



> This document represents the western science knowledge gathered in Shark Bay (Gathaagudu). It is a testament to the huge number of researchers who have spent days, months and years investigating and better understanding this area. We also acknowledge the depth of Indigenous Knowledge held by Malgana people as we step into a collaborative science future together.
>
> WAMSI Research Director Dr Jenny Shaw

Publication date: September 2020

Metadata: https://catalogue.aodn.org.au/geonetwork/srv/en/metadata.show?uuid=5aed1b92-3759-4b87-84e7-1590ecb2f195

Citation: Sutton A.L. and Shaw J.L. (2020) A Snapshot of Marine Research in Shark Bay (Gathaagudu): Literature Review and Metadata Collation (1949-2020). Prepared for the Western Australian Marine Science Institution, Perth, Western Australia. 180pp.

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Alicia Sutton uncovered the publications and drafted the content of the report. Jenny Shaw had report oversight and both contributed to the structuring, editing and finalising of the report.

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Funding Sources: This project is an initiative of the Western Australian Marine Science Institution, with funding support from the state government as part of the Western Australian Blueprint for Marine Science and the Shark Bay Priorities project. The Shark Bay Literature Review and Metadata Collation has been supported in-kind by a Steering Group including WAMSI partners: UWA, DPIRD and DBCA.

Report and metadata URL: www.wamsi.org.au/shark-bay-literature-review

ISBN: 978-0-9872761-4-8

Front cover image:

Modified image of a pixel composite mosaic of a time series of satellite observations of Shark Bay (2017. Surface Reflectance 25m Geomedian 2.0.0. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/120374

Table of Contents

Figures and Tables

Abbreviations and acronyms

ACAP	Agreement on the Conservation of Albatrosses and Petrels
AFMA	Australian Fisheries Management Authority
AFZ	Australian Fishing Zone
AIMS	Australian Institute of Marine Science
ANZECC	Australian and New Zealand Environment and Conservation Council
AODN	Australian Ocean Data Network
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
Bonn	Convention on the Conservation of Migratory Species of Wild Animals
CALM	Conservation and Land Management
CAMBA	China-Australia Migratory Bird Agreement
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CVI	Climate Vulnerability Index
DBCA	Department of Biodiversity, Conservation and Attractions
DPIRD	Department of Primary Industries and Regional Development
DPLH	Department of Planning, Lands and Heritage
DWER	Department of Water and Environmental Regulation
EBFM	Ecosystem Based Fisheries Management
EPA	Environmental Protection Authority
EPBC	Environment Protection and Biodiversity Conservation
FIU	Florida International University
FRDC	Fisheries Research and Development Corporation
IMAS	Institute for Marine and Antarctic Studies
IMOS	Integrated Marine Observing System
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
JAMBA	Japan-Australia Migratory Bird Agreement
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
MARPOL	International Convention for the Prevention of Pollution from Ships
MNR	Marine Nature Reserve
MPA	Marine Protected Area
MSC	Marine Stewardship Council
NESP	National Environmental Science Program
NRM	Natural Resource Management
ROKAMBA	Republic of Korea-Australia Migratory Bird Agreement
SBMR	Shark Bay Marine Reserves
SBWHA	Shark Bay World Heritage Area
SST	Sea surface temperature
UAV	Unmanned aerial vehicle
UNCLOS	United Nations Convention for the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
UWA	The University of Western Australia
VIMS	Virginia Institute of Marine Science
WA	Western Australia
WAFIC	Western Australian Fishing Industry Council
WAMSI	Western Australian Marine Science Institution

Acknowledgements

This document is testament to the huge number of researchers who have spent days, months and years in Shark Bay investigating and better understanding the science of this area. Your inquiry, dedication, discovery and publication of information has resulted in an extensive set of material for this unique and complex system. We would also like to acknowledge those scientists and others who not only provided their research but contributed to the accompanying metadata collation.

The Steering Group of Gary Kendrick (UWA), Gary Jackson (DPIRD) and Alan Kendrick (DBCA) oversaw this project from the outset. Each has a passion for the area and a long-standing professional commitment to protect this special place. Additional expertise from Luke Twomey (WAMSI), Aleta Johnston (WAMSI) and Gina Lincoln (WAMSI/Mosaic Environmental) was valued and added to the document.

It was Alicia Sutton (WAMSI/Carijoa) however, who uncovered the huge number of publications and skillfully translated and synthesised the knowledge into meaningful text. Her unflagging enthusiasm and attention to detail has ensured that this document is a valuable resource that will be used by many into the future. It is a credit to her skill and perseverance.

Additional reviews were carried out by Mervi Kangas (DPIRD), Arani Chandrapavan (DPIRD), Shaun Wilson (DBCA), Kelly Waples (DBCA) and Luke Skinner (DBCA). Cheryl Cowell (DBCA/ Shark Bay World Heritage Advisory Committee/ Shark Bay Shire) was always able and willing to provide information whenever needed. Maps were provided by DPIRD and DBCA. Paul Day (Carijoa) provided some additional assistance with metadata collation and Paul Orange (DPIRD) uncovered early Fisheries data.

The Shark Bay Priorities Project partnered with the World Heritage Advisory Committee. Their support throughout this process has been invaluable.

Many others have contributed to producing this document with advice, suggestions and provision of materials including maps, figures and photographic images. We very much appreciate and gratefully acknowledge your contributions. Thank you all.

This work represents western science knowledge gathered on Gathaagudu, the traditional Country of the Malgana people. We pay our respects to their elders past, present and emerging.

Jenny Shaw
Research Director
WAMSI

Carbla Point stromatolites
(Photo: H. Nakrem/ courtesy SBWHA)

Executive summary

Shark Bay

Shark Bay is the largest semi-enclosed bay in Australia encompassing 14,000km^2 bordered by a chain of barrier islands. Most of the Eastern and Western Gulfs of the Bay are included within the Shark Bay Marine Park (State waters), with the innermost portion of the Eastern Gulf protected by the Hamelin Pool Nature Reserve. Shark Bay is renowned for the Wooramel Seagrass Bank, one of the largest and most diverse seagrass meadows in the world, stromatolites of the hypersaline Hamelin Pool, the largest dugong population in the world and a diverse array of marine life including sharks and rays and a famous population of bottlenose dolphins.

The Shark Bay World Heritage Area (SBWHA) spans 22,000km^2 and 1500km of coastline, with up to 66% of the area covering the marine environment. The Shark Bay Marine Park and Hamelin Pool Nature Reserve are also included within the boundaries of the SBWHA. The SBWHA was inscribed in 1991 because of its outstanding universal value, which satisfied four International Union for Conservation of Nature (IUCN) natural criteria (VII, VIII, IX, X). Some of the features satisfying these criteria include the Wooramel Seagrass Bank, one of the largest and most diverse seagrass meadows in the world, and the stromatolites of the hypersaline Hamelin Pool, which are comparable to the fossil record. The SBWHA also boasts an extensive array of marine life including sharks, rays, turtles, dugongs and cetaceans, as well as scenic coastal beauty at locations such as Zuytdorp Cliffs and Peron Peninsula.

Purpose of document

In 2011, Shark Bay was negatively impacted by a marine heatwave that caused widespread losses to seagrass meadows and negative flow-on effects for associated species. Shark Bay is also a World Heritage Area (WHA) with values that, if lost from climate change and other anthropogenic pressures, could jeopardise its listing as a WHA. This has sparked a need to better understand the ecological resilience of Shark Bay in relation to extreme events and climate change.

Several calls have been made for a multidisciplinary and international science program to address priority research areas that could support integrated management decisions for Shark Bay. The Western Australian Marine Science Institution (WAMSI) has addressed these calls by developing a Shark Bay Science Plan in collaboration with a range of stakeholders. This literature review on Shark Bay, and accompanying metadata synthesis, will contribute to the WAMSI Shark Bay Science Plan by providing the background knowledge for formulating priority areas of research. It also addresses the need for a resource describing all work in Shark Bay over various disciplines. This document will be particularly useful for researchers, managers, and all those interested in Shark Bay and the extensive research that has been undertaken over multiple decades.

Breadth of review

A total of 775 pieces of literature were included in this document. A large portion of this review includes a synthesis of ecological assets including environmental conditions, ecosystem processes, benthic communities, planktonic communities, faunal communities and fisheries. The majority of research at Shark Bay has focused on bottlenose dolphins and fisheries, followed by microbial communities, seagrass communities and ecosystem-wide research (predation, foraging). To be more comprehensive, the review also includes information on Indigenous interests, social and economic drivers (tourism and fisheries are key drivers), threats and external drivers, current management and planning, and also legislative and administrative arrangements. Citations are listed at the end of this document. The citations, contact author, synthesis and metadata availability can be found at www.wamsi.org.au/shark-bay-literature-review.

1. Introduction

Amphibolis antarctica (wire weed) on shelly sediments in the hypersaline waters of L'Haridon Bight (Photo: Rachel Austin)

1.1 Background

Shark Bay is located at Australia's most westerly point in a marine transition zone between tropical and temperate Indian Ocean waters (25.7834°S, 113.2988°E). It is the largest semi-enclosed bay in Australia encompassing 14,000km^2 bordered by a chain of barrier islands. Most of the Eastern and Western Gulfs of the Bay are included within the Shark Bay Marine Park (State waters), with the innermost portion of the Eastern Gulf protected by the Hamelin Pool Nature Reserve. An additional Shark Bay Marine Park is located in Commonwealth waters immediately west of Bernier, Dorre and Dirk Hartog Islands. Shark Bay is renowned for the Wooramel Seagrass Bank, one of the largest and most diverse seagrass meadows in the world, stromatolites of the hypersaline Hamelin Pool, the largest dugong population in the world and a diverse array of marine life including sharks and rays and a famous population of bottlenose dolphins.

In 2011, Shark Bay was negatively impacted by a marine heatwave that sustained prolonged temperature anomalies of 2-4°C along the WA coastline. The heatwave caused widespread losses to seagrass meadows which had flow-on effects through the food chain and for species that relied on the meadows for shelter and nurseries.

There was a workshop held at The University of Western Australia (UWA) in early 2011 to address the then present scientific knowledge of Shark Bay. This resulted in a special issue of Marine and Freshwater Research on 'Science for the management of subtropical embayments: examples from Shark Bay and Florida Bay' released in 2012 which specifically called for a multidisciplinary and international science program focused on ecological resilience in Shark Bay (Kendrick *et al.* 2012).

In June 2018, a WAMSI/UWA workshop on 'Adapting to ecosystem change in the Shark Bay World Heritage Site' was held with 70 science and industry experts to identify gaps in knowledge and address whether current management strategies were adequate for responding to future extreme events and climate change (www.wamsi.org.au/shark-bay-workshop). Again, there was a clear call for collaboration among disciplines and institutions to identify and address priority research areas that could support integrated management decisions.

Outcomes from the June workshop were used in Climate Vulnerability Index (CVI) workshops that carried out rapid assessments of the exposure, sensitivity and adaptive capacity of Shark Bay World Heritage values (September 2018) and economic, social and cultural values (June 2019) to climate change.

WAMSI has addressed calls for a collaborative approach to tackle ecosystem change in Shark Bay and is developing a comprehensive science plan in partnership with a range of stakeholders. The WAMSI Shark Bay Science Plan will outline priority areas of research needed to help sustainably manage the marine environment of Shark Bay.

1.2 This review and information sources

This literature review on Shark Bay and the accompanying WAMSI Shark Bay metadata synthesis found at www.wamsi.org.au/shark-bay-literature-review (see section 10.4) will contribute to the WAMSI Shark Bay Science Plan by identifying scientific knowledge gaps in the marine environment and providing the background knowledge for determining priority areas of research (Fig. 1).

This review and accompanying metadata synthesis also addresses the need for a resource that describes all research work conducted in Shark Bay over various disciplines. Discussions with Traditional Owners in 2019 indicated that there was a keen interest in understanding the breadth of work that has been conducted. During a workshop later in the year, Malgana Elders, the Malgana Land and Sea Management Reference Group, Malgana rangers from both the DBCA, and the Malgana Land and Sea Management Program, were provided with a comprehensive list and synthesis of literature and associated metadata information.

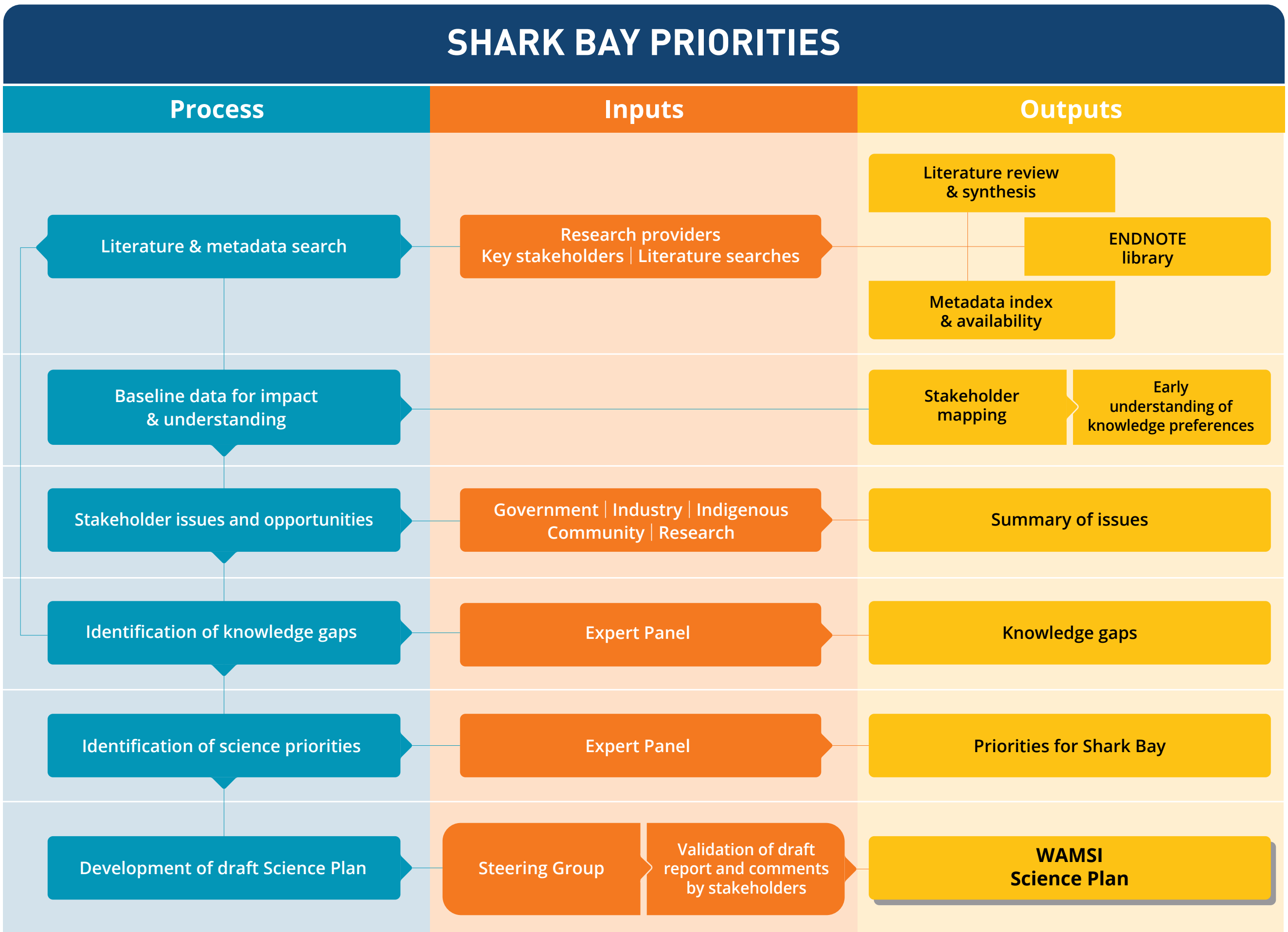


Figure 1 Shark Bay Priorities schema outlining the processes that will result in the WAMSI Shark Bay Science Plan.

1.2.1 Scope

The spatial scope of the review is the marine environment within the boundaries of the SBWHA, though some relevant information is provided for coastal and terrestrial environments and waters adjacent to the boundary. The review is largely focused on marine ecological assets, but also includes Indigenous interests, social and economic drivers, and other relevant information to form a comprehensive resource for Shark Bay.

1.2.2 Information sources

The information provided in this document was obtained via two pathways; contacting key researchers and searching the literature.

Forty-five key researchers were formally contacted by letter, or asked in face-to-face meetings, to provide any published research/ data (peer reviewed and grey literature) pertaining to Shark Bay. Researchers were also asked to provide associated metadata information, such as if data was freely available, where the data was held and contact details. A total of 35 responses were received, of which 18 provided requested lists of research and data.

A thorough search of the literature was undertaken in order to build upon the information received from key researchers. Firstly, the combination of search terms used in library databases and online search engines related to a predefined list of ecological assets, such as many of those outlined in section 3, e.g. mangrove AND Shark Bay, shark AND Shark Bay etc. Following this, more general searches were conducted using solely the term 'Shark Bay', as well as other location names, including but not limited to 'Faure Sill', 'Dirk Hartog Island' and 'Gascoyne', in order to identify any ambiguous literature or literature that did not fit within the pre-defined headings.

Searches of both the Department of Primary Industries and Regional Development (DPIRD) Fisheries library and Department of Biodiversity, Conservation and Attractions (DBCA) library were conducted. Relevant literature was formally requested if necessary.

Overall, the information gathered for this literature review came from published scientific papers, published and unpublished reports, theses and, to a small extent, websites such as the Shark Bay World Heritage Area website and government websites for tenure and lease information.

1.2.3 Layout

The headings and subheadings used in this document are themes derived from a combination of DBCA defined ecological values (see Kendrick *et al.* (2016)) and DPIRD Ecosystem Based Fisheries Management (EBFM) categories (see Fletcher *et al.* (2010)). Themes were then modified as necessary depending on the literature derived.

It is recognised that some of the knowledge presented in this document is suited to multiple themes and, as such, some information is repeated under more than one sub-heading.

2. Shark Bay World Heritage Area

Cape Peron, Francois Peron National Park
(Photo: Sheree Scarborough)

The SBWHA spans 22,000km^2 and 1500km of coastline, with up to 66% of the area covering the marine environment (Fig 2). The SBWHA is inclusive of Dirk Hartog, Dorre and Bernier Islands and extends south along the coastline to include Hamelin Pool and Zuytdorp Nature Reserve and cliffs. The salt mines at Useless Loop and Inlet were operating prior to World Heritage listing and are excluded from the boundary of the SBWHA, as is the Town of Denham.

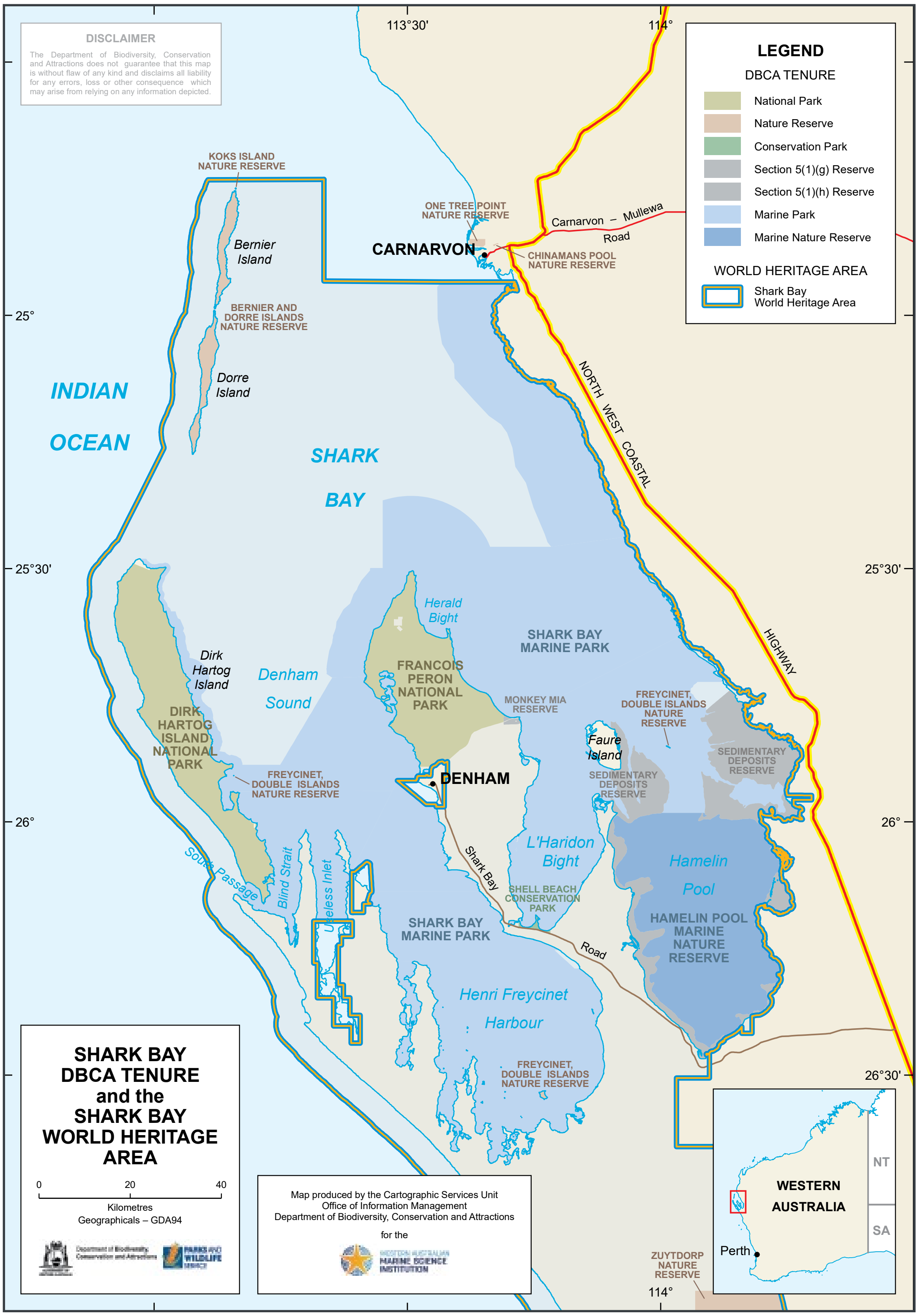


Figure 2 The marine environment encompassed within the Shark Bay World Heritage Area.

Shark Bay was inscribed on the World Heritage List in 1991 because of its 'Outstanding Universal Value'. To be included on the World Heritage List, a site needs to meet one of ten selection criteria; six cultural criteria and four natural criteria. The SBWHA satisfies all four natural criteria, which include:

Natural Criteria VII- to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.

Examples:

- Hamelin Pool has the most diverse and abundant formations of stromatolitic microbialites in one place, and formations are comparable to the fossil record
- Wooramel Seagrass Bank is one of the few marine areas dominated by carbonate sediments not associated with reef building corals and has one of the largest and the most diverse seagrass meadows in the world
- Faure Sill and high evaporation have produced the hypersaline environment of Hamelin Pool and L'Haridon Bight, which in turn is responsible for wide sweeping beaches consisting entirely of *Fragum* shells
- Zuytdorp Cliffs, Dirk Hartog Island, Heirisson and Bellefin Prongs provide exceptional coastal scenery, including the strongly contrasting colours of Peron Peninsula
- Diverse landscapes of peninsulas, islands, bays, lagoons and birridas
- Marine fauna are abundant and include dugongs, dolphins, sharks, rays, turtles and fish
- A rich flora creates extensive annual wildflower displays

Natural Criteria VIII- to have outstanding examples representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features.

Examples:

- Hamelin Pool has the most diverse and abundant formations of stromatolitic microbialites in one place, and formations are comparable to the fossil record
- Wooramel Seagrass Bank is one of the few marine areas in the world dominated by limestone sands formed by the precipitation of calcium carbonate from hypersaline water, rather than from reef building corals
- Faure Sill and high evaporation have produced the hypersaline environment of Hamelin Pool and L'Haridon Bight, which in turn is responsible for wide sweeping beaches consisting entirely of *Fragum* shells

Natural Criteria IX- to have outstanding examples representing significant ongoing ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals.

Examples:

- Distinct oceanic, metahaline and hypersaline zones due to the development of banks and sills which, in turn, have created three distinct biotic zones
- Hamelin Pool is a reversed estuary containing hypersaline waters
- Marine organisms have developed physiological adaptations to tolerate hypersaline conditions, such as the bivalve *Fragum erugatum*, which have created extensive and rare Holocene deposits, lithified sediments, supratidal flats and meromictic blue ponds
- Extensive seagrass meadows (i.e. Wooramel Seagrass Bank) have caused modification of the physical environment through formation of banks and sills from carbonate deposits, which has influenced water currents
- Shark Bay has one of the largest and most diverse seagrass meadows in the world and is a seagrass-based ecosystem that influences nutrient cycling, hydrological conditions and food chains, and provides important habitat and nursery grounds
- Marine species such as pink snapper and venerid clams have high genetic variability
- Hamelin Pool has the most diverse and abundant formations of stromatolitic microbialites in one place, and formations are comparable to the fossil record
- High species diversity due to location in a transition zone between temperate and tropical marine ecological provinces e.g. 323 fish species; 218 bivalve species; 80 coral species; 12 seagrass species
- Islands and peninsulas contain isolated fauna habitats and populations, such as the rufous hare-wallaby and banded hare-wallaby
- Diverse plant communities due to location in a transition zone between the Southwestern Botanical Province dominated by *Eucalyptus* species and the Eremean Province dominated by *Acacia* species
- Numerous temperate terrestrial fauna are at their northern range limits, including species of reptiles, amphibians and birds, and numerous arid reptiles and amphibians are at their coastal end ranges
- Tree heath vegetation south of the Freycinet Estuary has examples of ‘gigantism’ and has diverse plant and animal communities, including ~35% of Australia’s total bird species

Natural Criteria X- to contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Examples:

- Shark Bay is located in a transition zone between the Southwestern Botanical Province and the Eremean Province which has created a diverse biota consisting of endemic vascular plants, endemic reptiles, new species and range extensions for many species
- Five globally threatened mammals are found in Shark Bay in what could be the only or major populations remaining; the burrowing bettong (now classified as Near Threatened), rufous hare wallaby, banded hare wallaby, the Shark Bay mouse and the western barred bandicoot
- An 11,000 strong population of dugongs; one eighth of the world's population
- Humpback whales and southern right whales use Shark Bay during migration
- A population of now famous bottlenose dolphins live in Shark Bay and are visited and studied
- Provides an important habitat for green and loggerhead turtles; the area is a significant nesting area for loggerhead turtles
- An abundance of sharks and rays are present in Shark Bay, including manta rays which are considered globally threatened

Cape Peron, Shark Bay
(Photo: DBCA)

3. Ecological assets

Stingrays, Heron Island, Shark Bay
(Photo: iStock.com/eriktrampe)

3.1 Environmental conditions

3.1.1 Hydrology

3.1.1.1 Water sources and water budgets

The Wooramel River is the greatest source of freshwater discharge directly into Shark Bay, followed by the Gascoyne River further north near Carnarvon. Stable isotopes and salinity concentrations of water samples have been used to trace water sources in the Bay and estimate water budgets for the Eastern Gulf and Hamelin Pool (Price *et al.* 2012). Evaporation was estimated to account for half of the water volume lost from Hamelin Pool each year. Combined with restricted tidal fluctuations across Faure Sill, the water volume of the Pool is estimated to be replaced every 6-12 months.

3.1.1.2 Groundwater and surface run-off

Groundwater was investigated intensively in Hamelin Pool in the 1980s, and included documenting locations of groundwater input, measuring salinities, examining bacteria and investigating the production of iron-sulphide minerals (Burne and Hunt 1990).

Measurements of increased salinity in winter months and decreased salinity in summer months has provided some evidence for the intrusion of groundwater around the margins of Hamelin Pool (Suosaari *et al.* 2016a). Analytical modelling has also been used to quantify groundwater influx into Hamelin Pool (Abreu Araujo 2015).

Based on modelling of future climate scenarios, it is likely that run-off from winter rainfall will decrease for the Wooramel River catchment (Mpelasoka and Rustomji 2012).

3.1.1.3 Flooding

The flow of the Wooramel River into the Eastern Gulf of Shark Bay is not constant and only flows during flood events associated with cyclones or winter storms (Nott 2011; Mpelasoka and Rustomji 2012). The episodic flooding of the river, and the associated input of nutrients, could be one explanation for why seagrass communities adjacent to the Wooramel River have higher phosphorus concentrations compared with other meadows in the Bay (Fraser *et al.* 2012). An extreme flooding event occurred from December 2010 to February/ March 2011, which caused flood plumes with significant suspended sediment loads to spread up to 15km from the mouth of the Wooramel River. Reduced light conditions persisted for at least three months (Walker *et al.* 2012). This flooding event coupled with the 2011 marine heatwave are both believed to have played a role in the widespread loss of seagrass in Shark Bay, particularly for seagrasses close to the Wooramel River (Fraser *et al.* 2014; Thomson *et al.* 2015a). Such flooding events can cause increased sedimentation over seagrass meadows and also reduce photosynthetic activity due to reduced light levels.

If flooding of the Wooramel River was to increase under future climate change projections, the increased sediment load could be expected to negatively impact the seagrass at Faure Sill and, in turn, impact upon ideal growth condition for stromatolites in Hamelin Pool (Mpelasoka *et al.* 2012; Mpelasoka and Rustomji 2012).

3.1.2 Oceanography

Oceanic circulation is restricted within Shark Bay due to the presence of large barrier islands to the east and north of the Bay, length and shallowness of embayments and the presence of seagrass banks and sills.

During the summer months, southerly winds help to drive the seasonal Capes Current northward, which intrudes cooler waters into the western entrance of the Bay and sees a gradient to warmer temperatures in the inner gulfs (Pattiaratchi and Hetzel 2018) (Fig. 3).

During the winter months when southerly winds are weaker, the dominant southward flowing Leeuwin Current pushes warmer waters into the entrances of the Bay, which sees a gradient to cooler waters in the inner gulfs (Pattiaratchi and Hetzel 2018) (Fig. 4).

Large areas of Shark Bay are hypersaline due to evaporation exceeding rainfall by as much as ten times and, given this, Shark Bay is classified as an inverse estuary (Hetzel *et al.* 2013). A distinctive north-south gradient in salinity of 35-60psu is observed from the mouth of Shark Bay to Hamelin Pool due to the shallow depth of the Faure Sill restricting water exchange (Fig. 5). The tidal conditions of the region represent a mix between dominant diurnal and semi-diurnal regimes (Pattiaratchi and Hetzel 2018).

3.1.2.1 Shark Bay Outflow

The Shark Bay Outflow refers to the outflow of high salinity waters from Shark Bay to the continental shelf via deep channels.

The main outflow of high salinity water (and associated biological material) occurs through the Geographe Channel in the north, with the Naturaliste Channel between Dirk Hartog and Dorre Islands also facilitating significant outflow (Woo *et al.* 2006; Hetzel *et al.* 2010; Hetzel *et al.* 2012; Hetzel 2013; Hetzel *et al.* 2018). Less dense, low salinity surface water flows into Shark Bay via Geographe and Naturaliste Channels, while high density, high salinity water exits along the seabed through these same channels (Nahas 2004; Nahas *et al.* 2005).

These density-driven bottom currents play a major role in water exchange between Shark Bay and the ocean, and while outflow is enhanced during periods of low tidal mixing (Hetzel 2013), outflow is persistent through all stages of the tide, particularly for the Geographe Channel (Hetzel *et al.* 2018).

The high salinity waters flowing through the deep channels to the continental shelf form a distinct water mass (21.2-22.9°C and up to 36.1 ppt) that mixes with the Leeuwin Current and flows poleward (Hanson *et al.* 2005; Woo *et al.* 2006; Pattiaratchi and Woo 2009).

3.1.2.2 Mixing and transport

Wind or tide alone can be enough to mix the water column in the shallow regions of Shark Bay (< 15 m; not necessarily for shallow waters restricted by sills and banks), whereas both forces are needed to fully mix deeper channel waters (> 15 m) (Hetzel *et al.* 2013; Hetzel 2013; Hetzel *et al.* 2015). Burling *et al* (2003) used non-linear modelling to describe the tidal regime of Shark Bay in more detail, and Hunt and D'Adamo (1998) released drogues in surface and bottom waters to examine flushing of Monkey Mia lagoon across ebb and flood tidal cycles.

Modelling the release of neutrally buoyant pollutants also showed that wind enhanced dilution plays an important role in the hydrodynamic process within Monkey Mia (Luketina *et al.* 1998).

Hopeless Reach has also been examined in more detail and is found to be vertically well mixed in summer and stratified in winter (Burling *et al.* 1999). Hopeless Reach receives a steady discharge of salt from Hamelin Pool, largely though Herald Loop, given the restriction to water exchange across the shallow Faure Sill.

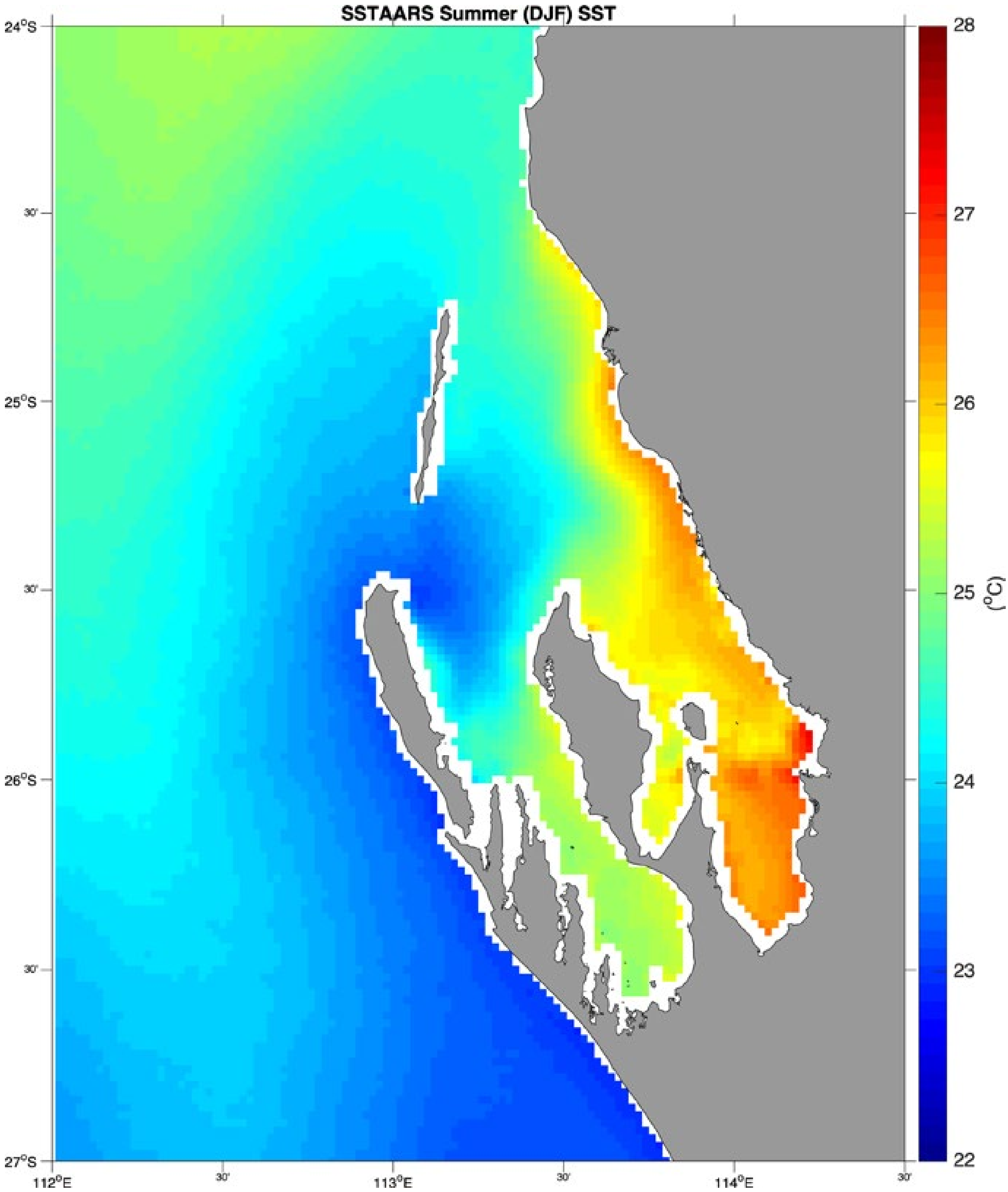


Figure 3 Mean summer sea surface temperature climatology map for Shark Bay. Map was created by Yasha Hetzel for this review using the dataset from Wijffels *et al.* (2018). N.B. there is a difference in the temperature scale for Figures 3 and 4.

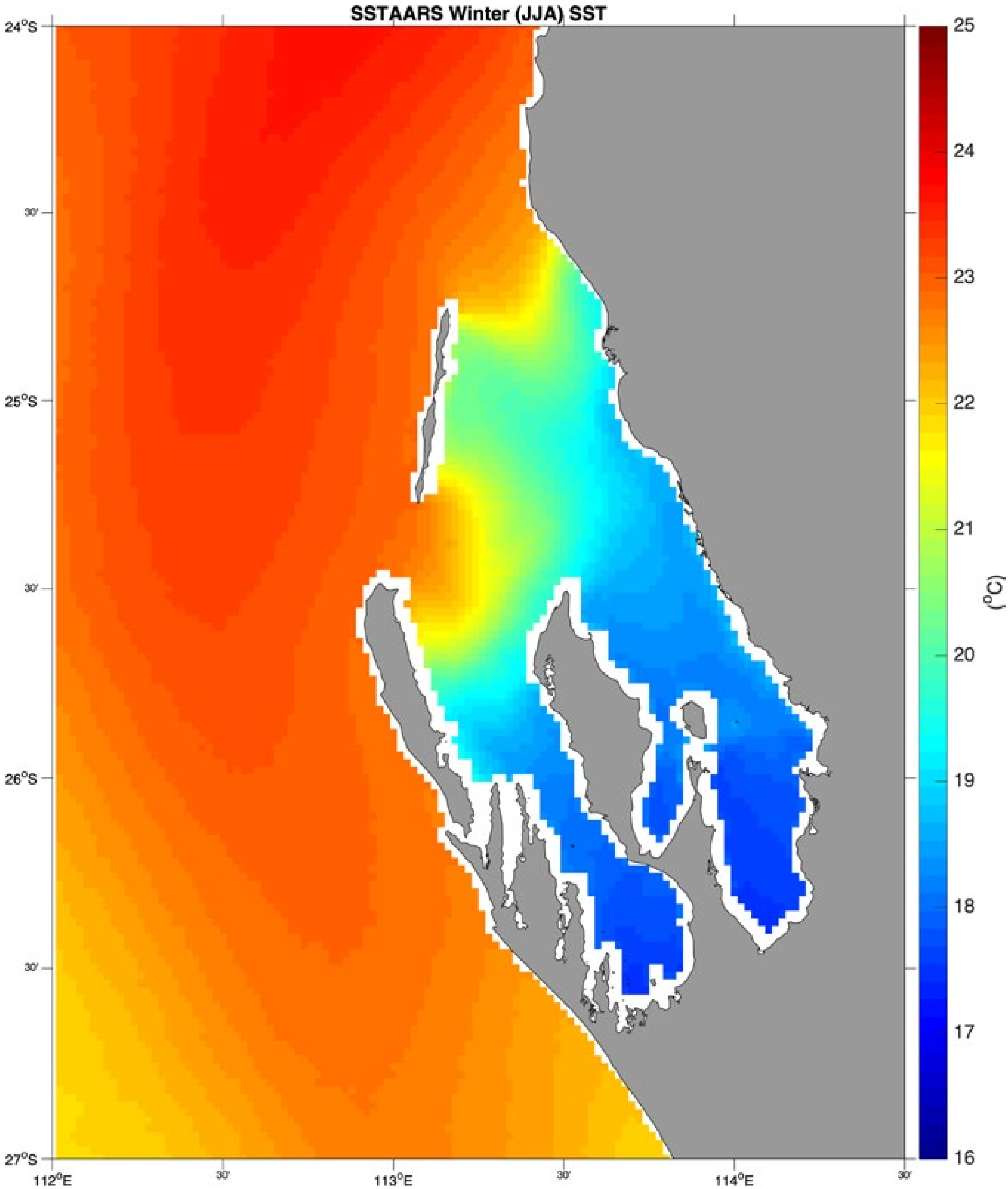


Figure 4 Mean winter sea surface temperature climatology map for Shark Bay. Map was created by Yasha Hetzel for this review using the dataset from Wijffels *et al.* (2018). N.B. there is a difference in the temperature scale for Figures 3 and 4.

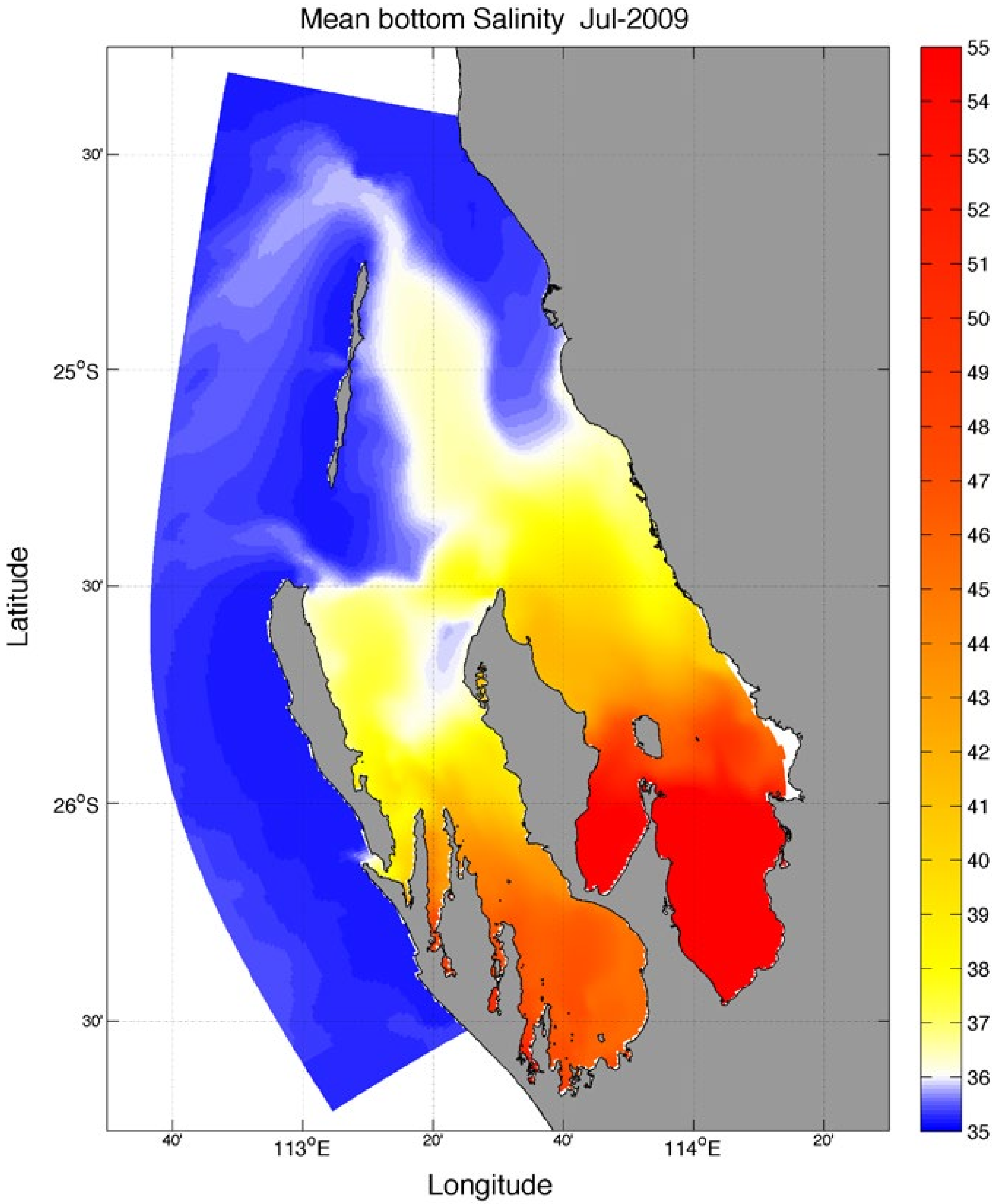


Figure 5 Mean bottom salinity (ppt), showing the outflow of dense water from Shark Bay for July 2009. Map was created by Yasha Hetzel using a numerical model (Hetzel *et al.* 2013)

3.1.3 Water quality

Water quality monitoring to establish baselines has been conducted for Monkey Mia (Trayler and Shepherd 1993), the wider Eastern Gulf (Pedretti *et al.* 1998), and Hamelin Pool (Ahearn 2019).

In the late 1980s, significantly contaminated interstitial water and seawater was detected at Monkey Mia, which was implicated in the death and disappearance of dolphins at Monkey Mia, though not conclusively proven (EPA WA 1989). Ongoing monitoring of nutrients and pathogens at Monkey Mia since 1989 have typically shown relatively stable concentrations (DBCA 2019b), though unexplained elevated concentrations of nitrogen and phosphorus were recorded in 2016.

Nutrient availability and fluxes in the water column examined for Shark Bay reveal a similar finding to sediments in that phosphorus is limited in the hypersaline waters of Shark Bay (Smith and Atkinson 1983; Smith and Atkinson 1984; Atkinson 1987; Pedretti *et al.* 1998). Phosphorus concentrations were below detection limits (<0.02 μM) for 65/70 sites sampled across Faure Sill, Wooramel Delta and surrounds in 2011 (Walker *et al.* 2012). Nitrogen is not typically limited due to the level of nitrogen fixation occurring in the system.

Dissolved organic material in the water column is found to be mostly derived from seagrass sources, but also terrestrial, planktonic and macroalgal sources within Shark Bay (Cawley *et al.* 2012).

Chlorophyll *a* concentrations (0.4-2.6ug/L) in the water column were found to be within the typical ranges of oceanic waters (Pedretti *et al.* 1998). A particular examination of an intertidal sand flat found that water mass flooding over the course of a few hours resulted in a progressive decline of chlorophyll *a* concentrations in the water column, which impacted on sestonic food availability (Peterson and Black 1991).

Some attention has been given to cadmium, which absorbs onto iron oxide particles in the water column and is then ingested by bivalves (Lawrance 1985; McConchie *et al.* 1988; Francesconi 1989; McConchie and Lawrance 1991).

Seawater temperature measured at Redcliff Bay, Hamelin Pool, Denham and Sandy Point has shown a slow increasing trend since monitoring began in 1985 (DBCA 2019b).

3.1.4 Sediment quality

Investigations since the 1980s have revealed that sediments in Shark Bay are generally limiting in phosphorus. Phosphorus and iron concentrations in sediments are found to decrease from oceanic to hypersaline environments, whereas organic carbon and total nitrogen are found to increase further into the Bay (Atkinson 1987; Atkinson 1990). Of total phosphorus, an estimated 90% of inorganic phosphorus is thought to be tied up in shells and shell fragments, whereas only 10-15% of organic phosphorus is estimated to be available in the Bay (Atkinson 1990).

However, local-scale examination of nutrients in sediments does not necessarily reflect the same large-scale gradient patterns (Fraser *et al.* 2012; Walker *et al.* 2012). Nutrient concentrations in sediments were found to be more variable across Faure Sill and Wooramel Bank region in 2011, and not strongly correlated with salinity. Concentrations of total P ranged from 3.1 - 25.3µg Pg ^{1} with higher concentrations identified closer to the Wooramel Delta and Faure Island, and higher nitrogen concentrations found at Faure Sill in comparisons to adjacent areas.

In relation to sediments of seagrass meadows, available inorganic nitrogen and phosphorus was linked to microbial activity across a salinity and phosphorus gradient from Guichenault Point to L'Haridon Bight (Fraser *et al.* 2018). Microbial communities from these sediments were dominated by the phyla Proteobacteria, but also contained Bacteroidetes, Planctomycetes, Firmicutes, Actinobacteria and Cyanobacteria.

Two distinct sediment populations/chemogeographic regions were identified across Shark Bay based on an analysis of hydrocarbons (Dunlop and Jefferies 1985).

Benthic photosynthesis and oxygen demand in permeable carbonate sediments was found to be influenced by boundary layer flow, and the flushing created from this flow was found to be important for oxygen uptake in coral sands (Rasheed *et al.* 2004).

In Hamelin Pool, an obligately halophilic (tolerable of high salt concentrations) representative of the purple sulfur bacteria, *Chromatium vinosum*, is found to occupy organic rich intertidal sediments (Bauld *et al.* 1986).

3.1.5 Geology

The geology of Shark Bay has been comprehensively described (Davies 1970b; Playford 1990; Playford *et al.* 2013), and many studies have focused on carbonate sediments and the formation of barriers and banks that helped to form hypersaline basins.

3.1.5.1 Sedimentary environment

Shark Bay has been placed into context in an examination of shelf sediments from the North West Shelf to the South West Shelf (Collins *et al.* 2014). Shark Bay wide studies have included a discussion of the geomorphology and history of carbonate sedimentation during the Pleistocene (Logan *et al.* 1970), and a detailed description of the sedimentary environment of Shark Bay, describing the outer calcareous eolianite barrier, inlets and submerged banks (Logan and Cebulski 1970).

Diagenesis, the change of sediments into sedimentary rock, has been investigated for carbonate sediments and quaternary carbonate sequences in Shark Bay (Logan 1974b; Logan *et al.* 1974b). Benthic formaniferans are thought to play a role in diagenesis pathways, and as a starting point, the benthic foraminiferan assemblages have been examined at Carbla Beach (Wood 2019).

Location specific sedimentary studies within Shark Bay have included a description of the geomorphic features and stratigraphy of the McLeod Evaporite Basin (Logan 1974a), a description of the composition of shallow marine silurian carbonates from the Gascoyne Platform (El-Tabakh *et al.* 2004), and a description of the features of algal-laminated sediments in Gladstone embayment (Davies 1970a).

3.1.5.2 Hypersaline basins

The development of large barrier banks of carbonate sediments, and the facilitation of bank formation by seagrass meadows, has gradually reduced tidal flow over time and created the hypersaline basins seen today in Shark Bay (Hamelin Pool and Freycinet Harbour) (Davies 1970b; Hagan and Logan 1974).

Faure Sill is the shallow seagrass bank reducing tidal flow into Hamelin Pool and has evolved from pre-Holocene topography shaping the initial sedimentation, seagrasses trapping sediments and sea-level fluctuations across time (Bufarale 2014; Bufarale and Collins 2015a).

In order to better understand the relationship between the Faure Channel-Bank Complex and Wooramel Delta, shallow seismic data, lithostratigraphic analysis and radiocarbon dating was used to investigate the internal architecture, facies, chronology, bank onset and growth history of Faure Sill (Bufarale and Collins 2015b).

Hamelin Pool and L'Haridon Bight are bordered by a Holocene coquina ridge system, and the architecture of these sedimentary rocks, composed of bivalves that have accreted during the last 5000 years due to sea level regression, have been investigated using cores and geophysical imaging (Jahnert *et al.* 2012) (Fig. 6).

Other geological features that have been investigated within hypersaline basins of Shark Bay include the prograding tidal-supratidal flat of Nilemah Embayment (Brown and Woods 1974), bank and wave-built platform formation in inlets of the Edel province (Read 1974a; Read 1974b), and the tidal flat of Hutchinson Embayment (Hagan and Logan 1975).

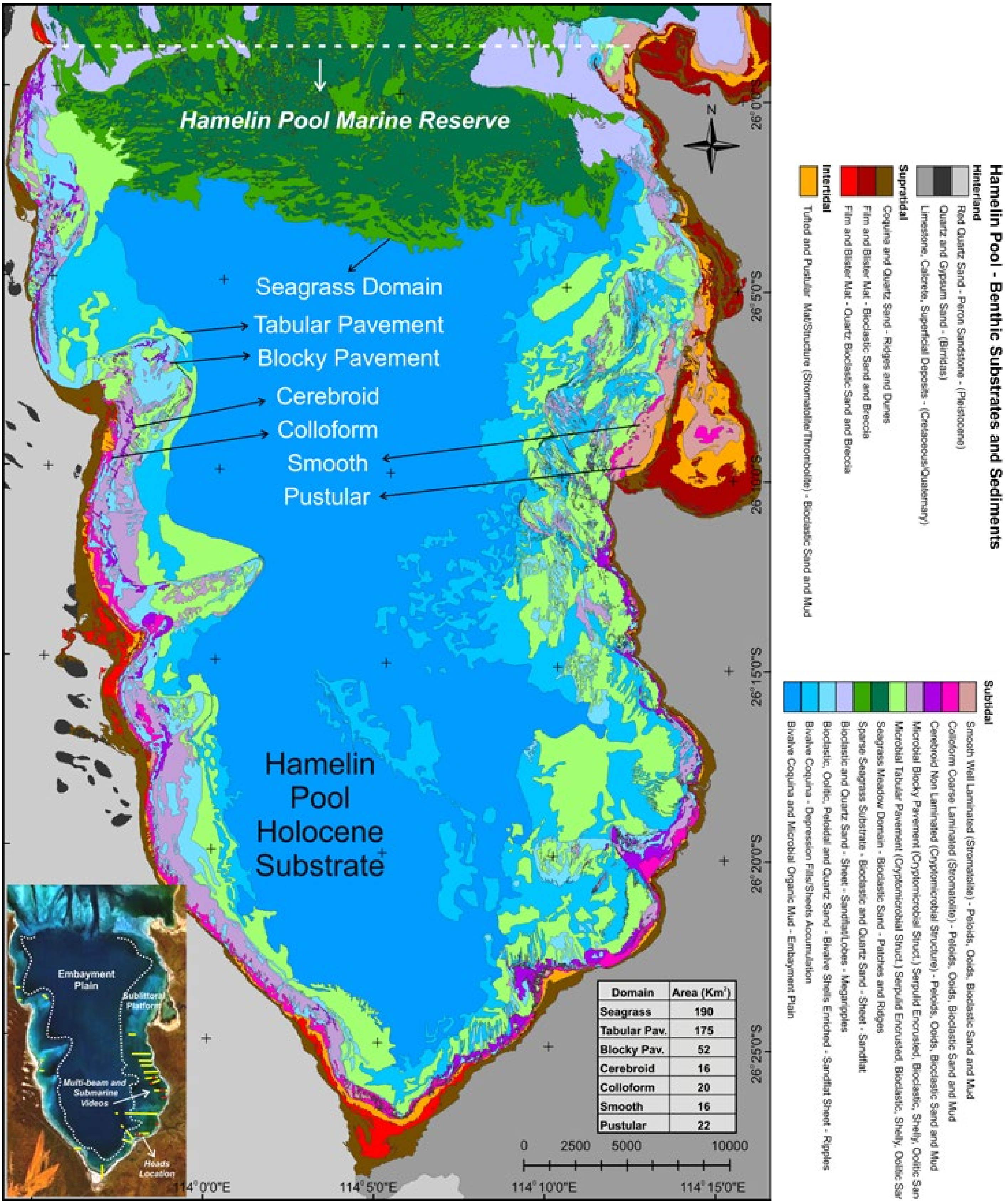


Figure 6 Benthic environment of Hamelin Pool showing sedimentary and organosubstrate classification (taken from Jahnert and Collins (2012) with permission).

3.1.6 Bathymetry

Shark Bay is relatively shallow, averaging 10-20 m and ranging from less than 1 m to ~30 m (in the northern region of the Bay) (Fig. 7). The Eastern and Western Gulfs have average water depths of ~12 m. The shallowness of Faure Sill restricts water flow into Hamelin Pool, which significantly contributes to the hypersaline conditions.

The land-sea interface along the Wooramel coastline has not been accurately mapped and is difficult to discern due to the very low shoreline gradient, variable tidal flat development and many tidal creeks leading into mangrove habitat (Eliot *et al.* 2012).

Hamelin Pool was used as a test site for deriving depth and substrate characteristics from multispectral data (Bierwirth *et al.* 1993) and, more recently, fluid lensing technology on drones has been used to generate centimetre scale 2D spatial resolutions and 3D bathymetry models of stromatolite reefs (Chirayath and Earle 2016).

Faure Sill was also used as a test case for whether HICO (Hyperspectral Imager for the Coastal Ocean) imagery could be used to detect changes in bathymetry over time (McKinna *et al.* 2012; Garcia *et al.* 2014). Detectable changes using HICO-derived depth was as low as 0.4 m, however, the imagery was less successful in waters deeper than 2 m.

3.2 Ecosystem processes

3.2.1 Biological connectivity

The biological connectivity of different species has primarily been assessed using genetics and estimates of recruitment and dispersal.

Within Shark Bay, genetic differences exist across sites for several species of clam, highlighting the importance of the bay as a location for genetic divergence of marine species (Johnson and Black 1990).

The first genetic study on pink snapper (*Chrysophrys auratus*) supported the suggestion of separate breeding populations within the Bay (Johnson *et al.* 1986).

Subsequent genetic studies on snapper have also identified a complex stock structure within the Bay (Whitaker and Johnson 1998), and in comparison to surrounding central coast waters (Gardner *et al.* 2017). Within the Eastern Gulf specifically, no evidence was found to suggest the presence of more than one genetic stock (Baudains 1999) (see section 3.6.2 for more detail). Nahas *et al.* (2003) used a combination of data collection and numerical modelling to examine the dispersal of pink snapper eggs and larvae, which supported the existence of discrete spawning populations in Shark Bay.

The population genetic structure of the mulloway, *Argyrosomus japonicus*, has been studied across the State and included samples caught in Shark Bay fisheries (Farmer 2008).

Genetics of the stripey snapper, *Lutjanus carponotatus*, have also been sampled across 51 locations to assess whether connectivity via larval dispersal was related to extreme gradients in coastal hydrodynamics; a significant genetic subdivision was found between Shark Bay and all northern regions suggesting restricted connectivity (DiBattista *et al.* 2017).

Coral specimens of *Pocillopora* from Shark Bay and the wider WA coastline have been used to investigate genetic diversity, gene flow and local adaptations (Thomas *et al.* 2016; Thomas *et al.* 2017).

The seagrass population of *Posidonia australis* is considered to have low genetic diversity in comparison to more southerly locations along WA (Sinclair *et al.* 2016).

The genetic diversity and connectivity of the mangrove, *Avicennia marina*, along the WA coastline sees a division into seven discrete sub-populations, Shark Bay being one, where propagule dispersal is generally limiting (Binks *et al.* 2019).

Shark Bay has been included in a larger investigation into the genetic structure of green turtle populations and foraging grounds across Australasia (Jensen 2010). Genetic profiles of loggerhead turtles have been documented for Shark Bay populations and compared with profiles from Cape Range (Pacioni *et al.* 2012).

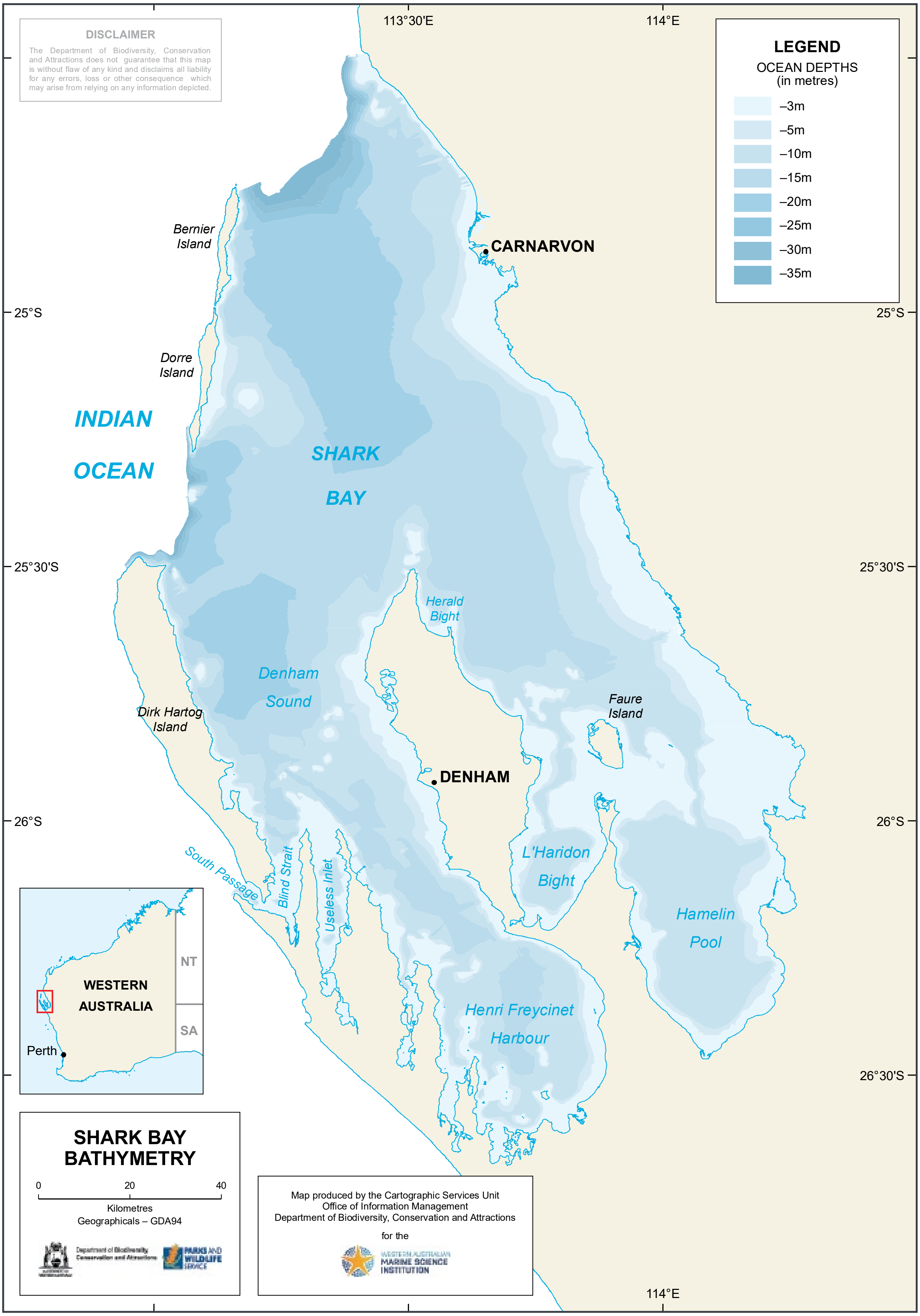


Figure 7 Bathymetry of Shark Bay.

The recruitment of invertebrates and fish to Shark Bay has primarily been related to environmental influences and the strength of the Leeuwin Current (Caputi 1993; Joll and Caputi 1995b; Caputi *et al.* 1996; Caputi *et al.* 1998; Lenanton *et al.* 2009a; Pearce *et al.* 2011; Caputi *et al.* 2019; Chandrapavan *et al.* 2019b).

3.2.2 Marine heatwave

The marine heatwave that negatively impacted Shark Bay resulted from a strong 2010-2011 La Niña event in the Pacific Ocean driving an intensified Leeuwin Current, now termed the Ningaloo Niño (Feng *et al.* 2013).

The typical volume of water transported via the Leeuwin Current during the summer months is 2 Sv (2,000,000 m^3/sec), whereas during February 2011, record strengths and a transport of 8 Sv was recorded along with relaxed southerly winds (Feng *et al.* 2013; Benthuysen *et al.* 2014). Water temperatures anomalies of 4-5°C warmer persisted for two weeks, and temperature anomalies of 2-4°C warmer persisted for two months.

Shark Bay is more susceptible to extreme temperatures given its shallow depths and sheltered embayment, though cooling from the seasonal Capes Current may alleviate temperatures near the entrances to the Bay (Hetzel 2014).

Causes, variability and predictability of the Ningaloo Niño continues to be investigated (Kataoka *et al.* 2018; Feng and Shinoda 2019). Hobday *et al.* (2018) provides a detailed characterisation of marine heatwave categories, which provides a consistent way to compare events across location and time while also increasing public awareness.

The effects of the 2011 marine heatwave were evident for benthic communities, fisheries and megafauna in Shark Bay.

3.2.2.1 Benthic communities

Loss of seagrass *Amphibolis antarctica* leaves was recorded during and immediately after the heatwave (Fraser *et al.* 2014). This was followed by a 696 – 921km^2 loss in spatial extent and thinning of dense meadows to sparse meadows of ~10% coverage; a reduction of 90% for some areas (Thomson *et al.* 2015a; Arias-Ortiz *et al.* 2018; Kendrick *et al.* 2019; Strydom *et al.* 2020). These losses occurred most extensively in the northern regions of Wooramel Bank and the Western Gulf.

Most of the seagrass loss occurred for the temperate species, *A. antarctica*, though some shoot density loss was also recorded for the temperate *Posidonia australis* (Kendrick *et al.* 2019), including 100% seed abortion during and one year after the marine heatwave (Sinclair *et al.* 2016). While *Posidonia australis* shoot densities have now shown recovery, *A. antarctica* has not, and early successional tropical species, such as *Halodule uninervis*, have become more common (Nowicki *et al.* 2017). It is predicted that temperate seagrasses will be lost from subtropical regions like Shark Bay as marine heatwaves increase in frequency and climate change accelerates (Hyndes *et al.* 2016).

The marine heatwave of 2011 was estimated to affect 30-100% of corals at Shark Bay depending on location (90-95% decline in coral cover near Bernier and Dorre Islands) (Moore *et al.* 2012; DBCA 2019b). Marine heatwaves are more likely to occur at subtropical reefs like Shark Bay during central pacific La Niña periods (Zhang *et al.* 2017).

With the exception of seagrasses and corals, the impacts of the 2011 heatwave on other benthic communities, such as soft sediment and infauna communities, is currently unknown.

3.2.2.2 Fisheries

The 2011 marine heatwave caused short and long-term impacts on fisheries within Shark Bay (Caputi *et al.* 2014b), including fish and invertebrate deaths and variations in recruitment, growth rates and catch rates (Pearce *et al.* 2011).

Scallop recruitment is typically lower when water temperatures are higher in strong Leeuwin Current years (Joll and Caputi 1995b; Lenanton *et al.* 2009a), thus the 2011 marine heatwave caused record low recruitment during 2011-2013 resulting in a closure of the fishery between 2012-2014 (Caputi *et al.* 2019). Improvements were seen for scallop recruitment when cooler water temperatures returned in 2014.

Catch rates of blue swimmer crabs in Shark Bay decreased to 2% of the pre-heatwave abundance and the fishery was closed between April 2012 and October 2013 (Caputi *et al.* 2019).

The availability of time series data in assessing the impacts of the 2011 marine heatwave on fish stocks has been valuable in indicating future management responses in the face of more frequent marine heatwaves (Caputi *et al.* 2016).

Following the 2011 marine heatwave, assessments of future climate effects on Western Australia's marine environment were made utilising multiple IPCC model predictions tailored to specific regions and relevant spatial and temporal scales, including for Shark Bay (Caputi *et al.* 2015).

3.2.2.3 Megafauna

The seagrass loss in Shark Bay associated with the 2011 marine heatwave impacted upon species that rely on a seagrass-based food web and/or ecosystem. Due to the k-selected traits of megafauna (long-lived, late to mature etc.), the effects of the 2011 marine heatwave were not immediately obvious.

Though a notable decline in dugong abundance was observed at Monkey Mia after the marine heatwave (Nowicki *et al.* 2019), dugong abundance for Shark Bay overall did not significantly decrease between 2007 and 2018 (Bayliss *et al.* 2019). However, the percentage of dugong calves did significantly decrease and there is indication of a collapse in breeding recruitment in 2012. The effects of this breeding collapse will not be detected in abundance estimates for decades.

Bottlenose dolphins at Monkey Mia were found to increase their foraging use of seagrass habitats after the 2011 marine heatwave (Miketa 2018), and evidence to date has shown that calving rates do not appear to be affected for dolphins at this location. Conversely, a significant decline in female reproductive rates has been observed for dolphins in the Western Gulf following the marine heatwave (Wild *et al.* 2019b).

A decline in green turtle abundance was also observed at Monkey Mia before and after the marine heatwave, and a reduction in the biomass of seagrass associated fishes was also linked to a 35% decline in pied cormorant densities, which preferentially forage in seagrass habitat (Nowicki *et al.* 2019). Those species with a more generalist diet, such as tiger sharks and loggerhead turtles, were found to be relatively resilient to the marine heatwave (Thomson *et al.* 2012b; Nowicki *et al.* 2019).

3.2.3 Coastal zone processes

3.2.3.1 Landscape vulnerability due to climate change

The vulnerability of landforms to changing environmental conditions has been assessed for the coastline of Shark Bay, and much of the coastline is considered to have a low vulnerability to changing environmental conditions such as weather, oceanography and climate change (Eliot *et al.* 2012). Exceptions to this included the Carnarvon coastline between Point Quobba and Grey Point, which is rated as having a moderate to high vulnerability to change, and the coastline from Cape Inscription to Cape Bellefin in the Western Gulf, which is rated as having a moderate vulnerability to change.

Additional focus was placed on areas of planning interest, including Nanga, Denham, Little Lagoon, Monkey Mia and Carnarvon. Under present sea level conditions, a tropical cyclone could cause inundation of the Monkey Mia settlement. The Carnarvon region has a high risk of flooding from the Gascoyne River, which could cause significant inundation and erosion, impacting upon a suite of features such as tidal flats, mangal communities, foredunes, spits and sand islands.

Storm surge events and flooding have probably been a driver of coastal morphology at Shark Bay (Jo Christensen pers. comm.).

3.2.3.2 Sea level and erosion

Sea level has played a significant role in shaping the unique formations seen in Shark Bay.

It is estimated that sea level has decreased by ~2 m over the last 4000-6000 years (Izuno *et al.* 2008; Collins and Jahnert 2014), which allowed for the accretion of bivalves to form the coquina ridge system that borders Hamelin Pool and L'Haridon Bight (Jahnert *et al.* 2012).

The higher sea levels during the last interglacial (marine isotope stage) allowed for more extensive coral reef development than observed for current conditions in Shark Bay (O'Leary *et al.* 2008).

The growth of the Faure Sill seagrass bank has been partly controlled by sea level fluctuations dating back to 8500 years BP (Bufarale 2014).

Sea level regression has allowed for the growth of stromatolites (1500-2300 years ago) and development of tidal flats (Izuno *et al*. 2008; Jahnert and Collins 2013; Collins and Jahnert 2014). Variations in sea level have created zonation patterns of microbialites (Burne and Johnson 2012), and sea level variation may partly explain the co-existence of the different microbialite mesostructures (stromatolites, thrombolites and cryptomicrobial deposits) in Shark Bay (Collins and Jahnert 2014). Sea level regression has exposed microbialite communities to erosion in the supratidal zones, which has resulted in microbialites extending seaward into the subtidal zones (Jahnert and Collins 2013; Collins and Jahnert 2014). This erosion has produced brecciated microbial deposits, which are broken fragments that have been recemented together. Looking to the future, sea level rise could lead to environmental instability, increased sediment transport, lower salinities and a subsequent decline in microbialite communities, which are considered highly susceptible to such environmental changes (Collins and Jahnert 2014).

The impacts of sea level rise have been investigated for Faure Sill and Hamelin Pool, and associated seagrass and microbialite communities. Under scenarios of 0.5m and 1m sea level rises, an increase in tidal range, current speed and stratification of the Hamelin Pool Basin was predicted from modelling the deepening of Faure Sill and Hamelin Pool (Taebi *et al*. in press). Under these scenarios, the intertidal zone is predicted to shift landward and decrease from 10km^2 to 5km^2 at Nilemah Embayment and from 20km^2 to 7km^2 and less at Hutchinson Embayment (Collins 2012). It is predicted that there would be a loss of stable microbial habitat with sea level rise, however, the adaptive capacity of microbialite communities is largely unknown.

As for seagrass meadows across Faure Sill, increased sea level will likely cause increased erosion of channels due to increased currents, but it may also allow for more colonisation due to increased water heights and a greater spread into Hamelin Pool under reduced salinity conditions (Walker *et al*. 2012; Taebi *et al*. in press).

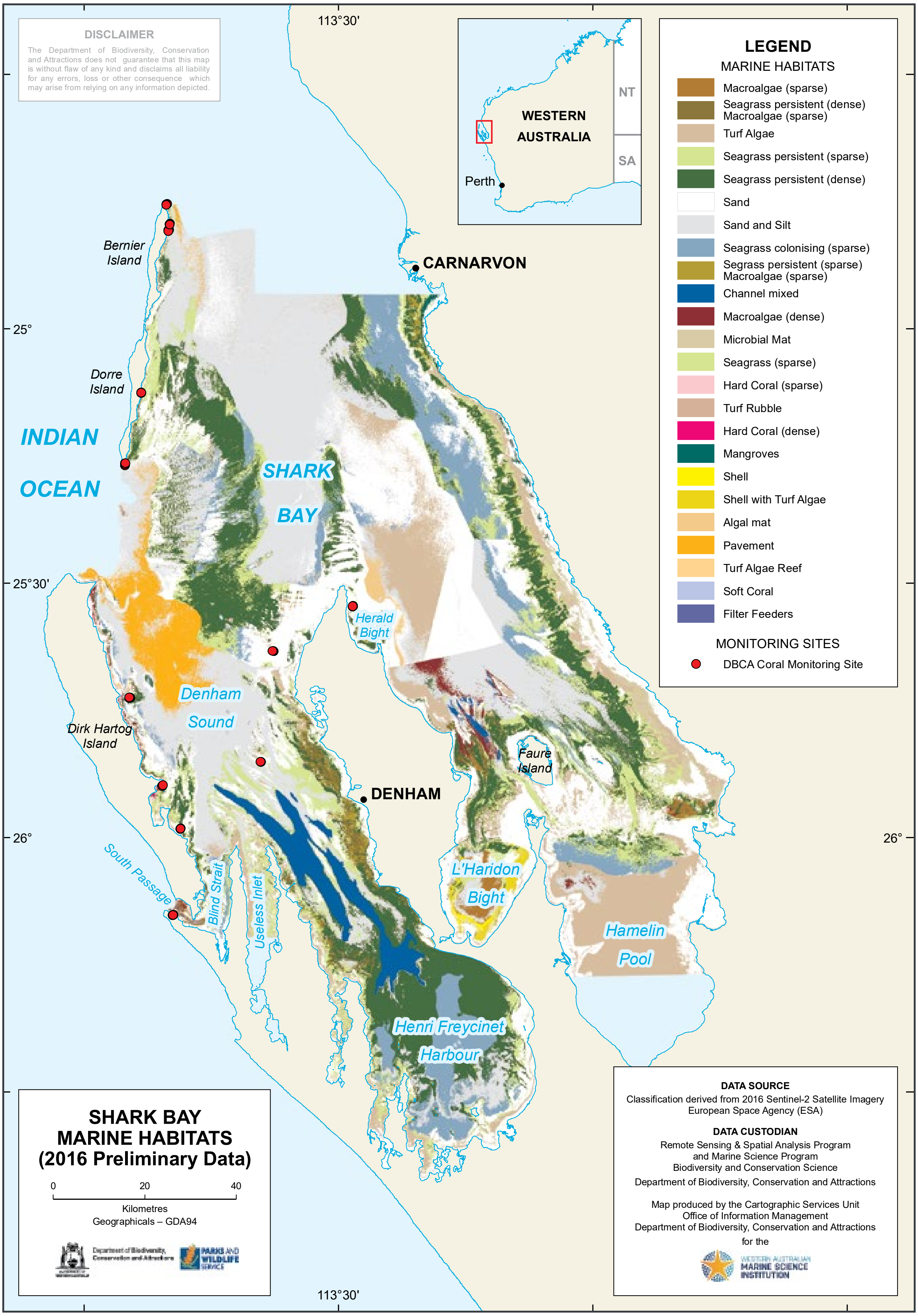
For some mangrove communities in Shark Bay, a sea level rise of 50cm would be enough to inundate existing communities, which would likely result in mangroves shifting landwards (Semeniuk 1994).

Projected sea level rise would also place some areas at risk of foredune plain mobilisation, such as Monkey Mia (Eliot *et al*. 2012).

3.2.3.3 Wave action

Large waves and subsequent inundation associated with cyclonic events are thought to have helped cause the deposition of cockle shell ridges in Hamelin Pool (Nott 2011). There is evidence for mega tsunamis transporting large calcrete blocks behind coastal cliffs and on islands of Shark Bay (Playford 2013).

Figure 8 Shark Bay marine habitats (2016 Preliminary data). This map was derived from published research undertaken to map the persistent seagrass extent across Shark Bay over time, in Strydom *et al*. (2020). All other marine habitats were mapped based on appropriate field data points and labelled as 'Other' in the Strydom *et al* 2020 published version, as persistent seagrass was the focus of the research. This map now reveals the marine classes 'Other' potentially represented in 2016, and should be used as a guide as it is likely that most of these 'Other' marine classes will have low to moderate confidence, with the exception of seagrass, sand and mangroves which will have a higher confidence.


DISCLAIMER
The Department of Biodiversity, Conservation and Attractions does not guarantee that this map is without flaw of any kind and disclaims all liability for any errors, loss or other consequence which may arise from relying on any information depicted.
113°30'
WESTERN AUSTRALIA
NT
SA
Perth
LEGEND
MARINE HABITATS
Macroalgae (sparse)
Seagrass persistent (dense) Macroalgae (sparse)
Turf Algae
Seagrass persistent (sparse)
Seagrass persistent (dense)
Sand
Sand and Silt
Seagrass colonising (sparse)
Segrass persistent (sparse) Macroalgae (sparse)
Channel mixed
Macroalgae (dense)
Microbial Mat
Seagrass (sparse)
Hard Coral (sparse)
Turf Rubble
Hard Coral (dense)
Mangroves
Shell
Shell with Turf Algae
Algal mat
Pavement
Turf Algae Reef
Soft Coral
Filter Feeders
MONITORING SITES
DBCA Coral Monitoring Site
CARNARVON
Bernier Island
25°
Dorre Island
INDIAN OCEAN
SHARK BAY
25°30'
Herald Bight
Denham Sound
Dirk Hartog Island
Faure Island
DENHAM
26°
South Passage
Blind Strait
Useless Inlet
L'Haridon Bight
Hamelin Pool
Henri Freycinet Harbour
SHARK BAY MARINE HABITATS (2016 Preliminary Data)
0 20 40
Kilometres
Geographicals – GDA94
DATA SOURCE
Classification derived from 2016 Sentinel-2 Satellite Imagery European Space Agency (ESA)
DATA CUSTODIAN
Remote Sensing & Spatial Analysis Program and Marine Science Program Biodiversity and Conservation Science
Department of Biodiversity, Conservation and Attractions
Map produced by the Cartographic Services Unit Office of Information Management
Department of Biodiversity, Conservation and Attractions
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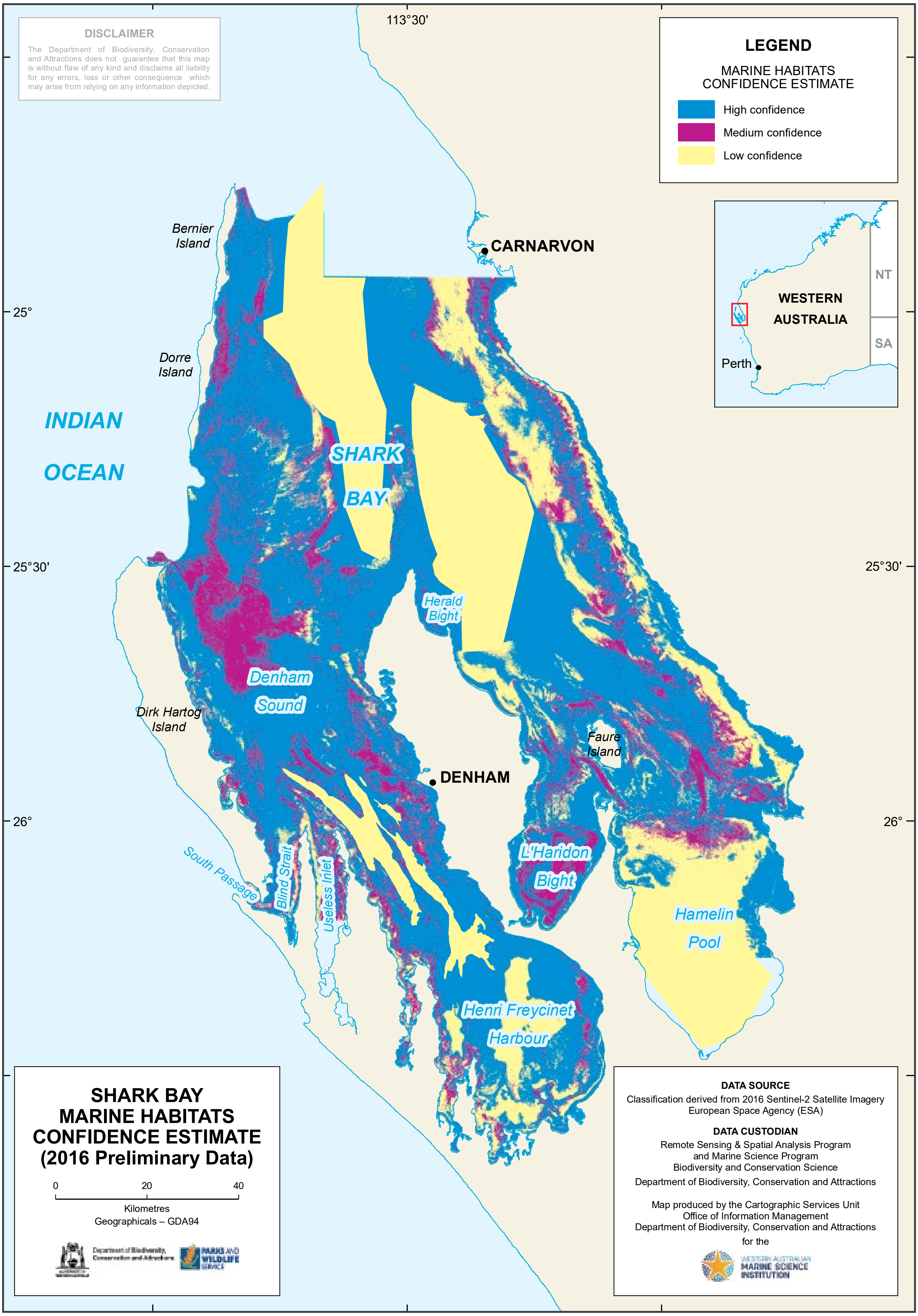


Figure 9 Confidence estimates for Shark Bay marine habitats (2016 Preliminary data).

3.3 Benthic communities

An overview of the diversity and distribution of benthic habitat is shown in Fig. 8 and Fig. 9, which are described in more detail in subsequent sections.

3.3.1 Seagrass communities

3.3.1.1 Species diversity and distribution

Shark Bay has one of the largest and most diverse seagrass meadows currently known in the world. The significance of seagrass to the functioning of the ecosystem, particularly at Wooramel Bank and Faure Sill, is one of the reasons for Shark Bay being listed as a World Heritage Site.

While 12 tropical and temperate species of seagrass occur at Shark Bay, *Amphibolis antarctica* accounts for 85% of the ~4000km^2 of total seagrass extent (McMillan *et al.* 1983; Walker *et al.* 1988; Walker 1989; Walker 1990; Burkholder *et al.* 2013a) (Fig.10). A description of the different meadow types found in Shark Bay and the rest of the northwest coast of WA can be found in McMahon *et al.* (2017a).

Halodule uninervis, a favourite food of dugongs, is the most widespread tropical species in the Bay, and tolerates hypersaline conditions (64 ppt) in the inner Eastern Gulf and the anoxic conditions at the Wooramel River mouth (Walker *et al.* 1988; Masini *et al.* 2001; Walker *et al.* 2012; Burkholder *et al.* 2013a).

Since the original mapping of seagrass extent in 1983-85 (Walker *et al.* 1988), maps have been further refined (Bruce 1997; Bruce *et al.* 1997) and updated as more monitoring of meadows is completed (Arias-Ortiz *et al.* 2018; Strydom *et al.* 2020) (Fig. 11 and 12).

3.3.1.2 Marine heatwave impacts

A robust understanding of seagrass extent in Shark Bay has been instrumental in assessing the loss of seagrass during and after the 2011 marine heatwave. While this isn't the only marine heatwave Shark Bay has experienced (Hobday *et al.* 2018), the 2011 heatwave was severe and a lot of attention since has focused on the significant losses to seagrass meadows and how this has impacted the functioning ecosystem.

Loss of *A. antarctica* leaves were recorded during and immediately after the heatwave (and Wooramel flooding) (Walker *et al.* 2012; Fraser *et al.* 2014), and was followed by a 696 – 921km^2 loss in spatial extent and thinning of dense meadows to sparse meadows of ~10% coverage; a reduction of 90% for some areas (Thomson *et al.* 2015a; Arias-Ortiz *et al.* 2018; Kendrick *et al.* 2019; Strydom *et al.* 2020) (Fig. 11 and 12). These losses occurred most extensively in the northern regions of Wooramel Bank and the Western Gulf.

Most of the seagrass loss occurred for the temperate species, *A. antarctica*, though some shoot density loss was also recorded for the temperate *Posidonia australis* (Kendrick *et al.* 2019), including 100% seed abortion during and one year after the marine heatwave (Sinclair *et al.* 2016).

While *P. australis* shoot densities have now shown recovery, *A. antarctica* is recovering at a slower rate in localised areas (Kendrick pers. comm.) Early successional tropical species, such as *H. uninervis*, have become more common, although this species generally only covered <10% of the sediment, whereas *A. antarctica* covered >80% (Nowicki *et al.* 2017).

It is predicted that temperate seagrasses will be lost from subtropical regions like Shark Bay as marine heatwaves increase in frequency and climate change accelerates (Hyndes *et al.* 2016), though this prediction is only based on known seagrass physiological tolerances to temperature. Presently, local adaptation and phenological plasticity is being investigated in the temperate seagrass *P. australis* in Shark Bay to assess whether populations of this species at their northern range limit have adapted to higher temperatures (Kendrick pers. comm.).

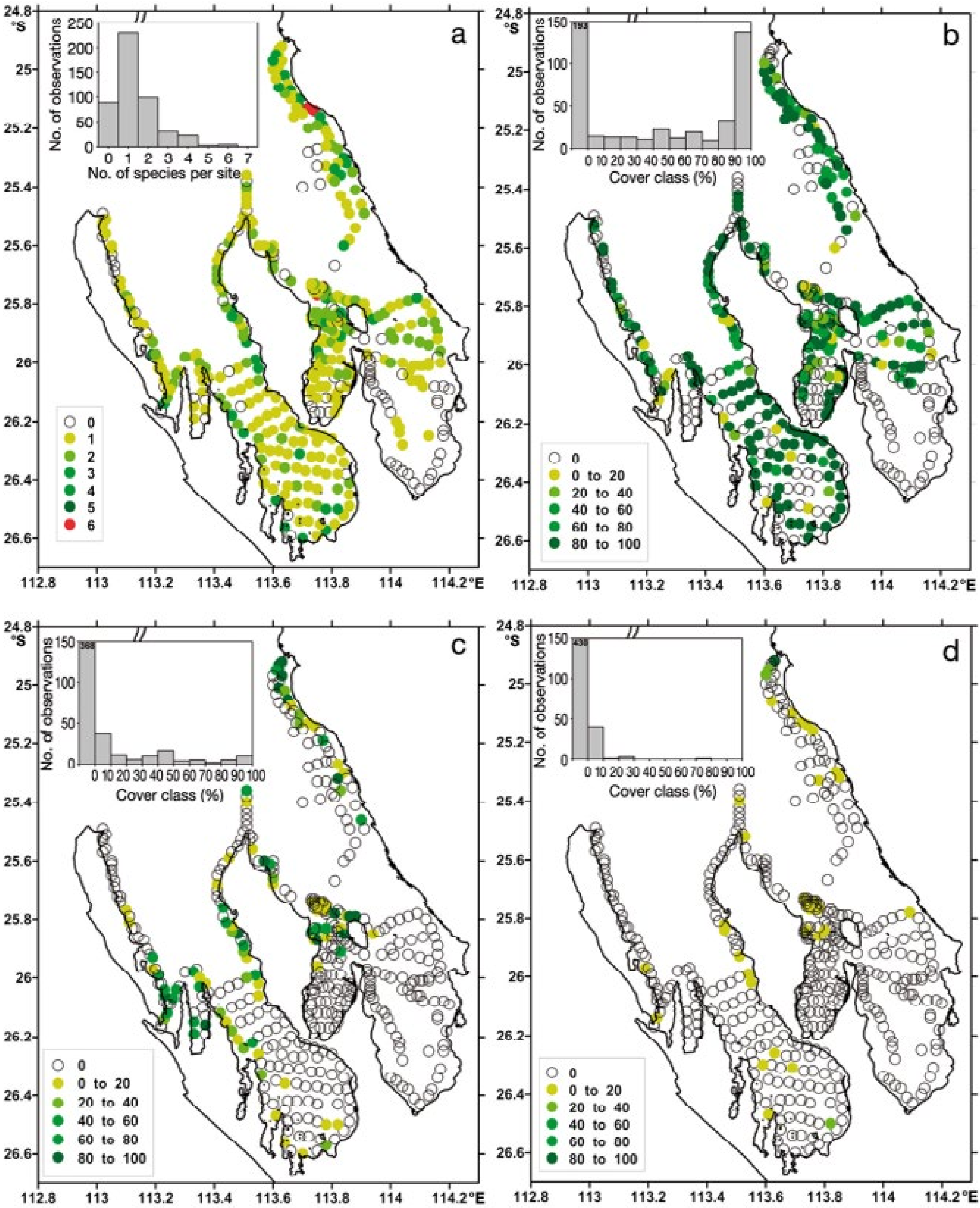


Figure 10 Seagrass taxa diversity across Shark Bay from (a) both summer and winter sampling effort, and average abundances of seagrass species across Shark Bay; (b) *Amphibolis antarctica*; (c) *Posidonia* spp.; (d) *Cymodocea angustata*; (e) *Halophila ovalis*; (f) *Halophila spinulosa*; (g) *Halodule uninervis*; and (h) *Syringodium isoetifolium*. Positions of the symbols indicate sampling locations. Insets show frequency histograms of species richness (a) or percent cover (b–h) (taken from Burkholder *et al* (2013a) with permission).

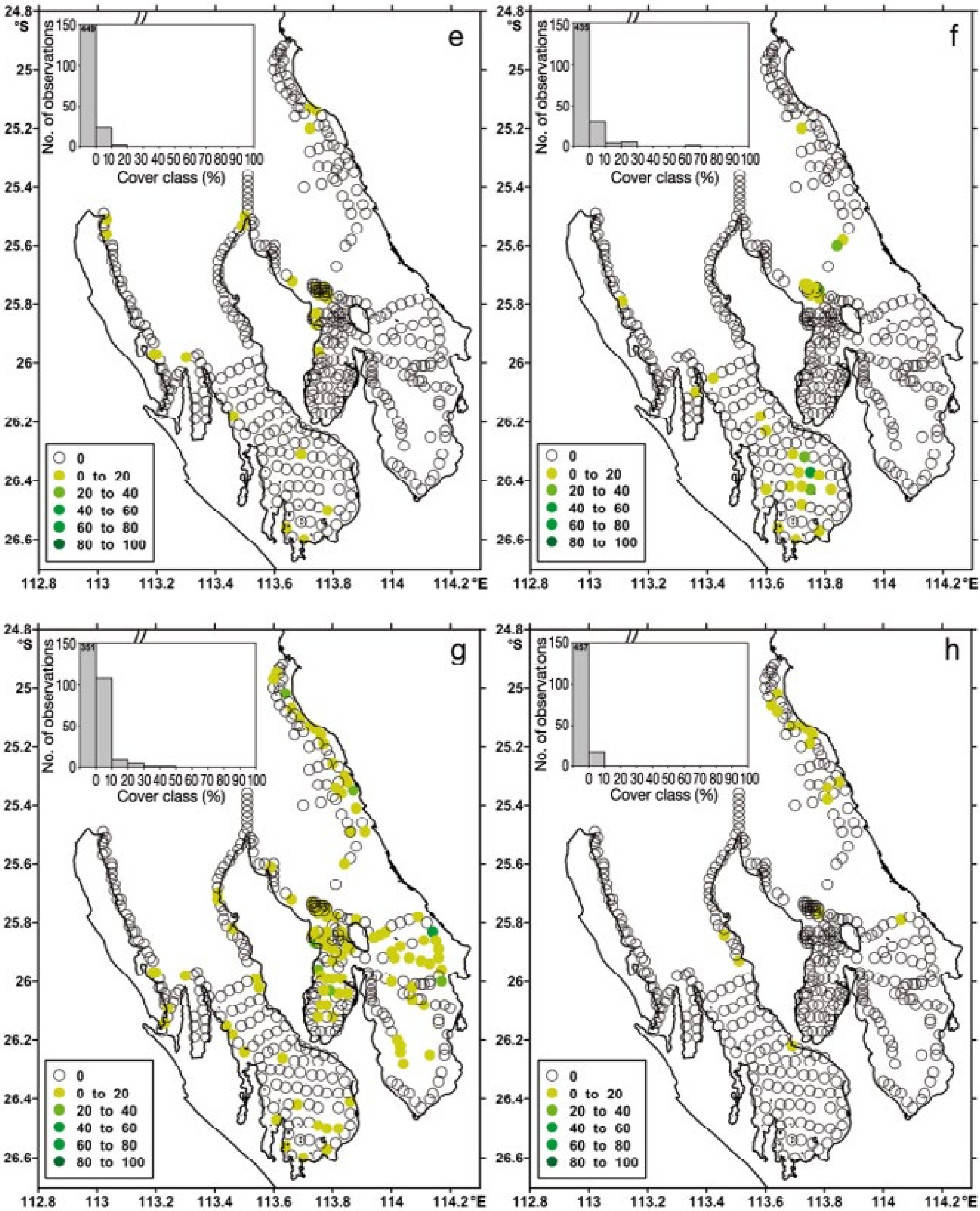


Figure 10 continued.

Figure 11 Coverage of dense and sparse seagrass meadows in Shark Bay in 2010, including DBCA seagrass monitoring sites. Seagrass coverage is based on input data used to determine change in seagrass extent over time published in Strydom *et al.* (2020).

Figure 12 Coverage of dense and sparse seagrass meadows in Shark Bay in 2016, including DBCA seagrass monitoring sites. Seagrass coverage is based on input data used to determine change in seagrass extent over time published in Strydom *et al.* (2020).

3.3.1.3 Consumption of seagrass

Several studies have investigated the flow-on effects of seagrass loss from the 2011 marine heatwave on food webs and ecosystem functioning, and these will be addressed in more detail under the sections on Faunal Communities and Ecosystem Processes. Besides this, rates of consumption of seagrass by megafauna and fishes has been assessed in relation to nutrient content (Burkholder *et al.* 2012), the contribution and/or reliance on seagrass as a food source (Anderson 1994; Belicka *et al.* 2012), salinity gradients (Bell *et al.* 2019), and risk of predation from tiger sharks (Burkholder *et al.* 2013b).

3.3.1.4 Physiology

Salinity gradients have been the focus of seagrass physiological studies given the hypersaline nature of the inner gulfs and, overall, seagrass biomass, extent and productivity is lower in salinities greater than ~42‰ (Walker 1985; Walker and McComb 1990).

Epiphytes growing on the stems of *A. antarctica* show a decline in diversity, species richness and calcium carbonate on leaves as salinity increases (Harlin *et al.* 1985; Kendrick *et al.* 1988; Walker and Woelkerling 1988).

Nutrient content of seagrass leaves and sediments have also been examined across salinity gradients at Faure Sill and Wooramel Delta, and salinity gradients did not appear to drive nutrient content or limitation (Fraser *et al.* 2012; Walker *et al.* 2012).

Sulphide intrusion was found to be greater for seagrasses in high salinity zones (Cambridge *et al.* 2012).

The view that Shark Bay, and ecosystem production, are phosphorus limited has also been questioned (Smith and Atkinson 1984), as phosphorus limitation in sediments doesn't necessarily correspond with phosphorus limitation in seagrasses (Fraser *et al.* 2012; Burkholder *et al.* 2013a; Fraser *et al.* 2018). *Amphibolis antarctica*, in particular, seems to be efficient at utilising phosphorus in a generally nutrient depleted system and there seems to be an agreed view that there is enough recycling of nutrients in the system to maintain the high productivity of seagrass meadows in Shark Bay (Walker and McComb 1985; Walker and McComb 1988; Walker 1990; Burkholder *et al.* 2013a; Fraser *et al.* 2018).

Physiological studies have also extended to experimental assessments of thresholds to light and sediment burial stress for several tropical species of seagrass (Statton *et al.* 2018), an assessment of clonal diversity of *Halodule* seagrass from two locations in Shark Bay (McMahon *et al.* 2017b), and Identification of a hybrid *Posidonia* clone based on morphology (Sinclair *et al.* 2019).

3.3.1.5 Restoration

Knowledge on the physiology and consumption of seagrasses in Shark Bay has helped to inform research on seagrass restoration, particularly following the widespread losses from the 2011 marine heatwave.

A review of revegetation techniques undertaken by Statton *et al.* (2012) looked at whether techniques used in Florida Bay, US could be similarly used in Shark Bay.

A transplant experiment was conducted at Useless Loop in 2012 and found intense grazing from fish within 10 m from the edge of the *P. australis* meadow (Statton *et al.* 2015).

Species that bioturbate (rework the soil) in Shark Bay, such as the heart urchin, *Breynia desori*, were found to disturb and redistribute seeds of *P. australis* before they could establish, and such bioturbators are considered a major inhibitor of seed based restoration (Johnson *et al.* 2018).

3.3.1.6 Blue Carbon

The large extent and high biomass of seagrass meadows at Shark Bay has produced the world's largest carbon stock for a seagrass ecosystem (Arias-Ortiz *et al.* 2018). This highlights Shark Bay as globally important for carbon capture, storage and sequestration (Fourqurean *et al.* 2012a; Fourqurean *et al.* 2012b; Lavery *et al.* 2013; Serrano *et al.* 2016a; Serrano *et al.* 2016b; Arias-Ortiz *et al.* 2018; Serrano *et al.* 2019). For example, *P. australis* mat escarpments of up to 2.8 m thick are found at Big Lagoon, and formations like these can harbour some of the largest organic carbon sinks recorded across the globe (Serrano *et al.* 2016b).

3.3.2 Macroalgal communities

Taxonomy of macroalgal species in Shark Bay has been a primary focus of studies to date. Despite the general lack of hard substrate in Shark Bay, a total of 161 taxa of benthic macroalgae have been found on subtidal rock platforms, sandflats or on seagrasses and other algae as epiphytes (Huisman *et al.* 1990; Kendrick *et al.* 1990).

There have been 66 species of macroalgae epiphytes found on the seagrass *A. antarctica*, and this diversity decreases as salinity increases across the Bay (Kendrick *et al.* 1988).

Red algae, Rhodophyta, is the most dominant group in Shark Bay (Huisman *et al.* 1990; Kendrick *et al.* 1990), and specific studies have investigated the salinity tolerances and biogeographic affinities of the family Corallinaceae (Barry and Woelkerling 1995), and why the relatively newly described *Spongophloae* is a separate genus (Huisman *et al.* 2011).

More recently, the macroalgae species associated with the pneumatophores of mangroves has been documented, which included new records for Shark Bay and three new red algae records for WA (Huisman *et al.* 2015).

Aside from taxonomy related studies, Belicka (2012) assessed the contribution of macroalgae to the diets of resident animals using fatty acids and stable isotopes.

3.3.3 Coral reef communities

3.3.3.1 Taxonomy and distribution

Some of the earliest research efforts on corals in Shark Bay focused largely on taxonomy and documenting species occurrence and distribution.

Modern day coral communities are found predominantly in the Western Gulf (excluding hypersaline waters) and along Bernier and Dorre Islands as scattered communities rather than extensive reefs (Veron and Marsh 1988; Marsh 1990). Up to 80 species from 28 genera have been documented and the most common families are Dendrophylliidae and Acroporidae (DBCA 2019b).

Coral community composition has been surveyed since 1996 by the Department of Biodiversity, Conservation and Attractions and predecessors (Bancroft 2009; DBCA 2019b). From this, coral cover (29.37 ± 3.14 %) has been estimated for Shark Bay and compared to other coral locations along the coastline of Western Australia (Speed *et al.* 2013; Gilmour *et al.* 2019).

Additional monitoring of corals has occurred in outer Shark Bay in order to establish baseline data to monitor changes over time (Miller *et al.* 2015; DBCA 2019b).

3.3.3.2 Reef development

To help inform why modern day reefs are as they are in Shark Bay, age-dating of reefs has been carried out at several locations around the bay, including Freycinet Harbour and Hamelin Pool. Findings show extensive reef development during the peak of the last interglacial period, ~120,000-130,000 years ago (Stirling *et al.* 1995; O'Leary *et al.* 2008), and modern coral reef assemblages are considered very comparable to these fossil reefs (Greenstein and Pandolfi 2008).

3.3.3.3 Physiology

Several studies have investigated some of the environmental conditions influencing corals at Shark Bay, but often as part of a statewide study of corals.

The corals at Shark Bay are exposed to a wide range of sea surface temperatures and have experienced heat stress events, such as marine heatwaves (Zinke *et al.* 2018). Such events are more likely to occur at subtropical reefs like Shark Bay during La Niña periods (Zhang *et al.* 2017).

Certain sites in Shark Bay are also impacted by damaging waves during storm events, however it is heat stress that was linked to most of the changes in coral cover (Gilmour *et al.* 2019).

The most damaging heat stress event was the marine heatwave of 2011, which was estimated to affect 30-100% of corals at Shark Bay depending on location (Moore *et al.* 2012). Coral cover near Bernier and Dorre Islands declined by 90-95% (DBCA 2019b).

Additional physiological studies have focused on *Pocillopora* specimens from Shark Bay and other locations, which have been used to investigate genetic diversity, gene flow and local adaptations (Thomas *et al.* 2016; Thomas *et al.* 2017). Similarly, genetic testing has revealed that the thermal stress-tolerant *Cyphastrea microphthalma* at Shark Bay is one of four genetic clusters identified across the North West Shelf of WA (Evans *et al.* 2019).

3.3.4 Microbial and microbialite communities

3.3.4.1 Significance

The living stromatolites found in the shallow, hypersaline waters of Shark Bay is one of the reasons the Bay was classified as a World Heritage site.

Hamelin Pool has the most diverse and abundant modern marine stromatolites of any one location, and formations are comparable to the fossil record. As such, the microbialite communities have been studied for more than 60 years (Skyring and Bauld 1990; Burns *et al.* 2009; Collins and Jahnert 2014).

In the face of a changing climate, the challenges for microbial communities in Shark Bay is discussed by Reinhold *et al.* (2019). A review of the biogeomorphological processes that impact on surficial CO_2 sequestration is also given by Morris *et al.* (2019), which provides a 3D biogemorphological mapping framework for Hamelin Pool that can be used to understand the impacts of sea level rise.

3.3.4.2 Distribution

These microbialite communities are found most extensively in Hamelin Pool, but can also be found at Rocky Point in L'Haridon Bight and Garden Point in the Henri Freycinet embayment (Jahnert and Collins 2013).

An overview of the distribution of microbial mats and stromatolites in Shark Bay is given in some of the early works by Playford and Cockbain (1976) and Golubic (1985). More recently, the unique geographic distribution of morphologically distinct stromatolite structures has been mapped (Suosaari *et al.* 2016b).

A georeferenced sedimentary and organosubstrate map has been produced for Hamelin Pool and L'Haridon Bight using a combination of video transects, aerial surveys, coastal and marine ground truth traverses, digital orthophotos and samples, which shows the distribution of different microbialite communities, as well as other substrates (Fig. 6) (Collins and Jahnert 2014).

Hamelin Pool contains the largest modern stromatolite community in the world and microbial mats and stromatolites occupy most of the 135km stretch of intertidal and subtidal zones. In general, non-lithifying mats are distributed in the upper intertidal zone and lithifying mats are distributed in the lower intertidal to subtidal zone. Burne *et al.* (2012) also explored how variation in sea level influences zonation of microbialites across these zones.

Substantial efforts have gone into mapping the subtidal microbial deposits in Hamelin Pool which occupy ~ 300km^2, an area ten times greater than occupied by intertidal mats (Jahnert and Collins 2011; Jahnert and Collins 2012).

3.3.4.3 Morphology

Microbial mats consist of layers of microbes which are structurally visible to the naked eye. Mats are typically dominated by cyanobacteria, but can also include bacterial, archaeal and eukaryote communities.

Microbial mats that do not develop carbonate build ups are known as non-lithifying mats and they can form extensive sheets (Wong *et al.* 2015; Suosaari *et al.* 2016b).

Microbial mats that do develop carbonate build up from precipitation and trapping of sediments and debris are known as microbialites; also referred to as stromatolite-forming, or lithifying mats (Logan 1961; Logan *et al.* 1974a; Playford and Cockbain 1976; Burne and Moore 1987).

As the sediment layer becomes dense and lithified, the microbes move up to the surface to survive and create a new layer while leaving behind a cumulative record of microbial mat activity. These layers of rock are what forms a stromatolite, and this distinguishes stromatolites from the other three broadly described microbialite mesostructures: leiolites, thrombolites and dendrolites.

Stromatolites have been the focus of most studies in Shark Bay, though a recent study has documented the seasonal and ephemeral occurrences of modern dendrolitic microbial mats forming in the intertidal zone (Suosaari *et al.* 2018).

Microbial mats found at Shark Bay have been further characterised based on the morphology of the surface and internal fabrics (Logan 1961; Logan *et al.* 1974a; Playford and Cockbain 1976; Golubic 1985; Wong *et al.* 2015; Suosaari *et al.* 2016b), and subtidal microbial deposits were found to have distinctive morphologies and fabrics compared with intertidal deposits (Jahnert and Collins 2011).

3.3.4.4 Lithified formations

Studies on the growth and formation of stromatolites have been pivotal for gaining a better understanding of evolutionary history and modern day communities in Shark Bay. It is estimated that conditions became suitable for stromatolite growth in Hamelin Pool around 1500-2300 years ago based on growth rates between 1-5 mm per decade (Izuno *et al.* 2008; Collins and Jahnert 2014). For high energy environments, growth rates only just exceed erosion rates (Chivas *et al.* 1990).

Studies have examined the internal fabrics of several mat types extracted from stromatolites (Reid *et al.* 2003; Hagan 2014), however, the gross morphology of stromatolites is not controlled by the type of microbial mat (Hoffman 1976). Instead, morphology of stromatolites has been related to environmental influences and biological communities (Playford 1979; Giusfredi 2014; Suosaari *et al.* 2016a). The most recent studies to weigh in on this long-discussed debate provide evidence that when the physical geography allows for a high-energy environment, environmental controls largely determine morphology, and where this is a low-energy environment, biological communities largely determine morphology (Suosaari *et al.* 2019a; Suosaari *et al.* 2019b).

Some insight into how biological communities can influence morphology is given by Awramik and Riding (1988), who show that eukaryotes play a significant role in the formation and maintenance of subtidal columnar stromatolites, and by Hein *et al.* (1993), who shows how secretions from diatoms of the *Mastogloia* genus help to facilitate trapping and binding of grains for stromatolite growth. Evidence has also been provided for stromatolites orientating their growth towards the sun (Awramik and Vanyo 1986), presumably for maximum photosynthetic benefit of microbes.

The majority of studies on microbialite communities in Shark Bay have focused on microbial diversity. Microbial diversity has been compared and characterised for different locations (Bauld 1984; Jahnert and Collins 2013; Wong *et al.* 2016), mat types and stromatolite morphologies (Burns *et al.* 2004; Papineau *et al.* 2005; Goh *et al.* 2009; Goh *et al.* 2010; Garby *et al.* 2013; Pagès *et al.* 2014a; Wong *et al.* 2015; Babilonia *et al.* 2018; Wong *et al.* 2018), and even individual stromatolite layers (Pagès *et al.* 2015).

There has been specific focus on archaeal communities (Goh *et al.* 2006; Leuko *et al.* 2007; Leuko *et al.* 2008; Goh *et al.* 2011; Wong *et al.* 2017), eukaryotes (Edgcomb *et al.* 2014), diatoms (John 1990; John 1991; John 1993), heterotrophic bacteria (Moriarty 1983), flagellates (Al-Qassab *et al.* 2002) and viruses (White *et al.* 2018).

Diversity of microbes has also been assessed in relation to salinity gradients (Leuko *et al.* 2009; Pagès *et al.* 2014a; Wong *et al.* 2016).

Stromatolites and associated microbial mats have been investigated at a biochemistry level. Different mat types and microbial communities have undergone lipid profiling and isotopic analyses (Palmisano *et al.* 1989; Allen *et al.* 2010; Pagès *et al.* 2015).

Ruvindy *et al.* (2016) used a metagenomic analysis to examine the metabolic pathways of microbial communities and Bauld *et al.* (1979), Bauld (1984) and Skyring (1984) measured rates of primary production and sulfate reduction for different mat types.

For smooth microbial mats in particular, the distribution of porewater solutes (iron, phosphate and sulfide) across day and night has been investigated (Pagès *et al.* 2014b), as has optical and pigment properties (D'Agostino *et al.* 2019; Fisher *et al.* 2019).

Leuko *et al.* (2011) specifically looked at the responses of the archaeon, *Halococcus hamelinensis*, to high levels of UV radiation, and D'Agostino *et al.* (2019) looked at UV screening compounds in mats.

The presence of quorum sensing (microbial communication allowing coordination of phenotypes across localized communities) has also been investigated for microbial mats (Charlesworth *et al.* 2019).

3.3.4.5 Non-lithified formations

Non-lithified microbial mats have not been as extensively studied as lithifying microbial mats. Allen *et al.* (2009; 2010) characterised communities using rDNA and lipid profiling and Wong *et al.* (2015) characterised communities at a discrete millimetre scale using tagged amplicon sequencing.

Suosaari *et al.* (2016b) described the distribution and communities of smooth and pustular mat types in the upper intertidal zone.

An insight into biogeochemical cycling and adaptive response of microbes of non-lithified mats was undertaken using metagenomics (Wong *et al.* 2018).

3.3.5 Mangrove communities

3.3.5.1 Diversity and distribution

The white mangrove, *Avicennia marina*, is the only species of mangrove documented for Shark Bay. The mangrove occurs in dense and often isolated stands along ~30% of the coastline and is the southernmost location in WA where extensive mangrove growth can be found (~1500 ha) (Keighery and Muir 2008; Kendrick *et al.* 2009; Heithaus *et al.* 2011; Huisman *et al.* 2015) (Fig. 13).

Variations in the morphology of mangroves occurs across salinity gradients, and three distinct morphotypes have been identified within the Bay which are likely providing different functional roles (Rule *et al.* 2014).

Several studies have placed mangroves from Shark Bay into context with other communities around Australia (Kenneally 1982; Semeniuk 1994; Bridgewater and Cresswell 1999), including assessing the genetic diversity and connectivity of *A. marina* along the WA coastline (Binks *et al.* 2019) and assessing distribution in relation to coastal dynamics, habitat and salinity in order to predict the effects of sea level rise on mangroves (Semeniuk 1994).

3.3.5.2 Ecosystem services

Mangrove communities provide important ecosystem services and support a wealth of flora and fauna.

A range of fish and invertebrate species are found in mangrove habitat in Shark Bay, but this may be for the purposes of shelter and nursing given no evidence to date has shown mangrove production directly supporting these local populations through the food web (Heithaus *et al.* 2011).

A number of bird species are directly associated and, in some cases, confined to mangroves, and this has been explored by Johnstone (1990) for Shark Bay and other areas along WA.

The aerial roots of mangroves, known as pneumatophores, also provide a reliable surface for settlement of algal epiphytes, and 51 species have been found on pneumatophores from mangroves in the Bay (Huisman *et al.* 2015).

3.3.6 Sponge communities

Sponge communities have received little attention in comparison to other benthic communities, and their distribution and composition is not adequately understood.

The use of sponges as tools by bottlenose dolphins has been the driving force of sponge related studies in the Bay.

The distribution of sponges was found to be relatively patchy based on presence in only 196 of the 1380 quadrats surveyed in a methodological study in the northern portion of the Western Gulf (Tyne *et al.* 2010). Of those 196 quadrats containing sponges, canonical sponges, *Echinodictyum mesenterinum*, which are used by dolphins, were found in 4% of quadrats (Tyne 2008; Tyne *et al.* 2012). Canonical sponges were only observed in water depths of > 10m, and bathymetric features such as slopes and channels were identified as reliable predictors of canonical sponge occurrence.

Other sponges that have been described from Shark Bay include one confirmed and several doubtful species records of the *Pione* genus (Fromont *et al.* 2005).

3.4 Planktonic communities

3.4.1 Phytoplankton

The phytoplankton community of Shark Bay has received limited and relatively localised attention.

Existing studies have focused on salinity gradients and nutrient availability as drivers of production (Hanson *et al.* 2005; Hanson *et al.* 2007), particularly in the solar salt ponds of Useless Inlet (Segal *et al.* 2006; Segal *et al.* 2009).

As salinity increases from outer Shark Bay to the hypersaline Hamelin Pool, the phytoplankton community transitions from an oceanic community to diatom dominated to dinoflagellate dominated in the hypersaline waters (Kimmerer *et al.* 1985; Hanson *et al.* 2005).

Heterotrophic flagellates have been specifically investigated off Denham with 41 species being identified, a new species being described, and range extension documented for many species not previously recorded in southern subtropical regions (Tong 1997).

3.4.2 Zooplankton

Studies on zooplankton communities are more prevalent for coastal and offshore waters outside of Shark Bay than inside.

Zooplankton abundance and species richness is reduced in hypersaline waters, and very few species are found here compared with more diverse communities in oceanic waters within the bay (Kimmerer *et al.* 1985).

Particular attention has been given to Cnidarians (Goy 1990; Gershwin 2014) and to the brine shrimp, *Artemia* sp., of the solar salt ponds, where their presence and consumption of particulate organic carbon in the water column benefits salt production (Bruce and Imberger 2009).

3.5 Faunal communities (non-commercial)

3.5.1 Invertebrate communities

Targeted studies on certain invertebrates are most common for Shark Bay, and are explained in more detail in the sections that follow. The exception to this is an investigation into the composition, richness, density and biomass of invertebrate fauna of seagrass meadows and bare sand habitat by Wells *et al.* (1985), where diversity and density was found to be greatest in seagrass beds as opposed to bare sand.

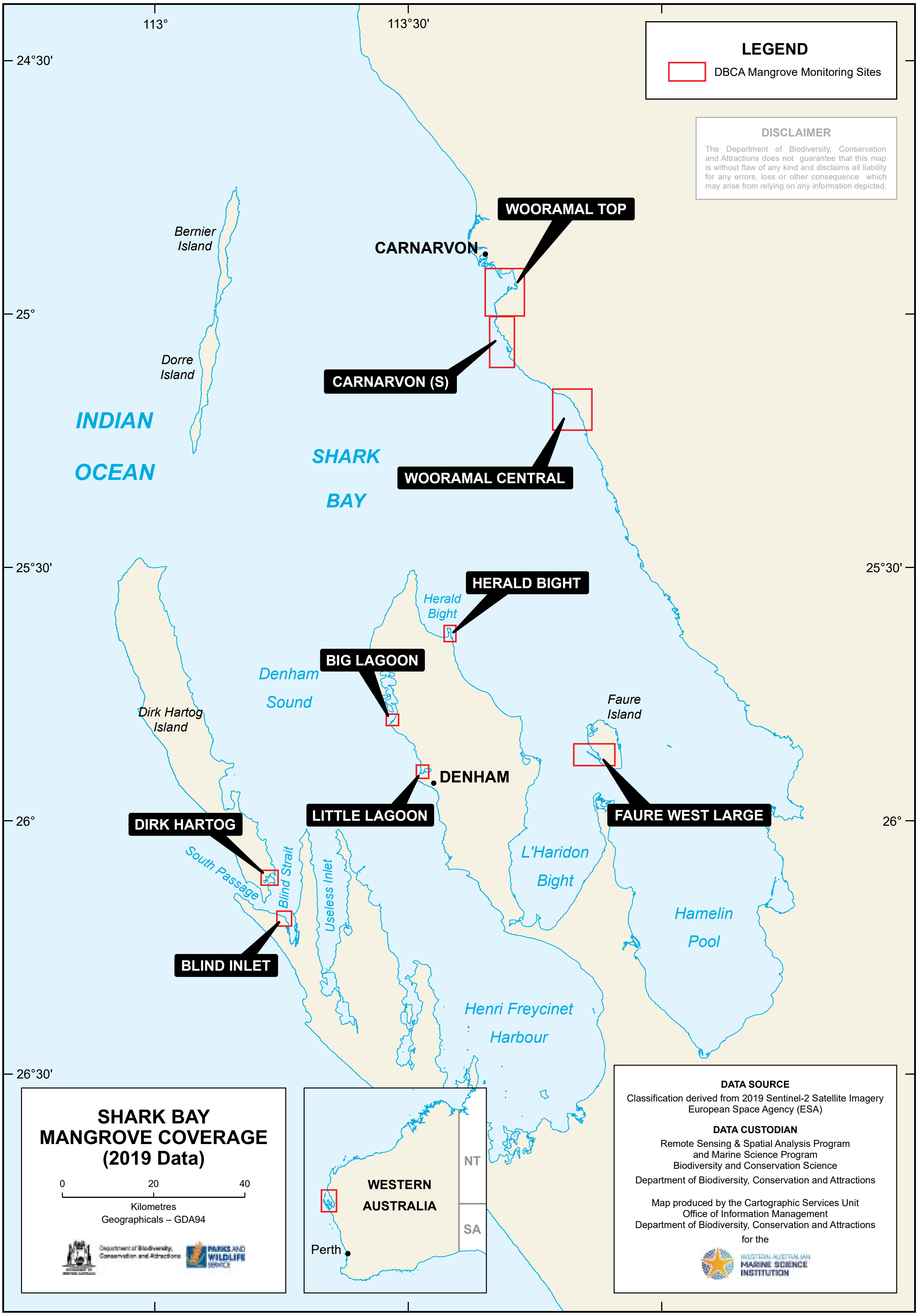


Figure 13a) Location of dense and isolated stands of mangroves in Shark Bay in 2019.

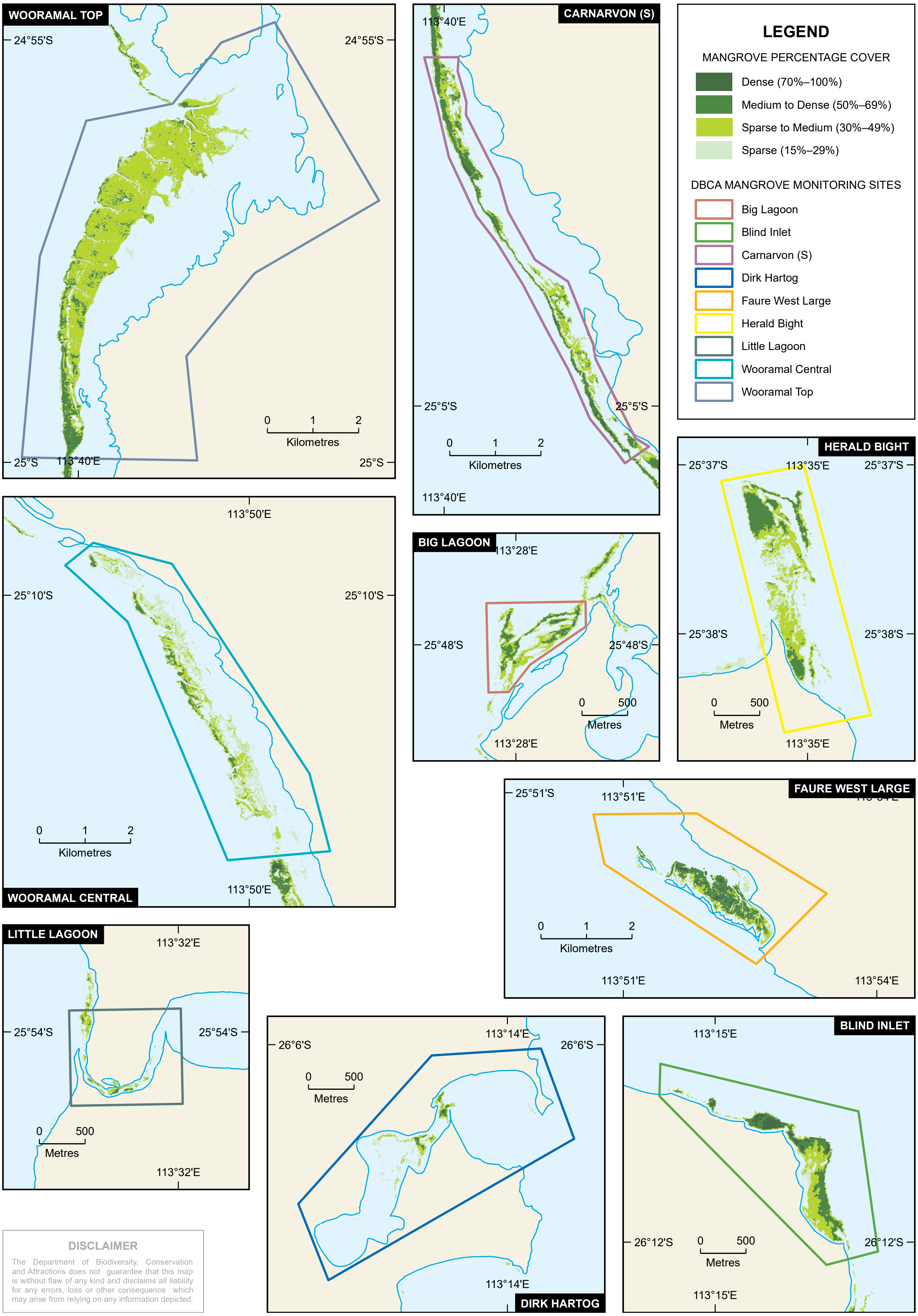


Figure 13b) Detailed view of the percent cover of mangroves at each location, including DBCA mangrove monitoring sites.

3.5.1.1 Molluscs

Bivalves have been the focus of most invertebrate studies in Shark Bay, however these have been location specific rather than for the understanding of broader patterns of distribution and diversity. At last count, over 218 species have been recorded (Slack-Smith 1990).

The diversity, abundance, growth and distribution of suspension feeding bivalves along intertidal flats has been examined (Peterson and Black 1987; Peterson and Black 1988), as has chlorophyll *a* concentrations in relation to their growth (Peterson and Black 1991), and how their presence does not seem to impact on the occurrence of other macro-infauna invertebrates on the flats (Black and Peterson 1988).

Clear patterns of zonation can be seen for sand-flat clams at Monkey Mia (Peterson 1991), and genetic differences exist across sites for several species of clam in the Shark Bay region, highlighting the importance of the Bay as a location for genetic divergence of marine species (Johnson and Black 1990).

More specifically, the biology of the cockle, *Fragum erugatum*, including its mutualistic relationship with photosynthetic zooxanthellae, has been explored given its ability to be one of two bivalves living in the hypersaline reaches of Shark Bay (Berry and Playford 1997; Morton 2000; Hickman 2003).

The internal tissues and organs of bivalves have been tested for different chemical elements, parasites and diseases. A range of bivalves, including pearl oysters, were assessed for cadmium concentrations, and while no strong correlations have been found with cadmium concentrations in surrounding seawater and sediments, cadmium accumulates in bivalves through ingestion of iron-oxide particles to which cadmium absorbs onto (McConchie *et al.* 1988; Francesconi 1989; McConchie and Lawrance 1991). The kidneys of the giant clam, *Tridacna maxima*, have been measured for arsenic containing sugar sulphates (Edmonds *et al.* 1982). Several bivalve species from Oyster Creek and further south within Shark Bay from the early 1990s were found to contain a range of parasites and diseases (Hine and Thorne 2000).

Besides bivalves, the ecology of the scavenging whelk, *Nassarius clarus*, has been the focus for Morton (2003), who investigated feeding behaviours along of the shores of Monkey Mia, and for Slack-Smith (2008), who examined salinity tolerances, diets and bivalve predation.

During a survey of fish species and benthos, Black *et al.* (1990) found that small gastropods dominated intertidal seagrass habitats and larger gastropods and bivalves dominated adjacent sand flats.

3.5.1.2 Crustaceans

Most studies on crustaceans in Shark Bay have focused on decapods and range from studies on diversity to studies on singular species.

Jones (1990a) documented the diversity, distribution, habitat and previous records of 232 species of decapods from Shark Bay. Some of these previous records came from Haig (1965) who described 28 species of crabs from WA more broadly, including recordings from Shark Bay.

Documenting the biogeographic limits and describing the habitat characteristics of the soldier crab, *Mictyris occidentalis*, was aided by examining 72 sites in Shark Bay, where crabs were typically found in low energy environments, such as leeward of spit shores (Unno and Semeniuk 2009). The sentinel crab *Macrophthalmus japonicus* was also redescribed to *Macrophthalmus pistrosinus* based on specimens from Shark Bay (Barnes and Davie 2008).

Besides decapods, 16 species of barnacles from shores and shallow waters were collected and incorporated into an identification guide for the Bay (Jones 1990b).

3.5.1.3 Others

Living and fossilised specimens of the sand dollar, *Peronella lesueuri*, were analysed to assess the concentration and distribution of magnesium throughout the bodies of the organisms (Macqueen *et al.* 1974).

Nematodes collected from loggerhead turtles have been documented and described (Lester *et al.* 1980; Berry and Cannon 1981). Nematodes have also been examined in commercial saucer scallops, where the presence of larval nematodes was considerable (Lester *et al.* 1980).

3.5.2 Finfish communities

3.5.2.1 Habitat associations

Given the extent and importance of seagrass meadows in Shark Bay, fish communities have been compared for seagrass and non-seagrass habitats.

Early work by Black *et al.* (1990) identified 58 species of fish from intertidal seagrass and adjacent sandflat habitat using beach seining. Travers and Potter (2002) found species richness and density of fishes to be higher in seagrass habitat when compared to bare sand. Similarly, more fishes (catches dominated by striped trumpeter, *Pelates sexlineatus*, and western butterfish, *Pentapodus vitta*) were caught in traps over seagrass areas compared to unvegetated areas, and depth and seagrass cover influenced species diversity (Heithaus 2004).

Fish abundance and distribution was sampled using trap surveys across Faure Sill, Wooramel Delta and east of the Peron Peninsula during 2011, where assemblages tended to be dominated by a few species, and the robustness of cover of canopy-forming seagrass being an important predictor of catch was supported (Walker *et al.* 2012).

Foraging impacts from herbivorous fishes on seagrass meadows is seagrass species dependent, and evidence suggests that seagrass beds may be shaped, in part, by the responses of herbivores to predation (Bessey *et al.* 2016). The holes and caves in scoured channels between seagrass meadows have also been identified as important for numerous reef fishes (Serrano *et al.* 2017).

The first study to examine fish in the hypersaline waters of Hamelin Pool using hand and tangle nets found six species from five families in a localised area in the southern end of the Pool (*Mugil cephalus, Mylio latus, Amphitherapon caudavittatus, Craterocephalus pauciradiatus, Sillago schomburgkii* and *Sillago analis*) (Lenanton 1977). A later study in Hamelin Pool in 2016 using baited remote underwater video systems (BRUVS), and spanning across multiple habitats and depths, found 66 species of fish from 38 families (Campbell 2017). There was a notable lack of herbivorous species compared with other locations in Shark Bay.

Forty-two species of fish were documented from mangrove habitat, and assemblages were distinct from sand and seagrass habitat and dominated by tropical and resident species, including the few-ray hardyhead, *Craterocephalus pauciradiatus* (52.5% of abundance) (King 2003).

A 1979 visual survey of fishes from South Passage, between Dirk Hartog Island and the mainland, documented 323 species and found that although most species were tropical, higher abundances were observed for the fewer cool temperate species present (Hutchins 1990). A later 2009 assessment of fish assemblages of South Passage and Blind Strait using baited remote underwater video systems identified 235 species (Clough 2011) and, through a qualitative comparison with 1979 findings, found some recreationally targeted fishes were less abundant. Findings from 2009 found reef habitats had a greater species richness than seagrass and sand habitats, and within reef habitats, living coral reefs supported a higher richness and abundance than limestone reefs.

The current finfish assessments made by DBCA are focused on communities associated with coral habitat inside and outside of the Shark Bay Marine Park. Though community composition within the marine park has remained stable, a decline has been observed for corallivores (coral dependant fishes) near Bernier and Dorre Islands following the loss of coral cover by approximately 90-95% as a result of 2011 marine heatwave (DBCA 2019b).

3.5.2.2 Large-scale community and population studies

The fish communities of Shark Bay have often been included in wider State studies and related to a suite of environmental and habitat characteristics.

Remote sampling of corals and fish in outer Shark Bay (and Ningaloo) in 2014 has been used to establish spatially replicated baseline data in order to monitor changes in community condition over time and attribute changes to major disturbances (e.g. temperature anomalies, cyclones) (Miller *et al.* 2015).

Ten years of data from commercial fishing, including relative abundance indices derived from catch rates, were used to assess the contributions of environmental factors and anthropogenic impacts on identifying the distribution of commercially important pelagic predators (tunas, marlins and mackerels) (Bouchet *et al.* 2017). Outer Shark Bay and adjacent waters were identified as a hotspot for pelagic fish, along with other locations throughout the Exclusive Economic Zone of WA.

Temperate and tropical fish communities along the coastline have been investigated to further understand the processes structuring communities along a latitudinal gradient (Ford and Roberts 2018), the role of co-occurring species in community organisation and resilience (Ford and Roberts 2019), and how geographical distance and environmental conditions influence the assemblage and community structure (Ford *et al.* 2017).

In terms of species-specific population studies, the biology and population genetic structure of the mulloway, *Argyrosomus japonicus*, has been studied across the state which included samples caught in Shark Bay fisheries (Farmer 2008).

Genetics of the stripey snapper, *Lutjanus carponotatus*, have also been sampled across 51 locations to assess whether connectivity via larval dispersal was related to extreme gradients in coastal hydrodynamics, and a significant genetic subdivision was found between Shark Bay and all northern regions suggesting restricted connectivity (DiBattista *et al.* 2017).

3.5.2.3 Diet

Selected species have formed the focus of dietary studies in Shark Bay. The dietary compositions of six abundant species from Monkey Mia, *Gerres subfasciatus*, *Upeneus tragula*, *Psammoperca waigiensis*, *Centrogenys waigiensis*, *Apogon victoriae*, *Apogon rueppellii*, were assessed in relation to mouth characteristics and vision (Linke *et al.* 2001). Mouth characteristics were also examined for *Sillago bassensis*, *Sillago vittata*, *Spratelloides robustus* and *Pseudorhombus jenynsii*, as well as habitat type, season and body size in relation to stomach contents (Schafer *et al.* 2002).

Diets of the adults and juvenile sparid, *Acanthopagrus latus*, differed depending on the type of habitat, where mangrove material, sesarmid crabs and small gastropods were common in the diet in mangrove habitats, and mytilid bivalves common in the diet for rocky habitats (Platell *et al.* 2007).

Lek *et al.* (2018) investigated the differences in diet of *Choerodon rubescens* and *Choerodon schoenleinii* across length classes, season and habitat type.

Though not directly diet related, two new trematode (Opecoelidae) species were found in the intestines and other organs of the flatfish *Pseudorhombus jenynsii* collected from Shark Bay (Bray 1990).

3.5.2.4 Biological oceanography

The Leeuwin Current is the dominant boundary current off the coast of WA and has a significant influence on the fish fauna of Shark Bay. Caputi *et al* (1996) used tidal and satellite-derived SST data to investigate the timing and strength of the Leeuwin Current and its influence on the recruitment of fish and invertebrate species. A review of the relationship between the Leeuwin Current and abundance of key scalefish species is presented by Lenanton *et al.* (2009b).

Otolith biochronologies have been used to investigate how the strength of the Leeuwin Current accounts for variance in annual growth patterns of marine fishes across 23 degrees of latitude, including Shark Bay, where stronger current flow during La Niña increased otolith growth in five species (Ong *et al.* 2018).

3.5.2.5 Methodology studies

Aside from in-water diver surveys, several different methods exist for capturing information on fish diversity and abundance.

Mid-water baited stereo-cameras were used to study spatial variation in pelagic fish and shark assemblages in Shark Bay, where observations of 248 pelagic fishes from 27 species and 10 families were made (Letessier *et al.* 2013).

Rova *et al.* (2007) investigated whether fish species from such camera footage could be identified using automated methods such as deformable template object recognition.

Sonar systems have also been explored as 'acoustic cameras' in their ability to produce images of different species at close range (Parsons *et al*. 2017).

In order to develop passive acoustic monitoring of vocalising fish species, acoustic recordings of several species were made along the WA coastline (Parsons *et al.* 2012a; Parsons *et al.* 2015). This included recording snapper, *Pagrus auratus*, in the Eastern and Western Gulfs of Shark Bay, however, little evidence was found to support vocalisation by snapper.

See section 3.6.9 for methodological studies relating to fisheries and bycatch.

3.5.3 Elasmobranchs

Given the prevalence of elasmobranchs in Shark Bay, case studies and research from the Bay are often included in global discussions on the ecological importance of elasmobranchs (Heithaus *et al.* 2010), the impact of exploiting elasmobranchs, and the impact elasmobranchs have on their prey (Ferretti *et al.* 2010). Tiger sharks have been the most extensively studied elasmobranch in Shark Bay.

3.5.3.1 Habitat, resource partitioning and competition

Visual surveys of elasmobranchs over sand flats in Shark Bay in 2006-2007 found 11 species of sharks and rays during the cold season and 21 species during the warm season (Vaudo and Heithaus 2009).

Given this diversity, several studies have examined habitat partitioning and competition among species. A review of coastal elasmobranchs as prey, predators and competitors which incorporated Shark Bay examples is given by Vaudo and Heithaus (2011a).

A survey of elasmobranchs across four different habitats in Shark Bay found that shallow waters are partitioned among species, reducing competition, and that the mean number of species and catch rates was greatest in seagrass habitat (White and Potter 2004).

A further investigation into one ray (*Rhinobatus typus*) and three shark species (*Carcharhinus cautus*, *Negaprion acutidens*, *Rhizoprionodon acutus*) found that competition for food is low given the differences in their diet (White *et al.* 2004).

Conversely, while Vaudo and Heithaus (2011b) found that most species were dependant on a seagrass-based food web, they provided evidence that overlap in resources was high among the elasmobranch community, such as for *Himantura* sp and *Glaucostegus typus*, and that perhaps there was enough prey to reduce competition and sustain diversity.

Large sharks (including tiger sharks) were found to occupy a different isotopic/feeding niche to bottlenose dolphins, as well as to smaller sharks and rays (Heithaus *et al.* 2013)

3.5.3.2 Tiger sharks

3.5.3.2.1 Population and distribution

From seven years of tag and release fishing data, tiger sharks showed a consistent peak in catches during Sep–May and a trough during Jun–Aug, suggesting a preference for warmer waters (Heithaus 2001a; Wirsing *et al.* 2006).

Five tiger sharks from Shark Bay were fitted with satellite transmitters to explore long-term movements and evidence is provided for mixing across the Indian Ocean basin (Heithaus *et al.* 2007c).

3.5.3.2.2 Habitat

Tiger sharks are found to prefer shallow habitats over deep habitats in Shark Bay, as well as shallow edge microhabitats over shallow interior microhabitats (Heithaus *et al.* 2006). Within those shallow habitats, tiger sharks appear to prefer seagrass habitats where their prey are most abundant (Heithaus 2001a; Heithaus *et al*. 2001; Heithaus *et al.* 2002a).

Despite this preference, tiger sharks at Monkey Mia were found to be relatively resilient to the seagrass die-off from the marine heatwave event in 2011, which is attributed to their more generalist diet (Nowicki *et al*. 2019).

3.5.3.2.3 Predator-prey interactions

Predator-prey interactions of tiger sharks form a strong focus in ecosystem research at Shark Bay (Dill *et al.* 2003b; Heithaus *et al.* 2007a; Wirsing *et al*. 2008b; Heithaus *et al.* 2009; Wirsing *et al.* 2010; Heithaus and Vaudo 2012; Heithaus *et al.* 2012).

There are three anti-predator behaviours observed in the marine environment that are also seen in the terrestrial environment: encounter avoidance, escape facilitation, and increased vigilance (Wirsing and Ripple 2011).

Predator-prey interactions have investigated the effect of predation and predation risk on loggerhead and green turtles (Heithaus *et al.* 2002b; Heithaus *et al.* 2005; Heithaus *et al.* 2007b), dugongs (Wirsing *et al.* 2007d; Wirsing *et al.* 2007c; Wirsing *et al.* 2007b; Wirsing *et al.* 2011), bottlenose dolphins (Heithaus 2001c; Heithaus 2001b; Heithaus and Dill 2002; Heithaus and Dill 2006), pied cormorants (Dunphy-Daly *et al.* 2010) and olive-headed sea snakes (Wirsing and Heithaus 2009).

The inclusion of prey availability was found to improve predictive models of abundance for tiger sharks in Shark Bay (Wirsing *et al.* 2007a).

The loss of top marine predators in an ecosystem, such as tiger sharks, can cause significant negative effects to ecological functioning (Heithaus *et al.* 2008a).

3.5.3.2.4 Diet

Sea snakes, dugongs, turtles and small elasmobranchs are common prey items for tiger sharks (Heithaus 2001a), and several studies have used stomach contents and stable isotopes to determine the diet of individuals.

Stomach contents from 84 tiger shark specimens showed overlap in male and female diets, but different diets for different ages (Simpfendorfer *et al.* 2001).

Stable isotopes of different body tissues have been assessed for individual specialisations or generalities, and age of tiger sharks is a factor to consider when observing variability in stable isotopes (Matich *et al.* 2010; Matich *et al.* 2011).

Tissues from tiger sharks collected at Shark Bay were also compared with east coast Australia individuals to examine variation across location, size and sex, and tiger sharks from Shark Bay showed a clear signature of a seagrass-based food web (Ferreira *et al.* 2017).

3.5.3.3 Other sharks

Less focus has been applied to sharks other than tiger sharks. Braccini and Taylor (2016) included sharks caught from Shark Bay in a WA wide study on spatial segregation patterns. More specific to Shark Bay, White *et al*. (2002) examined length at age and reproductive biology of the nervous shark, *Carcarhinus cautus*.

Spatial and temporal patterns of whale sharks tagged in Ningaloo have shown movement to Shark Bay, particularly the northern extent of the Bay (Norman *et al.* 2014; Norman *et al*. 2016; Reynolds *et al.* 2017).

Although a more methodological focus, imaging sonar has been used to detect sharks in a study examining the factors affecting sonar detection and identification (Parsons *et al.* 2014). Sonar systems have also been explored as 'acoustic cameras' in their ability to produce images of species at close range, which included the lemon shark and sandbar shark from the Ocean Park Aquarium (Parsons *et al.* 2017).

3.5.3.4 Rays

Acoustic telemetry has been used to examine coarse-scale diel and seasonal movements of rays using the shallow sandflats of the Bay (Vaudo and Heithaus 2012).

Semeniuk and Dill (2004) have investigated the environmental conditions that may influence the degree of grouping during rest periods for cowtail stingrays and found that smaller groups were more common in lower light conditions, and that the behaviour of grouping seems to be effective for predator detection and response.

Further still, there is evidence to suggest that cowtail stingrays rest with reticulate whiprays as they receive an earlier warning of predator approach due to the faster response time of whiprays (Semeniuk and Dill 2006).

Manta rays (*Manta birostris*) have also been observed in the deeper oceanic waters of Shark Bay (> 10m) (Preen *et al.* 1997), and their continuous and confirmed distribution has been mapped from Shark Bay northwards using photo-ID catalogues and aerial surveys (Armstrong *et al.* 2019).

3.5.4 Marine reptile communities

3.5.4.1 Sea snakes

Sea snake populations have been in decline across the globe, and Shark Bay is recognised as an important habitat for sea snakes (Udyawer and Heupel 2017).

3.5.4.1.1 Diversity and distribution

Studies focusing on sea snake diversity and distribution have more often than not included Shark Bay in larger geographical investigations, rather than solely focusing on the Bay itself.

Early work by Smith (1974) produced a taxonomic key to different species of sea snake in WA, which included specimens described from Shark Bay.

Including specimens from Shark Bay and the rest of northern Australia, Nitschke *et al.* (2018) used mitochondrial phylogeographic techniques to show that sea snakes from the *Hydrophis* clade had weak population differences whereas *Aipysurus* and *Emydocephalus* species show clear geographic patterns.

Udyawer and Heupel (2017) explored spatial and temporal patterns for sea snakes across the North West Shelf, and Shark Bay was noted as an important habitat for sea snakes.

The importance of Shark Bay is further reiterated by D'Anastasi *et al.* (2016b; 2016a) who conducted surveys across WA to clarify the distribution of sea snakes and documented the occurrence of two critically endangered species, *Aipysurus foliosquama* and *Aipysurus apraefrontalis*, in Shark Bay, further south than previously recorded. Sea snakes are commonly associated with seagrass meadows, sand over limestone, silt and sponge habitat.

The distribution of sea snakes has also been considered at a courser level during megafauna surveys of Ningaloo, Exmouth Gulf and Shark Bay (Hodgson 2007).

3.5.4.1.2 Ecology

Some ecological aspects have been investigated for two different sea snake species in Shark Bay.

Kerford (2005) examined habitat use, ecology, morphology and life history of the bar-bellied sea snake, *Hydrophis elegans*. Further, bar-bellied sea snakes trade food for safety when high tides expose them to predation by tiger sharks, and they will forage in seagrass habitat with scarce food options at high tide, but will forage exclusively over bare sand during low tide when conditions are more restrictive to sharks (Kerford *et al.* 2008). Following along the same line, the olive-headed sea snake has been shown to use certain seagrass microhabitats when tiger shark encounter rates are low and avoided meadow edges when encounter rates are high, suggesting snakes measure danger depending on predator density (Wirsing and Heithaus 2009).

3.5.4.1.3 Methodology studies

Sea snakes have formed part of the focus (along with other megafauna) for new or improved methodologies which have been tested in Shark Bay.

Sonar systems have been used and assessed as 'acoustic cameras' and have produced images from 14 species at close range, which includes sea snakes (from the Ocean Park Aquarium setting) (Parsons *et al.* 2017). Kangas and Thomson (2004) have also explored new designs for reducing bycatch in trawl fishing in the Bay, of which sea snakes are considered.

3.5.4.2 Marine turtles

3.5.4.2.1 Green turtles

Green turtles (*Chelonia mydas*) use Shark Bay as a foraging ground, while nesting takes place between Ningaloo and the Lacapede Islands. Information on green turtles is included in a review of marine turtles from WA (Limpus 2002), and Shark Bay was included in a larger investigation into the genetic structure of green turtle populations and foraging grounds across Australasia (Jensen 2010).

More specific to Shark Bay, important aspects of green turtle biology and ecology, such as sex ratios, size distributions, body condition and predation injuries are discussed in Heithaus *et al* (2005).

Health-related studies include confirming the presence of tumours (fibropapillomas) in a juvenile green turtle in the Bay, which was the first case for WA (Raidal and Prince 1996), and examining ten deceased specimens for plastic ingestion, of which parasite infestations were found but no plastics (Reinhold 2015).

Animal-borne video cameras have been attached to green turtles in order to learn more about their behaviours. Footage has revealed self-cleaning practices and diet preferences (Heithaus *et al*. 2002c), seasonal activity and foraging grounds (Thomson and Heithaus 2014), as well as interactions and behavioural dynamics between green turtles during encounters at limited and valuable habitat (Thomson *et al.* 2015b).

Video has been used to examine correlations between dive-surfacing patterns and behaviour of green turtles (Thomson *et al.* 2011), and some attention has been given to how deployment stress of animal-borne video recorders impacts green turtle behaviour (Thomson and Heithaus 2014).

Other methodological studies include validating visual methods to accurately assess body condition (Thomson *et al.* 2009); the importance of accounting for variation in dive-surfacing patterns when analysing boat-based survey data (Thomson *et al.* 2013); relating dive records to depth and water temperature at foraging sites (Thomson *et al.* 2012a); using mid-water BRUVS to reveal habitat use around Dirk Hartog Island (Letessier *et al.* 2015); exploring the use of sonar systems as acoustic cameras (Parsons *et al.* 2017); and using aerial surveys to estimate abundance and distribution of both green and loggerhead turtles combined for Shark Bay and other northwest locations (Preen *et al.* 1997).

3.5.4.2.2 Loggerhead turtles

The Loggerhead turtle (*Caretta caretta*) population from Shark Bay has been included in a review of marine turtles from WA (Limpus 2002), and the wider Indian Ocean (Baldwin *et al.* 2003).

Genetic profiles have been documented for Shark Bay populations and compared with profiles from Cape Range further north (Pacioni *et al.* 2012).

Heithaus *et al* (2005) investigated the biology and ecology of loggerhead turtle populations specific to Shark Bay, such as sex ratios, size distributions, body condition and predation injuries.

Similar to green turtles, a range of methodologies have been employed to learn more about the behaviours and movements of loggerhead turtles. Animal-borne cameras have been used to reveal diet preferences and diving patterns (Heithaus *et al.* 2002c; Thomson *et al.* 2011). Tags have been used to assess large-scale movement and habitat use patterns of adult male loggerhead turtles (Olson *et al.* 2012), and an abundance of female loggerheads have been tagged from Dirk Hartog Island nesting beaches (Prince 1997).

Loggerhead movements to Shark Bay after nesting at Ningaloo have been tracked (Mau *et al.* 2012), and movement of loggerheads has been remotely tracked in Shark Bay using community-based conservation (Wirsing *et al.* 2004).

Remote cameras have been trialled in monitoring nesting of loggerheads at the Turtle Bay rookery (Holley *et al.* 2012), and counts of turtle tracks and nesting success have been used to estimate the numbers of loggerheads nesting at the peak of each season at Turtle Bay (Reinhold and Whiting 2014).

Dive-surfacing patterns have been investigated in relation to analysing boat-based survey data and to correlate with depth and water temperatures at foraging grounds (Thomson *et al.* 2012a; Thomson *et al.* 2013).

Turtle Bay on Dirk Hartog Island is a major rookery for loggerhead turtles (Prince 1994), and together with nesting beaches at Shelter Bay and Dorre Island, Shark Bay supports approximately 70% of loggerheads found in WA (October to March).

Several biotic and abiotic factors affecting hatching and emergence success of loggerhead turtles have been investigated (Trocini *et al.* 2008).

Tedeschi *et al.* (2015b) examined multiple paternity of egg clutches and found no link between rates of multiple paternity and female population size. Given a changing climate and temperature dependent sex determination of turtle offspring, several studies have assessed the genetic responses of embryos to high temperatures in order to understand what could happen with rising temperatures (Tedeschi *et al.* 2015a; Tedeschi 2015; Tedeschi *et al*. 2016; Bentley *et al.* 2017).

Loggerhead specimens from Shark Bay have had incidences of parasitic trematodes (digeneans) and parasitic nematodes (Lester *et al.* 1980; Berry and Cannon 1981; Blair and Limpus 1982).

3.5.4.2.3 Predation

Tiger sharks are a major predator of marine turtles in Shark Bay. Turtles have been observed to change their behaviour and avoid feeding areas when there is a risk of tiger shark predation (Heithaus *et al.* 2008b).

Green turtles in good body condition have been shown to select safer, lower quality foraging areas when tiger sharks are present, as opposed to turtles in poor body condition that select high risk areas for high quality foraging (Heithaus *et al*. 2007b).

Male loggerhead turtles are predated upon by tiger sharks more often than females and, overall, loggerhead turtles tend to have more injuries from tiger sharks then green turtles (Heithaus *et al.* 2002b; Wirsing *et al.* 2008a).

On land, feral cats fitted with data-logger/radio-telemetry collars have been found to opportunistically predate on loggerhead turtle hatchlings (Hilmer *et al.* 2010).

3.5.4.2.4 Ecosystem

The links between marine turtles and seagrasses have formed some of the focus of ecosystem studies in Shark Bay.

The impacts of green turtles grazing on seagrass meadows has been investigated in several locations, including Shark Bay, where overfishing of sharks can increase green turtle populations and cause heavy grazing on seagrasses (Heithaus *et al.* 2014).

Burkholder *et al.* (2012) found that foraging turtles were more likely to consume faster growing seagrass species, but found no correlation with nutrient content of different seagrass species in Shark Bay.

Despite green turtles having a diet commonly comprised of macroplankton (cnidarians and ctenophores) as well as seagrass (Burkholder *et al.* 2011), the 2011 marine heatwave and associated seagrass loss caused a decline in green turtle abundance at Monkey Mia, but did not cause the same decline for loggerhead turtles which are adapted to a more generalist diet (Thomson *et al.* 2012b; Nowicki *et al*. 2019).

3.5.4.2.5 Management

In 2008, a marine turtle recovery plan was released for Western Australia, which included Shark Bay, and documented plans for the six species found in Western Australia waters (DEC 2008). Turtles are also managed as ecological values in the Shark Bay Marine Park by DBCA.

In 2017, a decade-long recovery plan for marine turtles around Australia was released, which also included information from Shark Bay (Commonwealth of Australia 2017).

3.5.5 Seabirds and shorebirds

3.5.5.1 WA wide

Records of seabirds and shorebirds in Shark Bay have often been included in studies encompassing more of the WA coastline.

Johnstone (1990) surveyed birds, including seabirds and shorebirds, from 83 blocks of mangroves between Cambridge Gulf and Shark Bay, and noted a range of ecological factors and specific mangrove associations.

An annotated checklist of 273 bird species from the Gascoyne region included seabirds and shorebirds from Shark Bay (Storr 1985).

The geographic range and status of seabirds and shorebirds have been documented for the southern Carnarvon Basin, which included Shark Bay (Johnstone *et al.* 2000).

Dunlop (2017) includes recordings from Shark Bay in an overview of using seabirds to monitor marine ecosystems in WA.

3.5.5.2 Shark Bay specific

An annotated checklist of birds species, including seabirds and shorebirds, around Shark Bay is provided by Storr (1990), and Birdlife WA and Birds Australia have both produced guides to birds of Shark Bay, giving an indication on how common or rare each species is (Birds Australia Western Australia Inc. 2006; Birdlife Western Australia 2018).

Aside from these checklists, there has been a focus on the islands and breeding populations of Shark Bay. Burbidge and Fuller (2000) presents information on the 16 species of birds that depend on the ocean for food (11 were true seabirds), and identifies 42 breeding sites on islands and islets, including Pelican Island which is a significant rookery for pelicans. Brown (2001) provides information on seabirds and breeding islands of Shark Bay, as well as other values, which contributed to Shark Bay being nominated for World Heritage listing.

All birds have been surveyed on Peron Peninsula and Dirk Hartog Island (Davies and Chapman 1975). Faure Island has also received specific attention, where 44 out of 97 birds were found to depend on beaches, mangroves, mudflats and tidal flats for food (Dell and Cherriman 2008).

3.5.5.3 Species specific

Pied cormorants (*Phalacrocorax varius*) have been found to modify their diving behaviour when there is a high risk of predation by tiger sharks (Dunphy-Daly *et al.* 2010).

Further, seagrass is the preferred shallow water foraging habitat of pied cormorants, and when the density of tiger sharks increases, cormorants decrease their use of such shallow water habitats (Heithaus 2005). Due to the preference of seagrass habitats by pied cormorants, cormorant densities at Monkey Mia declined by 35% following seagrass die-off from the 2011 marine heatwave, which was linked to a significant reduction in the biomass of seagrass-associated fishes in the system (Nowicki *et al.* 2019).

The breeding populations of wedge-tailed shearwaters (*Ardenna pacifica*) have been specifically studied in Shark Bay and, back in the early 1970s, there was an estimated 600 breeding pairs spread across five breeding islands (Serventy 1972). It is believed the population on Slope Island was negatively affected by salt works and foxes.

3.5.6 Marine mammal communities

3.5.6.1 Dugongs

3.5.6.1.1 Distribution and population

Some of the earliest work on estimating population size, distribution, habitat use and relationships of dugongs (*Dugong dugon*) with water temperature came from Anderson (Anderson 1982; Anderson 1986).

Since 1989, aerial surveys of dugongs have been carried out every five years with the aim of estimating population abundance, documenting distribution, and assessing change across time (Marsh *et al.* 1994; Preen *et al.* 1997; Gales *et al.* 2004; Holley *et al.* 2006;

Hodgson 2007; Hodgson *et al*. 2008; Bayliss *et al.* 2019). Overall, the dugong population in Shark Bay has remained relatively stable between 1989 and 2018 (Bayliss *et al*. 2019), though the percentage of calves decreased temporarily, following a likely collapse in breeding recruitment after the seagrass loss in 2011/12. One exception to this relatively stable abundance was when more dugongs were recorded in Shark Bay following Tropical Cyclone Vance in 1999, which was likely due to loss of foraging ground at Ningaloo Reef and Exmouth Gulf (Gales *et al.* 2004).

Distribution and movement patterns of dugongs have been determined from aerial surveys and remote tracking, and seasonal migration patterns are driven by sea surface temperature (Holley 2006; Holley *et al*. 2006).

South Cove near Gladstone National Park was identified as a potential mating ground for dugongs, where a range of mating behaviours were observed and documented (Anderson 1997).

3.5.6.1.2 Foraging

High abundances of foraging dugongs are sustained by extensive seagrass meadows in Shark Bay. Foraging habits have been documented for dugongs (Anderson 1986; Anderson 1998), and Burkholder *et al.* (2012) found a link with consuming faster growing seagrass species rather than a link with nutrient content. *Halophila spinulosa* growing in deeper waters has been suggested to sustain the long and deep diving behaviours of foraging dugongs (Anderson 1994).

3.5.6.1.3 Predation

Several studies have explored tiger shark predation on dugongs.

Dugongs are observed to change their behaviours when there is high risk of predation, such as spending more time in safe but lower quality feeding habitats (Wirsing *et al*. 2007d), avoiding shallow foraging grounds (Wirsing *et al.* 2007c), changing feeding tactics (Wirsing *et al.* 2007b), avoiding continuous rest periods (Wirsing and Heithaus 2012), and changing diving patterns (Wirsing *et al.* 2011).

Besides tiger sharks, Anderson and Robert (1985) investigated the presence of killer whales east of Dirk Hartog Island in relation to dugong predation.

3.5.6.1.4 Conservation

While much of the research on dugongs has links to conservation, two pieces of literature have focused specifically on conservation efforts. With a slow growing population and threats from anthropogenic impacts, a conservation strategy was discussed for Australia's dugongs back in the late 1990s (Marsh *et al.* 1999), and a discussion also arose on the effectiveness of Marine Protected Areas in protecting dugongs along the WA coastline (Preen 1998).

3.5.6.1.5 Methodology studies

Aside from aerial surveys, a range of other methodologies have been used to try and characterise aspects of dugong biology.

Passive acoustic methods have been used to try and record calls of dugongs and sonar systems have been explored as 'acoustic cameras' in order to produce images of dugongs at close range (Parsons *et al.* 2012b; Parsons *et al.* 2013; Parsons *et al.* 2017).

Time-depth recorders have been used to describe the diving behaviours of dugongs, of which five diving types were characterised (Chilvers *et al.* 2004).

Observational techniques have been employed to characterise scar types on dugongs (which aids in photoidentification), behaviours, foraging and interactions with dolphins (Anderson and Anderson 1982; Anderson 1995).

Unmanned aerial vehicles (UAV) have also been tested as a new tool for monitoring dugongs (Hodgson *et al*. 2013).

3.5.6.2 Dolphins

3.5.6.2.1 Overarching studies

Research has been underway on the bottlenose dolphin population in Shark Bay for over thirty years with a strong focus on social behaviour. The majority of research has been conducted in the Eastern Gulf in the vicinity of

Monkey Mia and Red Cliff Bay, however there is a second and more recent body of research that has focused on the Western Gulf. There have been numerous overarching global reviews and discussions on cetaceans that have incorporated case studies or data on bottlenose dolphins from Shark Bay. These have included long-term decadal reviews of dolphin research (Connor *et al.* 2000a; Mann and Karniski 2017; Connor 2018), discussions on behaviour, tool use and social evolution (Connor *et al.* 1998; Mann 2006b; Sargeant and Mann 2009; Mann and Patterson 2013; Cords and Mann 2014; Mann and Singh 2015), a discussion on rationality in dolphins (Connor and Mann 2005), and reviews of data collection, analyses and methodologies (Mann 1999; Mann *et al.* 2000b; Mann and Würsig 2014; Stanton and Mann 2014b). The rest of the studies detailed below are of more specific relevance to Shark Bay.

3.5.6.2.2 Population demographics

The life history and behaviour of female bottlenose dolphins from the Eastern Gulf is described by Richards (1996) and includes home range, range overlap, sexual maturity, births, weaning, associations and male interactions.

Another encompassing body of research is presented in Krzyszczyk (2013) and includes ontogeny and functions of speckling, sex-specific survival rates (Krzyszczyk *et al.* 2013a), causes of mortality, behavioural and social development and an assessment of methodology for collecting samples of exhaled breath condensate.

The abundance, apparent survival and temporary emigration of Indo-Pacific bottlenose dolphins has also been investigated for the Western Gulf (Nicholson *et al.* 2012), and population data has been explored using a Hierarchical Bayesian version of Pollock's Closed Robust Design (Rankin *et al.* 2016b).

For Shark Bay overall, bottlenose dolphins continue to use natal home ranges into adulthood (Tsai and Mann 2012).

The factors that influence reproductive success of female bottlenose dolphins have primarily been investigated for the Eastern Gulf (Mann *et al.* 2000a). Evidence suggests that female calving success depends on both genetic inheritance and social bonds (Frère *et al.* 2010b), and that calf survival decreases with maternal age (Karniski *et al.* 2018).

Colouration of dolphins is found to change with age, and speckling can indicate reproductive status and/or condition (Krzyszczyk and Mann 2012).

Levels of inbreeding were higher than expected for the dolphins in the Eastern Gulf, and inbred females, and females with inbred calves, were found to have reduced fitness, such as lower calving success (Frère *et al.* 2010a).

Behavioural strategies for reducing inbreeding show that adult males out compete juveniles or females prefer adults, and females reduce association with male offspring during breeding (Wallen *et al.* 2017).

The reproductive success and survival rates of bottlenose dolphins were compared for the Eastern Gulf population, which is considered relatively stable, and Bunbury population (southwest WA), which is forecast to decline (Manlik *et al.* 2016).

3.5.6.2.3 Biology

3.5.6.2.3.1 Morphology and identification

Individual skin pigment patterns on dolphins can reliably distinguish individual bottlenose dolphins by using a photographic pigment matching technique (Bichell *et al*. 2018).

Stereo-laser photogrammetry was used to reveal morphological differences for *Tursiops aduncus* individuals from the Shark Bay and the South West (Mandurah and Bunbury) populations, which likely reflects regional adaptations to local water temperatures (van Aswegen *et al.* 2019).

3.5.6.2.3.2 Predation

Predation on bottlenose dolphins has largely been investigated in the Eastern Gulf of Shark Bay and examples of predation from the Bay are included in a global review investigating predation on odontocetes by sharks (Heithaus 2001b).

Tiger sharks in Shark Bay were found to inflict up to 74% of scars on non-calves (Heithaus 2001c). Mothers and older calves were observed to exhibit a flight response to a juvenile great white shark swimming into their group (Connor and Heithaus 1996), and responses of a group to a non-lethal shark attack on a dolphin individual has been documented (Gibson 2006).

Witness interviews were used to describe events and behaviours of dolphins prior to and after a lethal attack by a tiger shark (Mann and Barnett 1999).

Habitat use by dolphins is also influenced by tiger shark predation and prey abundance (Heithaus and Dill 2006).

3.5.6.2.3.3 Vocalisations

Vocalisations have been studied for the bottlenose dolphins in the Eastern Gulf, and examples from Shark Bay have been included in a global study on origins and implications of vocal learning in bottlenose dolphins (Janik 1999).

In the Gulf, males have been found to produce a 'pop' vocalisation almost exclusively in the presence of consorted females (Connor and Smolker 1996; Vollmer *et al*. 2015).

Whistles have been heard by infants after periods of separation from their mothers (Smolker *et al.* 1993), and also by provisioned males at Monkey Mia who converged in their use of a particular whistle contour (Smolker and Pepper 1999).

3.5.6.2.3.4 Genetics

Genetics were used to discern three coastal populations of bottlenose dolphins (*Tursiops* spp.) off northwest Australia: Shark Bay, Coral Bay to Beagle Bay, and Cygnet Bay (Allen *et al.* 2016). These coastal populations were found to be genetically isolated from each other and from pelagic offshore dolphins sampled from the region of the Pilbara Trawl Fishery.

Within the Eastern Gulf, an investigation of population substructure suggests that female dolphins are more restricted in dispersal than males (Krützen *et al.* 2004b).

Microsatellite loci have been characterised for dolphins in the Eastern Gulf (Krützen *et al.* 2001), and single nucleotide polymorphisms have been used to examine parentage and genetic relatedness (Foroughirad *et al.* 2019).

Genetic discoveries from Shark Bay were included in a wider study showing that phenotypic evolution is driven by the nature-nurture interaction (Frère *et al.* 2011).

Other methodological studies involving dolphins from Shark Bay include using genetic markers to explore large-scale population-wide paternity and relatedness (Nater *et al.* 2009), and evaluating the usefulness of adaptive markers over neutral markers to guide conservation management (Manlik *et al.* 2019). Collecting DNA from dolphins has been discussed in relation to biopsy darting (Krützen *et al*. 2002), and for the less invasive method known as 'blow sampling' (Frère *et al.* 2010d).

3.5.6.2.3.5 Health

Bottlenose dolphins from Shark Bay have been found to suffer from seagrass-associated gastric impaction, which can cause emaciation and death (Krzyszczyk *et al*. 2013b).

A tattoo-like skin disease has been characterised for individuals in the Bay, and baseline data can be used to monitor changes in the prevalence of the disease and its use as a bioindicator (Powell *et al.* 2018; Powell *et al*. 2019).

Gaining knowledge on microbiomes and developing novel methods for obtaining samples from dolphins can be used to monitor health over time, and this is being done for bottlenose dolphins in Shark Bay (Nelson *et al.* 2015; Nelson *et al*. 2019).

In the late 1980s, significantly contaminated water was implicated in the death and disappearance of dolphins at Monkey Mia, though not conclusively proven (EPA WA 1989).

3.5.6.2.4 Behaviour

Bottlenose dolphins from the Eastern Gulf exhibit multiple levels of sociality (Stanton and Mann 2014a). Multivariable techniques were used to identify social learning and socially learned foraging tactics (Sargeant and Mann 2009), and Gibson and Mann (2009) examined the method and sample size required to quantify social patterns. Null models have also been used to try and explain the social networks of dolphins from the Eastern Gulf (Rankin *et al.* 2016a).

Calf social networks have been used to predict survival of calves and juveniles (Stanton and Mann 2012). Sex segregation in social relationships has been identified for dolphins in the Eastern Gulf and there is evidence for a sex bias in fission-fusion dynamics (Connor *et al*. 2010; Galezo *et al.* 2018).

Non-random social avoidance is also apparent among dolphins in Shark Bay, and a framework has been developed to identify this behaviour in other dolphin populations (Strickland *et al.* 2017).

Different behavioural states can also influence patterns of association, where dolphins associate with different individuals depending on whether they are foraging, socialising etc. (Gero *et al.* 2005). Loyalty of individuals to an affiliation group can also change over time with different degrees of commitment to a group observed for dolphins from the Eastern Gulf (Sharara *et al.* 2009).

Behavioural development has been investigated for calves and juveniles in the Eastern Gulf (Krzyszczyk *et al.* 2017). Female dolphins are observed to continually improve in foraging performance well beyond physical and sexual maturity (Patterson *et al.* 2016).

Innovation in relation to dolphins (including those from Eastern Gulf) is defined by Sargeant and Mann (2007), who discuss approaches for distinguishing innovative behaviours. Innovative and creative behaviours in Shark Bay dolphins has also been discussed in relation to the influence of sexual and natural selection on these behaviours (Patterson and Mann 2015).

Behavioural patterns of dolphins have been examined in relation to past aquaculture activity in Shark Bay and dolphins were found to avoid or minimise their time spent in these areas (Mann and Janik 1999; Kemper *et al.* 2003; Watson-Capps and Mann 2005). A systematic evaluation of the effects of entanglement on dolphin behaviour is provided by Miketa *et al.* (2017).

The frequency and timing of consortships by male dolphins is indicative of female attractiveness, and evidence suggests males are more attracted to a female when her calf is a couple of years old or shortly after she has lost an infant (Connor *et al.* 1996).

Other studies on sexual behaviour have shown that males alter females behavioural ecology through sexual coercion (Wallen *et al.* 2016), and that 'mounting' is more common in male-male interactions and 'goosing' (rostrum to genital contact) is more often directed toward females (Furuichi *et al.* 2013).

Age and sex-specific patterns of aggression were documented through long-term behavioural studies and analysis of tooth rake marks in male and female bottlenose dolphins (Scott *et al.* 2005). Aggression between males, tooth rake marks and alliance behaviour is also found to vary spatially (Hamilton *et al.* 2019). Lee *et al.* (2019) has constructed a demographic profile of injury risk and examined the healing time of tooth rake injuries.

In order to better understand behavioural responses of bottlenose dolphins, activity budgets were estimated for 55 female dolphins in the Eastern Gulf, and focal follows were more reliable in estimating individual level budgets than surveys (Karniski *et al.* 2015).

3.5.6.2.4.1 Male social behaviour

A sizeable body of research has focused on Monkey Mia male dolphin alliances in the Eastern Gulf.

Connor and Krützen (2015) review 30 years of dolphin male alliance research including fission-fusion dynamics and alliance stability.

Three levels of alliance exist: 2-3 males in a first order alliance cooperate to consort females; four or more males in a second order cooperate to defend or steal females from other groups (Connor *et al.* 1992a; Connor *et al.* 1992b); and two or more second order alliances can team up occasionally to form a third order alliance (Connor *et al.* 2011). Super alliances have also been identified whereby second order alliances can include as many as 14 males (Connor *et al.* 1999; Connor *et al.* 2001). Shark Bay alliances have helped to develop a general model of alliance size (Whitehead and Connor 2005).

Alliance stability can change across seasons and years (Connor and Smolker 1995; Connor and Mann 2006), and alliance structure can even change with habitat within Shark Bay (Connor *et al.* 2017).

Alliance relationships are complex and they support the ecological theory of extreme brain size evolution in mammals (Connor and Krützen 2003; Connor 2004; Connor and Whitehead 2005; Connor 2007; Randić 2008; Connor 2010; Randić *et al.* 2012). Male consortships have also been compared with that of chimpanzees in a study on social organisation (Connor and Vollmer 2009).

Some of the observed behaviours of male affiliations include synchronous surfacing and social behaviour (Connor *et al.* 2006b). Males also keep their own vocal labels, which could play a role in recognising partners and competitors (King *et al.* 2018).

The relationship between male alliance membership and their reproductive success has been assessed (Krützen *et al.* 2004a), as well as how social bonds among peers and kinship influence the evolution and maintenance of male alliance formation (Krützen *et al.* 2003; Gerber *et al.* 2019).

3.5.6.2.4.2 Female social behaviour

Research on female dolphin relationships has been carried out in the Eastern Gulf on Monkey Mia dolphins.

Factors such as home ranges and degree of relatedness were examined to determine whether they drive associations between female dolphins (Frère *et al.* 2010c). 'Contact swimming' is most often observed for female dolphins rather than males, which may be a signal of cooperation between females (Connor *et al*. 2006a).

Connor *et al.* (2005) presents a theoretical model of alliance formation for female (and male) dolphins based on rates that individuals interact in competition for resources. While female and males may form temporary associations, long term and more stable associations typically occur between same sex members, and females tended to have looser associations than males (Smolker *et al*. 1992).

Several studies have also focused on the relationships between mothers and calves, including social patterns and behavioural development (Mann 1997; Mann and Smuts 1999; Mann and Sargeant 2003; Mann *et al.* 2007; Gibson and Mann 2008; Stanto *et al.* 2011).

Behaviours have been assessed for an infant-mother pair prior to and following entanglement of the calf (Mann *et al.* 1995), as well as a mother's behaviour with a deceased calf (Connor and Smolker 1990).

Variables that can predict calf mortality, such as swimming in infant position (in contact under the mother), were identified during the first 12 months of life based on the behavioural ecology of calves and their mothers (Mann and Watson-Capps 2005). Mothers have also been observed to change their diving behaviour more often around female calves than male calves (Miketa *et al.* 2018).

3.5.6.2.5 Foraging ecology

Several studies have investigated foraging techniques and behaviours by bottlenose dolphins in the Eastern Gulf. Dolphins have displayed 'fish-whacking' which involves hitting fish with flukes to stun them during feeding (Smolker and Richards 1988). Dolphins also use fluke slaps to scare fish hiding in seagrass; a behaviour termed 'kerplunking' (Connor *et al.* 2000b). Sargeant *et al.* (2005) examines the ecological, social and developmental factors relating to the rare foraging tactic of "Beach hunting". Environmental heterogeneity is shown to be of importance in creating foraging diversity, and should be considered in studies of social learning (Sargeant *et al.* 2006).

Bottlenose dolphins are found to occupy a different isotopic/feeding niche to large sharks (incl. tiger sharks), as well as to smaller sharks and rays (Heithaus *et al.* 2013).

3.5.6.2.5.1 Tool use

Tool use is a foraging strategy of bottlenose dolphins and has been observed for dolphins in both the Eastern and Western Gulfs. The first description of sponging (dolphins carrying sponges on their rostrums) was given by Smolker *et al.* (1997) for the Eastern Gulf. Sponging is used during foraging and is believed to provide protection of the rostrum during benthic foraging activities. Sponging females display different behaviours to non-sponging females, such as diving for longer durations, foraging more often and spending more time alone (Mann *et al.* 2008).

Mitochondrial DNA analyses have been used to show that sponging is passed down within a single matriline, in what is known as cultural transmission (Krützen *et al.* 2005). Sponge foraging dolphins have exploited an empty niche (Patterson and Mann 2011; Krützen *et al*. 2014), and a social network analysis has been used to determine if spongers are culturally distinct from others in the population (Mann *et al.* 2012). An overall description of tool use and lifelong learning of tool use is given by Patterson (2012).

In the Western Gulf, sponging also occurs in females and is transmitted down through generations (Bacher 2008; Kopps *et al.* 2014b). Social transmission directly from mother to offspring is thought to drive sponge use (Wild *et al*. 2019a). There is evidence that this behaviour has influenced fine-scale genetic structure (Kopps *et al.* 2014a), though Bacher *et al.* (2010) provides evidence that mitochondrial gene variation is unlikely to be a viable alternative to cultural transmission when it comes to tool use. A recent discovery has found that males also exhibit sponge use and that it is a homophilous behaviour, whereby similar behaviour increases associations (Bizzozzero *et al*. 2019).

For both the Eastern and Western Gulfs, fatty acid signatures were used to show differences in diet between dolphin spongers and non-spongers (Krützen *et al.* 2014). The conditions under which sponging could be established and maintained is described by Kopps and Sherwin (2012). Given sponges are used as tools by dolphins, the ecological factors influencing the distribution of live sponge habitat and the occurrence of sponging has been investigated for Shark Bay (Tyne 2008; Tyne *et al.* 2010; Tyne *et al.* 2012).

Besides sponging, dolphins also engage in a rare behaviour known as 'conching' in both the Eastern and Western Gulfs, where dolphins carry conch shells on their rostrums (Allen *et al.* 2011). In the particular occurrences observed by Allen *et al.* (2011), fish were photographed inside the conch shell, indicating it could be another foraging tactic.

3.5.6.2.6 Marine heatwave

A comparison of bottlenose dolphin densities from pre (1997-2010) and post (2012-2014) seagrass die-off revealed a decrease in densities of close to 40% in the Eastern Gulf (Nowicki *et al.* 2019). Bottlenose dolphins in the Eastern Gulf were found to increase their use of seagrass habitats for foraging after the 2011 marine heat wave despite the decrease in seagrass extent and density (Miketa 2018; Nowicki *et al.* 2019).

As yet, calving rates following the 2011 marine heatwave do not appear to be affected in the Eastern Gulf (Miketa 2018). Conversely, in the Western Gulf, a significant decline in female reproductive rates was observed for resident bottlenose dolphins (Wild *et al.* 2019b).

3.5.6.2.7 Ecotourism and Monkey Mia provisioned dolphins

The provisioned dolphins at Monkey Mia are a popular tourist attraction, and the regularity and reliability of their visits have allowed for studies on their welfare and behaviour.

An early description of the habituated dolphins, their behaviours, and the potential for Monkey Mia to be a significant research site is given by Connor and Smolker (1985) and Edwards (1987).

Provisioned individuals are fed up to 1.5 kg of fish per day, and a study in the early 2000s found dolphins did not appear to strongly prefer certain species, sizes or states of fish (freshly caught or previously frozen) (Dill *et al.* 2003a).

Some of the past behavioural changes observed for provisioned mother/calf pairs included a decline in the number of associations and time spent socialising (Mann 2006a).

The survivorship of calves born to provisioned females has shown an increase over time, however, behavioural development continues to be affected (Foroughirad and Mann 2013).

Over the years that provisioning has occurred at Monkey Mia, researchers have reviewed and suggested a number of management strategies to minimise the effects of provisioning of dolphins (Wilson 1996; Higham and Bejder 2008), such as on maternal care and reducing the incidence of risky interactions with humans (Mann and Kemps 2003; Smith *et al.* 2008).

Dolphin watching vessels operate in Shark Bay, and there is evidence to suggest that dolphin abundance declines when two vessels are operating, as opposed to one or none (Bejder *et al.* 2006b). Short- term behavioural changes have also been observed during experimental vessel approaches (Bejder *et al.* 2006a).

Given human-dolphin interactions have been occurring at Shark Bay since the 1960s, it has often been included as a case study when examining the wider impacts of these interactions on the dolphins (Samuels *et al.* 2003; Bejder 2005; Mann *et al.* 2018). A guide has also been produced to assist researchers in their decision making when embarking on ecotourism research (Bejder and Samuels 2003).

3.5.6.3 Whales

3.5.6.3.1 Humpback whales

Humpback whales migrate past Shark Bay each year during their journey from feeding grounds in the Antarctic to tropical breeding grounds along the northwest of Australia. While there has been extensive research on this population, little of it has been focused on Shark Bay specifically.

Early works by Chittleborough have improved knowledge on reproduction of males and females (Chittleborough 1954; Chittleborough 1955a; Chittleborough 1955b; Chittleborough 1958b), age and growth (Chittleborough 1959a), population overlap (Chittleborough 1959b), stock sizes and population dynamics from commercial whaling catches (Chittleborough 1957; Chittleborough 1958a; Chittleborough 1960; Chittleborough 1962; Chittleborough 1963; Chittleborough 1965).

Building on this historical work with additional survey data, estimates of population size for the migrating west coast population of humpbacks has been refined and updated across time (Bannister and Hedley 2001; Hedley *et al*. 2011a; Hedley *et al.* 2011b; Paxton *et al.* 2011b; Salgado Kent *et al*. 2012). Temporal and spatial movements of humpback whales have been determined from historical whaling records and more recent aerial and boat based surveys, and Shark Bay is noted as an important location for whales during migration (Jenner *et al.* 2001).

Burton (2001) undertook aerial surveys at Shark Bay and found an increase in numbers in the Bay compared to previous records and also provided geographical distribution patterns.

A series of aerial surveys were conducted off Shark Bay between 1976-1999 (Bannister and Hedley 2001) and again in 2005 (Paxton *et al.* 2011a) to determine whether population size was increasing.

The most probable depth for humpback whale presence off Shark Bay was modelled to be 90 m (Paxton *et al.* 2011a).

3.5.6.3.2 Other whales

The presence of killer whales east of Dirk Hartog Island has been investigated in relation to dugong predation (Anderson and Robert 1985).

A stranded dead Shepherd's beaked whale was found on a beach in Shark Bay in 2008 and represents the northernmost record for this species, which is relatively data poor compared to other whale species (Holyoake *et al.* 2013).

3.6 Commercially fished species

3.6.1 Scalefish

Stock assessments have been carried out for key indicator stocks of demersal scalefish from the Gascoyne Coast Bioregion.

Levels of fishing for pink snapper, goldband snapper and South Gascoyne stocks of spangled emperor were found to be acceptable whilst North Gascoyne stocks of spangled emperor were subjected to unacceptable levels of fishing (Marriott *et al.* 2012).

The tailor (*Pomamtomus saltatrix*) stock has also been assessed, which overlaps the Gascoyne Coast and West Coast Bioregions, and in 2013 the stock was considered to have a low risk for sustainability due to having low inherent vulnerability, a relatively high spawning stock and an increasing trend of recruitment since 2004 (Smith *et al.* 2013).

Stock structure has been examined for two demersal teleosts, red emperor (*Lutjanus sebae*) and rankin cod (*Epinephelis multinotatus*), and for tailor through analysing stable isotopes of otoliths from specimens collected at different locations along WA, including Shark Bay (Edmonds *et al.* 1999; Stephenson *et al*. 2001).

Whiting (mostly *Sillago schomburgkii*) are an important component of the catch taken by the Shark Bay Beach Seine and Mesh Net Managed Fishery which has operated since the 1930s (Lenanton 1978; Gaughan and Santoro 2019). Early work has detailed a suite of aspects of the whiting fishery, including historical records, different species fished, distribution, seasonality, gear effectiveness, and research programs (Lenanton 1969). The general biology of whiting, including diet has also been examined (Lenanton 1970). More recent work has examined the biology of two co-occurring whiting species from different locations in Shark Bay, including otoliths and aging, growth differences and environmental influences (Coulson *et al.* 2005).

Specimens of the tarwhine, *Rhabdosargus sarba*, have been collected from Shark Bay and compared with those from Perth coastal waters and the Swan River. Comparisons were made for reproductive biology and hermaphroditism (Hesp and Potter 2003), the range of habitat types occupied, and to test the hypothesis that growth would be more rapid in the Swan River than Shark Bay or coastal Perth waters due to the higher productivity of an estuary system (Hesp *et al.* 2004a).

Similar biological studies have also been carried out for several *Choerodon* species in Shark Bay, where protogynous hermaphroditism, patterns of growth, maturity, and the habitats occupied by each species has been investigated (Fairclough 2005; Fairclough *et al.* 2008).

Other single species studies for Shark Bay have examined biological characteristics of the grass emperor (*Lethrinus laticaudis*), such as stock delineation, age, growth rate and reproductive biology to help inform a stock assessment model for the inner gulfs (Ayvazian *et al.* 2004).

The gonads of the yellowfin bream, *Acanthopagrus latus*, from across different age ranges and seasons has been examined to confirm the species was a protandrous hermaphrodite (Hesp *et al.* 2004b).

Spanish mackerel (*Scomberomorus commerson*) from Shark Bay, Abrolhos, Exmouth and Onslow are thought to originate from the same stock given the presence of permanent parasites in examined individuals (Lester *et al.* 2001).

3.6.2 Pink snapper

Pink snapper (*Chrysophrys auratus*) has been one of the most studied species in Shark Bay and many aspects of their general biology are reasonably well understood.

The population biology of pink snapper has been investigated in order to determine the cause of observed size differences of 0+ fish in the north and south portions of the Western Gulf (Tapp 2003).

The distribution and abundance of juvenile pink snapper and environmental influences on their distribution has been evaluated (Jackson *et al.* 2007).

The population structure, growth, reproduction and biomass estimates of different stocks of pink snapper has been examined from both the Western and Eastern Gulfs (Jackson *et al.* 2007).

Life history characteristics are also found to vary at small spatial scales, less than tens of kilometres (Jackson *et al.* 2010).

Parasites have also been examined from pink snapper caught in the late 1980s, where the prevalence of trematode parasites was 5.4% and found to most frequently infect 5-8 year old snapper (Williams *et al.* 1993).

3.6.2.1 Reproductive biology

Egg production through to sexual dimorphism in adults has been examined for pink snapper.

The daily egg production method involves the collection of eggs in plankton surveys to estimate spawning biomass, and this method has been evaluated for its application and effectiveness across time (Jackson and Cheng 2001; Norriss *et al.* 2006; Jackson *et al.* 2012).

A combination of data collection and numerical modelling in examining the dispersal of pink snapper eggs and larvae have supported the existence of discrete spawning populations in Shark Bay (Nahas *et al.* 2003).

A descriptive key to identifying 19 developmental stages of preserved pink snapper eggs has also been produced to help inform investigations on reproductive biology (Norriss and Jackson 2002).

Mackie (2009) developed a macroscopic and microscopic staging system for pink snapper gonads and female spawning activity in order to improve accuracy of fecundity estimates.

As adults, pink snapper exhibit sexual dimorphism where males develop a prominent hump on the head to a greater extent than seen in females (Moran *et al.* 1999).

3.6.2.2 Stock structure

Stock structure of pink snapper has been examined using stable isotopes, genetics and tagging, all of which provide evidence for separate stocks of pink snapper within Shark Bay.

Stable isotopic analyses from otoliths have revealed snapper are location specific within Shark Bay (Bastow *et al.* 2002), as well along the WA coast (Edmonds *et al.* 1999), and that the hypersaline waters of Shark Bay generate distinctive isotopic signatures. Analysis of stable isotopes has been combined with microchemical data to discriminate fish stocks and gain information on pink snapper nursery areas (Gaughan *et al.* 2002). Otoliths of pink snapper have also been analysed for concentrations of trace elements, which showed that concentrations were specific to the location of capture along the WA coast, including Shark Bay (Edmonds *et al*. 1989).

The first genetic study on pink snapper in Shark Bay supported the suggestion of separate breeding populations within the Bay (Johnson *et al.* 1986). Subsequent genetic studies have also identified a complex stock structure within the Bay (Whitaker and Johnson 1998), and in comparison to surrounding central coast waters (Gardner *et al.* 2017). Within the Eastern Gulf specifically, no evidence was found to suggest the presence of more than one genetic stock (Baudains 1999).

Around the same time genetics were being used to distinguish stocks, tagging was also being used to confirm the presence of separate pink snapper stocks within Shark Bay (Moran 1987). An assessment of the recapture of pink snapper tagged between 1982-1984 showed that a small number of snapper still used the area 15 years after tag and release and that, overall, data showed no mixing of snapper populations between the inner gulfs or between the ocean and inner gulfs (Moran *et al*. 2003). In another follow up assessment of this tagging data and more recent tagging efforts between 1990-2003, movement from tagging sites was highly restricted, particularly for juveniles and the data supported three management zones within Shark Bay (Norriss *et al.* 2012).

3.6.2.3 Fishing methods and management

Hand lines were primarily used to catch pink snapper in the Shark Bay region leading up to 1959 (Bowen 1961). Snapper traps were then trialled in 1959 and 1960. Due to potential negative effects of traps on snapper and their habitat, traps were removed from the fishery from the early 1960s, completely out by 1987. The effects of fish trapping on the fishery was investigated by Moran and Jenke (1989).

Pink snapper stocks inside Shark Bay were shown to be overfished in the late 1990s due to pressure mostly from recreational fishing. Different management approaches were used to manage recreational fishing from 1997-2003 (Jackson *et al.* 2005).

The fishery has also been compared with the contrasting management strategies used for the recreational fishery of the closely related sea bream in Sagami Bay, Japan (Mitchell *et al.* 2008).

Research and management strategies for the recreational snapper fishery in Shark Bay were summarised for 15+ years by Jackson and Moran (2012), and decreases in fishing effort were observed as a consequence of management measures (Wise *et al.* 2012).

One significant and successful management strategy included the implementation of a harvest tag system in 2003 which limited the number of harvest tags available each year (Jackson *et al.* 2016). Fortunately, a combination of effective biological research and robust management of the snapper fishery has led to the recovery of the recreationally important stock (Christensen and Jackson 2014).

Given the recovery, a code of conduct for recreational fishers in Shark Bay was released with the purpose of promoting sustainable practices and responsible fishing to minimise impact and prevent another decline (Recfishwest 2018).

Given the importance of pink snapper as a recreational and commercial species, the management, and research used to improve management, continues to be reviewed over time (Jackson 2000; Jackson *et al*. 2002; Moran and Kangas 2003; Moran *et al.* 2005). This has included investigating the impacts of trawl fishing on juvenile snapper and modelling the different trajectories of mature biomass and setting a total allowable catch as a management strategy (Stephenson and Jackson 2005). The fishery has also been used as a case study for how to manage snapper during the spawning season in Shark Bay (Jackson 2012).

3.6.3 Blue swimmer crabs

Stock allocation and assessment techniques were developed for blue swimmer crab (*Portunus armatus*) stocks in WA, including Shark Bay (Bellchambers *et al.* 2005), and a summary of the biology, stock status and management of blue swimmer crabs (up to 2009) is given by Harris *et al.* (2012; 2014).

Stock rebuilding of the Shark Bay Crab Fishery and development of a preliminary harvest strategy was informed by new biological data on blue swimmer crabs in Shark Bay, including growth, spawning periodicity, and fishery independent measures of recruitment and spawning biomass (Chandrapavan 2018; Chandrapavan *et al.* 2018). Understanding the influence of water temperature and marine heatwaves on the fishery will also increase understanding for future planning and management, such as identifying that juvenile blue swimmer crabs are most susceptible to heat stress when temperatures are above 24°C during December and January (Chandrapavan *et al.* 2019a).

3.6.4 Prawns

An early history of the Shark Bay Prawn Fishery, including the development of the fishery and management, is given by Slack-Smith (1978).

The fishery, fishing practices, science and management has been compared with the co-management of Exmouth Gulf prawn fishery in order to determine the best practices moving forward (Kangas *et al*. 2008).

The spawning-recruitment relationships for king (*Penaeus latisulcatus*) and tiger prawns (*Penaeus esculentus*) of Shark Bay is important for predicting future catches, and consideration should be given to the need for timely collection of stock and recruitment indices data, an understanding of the environmental effects on recruitment and the effects of fishing effort on the spawning stock (Caputi 1993; Caputi *et al.* 1998).

Stock recruitment relationships for the tiger prawn were assessed following a 50% decline in the Shark Bay fishery in the 1980s due to recruitment overfishing (Penn *et al*. 1995).

A spatial model of the brown tiger prawn fishery was developed to enable a description of the fishery in line with the current management strategies, improve time series of recruitment indices and to estimate proportions of prawns migrating between regions (Hall and Watson 2000).

For the western king prawn a difference in the duration of spawning seasons is observed for locations along the WA coastline, including Shark Bay, which has been attributed to temperature effects on ovary development (Penn 1980).

The migration of western king prawns from offshore spawning grounds to inshore nursery grounds in Shark Bay was found to be influenced by nocturnal tidal flow and reduced flow with increasing depth interacting with vertical movements of the larvae (Penn 1975).

Daily logbooks have been used in the modelling of commercial prawn catch and effort data (Craine *et al.* 2005). This commercial catch and effort data together with independent catch and effort data has been used in geostatistical modelling to help improve management of the Shark Bay Prawn Fishery (Mueller *et al.* 2008a; Mueller *et al.* 2008c).

To better inform catch predictions of prawns, fishery independent survey indices have been compared with annual landing relationships (Caputi *et al.* 2014a).

3.6.5 Scallops

3.6.5.1 Spawning and recruitment

The life history of the saucer scallop (*Ylistrum balloti*) has been investigated at three sites along the Western Australian coastline, including Shark Bay, and spawning was found to begin shortly after gonads commenced rapid weight gain following a lunar cycle (Joll and Caputi 1995a).

The strength of scallop recruitment was also found to be significantly correlated with the Leeuwin Current during the spawning season (Joll and Caputi 1995b).

The spawning-recruitment relationships for the Shark Bay Scallop Fishery is reviewed by Caputi *et al.* (1998) which recommended a need to further understand the environmental effects on recruitment. One such effect is the Shark Bay Outflow where the outflow of high salinity waters from Shark Bay to the continental shelf via deep channels could be flushing larvae out of the Bay (Hetzel *et al.* 2010).

Environmental factors have been investigated in relation to the variation in recruitment of scallops along WA, including Shark Bay, and whether or not assisted recovery measures can improve management in a changing environment (Chandrapavan *et al.* 2019b).

3.6.5.2 Management and fishing effort

A summary of the biology, stock status and management of saucer scallops (up to 2009) is given by Kangas *et al.* (2011).

Implementation of the Carnarvon Peron line in 1991 to prevent overharvesting of small-sized tiger prawns was evaluated in relation to spatial fishing effort distribution, and levels of effort for scallop fleets were considered in an attempt to minimise gear conflict and resource sharing issues (Kangas *et al.* 2012).

Experimental trials were conducted to determine repeat discard mortality rates of scallops (Chandrapavan *et al*. 2012b), and the best size for square mesh cod ends in order to improve selectivity of nets (Chandrapavan *et al.* 2012a).

To better predict scallop catches, fishery independent survey indices have been compared with annual landing relationships (Caputi *et al*. 2014a).

Catch predictions, resource sharing and management of scallops has also been improved through the use of geostatistical modelling (Mueller *et al.* 2005; Mueller *et al.* 2007; Mueller *et al.* 2008b; Mueller *et al*. 2008c; Mueller *et al.* 2012), which has most recently been suggested as a useful tool for 'hot spot' analyses to further improve management and catch predictions (Mueller *et al.* 2018).

3.6.6 Cockles

The Shark Bay Developmental Cockle Fishery is a relatively new fishery and coming to the end of a second three-year exemption to develop the fishery (WAFIC 2018). The fishery targets venus shell clams, such as *Gomphina undulosa* and *Callista impar*, which are currently sold to a handful of commercial establishments. The fishery has had to undergo regular Department of Health water testing to meet Quality Assurance Standards.

3.6.7 Aquaculture

The sheltered nature of Shark Bay and the relatively low levels of pollutants from urban and industrial development allow for ideal aquaculture conditions. A map of current aquaculture sites is shown in Fig. 14.

The species currently cultured include the blacklip oyster (*Pinctada margaritifera*), wing oyster (*Pteria penguin*), rock oysters (*Saccostrea glomerata*, *Saccostrea cucullata*, *Saccostrea scyphophilla*), Akoya pearl oyster (*Pinctada fucata*), Shark Bay pearl oyster (*Pinctada albina*), endemic Veneridae clams/cockles (*Callista inpar*, *Gomphina undulosa*, *Callista planatella*, *Antigona lamellaris*, *Circe rivularis*, *Circe sulcate*, *Paphia crassisulca*, *Paphia semirugata*, *Pitar nancyae*), and a variety of sponges from the families Spongidae, Irinildae, Thorectidae, Hymedesmiliidae, Latrunculliidae, Mycalidae and Raspailiidae (DoF 2004; Pan Holdings Pty Ltd 2017; Gaughan and Santoro 2019).

Trials are currently underway for the culture of native rock oyster species, *Saccostrea cucullata* and *Saccostrea scyphophilla* along the Wooramel Coast (Harvest Road Export Pty Ltd 2018).

Trials have previously occurred for an onshore pink snapper hatchery (DoF 2004).

A suite of species are considered as potential candidates for aquaculture in the conditions of Shark Bay, including finfish, aquarium fishes and marine invertebrates, but development of these cultures will depend on technological advances and market value (DoF 2004).

Diseases and parasites have been studied for a range of mollusc culture farms off Western Australia, including scallops off Shark Bay (Lester *et al*. 1980; Jones and Creeper 2006).

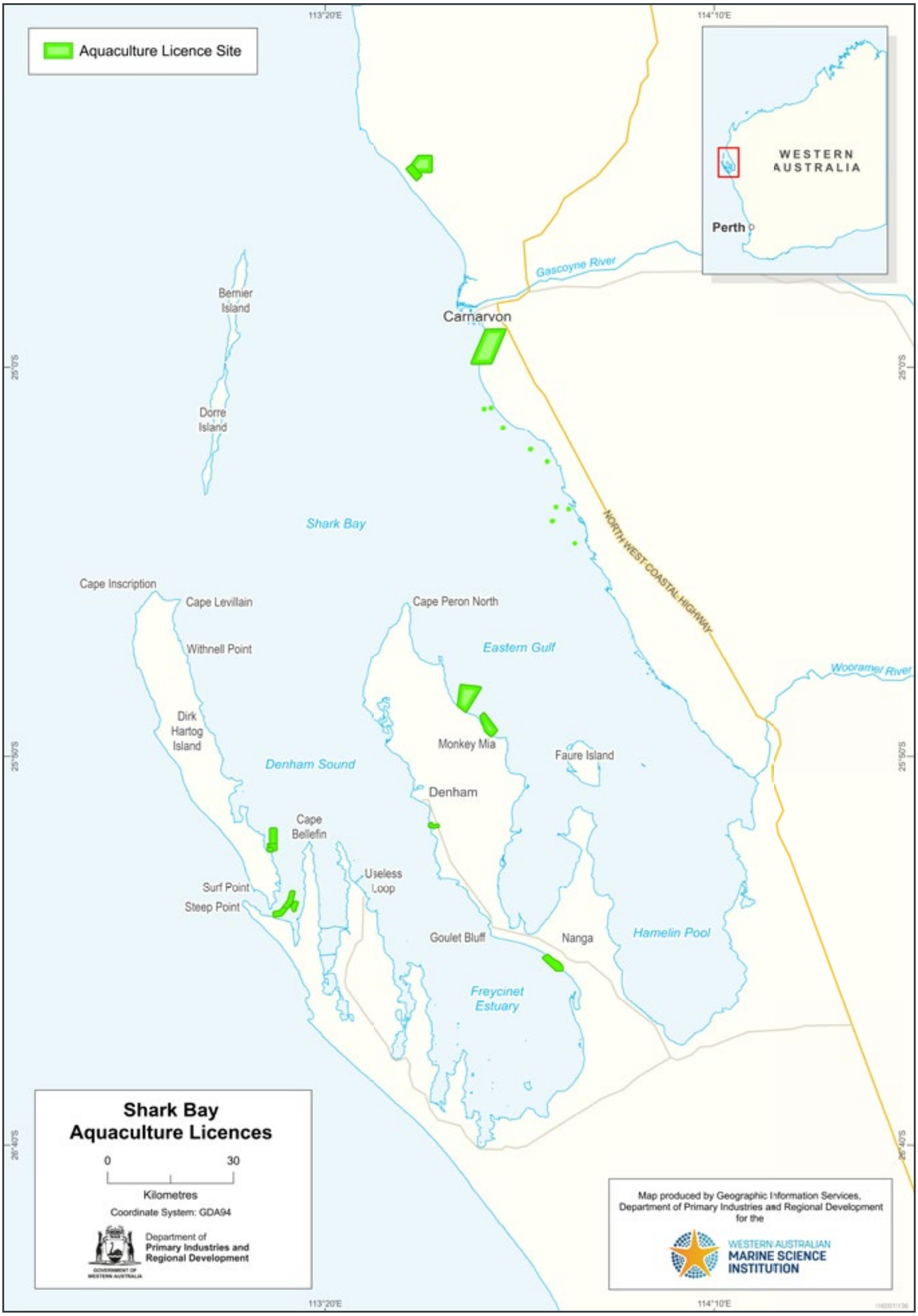


Figure 14 Current aquaculture licence sites in Shark Bay.

3.6.8 Environmental influences on fisheries

The waters off the coast of WA are considered relatively nutrient poor due to the presence of the dominant Leeuwin Current. Conditions are suited to supporting high value invertebrate fisheries more so than highly productive finfish fisheries as observed for other boundary current systems (Lenanton *et al.* 1991).

The Leeuwin Current transports tropical waters southwards, and across the summer months of 2010/11, anomalously warmer waters were carried south causing a marine heatwave that impacted 2000km of the WA coastline. This caused short and long-term impacts on fisheries within Shark Bay (Caputi *et al.* 2014b), including fish and invertebrate deaths and variations in recruitment, growth rates and catch rates (Pearce *et al.* 2011).

Scallop recruitment is typically lower when water temperatures are higher in strong Leeuwin Current years (Joll and Caputi 1995b; Lenanton *et al.* 2009a), thus the 2011 marine heatwave caused record low recruitment during 2011-2013, resulting in a closure of the fishery 2012-2014 (Caputi *et al.* 2019). Improvements were seen for scallop recruitment when cooler water temperatures returned in 2014.

Catch rates of blue swimmer crabs in Shark Bay decreased to 2% of the pre-heatwave abundance and the fishery was closed between April 2012 and October 2013 (Caputi *et al.* 2019).

The availability of time series data in assessing the impacts of the 2011 marine heatwave on fish stocks has been valuable in indicating future management responses in the face of more frequent marine heatwaves (Caputi *et al.* 2016). Following the 2011 marine heatwave, assessments of future climate effects on Western Australia's marine environment were made utilising multiple IPCC model predictions tailored to specific regions and relevant spatial and temporal scales, including for Shark Bay (Caputi *et al.* 2015).

Given the known examples in Shark Bay of scallop recruitment being negatively correlated and western king prawn catches being positively correlated with the strength of the Leeuwin Current (Joll and Caputi 1995b; Caputi *et al.* 1996; Lenanton *et al.* 2009a), fisheries-dependant data has been assessed for its effectiveness in detecting changes in the distribution and relative abundance of species in the face of climate change (Caputi *et al.* 2010).

Overall, climate change stressors such as increasing sea surface temperature, changes to the Leeuwin Current, rising sea levels and ocean acidification can impact upon fisheries and the functioning ecosystem in Shark Bay through affecting spawning and recruitment, range and distribution, community compositions and interactions, productivity and the establishment of introduced species (Gaughan and Santoro 2019).

3.6.9 Fishing method impacts

Trawling for scallops and prawns in Shark Bay started in the early 1960s and the practice has been assessed to determine the impact on soft bottom communities and fishes.

Trawling was found to have bycatch implications for fish species at different age and growth stages, such as observed for juvenile snapper and butterfish (Mant *et al.* 2006; Wakefield *et al.* 2007).

The impacts of trawling on fish and invertebrate abundance and diversity in Shark Bay has not previously been considered a significant issue, and environmental conditions are considered to have more of an influence on differences in faunal assemblages than trawl intensity (Kangas *et al.* 2006b; Kangas and Morrison 2013). Despite this, Shark Bay has recently been listed as a location that has a potential (not confirmed) risk to habitat due to high exposure and low protection from trawling, and may warrant further ecological risk assessments (Pitcher *et al.* 2019). Findings by Mazor *et al.* (2017) concurred with Shark Bay having a high exposure to trawling, but found the extensive spatial and temporal closures were enough to counteract the high exposure.

Currently, trawling is largely taking place over sand/shell habitat in the central bay, north Cape Peron and in northern areas of Denham Sound (Gaughan and Santoro 2019) (Fig. 18 and 19).

Experimental trials have compared the effectiveness of different square mesh panels and grid types in reducing trawl bycatch while retaining targeted species (Broadhurst *et al.* 2002; Kangas and Thomson 2004). Scientific observer programs have been trialled on commercial trawl fleets to monitor bycatch reduction device effectiveness (Kangas and Thomson 2004). Bycatch reduction devices are mandated in the Shark Bay trawl fishery.

Bycatch of listed species is required to be recorded in daily log books (Gaughan and Santoro 2019). Sea snakes are most commonly captured in prawn trawlers and the majority are said to be returned to the water alive. Turtles and elasmobranchs were occasionally captured in prawn trawl nets but this has reduced significantly with the implementation of bycatch reduction devices in the early 2000s.
Class A vessels for scallop trawls typically have low incidence of protected species bycatch due to legislated mesh sizes and short duration of trawls. Hourglass traps are used in the Shark Bay Crab Managed Fishery which minimises the catch of protected species to negligible levels. The use of line fishing in the Gascoyne Demersal Scalefish Managed Fishery is considered to be highly selective and of negligible risk to protected species.
Interactions with protected species from beach seine netting is also considered negligible as protected species, such as dugongs, turtles or dolphins are immediately released if accidentally captured.

3.6.10 Recreational fishing

Recreational fishing in Shark Bay targets the Shark Bay Blue Swimmer Crab Resource, Gascoyne Demersal Scalefish Resource, and Gascoyne Inner Shark Bay Scalefish Resource, and includes both shore-based and boat-based fishing activity (Fig. 15).

Targeted species include blue swimmer crab, pink snapper, goldband snapper, other tropical snappers, emperors, mulloway, trevallies, mackerel, blackspot tuskfish, goldspotted rockcod, other cods and western butterfish (Taylor *et al.* 2018; Gaughan and Santoro 2019).

Recreational boat based fishing at Shark Bay has been included in three WA statewide surveys to estimate effort and catch for all fished species (2011/12, 2013/14 and 2015/16) (Ryan *et al.* 2013; Ryan *et al.* 2015; Ryan *et al.* 2017). These three surveys have also provided an opportunity to determine the average weight of key species (from 27,000 measured specimens) in order to convert recreational catch estimates to harvested weight and inform accurate weight length data for key species (Smallwood *et al.* 2017).

For the Shark Bay region, aerial surveys have collected data on the spatial distribution of recreational fishers to estimate fishing effort around Carnarvon and Shark Bay (Smallwood and Gaughan 2013).

The Eastern Gulf, Denham Sound and Freycinet Estuary have been major attractions for recreational fishers since the 1960s (Shaw 2000; Jackson and Moran 2012; Wise *et al.* 2012).

Figure 15 Boat-based and shore-based recreational fishing activity in Shark Bay.

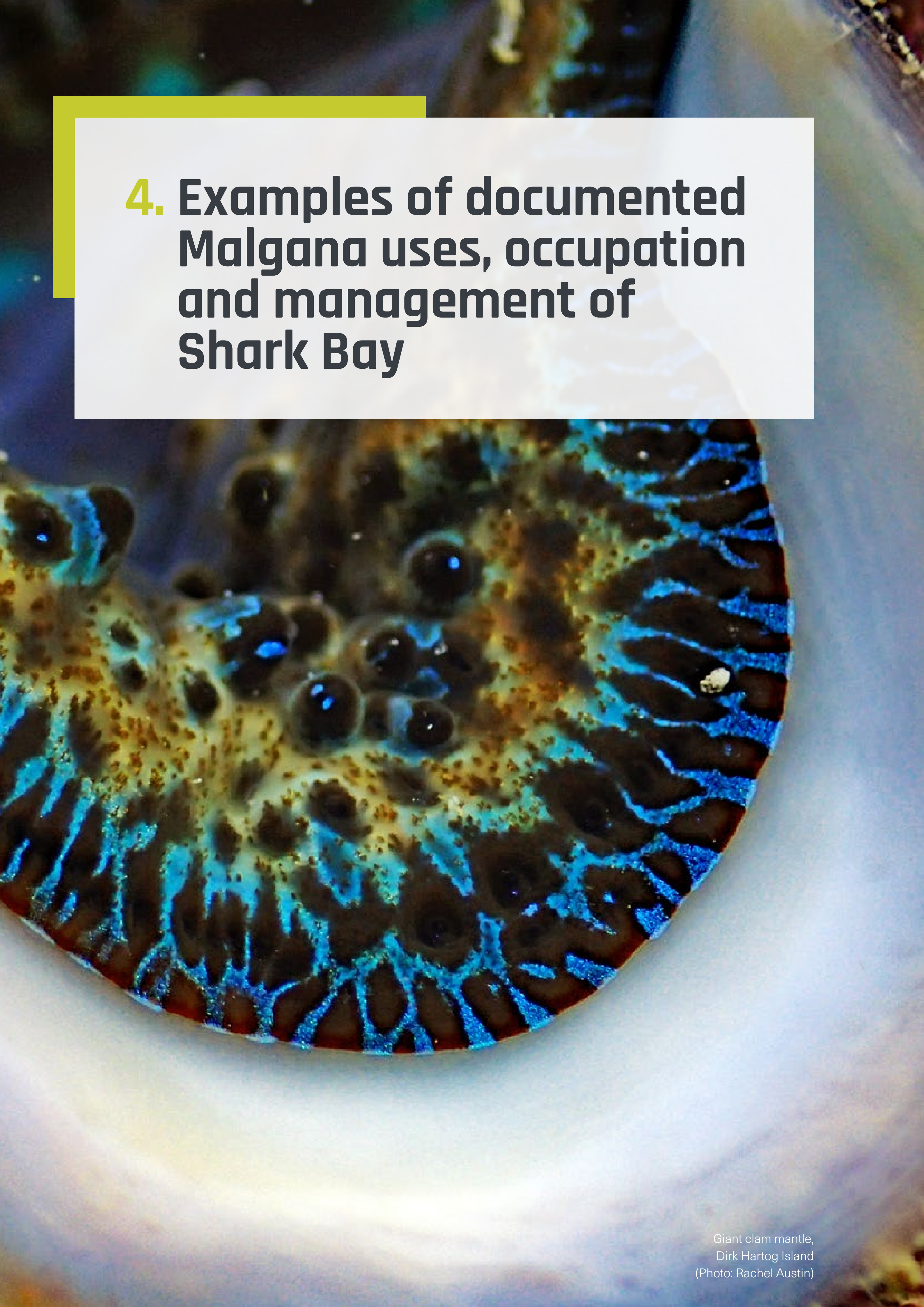
Figure 16 Pink Snapper Recreational Fishing Management Areas in Shark Bay.

Recreational boat-based fishers have been interviewed at boat ramps to gain a better understanding of fishing effort, catches, targeted species and popular fishing locations, which revealed pink snapper as the most popular catch and Freycinet Estuary as one of the most favoured locations (Sumner and Malseed 2001) (Fig. 15 and 16).

The recreational harvest of pink snapper and other snapper species was further estimated in order to determine how fishing effort changed with introduced management strategies (Sumner and Malseed 2002). More recently, updated estimates were derived for the annual recreational catch of pink snapper by boat-based fishers in the Denham, Monkey Mia and Nanga regions to determine the impact of removing management strategies in 2016 (Taylor *et al.* 2018).

Stromatolites at Carbla
(Photo: Gary Warner, DBCA)

4. Examples of documented Malgana uses, occupation and management of Shark Bay



Giant clam mantle,
Dirk Hartog Island
(Photo: Rachel Austin)

Indigenous values encompass a suite of natural, cultural, social, historical, language, livelihood and ecological values, and there is a wealth of knowledge from millennia of living in the Shark Bay environment that can greatly inform western knowledge.

Past research practices have not been formally structured to include and/or recognise Indigenous participation, traditional ecological knowledge or acknowledgement in written publications. Therefore, this section on Indigenous interests is by no means comprehensive. WAMSI acknowledges this gap in knowledge and together with the Malgana Traditional Owners, the Institution hopes to address this in the WAMSI Shark Bay Science Plan.

Malgana are the main focus in this section of the synthesis given their native title includes the immediate Shark Bay area and they are recognised as the first inhabitants of Shark Bay. Malgana people refer to their Country as 'Gathaagudu', which means 'two bays'.

An account of growing up and living in Shark Bay is given by Ada Mary Fossa, a 6th generation Indigenous resident of Shark Bay and Malgana Elder, in the book *'Stories, Laughter and Tears Through Bygone Years in Shark Bay'* (Fossa 2017).

4.1 Archaeological history

4.1.1 Occupation

Aboriginal people have occupied Shark Bay for up to 30,000 years based on materials collected from the Peron Peninsula (Bowdler 1990c; CALM 1996). Two periods of occupation are currently evident and include the late Pleistocene between 30,000-18,000 years ago, determined largely from emu egg shells, and the Holocene between 7000-6000 years ago, determined from Terebralia (mudwhelk) shell deposits (Bowdler 1990c; Bowdler 1990b; Bowdler 1990a). A vacation from the area between these time periods may have been linked to lower sea levels and limited freshwater during the cold glacial periods.

Excavations and collections have occurred at Eagle Bluff, Monkey Mia, the Silver Dollar site south of Denham and Zuytdorp Cliffs. The Silver Dollar site currently provides the oldest records of Aboriginal occupancy for Shark Bay, ~30,000 years before present (Bowdler 1990c).

Two rock shelters were excavated (test excavations only) at Monkey Mia in 1986 and charcoal remains were dated back to 620 and 1010 years before present (Bowdler 1995). Remains indicate a diet mainly comprised of marine organisms, and evidence suggests that dugongs and turtles may have only been exploited by Aboriginal people in the last 1000 years.

Middens dated ~ 4000 years before present were investigated along the Zuytdorp coast to determine the level of occupancy by Aboriginal people, which was suggested to only be occasional (Morse 1988).

Similarly, Eagle Bluff sites were estimated to be as old as ~4000 years before present (Bowdler 1999). Edel Land, including CrayFish Bay and Willyah Mia, is also a significant place for Malgana people, and the numerous middens and camps indicated the region provided reliable food sources.

Approximately 70-100 Malgana people currently live in Shark Bay, while ~300 and ~400 people live in Geraldton and Carnarvon, respectively (Federal Court of Australia 2018).

4.1.2 Culturally important sites

Middens (pits for food waste) are the most common archaeological signature found in Shark Bay (Bowdler 1990c; McGann 1999). There have been 80 midden sites identified across the coastline of Shark Bay which show evidence of Malgana people living near and relying on the sea (Bowdler 1990c; Smith *et al.* 2006a; McCluskey 2008).

Other culturally important sites include quarries, rock shelters, artefact shelters, burials, stone arrangements and camps, including Willyah Mia. To date, about 130 registered Aboriginal heritage sites exist in Shark Bay.

The Lock Hospitals on Bernier and Dorre Islands, which were used between 1908-1918 for Aboriginal people believed to be ill, are also protected under the Aboriginal Heritage Act. Many people suffered and died at these hospitals and memorials have been established on the islands in recognition of this (McCluskey 2008).

4.2 Pearling and other industries

Many Malgana people were heavily involved in the pearling industry throughout the 1860s-1930s, and detailed accounts of this history is given by Moore (1994) and McGann (1999). After the collapse of the pearling industry, Aboriginal people transitioned across to the fishing industry (McCluskey 2008).

Malgana people were also involved in other industries including guano mining, sandalwood harvesting and sheep shearing (Federal Court of Australia 2018).

4.3 Traditional hunting and fishing

Some of the marine based foods hunted and collected by Malgana people include mullet, bluebone, whiting, snapper, oysters, mussels, crabs, prawns, scallops, cockles, little 'redies', black snapper seabird eggs (cormorants, seagulls and divers), turtle eggs, turtles and dugongs (Federal Court of Australia 2018).

Malgana people are able to hunt dugongs and turtles in Shark Bay, however written permission from DBCA is required before any hunting or gathering of any species takes place within a marine nature reserve (i.e. Hamelin Pool) or sanctuary area of the Shark Bay Marine Park, unless otherwise allowed for in relevant management plans (Department of Parks and Wildlife 2016).

Traditional fishing by Malgana people included the use of nets, hooks and spears and, today, also includes the addition of fishing lines (Federal Court of Australia 2018). Some of the most common fish caught include Mulgarda (mullet), Bulhamarda (black snapper), Kuramata (Spanish bream), Nungs (yellowtail/ spine tail), Ngulu (black trevally), Mulhagadara (whiting), Kerung (trumpeter), Irrumarri (bream), Ngagiya (flathead), Mardirra (pink snapper) and Wudgagarri (tailor).

Malgana people are still actively involved in the commercial fishing industry. Shark Bay was included in the Draft Aboriginal Fishing Strategy Report for WA (Franklyn QC 2003). This report presented a series of recommendations and allowances, including an exemption for the beche-de-mer (sea cucumber) fishery in Shark Bay, though little to no harvesting actually occurs and customary fishing across WA is considered negligible (DEH 2004a; DPIRD 2018b; Hart *et al.* 2018).

4.4 Conservation management and ranger programs

Malgana people and DBCA have collaborated on a number of conservation related management projects, including clean-ups, dugong and turtle research and interpretive projects (Shire of Shark Bay 2019). Funding was also awarded for Malgana people to be involved in the state's Aboriginal Ranger Program for 2018 and 2019. The Round Two 2019 funding granted was $1m and included eight new jobs and training for seven rangers.

One objective presented in the Gascoyne Aboriginal Land and Sea Management Strategy is to develop an Aboriginal Land and Sea Management Team within the Shark Bay Local Government that includes activities such as cultural resource management of dugongs, turtles and finfish as well as joint coordination of marine reserve management (Sentance and Rowe 2016). The aspirations outlined in the Plan for our Parks (Government of Western Australia 2019) is to work towards joint management of marine and terrestrial parks and reserves with Traditional Owners, and this includes Shark Bay.

December 2019 WAMSI Workshop

Supported by the WAMSI partnership, the historic meeting between Malgana Elders, the Malgana Land and Sea Management Reference Group, Malgana rangers from both the DBCA, and the Malgana Land and Sea Management Program, brought together western science and Aboriginal knowledge to contribute to the Shark Bay Science Plan. *(Photos: WAMSI)*

5. Social drivers

Denham Jetty
(Photo: iStock.com/Kelvin Choi)

5.1 Social amenity

A general overview of the social values of Shark Bay is given by Thomson-Dans (2008), including historical recounts, natural phenomena, landscapes and major attractions.

5.1.1 Historical maritime values

The first recorded landing of Europeans in Western Australia was that of Dirk Hartog in 1616 (Stanbury 1986; Cooper 1997; Christensen 2008; McCluskey 2008; Christensen 2009). Seven more early explorers landed in Shark Bay, with the last recorded to be Henry Mangles Denham in 1858.

A comprehensive review of early maritime history is given by Christensen (2008) and is not repeated here. The review discusses the European discovery of Shark Bay between 1616-1772, the scientific explorations of the Baudin and Freycinet Expeditions between 1808-1818, and geographical reconnaissances and hydrographic surveys between 1822-1858.

A total of 14 shipwrecks have been recorded within the SBWHA (Henderson 1986; DoF 2004; McCluskey 2008). Three of these are officially recognised as historical shipwrecks, which includes the Zuytdorp (1712) located off Zuytdorp Cliffs, the Perserverant (1841) located northeast off Dirk Hartog Island and Gudrun (1901) located on the flats north of Cape Peron.

Associated with shipwrecks are the shipwreck survivors' camps found at Shark Bay. These include the Zuytdorp, Perserverant, North Star, Gudrun, Britisher and Macquarie survivors' camps, which were designated based on the finding of colonial artefacts.

Evidence of station landings are found at Hamelin Pool, Carrarang Peninsula and Wooramel River (Stanbury 1986).

Fry (1995) and Thomson-Dans (2008) both provide general recounts of the maritime history of Shark Bay.

Other historical maritime values contributing to the early economy in Shark Bay, such as whaling, guano mining and pearling, are presented in section 6.1.1.

5.1.2 Recreational water-based activities

Recreational fishing is the most popular water based activity for locals and visitors to Shark Bay (McCluskey 2008).

Line fishing is the most popular form of fishing, followed by ballooning and netting (CALM 1996; Smallwood and Gaughan 2013).

Popular shore-based (and small dinghy-based) fishing occurs at accessible locations such as Denham, Monkey Mia, Freycinet and Grey Point (Fig. 15) (Sumner and Malseed 2001; DoF 2004; Taylor *et al.* 2018). Boat based fishing largely occurs around Dorre and Bernier Islands, off the west coast of Dirk Hartog Island and along the coast to Zuytdorp Point (Fig. 15 and 16).

A 1998-99 estimate for total annual recreational fishing effort in Shark Bay revealed ~89,000 fisher days, with over 50% attributable to boats launched from public ramps at Nanga, Denham and Monkey Mia, 20% attributed to boats launched from beaches (e.g. Tamala Station) in the marine park and 25% for shore-based fishing (Sumner *et al.* 2002).

A 2016/17 study found the estimated total for boat-based recreational fishing to be 41,447 party hours for inner Shark Bay and within the Oceanic Management Zone (Taylor *et al.* 2018). Fishing effort was greatest between March and August, with May being the most popular.

Other popular water-based activities in Shark Bay include swimming, diving and boating (CALM 1996; McCluskey 2008).

Some of the favoured diving locations are also popular with recreational fishers (CALM 1996). Sanctuary Zones which would minimise this interaction include Gudrun Wreck, Mary Anne Island, Sandy Point and Surf Point Sanctuary Zones.

Monkey Mia provides ideal conditions for water sports such as skiing, jet skis and windsurfers. To avoid conflict among users and to avoid damage to sensitive marine habitats, some areas in Shark Bay place restrictions on motorised watersports and boats.

5.1.3 Landscapes and visual amenity

The natural coastal landscapes contribute immensely to the visual amenity of Shark Bay and addresses the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Criteria VII- to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance. There is limited coastal development outside of main towns, though salt mining infrastructure has impacted on aesthetics. Some of these natural landscapes include, but are not limited to:

- Shell Beach is made up of millions of white cockle shells spanning 60km long and 10m deep, and is one of only a few locations in the world where shells have replaced sand in such an extensive way.
- Francois Peron National Park provides a stark contrast between red cliffs and blue waters offering a series of lagoons for swimming. The location is popular among artists and photographers.
- Eagle Bluff is popular for its high cliff and expansive views across Denham Sound and Useless Loop. The location is good for marine wildlife viewing, including dugongs.
- Steep Point, within the Edel National Park, is the most westerly point of mainland Australia and has become a popular ‘bucket list’ attraction. The National Park also offers views of Zuytdorp Cliffs, which extend for 200km from the Murchison River to Pepper Point.
- Dirk Hartog Island offers a range of natural sceneries from cliffs to blowholes to calm beaches. Turtle Bay is located on the northern tip of the island and is a significant rookery for loggerhead turtles.

5.1.4 Educational and scientific values

A historic account of the scientific research in the marine environment between 1951-1990 is given by Christensen (2008), who talks about the rise and development of research relating to population dynamics of whales, fisheries related species, sedimentation and biofacies, and biological survey expeditions (e.g. Expedition to Bernier and Dorre Islands).

Education is continually mentioned throughout the SBWHA Strategic Plan as a means to strengthen the respect and appreciation of the SBWHA (McCluskey 2008). Strategies include ‘encourage wildlife interactions that maximise educational opportunities and foster support for wildlife conservation’ and ‘develop, and promote the provision of, accurate and consistent information about the World Heritage Property to visitors across all tenures’. Given the large area of Shark Bay and limited field staff to monitor and regulate activities, education of locals and visitors is key to maintaining the unique environmental values of the Bay (CALM 1996). For a long time the visitor centre at Monkey Mia was the only public education facility in Shark Bay, but today, the Shark Bay World Heritage Discovery and Visitor Centre can also be found in Denham. A number of interpretive signs have been erected at popular coastal locations and on walking trails to continue the educational experience in the field.

The Department of Transport’s Marine Education group offers sea kayaking expeditions in Shark Bay to metropolitan and regional secondary schools throughout WA. The sea treks explore the coastlines, mangroves, tidal flats and offer the opportunity to see marine wildlife, visit the Ocean Park Aquarium and engage in an Indigenous cultural session.

Curtin University offers an annual field trip to Shark Bay for students studying geology. The trip is hosted by Bush Heritage at Hamelin Station Reserve and students are able to explore coquina quarries and stromatolites as well as other geological features. The University of Western Australia have previously offered a field course in Evolutionary Biology of Marine Mammals which includes a two week field trip to Shark Bay. Murdoch University offers a 10-day Story Telling in Australia short course which includes a 10-day field trip to Monkey Mia, Pilbara and Karijini National Park.

The Shark Bay World Heritage Advisory Committee provides guidance on appropriate research projects in Shark Bay.

5.2 Public health

Water quality has been measured at Monkey Mia foreshore since 1989 and includes testing for pathogens such as faecal *Enterococci* (DBCA 2019b). This is due to historical waste treatment in the area of Monkey Mia. The risk of pathogens is considered to be relatively low for the rest of Shark Bay and therefore not measured. The sampling design does not currently include control or reference sites and findings are compared to the Australia and New Zealand Environment and Conservation Council, and the Agriculture and Resource Management Council of Australia and New Zealand 2000 guidelines (ANZECC/ARMCANZ). *Enterococci* concentrations have remained below guidelines levels and stable since 1989.

Under the Marine Biotoxin Monitoring and Management Plan, bivalves from Shark Bay are tested for contamination (WA Department of Health 2016).

6. Economic drivers

Dolphin (Piccolo) chasing fish in Monkey Mia shallows (Photo: Simon Allen)

6.1 Fisheries

6.1.1 Early beginnings

A collection of files from the Department of Fisheries relating to Shark Bay and spanning back to the early 1900s (also relating to the late 1800s) are held at the State Records Office of Western Australia. These records mostly relate to pearling (e.g. licences), but also include other fisheries and whaling.

6.1.1.1 Pearling

Shark Bay was officially established as a pearling centre in 1870 though pearls had been taken since the 1850s (Cooper 1997; McGann 1999; Christensen 2008). Pearl oysters were easy to access as they grew on shallow banks.

Willyah Miah in Useless Inlet was the first and largest pearling camp established in Shark Bay, and other camps were set up at Denham (Freshwater Camp) and on Dirk Hartog Island and Peron Peninsula (Stanbury 1986). A detailed account of Willyah Miah, including the history of Indigenous and Asian labourers, involvement of women and children, the living and working conditions and site descriptions of numerous pearl shell middens is given by McGann (1999).

Pearling vessels became licensed in 1873 and the Shark Bay Pearl Fishing Act was first implemented in 1886, which only allowed lease and sublease holders to collect pearls and pearl oysters (Cooper 1997).

The pearling industry closed in 1892 due to overexploitation. Early fisheries reporting on the pearling industry in Shark Bay was the responsibility of William Saville-Kent between 1893-94, who was the first applied marine biologist in the region tasked with reporting on measures to help protect and maintain the long term sustainability of the pearling industry (Harrison 2005; Christensen 2008). Saville-Kent is also credited with pioneering a transplantation experiment to acclimatise *Pinctada maxima* to Shark Bay conditions (Fisheries Department 1949).

The industry resumed again after WWI but declined again due to a dry market. The pearling industry did not recover to previous performances following a crash during the Great Depression in the early 1930s. The economic management of the pearling industry between 1860-1930 for the whole of WA is detailed by Moore (1994).

6.1.1.2 Whaling

Whaling along the WA coast began in the late 1700s/early 1800s (Cooper 1997; Smith *et al.* 2006a) and occurred in the general Shark Bay region from then until the 1960s. Humpback whales, southern right whales and sperm whales were targeted in the Shark Bay region.

Whale processing factories were opened further north of Shark Bay at Norwegian Bay (1915) and Point Cloates (1949). It wasn't until 1949 that a whaling station opened at Babbage Island (Carnarvon) with funding from the Commonwealth Government (McCluskey 2008). Operations ceased in 1963 after an estimated 7852 humpbacks were killed, and the station was then purchased by Nor West Whaling and converted into a facility for processing prawns.

6.1.1.3 Finfish fisheries

Fishing boats targeting snapper began in 1908 and primarily occurred around the western lying islands, the inner reaches of Shark Bay and off Carnarvon (Cooper 1997). Fishing boats would then return to Fremantle or Geraldton for unpacking and processing. Trap fishing for snapper was introduced in the 1950s but was eventually banned as the practice reduced the quality of the fish and, in turn, the market value.

Beach seine net fishing began in the early 1930s due to a failing pearl industry (Cooper 1997). The fishery was slow growing due to logistical constraints. The introduction of powered boats/jets in the 1970s revolutionised net fishing, which has continued to present day.

6.1.1.4 Prawns

CSIRO and WA Fisheries Department conducted surveys in Shark Bay between 1952-1962 to assess the size of prawn stocks (Cooper 1997). In 1960, the Australian Pearling Company began commercial trawling, which went on to fail due to poor catches and inefficient management. Nor West Whaling then began processing prawns in 1963 in Denham, and by 1966, 16 trawlers were fishing for prawns.

6.1.1.5 Other fishing

Commercial fishing for crayfish began in 1957 at South Passage (Cooper 1997). The fishery was deemed not sustainable by the end of 1960, but has since gradually returned.

Harvesting of oysters was found not to be a viable industry in Shark Bay (Cooper 1997).

Harvesting of scallops stemmed from the collection as a by-product of prawn trawling (Cooper 1997). In 1983, there was a turn-around in the market and the export of scallops became viable.

Green and loggerhead turtles were caught commercially between 1940-1960 in Shark Bay and exported to France (Cooper 1997).

6.1.1.6 Fish processing factories

Two cannery and processing factories opened in Monkey Mia and Herald Bight in 1912 and 1933, respectively, but neither factory survived for long (Cooper 1997). There were only two other fish buyers and processors in Denham prior to 1938.

In 1944, commercial operations opened up to transport iced fish by road (Cooper 1997). Many net fishermen took part in catching, marketing and selling fish themselves using these fish trucks. Between 1971-1987, the Geraldton Fish Market at Denham became the main seafood buyer, even for net fishermen, and continued to handle a significant proportion of the fish caught in Shark Bay until recent times.

6.1.2 Current day fisheries

Commercial fishing is one of the main industries operating in Shark Bay today, which was largely a result of the weakening pearl industry in the 1930s (Shire of Shark Bay 2017). The fisheries operating in the Bay, like any other fishery, are reliant on economic drivers such as market value and supply and demand, with invertebrates dominating most of the commercial catch. A breakdown of the economic aspects of key fisheries in Shark Bay is given in Table 1 (Gaughan and Santoro 2019).

The Gascoyne Demersal Scalefish Fishery, Shark Bay Beach Seine and Mesh Net Fishery (Fig. 17), Shark Bay Scallop Managed Fishery (Fig. 18) and Shark Bay Prawn Managed Fisheries (Fig. 19) have operated since the 1960s, and were soon followed by the Shark Bay Crab Managed Fishery. Economic drivers for each fishery are assessed annually and can be found in the annual State of the Fisheries reports (e.g. Gaughan and Santoro 2019).

The extent of economic activity directly related to commercial fishing activities, including for Shark Bay, and any flow-on effects into the wider WA economy was assessed in the 1990s (McLeod and McGinley 1994).

A socio-economic analysis was undertaken for the Shark Bay crab fishery in 2014/15 as a reference to compare against future performance (Daley and van Putten 2018). The criteria included gross value of production, profitability, supply chain resilience and employment and flow-on benefits. Adaptations over time were recommended in order to ensure the long-term economic sustainability of the fishery.

Daily logbooks and processor information were used to model commercial catch and effort for prawns and price data to assess periods of time when profitability was low (Hesp *et al.* 2017). Suggestions for improved revenue and profitability included expanding moon closure periods and spreading the number of fishing days later into the year.

A limited number of fishing charters operate out of Shark Bay (CALM 1996). These vessels operate from Monkey Mia and Denham and offer half to full day fishing and marine wildlife encounter opportunities, as well as live-aboards.

Table 1 Most recent estimates of social and economic outcomes of the main commercial fisheries operating in Shark Bay.

Commercial Fishery	Shark Bay Prawn Resource	Saucer Scallop Resource	Shark Bay Blue Swimmer Crab Resource	Gascoyne Inner Shark Bay Scalefish Resource	Gascoyne Demersal Scalefish Resource *data presented is for the whole Gascoyne region
Target Species	Western king prawns Brown tiger prawns Other: endeavour and coral prawns	Saucer scallops	Blue swimmer crabs	Whiting Sea mullet Tailor Western yellowfin bream	Pink snapper Goldband snapper Other: tropical snappers, emperors, cods, mulloway, trevallies
Total catch for 2017	1608 t	460 t meat weight 2301 t incl. shell	443 t	156 t	133 t for pink snapper 144 t for other
Economic Value	$26.4m (incl. incidental catches of coral prawns, cuttlefish, squid, octopus and bugs)	$18.4m (including scallop catch from prawn fishing vessels)	$3.08m	$1-5m for SBBSMNF	$1-5m
Employment	100 skippers and crew 37 processing and support staff	40 skippers and crew 90 crew employed in prawn fishery that can also take scallops	Trap sector 12 skippers and crew 30-35 processing staff Trawl sector 100 skippers and crew 35 processing and support staff	12 fishers	32-48 skipper and crew
Licences/ Operators	18	11	4	6 vessels for SBBSMNF	16
Date Assessed	2017	2017	2017	2017	2017
Source	Gaughan & Santoro 2019	Gaughan & Santoro 2019	Gaughan & Santoro 2019	Gaughan & Santoro 2019	Gaughan & Santoro 2019

SBBSMNF: Shark Bay Beach Seine and Net Fishery

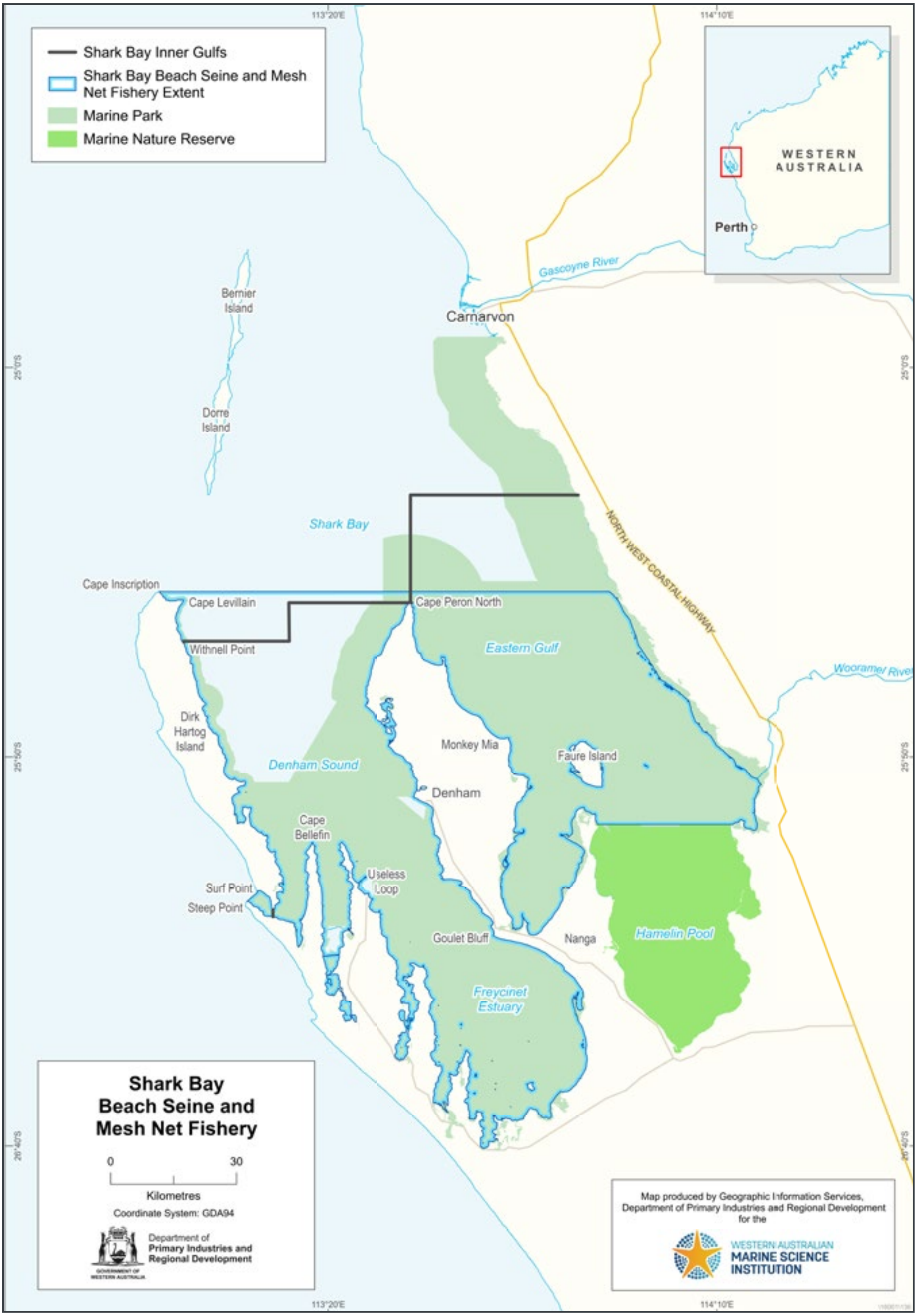


Figure 17 Spatial extent of the Shark Bay Beach Seine and Mesh Net Managed Fishery.

Figure 18 Spatial extent of the Shark Bay Scallop Managed Fishery.

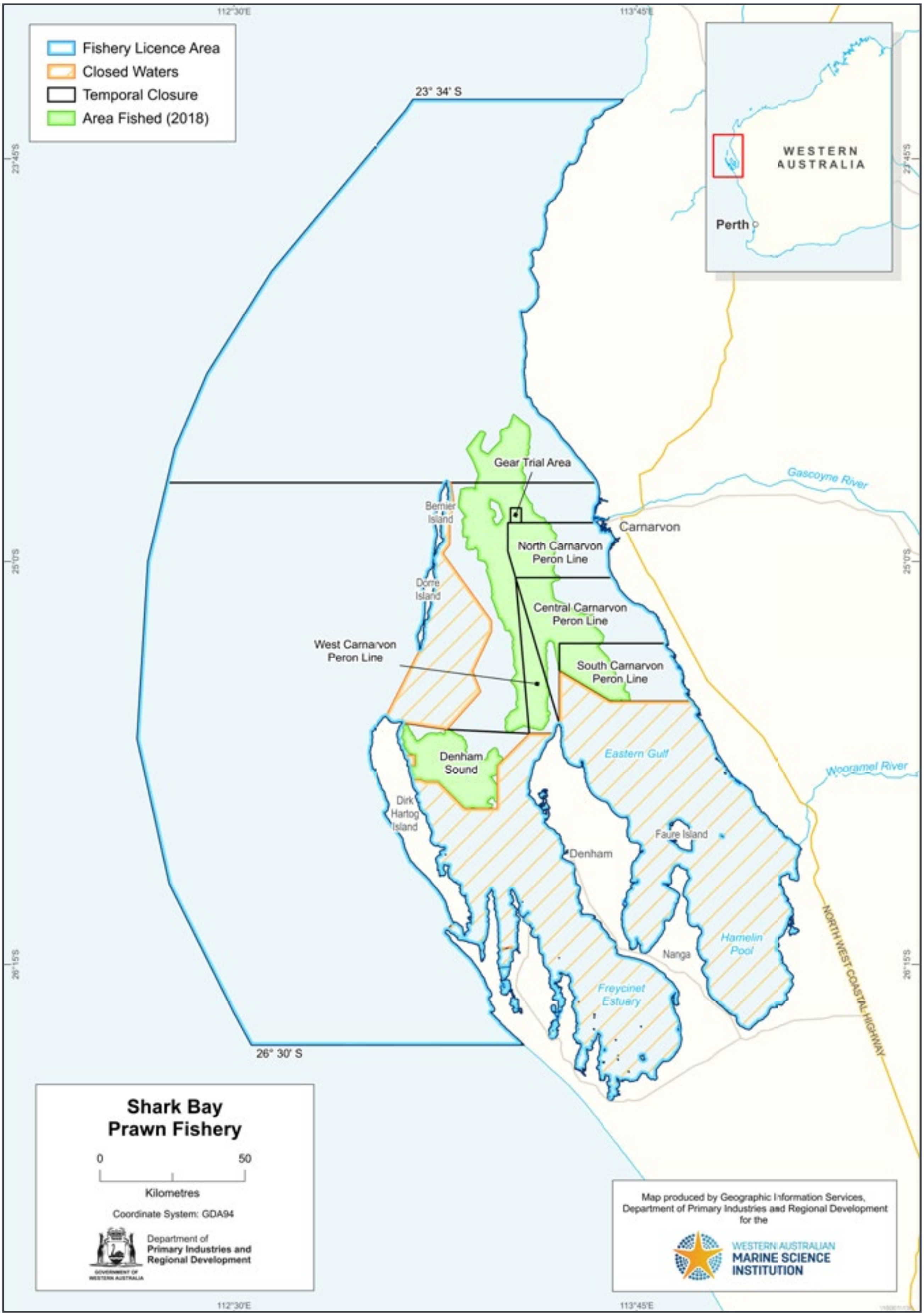


Figure 19 Spatial extent of the Shark Bay Prawn Managed Fishery.

6.2 Aquaculture

Several licences exist for aquaculture in Shark Bay and are primarily located off the east coasts of the Peron Peninsula and Dirk Hartog Island, and off Denham (Makira and Ecologia Environmental Consultants 1997; Pan Holdings Pty Ltd 2017; Gaughan and Santoro 2019).

Most licences are for non *Pinctada maxima* invertebrate species, followed by finish, with Blue Lagoon Pearls leading the industry in Shark Bay with over 19 years of operation (Shire of Shark Bay 2017). A licence and hatchery for *P. maxima* pearl oyster seed is also located at Oyster Creek in Carnarvon.

Trials are currently underway for the culture of native rock oyster species, *Saccostrea cucullata* and *Saccostrea scyphophilla* along the Wooramel Coast (Harvest Road Export Pty Ltd 2018).

Trials have previously occurred for an onshore pink snapper hatchery (DoF 2004).

A suite of species are considered as potential candidates for aquaculture in Shark Bay, including finfish, aquarium fishes and marine invertebrates, but development of these cultures will depend on technological advances and market value (DoF 2004).

Other license holders for aquaculture include Tasmanian Seafoods, WA Ocean Park and a private holder.

Shark Bay is included in an assessment of the economic and technical feasibility of marine aquaculture, particularly edible oysters and finfish, for the Pilbara-Gascoyne coast (Australian Venture Consultants 2016a; Australian Venture Consultants 2016b). For edible oysters, the most suitable coastal site was located 12km north of Carnarvon. For the finfish species, yellowfin tuna, greater amberjack and mahi mahi, a site off the northeast coast of Bernier Island was considered most suitable for aquaculture.

6.3 Shipping and maritime

Useless Loop is one of three deep water port facilities along the Gascoyne coast and services vessels, approximately 40 ships per year, exporting salt (McCluskey 2008; Gaughan and Santoro 2019). Other jetty and harbour facilities are located in Denham, Monkey Mia and Carnarvon and are used for commercial and recreational fishing and boating activities.

6.4 Tourism

Tourism is one of the main industries sustaining the local economy of Shark Bay (McCluskey 2008), which was greatly facilitated by the sealing of the Denham-Hamelin Road in the 1980s, the construction of the Monkey Mia Resort in 1989 and the World Heritage listing in 1991.

Visitation has remained stable at 100,000-130,000 visitors annually since 1998 (Smith *et al.* 2006a; Smith *et al.* 2006b; McCluskey 2008; Tourism WA 2018), with winter months (June to August), particularly July school holidays, being most popular. The majority of visitors are first-time visitors, which is a pattern observed from Monkey Mia social surveys spanning back to 1988 (WATC 1988; CALM 2002a; CALM 2002b; CALM 2003; Smith and Newsome 2004), and Monkey Mia tends to form part of a multi-destination itinerary (Smith and Newsome 2004; Smith *et al.* 2006a).

A large proportion of visitors to Shark Bay are domestic (up to 72%) (Tourism WA 2018), followed by international visitors, and the majority are travelling with family or as a couple. One to three day stays have been a common trend observed across time (Smith and Newsome 2004; Smith *et al.* 2006a), though the most recent estimates for 2016-2018 average a stay of four nights (Tourism Research Australia 2018; Tourism WA 2018).

Most visitors planned visits or activities related to the marine or coastal environment, with Monkey Mia, Shell Beach, Denham and Hamelin Pool stromatolites being among the most popular places to visit (Reark Research 1995; Smith *et al.* 2006a). Viewing dolphins and dolphin interactions had the most participation from visitors at >90% (Reark Research 1995; Smith and Newsome 2004; Smith *et al.* 2006a).

Out of the tourism-related businesses operating in the Shark Bay region, the majority offer employment opportunities for one or more employees (Tourism Research Australia 2018). Marine-related tourism operators offer eco cultural tours, fishing charter tours, nature tours, diving tours and water sports.

6.4.1 Nature-based and wildlife tourism

Stromatolite viewing in Hamelin Pool is a popular attraction and is considered a 'short-stop' site where visitors use the Hamelin Pool Marine Nature Reserve as a 'convenient break' whilst travelling to other locations within Shark Bay (McGuiness *et al.* 2016).

The bottlenose dolphin population and the provisioned dolphins at Monkey Mia are a main attraction for many tourists visiting Shark Bay, and Monkey Mia itself is estimated to attract more than 100,000 tourists each year.

The dolphin provisioning program at Monkey Mia is one of the longest running such programs worldwide. While the Malgana people have fished the waters of Shark Bay for millennia and interacted with the dolphins, the first reported interactions between dolphins and people occurred in the 1940s and 50s when local fishers were beach seine netting. Fishers first started feeding the dolphins back in the 1960s (CALM 1993; Smith *et al.* 2006a; Smith *et al.* 2006b). The first written reports of the human-dolphin interactions at Monkey Mia date back to the late 1970s and early 80s when seven dolphins were reported to visit the shallows near the shore and were hand fed by fishers and visitors to the caravan park on that site (Connor and Smolker 1985; Orams 1997).

As visitor numbers increased over the years, the amount of food provided to the dolphins increased, and this eventually resulted in visiting dolphins likely receiving their total daily food requirements from hand feeding alone. This was recognised as problematic for the long term health of the dolphins and the provisioning became regulated by the Shire and CALM (now DBCA) in 1989. From that time on, feeding was reduced to 1.5-2kg per day per dolphin and was managed by Shire rangers (CALM 1993). This was continued up until 1996 when CALM took over the management. The feeding of provisioned dolphins and interactions with dolphins from the shore or via commercial tour operators is currently managed by DBCA under a similar regime to that originated by the Shire and CALM. An adaptive management strategy has been used which has been able to respond to research on the dolphins and adjust management accordingly for the long term health of the dolphins and sustainability of the program (Foroughirad and Mann 2013). The program and its management is regularly reviewed and updated (Martinez and Orams 2018).

A social survey of residents and tourists of Shark Bay indicated that there was support for a balanced relationship between tourism and the environment, but residents placed greater emphasis on tourism development while tourists gave more weight to environmental protection (Dowling 1991).

Another survey of 244 visitors found that proximity and probability of an interaction with dolphins was highly valued, but that 80% would support management regulations to address welfare concerns if it meant trading off these parts of the dolphin encounter experience (Bach and Burton 2017). Though seeing dolphins in their natural environment was ranked as extremely important for a majority of visitors, up to 60% said they would still visit Shark Bay if dolphin viewing did not exist (n= 355), even if it was for a short duration (Stoeckl *et al.* 2005; Smith *et al.* 2006a).

The presence of dolphins also has a positive influence on businesses and tour operators. A 2004 estimate of regional expenditure found that between 20-42% is directly attributed to dolphin viewing and interactions (Stoeckl *et al.* 2005). An additional survey of tour operators found that while short term absence of dolphins would not affect business, if dolphins were not present for an entire season, this would have significant negative effects (Smith *et al.* 2006a).

A range of other activities have been promoted in Shark Bay since the Smith *et al.* (2006a) study in order to help safeguard against the potential loss of provisioned dolphins in Monkey Mia. See section 3.5.6.2.7 for more information on dolphin and tourism interactions.

Ocean Park Aquarium is estimated to attract ~48,000 visitors each year (Shire of Shark Bay 2017), and is permitted to capture marine life for inclusion in the aquarium. Other popular marine activities include whale watching, marine safari trips, snorkelling, diving, fishing charters, recreational fishing, sailing and windsurfing.

Among suggestions for new tourism activities and infrastructure from a business and economic conditions survey, were dive and snorkel trails as well as additional fishing jetties (Urbis 2019).

6.4.2 Historical tourism

Historical tourism is also popular among tourists given the history of early European settlement days and the rich fishing history. Historical based attractions include the pearling camp 'Freshwater Camp' and the Old Pearler Restaurant and St Andrew's Church buildings which are made out of shell block.

6.4.3 Indigenous tourism

There are over 130 Aboriginal heritage sites in Shark Bay. The Malgana people offer cultural walking tours to visitors, which includes treks through bushland and introductions to bush tucker and natural medicines (Shire of Shark Bay 2017). Wula Guda Nyinda Eco Cultural Adventures also operates out of Monkey Mia and provides visitors with a range of experiences that explore Aboriginal culture, history and tradition.

There is support to grow cultural tourism in the Gascoyne region by establishing a Cultural Tourism Corridor from Shark Bay and Carnarvon through to Mount Augustus by offering day and overnight experiences (Sentance and Rowe 2016).

6.5 NGOs

Bush Heritage Australia and the Australian Wildlife Conservancy are two non-governmental organisations operating in Shark Bay.
Bush Heritage Australia purchased the Hamelin Station Reserve in 2015 with the aim to conserve and restore the reserve in collaboration with the Malgana and Nanda Traditional Owners. Bush Heritage operates the Hamelin Outback Station Stay, a previous sheep station, which provides accommodation in shearers quarters and camp sites. Bush Heritage also supports a number of research partnerships, including the monitoring of fish and sea snake assemblages of Hamelin Pool and stromatolite research.

The Australian Wildlife Conservancy has managed Faure Island in Shark Bay since 1999. The Conservancy carries out feral herbivore, feral cat and fox controls, wildlife translocations and fire management on the island. As a result, Faure Island is declared feral animal free, and is used to protect, conserve and re-introduce nationally threatened mammals, such as the Shark Bay mouse, burrowing bettongs, banded-hare wallabies and western barred bandicoots. The island is also a significant breeding area for seabirds, particularly the pied cormorant, and has migratory stopovers for shorebirds.

6.6 Aboriginal Corporations

The Yamatji Marlpa Aboriginal Corporation (YMAC) is the regional Native Title representative body for Indigenous groups in the Pilbara, Murchison and Gascoyne regions and provides assistance to Native Title holders and claimants. The YMAC also aims to ensure continuation of heritage and culture and to seek outcomes that provide a strong legacy for Yamatji and Pilbara people, such as active involvement in community, environment and economic development projects.

The Malgana Aboriginal Corporation is a Registered Native Title Body Corporate and is the representative body for the Malgana people. The Malgana Aboriginal Corporation is responsible for Native Title spanning ~28,800km^2 across the Shark Bay Region.

The Nanda Aboriginal Corporation is a Registered Native Title Body Corporate and is the representative body for the Nanda people. The Nanda Aboriginal Corporation is responsible for Native Title spanning ~17,000km^2 from Shark Bay to Kalbarri.

The Yinggarda Aboriginal Corporation and Nganhurra Thanardi Garrbu Aboriginal Corporation are Registered Native Title Body Corporates and represents the Yinggarda, Baiyungu and Thalanyji people. The joint Gnulli Native Title claim under the responsibility of the two corporations covers ~71,354km^2, and the Yinggarda Aboriginal Corporation is responsible for the area spanning from Shark Bay to the southern end of Lake Macleod and inland.

6.7 Agriculture

No agricultural practices operate within the SBWHA, but extensive horticultural operations occur across Carnarvon and a small operation is established on the Wooramel River (McCluskey 2008).

6.8 Pastoralists and graziers

Pastoral leases in and around the SBWHA were first given out in the 1860s in small land chunks which were later amalgamated to form stations: Dirk Hartog Island, Carrarang, Tamala, Nanga, Peron, Faure Island, Hamelin, Yaringa, Carbla and Murchison House (Cooper 1997). These were all originally developed as sheep stations for wool production, but have since been replaced with cattle and goats (McCluskey 2008). It wasn't until 1925-1927 that artesian bores were sunk to access the huge artesian water basin below, which had positive impacts on pastoralism and grazing. Some pastoral leases have been claimed for conservation estates.

6.9 Mining and logging

6.9.1 Guano

Guano mining was the first commercial operation in Shark Bay (Cooper 1997). Commercial mining was authorised in 1850 at Egg Island and islands in Freycinet Estuary (Stanbury 1986; DEC 2012), though legal and illegal mining had been occurring as early as 1847. The industry was overexploited and near exhausted by the end of the 1900s, though some mining still occurred up until 1915.

6.9.2 Gypsum

Gypsum has been occasionally mined at Brown Inlet and Heirisson Prong and exported from Useless Loop by Shark Bay Salt Joint Ventures (Cooper 1997; McCluskey 2008; DEC 2012). Peron Peninsula was surveyed and drilled to reveal millions of tonnes of gypsum by another venture, but the mining project did not go ahead and leases obtained in 1984 have since been relinquished.

6.9.3 Heavy mineral sands

Exploration licences have been used to assess resources of heavy mineral sands in Shark Bay, particularly on lands south of Nanga adjoining the SBWHA (DEC 2012). The largest deposit discovered in 2000 was an area known as Amy Zone, which is 35km long, 3km wide and 10-50m thick. Feasibility studies in 2003, 2009 and 2013 have revealed that the Zone can support high-volume, low-cost and long-life mining, with zircon being the main source of revenue (Gunson Resources Limited 2010), and project development is still underway.

6.9.4 Oil and gas

The World Heritage listing of Shark Bay does not prevent mineral exploration and development, however, the proposals considered by the Environmental Protection Authority (EPA) are not allowed to compromise the values that were used to establish the listing.

Regions of the SBWHA that do exclude drilling and production are Hamelin Pool Marine Nature Reserve, eight Sanctuary zones and three Recreation zones, as well as six Special Purpose zones if activities would impact upon the conservation purpose (McCluskey 2008). As such, there have been no active petroleum tenements in Shark Bay for 30 years (DoF 2004; DEC 2012).

In 2002, Euro Pacific Energy's petroleum exploration tenement expired, which included an area extending from Bernier and Dorre Islands to the Carnarvon coastline. No field exploration took place and the tenement has not been renewed.

Two areas have been released for oil and gas exploration offshore of Carnarvon in the Southern Carnarvon Basin (Gaughan and Santoro 2019), but again, field operations have not begun.

Prior to this, in the 1950s, West Australian Petroleum Pty Ltd sank 18 exploration wells on Dirk Hartog Island (Playford and Johnstone 1959; DEC 2012), Oceania Petroleum sank one well in 1973 just onshore at Tamala, Pace Petroleum sunk one well in 1997 near Amy Zone and Magellam Petroleum Australia sank two wells bordering Hamelin Pool in 1968 (Department of Mines, Industry Regulation and Safety 2019). Several more wells were sunk further inland outside of the SBWHA.

6.9.5 Salt

Solar salt mining began in the 1960s in Useless Loop (Cooper 1997; DEC 2012). Shark Bay Salt (now Shark Bay Salt Joint Ventures) closed Useless Loop to the sea with an earthworks bar. More bars were constructed between 1973-1975, which caused conflict with fishers given Useless Loop and the Inlet were natural nurseries for fish. The government also leased out 12,000 hectares for brine concentration in Useless Inlet in 1967.

Salt mining produced many local jobs which led to the establishment of a local township. Some fishermen transitioned across to salt work because of declining fish stocks and closures in the early 1970s.

Geraldton Salt Refiners began operations in 1980 with the purpose of refining salt from Shark Bay Salt Joint Ventures. The business was significantly sustained by the needs of Woodside for salt in their oil drilling practices. Salt mining also takes place at Lake McLeod in Carnarvon.

Salt mining operations are excluded from the SBWHA and are governed by the *Shark Bay Solar Salt Industry Agreement Act* (DEC 2012).

6.9.6 Shell deposit extraction

Shell grit (*Fragum erugatum*) mining began in Shark Bay in the 1940s due to the masses of coquina shell deposits continually observed on shores (Cooper 1997; DEC 2012). Shell deposits are excavated and used in poultry farming and for extender and filler building materials. The consolidated shell has been extracted from quarries near L'Haridon Bight and Hamelin Pool Telegraph Station and has traditionally been used in building construction (DoF 2004; McCluskey 2008; DEC 2012). However, the coquina resource is limited and, therefore, regulated by Shire of Shark Bay and the *Hamelin Pool Common Management Plan 2001*.

6.9.7 Sandalwood

Sandalwood harvesting began in 1860 and soon became a major commercial activity in Shark Bay (Cooper 1997; Edwards 1999). Cutting occurred on the Peron Peninsula, Wooramel River and on early pastoral stations around Shark Bay. Most of the sandalwood supply was exhausted by 1939 and only a few licensed cutters are now allowed.

7. Threats and external drivers

Big Lagoon, Shark Bay
(Photo: Rory Chapple, DBCA)

7.1 Climate change

7.1.1 Observed trends in Shark Bay region

The annual averaged air temperature in the Shark Bay region has increased by ~1.0°C since 1910 and annual mean rainfall has decreased by 10-20mm per decade since 1970 (NESP Earth Systems and Climate Change Hub 2018).

Sea surface temperatures along the WA coastline have increased by 1.2°C since 1960. Maximum rates of increase are typically observed during summer, which has been observed for locations in Shark Bay (NESP Earth Systems and Climate Change Hub 2018). Two marine heatwaves have impacted upon the Shark Bay marine environment. The 1999 marine heatwave saw greater than average temperatures in the Shark Bay region from February through to September with the peak increase occurring in April. The second marine heatwave occurred in 2011 and peak temperature increases occurred in February for the Shark Bay region.

7.1.2 Projections for Shark Bay

Climate change is the biggest threat facing Shark Bay marine and terrestrial environments and, furthermore, it threatens to degrade the unique values that designate Shark Bay as a World Heritage Area. Climate change projections and confidence ratings for Shark Bay as stated on the Climate Change in Australia government website and in the National Environmental Science Program (NESP) Earth Systems and Climate Change Hub report (2018) include:

- Increased average air temperatures in all seasons (very high confidence)
- More hot days and warm spells with a substantial increase in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells (very high confidence)
- Decreasing winter and spring rainfall (high confidence). Rainfall changes in summer and autumn are not as clear
- More intense extreme short-duration rainfall (high confidence) and the wettest day of the year will get wetter
- Fewer but more intense tropical cyclones (medium confidence)
- A small winter decrease in wind later in the century
- A small increase in spring wind speeds (low confidence)
- Increased fire weather risk (low confidence)
- Increased potential evapotranspiration in all seasons (high confidence)
- Decreased humidity in winter and spring (high confidence) and in summer and autumn (medium confidence) later in the century
- Increased winter radiation (medium confidence) later in the century
- Rising mean sea level and increased height of extreme sea-level events (very high confidence)

The fluxes of Wooramel River flow and associated sediment transport has also been modelled under climate change scenarios given its potential to negatively impact Faure Sill and the stromatolites in Hamelin Pool. Projections include median increases in the duration of flood-flows of 5-11%, 9-21% and 15-33% for 2030, 2050 and 2070, respectively. Projections on future sediment yields requires further modelling.

7.1.3 Climate Vulnerability Index

Climate Vulnerability Index (CVI) workshops were held to determine the extent to which climate change would impact on the outstanding universal value of the SBWHA and also to what extent climate change would impact on the economic, social and cultural dependency on the SBWHA. CVI is a rapid assessment tool that was developed specifically for World Heritage Properties (Day *et al.* 2020). The CVI assessment occurs in two stages:

1) Assessing the exposure, sensitivity and adaptive capacity of key World Heritage values to determine the Outstanding Universal Value Vulnerability. This occurred in a Shark Bay workshop held by the Shark Bay World Heritage Advisory Committee (SBWHAC), NESP in September 2018 (NESP Earth Systems and Climate Change Hub 2018; Heron *et al.* 2020).

2) Assessing economic, social and cultural dependencies upon the SBWHA and their adaptive capacity to climate change to determine the Community Vulnerability. This occurred in a WAMSI/SBWHAC Perth workshop in June 2019 (Heron *et al.* 2020).

The assessments took place under the climate change scenario of:

- Extreme marine temperature events: five per decade (determined using coral report analysis for RCP8.5)
- Doubling of frequency of severe storms
- Air temperature increase of 1°C

These were identified as stressors that would have the greatest potential impact on Shark Bay's outstanding universal value (NESP Earth Systems and Climate Change Hub 2018; Heron *et al.* 2020).

The adaptive capacity of the SBWHA to climate change, based on local management responses, scientific/technical support and effectiveness to address stressors, was rated as 'very low' for air temperature change, 'low' for storm intensity and frequency and 'very low' for extreme marine heat events. Overall, Shark Bay's outstanding universal value is considered to be highly vulnerable to climate change (NESP Earth Systems and Climate Change Hub 2018; Heron *et al.* 2020).

At the stage two workshop considering economic, social and cultural implications, economic and social adaptive capacity was rated as low, and cultural adaptive capacity was rated as moderate. Overall, Community Vulnerability was considered high (Heron *et al.* 2020).

7.2 Water quality

7.2.1 Nutrients

Nutrient availability and fluxes in the water column examined for Shark Bay reveal that phosphorus is limited in hypersaline waters (Smith and Atkinson 1983; Smith and Atkinson 1984; Atkinson 1987; Pedretti *et al.* 1998). Nitrogen is not typically limited due to the level of nitrogen fixation occurring in the system. The balance of nutrient availability in the bay is particularly important to the expansive seagrass meadows, as high nutrient concentrations in the water column can stimulate the growth of algae and reduce the light available to seagrass for photosynthesis. Likewise, low nutrient availability in the sediments can limit seagrass growth and high nutrient concentrations can become toxic (Statton *et al.* 2012). Excessive nutrient loads and algal growth can also lead to deoxygenation of the water column and subsequent fish kills.

7.2.2 Sedimentation

An increase in sedimentation in Shark Bay is likely to result from increased flood-flow volumes from the Wooramel River. Such flooding events can cause increased sedimentation over seagrass meadows and also reduce photosynthesis due to reduced light levels. If flooding of the Wooramel River was to increase under future climate change projections, the increased sediment load could be expected to negatively impact the seagrass at Faure Sill and, in turn, impact upon ideal growth conditions for stromatolites in Hamelin Pool (Mpelasoka *et al.* 2012; Mpelasoka and Rustomji 2012).

7.2.3 Heavy metals

Cadmium has been found to absorb onto iron oxide particles in the water column and subsequently be ingested by bivalves (Lawrance 1985; McConchie *et al.* 1988; Francesconi 1989; McConchie and Lawrance 1991).

7.2.4 Oil spills

Shark Bay was included in a recent assessment of oil pollution risk for the Mid West coast of WA which, in general, has relatively less large vessel traffic compared to further north or south (Navigatus Consulting 2018). Shark Bay is considered to have 'low complexity' given the consistent seafloor depths and adequate sea room. The shorelines of Shark Bay were rated as having a 'low exposure' to oil, whereas waters offshore of Shark Bay had a more 'moderate exposure' to oil given the potential for large spills from oil tankers traversing the WA coastline. Exposure was included in the risk models along with other factors, such as protection priorities. Overall, the majority of the Shark Bay shoreline had a 'very low' risk of oil spill pollution. Portions of the shoreline that received a 'moderate' risk rating included the north and western margins of Dirk Hartog Island, which reflects the proximity to offshore transport routes.

There is potential for oil spills from recreational and commercial vessels as a result of damage, sinking, or collisions, though this is unpredictable and likely to be a very rare occurrence.

7.3 Introduced marine pests and diseases

Tropical and temperate biotic provinces overlap at Shark Bay creating environmental conditions that could be conducive to the establishment of a wide range of introduced species.

Ten introduced species were detected from settlement plates placed around four locations in Shark Bay, and included eight bryozoans, one tunicate and one hydroid. Introduced species were also found in areas without commercial traffic and ballast water discharge, indicating that hull fouling of recreational boats may be one cause of introductions (Wyatt *et al.* 2005). In addition, three crustacean species and two barnacles have previously been identified for Shark Bay, while several more have been documented at some point for the Gascoyne region (Huisman *et al.* 2008).

The Useless Loop Port is considered to have a low inoculation risk given the low risk rating of visiting vessels and the typical single, short visits to the port (Bridgwood and McDonald 2014). The temperature and salinity conditions of the port environment are considered potentially compatible with 19 introduced species, of which 10 present the greatest likelihood of infection and establishment.

7.4 Other anthropogenic pressures

7.4.1 Tourism

An increase in tourism in Shark Bay has the potential to impact on the marine environment through increasing waste production (including discharging untreated sewage from boats), boating activity and wildlife collisions, disturbance to marine wildlife, feeding of wildlife, and habitat degradation from anchoring. There is also potential to cause damage and degradation to coastal habitats and wildlife, such as dune vegetation, erosion and nesting areas.

DBCA is responsible for issuing permits, licences, leases and authorisations that help to alleviate pressures associated with tourism activities, such as licensing for fauna interactions (see section 8.1.4).

7.4.2 Fishing pressure

Recreational and commercial fisheries are managed by DPIRD, and the status of fisheries operating in Shark Bay is assessed annually. Management measures are in place to reduce fishing pressure, prevent overfishing and ensure sustainability of stocks into the future. Pink snapper were fished to the brink of collapse inside Shark Bay in the late 1990s due mostly to recreational fishing. Fortunately, a combination of effective biological research and robust management of the snapper fishery has led to the recovery of the recreationally important stock (Christensen and Jackson 2014). Given the recovery, a code of conduct for recreational fishers in Shark Bay was released with the purpose of promoting sustainable practices and responsible fishing to minimise impact and prevent another decline (Recfishwest 2018).

7.4.3 Coastal development

Shark Bay has a growing resident population and a growing number of domestic and international visitors. There is a strong focus on economic development which is promoted in the 2017 Shark Bay Investment Prospectus (Shire of Shark Bay 2017). Denham and Monkey Mia have received upgrades to jetties and boat ramps in a $20 million public amenity and infrastructure investment. The beachfront Monkey Mia Dolphin Resort is currently undergoing a $15 million redevelopment, which includes construction of a beachfront plaza.

In 2013, a feasibility study and economic/social impacts study were undertaken for a proposed new marina facility in Denham (Brighthouse Strategic Consultants 2013; Shire of Shark Bay 2013).

7.4.4 Mining, oil and gas

The World Heritage listing of Shark Bay does not prevent mineral exploration and development, however, the proposals considered by the EPA are not allowed to compromise the values that were used to establish the listing (EPA WA 2003). EPA advice states:

> "that there be a presumption against petroleum development activities within the Shark Bay World Heritage Property on the basis that these activities could not be carried out without significantly affecting the values for which the Property has been credited World Heritage status. This would not preclude the assessment of a petroleum proposal under Part IV of the Environmental Protection Act 1986, but the circumstances associated with the proposal would need to have been designated by the State to be of exceptional importance and of a strategic nature. Given the presumption against petroleum development activities within the Shark Bay World Heritage Property, there could be little justification for allowing the pre-requisites to development, that is, activities such as preliminary exploration, seismic survey and exploration drilling, to be carried out on targets within the Shark Bay World Heritage Property"

For scenarios where proposals may be considered, such as directly outside the World Heritage boundary, potential impacts such as underwater noise pollution and seismic impacts on zooplankton through to marine mammals, disturbance to benthic habitats from drilling or dredging, release of formation water, shipping and transport, and increased risks of oil spills would need to be assessed for their impact on fauna that move in and out of the SBWHA.

Regions of the SBWHA that do exclude drilling and production are Hamelin Pool Marine Nature Reserve, eight Sanctuary zones and three Recreation zones, as well as six Special Purpose zones if activities would impact upon the conservation purpose (McCluskey 2008).

8. Management and administrative agencies

Wooramel Coast (Image courtesy SBWHA)

8.1 Conservation management

8.1.1 Overview

DBCA is the primary management agency responsible for the implementation of state and national legislation and the day to day management of the SBWHA and Shark Bay marine reserves. DBCA is also tasked with responsibilities in Commonwealth waters through bilateral agreements (see EPBC Act 1999).

Of relevance to this document, DBCA is responsible for:

- Managing the marine estate (such as marine parks and reserves) under the Conservation and Land Management Act 1984 (see section 9.2), Conservation and Land Management Regulations 2002, Biodiversity Conservation Act 2016 and Biodiversity Conservation Regulations 2018
- Managing the operational aspects of the SBWHA on behalf of the Commonwealth
- Overseeing the development and implementation of management plans
- Liaising with agencies, land owners and other parties to ensure that development and management activities do not threaten World Heritage values
- Consulting with agencies and the community to identify and regularly review priorities for the protection of World Heritage values
- Conducting or encouraging relevant research
- Distributing information and implementing educational activities and
- Reporting to the Australian Government

The Department of Water and Environmental Regulation (DWER) is responsible for administering the Environmental Protection Act 1986 (see section 9.2). In addition, if an action has the potential to adversely impact on the SBWHA, then as required under the EPBC Act 1999, the action will need to undergo an environmental impact assessment and approval process as carried out by DWER.

8.1.2 Management plan responsibilities

DBCA is responsible for implementing the following management plans in relation to Shark Bay:

- Shark Bay Marine Reserves Management Plan 1996-2006
- Shark Bay Terrestrial Reserves and Proposed Reserve Additions Management Plan 2012
- Shark Bay World Heritage Property Strategic Plan 2008-2020 (plus other State Government agencies)

8.1.3 Managing and monitoring ecological assets within Shark Bay Marine Reserves

DBCA undertakes and facilitates marine research and monitoring in relation to ecological assets within the Shark Bay Marine Reserves. The broad objectives of marine research within Shark Bay marine reserves (and all WA marine parks and reserves) as per Kendrick *et al.* (2016) include:

1) Determining biological, ecological and human use patterns and processes in marine ecosystems
2) Improving the design and configuration of marine protected areas to protect the full range of ecosystems, at levels that ensure ecological viability and reflect the diversity of the system
3) Determining ecological processes and assessing anthropogenic pressures relevant to managing threatened marine fauna

There have been 23 ecological assets/values identified for marine parks and reserves across WA (Kendrick *et al.* 2016), and those identified in the Shark Bay Marine Reserves Management Plan 1996-2006 include:

- Geomorphology
- Sediment quality
- Water quality
- Microbial communities
- Seagrass communities
- Mangroves and saltmarshes
- Coral reef communities
- Finfish communities
- Dugong
- Monkey Mia dolphins
- Macroalgal communities
- Invertebrate communities
- Cetaceans
- Marine turtles
- Sea snakes
- Seabirds

The most recent report on the ecological monitoring within Shark Bay marine reserves, as coordinated by the Marine Science Program, includes information on water quality, seagrass communities, mangroves, coral reef communities and finfish communities (DBCA 2019b).

The Conservation and Parks Commission is an independent authority and was formed from the amalgamation of two vesting authorities, the Marine Parks and Reserves Authority and the Conservation Commission. The Commission was established under the Conservation and Land Management Act 1984 with a role to conserve WA's biological diversity and ensure ecologically sustainable management of the conservation estate. The Commission provides independent advice to the Minister and prepares management plans for vested land and waters under the control of the Commission. The predecessor, Marine Parks and Reserves Authority, undertook a 10 year audit and review of the Shark Bay Marine Reserves Management Plan 1996-2006 in April 2010 (MPRA 2010). A key finding of the review was that the Management Plan was outdated and inadequate for management purposes and that an updated plan should be developed.

8.1.4 Permits and licences

Of relevance to Shark Bay, DBCA issues licences, permits, leases and authorities under the Conservation and Land Management Act 1984 and Biodiversity and Conservation Act 2016. Marine activities in Shark Bay that would require these permissions include:

- Commercial operations
- Commercial photography and filming
- Moorings in marine parks and reserves
- Native fauna licences
- Native flora licences
- Remotely piloted aircraft/drones

Additionally, authorisations are required if an action will take or disturb threatened fauna and/ or disturb a threatened ecological community.

Depending on the tenure, some of these permissions relate to the conservation estates under the Conservation and Land Management Act 1984, and some relate only to marine fauna and flora.

8.2 Fisheries management

8.2.1 Overview

Of relevance to this document, DPIRD is responsible for the management of recreational and commercial fishing, aquaculture and pearling activity across state and Commonwealth waters out to 200nm (Australian Fishing Zone). In particular, DPIRD:

- Manages fisheries, in accordance with the Aquatic Resources Management Act 2016 (see section 9.2), Fisheries Adjustment Schemes Act 1987, Fishing and Related Industries Compensation (Marine Reserves) Act 1997, Shark Bay Marine Reserves Management Plan 1996-2006 and Shark Bay World Heritage Property Management Paper for Fish Resources

- Assesses aquaculture proposals in accordance with the environmental impact assessment process and procedures established under the Fish Resources Management Act 1994, including consideration of the impacts on World Heritage values under the EPBC Act 1999 (see section 9.3) and
- Regularly monitors and reports on the status of targeted fish species in Shark Bay

The major fishery resources found in Shark Bay and assessed under the Gascoyne Coast Bioregion include the Saucer Scallop Resource, Shark Bay Prawn Resource, Shark Bay Blue Swimmer Crab Resource, Gascoyne Demersal Scalefish Resource and Gascoyne Inner Shark Bay Scalefish Resource. Smaller fisheries that have licences to operate in Shark Bay include the Shark Bay Developmental Cockle Fishery, aquaculture of blacklip oyster (*Pinctada margaritifera*), the Marine Aquarium Fish Managed Fishery, West Coast Rock Lobster Fishery, commercial Abalone Managed Fishery and Specimen Shell Managed Fishery. The commercial and recreational operations for each of these fisheries is overseen and managed by DPIRD.

Since 1994, Shark Bay has been included in annual State of the *Fisheries and Aquatic Resources Reports* which includes status reports and accumulative data on fisheries and aquatic resources for the whole of Western Australia (e.g. Gaughan and Santoro 2019). These annual reports include updates on the fisheries operating in Shark Bay, including catch and landings for commercial and recreational fishing.

Ecologically sustainable development reporting has been carried out for the Shark Bay Prawn Fishery, Shark Bay Scallop Fishery and Marine Aquarium Fish Managed Fishery (Kangas *et al.* 2006a; Kangas *et al.* 2006c; Smith *et al.* 2010). Some fisheries in WA have been assessed and certified against Marine Stewardship Council (MSC) standards. The West Coast Rock Lobster Fishery was the world's first fishery to be certified, and became certified for the fourth time in 2017. The Shark Bay Prawn Fishery was granted MSC certification in 2015 after being assessed against the MSC standards (Kangas *et al.* 2015), and after previously being positively assessed against the Commonwealth Guidelines for Assessing the Ecologically Sustainable Management of Fisheries (Environment Australia 2002). The Shark Bay Snapper Fishery has previously been assessed against the Commonwealth Guidelines for Assessing the Ecologically Sustainable Management of Fisheries and was found to operate in accordance with those Guidelines (DEH 2004b). The Abalone Managed Fishery has also received MSC certification (Hart *et al.* 2017).

A series of fisheries research reports have been produced by DPIRD which complement annual reporting and management, and these are summarised together with scientific publications under section 3.6.

8.2.2 Management plan responsibilities

Management of the fisheries occurring in Shark Bay are guided by a series of management papers including the Shark Bay Crab Managed Fishery Draft Management Plan 2015 (DoF 2015), Shark Bay Prawn Managed Fishery Bycatch Action Plan 2014 – 2019 (DoF 2014a), Shark Bay Prawn Managed Fishery Harvest Strategy 2014-2019 (DoF 2014b), Shark Bay Prawn and Scallop Fisheries Report (DoF 2010), Draft Aquaculture Plan for Shark Bay (DoF 2004), Marine Aquarium Fish Resource of Western Australia Harvest Strategy 2018 – 2022 (DPIRD 2018a), West Coast Rock Lobster Harvest Strategy and Control Rules 2014 – 2019 (DoF 2014c), Abalone Resource of Western Australia Harvest Strategy 2016 – 2021 (DoF 2017) and Specimen Shell Fishery Management Plan 1995. A shift to an Ecosystem Based Fisheries Management approach is detailed in Fletcher *et al.* (2016) which discusses how a single comprehensive harvest strategy can address all target species, sector allocations, economic, social and ecological objectives.

DPIRD also has responsibilities towards the:

- Shark Bay World Heritage Property Strategic Plan 2008-2020
- Fisheries Environmental Management Plan for the Gascoyne Region 2002
- Gascoyne Aquaculture Development Plan 1996

In 2000, a comprehensive Fisheries Environmental Management Review was undertaken for the Gascoyne region which included histories, descriptions and environmental considerations of the fisheries operating in Shark Bay, as well as legislative and administrative arrangements, stakeholder interests and environmental management issues (Shaw 2000; Shaw 2002).

8.2.3 Permits and licences

Of relevance to Shark Bay, DPIRD issues licences, permits and leases under the Aquatic Resources Management Act 2016. Marine activities in Shark Bay that would require authorisation include:

- Commercial fishing
- Recreational fishing
- Fish processing
- Aquaculture

8.3 Shark Bay World Heritage Advisory Committee

The SBWHAC was formed in 2012 following the amalgamation of the Shark Bay World Heritage Area Community Consultative Committee and Shark Bay World Heritage Property Scientific Advisory Committee.

The SBWHAC provides advice to the Minister of the Environment and to the National Environmental Protection Council (formerly Environmental Protection Heritage Council). Advice includes matters relating to:

- Protection, conservation, presentation and management of the SBWHA from the viewpoint of the community
- Research priorities which contribute to the protection and conservation of the SBWHA and understanding of its natural history
- New information or developments relevant to protection, conservation or presentation of the SBWHA
- The scientific basis of management principles and practices
- Legislative processes for environmental assessment and
- The maintenance of outstanding universal values and integrity of the SBWHA

8.4 Local Government

The SBWHA is located in the Shire of Shark Bay and Shire of Carnarvon. The Shires are responsible for decision making and management in accordance with the Local Government Act 1995. The Shires in partnership with state and Commonwealth agencies are responsible for implementing policies to help protect and conserve World Heritage values. The Shire's responsibilities include:

- Managing shire reserves within the SBWHA
- Working with state government agencies and other key stakeholders to ensure SBWHA values are not compromised and
- Providing input into the management planning process for the SBWHA

Management plans under the responsibility of the Shire of Shark Bay include:

- Shire of Shark Bay Town Planning Scheme No. 4
- Shark Bay (Yandani Gutharragudu) Investment Prospectus 2017
- Shark Bay Strategic Community Plan 2018-2028
- Shark Bay Corporate Business Plan 2019-2023
- Shark Bay Strategic Resource Plan 2019-2034
- Shark Bay Local Tourism Planning Strategy 2014

The Shire of Shark Bay (and surrounding Shires) also has some responsibilities towards the following regional plans:

- Gascoyne Regional Development Plan 2010-2020
- Gascoyne Regional Tourism Strategy 2014
- Gascoyne Regional Planning and Infrastructure Framework 2015
- Roads 2030 Strategies for Significant Local Government Roads - Gascoyne Region 2013

8.5 Adaptive management

The marine ecosystem of Shark Bay and the natural values that designate it a World Heritage Area are under threat from climate change. There is a need to understand how Shark Bay will adapt to ecosystem change and how adaptive management frameworks can incorporate ecosystem change. There are many definitions of adaptive management, though essentially it can be broken down to continually improving management practices when new knowledge is obtained. For Shark Bay following the 2011 marine heatwave, there is a need to develop rapid response plans and to understand the consequences of ecosystem change in order to better inform adaptive management.

The two primary state government agencies with management responsibilities in Shark Bay, DBCA and DPIRD, are currently working under an adaptive management framework that could benefit from understanding how Shark Bay will respond and adapt to ecosystem change.

The ecological monitoring carried out by DBCA in the Shark Bay marine reserves has provided benchmarks for which to assess the condition of ecological values over time (DBCA 2019b). DBCA states that

> "The information in this report provides a benchmark assessment of the condition of key ecological values of the Shark Bay marine reserves and some of the pressures acting on them. The analyses and synthesis information provided here and in subsequent updated reports will inform adaptive management of the Shark Bay marine reserves by providing a knowledge-based understanding around key management objectives"

Two examples of ongoing adaptive management by DBCA include the provisioned dolphins off the shores of Monkey Mia and commercial operations in Red Cliff Bay. DBCA and predecessors have managed the provisioning of dolphins since 1996 and have adapted management based on updated science and reviews of the feeding program (e.g. Wilson 1996). Research by Bejder *et al.* (2006b) revealed that an increase in the number of tour operators, from one to two, offering marine mammal interactions corresponded to a significant average decline in dolphin abundance at Red Cliff Bay. Research such as this was used to inform management and led to the establishment of the Red Cliff Bay Marine Mammal Interaction Restriction Area, where a maximum of one commercial vessel is allowed a licence to enter the zone and conduct marine mammal interactions. The licence also states extra conditions, such as no feeding of marine mammals and speed restrictions (DBCA 2019a).

The EBFM framework implemented by DPIRD allows for the reassessment and amendment of risks to assets and issues based on the monitoring outcomes of the previous year (Fletcher *et al.* 2010). The annual State of the Fisheries reports use the EBFM approach to present assessments and risk status of assets (Gaughan and Santoro 2019).

An example of effective adaptive management by DPIRD and predecessors (before the implementation of EBFM) is that of pink snapper. When pink snapper were fished to the brink of collapse in the late 1990s, a series of adaptive management strategies and targeted research led to the recovery of spawning stocks (Jackson and Moran 2012). Long-term monitoring of recreational fishing in Shark Bay has been able to show the immediate response of fishers to these different adaptive management strategies (Wise *et al.* 2012). Today, seasonal closures, bag limits and minimum legal size limits are still used to manage pink snapper stocks in Shark Bay.

9. Tenure and legislation

Juvenile cardinal fish, Faure Sill
(Photo: Rachel Austin)

9.1 Existing tenure

9.1.1 State and Commonwealth waters

Western Australian state waters encompass the coastline out to three nautical miles, including estuaries and embayments, and are managed by the Western Australian Government and state legislation.

Commonwealth marine waters stretch from 3 to 200 nautical miles from the coast and are managed by the Australian Government and Commonwealth legislation.

9.1.2 Marine protected areas

9.1.2.1 Shark Bay Marine Park (State)

The Shark Bay Marine Park was established in 1990 and encompasses 748,725 hectares which includes most of the waters from the inner gulfs. The Park is currently managed in accordance with the Shark Bay Marine Reserves Management Plan 1996-2006. Four types of zoning are found within the Park and include:

- General Use Zone
- Sanctuary Zones
  - Disappointment Reach Sanctuary Zone
  - Gudrun Wreck Sanctuary Zone
  - Big Lagoon Sanctuary Zone
  - Sandy Point Sanctuary Zone
  - Surf Point Sanctuary Zone
  - Lharidon Bight Sanctuary Zone
  - Eighteen Mile Sanctuary Zone
  - Mary Anne Island Sanctuary Zone
- Special Purpose Zones
  - Wooramel Special Purpose Zone for seagrass protection
  - Gladstone Special Purpose Zone for dugong protection
  - Cape Peron Special Purpose Zone for wildlife viewing and protection
  - Big Lagoon Special Purpose Zone for nursery protection
  - Freycinet Special Purpose Zone for habitat protection
  - Boorabuggatta Special Purpose Zone for habitat protection
- Recreation Zones
  - Dubaut Inlet Recreation Zone
  - Monkey Mia Recreation Zone
  - Little Lagoon Recreation Zone

9.1.2.2 Hamelin Pool Marine Nature Reserve (State)

Hamelin Pool Marine Nature Reserve was established to protect the stromatolites in Hamelin Pool. The reserve was established in 1990 and spans 132,000 hectares, and is the only marine nature reserve in Western Australia. The reserve does not allow fishing, and boating is not permitted over stromatolites or within 300m of the shore. The reserve is currently managed in accordance with the Shark Bay Marine Reserves Management Plan 1996-2006.

9.1.2.3 Shark Bay Marine Park (Commonwealth)

The Commonwealth Shark Bay Marine Park is one of 13 marine parks that form part of the Australian North-west Marine Parks Network. The Marine Park lies adjacent to the World Heritage Area and the state-managed Shark Bay Marine Park and covers 7443km^2. The Marine Park is a Multiple Use Zone of class IUCN VI which means the purpose of the area is to conserve ecosystems and habitats together with cultural values and sustainable use of natural resources. The Marine Park allows activities such as general use, recreational fishing and commercial shipping, but requires authorisations for commercial fishing, aquaculture, pearling, tourism, mining, research and monitoring. Management of the Marine Park is in accordance with the North-west Marine Parks Network Management Plan 2018.

9.1.3 World Heritage Area

The SBWHA was inscribed on the World Heritage List in 1991. The SBWHA spans 22,000km^2 of which 66% is marine. The SBWHA is managed in accordance with the EPBC Act 1999 and the Shark Bay World Heritage Property Strategic Plan 2008-2020. See section 2 for more information on the SBWHA.

9.1.4 Terrestrial parks and reserves

The terrestrial parks and reserves are managed in accordance with the Shark Bay Terrestrial Reserves and Proposed Reserve Additions Management Plan 2012. The existing terrestrial parks and reserves falling within the Shark Bay World Heritage Area include:

- Francois Peron National Park
- Dirk Hartog Island National Park
- Shell Beach Conservation Park
- Monkey Mia Conservation Reserve
- Zuytdorp Nature Reserve
- Bernier and Dorre Islands Nature Reserve
- Koks Island Nature Reserve
- Friday Island Nature Reserve
- Charlie Island Nature Reserve
- Freycinet - Double Islands Nature Reserve

9.1.5 Pastoral leases

Pastoral leases make up 6%, or 131,732 hectares, of the SBWHA. Portions of pastoral lands have been relinquished and are now used for conservation purposes (232,750 ha) and proposed conservation reserves (80,015 ha). Pastoral leases are managed in accordance with the Land Administration Act 1997.

9.1.6 Native title

There are three Native Titles that exist within and around the SBWHA:

- Malgana Shark Bay People: granted Native Title in December 2018 which includes ~28,800km^2 across Shark Bay, the Shark Bay Marine Park, Dirk Hartog Island National Park, Edel Land Peninsula and Steep Point, the town of Denham, Peron Peninsula and some pastoral leases. The Malgana Aboriginal Corporation is responsible for the Native Title across this region
- Nanda People: granted Native Title in November 2018 which includes ~17,000km^2 encompassing the town of Kalbarri, Kalbarri National Park, the Zuytdorp Nature Reserve and the Toolonga Nature Reserve. The Nanda Aboriginal Corporation is responsible for the Native Title across this region
- Gnulli (Yinggarda, Baiyungu and Thalanyji People): granted Native Title in December 2019 which includes ~71,354km^2 across the Shires of Ashburton, Carnarvon, Exmouth and Upper Gascoyne Murchison and Shark Bay. The Yinggarda Aboriginal Corporation and Nganhurra Thanardi Garrbu Aboriginal Corporation are responsible for the Native Title across this region

9.2 State legislation

9.2.1 Conservation and Land Management Act 1984

The purpose of the Conservation and Land Management Act 1984 is to "make better provision for the use, protection and management of certain public lands and waters and the flora and fauna thereof, to establish the Conservation and Parks Commission, to confer functions relating to the conservation, protection and management of biodiversity and biodiversity components, and for incidental or connected purposes".

9.2.2 Biodiversity Conservation Act 2016

The Biodiversity Conservation Act 2016 "provides for the conservation and protection of biodiversity and biodiversity components in Western Australia, the ecologically sustainable use of biodiversity components in Western Australia, the repeal of the Wildlife Conservation Act 1950 and the Sandalwood Act 1929 and the consequential amendments to other Acts, and for related purposes".

The Act is supported by the Biodiversity Conservation Regulations 2018.

9.2.3 Environmental Protection Act 1986

The Environmental Protection Act 1986 provides "for an Environmental Protection Authority, for the prevention, control and abatement of pollution and environmental harm, for the conservation, preservation, protection, enhancement and management of the environment and for matters incidental to or connected with the foregoing".

The Act is supported by the Guidance Statement for Assessment of Development Proposals in Shark Bay World Heritage Property No. 49 (2000).

9.2.4 Aquatic Resources Management Act 2016

The Aquatic Resources Management Act 2016 provides for "the ecologically sustainable development and management of the state's aquatic resources, the development of strategies and plans for the conservation of aquatic resources and the protection of aquatic ecosystems, the development and management of aquaculture that is compatible with the protection of aquatic ecosystems, the management of aquatic biosecurity, the repeal of the Fish Resources Management Act 1994 and the Pearling Act 1990, and consequential amendments to various other written laws, and for incidental and related purposes".

9.2.5 Aboriginal Heritage Act 1972

The Aboriginal Heritage Act 1972 makes "provision for the preservation on behalf of the community of places and objects customarily used by or traditional to the original inhabitants of Australia or their descendants, or associated therewith, and for other purposes incidental thereto".

9.2.6 Shark Bay Solar Salt Industry Agreement Act 1983

The Shark Bay Solar Salt Industry Agreement Act 1983 ratifies "an agreement between the State of Western Australia and Agnew Clough Limited, Mitsui Salt Pty. Ltd., and Australian Mutual Provident Society with respect to the establishment and carrying on of a solar salt industry and other allied mining and ancillary industries".

9.2.7 Other State Acts

Other State Acts that have relevance to Shark Bay include:

- Agriculture and Related Resources Protection Act 1976
- Bush Fires Act 1954
- Fisheries Adjustments Scheme Act 1987
- Fishing and Related Industries Compensation (Marine Reserves) Act 1997
- Heritage Act 2018
- Jetties Act 1926
- Land Administration Act 1997
- Local Government Act 1995
- Marine and Harbours Act 1981
- Marine Navigational Aids Act 1973
- Maritime Archaeology Act 1973
- Mining Act 1978
- Petroleum (Submerged Lands) Act 1982
- Planning and Development Act 2005
- Public Works Act 1902
- Shipping and Pilotage Act 1967
- Soil and Land Conservation Act 1945
- State Petroleum Act 1967
- State Petroleum (Submerged Lands) Act 1982
- Titles (Validation) and Native Title (Effect of Past Acts) Act 1995
- Western Australian Marine Act 1982
- Western Australian Tourism Commission Act 1985

9.3 Commonwealth legislation

9.3.1 Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)

The EPBC Act provides protection and conservation for matters of national environmental significance, such as threatened species and ecological communities, migratory species, world heritage properties and heritage places. The EPBC Act also replaced the World Heritage Properties Conservation Act 1983.

The objects of the Act are:

a) to provide for the protection of the environment, especially those aspects of the environment that are matters of national environmental significance

b) to promote ecologically sustainable development through the conservation and ecologically sustainable use of natural resources

c) to promote the conservation of biodiversity

d) to provide for the protection and conservation of heritage

e) to promote a co-operative approach to the protection and management of the environment involving governments, the community, land-holders and indigenous peoples

f) to assist in the co-operative implementation of Australia's international environmental responsibilities

g) to recognise the role of Indigenous people in the conservation and ecologically sustainable use of Australia's biodiversity and

h) to promote the use of Indigenous peoples' knowledge of biodiversity with the involvement of, and in cooperation with, the owners of the knowledge

9.3.2 Underwater Cultural Heritage Act 2018

The Underwater Cultural Heritage Act 2018 replaced the Historic Shipwrecks Act 1976 in July 2019. The Act provides protection for underwater cultural heritage in Australian waters, such as shipwrecks and aircraft remains.

The objects of the Act are:

a) to provide for the identification, protection and conservation of Australia's underwater cultural heritage

b) to enable the cooperative implementation of national and international maritime heritage responsibilities and

c) to promote public awareness, understanding, appreciation and appropriate use of Australia's underwater cultural heritage

9.3.3 Native Title Act 1993

The Native Title Act 1993 recognises and protects native title and covers actions affecting native title, compensation for actions affecting native title and determination of native title existence.

The main objects of the Act are:

a) to provide for the recognition and protection of native title

b) to establish ways in which future dealings affecting native title may proceed and to set standards for those dealings

c) to establish a mechanism for determining claims to native title and

d) to provide for, or permit, the validation of past acts, and intermediate period acts, invalidated because of the existence of native title

9.3.4 Offshore Petroleum and Greenhouse Gas Storage Act 2006

The Offshore Petroleum and Greenhouse Gas Storage Act 2006 replaced the Petroleum (Submerged Land) Act 1967 in July 2008 and outlines the agreement between Commonwealth and State Governments for exploiting offshore resources.

The objects of the Act are to provide an effective regulatory framework in offshore areas (from 3nm) for:

a) petroleum exploration and recovery and

b) the injection and storage of greenhouse gas substances

9.3.5 Fisheries Management Act 1991

The Fisheries Management Act 1991 defines the Australian Fishing Zone, outlines Statutory Fishing Rights, licences, permits and offences and also responsibilities towards ecologically sustainable development. The Australian Fisheries Management Authority (AFMA) was established under the Act.

The objects of the Act are:

a) implementing efficient and cost-effective fisheries management on behalf of the Commonwealth

b) ensuring that the exploitation of fisheries resources and the carrying on of any related activities are conducted in a manner consistent with the principles of ecologically sustainable development (which include the exercise of the precautionary principle), in particular the need to have regard to the impact of fishing activities on non-target species and the long term sustainability of the marine environment

c) maximising the net economic returns to the Australian community from the management of Australian fisheries

d) ensuring accountability to the fishing industry and to the Australian community in AFMA's management of fisheries resources and

e) achieving government targets in relation to the recovery of the costs of AFMA

In addition, the Minister, AFMA and Joint Authorities are to have regard to the objectives of:

a) ensuring, through proper conservation and management measures, that the living resources of the AFZ are not endangered by overexploitation

b) achieving the optimum utilisation of the living resources of the AFZ

c) ensuring that conservation and management measures in the AFZ and the high seas implement Australia's obligations under international agreements that deal with fish stocks

d) to the extent that Australia has obligations:

   i. under international law or

   ii. under the Compliance Agreement or any other international agreement

in relation to fishing activities by Australian-flagged boats on the high seas that are additional to the obligations referred to in paragraph (c)—ensuring that Australia implements those first-mentioned obligations and

e) ensuring that the interests of commercial, recreational and Indigenous fishers are taken into account

but must ensure, as far as practicable, that measures adopted in pursuit of those objectives must not be inconsistent with the preservation, conservation and protection of all species of whales.

9.4 International treaties and agreements

9.4.1 World Heritage Convention

The Convention Concerning the Protection of the World Cultural and Natural Heritage, or World Heritage Convention, was established by UNESCO in 1972. The Convention promotes cooperation among countries to protect and preserve World Heritage Areas for future generations. Australia signed the Convention in 1974 and agreed to responsibility of protecting the values of these areas, such as the SBWHA.

9.4.2 Climate agreements

Australia is party to the Kyoto Protocol and the Paris Agreement. The Kyoto Protocol was entered into force in February 2005 and Australia ratified the agreement in December 2007. The aim of the Protocol was to set internationally binding emission reduction targets. The Paris Agreement was entered into force in November 2016 and Australia also ratified the agreement at the same time. The Agreement aims to prevent global temperatures reaching 2°C (ideally below 1.5°C) above pre-industrial levels within this century. Australia has committed to the target of reducing emissions to 26-28% on 2005 levels by 2030.

9.4.3 International Convention for the Prevention of Pollution from Ships

The International Convention for the Prevention of Pollution from Ships (MARPOL) provides regulations to prevent pollution from vessels, whether that be from accidental pollution or routine operations. Australia is a party to the agreement and implements MARPOL through the Protection of the Sea (Prevention of Pollution from Ships) Act 1983 and the Navigation Act 2012.

9.4.4 United Nations Convention for the Law of the Sea

The United Nations Convention for the Law of the Sea (UNCLOS) is an agreement that defines the rights and responsibilities of nations that use the world's oceans, and provides guidance on how to conduct business and manage the natural resources in the marine environment. Exclusive Economic Zones (EEZ) for coastal countries were established under UNCLOS, and Australia declared its EEZ in 1979.

9.4.5 CITES

Australia signed as a party to CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) in 1976 and upholds a list of CITES species under the *Environment Protection and Biodiversity Conservation Act 1999.* See section 9.5.3.1 for more information on the species from Shark Bay listed under CITES.

9.4.6 The Convention on Conservation of Southern Bluefin Tuna

Though not likely to be encountered within the SBWHA, southern bluefin tuna, *Thunnus maccoyii*, are afforded significant recognition by the Convention on Conservation of Southern Bluefin Tuna, due to it being a highly valuable and highly migratory species. The agreement is between Australia, Japan and New Zealand with the objective to conserve and sustain global stocks.

9.4.7 Migratory species

Australia is party to five agreements relating to migratory species and these are explained in more detail in section 9.5.3.

9.5 Listed species

9.5.1 Protected species (Commonwealth legislation)

The EPBC Act 1999 provides nationwide protection of the environment and conservation of biodiversity, including Commonwealth waters within the Exclusive Economic Zone exclusive of State managed waters (three nautical miles). Without a permit, it is illegal to kill, injure, take, trade, keep or move a member of a:

- Listed threatened species or ecological community
- Listed migratory species (see section 9.5.3.3)
- Listed marine species

If an action is likely to impact upon threatened species and ecological communities, then it must undergo an environmental assessment and approval process.

The EPBC Act 1999 also has a listing of 'Whales and other cetaceans', where all cetaceans are protected within the Australian Whale Sanctuary that encompasses all Australian waters. It is illegal to injure, take, trade, keep, move, harass, chase, herd, tag, mark or brand a cetacean without a permit.

The EPBC Protected Matters Search Tool was used to identify which listed species were occurring, or possibly occurring, in the Shark Bay region, and these are given in Table 3.

Table 2 Commonwealth listed species under the EPBC Act 1999 occurring, or potentially occurring, within Shark Bay. Listings obtained from the EPBC Protected Matters Search Tool. Species are included here if they are categorised as migratory, marine, or threatened. Not all listings are considered threatened.

Species name	Common name	EPBC listing	Comment
	Fishes and sharks		
Campichthys galei	Gale's Pipefish	Marine	Species or species habitat may occur within area
Choeroichthys suillus	Pig-snouted Pipefish	Marine	Species or species habitat may occur within area
Festucalex scalaris	Ladder Pipefish	Marine	Species or species habitat may occur within area
Filicampus tigris	Tiger Pipefish	Marine	Species or species habitat may occur within area
Halicampus brocki	Brock's Pipefish	Marine	Species or species habitat may occur within area
Haliichthys taeniophorus	Ribboned Pipehorse	Marine	Species or species habitat may occur within area
Hippocampus angustus	Western Spiny Seahorse	Marine	Species or species habitat may occur within area
Hippocampus histrix	Spiny Seahorse	Marine	Species or species habitat may occur within area
Hippocampus planifrons	Flat-face Seahorse	Marine	Species or species habitat may occur within area
Hippocampus trimaculatus	Three-spot Seahorse	Marine	Species or species habitat may occur within area
Lissocampus fatiloquus	Prophet's Pipefish	Marine	Species or species habitat may occur within area
Nannocampus subosseus	Bonyhead Pipefish	Marine	Species or species habitat may occur within area
Solegnathus lettiensis	Gunther's Pipehorse	Marine	Species or species habitat may occur within area
Solenostomus cyanopterus	Robust Ghostpipefish	Marine	Species or species habitat may occur within area
Stigmatopora argus	Spotted Pipefish	Marine	Species or species habitat may occur within area
Syngnathoides biaculeatus	Double-end Pipehorse	Marine	Species or species habitat may occur within area
Trachyrhamphus bicoarctatus	Bentstick Pipefish	Marine	Species or species habitat may occur within area
Carcharias taurus (west coast population)	Grey Nurse Shark (west coast population)	Vulnerable	Species or species habitat known to occur within area
Carcharodon carcharias	Great White Shark	Vulnerable; Migratory	Species or species habitat known to occur within area
Rhincodon typus	Whale Shark	Vulnerable; Migratory	Species or species habitat known to occur within area
	Marine/water birds		
Actitis hypoleucos	Common Sandpiper	Marine; Migratory	Species or species habitat known to occur within area
Anous stolidus	Common Noddy	Marine; Migratory	Species or species habitat likely to occur within area

Species name	Common name	EPBC listing	Comment
	Marine/water birds		
Anous tenuirostris melanops	Australian Lesser Noddy	Vulnerable; Marine	Species or species habitat may occur within area
Apus pacificus	Fork-tailed Swift	Marine; Migratory	Species or species habitat likely to occur within area
Ardea alba	Great Egret	Marine	Breeding known to occur within area
Ardea ibis	Cattle Egret	Marine	Species or species habitat may occur within area
Arenaria interpres	Ruddy Turnstone	Marine; Migratory	Roosting known to occur within area
Calidris acuminata	Sharp-tailed Sandpiper	Marine; Migratory	Species or species habitat known to occur within area
Calidris alba	Sanderling	Marine; Migratory	Roosting known to occur within area
Calidris canutus	Red Knot	Endangered; Marine; Migratory	Species or species habitat known to occur within area
Calidris ferruginea	Curlew Sandpiper	Critically Endangered; Marine; Migratory	Species or species habitat known to occur within area
Calidris melanotos	Pectoral Sandpiper	Marine; Migratory	Species or species habitat known to occur within area
Calidris ruficollis	Red-necked Stint	Marine; Migratory	Roosting known to occur within area
Calidris tenuirostris	Great Knot	Critically Endangered; Marine; Migratory	Roosting known to occur within area
Catharacta skua	Great Skua	Marine	Species or species habitat may occur within area
Charadrius leschenaultii	Greater Sand Plover	Vulnerable; Marine; Migratory	Roosting known to occur within area
Charadrius ruficapillus	Red-capped Plover	Marine	Roosting known to occur within area
Charadrius veredus	Oriental Plover	Marine; Migratory	Species or species habitat may occur within area
Chrysococcyx osculans	Black-eared Cuckoo	Marine	Species or species habitat known to occur within area
Diomedea amsterdamensis	Amsterdam Albatross	Endangered; Marine; Migratory	Species or species habitat may occur within area
Diomedea exulans	Wandering Albatross	Vulnerable; Marine; Migratory	Species or species habitat may occur within area
Fregata ariel	Lesser Frigatebird	Marine; Migratory	Species or species habitat known to occur within area
Gallinago megala	Swinhoe's Snipe	Marine; Migratory	Roosting likely to occur within area
Gallinago stenura	Pin-tailed Snipe	Marine; Migratory	Roosting likely to occur within area
Haliaeetus leucogaster	White-bellied Sea-Eagle	Marine	Species or species habitat known to occur within area
Heteroscelus brevipes	Grey-tailed Tattler	Marine; Migratory	Roosting known to occur within area
Himantopus himantopus	Pied Stilt	Marine	Roosting known to occur within area
Hirundo rustica	Barn Swallow	Marine	Species or species habitat known to occur within area
Larus novaehollandiae	Silver Gull	Marine	Breeding known to occur within area

Species name	Common name	EPBC listing	Comment
	Marine/water birds		
Larus pacificus	Pacific Gull	Marine	Breeding known to occur within area
Limosa lapponica baueri	Bar-tailed Godwit	Vulnerable; Marine; Migratory	Species or species habitat known to occur within area
Limosa lapponica baueri	Northern Siberian Bar-tailed Godwit	Critically Endangered	Species or species habitat known to occur within area
Limosa limosa	Black-tailed Godwit	Marine; Migratory	Roosting known to occur within area
Macronectes giganteus	Southern Giant Petrel	Endangered; Marine; Migratory	Species or species habitat may occur within area
Macronectes halli	Northern Giant Petrel	Vulnerable; Marine; Migratory	Species or species habitat may occur within area
Merops ornatus	Rainbow Bee-eater	Marine	Species or species habitat may occur within area
Motacilla cinerea	Grey Wagtail	Marine	Species or species habitat may occur within area
Motacilla flava	Yellow Wagtail	Marine	Species or species habitat known to occur within area
Numenius madagascariensis	Eastern Curlew	Critically Endangered; Marine; Migratory	Species or species habitat known to occur within area
Numenius minutus	Little Curlew	Marine; Migratory	Roosting likely to occur within area
Numenius phaeopus	Whimbrel	Marine; Migratory	Roosting known to occur within area
Pandion haliaetus	Osprey	Marine; Migratory	Breeding known to occur within area
Pluvialis squatarola	Grey Plover	Marine; Migratory	Roosting known to occur within area
Pterodroma mollis	Soft-plumaged Petrel	Vulnerable; Marine	Species or species habitat may occur within area
Puffinus carneipes	Flesh-footed Shearwater	Marine; Migratory	Species or species habitat likely to occur within area
Puffinus pacificus	Wedge-tailed Shearwater	Marine; Migratory	Breeding known to occur within area
Recurvirostra novaehollandiae	Red-necked Avocet	Marine	Roosting known to occur within area
Rostratula benghalensis (sensu lato)	Painted Snipe	Endangered; Marine	Species or species habitat known to occur within area
Sterna anaethetus	Bridled Tern	Marine; Migratory	Breeding known to occur within area
Sterna bengalensis	Lesser Crested Tern	Marine	Breeding known to occur within area
Sterna bergii	Crested Tern	Marine; Migratory	Breeding known to occur within area
Sterna caspia	Caspian Tern	Marine; Migratory	Breeding known to occur within area
Sterna dougallii	Roseate Tern	Marine; Migratory	Breeding known to occur within area
Sterna fuscata	Sooty Tern	Marine	Breeding known to occur within area
Sterna nereis	Fairy Tern	Vulnerable; Marine	Breeding known to occur within area
Thalassarche carteri	Indian Yellow-nosed Albatross	Vulnerable; Marine; Migratory	Foraging, feeding or related behaviour may occur within area

Species name	Common name	EPBC listing	Comment
	Marine/water birds		
Thalassarche cauta	Shy Albatross	Vulnerable; Marine; Migratory	Species or species habitat may occur within area
Thalassarche impavida	Campbell Albatross	Vulnerable; Marine; Migratory	Species or species habitat may occur within area
Thalassarche melanophris	Black-browed Albatross	Vulnerable; Marine; Migratory	Species or species habitat may occur within area
Thalassarche steadi	White-capped Albatross	Vulnerable; Marine; Migratory	Foraging, feeding or related behaviour likely to occur within area
Tringa glareola	Wood Sandpiper	Marine; Migratory	Roosting known to occur within area
Tringa nebularia	Common Greenshank	Marine; Migratory	Species or species habitat known to occur within area
Xenus cinereus	Terek Sandpiper	Marine; Migratory	Roosting known to occur within area
	Marine reptiles		
Aipysurus laevis	Olive Seasnake	Marine	Species or species habitat may occur within area
Aipysurus pooleorum	Shark Bay Seasnake	Marine	Species or species habitat may occur within area
Caretta caretta	Loggerhead Turtle	Endangered; Marine; Migratory	Breeding known to occur within area
Chelonia mydas	Green Turtle	Vulnerable; Marine; Migratory	Breeding known to occur within area
Dermochelys coriacea	Leatherback Turtle	Endangered; Marine; Migratory	Foraging, feeding or related behaviour known to occur within area
Disteira kingii	Spectacled Seasnake	Marine	Species or species habitat may occur within area
Disteira major	Olive-headed Seasnake	Marine	Species or species habitat may occur within area
Emydocephalus annulatus	Turtle-headed Seasnake	Marine	Species or species habitat may occur within area
Ephalophis greyi	North-western Mangrove Seasnake	Marine	Species or species habitat may occur within area
Hydrophis elegans	Elegant Seasnake	Marine	Species or species habitat may occur within area
Natator depressus	Flatback Turtle	Vulnerable; Marine; Migratory	Foraging, feeding or related behaviour known to occur within area
Pelamis platurus	Yellow-bellied Seasnake	Marine	Species or species habitat may occur within area
	Marine mammals		
Dugong dugon	Dugong	Marine; Migratory	Breeding known to occur within area
Pelamis platurus	Minke Whale	Whales and other Cetaceans	Species or species habitat may occur within area
Balaenoptera borealis	Sei Whale	Vulnerable; Whales and other Cetaceans; Migratory	Species or species habitat may occur within area
Balaenoptera edeni	Bryde's Whale	Whales and other Cetaceans; Migratory	Species or species habitat may occur within area
Balaenoptera musculus	Blue Whale	Endangered; Whales and other Cetaceans; Migratory	Migration route known to occur within area

Species name	Common name	EPBC listing	Comment
	Marine reptiles		
Balaenoptera physalus	Fin Whale	Vulnerable; Whales and other Cetaceans; Migratory	Species or species habitat likely to occur within area
Delphinus delphis	Common Dolphin	Whales and other Cetaceans	Species or species habitat likely to occur within area
Eubalaena australis	Southern Right Whale	Endangered; Whales and other Cetaceans; Migratory	Species or species habitat likely to occur within area
Grampus griseus	Risso's Dolphin	Whales and other Cetaceans	Species or species habitat may occur within area
Megaptera novaeangliae	Humpback Whale	Vulnerable; Whales and other Cetaceans; Migratory	Congregation or aggregation known to occur within area
Orcinus orca	Killer Whale	Whales and other Cetaceans; Migratory	Species or species habitat may occur within area
Pseudorca crassidens	False Killer Whale	Whales and other Cetaceans	Species or species habitat likely to occur within area
Stenella attenuata	Spotted Dolphin	Whales and other Cetaceans	Species or species habitat may occur within area
Tursiops aduncus	Indian Ocean Bottlenose Dolphin	Whales and other Cetaceans	Species or species habitat likely to occur within area
Tursiops truncatus s. str.	Bottlenose Dolphin	Whales and other Cetaceans	Species or species habitat likely to occur within area

9.5.2 Protected species (State legislation)

Protected species in Western Australian waters (within 3 nautical miles of the coast) are legislated by the Biodiversity Conservation Act 2016 and Biodiversity Conservation Regulations 2018. These two documents replaced the Wildlife Conservation Act 1950 and the Sandalwood Act 1929 on 1 January 2019. The conservation categories for species include:

- Critically endangered (CR)- extremely high risk of extinction in the wild in the immediate future
- Endangered (EN)- very high risk of extinction in the wild in the near future
- Vulnerable (V)- high risk of extinction in the wild in the medium term
- Extinct (EX)- extinct in the wild and captivity
- Extinct in the wild (EW)- only existing in captivity, cultivation or as a naturalised population outside previous range
- Migratory species (MI)- species that visit Australia and Australian waters or those protected under international agreements
- Species of special conservation interest (conservation dependent fauna) (CD)- species dependant on conservation to prevent a threatened status
- Other specially protected fauna (OS)- needing special protection to ensure their conservation
- Priority 1: Poorly-known species (P1)- known from a very small number of locations (5 or less) which appear to be under immediate threat. Further survey needed
- Priority 2: Poorly-known species (P2)- known from a very small number of locations (5 or less) which tend to be on conservation managed lands, and appear to be under threat. Further survey needed
- Priority 3: Poorly-known species (P3)- known from several locations and does not appear under imminent threat. Further survey needed
- Priority 4: Rare, Near Threatened and other species in need of monitoring (P4)- adequately known but require regular monitoring

The DBCA NatureMap tool and most recent Threatened and Priority Fauna List were used to identify which conservation listed species were occurring in the Shark Bay region, and these are given in Table 3.

Table 3 State listed species identified for Shark Bay as determined by DBCA NatureMap and Threatened and Priority Fauna List.

Scientific name	Common name	WA status
	Sharks	
Rhincodon typus	Whale shark	OS
	Birds	
Actitis hypoleucos	Common Sandpiper	MI
Amytornis textilis textilis	Western Grasswren	P4
Anous stolidus	Common Noddy	MI
Apus pacificus	Fork-tailed Swift	MI
Ardenna carneipes	Flesh-footed Shearwater, Fleshy-footed Shearwater	VU
Ardenna pacifica	Wedge-tailed Shearwater	MI
Arenaria interpres	Ruddy Turnstone	MI
Calamanthus campestris hartogi	Dirk Hartog Island Rufous Fieldwren	VU
Calidris acuminata	Sharp-tailed Sandpiper	MI
Calidris alba	Sanderling	MI
Calidris canutus	Red Knot	EN
Calidris ferruginea	Curlew Sandpiper	CR
Calidris melanotos	Pectoral Sandpiper	MI
Calidris ruficollis	Red-necked Stint	MI
Calidris subminuta	Long-toed Stint	MI
Calidris tenuirostris	Great Knot	CR
Charadrius dubius	Little Ringed Plover	MI
Charadrius leschenaultii	Greater Sand Plover, Large Sand Plover	VU
Charadrius mongolus	Lesser Sand Plover	EN
Charadrius veredus	Oriental Plover	MI
Chlidonias leucopterus	White-winged Black Tern, White-winged Tern	MI
Falco hypoleucos	Grey Falcon	VU
Falco peregrinus	Peregrine Falcon	OS
Fregata ariel	Lesser Frigatebird	MI
Gelochelidon nilotica	Gull-billed Tern	MI
Glareola maldivarum	Oriental Pratincole	MI
Hirundo rustica	Barn Swallow	MI
Hydroprogne caspia	Caspian Tern	MI
Leipoa ocellata	Malleefowl	VU
Limicola falcinellus	Broad-billed Sandpiper	MI
Limnodromus semipalmatus	Asian Dowitcher	MI
Limosa lapponica	Bar-tailed Godwit	MI (& VU or CR at subsp. Level)
Limosa limosa	Black-tailed Godwit	MI
Macronectes giganteus	Southern Giant Petrel	MI
Malurus lamberti bernieri	Shark Bay Variegated Fairy-wren	VU

Scientific name	Common name	WA status
	Birds	
Malurus leucopterus leucopterus	Dirk Hartog black and White Fairy-wren	VU
Numenius madagascariensis	Eastern Curlew	CR
Numenius minutus	Little Curlew, Little Whimbrel	MI
Numenius phaeopus	Whimbrel	MI
Oceanites oceanicus	Wilson's Storm-petrel	MI
Onychoprion anaethetus	Bridled Tern	MI
Oxyura australis	Blue-billed Duck	P4
Pandion cristatus	Osprey, Eastern Osprey	MI
Philomachus pugnax	Ruff (Reeve)	MI
Plegadis falcinellus	Glossy Ibis	MI
Pluvialis fulva	Pacific Golden Plover	MI
Pluvialis squatarola	Grey Plover	MI
Puffinus huttoni	Hutton's Shearwater	EN
Rostratula australis	Australian Painted Snipe	EN
Stercorarius antarcticus lonnbergi	Brown Skua, Subantarctic Skua	P4
Sterna dougallii	Roseate Tern	MI
Sterna hirundo	Common Tern	MI
Sternula albifrons	Little Tern	MI
Stipiturus malachurus hartogi	Dirk Hartog Island Emu-wren	VU
Thalassarche cauta cauta	Shy Albatross	VU
Thalassarche chlororhynchos	Atlantic Yellow-nosed Albatross	VU
Thalassarche chrysostoma	Grey-headed Albatross	VU
Thalasseus bergii	Crested Tern	MI
Tringa brevipes	Grey-tailed Tattler	MI & P4
Tringa glareola	Wood Sandpiper	MI
Tringa nebularia	Common Greenshank, Greenshank	MI
Tringa stagnatilis	Marsh Sandpiper, Little Greenshank	MI
Tringa totanus	Common Redshank, Redshank	MI
Xenus cinereus	Terek Sandpiper	MI
	Marine reptiles	
Caretta caretta	Loggerhead Turtle	EN
Chelonia mydas	Green Turtle	VU
Dermochelys coriacea	Leatherback Turtle	VU
Eretmochelys imbricata	Hawksbill Turtle	VU
	Marine mammal	
Dugong dugon	Dugong	OS
Eubalaena australis	Southern Right Whale	VU
Hydromys chrysogaster	Water-rat, Rakali	P4
Megaptera novaeangliae	Humpback Whale	CD
Neophoca cinerea	Australian Sea Lion	VU

9.5.3 International species agreements

9.5.3.1 CITES

Australia signed as a party to CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) in 1976 and upholds a list of CITES species under the *Environment Protection and Biodiversity Conservation Act 1999.*

There are three levels of protection for CITES listed species:

- Appendix I: most endangered species and threatened with extinction. No trade allowed except for non-commercial purposes
- Appendix II: not currently threatened with extinction but may become so. Includes 'look alike species' and permits are needed for international trade
- Appendix III: species that are already regulated by a party to CITES, and of which require international support to ensure sustainability and legal trade

There are 2,428 species found in Australia that are listed as CITES species (www.speciesplus.net/species). Table 4 provides a list of CITES species occurring, or potentially occurring, in Shark Bay.

Table 4 CITES listed species occurring, or potentially occurring, in Shark Bay.

Scientific name	Common name	CITES listing
Balaenoptera borealis	Sei Whale	Appendix I
Balaenoptera edeni	Bryde's Whale	Appendix I
Balaenoptera musculus	Blue Whale	Appendix I
Balaenoptera physalus	Fin Whale	Appendix I
Caretta caretta	Loggerhead Turtle	Appendix I
Chelonia mydas	Green Turtle	Appendix I
Dermochelys coriacea	Leatherback Turtle	Appendix I
Dugong dugon	Dugong	Appendix I
Eretmochelys imbricata	Hawksbill Turtle	Appendix I
Eubalaena australis	Southern Right Whale	Appendix I
Megaptera novaeangliae	Humpback Whale	Appendix I
Natator depressus	Flatback Turtle	Appendix I
Carcharodon carcharias	Great White Shark	Appendix II
Delphinus delphis	Short-beaked Common Dolphin	Appendix II
Falco hypoleucos	Grey Falcon	Appendix II
Grampus griseus	Risso's Dolphin	Appendix II
Haliaeetus leucogaster	White-bellied Sea Eagle	Appendix II
Hippocampus angustus	Western Spiny Seahorse	Appendix II
Hippocampus histrix	Spiny Seahorse	Appendix II
Hippocampus planifrons	Flat-face Seahorse	Appendix II
Manta alfredi	Reef Manta Ray	Appendix II
Manta birostris	Giant Oceanic Manta Ray	Appendix II
Orcinus orca	Killer Whale	Appendix II
Pandion haliaetus	Eastern Osprey	Appendix II
Pseudorca crassidens	False Killer Whale	Appendix II
Rhincodon typus	Whale Shark	Appendix II
Scleractinia spp.	Scleractinian Corals	Appendix II
Stenella attenuata	Spotted Dolphin	Appendix II
Tursiops truncates s. str.	Bottlenose Dolphin	Appendix II
Tursiops aduncus	Indian Ocean Bottlenose Dolphin	Appendix II

9.5.3.2 International Convention for the Regulation of Whaling

Australia was a party to the *International Convention for the Regulation of Whaling* that was signed in 1946 which aimed to conserve and manage whale stocks and the whaling industry. Australia ceased whaling in 1979, including in Shark Bay, and continues to uphold the global moratorium on commercial whaling. All cetaceans are protected under the *Environment Protection and Biodiversity Conservation Act 1999*, and are offered protection within the Australian Whale Sanctuary which includes all waters within the Exclusive Economic Zone.

9.5.3.3 Migratory species agreements

Due to migratory species having the ability to traverse multiple countries, Australia is a cooperative party to five international migratory species agreements:

- Bonn Convention (also known as the Convention on the Conservation of Migratory Species of Wild Animals): aims to conserve the habitat and migration routes of migratory species and provides the legal framework for coordinated conservation measures across migratory ranges
- CAMBA (China-Australia Migratory Bird Agreement): a bilateral migratory bird agreement with China since 1986 that conserves and protects migratory birds and important habitats, as well as protects species from take or trade (some limited exceptions)
- JAMBA (Japan-Australia Migratory Bird Agreement): a bilateral migratory bird agreement with China since 1974 that conserves and protects migratory birds and important habitats, as well as protects species from take or trade (some limited exceptions)
- ROKAMBA (Republic of Korea-Australia Migratory Bird Agreement): a bilateral migratory bird agreement with the Republic of Korea since 2007 that conserves and protects migratory birds and important habitats, as well as protects species from take or trade (some limited exceptions)
- ACAP (Agreement on the Conservation of Albatrosses and Petrels): aims to conserve albatrosses and petrels by coordinating international activities to mitigate threats to their populations

The EPBC Protected Matters Search Tool was used to identify which migratory species were listed for the Shark Bay region, and these are listed in Table 5.

Table 5 Commonwealth listed migratory species identified for Shark Bay using the EPBC Protected Matters Search Tool.

Species name	Common name	Agreement	Comment
	Rays and sharks		
Manta alfredi	Reef Manta Ray	Bonn	Species or species habitat may occur within area
Manta birostris	Giant Manta Ray	Bonn	Species or species habitat may occur within area
Lamna nasus	Mackerel Shark	Bonn	Species or species habitat may occur within area
Carcharodon carcharias	Great White Shark	Bonn	Species or species habitat known to occur within area
Rhincodon typus	Whale Shark	Bonn	Species or species habitat known to occur within area
	Marine/water birds		
Actitis hypoleucos	Common Sandpiper	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Anous stolidus	Common Noddy	CAMBA, JAMBA	Species or species habitat likely to occur within area
Apus pacificus	Fork-tailed Swift	CAMBA, JAMBA, ROKAMBA	Species or species habitat likely to occur within area
Arenaria interpres	Ruddy Turnstone	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Calidris acuminata	Sharp-tailed Sandpiper	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Calidris alba	Sanderling	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Calidris canutus	Red Knot	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Calidris ferruginea	Curlew Sandpiper	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Calidris melanotos	Pectoral Sandpiper	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Calidris ruficollis	Red-necked Stint	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Calidris tenuirostris	Great Knot	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Charadrius leschenaultii	Greater Sand Plover	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Charadrius veredus	Oriental Plover	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat may occur within area
Diomedea amsterdamensis	Amsterdam Albatross	Bonn, ACAP	Species or species habitat may occur within area
Diomedea exulans	Wandering Albatross	Bonn, ACAP	Species or species habitat may occur within area
Fregata ariel	Lesser Frigatebird	CAMBA, JAMBA, ROKAMBA	Species or species habitat known to occur within area
Gallinago megala	Swinhoe's Snipe	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting likely to occur within area
Gallinago stenura	Pin-tailed Snipe	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting likely to occur within area

Species name	Common name	Agreement	Comment
	Marine/water birds		
Heteroscelus brevipes	Grey-tailed Tattler	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Limosa lapponica baueri	Bar-tailed Godwit	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Limosa limosa	Black-tailed Godwit	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Macronectes giganteus	Southern Giant Petrel	Bonn, ACAP	Species or species habitat may occur within area
Macronectes halli	Northern Giant Petrel	Bonn, ACAP	Species or species habitat may occur within area
Numenius madagascariensis	Eastern Curlew	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area
Numenius minutus	Little Curlew	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting likely to occur within area
Numenius phaeopus	Whimbrel	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Pandion haliaetus	Osprey	Bonn	Breeding known to occur within area
Pluvialis squatarola	Grey Plover	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Puffinus carneipes	Flesh-footed Shearwater	JAMBA, ROKAMBA	Species or species habitat likely to occur within area
Puffinus pacificus	Wedge-tailed Shearwater	JAMBA	Breeding known to occur within area
Sterna anaethetus	Bridled Tern	CAMBA, JAMBA	Breeding known to occur within area
Sterna bergii	Crested Tern	JAMBA	Breeding known to occur within area
Sterna caspia	Caspian Tern	JAMBA	Breeding known to occur within area
Sterna dougallii	Roseate Tern	CAMBA, JAMBA	Breeding known to occur within area
Thalassarche carteri	Indian Yellow-nosed Albatross	Bonn, ACAP	Foraging, feeding or related behaviour may occur within area
Thalassarche cauta	Shy Albatross	Bonn, ACAP	Species or species habitat may occur within area
Thalassarche impavida	Campbell Albatross	Bonn, ACAP	Species or species habitat may occur within area
Thalassarche melanophris	Black-browed Albatross	Bonn, ACAP	Species or species habitat may occur within area
Thalassarche steadi	White-capped Albatross	Bonn, ACAP	Foraging, feeding or related behaviour likely to occur within area
Tringa glareola	Wood Sandpiper	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Tringa nebularia	Common Greenshank	CAMBA, JAMBA, ROKAMBA, Bonn	Species or species habitat known to occur within area

Species name	Common name	Agreement	Comment
	Marine/water birds		
Xenus cinereus	Terek Sandpiper	CAMBA, JAMBA, ROKAMBA, Bonn	Roosting known to occur within area
Caretta caretta	Loggerhead Turtle	Bonn	Breeding known to occur within area
Chelonia mydas	Green Turtle	Bonn	Breeding known to occur within area
Dermochelys coriacea	Leatherback Turtle	Bonn	Foraging, feeding or related behaviour known to occur within area
Natator depressus	Flatback Turtle	Bonn	Foraging, feeding or related behaviour known to occur within area
	Marine mammals		
Dugong dugon	Dugong	Bonn	Breeding known to occur within area
Balaenoptera borealis	Sei Whale	Bonn	Species or species habitat may occur within area
Balaenoptera edeni	Bryde's Whale	Bonn	Species or species habitat may occur within area
Balaenoptera musculus	Blue Whale	Bonn	Migration route known to occur within area
Balaenoptera physalus	Fin Whale	Bonn	Species or species habitat likely to occur within area
Eubalaena australis	Southern Right Whale	Bonn	Species or species habitat likely to occur within area
Megaptera novaeangliae	Humpback Whale	Bonn	Congregation or aggregation known to occur within area
Orcinus orca	Killer Whale	Bonn	Species or species habitat may occur within area

10. Research groups, data and monitoring programs

Dr. Simone Strydom assessing seagrass density and cover at DBCA long-term monitoring sites in March 2020 (Photo: DBCA)

10.1 Research groups and project websites

The below listed research groups have focused significant research efforts on the Shark Bay marine environment. The associated project websites contain a wealth of information, including access to scientific publications.

10.1.1 Seagrass Research- Kendrick Lab (UWA)

Seagrass Research focuses on the ecology, genetics and evolution, and restoration of benthic habitat forming species, particularly seagrasses, but also corals and macroalgae. Seagrass Research has been monitoring the recovery of seagrass meadows in Shark Bay after the 2011 marine heatwave, and in collaboration with the Shark Bay Malgana Indigenous community, is currently undertaking a project to help restore and assist the recovery of seagrass meadows in Shark Bay.

Project website: www.seagrassresearch.net

10.1.2 Shark Bay Ecosystem Research Project- Heithaus Lab (FIU)

The Shark Bay Ecosystem Research Project is an international collaboration of researchers focusing on the ecosystem processes and ecological interactions of marine life and habitats within Shark Bay. In particular, the project has provided the most detailed study of the ecological role of sharks in the world.

Project website: http://faculty.fiu.edu/~heithaus/SBERP/

10.1.3 Blue Carbon and Seagrass Research- Lavery Lab (ECU)

Blue Carbon Research documents the role of Shark Bay's seagrass ecosystems in capturing and storing atmospheric carbon dioxide and potential emissions of CO_2 to the atmosphere following disturbances such as the 2011 marine heatwave. Seagrass research is assessing the genetic variability of seagrasses in Shark Bay and its role in resilience and recovery potential of the meadows.

Project website: www.ecu.edu.au/schools/science/research-activity/centre-for-marine-ecosystems-research/research-themes/blue-carbon-and-paleo-reconstruction/related-content/lists/blue-carbon-stocks-and-losses-in-the-iconic-shark-bay-world-heritage-area

10.1.4 The Shark Bay Dolphin Project

The Shark Bay Dolphin Project is a long-term study that was officially established in 1984. The project focuses on the wild population of bottlenose dolphins in the waters off Monkey Mia in the Eastern Gulf of Shark Bay, and has included research on their behaviour, ecology, genetics, development, communication, social structure, predators and prey. Celine Frere's Research Group also conducts research under the Project.

Project website: www.monkeymiadolphins.org

10.1.5 Shark Bay Dolphin Research

10.1.5.1 Dolphin Alliance Project

The Dolphin Alliance Project investigates alliances among wild male bottlenose dolphins in the waters off Monkey Mia in the Eastern Gulf of Shark Bay. Dolphins have been observed since 1982, and the first discovery of alliances came in 1987 when adult males were observed swimming in pairs or trios to herd single females. Since then, there have been discoveries of male "super alliances" and juvenile male alliances.

Project website: www.sharkbaydolphins.org/dolphin-alliance-project

10.1.5.2 Dolphin Innovation Project

The Dolphin Innovation Project primarily operates out of Useless Loop in the Western Gulf of Shark Bay and was initiated in 2007. The project investigates tool use by wild bottlenose dolphins and has confirmed that dolphins learn tool use behaviours through cultural transmission.

Project website: www.sharkbaydolphins.org/dolphin-innovation-project

10.2 Databases and accessibility

A number of databases exist where data collected from Shark Bay is deposited and made freely available for other agencies and researchers to use (Table 6).

Table 6 Databases containing information and data relevant to Shark Bay.

Database	Website	Data access	Shark Bay data examples
Integrated Marine Observing System (IMOS)	http://imos.org.au/	Data freely available	SST and surface chlorophyll maps via OceanCurrent
Australian Ocean Data Network (AODN)	https://portal.aodn.org.au/	Metadata and/or data freely available	Physical and biological datasets North West Marine Research Inventory WAMSI Project No. 3.8
Australian Government	https://data.gov.au/	Data and/or metadata freely available	Metadata from research projects Maps
Marlin- CSIRO	www.marlin.csiro.au/	Metadata only	Oceanographic data Habitat maps
Australian Institute of Marine Science (AIMS)	www.aims.gov.au/docs/data/data.html	Metadata, free data access and restricted data access	Temperature logger data 2012-2014 Remote sampling of corals and fish Whale shark migration patterns
National Map	https://nationalmap.gov.au/about.html	Data freely available and restricted access	Bathymetry Satellite imagery Coastal elevation models Mangrove canopy cover
SeaMap Australia	https://seamapaustralia.org/	Data freely available	Benthic habitat maps
Department of Transport	www.transport.wa.gov.au/imarine/	Data freely available and/or restricted access	Nautical charts Tide, wave and weather data Geographic data
Digital Earth Australia- Geoscience Australia	www.ga.gov.au/dea	Data freely available	Intertidal digital elevation and extent models High and low tide composites Waterbodies
Open Data Cube	www.opendatacube.org	Data freely available	Satellite data
Coastal Oceanography	http://anfog.ecm.uwa.edu.au/Model/model.php	Data freely available. Contact: ivica.janekovic@uwa.edu.au	Real time data for: Wind, air temperature, precipitation, reflectivity, mean available convective potential energy Surface currents, sea temperature, salinity
Reef Life Survey	https://reeflifesurvey.com/	Data freely available	Fish and invertebrates Benthic photo quadrats Cryptic fish

10.3 Monitoring programs

A list of current, or recently completed, monitoring programs underway in Shark Bay are given in Table 7. These monitoring programs are carried out by WA government departments and Commonwealth agencies.

Table 7 Current, or recently completed, monitoring programs in Shark Bay.

Agency	Data	Methods	Location	Time frame	Frequency	Contact	Comments
Water quality							
DBCA	Seawater temperature	In-situ loggers, satellites	Redcliff Bay, Hamelin Pool, Denham, Sandy Point	1985- ongoing	Modelled in situ seawater temperature averaged twice weekly across nocturnal periods	thomas.holmes@dbca.wa.gov.au	
DBCA/ RAC Monkey Mia Resort	Nitrogen (Total N and DIN)	Water samples at 1 m depth	Foreshore adjacent to Monkey Mia Resort	1989- ongoing	1989, 2001, 2002, 2004, 2005, 2009, 2010, 2012-14, 2016	thomas.holmes@dbca.wa.gov.au	
DBCA/ RAC Monkey Mia Resort	Phosphates (Total P & orthophosphate)	Water samples at 1 m depth	Foreshore adjacent to Monkey Mia Resort	1989- ongoing	1989, 2001, 2002, 2004, 2005, 2009, 2010, 2012-14, 2016	thomas.holmes@dbca.wa.gov.au	
DBCA/ RAC Monkey Mia Resort	Pathogens (faecal *Enterococci* spp.)	Water samples at 1 m depth	Foreshore adjacent to Monkey Mia Resort	1989- ongoing	1989, 1990, 2001, 2002, 2004, 2005, 2010-14, 2016	thomas.holmes@dbca.wa.gov.au	
BoM	Rainfall	Recorded from Denham	Denham	1945- ongoing	Annually		
Wooramel and Gascoyne river discharge							
DWER	River discharge		Eastern Gulf	1957-2019	Annually		
Sea level							
BoM	Sea level	Logging station	Carnarvon	1985-ongoing	Monthly recordings		
Atmospheric temperature							
BoM	Daily maximum atmospheric temperature (°C)	Weather station	Carnarvon, Denham	1945-ongoing (Car), 1988-ongoing (Den)	Daily		

Agency	Data	Methods	Location	Time frame	Frequency	Contact	Comments
Groundwater availability							
BoM	Rainfall	Used as a surrogate for above and below ground water availability	Carnarvon, Denham, Useless Loop	1945-ongoing (Car), 1945-ongoing (Den), 1983-2015 (Use)	Annually		
Seagrass communities							
DBCA	Areal extent (total seagrass)	Landsat (30x30m) or Sentinel II (10x10m) imagery	Shark Bay	2010- ongoing	2014, 2016	thomas.holmes@dbca.wa.gov.au	2002 comparative data available
DBCA	Community composition	Benthic images from drop cameras/ 1 m height	Western Gulf, Peron, Monkey Mia, Eastern Gulf	2010- ongoing	2013 ,2016, 2018	thomas.holmes@dbca.wa.gov.au	Monitoring sites < 8m depth. 1996 comparative data available
DBCA	*P. australis* shoot density	20 x 20 cm quadrats at 1.5 m intervals along 3 x 10 m transects	Western Gulf, Peron, Monkey Mia, Eastern Gulf	2010- ongoing	2011, 2014, 2016	thomas.holmes@dbca.wa.gov.au	Predominantly Western Gulf. Wooramel Bank difficult to access; only limited time-series data exist for these sites
DBCA	*P. australis* canopy height	20 x 20 cm quadrats at 1.5 m intervals along 3 x 10 m transects	Western Gulf, Peron, Monkey Mia, Eastern Gulf	2010- ongoing	2011, 2014, 2016	thomas.holmes@dbca.wa.gov.au	Predominantly Western Gulf. Wooramel Bank difficult to access; only limited time-series data exist for these sites
DBCA	*P. australis* % cover	1 image, 1m above canopy at 1 m intervals along 3 x 10 m transects (30 images per site)	Western Gulf, Peron, Monkey Mia, Eastern Gulf	2010- ongoing	2011, 2014, 2016	thomas.holmes@dbca.wa.gov.au	
DBCA	*A. antarctica* stem density	All stems counted in x3 randomly placed 20 x 20 cm quadrats per transect	Eastern Gulf, Western Gulf	2010- ongoing	2014, 2016, planned for March 2020	thomas.holmes@dbca.wa.gov.au	Initial assessments only
DBCA	*A. antarctica* # clusters per stem	1 randomly collected stem per meter (x10 stems per transect), # clusters counted per stem	Eastern Gulf, Western Gulf	2010- ongoing	2014, 2016, planned for March 2020	thomas.holmes@dbca.wa.gov.au	Initial assessments only

Agency	Data	Methods	Location	Time frame	Frequency	Contact	Comments
Seagrass communities							
DBCA	*A. antarctica* # leaves per cluster	1 randomly collected stem per meter (x10 stems per transect), # leaves counted per cluster (note: the same stem that is collected for # clusters per stem is used for # leaves per cluster; x30 stems collected per site total)	Eastern Gulf, Western Gulf	2010- ongoing	2014, 2016, planned for March 2020	thomas. holmes @dbca. wa.gov.au	Initial assessments only
DBCA	*A. antarctica* canopy height	1 randomly collected stem per meter (x10 stems per transect), maximum extent measured from base to highest leaf tip (cm) per stem (note: the same stem that is collected for # clusters per stem is used for # leaves per cluster; x30 stems collected per site total)	Eastern Gulf, Western Gulf	2010- ongoing	2014, 2016, planned for March 2020	thomas. holmes @dbca. wa.gov.au	Initial assessments only
Mangroves							
DBCA	Arial extent	ALSO AVINIR-2 and SPOT 6 satellite imagery (10-25 m pixel footprints), aerial imagery (0.5 m pixel footprints) and field surveys	Carnarvon coast region, Peron Peninsula, western edge of Western Gulf	2007-ongoing	2007, 2009, 2010, 2013, 2015	thomas. holmes @dbca. wa.gov.au	
DBCA	Canopy density	ALSO AVINIR-2 and SPOT 6 satellite imagery and field measurements of projected foliage cover	Carnarvon coast region, Peron Peninsula, western edge of Western Gulf		2010, 2015	thomas. holmes @dbca. wa.gov.au	
Coral reef communities							
DBCA	Coral cover	Benthic images and transects 1 m height (benthic video in 1996)	Western Gulf, east coast of Bernier and Dorre Islands	2011-ongoing	2010, 2011, 2013, 2015, 2018	thomas. holmes @dbca. wa.gov.au	1996 comparative data available
DBCA	Community composition	Benthic images and transects 1 m height (benthic video in 1996)	Western Gulf, east coast of Bernier and Dorre Islands	2011-ongoing	2010, 2011, 2013, 2015, 2018	thomas. holmes @dbca. wa.gov.au	1996 comparative data available

Agency	Data	Methods	Location	Time frame	Frequency	Contact	Comments
Finfish communities							
DBCA	Target species abundance	stereo-DOV, belt transects, during winter in 2010/11 and summer in 2015/18. stereo-BRUV in 2018	Western Gulf, east coast of Bernier and Dorre Islands	2010- ongoing	2010, 2011, 2015, 2018	thomas. holmes @dbca. wa.gov.au	Sites located on coral dominated habitats
DBCA	Community composition	stereo-DOV, belt transects, during winter in 2010/11 and summer in 2015/18. stereo-BRUV in 2018	Western Gulf, east coast of Bernier and Dorre Islands	2010- ongoing	2010, 2011, 2015, 2018	thomas. holmes @dbca. wa.gov.au	Sites located on coral dominated habitats
DBCA	Species richness	stereo-DOV, belt transects, during winter in 2010/11 and summer in 2015/18. stereo-BRUV in 2018	Western Gulf, east coast of Bernier and Dorre Islands	2010- ongoing	2010, 2011, 2015, 2018	thomas. holmes @dbca. wa.gov.au	Sites located on coral dominated habitats
Loggerhead turtle tagging program							
DBCA/ Woodside	Body and carapace mea-surements, egg counts	Field measurements and tagging	Turtle Bay	1994- ongoing	Annually	tim. grubba@ woodside. com.au, thomas. holmes @dbca. wa.gov.au	
Prawns *							
DPIRD	Catch rates, size structure	Trawls	Denham Sound, central/ northern SB	1982- ongoing	Annually- November	mervi. kangas @dpird. wa.gov.au	Monitoring dates back to 1962 if include commercial and log book data. Data collection more compre-hensive in last 5 years
DPIRD	Spawning and recruitment, sex ratios	Aboard commercial vessels using nets	Central SB, Eastern Gulf	2000- ongoing	Twice per year	mervi. kangas @dpird. wa.gov.au	Data collection more compre-hensive in last 5 years
Scallops *							
DPIRD	Total counts, 0+, 1+ and adult counts, sub-samples of length frequency		Northern SB, Denham Sound	1982- ongoing	Annually- Nov; additionally Feb and June since 2011	mervi. kangas @dpird. wa.gov.au	Since 2011, temperature, salinity and ph have been measured in a subset of samples. Additional surveys since 2011 were multispecies focused

Agency	Data	Methods	Location	Time frame	Frequency	Contact	Comments
Crabs *							
DPIRD	Catch rates, sex, breeding condition, size composition	Scallop trawl surveys	Central SB, Western Gulf, Eastern Gulf	2002-ongoing	Annually in Nov; additionally Feb and June since 2011	mervi.kangas@dpird.wa.gov.au	Since 2011 surveys were expanded to monitor double the sites and include the Eastern Gulf. Monitoring dates back to 1989 if include commercial and log book data
DPIRD	Catch rates, sex, breeding condition, size composition	Monitoring of commercial crab trap vessel data	Central and northern SB, Eastern Gulf	2000-2013	Almost monthly	mervi.kangas@dpird.wa.gov.au	Ceased as trawl monitoring was more informative
Finfish - Snapper							
DPIRD	Catch rates, sex, length frequency	Ichthyoplankton surveys, trawl, trap, line fishing	Eastern & Western Gulfs	1997-2013	Mostly annual surveys	gary.jackson@dpird.wa.gov.au	NHT, FRDC funding. Focus - assessment of snapper stocks
Finfish - Grass emperor							
DPIRD	Catch rates, sex, length frequency	Traps, line fishing	Eastern & Western Gulfs	1999-2002	Mostly annual surveys	gary.jackson@dpird.wa.gov.au	FRDC Project 1999/152
Finfish - Baldchin							
Murdoch	Catch rates, sex, length frequency	Spear, line fishing	Eastern & Western Gulfs	Early 2000s		david.fair-clough@dpird.wa.gov.au	FRDC Project
Finfish - Communities							
DPIRD	Community composition	Traps	Eastern & Western Gulfs	1999-2001		gary.jackson@dpird.wa.gov.au	NHT, Environmental, habitat data
Recreational fishing							
DPIRD	Catch, effort, other	Boat ramp surveys	Monkey Mia, Denham, Nanga	1999-2010, 2016/17, 2018/19	Monthly	gary.Jackson@dpird.wa.gov.au	Most recent surveys RFIF funded

* Fisheries independent (standardised scientific survey at sea not affected by changes in fishing efficiency) data collected by Fisheries, DPIRD, as opposed to commercial data collected by commercial fishers

10.4 Metadata synthesis

A metadata synthesis was performed for 962 literature/data sources and is provided in the accompanying WAMSI Shark Bay metadata synthesis document found at www.wamsi.org.au/shark-bay-literature-review. Not all 962 sources were included in this literature review document as some sources were references only (e.g. no abstract, no document), in excess of already included sources, supplements or online datasets, however, they are included in the metadata synthesis. The aim of the synthesis was to capture as much metadata information as possible, particularly information on data formats, data availability, data repositories and metadata contacts. Where possible, the metadata included was sourced directly from researchers, however, this was not available from all the sources.

The majority of the research and data sources included in the metadata synthesis focused on ecological assets. Of those ecological assets, 177 outputs were for bottlenose dolphins and 130 outputs related to commercial fisheries. Microbialite communities, seagrass communities, marine turtles and elasmobranchs were also popular fields of study (Fig. 20). It should be noted that many research/data outputs were relevant to more than one ecological asset.

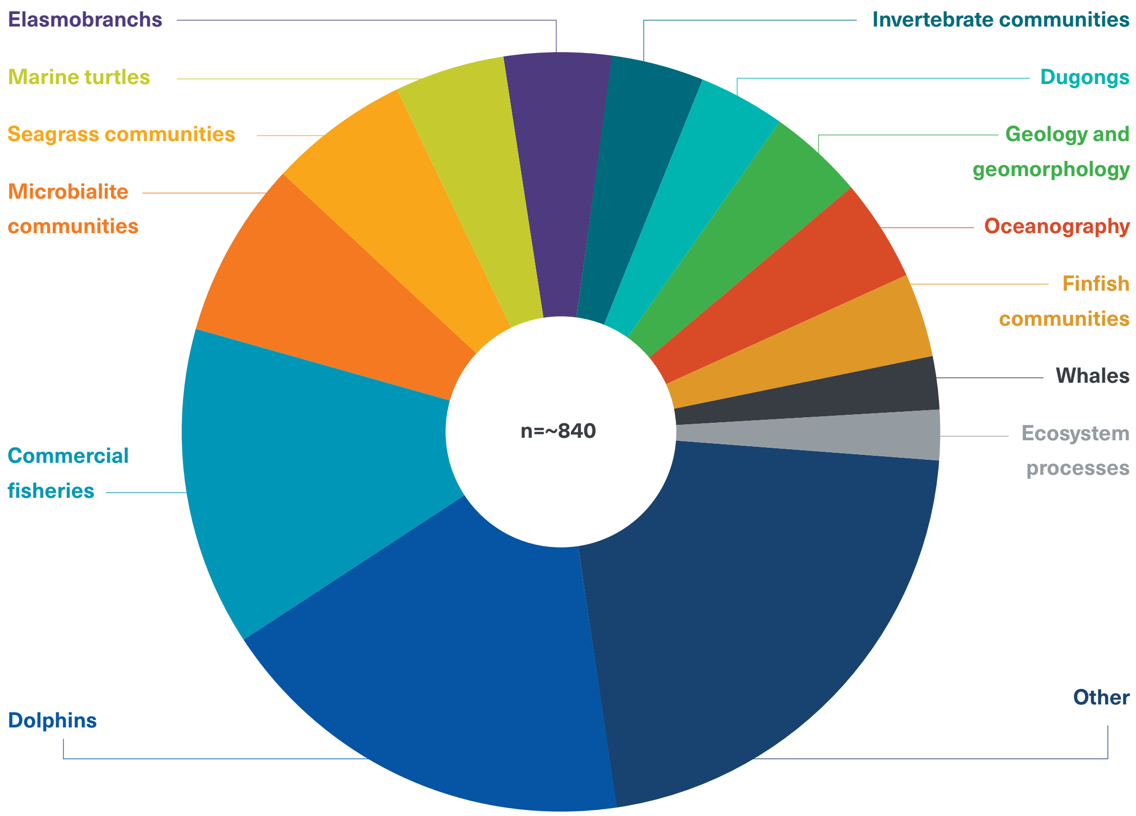


Figure 20 Common ecological assets researched at Shark Bay. 'Other' includes: recreational fisheries, seabirds, coral reef communities, ecological interactions, mangrove communities, sea snakes, water quality, algal communities, planktonic communities, hydrology, aquaculture, sediment quality, bathymetry, introduced species and sponges.

An indication of the increase in literature outputs over time is given in Fig. 21. The majority of the literature outputs were scientific papers (~500) followed by reports (~110) (Fig. 22). DPIRD Fisheries (~121) and The University of Western Australia (~115) authored the most outputs, and several other national and international universities were relatively active in Shark Bay (Fig. 23).

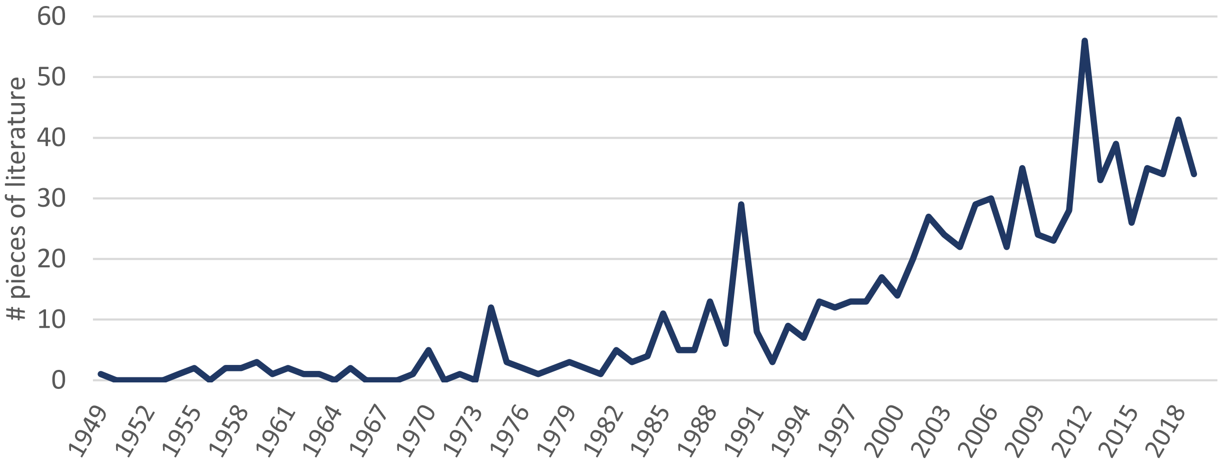


Figure 21 Literature outputs for Shark Bay since 1949.

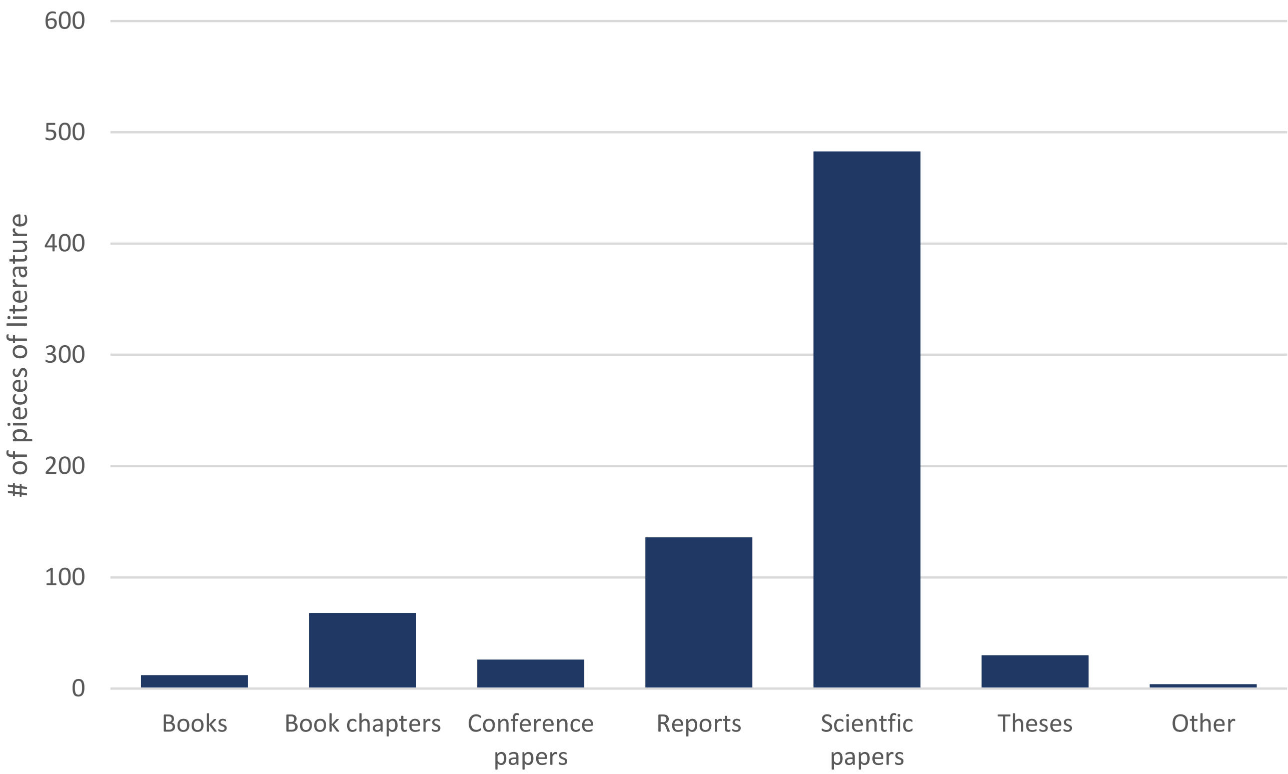
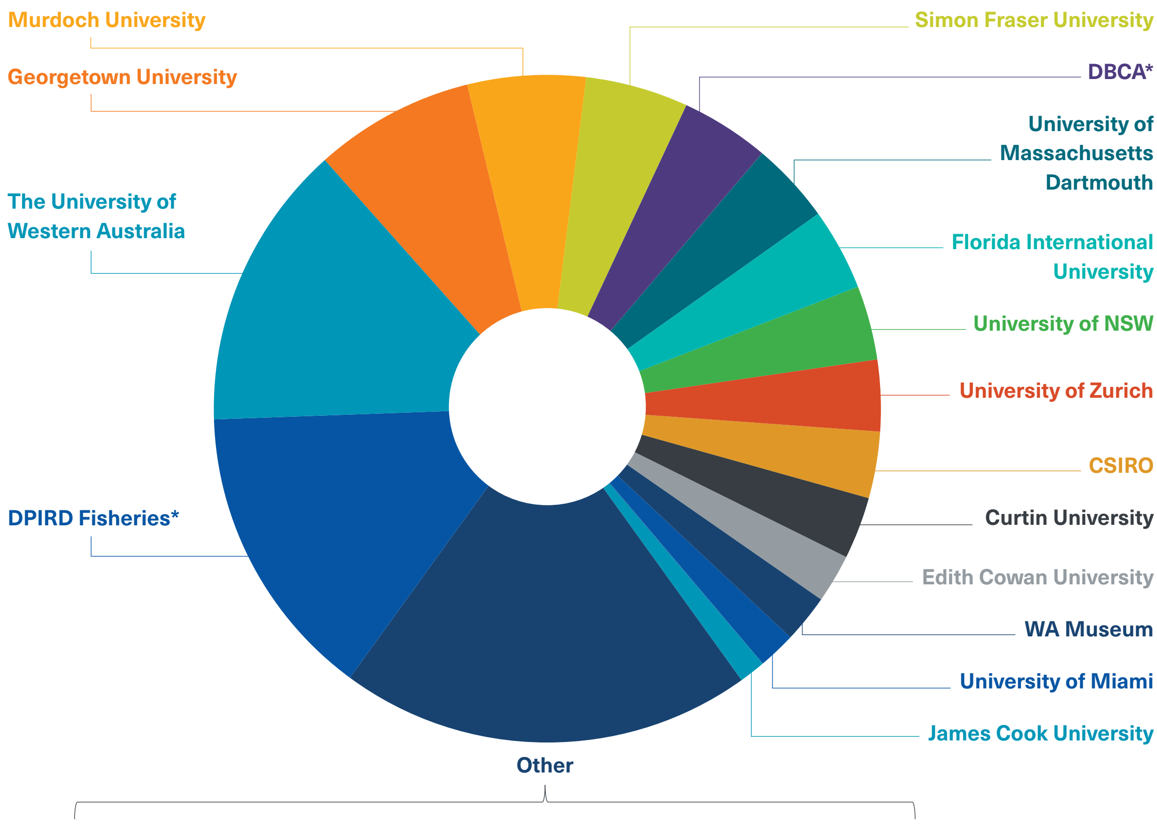


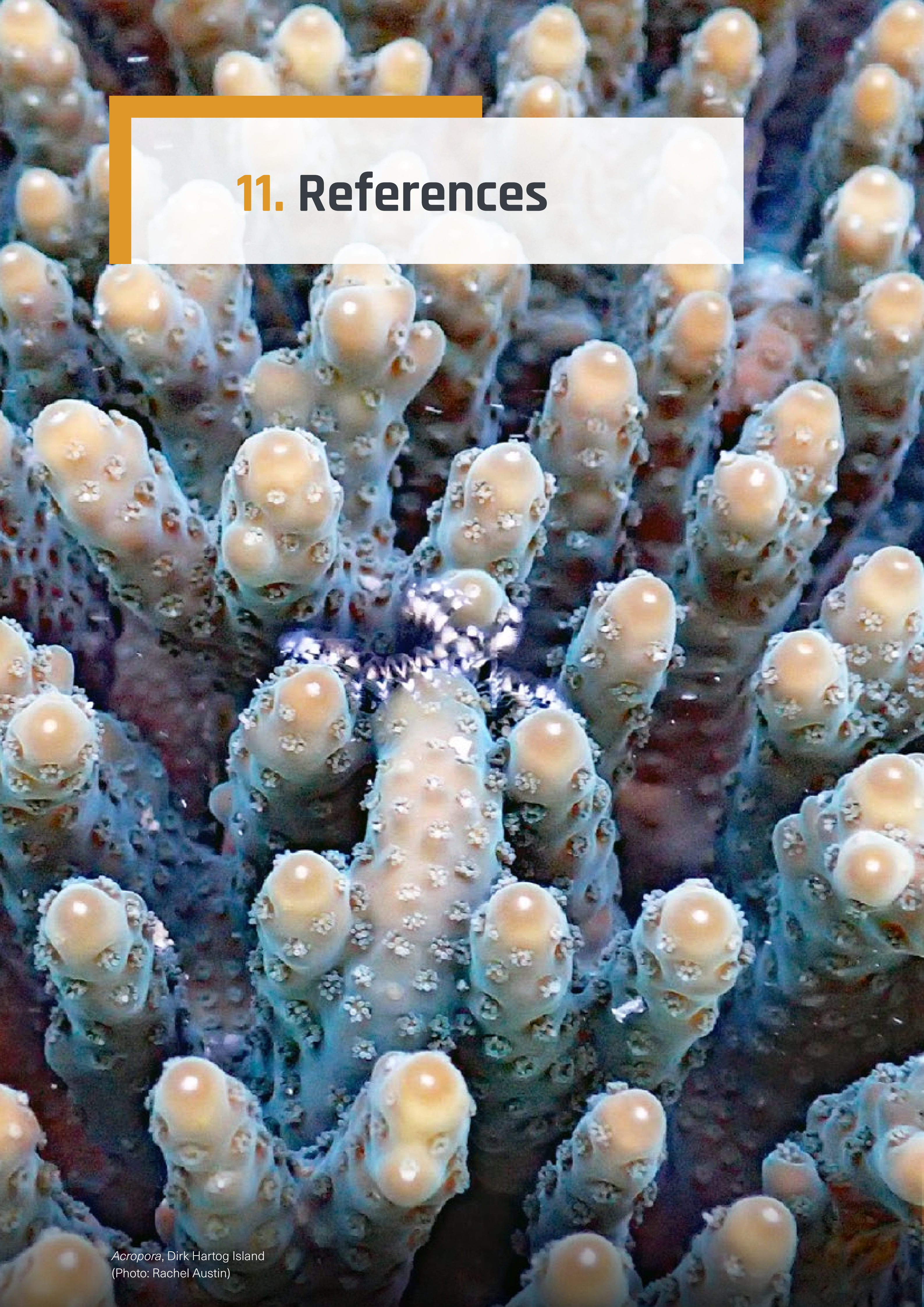
Figure 22 Categories of literature outputs used in the WAMSI Shark Bay Literature Review.



Australia Institute of Marine Science
Australian National University
Australian Venture Consultants
Baas Becking Geobiological Lab
Birdlife WA
Birds Australia WA Inc
British Museum of Natural History
California Academy of Sciences
Conservation Council WA
Centre for Whale Research
Columbia University
Cornell College
CRC for Sustainable Tourism
Dalhousie University
Damara WA
De Montfort University
Department of Agriculture
DPLH*
DWER*
Ecocean
Economic Research Associated
Environment Australia
FRDC
Freie Universität Berlin
Geological Survey of Canada
Geological Survey of WA
Geosciences Australia
Griffith University
IMAS
JAMSTEC
Kenyon College
La Trobe University
Macquarie University
Massey University
Montana State University
Mote Marine Laboratory
NASA Ames Research Center
Northern Rivers College of Advanced Education
Project Manta
Queen's University Belfast
Queens College
Rangelands NRM
Recfishwest
Rick Scoones & Associates
Smithsonian Institution
Texas A&M University
The Shire of Shark Bay
The University of Adelaide
The University of Hong Kong
The University of Michigan
The University of Tokyo
Tokyo University of Marine Science and Technology
UMASS-Dartmouth
University College London
University of Bristol
University of Calgary
University of California
University of Cambridge
University of Canberra
University of Canterbury
University of Carolina
University of Colorado
University of Florida
University of Jordan
University of Leeds
University of Maryland
University of Melbourne
University of Michigan
University of New England
University of North Carolina
University of Otago
University of Queensland
University of Rhode Island
University of Southern California
University of St Andrews
University of Sydney
University of Texas
University of the Sunshine Coast
University of Washington
University of Technology Sydney
VIMS
WA Herbarium
Woods Hole Oceanographic Institution
Woodside Energy

Figure 23 Local, national and international institutions and agencies that have produced a literature output for Shark Bay. Only first author institutions details are included. * includes all predecessors.

11. References



Acropora, Dirk Hartog Island
(Photo: Rachel Austin)

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