Western Australian School of Mines
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Geomorphology, Growth Pattern and Substrates of the Inshore Kimberley Reefs, Western Australia: A Spatial Analysis Approach

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

Coral reefs are ranked highly among the Earth's most valuable ecosystems and are considered the rainforests of the ocean in terms of biodiversity richness. However, coral reefs are very sensitive to environmental change and are among the most vulnerable and threatened ecosystems on Earth. At present, coral reefs are under threat from a range of natural and anthropogenic disturbances, which may be exacerbated by global climate change. It is estimated that about 60% of the world's coral reefs will be threatened if the present disturbance to coral reef environments continues.

Coral reefs occur extensively along the northwest coast of Australia, forming a major geomorphic feature of the Kimberley Bioregion. However, very little is known about the habitats and substrates of the reefs in this region as the remoteness of the Kimberley coast and its extreme coastal conditions, including macrotidal regimes, high turbidity, and complex coastline morphology have resulted in limited research opportunities. Previous studies have been conducted on a broad scale, but no geomorphological, surface substrate and habitat maps of the reefs have been produced. Such maps would provide researchers and reef managers with significant information and estimations of reef growth and productivity.

The primary aim of this study is to obtain detailed geomorphological information on reefs in the Kimberley Bioregion. This study used remote sensing and Geographic Information Systems (GIS), as well as multiple other data sources, to map intra-reef geomorphic zones and the associated key habitats and substrate types of shallow nearshore reefs.

Outcomes of this study showed that the Kimberley reefs possess strong morphological complexity and clear regional patterns. The study revealed that the number of Kimberley reefs is considerably (60%) greater than previously thought; the total combined reefal area of the Kimberley reefs is approximately 1,950 km^2. Fringing reefs have been identified as the dominant reef type and are widely distributed throughout the Kimberley Bioregion. After fringing reefs, planar reefs were found to be the next most dominant type. It was also found that tidal range affected the

distribution of reef geomorphologies. A prominent reef morphotype (*i.e.* 'high intertidal') was defined for the first time.

As part of the study a detailed analysis of the geomorphology, key substrates and habitats of 30 reef platforms was conducted. It was found that by applying unsupervised classification to Landsat images and using available ground-truth information for contextual editing, detailed geomorphology maps of coral reefs and their associated habitats and substrates could be obtained with relatively high accuracies (*i.e.* 64–77%) using a confusion matrix.

A comprehensive geodatabase of the Kimberley reefs entitled 'ReefKIM' was constructed. The ReefKIM facilitates the crowdsourcing of data from individuals permanently connected with the marine environment (*e.g.* rangers, commercial and recreational fishers and traditional owners) through user-friendly web-based interactive maps and/or smartphone/tablet applications.

The study provides researchers in various disciplines with a robust foundation to foster further work to improve knowledge of these biodiverse yet poorly known macrotidal reef systems. The outcomes of this study will also contribute to a better understanding of the Kimberley reefs, and provide marine park managers with essential and quality scientific information so that better management decisions can be made in this area.

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“*What gets measured gets managed*”

Dr. Peter F. Drucker
(1909 – 2005)

PUBLICATIONS INCLUDED WITHIN THIS THESIS

Published Journal Papers

1) **Kordi, M.N**., and O’Leary, M. (2016). Geomorphic Classification of Coral Reefs in the North Western Australian Shelf, Regional Studies in Marine Science, 7, 100–110.

2) **Kordi, M.N**., and O’Leary, M. (2016) A Spatial Approach to Improve Coastal Bioregion Management of the North Western Australia. Ocean & Coastal Management, 127, 26-42

3) **Kordi, M.N**., Collins, L.B., O'Leary, M., and Stevens, A. (2016). ReefKIM: An integrated geodatabase for sustainable management of the Kimberley Reefs, North West Australia. Ocean & Coastal Management, 119, 234-243

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ACRONYMS

λ	Wavelength
ν	Frequency
°C	Degree Celsius
AHO	Australian Hydrographical Office
AOI	Areas of interest
BOM	Bureau of Meteorology
ca.	Approximately
CAN	Canning Bioregion
CCSA	Conservation Council of South Australia
cf.	Compare
CO_2	Carbon dioxide
DEM	Digital elevation model
DN	Digital number
DPaW	Department of Parks and Wildlife
DSEWPaC	Department of Sustainability, Environment, Water, Population and Communities
E	East
e.g.	For example
EMR	Electromagnetic radiation
ENVI	Environment for Visualizing Images software
EROS	Resources Observation and Science Centre
ESRI	Environmental Systems Research Institute
et al.	And others
ETM+	Landsat 7 sensor Thematic Enhanced Mapper Plus
GA	Geoscience Australia
GBR	The Great Barrier Reef
GBRMPA	The Great Barrier Reef Marine Park Authority
GCRMN	Global Coral Reef Monitoring Network
GDA94	Geocentric Datum of Australia 1994

GIS	Geographic Information System/Science
GPS	Global Positioning Systems
GSWA	Geological Survey of Western Australia
HR	High-resolution
Hz	Hertz
i.e.	That is
ICLARM	International Centre for Living Aquatic Resources Management
ICRAN	International Coral Reef Action Network
ICRI	International Coral Reef Initiative
IMaRS-USF	Institute for Marine Remote Sensing-University of South Florida
IRD	Institute de Recherche pour le Development
ISODATA	Iterative Self-organizing Data Analysis
KIM	Kimberley Bioregion
km	Kilometre
km^2	Square kilometre
KML	Keyhole Markup Language
KMRP	The Kimberley Marine Research Program
KSD	King Sound Bioregion
LAT	Lowest astronomical tide
LiDAR	Light Detection and Ranging
m	Metre
MHWN	Mean high water neap
MHWS	Mean high water spring
MSL	Mean sea level
N	North
NASA	National Aeronautics and Space Administration
NE	North-east
NGO	Non-governmental organisation
NIR	Near-infrared wavelength
nm	Nanometre
NOAA	National Oceanic and Atmospheric Administration

NW	North-west
NWS	North West Shelf Bioregion
OLI	Landsat 8 sensor Operational Land Imager
Orthophotographs	An aerial photograph geometrically corrected
OSS	Oceanic Shoals Bioregion
Pan	Panchromatic waveband
pixel	Picture element
RADAR	Radar Detection and Ranging
ReefKIM	Geodatabase of the Kimberley reefs
RGB	Red, green, and blue color composite
RMSE	Root mean square error
S	South
SE	South-east
SD	Standard deviation
SQL	Structured Query Language
SST	Sea surface temperature
SW	South-west
SWIR	Short-wave infrared wavelengths
TIR	Thermal infrared wavelengths
TM	Landsat 5 sensor Thematic Mapper
UNEP	United Nations Environment Program
USGS	United States Geological Survey
VHR	Very high-resolution
VNPA	Victoria National Parks Association
VOC	The Vereenigde Oost-Indische Compagnie (the Dutch East India Company)
W	West
WAM	Western Australian Museum
WAMSI	The Western Australian Marine Science Institution
WRI	World Resources Institute

CHAPTER ONE

1 GENERAL INTRODUCTION

1.1 The importance of coral reefs

Coral reefs are ranked highly among the Earth's most valuable ecosystems and are considered the most biologically diverse of all oceanic regions (Hughes *et al.*, 2003). Although coral reefs cover only 0.2% of the ocean floor, they contain more than 25% of all marine species (Wilkinson, 2008). Moreover, coral reefs play an essential role in biogeochemical cycles, especially in the carbon cycle (Hatcher *et al.*, 1992; NOAA, 2009). Coral reefs are widely distributed in the oceans and they mainly occur in shallow (< 30 m water depth), clear, and warm waters between latitudes 30°N and 30°S (Veron, 2008; NASA, 2009). However, they also have been observed in deeper and cooler waters (Roberts *et al*., 2006; Bridge, 2013).

Hatcher (1997) described the coral reef as a complex system, because a variety of biological, physical, and chemical processes can take place over a range of spatial and temporal scales. Thus, coral reefs have been defined by numerous studies from different perspectives, including biological (Achituv and Dubinsky, 1990; Bellwood *et al.*, 2004), geomorphological (Hopley, 1982; Snead, 1982; Davis and FitzGerald, 2004), ecological (Hatcher, 1997), and geological (Head, 1987; Hallock, 1997; Coch, 1995; Montaggioni and Braithwaite, 2009).

Coral reefs have been given more attention since the 1990s, when estimates showed that approximately 10% of all coral reefs worldwide had disappeared (Wilkinson, 1993). In recent times, coral reefs have been severely damaged by a number of factors, including climate change, pollution, sediment runoff from land, and human activities (Wilkinson, 2008). Furthermore, it is estimated that about 60% of the world's coral reef will be threatened if the current disturbance to coral reef environments continues (Hughes *et al.*, 2003; McGinley and McClary, 2008). At present, coral reefs are under threat from a range of natural and anthropogenic disturbances, which will be exacerbated by global climate change (Hatcher *et al.*, 1989; Bellwood *et al.*, 2004, Maynard *et al.*, 2015).

Coral reefs are very sensitive to environmental change. The increased rate of CO_2 emissions caused by anthropogenic activities has had a negative impact on Earth’s climate leading to an increase in air and sea temperatures, sea level rise, and ocean acidification (Wilkinson, 2008). Because of these changes, coral reef systems are considered among the most vulnerable and threatened ecosystems on Earth (Nicholls *et al.*, 2007; De'ath *et al.*, 2009). While broad-scale disturbances such as tropical cyclones and bleaching cannot be prevented, it is possible to limit human impacts on reefs targeted for conservation.

Coral reefs are crucially important marine ecosystems. They are considered the rainforests of the ocean in terms of biodiversity richness (Hatcher and Hatcher, 2004; Swart, 2013). They also have a great socioeconomic value. Cesar *et al.* (2003) estimated that the overall value of the world’s coral reefs is about $30 billion per year. Hence, long-term conservational plans based on science are needed for sustainable management of coral reef ecosystems (Hatcher, 1999; Veron, 2008).

1.2 Coral reefs of Australia

Coral reefs are widespread along the tropical coastline of Australia. They cover a considerable area of nearly 50,000 km^2, corresponding to more than 17% of the total area of reefs on Earth (Wilkinson, 2008; Short and Woodroffe, 2009), which makes the Australian coast the second-largest area of coral reefs worldwide after Indonesia (Spalding *et al.*, 2001). The north-eastern coast of Australia comprises the Great Barrier Reef (GBR), which is one of the best understood and managed coral reef systems in the world (Hopley, 1982; Hopley *et al.*, 2007). On the other side of the Australian continent, the north-west coast is characterised by magnificently diverse coral reef systems extending from 10° to 28°S. These include the Houtman Abrolhos and Ningaloo Reefs, oceanic atolls and islands that include Ashmore Reef, Seringapatam Reef, Scott Reefs, and Rowley Shoals, as well as isolated nearshore reefs and scattered fringing reefs that occur along the Kimberley coast (Collins *et al.*, 1993; Lough, 1998; Collins and Testa, 2010). Most of these nearshore and fringing reefs remain poorly studied, with the exception of some isolated and remote offshore oceanic reefs and islands (Smith *et al*, 2008; Wilkinson, 2008; Collins, 2011*b*).

1.3 Coral reefs of north-western Australia

Coral reefs bordering north-western Australia connect the western Indo-Pacific and Western Australian coastal ecosystems, which makes them vital to ecosystem health in the face of climate change (Masini *et al.*, 2009). Despite this, very few geomorphic studies of the Kimberley coral reefs have been carried out, and only a vague knowledge of these reefs existed until the late 1940s. Since 1948, the Kimberley coral reefs have been investigated by a few pioneering studies. Admiralty charts and aerial photography were used in these studies to show the major features of the coral reefs and islands, which enabled more detailed studies of reef classification and their growth history during the Holocene and Pleistocene (Teichert and Fairbridge, 1948; Fairbridge, 1950, 1967). Further studies found that the Kimberley reefs were home to a large number of species (DSEWPaC, 2012). It was also noticed that there is a marked difference in the faunal diversity between offshore and inshore reefs in this region, caused by a variation of habitats (DSEWPaC, 2012). Based on these preliminary findings, the Kimberley region has been subdivided into bioregions (Figure. 1.1) (Thackway and Cresswell, 1988). Subsequently, the most significant offshore reefs of the North West Shelf Bioregion (NWS) (*e.g.* Browse Reef), and the Oceanic Shoals Bioregion (OSS) (*e.g.* the Rowley Shoals reefs, and Scott Reefs) were studied in detail (Collins, 2011*a*; Collins *et al.*, 2011).

1.4 Coral reefs of the Kimberley Bioregion

Unlike the offshore reefs, the Kimberley Bioregion (hereafter referred to as the KIM) reefs occur mainly along the Kimberley coast (Figure. 1.1), forming most of the geomorphic features of this coast (Collins, 2009). These reefs have been classified as three distinct types: fringing reefs adjacent to cliffed shores, reefs developing on bedrock edges, and large reef complexes (Brooke, 1997). Fringing reefs are widespread along the Kimberley coast and are distributed along the mainland in a varied pattern (Brooke, 1995; Blakeway, 1997); nevertheless, as aforementioned, these reefs have been much less studied than the offshore reefs and are poorly known (Collins, 2011*a*). In addition, Teichert and Fairbridge (1948) noticed that fringing reefs exist around the margins of many islands in this region.

Despite what might be considered an unsuitable environment for coral build-up with high sediment input, macrotidal regimes, highly turbid water, and raised sea surface temperature, coral reefs have been observed in the intertidal zone between shallow rocky shoals, along muddy shores, and in some bays (Wilson, 1972; O'Connor, 1989). In addition, some geographic and geomorphic estimates of reef location, thickness, and reef area, based on reef form classes, have been provided by surveys of selected reefs (Brooke, 1997). Recently, studies conducted on Montgomery Reef and some of the reefs of Talbot Bay demonstrated the unique nature of these reefs and their coral communities (Wilson and Blake, 2011; Wilson *et al.*, 2011). Furthermore, a recent study of the biogeography of the Kimberley coral reefs documented a relationship between historical processes of reef growth and reef geomorphology (Wilson, 2013). Nonetheless, there are many gaps in our understanding of the reefs of the KIM.

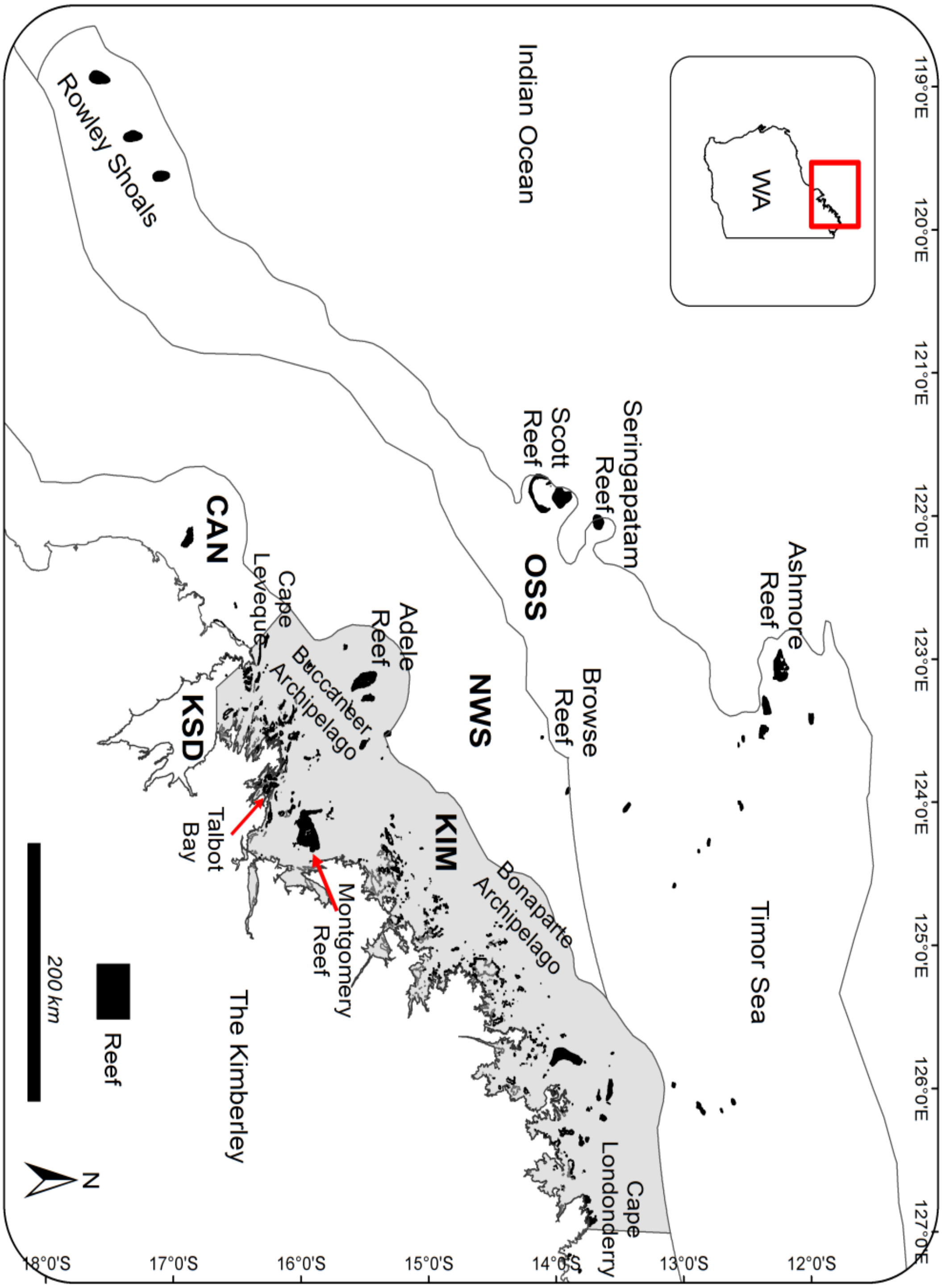

Figure 1.1. Map of north-western Australia displaying the spatial distribution of reefs illustrating the major reefs mentioned in this study. Bioregions are the Oceanic Shoals Bioregion (OSS), the North West Shelf Bioregion (NWS), the Kimberley Bioregion (KIM) (shaded area), King Sound Bioregion (KSD), and Canning Bioregion (CAN).

1.5 Study area

1.5.1 A historical background of the Kimberley coast

More than 14 decades have passed since the remote north-western margin of the Australian continent was named ‘the Kimberley’ in 1879 after John Wodehouse, the first Earl of Kimberley and the third Baron Wodehouse (Room, 2006). The anthropogenic history of the Kimberley region did not start here, however, but began tens of thousands of years earlier. Archaeologists have suggested that the Kimberley was probably one of the gateways to Australia for the people who migrated from Southeast Asia over 40,000 years ago (O'Connor, 1999). Furthermore, it has been suggested that this coast may have been visited by the ancient Egyptians, Phoenicians, and Chinese (Wilson, 1980).

The Kimberley coastline remained uncharted and poorly known until the beginning of the 16th century, when Portuguese sailors began their expeditions of exploration (Wilson, 1980). By the mid-17th century, the Kimberley coast had been visited by a succession of European ships during their voyages of exploration (Figure 1.2). The first attempt to chart the coastline of the Kimberley and to gain a better understanding of this region was made by the Dutch navigator Abel Tasman during his second voyage of exploration with a fleet of three ships from the Dutch East India Company or Vereenigde Oost-Indische Compagnie (VOC) in 1644 (McGonigal, 1990). Afterwards, in late 1687, the coast was visited by Captain Read on an English privateer, the *Cygnet.* Thereafter, in 1699, William Dampier on the English ship *Roebuck* revisited the Kimberley coast on a voyage made prominent after he assembled his observations and knowledge about this area in a book called ‘*A New Voyage around the World*’ (Wilson, 1980) (see Chapter 3).

The Kimberley coast remained isolated until the onset of the 19th century, when two French ships from the Institute de France namely *Le Geographe* and *Le Naturaliste* visited the coast (Schilder, 1988). As a result of this expedition, the Kimberley coast was surveyed in detail and a number of places and features of this coast were named (Edwards, 1991). A few years later, in 1819, Phillip Parker King, commanding the *Mermaid*, visited the coast. During this voyage, the coast was surveyed, topographic information was collected and many coastal features were named (*e.g.* Montgomery

Reef was named after the ship's surgeon Andrew Montgomery) (Wilson, 1980). Last but not least, the coast’s features were charted in great detail during the maritime expedition and hydrographical surveys that were conducted by the *Beagle* on her third voyage commanded by John Wickham in 1837 (Ingleton, 1944). As a result of these expeditions, numerous places along the Kimberley coastline such as islands, sounds, bays, and reefs have been charted and named, leaving behind a tremendous legacy and rich history of the area. Today, the Kimberley is one of the regions governed by the Western Australia State Government, occupying an area of about 424,000 km^2.

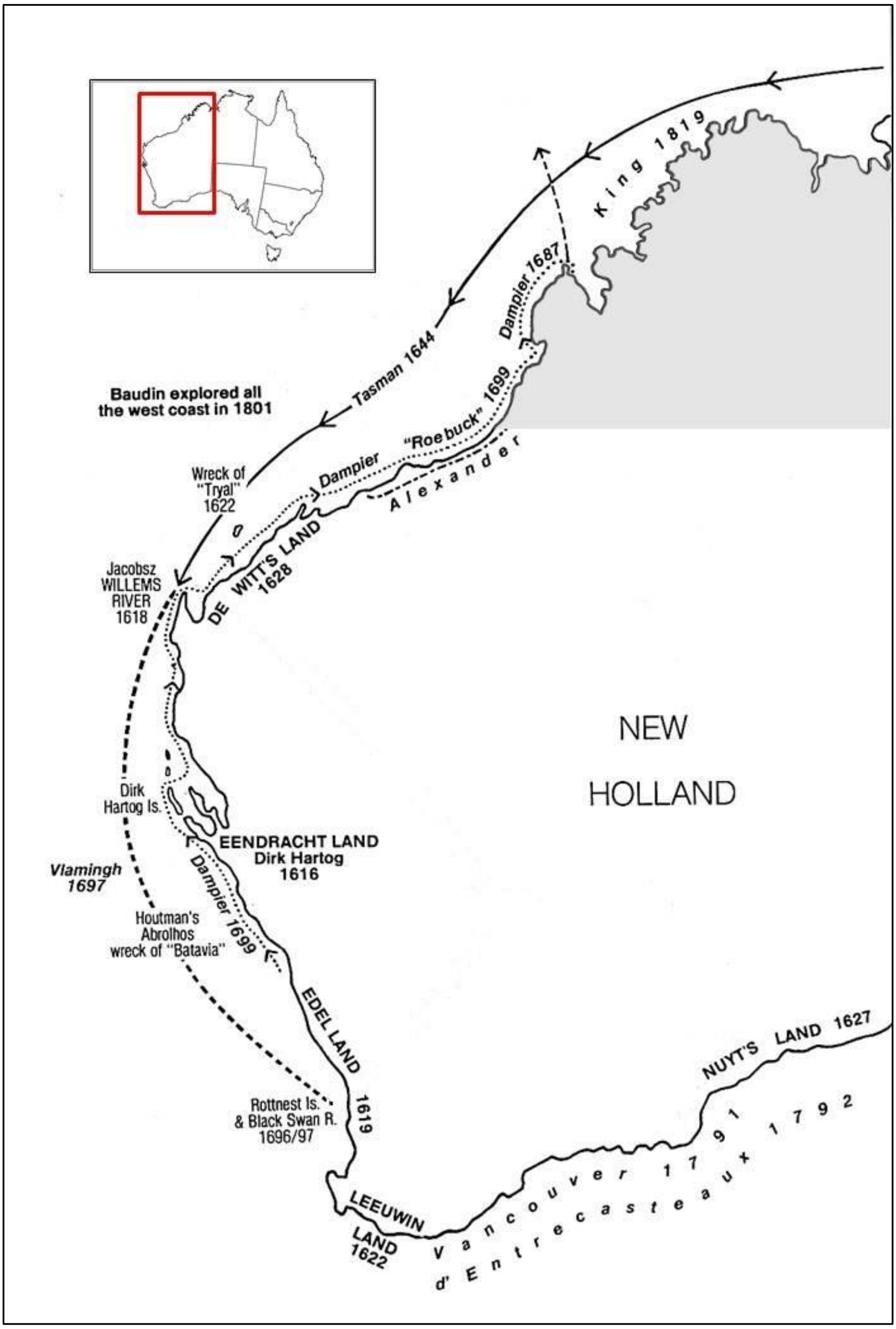

Figure 1.2 A chart of Western Australia (formerly New Holland) shows the voyages of exploration that approached this coast. The shaded area near the top represents the current Kimberley region (modified from Wilson, 1980).

1.5.2 Characteristics of the Kimberley coast

The KIM covers an area of 60,000 km^2. Its coastline stretches from Cape Londonderry in the north to Cape Leveque in the south (122°–126°E; 13°–16°S). The presence of numerous bays, capes, deep inlets, and archipelagos has resulted in a very complex coastline. The straight-line distance between the two above-mentioned capes is about 500 km, while the actual length of the coastline (excluding islands) is more than 5,000 km. The KIM encompasses at least 2413 islands and more than 850 reefs (see Section 3.3.1 and Section 3.3.5 in Chapter 3).

1.5.3 Coastal geology

The KIM is situated on the inner continental shelf of north-western Australia, where coral reefs are the main geomorphic feature along the continental shelf (Collins, 1995; Collins, 2011*b*). Geologically, it is dominated by the Proterozoic Kimberley Basin, which mainly consists of sandstones, siltstones, volcanics, and intrusive igneous rocks (Griffin and Grey, 1990). The southern part of the bioregion lies within the King Leopold Orogen. At this location, the folded and faulted King Leopold Fold Belt has been dissected into numerous islands as a result of the drowning of the continental shelf during the Holocene (Wright, 1964).

1.5.4 Climate and oceanography

The KIM is situated in a tropical marine region and is characterised by a predominately tropical climate. Annual average temperatures range between 26°C and 30°C. Rainfall averages 300 mm per year (BOM, 2012). The region is also prone to frequent tropical cyclones (on average three per year) and is characterised by prevailing southwesterly swells (Lough, 1998).

Sea surface temperatures (SST) range between 22°C and 28°C. Salinity is moderate (34.5–35.7), resembling the waters of the Indonesian Throughflow (Collins and Testa, 2010). Nearshore areas have turbid waters due to high nutrient levels and continental sediment input.

The north-western Australian shelf is tidally dominated and has the largest tidal range in the southern hemisphere. The Kimberley coast is characterised by a macrotidal regime with mean spring tides of 9.2 m, giving it the highest tidal range of any coral reef system in the world (Purcell, 2002; Wolanski and Spagnol, 2003). The highest tidal range (over 11 m) is found near Derby and Collier Bay in the southern Kimberley (see Figure 3.11 in Chapter 3). The tidal cycles in the Kimberley produce tidal rapids around the narrow passages between islands, particularly in the southern part of the region near Sunday Island and One Arm Point. The macrotides also produces tidal waterfalls in many creeks, and 'horizontal waterfalls' when the water flows off elevated reefs (Wilson, 2013). Moreover, the macrotides create broad intertidal zones, which are widespread along the Kimberley coast. Numerous coral reef communities have been observed in these intertidal zones. The wide mudflats formed by the high tides are ideal environments for mangrove growth, fish nurseries, birds, shellfish, and many reptile species.

The remoteness of the region has resulted in limited research opportunities in the study area and there is still much to learn about the coral reef habitats in the KIM. Chin *et al.* (2008) suggested that these reefs should be considered of international significance and that they required further study. In addition, Wilson (2013) suggested that describing the Kimberley coral reefs and their ecology required geomorphic studies.

At present, the Kimberley coral reefs are under potential threats from anthropogenic disturbances due to the rapid increase in oil and gas extraction, mining activities, and the tourism industry. This necessitates timely management to protect the marine environment from negative impacts (Wood and Mills, 2008; Collins, 2011*b*). Therefore, monitoring of the coral reefs is essential for their protection and preservation.

LITERATURE REVIEW

The development of a geomorphic classification of coral reefs has been closely linked to the improvement of reef mapping techniques. For instance, the three basic classes of reef include fringing, barrier, and atoll were identified by Darwin (1842) and formed the basis for his global map of coral reefs. In the 1920s, the advent of aerial photography allowed coral reefs to be viewed in plan view, allowing for a more detailed analysis of the spatial characteristics of reefs and the mapping their features in greater detail. The pioneering geoscientific work on Australian reef classification was conducted by Fairbridge (1950, 1967), who recognised the role of antecedent topography, eustasy, and physical processes in generating reef morphology; first working on the Great Barrier Reef (GBR) and later on the reefs of northern Australia, including the Kimberley coast (Finkl, 2011). Subsequently, as knowledge of reefal processes increased, Hopley (1982) was able to develop an evolutionary reef classification scheme for the GBR. Accordingly, reef classification and reef typology at global, regional and reefal scales have been dramatically improved (Andréfouët *et al.*, 2006; Hopley *et al.*, 2007; Andréfouët, 2011; Rowlands *et al.* 2014).

There are still many reef regions of the world where the accurate numbers and extent of coral reefs are underestimated or unknown. One such area is the KIM of north-west Australia where there have only been a limited number of global scale mapping efforts that have advanced our understanding of reef formation and growth, as well as providing information for monitoring of coral reef health and to support informed decisions about coral reef use and management (Spalding, 2001; Wilkinson, 2008), but they still lack the resolution required to provide realistic reef census data at regional and local scales. Despite efforts that have been made to fill this gap, no significant spatial dataset detailing the size and distribution of the Kimberley coral reefs and their attributes exists.

The Reefs of North West Australia occur within two distinct bioregions, the shelf edge Oceanic Shoals Bioregion (OSS) and the inner shelf Kimberley Bioregion (KIM) (see Figure 3.1 in Chapter 3). The OSS, which includes the Rowley Shoals and Scott Reef has seen significant scientific investigations, due in part to its proximity to the Browse Gas Fields. In particular, the morphology and growth history of these reefs have been examined using a number of methodologies including coring, U-series dating and vertical seismic profiling (Collins, 2011*a*; Collins *et al.*, 2011).

The inner shelf reefs of the Kimberley have seen limited scientific study due in part to the geographic remoteness of the region and limited infrastructure. Early investigations by Teichert and Fairbridge (1948) noted that fringing reefs exist around the margins of many islands in the region, despite the normally unsuitable environment for coral build-up, including high sediment input, macrotidal regimes, highly turbid water and raised sea surface temperatures. Wilson (1972) and O'Conner (1989) observed reefs in the intertidal zone between shallow rocky shoals, along muddy shores, and in some bays. Geographic and geomorphic estimation of reef location, thickness, and reef area was provided by Brooke (1997), who demonstrated that fringing reefs were widespread along the Kimberley coast and could be classified into three reef forms: fringing reefs adjacent to a cliffed shore; reefs developing on bedrock edges; and large reef complexes. Recent studies of Montgomery Reef and Talbot Bay by Wilson and Blake (2011) and Wilson *et al.* (2011) revealed the unique nature of these reefs and their habitats and substrates and documented the relationship between the unique physical processes and reef geomorphology. Despite these studies, there are still many unknowns in our understanding of the fringing reefs of the KIM.

The Kimberley, located in north-western Australia, has been subdivided into several marine bioregions, including the Oceanic Shoals Bioregion (OSS), the North West Shelf Bioregion (NWS), and the Kimberley Bioregion (KIM) (Thackway and Cresswell, 1988). The KIM contains the second largest reef system (after the Great Barrier Reef) in Australia spanning four degrees of latitude between Cape Londonderry and Cape Leveque (see Figure 4.1 in Chapter 4). The region is recognised as being globally significant, due to its geographic remoteness and inaccessibility. It represents one of the largest and least impacted marine ecosystems on the planet (Masini *et al.*, 2009). However, this remoteness has also resulted in only limited and infrequent scientific studies of the Kimberley marine environments being conducted (Chin *et al.*, 2008).

Presently, threats from localised anthropogenic impacts are considered low (Collins, 2011*b*), however this could change given the increase in mining activities in the region with the recent discovery of large gas fields in the offshore Browse and Bonaparte Basins and the increase in the number of tourists visiting the region. Additionally, the geographic remoteness of the Kimberley will not necessarily afford it any protection from climate-related changes such as changing sea surface temperature, ocean acidification and predicted increases in the intensity of cyclones. Accordingly, the condition of the reefs needs to be urgently assessed and the associated habitats and substrates mapped and monitored to enable researchers and managers to accurately measure and document changes over time.

Until the late 1940s, there was a paucity of knowledge about the habitats and substrates of the Kimberley reefs. This changed slightly in 1948, when the first pioneering studies were conducted. In these studies, admiralty charts and aerial photography were used to map the major features of particular reef platforms (Teichert and Fairbridge, 1948; Fairbridge 1950, 1967). However, in the 50 years that followed, very few scientific investigations were undertaken in the region and only recently has the true size and nature of the Kimberley coral reefs been determined (Collins *et al*., 2015). More recent studies have shown that the Kimberley reefs are home to a large number of species (DSEWPaC, 2012) and that there is a marked difference in faunal diversity between the offshore and inshore reefs of the region (DSEWPaC, 2012; Richards *et al*., 2013). To date, almost no remote sensing studies have been undertaken to map the habitats and substrates from a geomorphological perspective at the reef scale in the KIM. Recent work by Wilson (2013) highlighted the need for further geomorphic studies of the Kimberley reefs and their ecologies.

The study and management of coral reefs in the Kimberley present a number of challenges, the first of which relates to the geographic remoteness and the large size of the region. Accessing the region is both prohibitively expensive and time-consuming (Chin *et al*., 2008). The application of remote sensing technologies in conjunction with limited ground-truth surveys has been adopted as a more cost effective approach for dealing with the challenges of reef mapping (Dahdouh-Guebas, 2002; Veron, 2008). Depending on the resolution of the equipment employed, it is possible to map (with increasing resolution) reef geomorphology, substrate type, habitats and biological communities (Leon and Woodroffe, 2011).

Remote sensing was first employed to map reef systems shortly after Landsat-1 was launched in the early 1970s (Smith *et al*., 1975; Jupp *et al*., 1985). Since then, the use of remote sensing has become a common reef-detection method and has been used in the majority of coral reef studies conducted around the world. While there are many new remote sensors that can capture multispectral images with sub-meter resolution (*e.g*. QuickBird, WorldView-2 and 3), the Landsat TM is capable of mapping reef geomorphology and habitats at a regional scale (Bierwirth, *et al*. 1993; Luczkovich *et al*., 1993; Ahmad and Neil, 1994; Zainal, 1994; Mumby and Edwards, 2000; Andréfouët *et al*., 2003; Palandro *et al*., 2003; Purkis and Pasterkamp, 2004). The coral reefs of the Kimberley have not been studied by remote sensing except at a global scale (Spalding *et al.,* 2001; Wilkinson, 2008; ReefBase, 2015) and the maps produced thus far lack the detail required to provide information on reef geomorphology and their key benthic communities. Further, these maps cannot be used for monitoring and management purposes.

Remote sensing can be integrated into a Geographic Information System (GIS) environment that has the ability to produce dynamic maps. Such maps can be updated as new data become available and also reduces effort, costs and time (Johnson, 2000). The produced maps can be used to characterise the habitat types and substrates of each reef. This knowledge enables estimations to be made of likely types of habitats and substrates that can then be tested against available field data. This database will also lead to a better understanding of any changes to the spatial distribution of the reefs over time and pave the way for future studies on coral reefs in the region. There are currently no published works in relation to the use of remote sensing data for monitoring coral reefs in the KIM.

1.6 Study aims and objectives

The main aim of this study is to gain a regional understanding of the geomorphology of the Kimberley reefs to bridge the currently existing knowledge gap about fringing and nearshore reefs along the Kimberley coast. This study will seek answers to the main research question: '*How can we improve our understanding about the geomorphology of the Kimberley reefs?*'

At the outset, several steps need to be taken to address this question. These steps can be subdivided into three specific objectives:

1) Creation of a dedicated reef census map, and development of a geomorphic classification scheme for the Kimberley reefs.

2) Mapping of the intra-reef geomorphology and collection of information about key habitats and substrates.

3) Construction of a geodatabase with information about the Kimberley reefs (ReefKIM) for better informed reef management.

This study intends to provide a spatial analysis of fringing and nearshore reefs along the Kimberley coast. This spatial approach is expected to lead to an analysis of the reefs' geomorphologic patterns, new information about reef statistics, and to a description of reef classification and distribution by type. The resulting data will provide a reliable, spatially constrained dataset for biodiversity assessment and reef structure comparisons. It will also provide stakeholders and beneficiaries, such as marine park authorities, universities, Traditional Owners, and non-governmental organization (NGOs) with quality information relevant to the monitoring, conservation, and management of these vital natural resources. Furthermore, it will pave the way for future studies in various disciplines beyond the scope of this study.

1.7 Thesis Structure

This thesis is subdivided into six chapters. As mentioned in the preface, the manuscript consists of a series of research publications, hence, relationships between these chapters/research papers are presented in the introductory and concluding chapters, where they are placed in a wider context. Because all chapters are stand-alone manuscripts, their formats may differ based on the requirements and formatting guidelines of each individual journal. In addition, there is a small amount of unavoidable repetition, particularly in the methodology sections.

Chapter One (this chapter) starts with an overview highlighting the importance of coral reefs and their ecological and socioeconomic value. This is followed by general information about the coral reefs of Australia, with particular emphasis on reefs of the KIM and a description of the study area, including some historical background and perspectives for the future of the reefs of the KIM. Finally, the goals of this study and thesis structure are outlined in the last two sections of this chapter.

Chapter Two explains the application of geospatial technology to coral reef studies. Basic concepts of remote sensing are illustrated and an overview of the utilisation of this technique for the detection of coral reefs is provided. The chapter also illustrates how sensor characteristics and the image classification approach can improve reef mapping. Then, an overview of the significant role that Geographic Information Systems (GIS) has played in supporting coral reef studies is provided. Lastly, the usefulness of compiling a geodatabase for the integration of geospatial data and its implications for the study and management of coral reefs is demonstrated.

Chapter Three includes a regional-scale distribution map of exposed and intertidal reefs. It shows how reefs in the Kimberley can be classified into types, adopting widely recognised reef classification and typology schemes. It also illustrates the usefulness of GIS to process and produce maps as well as to provide some of the first detailed spatial analysis of reef distribution. Significant information such as reef statistics and descriptions of reef distribution are analysed to explain the reefs' geomorphology patterns.

Chapter Four shows how Landsat images and orthophotographs were utilised to determine the boundaries of geomorphic zones and associated reef substrates and habitats. It also demonstrates how the accuracy of image classification can significantly improve when ground-truthing, aerial photographs, and in situ images are integrated. Examples of detailed maps and information about the intra-reef geomorphic zones and habitats, as well as substrate types of selected fringing and planar reefs, are presented.

Chapter Five demonstrates the usefulness of developing an integrated geodatabase (ReefKIM) as a practical tool for scientists and marine park managers to facilitate better monitoring and sustainable management of Kimberley reefs. It also shows how new technologies can be employed to crowdsource data from a wide range of users through web-based and/or smartphone applications, adding value to the geodatabase.

Chapter Six summarises the key findings and significance of the study. It also provides links between individual chapters/manuscripts. Finally, it concludes the study by outlining implications and recommendations for future studies.

Appendices comprise all the additional information which is related to the study in three sections include,
Appendix A: co-author contribution statement.
Appendix B: geomorphic, habitat and substrate maps.
Appendix C: reefs information held in the geodatabase (REEFKIM).

CHAPTER TWO

2 USING GEOSPATIAL TECHNOLOGIES IN THE STUDY AND MANAGEMENT OF CORAL REEFS

This chapter reviews the literature and previous research on geospatial technologies. The introductory section of this chapter explains the application of geospatial technologies in coral reef studies. The second section illustrates the use of remote sensing in detecting coral reefs and demonstrates that the selection of an appropriate sensor and classification approach can lead to significant improvements in mapping reefs. The third section describes the key function of GIS in supporting coral reef studies. Finally, the last section of this chapter demonstrates the usefulness of a geodatabase in integrating geospatial data and discusses the implications of this database in relation to the management of coral reefs.

2.1 Introduction

The study of coral reefs along the Kimberley coastline and its adjacent islands represents a significant challenge to scientists and marine park managers, as the majority of these reefs are relatively inaccessible. In addition to being isolated, the extreme conditions of the KIM (including its macrotidal regimes, frequent tropical cyclones and turbid water) have led to a dearth of studies of the Kimberley coast. Frequent field surveys are essential to identify changes to the ecosystem over time. However, field surveys are prohibitively expensive, time consuming and weather dependent. Many of the challenges that arise in studying difficult environments can be addressed using geospatial technologies. Further, geospatial technologies can significantly increase the knowledge database required to efficiently manage the coast and its reefs (Mumby *et al.*, 1995; Andréfouët, 2008).

Geospatial technology represents a multidisciplinary approach that combines several disciplines and professional specialisations (van Manen *et al.*, 2009). Geospatial data refers to information that identifies the geographic location of features (*e.g.* reefs and other coastal features). Points, lines and polygons are used to represent the position and coordinates of these reefs and costal features. Geospatial data includes information collected in the field using Global Positioning Systems (GPS), information derived from the interpretation of remotely sensed datasets (*e.g.* satellite images and aerial photographs) and datasets digitised from maps and charts.

Geospatial technologies have been widely applied in the management of coral reefs and coastal environments (see Section 3.1 in Chapter 3 and Section 4.1 in Chapter 4). Geospatial technologies have had a significant role in many coral reef studies, however, no regional investigations of coral reefs in the KIM have been undertaken using these technologies. Consequently, there is a lack of quantitative data in relation to the KIM reefs at a regional scale. This investigation is one of the first regional studies to use geospatial technologies to investigate the coral reefs of the KIM.

2.2 Remote sensing

Algal symbionts require light for photosynthesis. Thus, coral reefs typically develop in shallow waters (*i.e.* in approximately 30 m of clear water and less in turbid water) (Mumby and Harborne, 2006) although some reefs have been identified in deep and cool waters (Roberts *et al*., 2006; Bridge, 2013). Passive remote sensors can detect the electromagnetic radiance (EMR) reflected by benthic habitats and substrates (Figure 2.1).

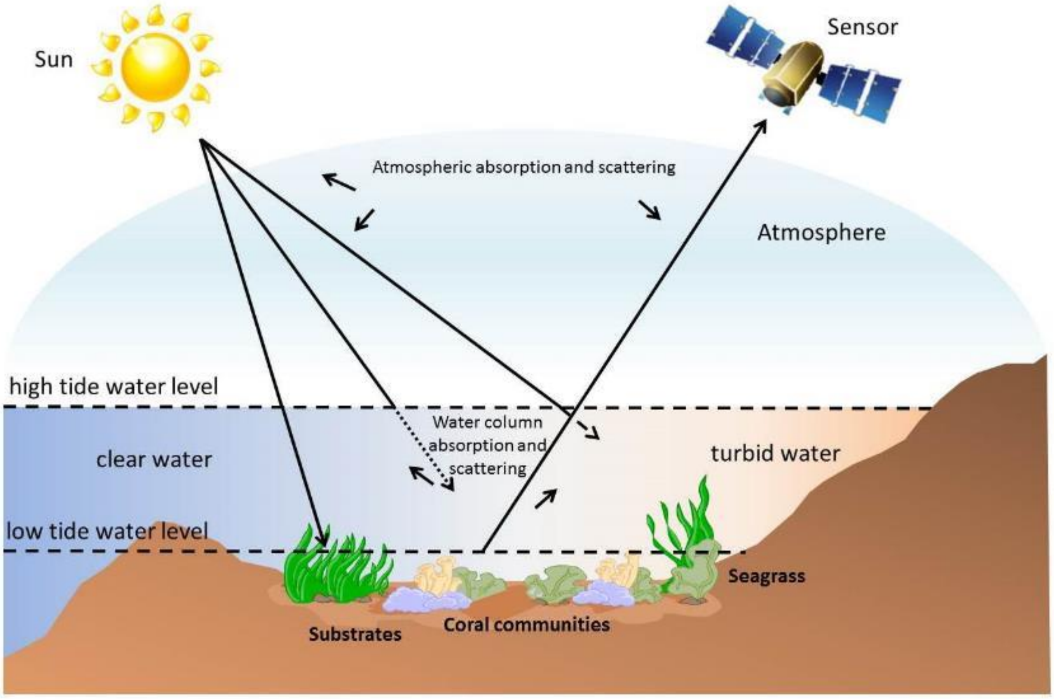

Figure 2.1. Simplified diagram of the passage of electromagnetic radiation through the atmosphere and water column as it is reflected from the surface of a coral reef and recorded by a satellite sensor.

Remote sensing concepts were first applied in the 1920s to detect intertidal and submerged marine features, including coral reefs. Around this time, aerial photographs were used to map the Great Barrier Reef (GBR) and later the reefs of Northern Australia and the Kimberley coast (Teichert and Fairbridge, 1948; Fairbridge 1950, 1967; Hopley, 1982; Finkl, 2011).

There are two types of remote sensors: active and passive. Active sensors transmit their own energy to targeted objects; this energy is then reflected back and received by the sensor (*e.g.* acoustic systems, SONAR and LiDAR). Conversely, passive sensors detect the solar EMR reflected from targeted objects (Figure 2.1).

Passive sensors use parts of the electromagnetic spectrum to measure the reflected EMR. The wavelengths of the visible EMR represent a narrow portion of the electromagnetic spectrum (ranging between 400–700 nm) (Figure 2.2). However, for the majority of coral reefs (and for use in coastal management studies), it is preferable to measure visible or near-infrared reflected light, as these wavelengths provide more useful data (Goodman *et al.*, 2013). Short wavelengths in the visible spectrum (*e.g.*

blue wavelengths) are capable of penetrating deeper into the water than longer wavelengths. Longer wavelengths (*i.e.* those over 800 nm such as infrared wavelengths) are only able to penetrate the first few metres below the water surface (Green *et al.*, 2000).

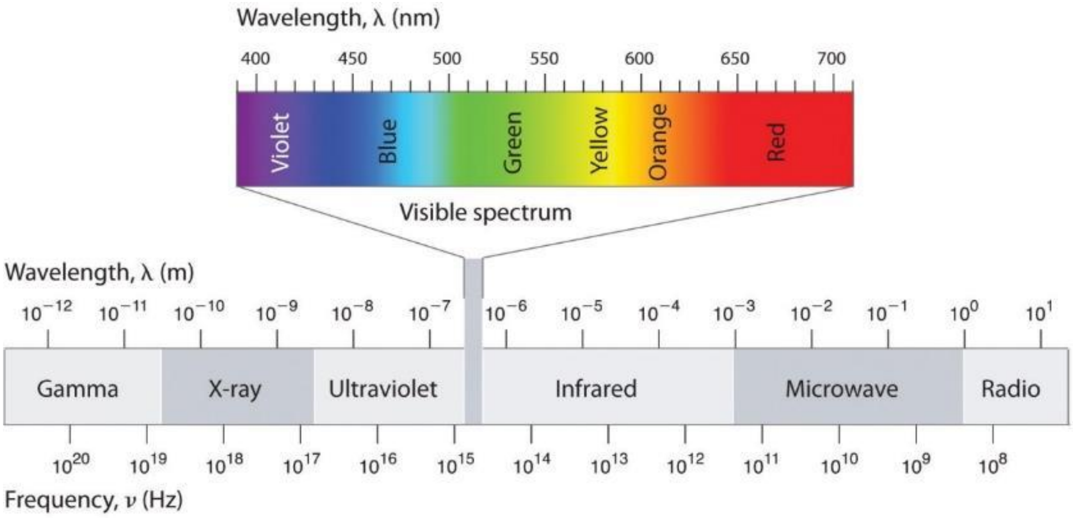

Figure 2.2. Electromagnetic spectrum (Source: Averill and Eldredge, 2011).

Remote sensors record any information detected in digital format. The attributes of images (*e.g.* the brightness and colours on the electromagnetic spectrum) are associated with a position location for each picture element (*i.e.* pixel) and represented in a digital image. The image is made up of pixels arranged in rows and columns and is commonly referred to a 'raster image'.

The detail of information acquired in remotely sensed images is dependent upon the descriptive resolution of the sensor (Andréfouët *et al.*, 2002). Each sensor has four resolutions: spatial, spectral, radiometric and temporal resolutions (Green, 2000).

Spatial resolution refers to the size of the smallest detail of an object that a sensor is able to detect and is often measured in metres (*e.g.* Landsat images have a 30 m spatial resolution) (Table 2.1).

Spectral resolution is a sensor's sensitivity to the different wavelengths of EMR reflected by objects on the ground and usually refers to a sensor's number of bands and their bandwidths (*e.g.* the Landsat TM sensor has seven bands) (Table 2.1).

Radiometric resolution refers to the ability of a sensor to measure the signal strength or brightness of an object and is often referred to as ‘contrast’. It is expressed as an amount of grey value levels and its value number is defined by a number of bits (*i.e.* binary numbers). For example, the radiometric resolution of Landsat TM is eight bits (*i.e.* 256 grey values).

Temporal resolution is the time interval between two identical flights over the same zone and is also referred to as the repetition rate. The altitude of the satellite in orbit and the characteristics of the sensor (*i.e.* swath width) determine the temporal resolution (*e.g.* the temporal resolution of Landsat sensors is 16 days).

In selecting remote sensors for reef and habitat mapping, technical constraints may make it necessary to compromise in relation to the resolutions used. It is essential that an appropriate sensor is selected that can detect spatial and textural differences in habitats. Additionally, repetition rate is important in coral reef studies, as cloud cover, tide and water turbidity are frequently changing.

Table 2.1. Landsat satellites and sensors and their technical specifications.

Satellite	Sensor*	Band	Wavelength (µm)	Resolution (m)
Landsat 5	(TM)	1 Blue	0.45 - 0.52	30
		2 Green	0.52 - 0.60	30
		3 Red	0.63 - 0.69	30
		4 Near Infrared (NIR)	0.76 - 0.90	30
		5 Short-wave Infrared (SWIR) 1	1.55 - 1.75	30
		6 Thermal Infrared (TIRS)	10.40 - 12.50	60
		7 Short-wave Infrared (SWIR) 2	2.08 - 2.35	30
Landsat 7	(ETM+)	1 Blue	0.45 - 0.52	30
		2 Green	0.52 - 0.60	30
		3 Red	0.63 - 0.69	30
		4 Near Infrared (NIR)	0.77 - 0.90	30
		5 Short-wave Infrared (SWIR) 1	1.55 - 1.75	30
		6 Thermal Infrared (TIRS)	10.40 - 12.50	60
		7 Short-wave Infrared (SWIR) 2	2.09 - 2.35	30
		8 Panchromatic	0.52 - 0.90	15
Landsat 8	(OLI)	1 Coastal aerosol	0.43 - 0.45	30
		2 Blue	0.45 - 0.51	30
		3 Green	0.53 - 0.59	30
		4 Red	0.64 - 0.67	30
		5 Near Infrared (NIR)	0.85 - 0.88	30
		6 Short-wave Infrared (SWIR) 1	1.57 - 1.65	30
		7 Short-wave Infrared (SWIR) 2	2.11 - 2.29	30
		8 Panchromatic	0.50 - 0.68	15
		9 Cirrus	1.36 - 1.38	30
		10 Thermal Infrared (TIRS) 1	10.60 - 11.19	30
		11 Thermal Infrared (TIRS) 2	11.50 - 12.51	30

* Landsat sensors crosse every point on earth once every 16 days.

Shortly after Landsat images became available in the 1970s, reef mapping techniques dramatically improved. Upon examination, Landsat images were found to be a useful data resource for the study and management of reefs (Smith *et al.*, 1975; Hammack, 1977). Since then, the use of satellite images has increased researchers' ability to identify the morphology and habitats of coral reefs (Mumby *et al.*, 1997). Further, the accuracy and cost effectiveness of the Landsat sensor has led to it being commonly used as a reef detection method (*e.g.* Luczkovich *et al.*, 1993; Green *et al.*, 1996; Mumby and Edwards, 2000; Capolsini *et al.*, 2003; Hochberg and Atkinson, 2003; Palandro *et al.*, 2003; Tilmant, 2004). Accordingly, remote sensing has been extensively used in the mapping of the geomorphology and habitats of coral reefs and is one of the most effective techniques used in reef studies (Mumby *et al.*, 2004). Remotely sensed data provide a variety of significant information related to coral reefs (*e.g.* coral reef structure, reef habitats and substrates and the biophysical parameters of seas and oceans) and changes in these elements over time (Phinn *et al.*, 2000).

Information about reef structure, including reef location, spatial distribution and geomorphological classification, can be obtained at a regional scale using remote sensing. A number of methods have been developed to extract information from remotely sensed data, however, in some circumstances (*e.g.* turbid water) extracting this information is challenging due to light attenuation in water.

Remote sensing data can also be used to map intra-reef geomorphological zones and their associated habitats and substrates (see Chapter 4). The level of discrimination between different coral species and the quantitative assessment of habitats and the cover density of substrates is dependent upon a sensor's resolution and the amount of ground-truth data available (Green *et al.*, 2000; Mumby *et al.*, 2004).

Remote sensing is commonly used to identify marine biophysical parameters such as SST, water quality, salinity and currents and waves. These datasets are usually derived using spatially moderate and/or coarse-resolution sensors. Information concerning the marine tropical atmosphere, which is important in coral reef studies and management, can also be obtained, including data on solar radiation, precipitation and wind direction and speed (Mumby *et al.*, 2004).

Remote sensing images are considered the ideal method for detecting ecological and geomorphological changes in reefs over time, as in addition to the archive of images obtained over the last four decades, new data are being acquired at regular intervals (Andréfouėt *et al.*, 2001). Other research has shown that remote sensing techniques are very useful in monitoring and detecting changes in reef geomorphology and the status of reef habitats (Mumby *et al.*, 2004). Further, remote sensing can be applied as a practicable management tool to track human activities that may have a negative impact on coral reef environments (Bina, 1982; Bunce *et al.*, 2000).

Compared to field-based surveys, the use of remote sensors in coral reef studies has a number of advantages. Remote sensors can quickly collect data from large areas and the data gathered is particularly useful in mapping coral reefs at the local and global scale (Hochberg and Atkinson, 2003). Additionally, the remote sensing method does not require large amounts of staff, time and money; thus, it is more cost-effective and efficient than field surveys (Mumby *et al.*, 1999).

Remote sensing also facilitates the study of inaccessible reefs in remote regions with macrotidal regimes and can mitigate the potential risks arising dangerous associated with marine predators (*e.g.* sharks and saltwater crocodiles). Further, remote sensing has enabled the past status of reefs to be examined and comparisons made between the past and current states of reefs. Thus, any changes that may have occurred to reefs are identifiable. Remote sensing images can also be employed as a planning tool to determine field survey requirements, improve their efficiency and ensure that the locations of habitats have been adequately sampled (Salm *et al.*, 2000). Finally, remote sensing datasets are often available in digital formats; this reduces the amount of errors that can occur in the digitising process and enhances the validity of the results (ICRI, 1997).

However, field surveys can not be completely excluded from any coral reef study (Dahdouh-Guebas, 2002), as essential information about coral communities (*e.g.* substrates and habitats) can only be acquired in the field (Wilkinson *et al.*, 2003; Tilmant, 2004). Further, ground observations are vital, as they provide detailed ground-truth information that can be used to validate and interpret satellite images (ICLARM, 1999; Tilmant, 2004). Ground-truth information can also assist in extrapolating information to unsurveyed areas with similar spectral characteristics (Mumby *et al.*, 2000, 2004).

Despite the advantages of passive remote sensing in coral reef studies, the method has some limitations. One of the most common limitations of remote sensing is that visible light attenuates when penetrating water, particularly in high turbidity water (Mumby *et al.*, 2004). Another limitation is that most freely available remote sensing datasets have low to moderate spectral and spatial resolution (Bryant *et al.*, 1998; Mumby *et al.*, 2000).

2.3 Geographic Information Systems

As mentioned in Section 2.2, a considerable amount of information can be derived from remote sensing images. Integrating these images in a GIS environment can provide additional valuable information (Salm *et al.*, 2000; Thanilachalam and Ramachandran, 2002). The advent of remote sensors, powerful computers and software has led to vital advances in geospatial technology. Today, most geospatial datasets are accessed, manipulated and analysed using GIS. This allows geospatial data from various sources to be integrated, analysed and presented in consistent formats and facilitates advanced studies and management efforts. GIS can manipulate datasets from various sources and different dates that can then be stored, archived and displayed in a georeferenced format (Drummond *et al.*, 1997; Stanbury and Starr, 1999).

The use of GIS data overlays enables comparisons to be made and links created with datasets with common spatial properties. Such overlays enhance data interpretation, reveal correlations and allow distribution patterns between different phenomena and zones of stressed or potentially stressed reefs to be identified (El-Raey *et al.*, 1996; Bryant *et al.*, 1998; Salm *et al.*, 2000; Crosby *et al.*, 2002). Further, GIS allows digitised and georeferenced non-digital data to be integrated with other data (Chapman and Turner, 2004). Such spatial analyses support Marine Park and coastal managers in their efforts to monitor coastal development and assess the impacts of different hazards on the coastal environment (Gayanilo *et al.*, 1998; Freire, 2001; Puotinen, 2005*a*, 2007).

2.4 Geodatabases

A GIS-based database (or geodatabase) is a computer-based system that can compile and process different types of information (*e.g.* location and attribute data) of a particular feature or location. Developing a geodatabase is a continuous and dynamic process, and such databases allow researchers and managers to identify and monitor changes in reefs. Further, these databases create a better understanding of reefs and improved management practices. Additionally, GIS is a useful tool for communicating to the general public through interactive web-based maps (Fritz *et al.* 2009; Comber *et al.* 2013). Web-based GIS has been used to increase awareness of the importance of coral reefs and the need for conservation. Further, geodatabases can be easily distributed across the Internet through web map data management platforms (*e.g.* ReefBase and Eye on the Reef); this expedites data exchange among the scientists and managers dealing with similar coastal related matters (Crosby *et al.*, 2002).

2.4.1 Geospatial computing for crowdsourcing

Traditionally, geospatial information has been processed using personal computers and/or servers. However, rapid advancements in the capabilities of mobile devices (*e.g.* smartphones and tablets) have led to a growing trend in geospatial computation being undertaken with these devices (Chen and Guinness, 2014). The features of these devices (including portability, internet connectivity, GPS receivers and digital cameras) make them useful tools for the collection and/or generation of geospatial information in the field. Further, any collected data can be 'crowdsourced' to a geodatabase and displayed on a web-based map. This allows researchers and managers to access large databases of geospatial information for further data collection and identify gaps in knowledge.

Environmental and geomorphological complications make the management of coral reefs a challenging task (Phinn *et al.*, 2006). The study and management of coral reefs requires the use of a range of technologies that support data collection, processing, analysis and dissemination. The visual capability of geospatial technologies is important, as (in addition to bridging gaps in knowledge) these technologies can lead to a better understanding of coral reefs and improved management practices. Spatial analysis techniques are increasingly being used to represent complex coral reef problems and processes such as bleaching, stress and other hazards (Andréfouët *et al.*, 2002; Puotinen, 2005*a*; Smith *et al.*, 2008).

CHAPTER THREE

GEOMORPHIC CLASSIFICATION OF CORAL REEFS IN THE NORTH WESTERN AUSTRALIAN SHELF

The usefulness of geospatial technologies and their application to coral reef studies was presented in Chapter 2. This chapter shows how a geospatial approach can be employed to address the first objective which is 'creation of a dedicated reef census map, and development of a geomorphic classification scheme for the Kimberley reefs'. It also illustrates the usefulness of GIS to process and produce maps as well as to provide some of the first detailed spatial analysis of reef distribution in the Kimberley. Significant information such as reef statistics and descriptions of reef distribution are analysed to explain the reefs' geomorphology patterns.

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Geomorphic classification of coral reefs in the north western Australian shelf

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HIGHLIGHTS

- Reef distribution shows significant geomorphological complexity.
- Fringing reefs are the dominant reef type and are widely distributed.
- Planar reefs are isolated and located some distance from the mainland coast.
- High intertidal reefs are remarkable features of the Kimberley Bioregion.
- The resulting data provides a reliable, spatially constrained dataset for coastal management.

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ABSTRACT

Coral reefs occur extensively along the northwest Australian continental shelf in the Kimberley Bioregion (KIM), forming major geomorphic features along and just off the coast. These reefs have not been studied in as much detail as the offshore reefs and are poorly known due to the coastal conditions, including extremely high tide regimes, high turbidity and complex coastline morphology. This study aims to establish a regional-scale distribution map of exposed and intertidal reefs of the KIM and to classify the Kimberley reefs into types, adopting widely recognised reef classification and typology schemes. Remote sensing and Geographic Information Systems (GIS) were used in this study to process and produce digital maps as well as to provide some of the first detailed spatial analysis of reef distribution. Outcomes of this study showed that the Kimberley reefs possess strong morphological complexity and clear regional patterns. The study revealed that the number of Kimberley reefs and their area are considerably (60%) greater than previously thought; the total combined reefal area is approximately 1,950 km^2. Fringing reefs have been identified as the dominant reef type and are widely distributed throughout the KIM. It was also found that tidal range affected the distribution of reef geomorphologies. The outcomes of this study will contribute to a better understanding of the Kimberley reefs, and provide marine park managers with essential and quality scientific information so that better management decisions can be made in this area.

1. Introduction

1.1. Reef mapping and classification

Coral reefs are widely distributed through the world's tropical oceans and commonly rise abruptly from relatively deep water creating a major navigational hazard, but can also provide a safe anchorage. There are many famous examples of ships running aground on coral reefs, the wrecks of the VOC ship Batavia in 1629 and the HMS Pandora in 1779 being just two notable Australian examples (Green, 1975; Edwards et al., 2003). The increase in international shipping during the 18th and 19th century saw maritime nations and international trading companies seek ways to reduce shipping losses through improved charting, but also sought a scientific understanding of where reefs are likely to be encountered and how they form. In fact few questions in 19th century science aroused more controversy than the origin of coral reefs. So when

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HMS Beagle departed in 1831 on its 5-year journey of discovery around the world, it not only carried a young Charles Darwin but also secret instructions from the Admiralty requiring a detailed geological investigation on how coral reefs formed.

The result was that in 1842 Darwin published *The Structure and Distribution of Coral Reefs*, the first of three major monographs arising from observations and data he collected during his voyage on the Beagle. This monograph put forth the theory of atoll formation through island subsidence and included the first detailed map of the distribution of different kinds of coral reefs through the Indo-Pacific and Caribbean region. This map represents the first global census of coral reefs and presented the first geomorphic reef classification scheme which is still in use today. Joubin (1912) expanded Darwin's original reef census by producing a series of five 1:10,000,000 scale reef maps covering the entire globe. His work combined existing survey charts as well as observations and voyage reports from a range of sources.

Following Joubin's work, there was almost no other attempt to systematically map coral reefs on a global scale until the launch of the Landsat series of satellites in the 1970's, which for the first time allowed the detection of coral reefs using moderate-resolution satellite imagery (Jupp et al., 1985), and the opportunity to map reefs globally. Most recently, the United Nations Environment Program (UNEP) funded the Global Reef Monitoring Network (GRMN) and the International Coral Reef Action Network (ICRAN) to build and maintain a global reef GIS database *ReefBase*, which provides a repository for available knowledge about coral reefs. The Millennium Coral Reef Mapping Project is using a suite of high-resolution spaceborne remotely sensed imagery systematically map and classify coral reefs worldwide (IMaRS-USF and IRD, 2005; ReefBase, 2015).

The development of a geomorphic classification of coral reefs has been closely linked to the improvement of reef mapping techniques (Kordi et al., 2016). For instance, the three basic classes of reef include fringing, barrier, and atoll were identified by Darwin (1842) and formed the basis for his global map of coral reefs. In the 1920s, the advent of aerial photography allowed coral reefs to be viewed in plan view, allowing for a more detailed analysis of spatial characteristics of reefs and mapping their features in greater detail. The pioneering geoscientific work on Australian reef classification was conducted by Fairbridge (1950, 1967), who recognised the role of antecedent topography, eustasy, and physical processes in generating reef morphology, first working on the Great Barrier Reef (GBR) and later on the reefs of northern Australia, including the Kimberley coast (Finkl, 2011). Subsequently, as knowledge of reefal processes increased, Hopley (1982) was able to develop an evolutionary reef classification scheme for the GBR. Accordingly, reef classification and reef typology at the global, regional and reefal scales have been dramatically improved (Andréfouët et al., 2006; Hopley et al., 2007; Leon and Woodroffe, 2013; Madden et al., 2013; Roelfsema et al., 2013; Rowlands et al., 2014).

There are still many reef regions of the world where the accurate numbers and extent of coral reefs are underestimated or unknown. One such area is the Kimberley bioregion of north-west Australia where there have only been a limited number of global scale mapping efforts that have advanced our understanding of reef formation and growth, as well as providing information for monitoring of coral reef health and to support informed decisions about coral reef use and management in this region (Spalding et al., 2001; Wilkinson, 2008), but they still lack the resolution required to provide realistic reef census data at regional and local scales. Despite efforts that have been made to fill this gap, no significant spatial map detailing the size and distribution of the Kimberley reefs and their attributes exists.

1.2. North west Australian reef systems

The Reefs of North West Australia occur within two distinct bioregions, the shelf edge Oceanic Shoals bioregion (OSS) and the inner shelf Kimberley bioregion (KIM) (Fig. 1). The OSS, which includes the Rowley Shoals and Scott Reef have seen significant scientific investigations, due in part to their proximity to the Browse Gas Fields. In particular, the morphology and growth history of these reefs have been examined using a number of methodologies such as coring, U-series dating and vertical seismic profiling (Collins, 2011; Collins et al., 2011).

The inner shelf reefs of the Kimberley have seen limited scientific study due in part to the geographic remoteness of the region and limited infrastructure. Early investigations by Teichert and Fairbridge (1948) noted that fringing reefs exist around the margins of many islands in the region, despite the normally unsuitable environment for coral build-up, including high sediment input, macrotidal regimes, highly turbid water and raised sea surface temperatures. Wilson (1972) and O'Connor (1989) observed reefs in the intertidal zone between shallow rocky shoals, along muddy shores, and in some bays. Geographic and geomorphic estimation of reef location, thickness, and reef area was provided by Brooke (1997), who demonstrated that fringing reefs were widespread along the Kimberley coast and could be classified into three reef forms: fringing reefs adjacent to a cliffed shore; reefs developing on bedrock edges; and large reef complexes. Latest studies of Montgomery Reef and Talbot Bay by Wilson (2013) and Wilson et al. (2011) revealed the unique nature of these reefs and their habitats and substrates and documented the relationship between the unique physical processes and reef geomorphology. Despite these studies, there are still many unknowns in our understanding of the Kimberley reefs.

This study intends to provide a spatial analysis of fringing and nearshore reefs along the Kimberley coast. The spatial approach is expected to lead to an analysis of the reefs' geomorphologic patterns, new information about reef statistics, and to a description of reef classification and distribution by type. The resulting data will provide a reliable, spatially constrained dataset for biodiversity assessment and reef structure comparisons. It will also provide stakeholders and beneficiaries, such as marine park authorities, universities, Traditional Owners, and non-governmental organisation (NGOs) with quality information relevant to the monitoring, conservation, and management of these vital natural resources. Furthermore, it will pave the way for future studies in various disciplines beyond the scope of this study.

2. Methodology

2.1. Study area

The KIM covers a massive area 60,000 km^2, stretching from Cape Londonderry (13°S) in the north to Cape Leveque in the south (16°S). The KIM coast is characterised by deep inlets, capes and archipelagos forming a very complex coastline (Fig. 1). It has extensive fringing coral reefs that exceed the Ningaloo Reef in their biological diversity and it supports a huge range of marine habitats (DEC, 2011). In some parts of the Kimberley coast the spring tide reaches more than 11 m, making it the highest tidal range of any coral reef system in the world and the second largest tide after Fundy Bay in Canada (Purcell, 2002; Wolanski and Spagnol, 2003). Kimberley coral reefs are the main geomorphic feature along the continental shelf between the latitudes of 12°S and 18°S (Collins, 2011). Currently, activities such as oil and gas extraction, mining, and tourism are increasing in this region, necessitating timely management to protect the marine environment (Wood and Mills, 2008).

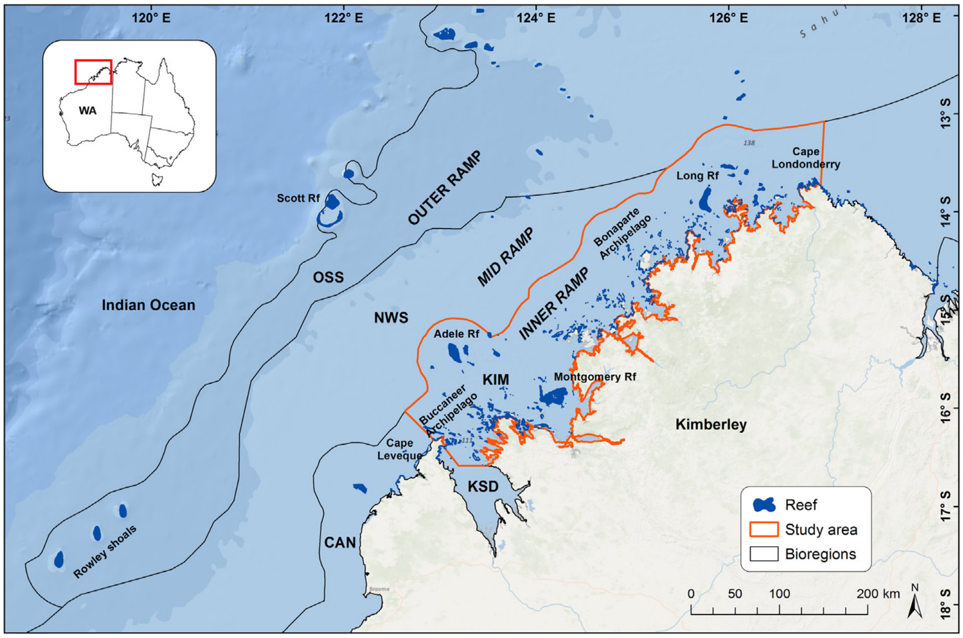

Fig. 1. Map of the North West Shelf (NWS) showing the spatial distribution of reefs, bioregion boundaries and the continental shelves (ramp) subdivision. Boundaries of the study area, the Kimberley bioregion (KIM), is highlighted with red lines. The Oceanic Shoals bioregion (OSS) and the North West Shelf bioregion are at the seaward margin of the KIM. The King Sound bioregion (KSD) and Canning bioregion (CAN) are at the south of the KIM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Datasets and their sources that have been used in this study.

	Datasets (raster)	Sources	Resolution
Input datasets	(a) Satellite images		
	–Landsat 5 (TM)	The United States Geological Survey (USGS)	30 m
	–Landsat 7 (ETM+)	The United States Geological Survey (USGS)	30 m
	–Landsat 8 (OLI)	The United States Geological Survey (USGS)	30 m
	(b) Orthophotographs	Landgate, Western Australia	0.6 m
	(c) Bathymetric maps	Geoscience Australia (GA), Australian Hydrographical Office (AHO)	Vary
	Datasets (feature classes)	Description	
Derived datasets	Reefs	Major reefs occurred along the KIM including reefs size, shape and types.	
	Coastline	Land–water boundary mapped using the Mean Low Water Neap (MLWN) level to ensure that mangroves and reef flats are not included on the land.	
	Islands	Islands, islets, exposed rocks and cays of the KIM as defined by the Geoscience Australia.	

2.2. Datasets

There are two groups of datasets that have been utilised in this study: input datasets and derived datasets. The input datasets, including satellite images, orthophotographs and bathymetric charts, were acquired from different sources, whereas the derived datasets were extracted mainly from these input datasets (Table 1). All input datasets were assembled, georeferenced and projected to the coordinate system of Australia (Geocentric Datum of Australia GDA94) using ESRI's ArcGIS 10.

2.3. Field surveys

Ground-truth data, which included field surveys, observations and georeferenced field photographs for more than 2500 points, were collected between 2009 and 2014 from primary and secondary sources using handheld GPS devices (WA Museum Woodside Collection Project Kimberley, 2008–2011; Wilson and Blake, 2011; Wilson et al., 2011, WAMSI 1.3.1 Reef Geomorphology Project, 2012–2015; Solihuddin et al., 2015) These observations, were made on various dates, encompassed descriptive geomorphological information, habitats and substrates, and were used as reference data for validation purposes.

2.4. Geomorphic classification of the Kimberley reefs

A reef evolutionary or genesis model developed by Hopley (2011) has not been incorporated in this study, due to the simple fact that unlike the Great Barrier Reef, Kimberley reefs have not received the same level of geological and geomorphological investigation. Instead a geomorphological typology classification scheme using a simple hierarchy (*i.e.* primary, secondary and tertiary) of geometric criteria (Fig. 7) has been developed for the Kimberley reefs, using the same categories as in Hopley (1982) and Hopley et al. (2007).

2.4.1. Oceanic shoals bioregion

The continental margin of the Kimberley has a ramp-like profile that can be subdivided bathymetrically into an outer, mid and inner ramp (James et al., 2004). The outer ramp (>120 m water depth) has a relatively steep seaward slope and corresponds to the OSS bioregion. Reefs here are tower-like, rising from an old Miocene shoreline, with heights of 200–400 m above the seafloor, and consist of multiple stages of Pleistocene to Holocene reef growth stages separated by hiatuses (Collins et al., 2011). Termed 'slope atolls' by Wilson (2013), their morphologies include annular (*e.g.* Mermaid Reef at Rowley Shoals (Fig. 8(b))), lunate (*e.g.* south

Scott Reef (Fig. 8(a))), and platform (*e.g.* Ashmore Reef (Fig. 8(c))) types. Similar submerged forms, in which *Halimeda* is a significant sediment contributor, are termed 'banks' by Heyward et al. (1997) and Wilson (2013); these occur to the north on the Sahul Shelf. The OSS bioregion is included here for comparative purposes, but the focus of this study is on the KIM.

2.4.2. Kimberley bioregion

The primary level of the geomorphological classification scheme shown in Fig. 7 represents reef flat elevations against a tidal datum. The first category is *high intertidal reef*, where the reef flats are situated above the mean low water neap (MLWN) tidal level. The second category is *low intertidal reef*, where the reefs flats are situated between the level of the mean low water spring (MLWS) and MLWN tidal levels. The third category is *subtidal reef*, which is situated below the MLWS level. The secondary level is based on descriptive morphological characteristics and include fringing, planar, patch and shoal reefs. The tertiary level divides each reef type into subclasses based on more detailed reef geometry and substrate type, these reef classes are described below.

Fringing reefs

Fringing reefs are well developed and widespread throughout the Kimberley and vary in shape and size, and can be found along both the mainland and islands coasts. The majority of fringing reefs in the KIM can be further classified into five subclasses which include: (1) Headland, (2) Bayhead, (3) Narrow Beach Base, (4) Inter-Island and, (5) Circum-Island. Several of these classes, resemble the fringing reefs of the GBR that were identified by Hopley et al. (2007) with some modifications (Fig. 9).

1. *Headland* fringing reefs are found on many islands and mainland coasts. They are mainly developed on rocky intertidal shores that are often exposed to prevailing ocean swells and waves generated by passage of cyclones (*e.g.* reefs on NW Maret Island (Fig. 9(b))) and reefs on Cape Londonderry (Fig. 9(d)).
2. *Bayhead* fringing reefs also occur on many islands and mainland coasts. They are developed in embayments and advance towards the head of the bay (*e.g.* reef on SE Irvine Island (Fig. 9(a))); reef on Cygnet Bay (Fig. 9(c); and reef on E Tallon Island (Fig. 9(g))).
3. *Narrow beach-based* fringing reefs are frequently found on island shores and occasionally on mainland shores. They are developed along extended sandy coasts (*e.g.* reefs on E Maret Island (Fig. 9(b)); and reef on N One Arm Point (Fig. 9(c))).
4. *Inter-Island* fringing reefs are developed between two or more high islands and/or a peninsula. These islands are connected together by their fringing reefs. This type of fringing reef is largely found towards the southern end of the KIM (*e.g.* reef between Bathurst and Irvine Islands (Fig. 9(a)); and Turtle reef which connects Molema Island and other Islands to the south; and northward, Molema Island to a peninsula (Fig. 9(f))).
5. *Circum-Island* fringing reefs are the most common type in the KIM. They are developed around high islands (*e.g.* Cockatoo Island (Fig. 9(e))).

Additionally, there are distinctive features of high intertidal fringing reefs that are common across these five subclasses. These is high intertidal flat-topped reefs with distinctive lithified algal terraces and coralline algae (rhodolith banks) which form coral filled pools during low tides, as well as Porites micro-atolls (*e.g.* reef between Bathurst and Irvine Islands (Fig. 9(a))); Turtle reef on north and south Molema Island (Fig. 9(f)); and reef on east Tallon Island (Fig. 9(g)).

Planar reefs

The planar reefs of the KIM are mainly characterised by their large area and are situated some distance offshore. These reefs are considered senile, where the lagoon is either completely infilled or semi infilled and a reef flat extends across the entire reef platform. The reef flats are usually emergent at low tides and can have a central low island and/or a sand cay. Planar reefs can be divided into two subclasses based on substrate type: (1) Sand Lagoon and (2) Coralgal (Fig. 10).

1. *Sand lagoon* planar reefs are the more common reef type with large areas of the central lagoon dominated by mobile sand sheets and sand filled lagoons, though it is not known whether these sand infilled relatively shallow or deep lagoons (*e.g.* Long Reef (Fig. 10(b))). Sand cays or vegetated sand islands can also be a characteristic feature.
2. *Coralgal planar* reefs are mainly found on larger reef platforms that have a central high island. They are characterised by distinctive lithified algal terraces and coralline algae (rhodolith banks) predominantly towards the edge of the reef flat (*e.g.* Montgomery Reef (Fig. 10(c)). Some reef islands such as Adele Reef appear to show both coralgal and sand lagoon morphologies (Fig. 10(a))).

Patch Reefs

Patch reefs are mainly <2 km in length. They can be divided into two subclasses based on perimeter geometry: (1) *Irregular margin* refers to patch reefs that have dentate or rugged edges; and (2) *Unbroken margin* refers to patch reefs that have circular, elliptic or regular edges (Fairbridge, 1950, 1967; Hopley, 1982).

Shoals

Shoals are submerged features and difficult to discern using airborne or satellite remote sensing techniques, therefore they were not catalogued as part of this study. However, they can be broadly divided into three subclasses based on dominant substrate types. The most common substrates that have been identified include (1) *Sand*, (2) *Reef*, and (3) *Proterozoic Basement*.

2.5. Coastline mapping approach

The Kimberley coastline has been mapped using a variety of different geomorphic and geological classification schemes (Teichert and Fairbridge, 1948; Brooke, 1997; IMaRS-USF and IRD, 2005; ReefBase, 2015). However, most existing maps of the Kimberley coast were derived from low or moderate spatial resolution data sources. Furthermore, due to the macrotidal systems in this region, defining land–water boundaries marked by tides can be complicated and may not represent the shoreline in a geomorphic sense (*i.e.* Mangrove zones and sections of the reef flats are commonly classified as land on these maps). For this study, the marine–terrestrial boundary was remapped using the Mean High Water Neap (MHWN) level to ensure that mangroves and reef flats are not included on the land (Fig. 2). A set of 24 orthophotographs that cover the entire KIM was used to accurately delineate the shorelines of mainland and nearshore islands. These orthophotographs were mainly in true colour composites (*i.e* RGB 321) and geometrically corrected, and had been acquired during MLWN tides. Although they usually do not have near infrared (NIR) bands as satellite images do, their spatial resolution is very high (<1 m) (see Table 1) and this resolution can bring out detailed features on the ground (Fig. 2).

2.6. Reef mapping approach

The visibility of a reef depends on water clarity and exposure, however the extraordinary conditions of the Kimberley marine environment (*i.e.* extremely high tides and water turbidity) has the potential to prevent effective detection or mask reef features in this region. Hence mapping of reefs using remote sensing images alone

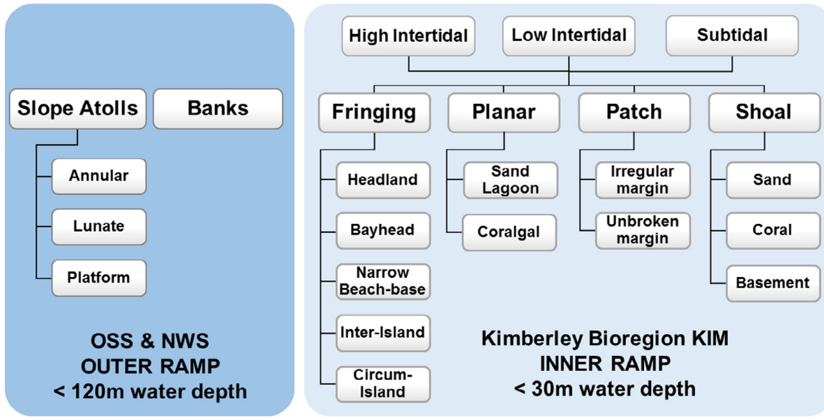

Fig. 2. A geomorphological typology classification scheme of the North West Shelf. The left section represents reefs from mainly the Oceanic Shoal bioregions (OSS) and partially from the North West Shelf bioregion (NWS). The right section represents reefs of the Kimberley bioregion (KIM).

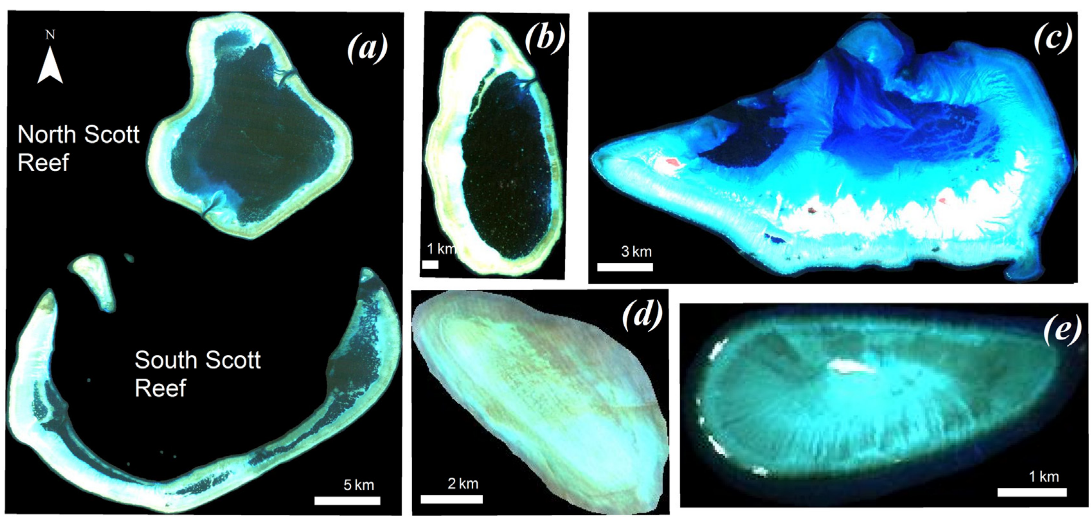

Fig. 3. Morphology of slope atolls of the outer ramp and OSS bioregion. Examples of slope atolls are: annular reefs (a) North Scott Reef and (b) Mermaid Reef; lunate reefs (a) South Scott Reef; platform reefs (c) Ashmore Reef and (e) Cartier Reef; banks (d) Heywood Shoal.

was not going to be sufficient to detect the accurate number of reefs (Fig. 3).

Accordingly, a mapping process was developed for this study in order to determine reef locations precisely (Fig. 4). First, 18 bathymetric charts which cover the study area were used as a base map. Although the bathymetric maps do not present reefs and coastal features at a geomorphic standard, they are a good source of information on reef locations and water depth. Areas of interest, such as islands, reefs and shoals, were roughly delineated using ArcMap 10.1. The digitised map features were then stored in a vector format (Fig. 4). Next, a dataset was developed using Landsat TM, ETM+ and OLI images at a consistent ∼30 m resolution and using the visible (RGB) and near infrared (NIR) bands. More than 60 scenes covering the entire study area were acquired between 2000 and 2014. Regardless of the cloud cover, reefs could be detected on sections of the images that has no cloud cover because each scene covers a relatively large area (170 km north–south × 183 km east–west). However, mapping of reefs using satellite images is restricted to shallow areas (<10 m for nearshore reefs and <30 m offshore reefs) (Kordi and O'Leary, 2016). These data were then validated using ground truth and very high resolution orthophotos. Remote sensing images and digitised map features were imported to ArcMap 10.1 as data layers (Fig. 4). Remote sensing images were then used as a base map and reef polylines were overlaid on these images to allow visual identification of coral reefs. Masking algorithms were applied using NIR bands to delineate islands and visible bands to delineate reefs. All detectable islands and reefs were accurately recorded and classified according to the reef classification that has been developed for this study. Moreover, a reef that has multiple features (*i.e.* comprising more than one polygon) is recorded in the GIS database as a single reef.

3. Results

3.1. Coastline, island and reef mapping

The geology of the Kimberley coast is characterised by a heavily jointed, faulted, and folded palaeo Proterozoic metasediment and volcanics which has resulted in a complex, highly discordant ria type coastline. The straight-line distance between Cape Londonderry and Cape Leveque is approximately 500 km, while the actual length of the coastline is 10 times longer, exceeding 5000 km in length. However, if the lengths of island coastlines are taken into account, the total length of the Kimberley coastline is approximately 10,000 km (Fig. 5).

A total of 2413 islands were mapped within the KIM, the vast majority being high rocky islands with only 31 low or reef islands recorded. Islands show significant geomorphologic complexity and spatial variability, with island numbers varying both latitudinally (Table 2) and across the shelf (Fig. 6).

Islands are primarily clustered into two main regions with about 40% of the islands situated between 14°S and 15°S near the

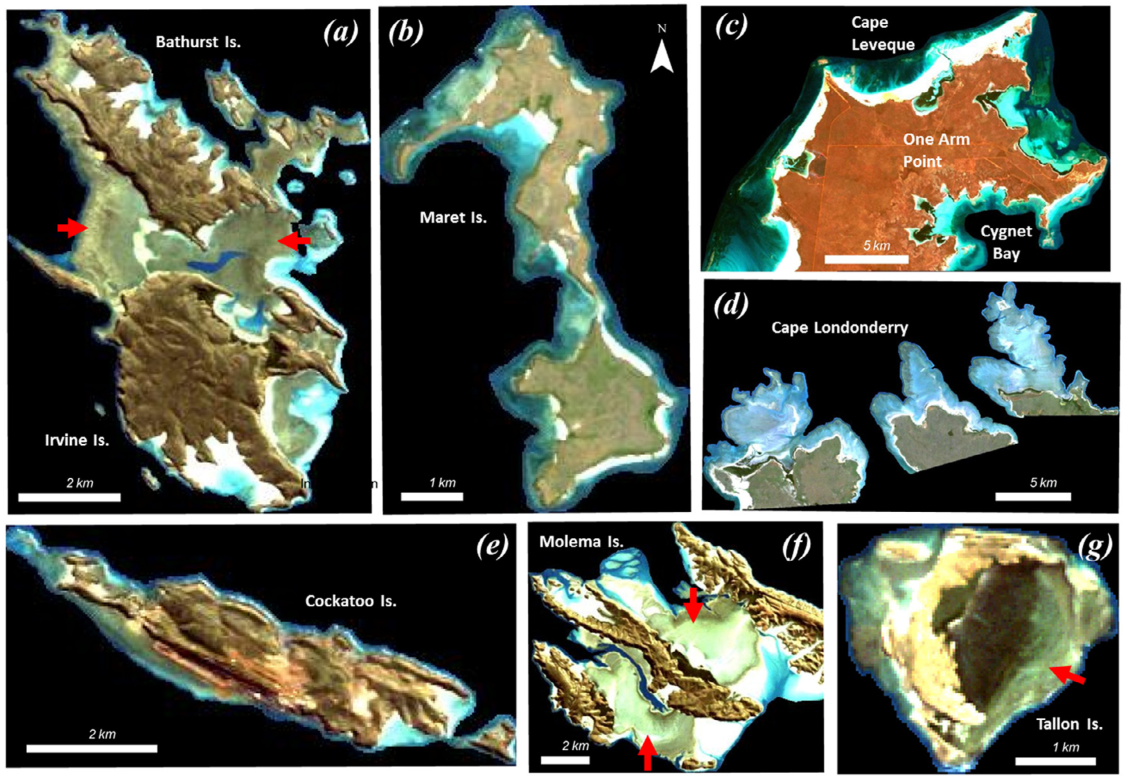

Fig. 4. Morphology of fringing reefs of the KIM bioregion. Examples of fringing reefs: (1) high intertidal fringing reefs (reefs are indicated by red arrows) (a) reef between Bathurst and Irvine Islands, (f) Turtle reef north and south Molema Island and (g) reef on the eastern side of Tallon Island; (2) low intertidal headland fringing reefs (b) reefs on NW Maret Island and (d) Cape Londonderry; low intertidal bayhead fringing reefs (a) reefs on SE Irvine Island and (c) reefs on Cygnet Bay S One Arm Point; low intertidal headland fringing reefs on narrow beach base (c) reefs on sandy beach N One Arm Point; and low intertidal circum-island fringing reefs (e) reef around Cockatoo Island. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Number and percentage of islands by latitude across the Kimberley bioregion.

Latitude (°S)	Number	%
13°30′–14°00′	85	3.5
14°00′–14°30′	441	18.3
14°30′–15°00′	513	21.3
15°00′–15°30′	385	16.0
15°30′–16°00′	129	5.3
16°00′–16°30′	784	32.5
16°30′–17°00′	76	3.1
Total	**2413**	**100**

Table 3
Frequency and percentage of island by area category in the Kimberley bioregion.

Area (km^2)	Number	%
<0.25	853	35.4
0.25–0.5	466	19.3
0.5–1.0	518	21.5
1.0–5.0	534	22.1
5.0–10	19	0.8
10–20	11	0.5
20–30	6	0.2
30–40	2	0.1
40–50	2	0.1
>50	2	0.1
Total	**2413**	**100**

mainland coastline and in the Bonaparte Archipelago, while the other group comprising about 36% of the islands is found between 16°S and 17°S in the Buccaneer Archipelago (Table 2).

The vast majority of Kimberley Islands are relatively small in size; over 35% of islands have an area of less than 25 hectares (<0.25 km^2) and are little more than exposed rocks or islets, more than 75% of islands have an area of less than 1 km^2. The number of islands decreases exponentially with size; with less than 2% of islands having an island area larger than 5 km^2(Table 3).

In terms of spatial variability, the number of islands decreases dramatically moving away from the coastline (Fig. 6). Over 63% of all islands are found within a short distance (<5 km) of the mainland coast, a further 30% of islands are found between 5 and 20 km offshore and, only 7% of islands are found at distances greater than 20 km from the Kimberley coastline. While there appears to be no relationship between island size and distribution, approximately 13% of total island area is located within <5 km of the mainland coast, this increases significantly to more than half of the island area (over 55%) between 5 km and 20 km from the mainland coast. Between 20 and 30 km from the coast island area steeply declines to reach about 24% of the total island area. An additional drop in total island area continues until it reaches its lowest value of <2% between 30 and 40 km from the coastline.

3.2. Reef distribution and size

Coral reefs occur extensively throughout the KIM and display a remarkable geomorphological diversity. A total of 853 reefs, with a combined reefal area of approximately 1950 km^2 were identified and mapped throughout the KIM. Each mapped reef was accurately recorded and classified according to the reef classification scheme described above (Fig. 11).

Fringing reefs are by far the most common type of reef, accounting for 687 reefs, covering more than 910 km^2 of reefal area fringing almost a quarter of the total Kimberley mainland and island coastline. The majority of fringing reefs (70%) have developed around islands (Fig. 11).

Table 4
Lengths and areas of reefs by type.

Reef type	Number	Length (km)				Area (km^2)			
		Min	Max	Mean ± SD	Total	Min	Max	Mean ± SD	Total
Fringing	687	0.03	9.3	1.8 ± 14.0	2638.7	0.5×10^{-4}	32.6	1.3 ± 3.3	910.7
Planar	20	3.2	22.1	10.9 ± 41.1	259	1.4	352.4	45.5 ± 90.1	909.4
Patch	133	0.04	2.9	0.85 ± 1.6	103	3.7×10^{-4}	3.4	0.27 ± 0.5	35.4
Shoal	13	1.3	12.4	4.9 ± 10.2	76.1	0.6	18.7	7.1 ± 6.9	92.3
Total	**853**				**3076.8**				**1948**

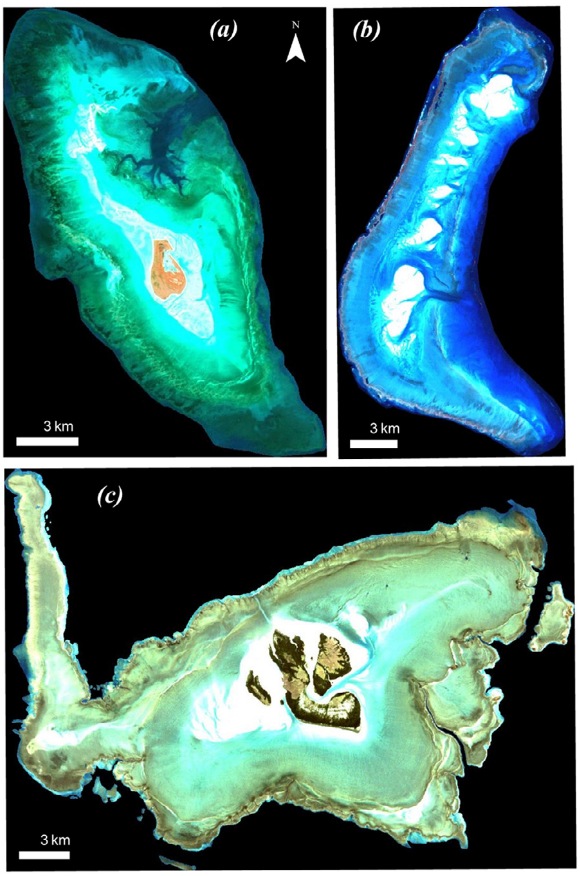

Fig. 5. Low intertidal planar reef (a) Adele Reef and (b) Long Reef; and high intertidal planar reef (c) Montgomery Reef.

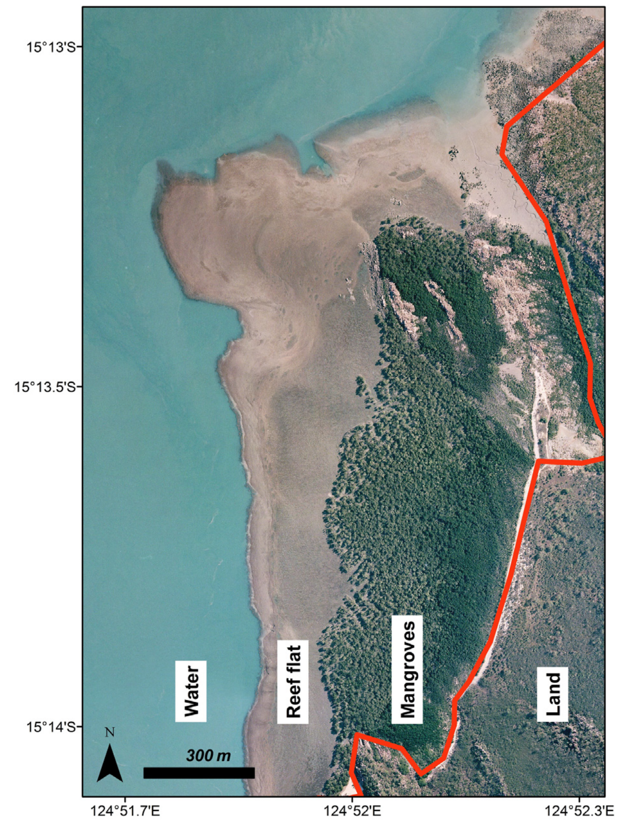

Fig. 6. A high-resolution orthophotographs in true colour composite shows part of the geomorphic features of the coastline. The red line represents the coastline which has been accurately delineated in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There are approximately 20 planar reefs in the KIM, though their combined reefal area of >909 km^2 is almost equivalent to the fringing reef area (Table 4). Fringing and planar reefs together comprise approximately 93% of the total reef area in the KIM. The remaining reefal area is covered by patch reefs (2%) and shoals (5%) (Fig. 11).

Despite their large number and abundant distribution, individual fringing reefs are relatively small in size having a mean area of 1.3 km^2, whereas shoal reefs are somewhat larger having a mean area of 7.1 km^2 and planar reefs are significantly larger again having a mean area of 45.5 km^2. Among all the reef types of the study area, Patch reefs have the smallest size with a mean area of <1 km^2 (Table 4).

Regarding spatial variability, the number of reefs declines markedly with distance from the mainland coast (Fig. 12). As with the Kimberley islands nearly half of the reefs are located in close proximity (<5 km) to the Kimberley coastline, a further 33% of reefs are found between 5 and 20 km off shore. The number of reefs drops continuously up to 40 km off shore, with a slight increase (3%) beyond 40 km; this pattern can be attributed to fringing reefs being the dominant reef type. More than half of the total reef area in the Kimberley (>54%) is found within 10 km of the coastline. At distances >10 km from the coast, reef areas fall significantly to less than 4% at 25 km off shore, with a small increase in the reef area between 25 and 35 km. An additional drop in reef area occurs at 40 km to reach its minimum value (<0.5%). However, more than 40 km from the coastline of the Kimberley coastline the reef areas jump dramatically to approximately 15% which can be explained by a small number of large planar reefs located at this distance from the coast.

3.2.1. Reef distribution by latitude

Fringing reefs are found throughout the Kimberley but have particularly high concentrations within the archipelago regions. These include the Bonaparte Archipelago in the North (14°S–15°S) and the Buccaneer Archipelago in the South (16°S–17°S). These regions account for 33% and 39%, respectively of the total number of fringing reefs (Table 5).

Planar reefs are mainly developed offshore. Although they are relatively few in number, they are characterised by a large reefal area. They are clustered in two main areas, with 38% of their area found between 13°30′S and 14°30′S and over 52% of their area

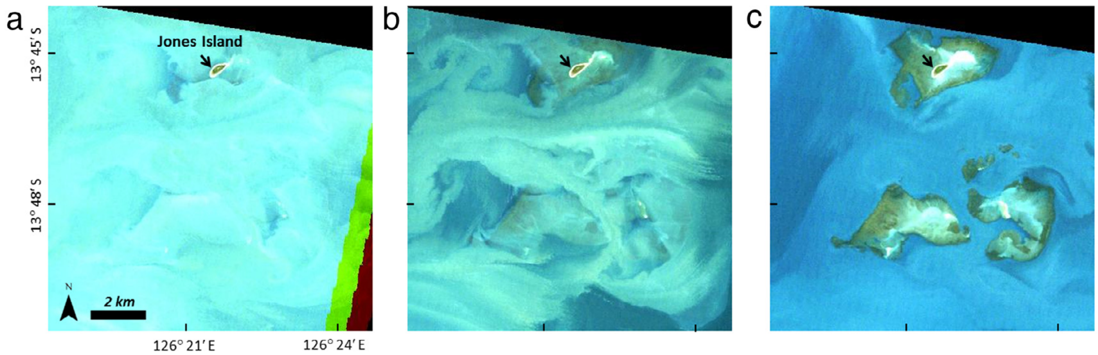

Fig. 7. Landsat 5 TM images of reefs near Jones Island (north of the KIM) acquired on three different dates, (a) acquired in 30/04/2010 at extremely high tide (∼6 m); (b) acquired in 17/01/2010 at high tide (∼4 m); and (c) acquired in 21/10/2011 at low tide (<2 m).

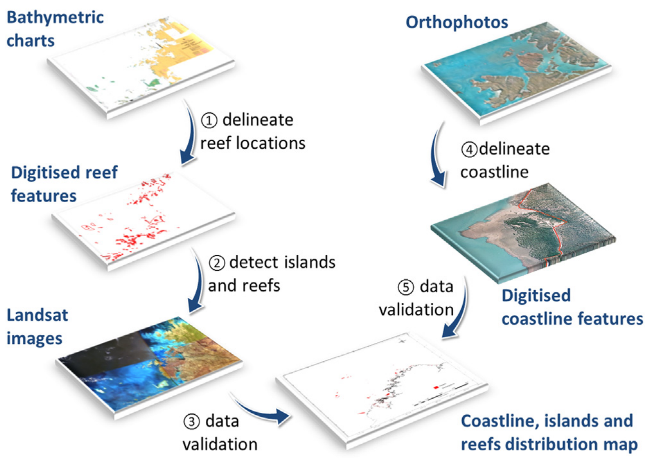

Fig. 8. Methods employed to map locations and dimensions of the coastline, islands and reefs on the study area.

situated between 15°S and 16°S, including Montgomery Reef, and the Adele complex of 6 reefs. Planar reefs are rare or non-existent between 14°30′S and 15°00′S (Table 5).

Patch reefs are smaller in size and are widespread across the Kimberley coast. They are often hard to identify. Approximately 133 reefs have been counted in the bioregion within a short distance of the mainland coast. Their number gradually increases from the north towards the south of the Kimberley coast. They make up the highest proportion (42%) of reefs between 15°00′S and 16°00′S, south of which their number decreases (Table 5).

Submerged reefs or shoals are far less numerous. Approximately 13 reefs of this type have been mapped. Their number varies from the north to the south of the bioregion. However, they reach their greatest density in the south between 16°00′S and 16°30′S, and are rare or non-existent between 14 °30′S and 15°00′S and on the outer edge of the KIM (table).

4. Discussion

Despite the early work of Teichert and Fairbridge (1948) and more recent investigations by Brooke (1997) and Wilson (2013), the KIM was never considered to be a major reef province. This view is mainly due to the low number of scientific studies which have investigated Kimberley reef systems, which can be attributed to its remoteness, lack of research infrastructure and settlements, challenging environmental conditions, and the focus of most Australian reef researchers towards the higher profile GBR. The results of this study show that the total area of the Kimberley reef is 1948 km^2 and the number of reefs is 853 which is significantly greater (>60% greater) than the reef number found

Table 5
Frequency of reef types by latitude in the Kimberley bioregion.

Latitude (°S)	Fringing	Planar	Patch	Shoal	Total
13°30′–14°00′	48	6	6	3	**63**
14°00′–14°30′	140	2	9	2	**153**
14°30′–15°00′	119	0	13	0	**132**
15°00′–15°30′	74	4	56	1	**135**
15°30′–16°00′	11	7	19	2	**39**
16°00′–16°30′	259	1	29	5	**294**
16°30′–17°00′	36	0	1	0	**37**
Total	**687**	**20**	**133**	**13**	**853**

in other available sources of information on reefs in this region (*i.e.* ReefBase and the Millennium Coral Reef Mapping Project). Compared with the GBR the Kimberley has a longer coastline, a greater number of islands, and although its total reefal area is 10 times smaller than the GBR (∼2000 km^2 compared to 20,000 km^2). Based on information of world's reef statistics (Spalding et al., 2001), this study has confirmed that the Kimberley as one of the top 20 largest continental shelf reef provinces in the world.

Reef distribution in the KIM shows significant morphological complexity with clear regional patterns. Fringing reefs were found the dominant reef type and were widely distributed throughout the KIM. Coastal fringing reefs were more common in the northern Kimberley having developed intermittently along the extended mainland ria coast. These fringing reefs were observed more intermittent along the southern coast and areas proximal to major river mouths as a result of increased terrestrial runoff and higher water turbidity (Wilson, 2013).

The study showed that fringing island reefs have a far greater latitudinal spread and they were more common than other reef types in the KIM. As expected, fringing reef distribution associates strongly with the distribution of islands. The highest numbers of fringing reefs in the KIM were found around nearshore high islands of the Buccaneer Archipelago. At this location the folded and faulted King Leopold Fold Belt has been dissected into many islands as a result of drowning of the continental shelf during the Holocene (Solihuddin et al., 2015). Fringing reefs were also abundant in the Bonaparte Archipelago at the north of the KIM; the history of these islands indicates that the area was previously part of the mainland (Johnson et al., 2010). Both these areas have previously been suggested as being important for fringing reef development (Wilson, 2013).

It is also found that fringing reefs with a westerly aspect often have a wider, geomorphically mature reef flat with a steeply sloping reef front; these reefs were more often exposed to higher energy ground swells. Fringing reefs with an easterly aspect generally have a narrower gently sloping reef flat and tend to be sheltered from high swell energy. The asymmetric style of fringing reef development was particularly apparent around most islands

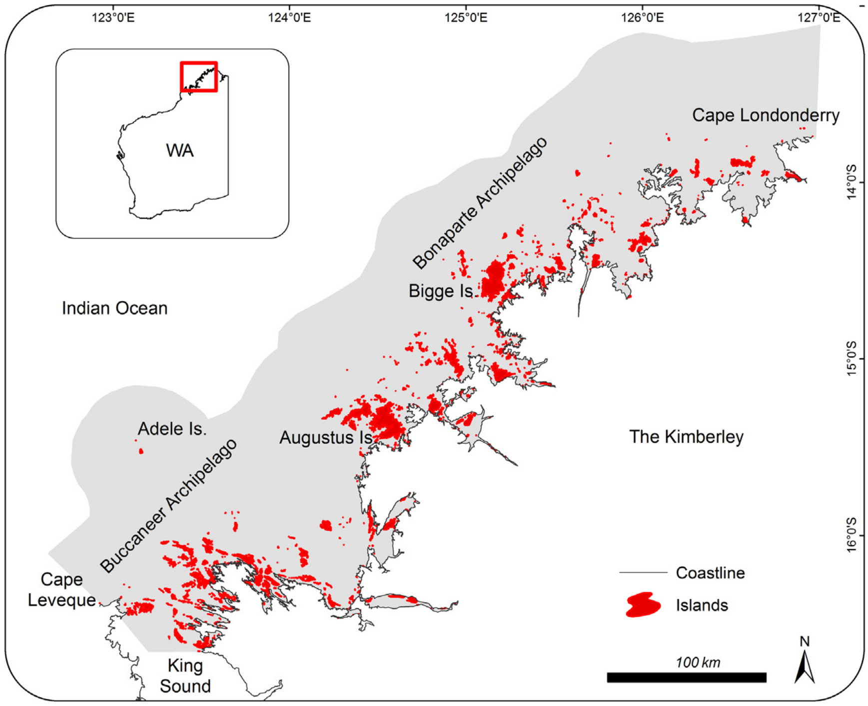

Fig. 9. A digitised map shows the complexity of coastline features and island distribution along the Kimberley bioregion coast.

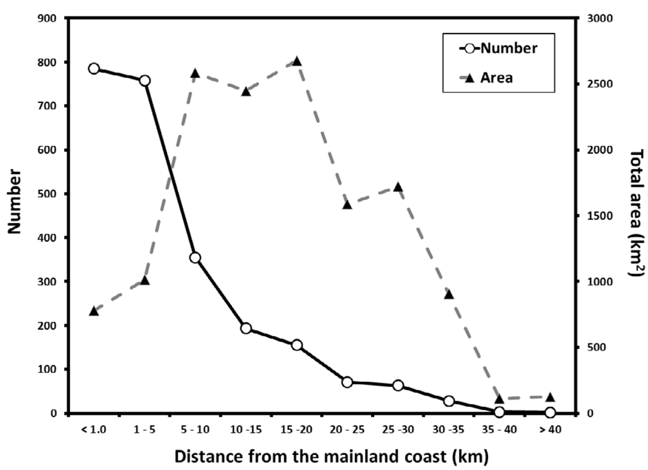

Fig. 10. The number and size of islands across the north-west continental shelf. The horizontal axis represents distances from the Kimberley mainland coastline. The left vertical axis represents the number of islands and the correlation between the number of islands and distance from the coastline is shown in the black solid line. The right vertical axis represents total island area in (km^2) and the correlation between the island areas and distance from the coastline is shown by the grey dashed line.

in the Bonaparte Archipelago. This indicates that either exposed reefs grow faster than sheltered reefs, or they start growing earlier (Wilson, 2013).

A notable subclass of fringing reef 'inter-island' falls within this category. This type of reef was particularly common in the Buccaneer Archipelago (*e.g.* Molema Island, Bathurst–Irvine Islands, and Woninjaba Islands) (Kordi and O'Leary, 2016). The reef platform connects two or more islands and seems to have been formed by a coalescence of the fringing reefs that are attached to these islands (Hopley, 1982). Where coalescence is incomplete, many deep pools can be observed (*e.g.* reef between Bathurst–Irvine Islands) (Kordi and O'Leary, 2016; Solihuddin et al., 2016).

High intertidal fringing reef is a newly defined reef morphotype and is characterised by reef flat elevations above the level of MHWS tides, coralline algal terraces, and rhodolith banks (Richards and O'Leary, 2015). This reef type was best developed in the Buccaneer Archipelago and Sunday Island group, where tidal ranges can exceed 10 m (Kordi and O'Leary, 2016). However it is still unknown what process is ultimately driving the development of these high intertidal reefs.

The mapped planar reefs showed that these reefs were isolated features usually located some distance from the mainland coast, beyond the fringing reef zone in water depths of 30–50 m. These reefs appear to have developed on shallow, pre-existing topographic highs, between palaeoriver channels (Collins et al., 2015). The majority of these reefs have reached sea level with the reef flat mostly blanketed by a sand sheet and surrounded by an intertidal reef platform or rampart. Based on Hopley's evolutionary classification scheme these reefs can be classed as senile in that they have a central low, vegetated island (*e.g.* Adele Reef) or an unvegetated sand cay (*e.g.* Long Reef).

Patch reefs were scattered over the KIM. These reefs usually occur in low intertidal or subtidal zones. Due to their small size, their features are often difficult to detect using moderate spatial resolution remote sensing images, and/or because of high water turbidity rendering statistics unreliable. Thus, patch reefs have not been mapped in great detail in this study. Due to the lack of adequate information on patch and shoal types in addition to their small size and depth under water, where they do not represent an area of great significance, these reefs have not been studied in as much detail as high intertidal and low intertidal fringing and planar reefs. Therefore they have been noted in this study in terms of basic information such as their distribution, number and area, based on available data.

The study showed a steady relationship between island distribution and reef size because there were an abundance of reefs attached to islands near the coast. Thus, most Kimberley reefs can be found within 10 km of the mainland coast. However, some reefs cannot be identified within a distance less than 5 km from the shoreline where reef area drops significantly although the island's area remains high. The reason was most of the reefs are located on steeply sloped forereefs and in a water depth >5 m where

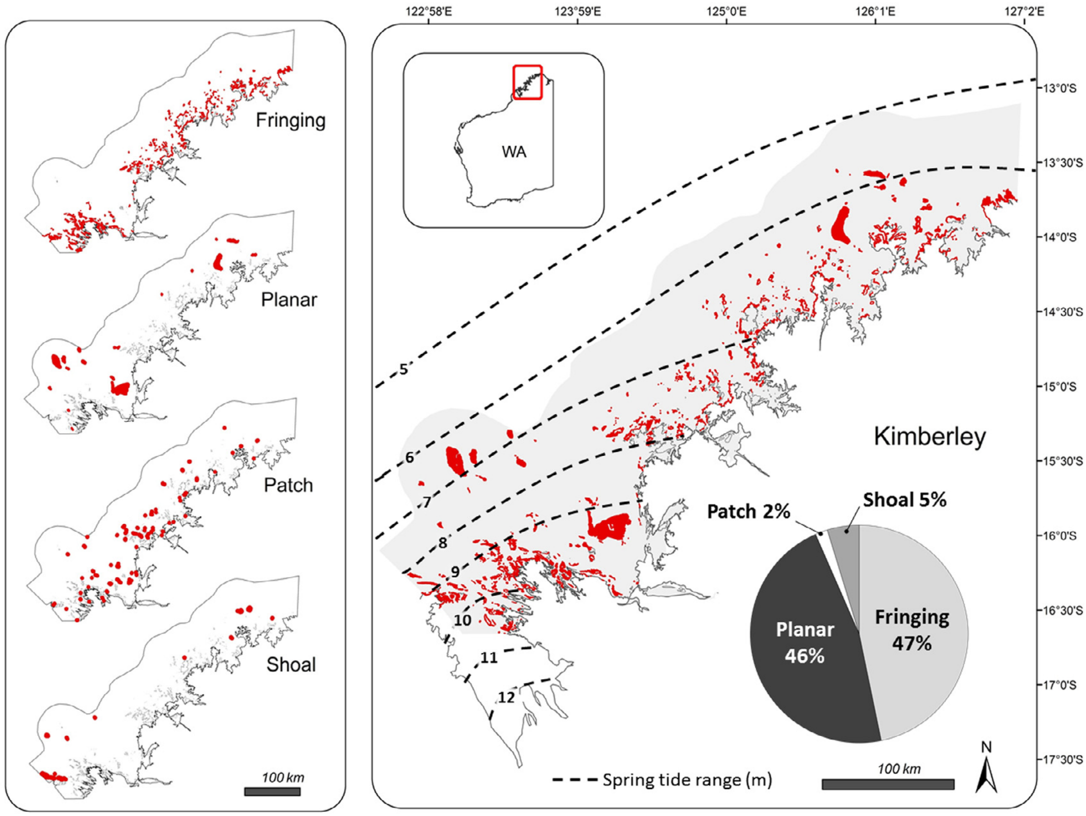

Fig. 11. (*left plate*) Reef distribution in the Kimberley bioregion by type: fringing; planar; patch; and shoals. (*right plate*) Distribution map of reefs in the Kimberley bioregion with spring tidal range contours (calculated from the National Tidal Unit, Australian Bureau of Meteorology). The pie chart shows the percentage of area coverage of each reef type.

they cannot be detected using remote sensing images due to high turbidity. In such extreme conditions, high-resolution bathymetric and topographic data can be more efficient (Brooke et al., 2010). This statistic was particularly significant from a management perspective as their close proximity to the coast means that there is a higher potential for reefs to be threatened or impacted by land use change.

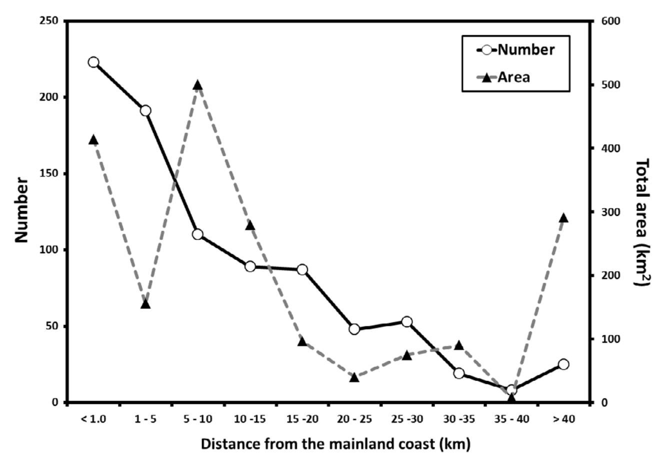

Fig. 12. Number and size of reefs across the north-western shelf. The horizontal axis represents distance from the Kimberley mainland coastline. The left vertical axis represents the number of reefs and the correlation between the reefs number and distance from the coastline is shown by the black solid line. The right vertical axis represents total reef area in (km^2) and the correlation between reef areas and distance from the coastline is shown by the grey dashed line.

5. Conclusions

In summary, this study presented the most comprehensive dataset of reef typology and distribution for the KIM. The study provided a firm scientific determination of the scale of reef habitats in the Kimberley.

The resulting data was the first most detailed spatial analysis of the KIM and will thus make available a reliable, spatially constrained dataset for biodiversity assessment and reef structure comparisons. Furthermore, it will provide scientists and managers with quality information relevant to the monitoring, conservation and management of these vital natural resources. It also paves the way for future studies addressing the major threats to reef ecosystems in this region.

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CHAPTER FOUR

A SPATIAL APPROACH TO IMPROVE COASTAL BIOREGION MANAGEMENT OF THE NORTH WESTERN AUSTRALIA

Mapping and geomorphic classification of the Kimberley reefs have been illustrated in Chapter 3. This chapter focuses on how Landsat images and orthophotographs were utilised to approach the second objective of this study which is 'mapping of the intra-reef geomorphology and collection of information about key habitats and substrates'. It demonstrates how accuracy assessment of image classification can significantly improve when ground-truthing, aerial photographs, and in situ images are integrated. Examples of detailed maps and information about intra-reef geomorphic zones, habitat and substrate types of selected fringing and nearshore reefs are presented.

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A spatial approach to improve coastal bioregion management of the north western Australia

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ABSTRACT

Coral reefs are a major coastal feature of the Kimberley bioregion in north-western Australia; however, very little is known about the habitats and substrates of the reefs in this coast. Previous studies have been conducted on a broad scale, but no geomorphological, surface substrate and habitat maps of the reefs have been produced. Such maps would provide researchers and coastal zone managers with significant information and estimations of reef growth and productivity. The primary aim of this study was to obtain detailed information on reefs in the Kimberley bioregion. This study used remote sensing and Geographic Information Systems (GIS), as well as multiple other data sources, to map reef geomorphic zones and the associated key habitats and substrate types of shallow nearshore reefs. Despite the macrotidal regimes and the turbid waters of the study area, remote sensing was effectively used to identify the dominant habitats and substrate types of eight reef platforms. This study provides long-term quantitative assessments of the main habitats and substrates of these reefs and offers a better understanding of reefs in the Kimberly bioregion. It is also a source of valuable information for the marine park and coastal managers investigating the coral reefs that have been targeted for conservation, but have not yet been the subject of regional analysis.

1. Introduction

The Kimberley coast, located in north-western Australia, has been subdivided into several marine bioregions, including the Oceanic Shoals bioregion (OSS), the North West Shelf bioregion (NWS), and the Kimberley bioregion (KIM) (Thackway et al., 1998). The KIM contains the second largest reef system after the Great Barrier Reef (GBR) in Australia spanning four degrees of latitude between Cape Londonderry and Cape Leveque (Fig. 1). The region is recognised as being globally significant, due to its geographic remoteness and inaccessibility. It represents one of the largest and least impacted marine ecosystems on the planet (Masini et al., 2009). However, this remoteness has also resulted in only limited and infrequent scientific studies of the Kimberley marine environments being conducted (Chin et al., 2008).

Presently, threats from localised anthropogenic impacts are considered low (Collins, 2011), however this could change given the increase in mining activities in the region with the recent discovery of large gas fields in the offshore Browse and Bonaparte Basins and the increase in the number of tourists visiting the region. Additionally, the geographic remoteness of the Kimberley coast will not necessarily afford it any protection from climate-related changes such as changing sea surface temperature, ocean acidification and predicted increases in the intensity of cyclones. Accordingly, the condition of the reefs needs to be urgently assessed and the associated habitats and substrates mapped and monitored to enable researchers and managers to accurately measure and document changes over time.

Until the late 1940s, there was a paucity of knowledge about the habitats and substrates of the Kimberley reefs. This changed slightly in 1948, when the first pioneering studies were conducted. In these studies, admiralty charts and aerial photography were used to map the major features of particular reef platforms (Fairbridge, 1950, 1967; Teichert and Fairbridge, 1948). However, in the 50 years that followed, very few scientific investigations were undertaken in the region and only recently has the true size and nature of

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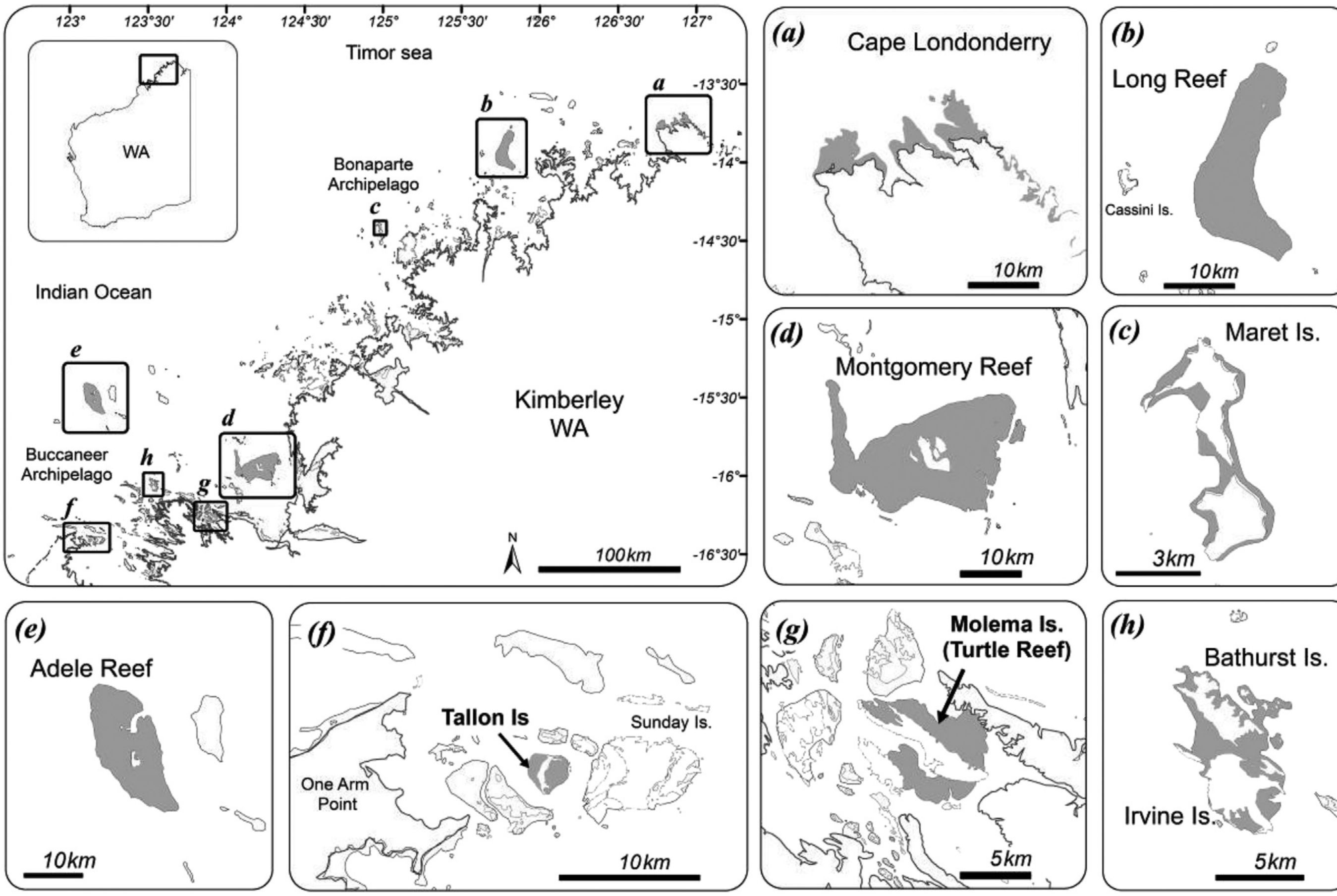


Fig. 1. Map of the Kimberley bioregion showing the location of reefs in this study. (a) Cape Londonderry; (b) Long Reef; (c) Maret Islands; (d) Montgomery Reef; (e) Adele Reef; (f) Tallon Island; (g) Molema Island (Turtle Reef); and (h) Bathurst and Irvine Islands.

the Kimberley coral reefs been determined (Collins et al., 2015). More recent studies have shown that the Kimberley coast is home to a large number of species (DSEWPaC, 2012) and that there is a marked difference in faunal diversity between the offshore and inshore reefs of the region (DSEWPaC, 2012; Richards et al., 2013). To date, almost no remote sensing studies have been undertaken to map the habitats and substrates from a geomorphological perspective at the reef scale in the KIM. Recent work by Wilson (2013) highlighted the need for further geomorphic studies of the Kimberley coast and their ecologies.

1.1. Remote sensing

The study and management of the coastal zone in the Kimberley present a number of challenges, the first of which relates to the geographic remoteness and the large size of the region. Accessing the region is both prohibitively expensive and time-consuming (Chin et al., 2008). The application of remote sensing technologies in conjunction with limited ground-truth surveys has been adopted as a more cost effective approach for dealing with the challenges of reef mapping (Dahdouh-Guebas, 2002; Veron, 2008). Depending on the resolution of the equipment employed, it is possible to map (with increasing resolution) reef geomorphology, substrate types, habitats and biological communities (Leon and Woodroffe, 2011).

Remote sensing was first employed to map coastal features and reef systems shortly after Landsat-1 was launched in the early 1970s (Jupp et al., 1985; Smith et al., 1975). Since then, the use of remote sensing has become a common reef-detection method and has been used in the majority of coral reef studies conducted around the world. While there are many new remote sensors that can capture multispectral images with sub-meter resolution (e.g. QuickBird, WorldView-2 and 3), the Landsat is capable of mapping reef geomorphology and habitats at a regional scale (Ahmad and Neil, 1994; Andréfouët et al., 2003; Bierwirth et al., 1993; Luczkovich et al., 1993; Mumby and Edwards, 2000; Palandro et al., 2003; Purkis and Pasterkamp, 2004; Zainal, 1994). The coral reefs of the Kimberley have not been studied by remote sensing except at a global scale (Spalding et al., 2001; Tupper et al., 2011; Wilkinson, 2008) and the maps produced thus far lack the detail required to provide information on reef geomorphology and their key benthic communities. Further, these maps cannot be used for monitoring and management purposes.

Remote sensing can be integrated into a Geographic Information System (GIS) environment that has the ability to produce dynamic maps. Such maps can be updated as new data become available and also reduces effort, costs and time (Johnson, 2000). The produced maps can be used to characterise the habitat types and substrates of each reef. This knowledge enables estimations to be made of likely types of habitats and substrates that can then be tested against available field data. This database will also lead to a better understanding of any changes to the spatial distribution of the reefs over time and pave the way for future studies on coral reefs in the region. There are currently no published works in relation to the use of remote sensing data for monitoring coral reefs in the KIM.

The main goal of this study was to provide detailed geomorphological information on the reefs of the KIM to gain a better understanding of these coastal ecosystems. Landsat images and orthophotographs were utilised in this study to determine the boundaries of the geomorphic zones, associated substrates and habitats of eight selected reefs (Fig. 1). Ground-truth data, aerial photographs and *in situ* images were obtained to ensure that the image classes had been correctly identified. The results of this study provide a powerful management tool for coastal planners and managers involved in coastal conservation and resource assessments and should also facilitate marine protected area planning and habitat mapping at a reefal scale.

2. Methodology

2.1. Study area

The Kimberley bioregion stretches between Cape Londonderry in the north to Cape Leveque in the south (122°–126°E; 13°–16°S). The presence of numerous bays, capes and archipelagos has resulted in a very complex coastline (Fig. 1). The straight-line distance between these two capes is approximately 500 km; however, the actual length of the mainland coastline is more than 5000 km. The inner shelf region is characterised by numerous islands that support extensive fringing reefs and associated coral habitats. The Kimberley bioregion is comprised of at least 2413 islands and more than 853 reefs (Kordi et al., 2016). The area is characterised by a macrotidal regime with spring tides exceeding 11 m in the southern bioregion, the highest tidal range of any coral reef system in the world (Purcell, 2002; Wolanski and Spagnol, 2003). As ground-truth data was only available for some sites, this study had to be limited to the following reefs: Cape Londonderry Reef, Long Reef, Montgomery Reef, Maret Islands Reef, Adele Reef, Tallon Island Reef, Molema Island (also known as Turtle Reef) and Bathurst and Irvine Reefs (Fig. 1).

2.2. Remote sensing datasets

This study utilised Landsat 5 TM and Landsat 8 OLI images to map reef geomorphology and habitats. Despite the moderate spatial resolution (~30 m) of Landsat sensors, it has a long term archive that was accessible at no cost, which gives the opportunity to choose images that were acquired close enough to the field survey dates (Table 1). A colour composites of 4-band (red, blue, green, and near-IR) imagery were used. The scenes were selected according to the best available visibility and relatively clear waters. The study was limited to the eight aforementioned reefs (see Fig. 1). These reefs were selected because they are large enough to be detected by Landsat sensors. Further, good quality satellite images could be obtained at low tide (i.e. when the reefs were exposed) (Fig. 2) and most importantly, ground-truth data and/or very high spatial resolution orthophotographs were available. Furthermore, the reefs selected were all formed under a variety of conditions, including different geographic location and tidal and hydrodynamic regimes. These particular reefs are also analogues for other reefs in the region.

In some instances, cloud cover density affected the satellite images obtained in the study. Additionally, in other instances, the detection of reef features was restricted by the clarity of water, high tides and water turbidity (all factors that can prevent the effective detection of benthic environments). Thus, from 2009 to 2014, more than one scene of each of the targeted reef areas (i.e. Path 108/Row 70; Path 109/Row 70; and Path 110/Row 71) were acquired from the United States Geological Survey (USGS) and Earth Resources Observation and Science Centre (EROS) (Table 1). The large scene size of Landsat (170 km north-south by 183 km east-west) enabled reef features to be detected on sections of the images of the reefs with no cloud cover and/or at low tides.

Table 1
Satellite sensors and acquisition dates for the imagery covering each location.

Location	Sensor	Acquisition date	Path	Row
Adele Reef	Landsat 5 TM	03/03/2009	110	71
Bathurst & Irvine Islands	Landsat 8 OLI	21/06/2014	110	71
Cape Londonderry	Landsat 5 TM	21/10/2011	108	70
Long Reef	Landsat 5 TM	19/06/2010	109	70
Maret Islands	Landsat 5 TM	28/10/2011	109	70
Molema Island	Landsat 5 TM	07/04/2010	110	71
Montgomery Reef	Landsat 5 TM	13/10/2009	110	71
Tallon Island	Landsat 8 OLI	23/07/2014	110	71

2.3. Ground-truth data

Fieldwork activities were conducted in the eight targeted reefs between 2009 and 2013 by this study and from other secondary sources comprises Western Australian Museum Woodside Collection Kimberley Project 2008–2012; Wilson and Blake (2011); Wilson et al. (2011) providing more than 1000 ground control points (Table 2). A handheld global positioning system (GPS) with relatively high accuracy (±2 m) was used to obtain elevation measurements and coordinates. Habitat and substrate information was precisely recorded, however due to visibility limitations, the maximum water depth surveyed was 5 m. Georeferenced field photographs, aerial photography, and 15 orthophotographs (in true colour composites (RGB 321) of a very high spatial resolution <1 m) were also used for verification and measuring purposes (Bouvet et al., 2003). Locations of these ground-truth points are presented on the map of each reef in the results section. The time lag between the ground observations being made and the satellite images acquired varied from a few days to a few weeks.

2.4. Data processing

Pre-processing and post-processing procedures were applied to improve remote sensing image classification performance (Fig. 3). Images were first calibrated and converted to the Australian standard and GDA94 datum before being geometrically corrected with ESRI's ArcGIS 10 software package using ground-truth points with a root mean square error (RMSE) of <1.0 pixel. As images were mainly acquired at low tide when water depths varied between 0 and <5 m at the forereef slope, the improvement from water column correction was very marginal (<1%) and could be disregarded. The images were grouped into subsets and manually assigned to areas of interest (AOI) (i.e. shallow subtidal and intertidal reef platforms). Areas that were not of interest for mapping purposes were masked to reduce the variability of spectral classes (Kaczmarek et al., 2010; Madden et al., 2013; Phinn et al., 2008). Masking algorithms were applied using NIR bands 4 and 5 to mask land. Band 1 (blue) was used to delineate the threshold between deep and shallow water pixels (Naseer and Hatcher, 2004).

Geomorphological zones of these intertidal and shallow reefs at low tides were manually delineated as they usually have distinct boundaries that can be easily recognised in aerial photography and satellite images (Andréfouët et al., 2006; Fairbridge, 1967; Hopley, 1982; Hopley et al., 2007; Mumby and Harborne, 1999; Teichert and Fairbridge, 1948). Fig. 4 provides an example of how the zones were visualised using ground-truth data. Geomorphological descriptions of zones based on substrates, habitats, and tidal zones

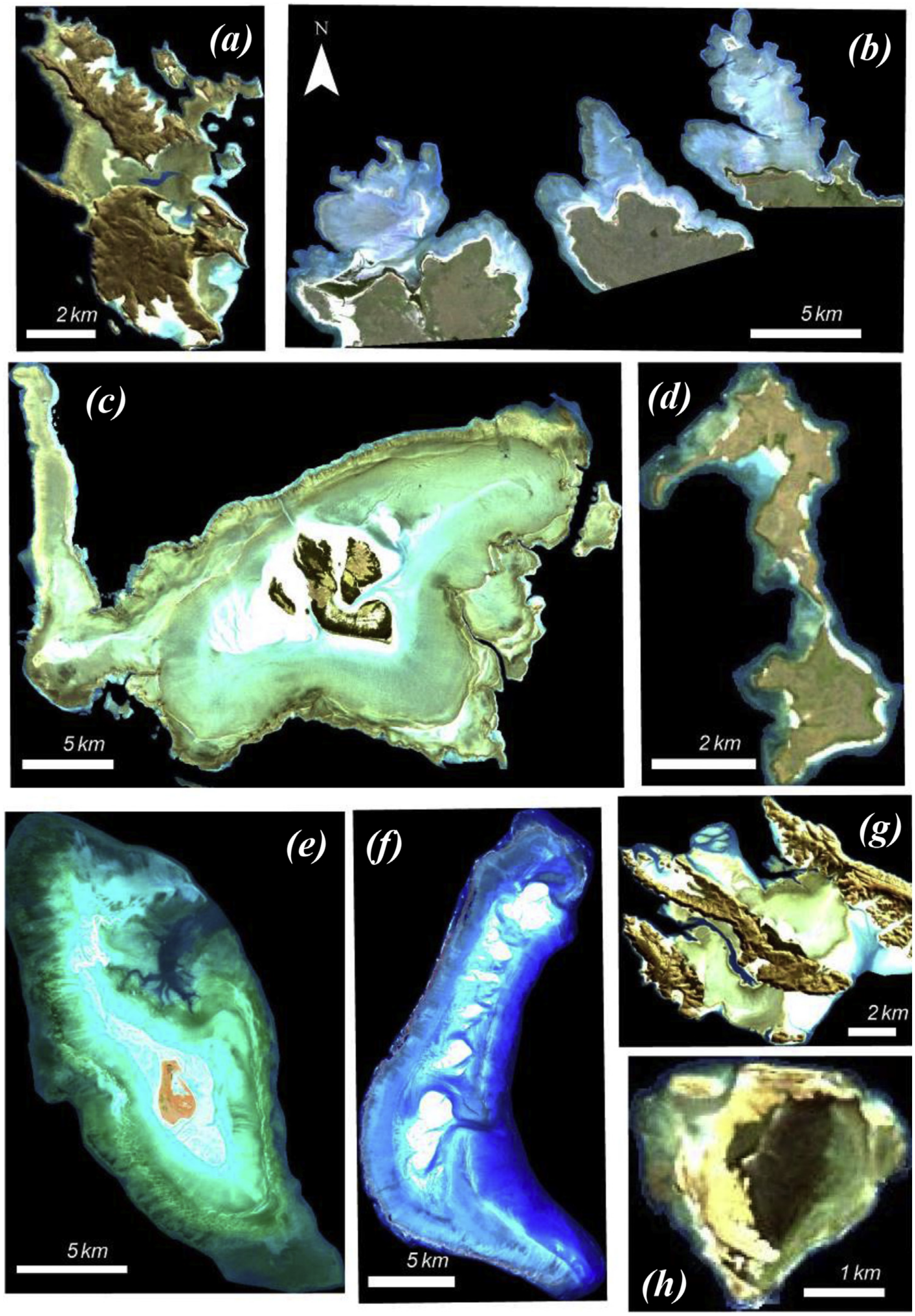


Fig. 2. Satellite images used to map intra-reef geomorphology and associated substrates for the targeted reefs of this study: (a) Bathurst and Irvine Islands; (b) Cape Londonderry; (c) Montgomery Reef; (d) Maret Islands; (e) Adele Reef; (f) Long Reef; (g) Molema Island; and (h) Tallon Island.

Table 2
Field data per location.

Reef	Control points	Survey date
Adele Reef	212	13–18/10/2009
Bathurst & Irvine Islands	187	1–9/08/2014
Cape Londonderry	42	10/02/2012
Long Reef	105	20–24/10/2010
Maret Islands	86	24/10/2012
Molema Island	126	3–12/09/2010
Montgomery Reef	145	19–24/10/2009
Tallon Island	203	1–10/07/2014

were recorded for each reef. Table 3 provides an example of the characteristic geomorphological zones and associated substrates and habitats found on Montgomery Reef.

The colour composite (RGB 421) of each image was used in the classification. Iterative Self-organizing Data Analysis (ISODATA), a statistics-based unsupervised classification technique, was applied using ENVI 4.3 software. Unsupervised classification has been shown to be very effective in identifying spectral clusters in remote sensing data (Campbell, 2002; Kakuta et al., 2010; Madden et al., 2013). In this study, spectral classes were assessed and combined into seven classes based on expert-guided knowledge

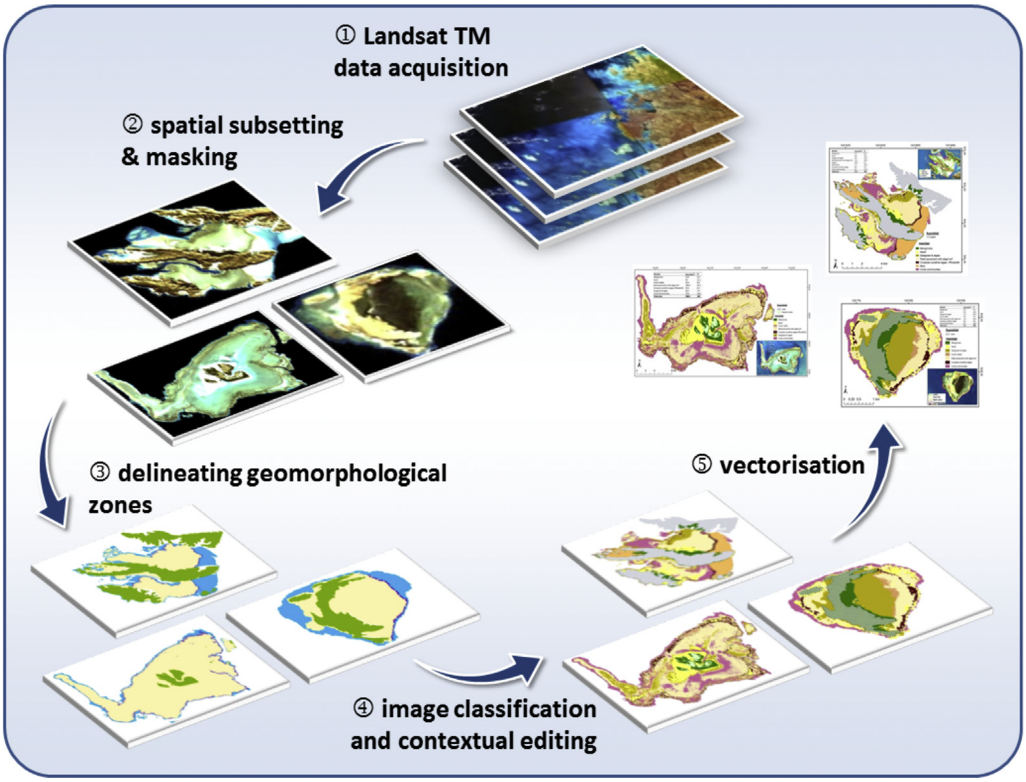


Fig. 3. Methodological scheme of Landsat data acquisition, processing, integration and analysing.

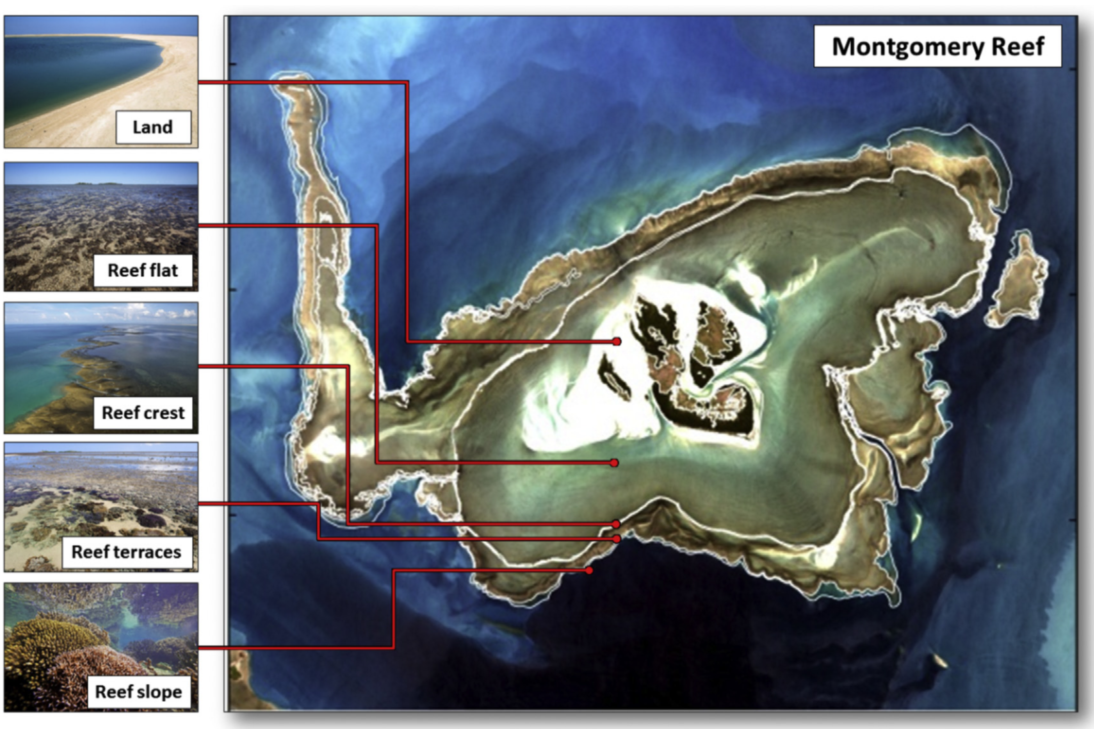


Fig. 4. Schematic representation of typical geomorphological zonal boundaries and associated habitat and substrate cover in the Kimberley bioregion. (Photos courtesy of Kimberley Media).

segmentation. Additionally, orthophotographs and ground-truth data were used to verify the accuracy of the classification. The thematic accuracy of image classification represents a quantitative estimation of the degree of correspondence between classified images and ground-truth data. The validity of the classification can be determined based on the results of the accuracy assessment.

Table 3
Defining the geomorphological zones and associated substrates and habitats on Montgomery Reef.

Geomorphic zone	Description	Tidal zone	Key substrates/habitats
Land	An area above the high tide water level.	Supratidal	Sand, mud, vegetation, rocks
Reef flat	A wide shallow zone on top of the reef platform usually exposed during low tides.	Intertidal	Mangroves, sand, coral rubble, reef pavement, algal turf, seagrass, coral communities
Lagoon	A combination between deeper antecedent topography and contemporary reef growth, major sinks of sediment.	Intertidal	Sand, coral communities
Reef crest	The highest point of the reef between reef flat and reef slope. It is mostly exposed at low tide.	Intertidal	Sand, coral rubble, crustose coralline algae, rhodolith
Forereef slope	An area from the seaward edge of the reef crest downwards (average steep slopes 30°) or gently sloped (terraced).	Subtidal	Coral communities, seagrass, Macroalgae

When using passive sensors of moderate spectral and spatial resolutions, the similarity of spectral reflection from habitat and substrate types can make discriminating between features difficult. However, some habitats usually occur in predictable geomorphological zones based on wave exposure and depth (Mumby et al., 1998). By way of example, seagrass is most likely to be found in sheltered settings on reef flats, but if a feature was classified as seagrass on a forereef slope or reef crest zone, it would very likely to have been misclassified because such zones are dominated by corals. In these circumstances, classified images were contextually edited and reassigned to the dominated class before assessing errors could occur. The habitat and substrate classification map was coupled with the geomorphological zonation map to produce additional maps that were then assigned two independent labels, the first for habitats and substrates, and the second for the geomorphological zone.

Classified images were vectorised to produce a reefal-scale map of the geomorphological features of the study area. A digital elevation model (DEM) sourced from Geoscience Australia (GA) was used to identify the geomorphic zone of reefs. Maps were developed that presented all the related information of a reef platform on one map. The template used for these maps consisted of the following:

(i) a substrates and habitats classification map with a latitude and longitude grid and scale bar;
(ii) a map legend showing the map's features based on geomorphic zones;
(iii) a geomorphic zones map showing the geomorphic units of the reef platform;
(iv) a satellite image showing the ground-truth point locations; and
(v) a table of descriptive statistics of the habitats and substrates based on statistics derived using the GIS data analysis.

2.5. Accuracy assessment

The accuracy of the habitats and substrates map was assessed based on the computation of a confusion matrix process. A confusion matrix is a form of cross-tabulation that gives a quantitative estimation of the degree of correspondence between the classified images in columns and the reality (i.e. ground-truth) in rows (Foody, 2002; Stehman, 2009). Ground-truth data was compared with the predicted cover types on the habitat and substrate map to assess the overall accuracy of the map. The overall accuracy is the statistical value produced that measures the agreement between two different maps (e.g. classified and ground-truth maps). The number of correctly classified pixels are added together and then dividing by the total number of pixels to calculate the statistical value. This is also useful in assessing the accuracy of the individual informational classes (Mumby et al., 1997). Overall accuracies should be more than 60% for reef management purposes (Green et al., 2005).

3. Results

Seven classes of habitats and substrates were identified in five intra-reef geomorphic zones, including two reef types (i.e. fringing and planar). Overall accuracies using a confusion matrix process ranged between 64.4% and 77.1% (Table 4). Adele reef has a high overall accuracy of 77.1% and a Kappa coefficient of 0.73. While lower overall accuracy of 64.4% and a Kappa coefficient of 0.58 were found for Cape Londonderry. A standard template of reef map figure presenting all the related information for each targeted reef platform was produced. The template consists of substrate and habitat classification maps with a latitude and longitude grid and scale bar, a legend showing the features of the map based on geomorphic zones and a geomorphic zones map showing the intra-reef geomorphic units of the reef platform. Each geomorphic unit is presented in a different colour on the platform. Also ground-truth locations were added to the satellite images. Finally, a table of descriptive statistics of habitats and substrates was produced.

3.1. Fringing reefs

3.1.1. The Maret Islands

The Maret Islands consist of two connected islands: North Maret and South Maret. These islands are situated in the Bonaparte Archipelago approximately 35 km off the coast of the Kimberley mainland (Fig. 1c). The reef morphology on the Maret Islands is typical to that of most fringing reefs across the Bonaparte Archipelago. However, it should be noted that a marked difference exists between windward and leeward reefs. Generally, the reefs on the Maret Islands are intertidal and have a circum-island morphology; however, parts of the reefs on the north-western side of both islands are headland-attached and exposed to the swell on the seaward shore and (based on the ground observations) dominated by domal faviids. Reefs on the eastern side of both islands (i.e. the

Table 4
The overall accuracy and kappa coefficient of each reef.

Reef	Overall accuracy (%)	Kappa coefficient (κ)
Adele Reef	77.1	0.73
Bathurst & Irvine Islands	73.1	0.68
Cape Londonderry	64.4	0.58
Long Reef	68.9	0.63
Maret Islands	66.4	0.61
Molema Island	69.3	0.64
Montgomery Reef	70.2	0.65
Tallon Island	75.6	0.71

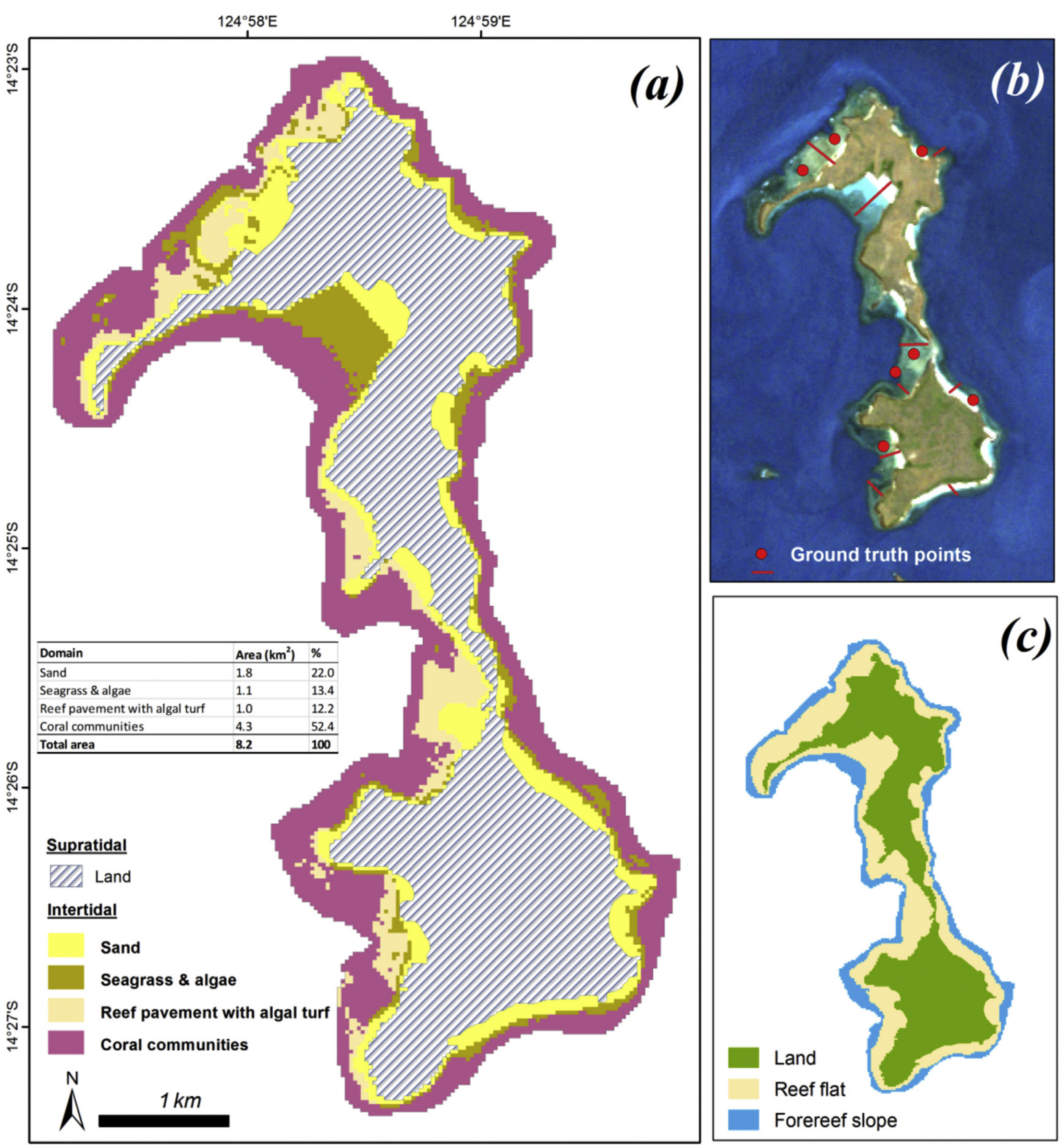
leeward shores) can be classified as narrow beach and rock-base fringing reefs and are protected from swells. Ground observations shows that *Acropora* dominates the coral community. Fig. 5 shows that the reef flat is wider towards the western, windward side of both the islands. Sand covers approximately 22% of the reef area on both sides of the reef and on the western side more than 12% of the area is covered by reef pavement with algal turf. Seagrass and algae are also present on the reef flat covering more than 13% of its area. Coral communities are prolific on the reef flat on both sides of the reef and prevail on the forereef slope covering more than 52% of the reef area.

3.1.2. Cape Londonderry

The reefs around Cape Londonderry are the northern-most mainland fringing reefs of the KIM (Fig. 1a). These reefs developed on three rocky headlands and are exposed to ocean swell. The reef flats are elongated, face northwest and extend between 5 and 7 km seawards and are irregularly shaped (Fig. 6). These reefs are considered to be intertidal and headland-attached fringing reefs. Based on a classification verification that used very high-resolution aerial photography (<1 m spatial resolution), the habitats and substrates on the reef flats resemble other fringing reefs in this category. The reef flats are relatively level and reef pavement with algal turf dominates covering approximately 36% of the reef flats. Mangroves that have developed on the mud flats behind the sandy beaches of these three headlands and cover over 6% of the reef area. Sand and coral rubble are dispersed across the reef flats and cover more than 21% of the area. Seagrass and algae form a prolific covering approximately 12% of the reef flat. Coral communities are abundant on the forereef slope covering nearly 24% of the reef.

3.1.3. Molema Island

Molema Island is a high island situated in Talbot Bay on the northern Yampi Peninsula, adjacent to the mainland shore (Fig. 1g). On the north-eastern side, Molema Island is connected to a peninsula by a reef complex that extends approximately 3 km, and



Domain	Area (km²)	%
Sand	1.8	22.0
Seagrass & algae	1.1	13.4
Reef pavement with algal turf	1.0	12.2
Coral communities	4.3	52.4
Total area	8.2	100

Fig. 5. (a) Habitat/substrate classification map of the Maret Islands Reef; (b) satellite image of the Maret Islands with ground-truth point locations highlighted; (c) geomorphic zones map.

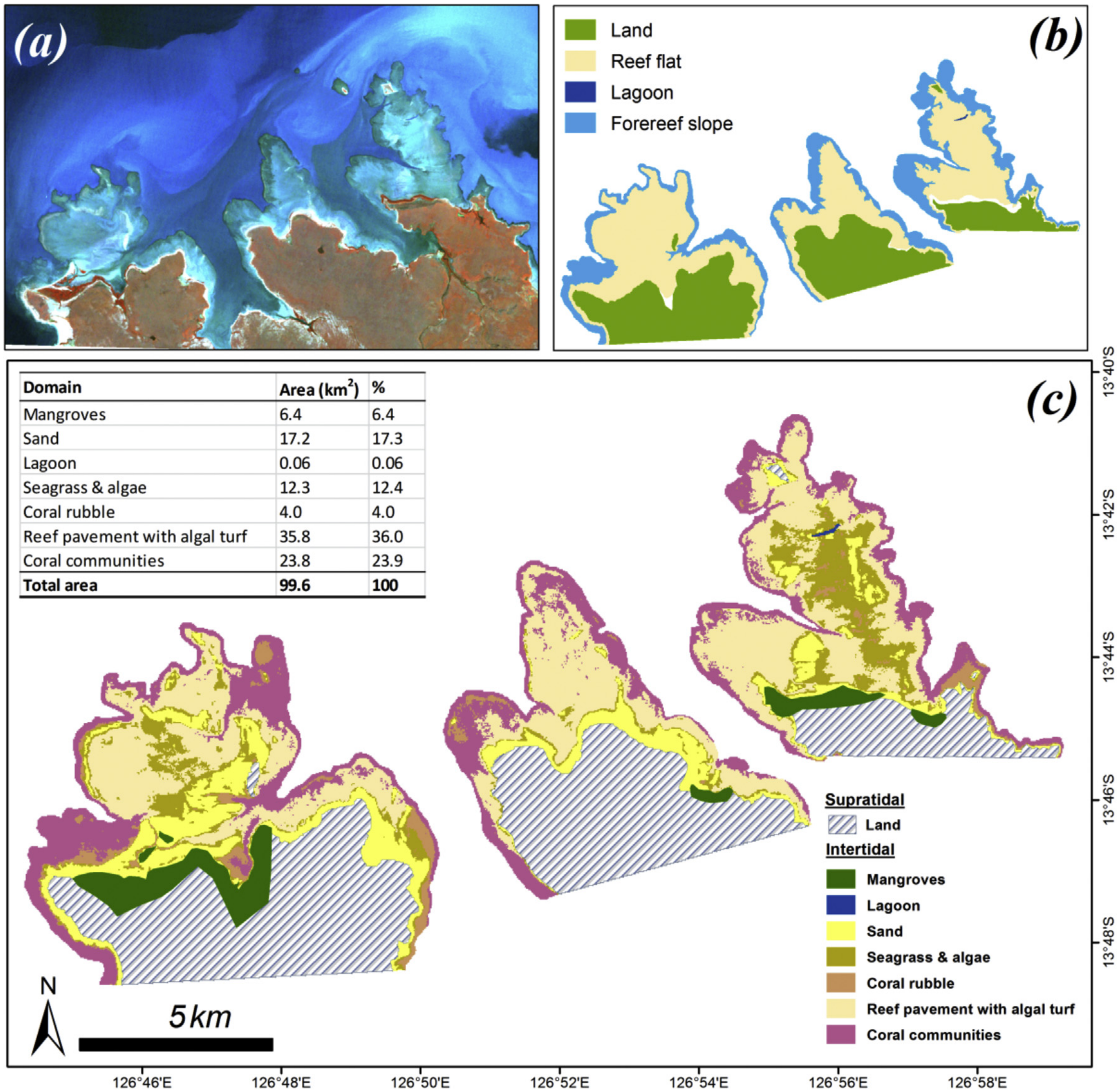
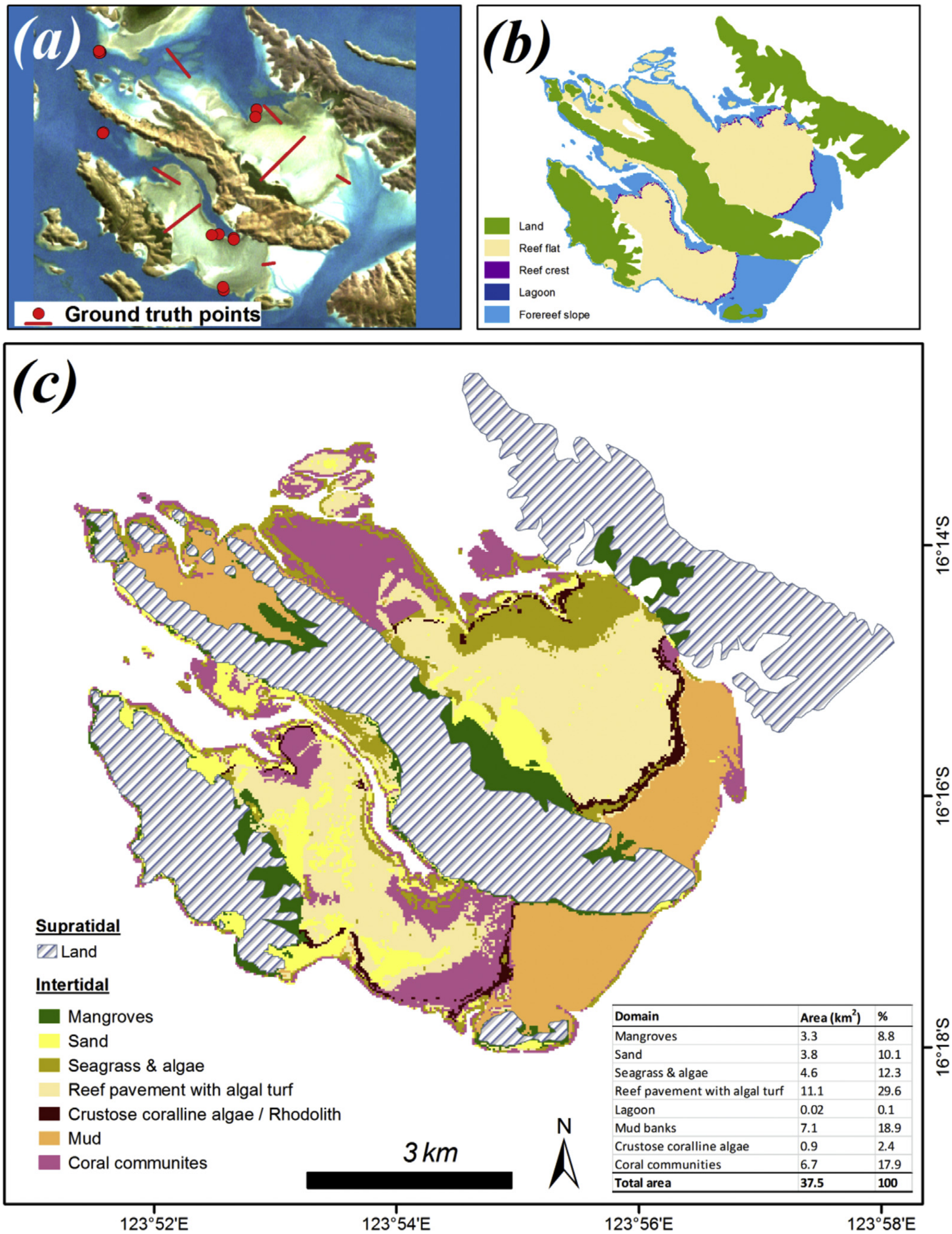


Fig. 6. (a) Satellite image of Cape Londonderry—the classification map was verified using very high-resolution (<1 m spatial resolution) aerial photography; (b) geomorphic zones map; (c) habitat/substrate classification map of Cape Londonderry Reefs.

on the south-western side, the island is connected to another island by a reef complex that extends approximately 2 km. These reefs are known as the "Turtle Reef" (Fig. 7). Being surrounded by a number of islands, both reefs are protected from high wave energy. The reef platforms are elevated and during extremely low spring tides, the sea level exposure may be more than 4 m. These types of fringing reefs are classified as high intertidal and inter-island reefs. Mangroves have developed on the muddy flats behind the sandy beaches on the islands and the peninsula and cover about 9% of reef area. Sand cays cover approximately 10% of the area of the reef flat and sand fans and rubble are present on the reef edges. The reef flats are mainly covered by reef pavement with algal turf (>29%) and seagrass and algae covers approximately 12% of the reef flats, particularly on the northern reef. The reef edges are terraced with a veneer of crustose coralline algae with banks of rhodoliths in a landward direction. There are three wide mud flats: one each on the northern and southern sides of the eastern part of Molema Island and the third is on the western side. These mud flats are relatively large and occupy approximately 19% of the reef area. They are located on a lower level than the reef flats, but are still exposed during tidal cycles. The coral communities show vigorous growth and cover nearly 18% of the reef flat margins and forereef slope.

3.1.4. Bathurst and Irvine Islands

Bathurst and Irvine Islands are high islands situated in the Buccaneer Archipelago approximately 14 km off the Kimberley mainland shore (Fig. 1h). The two islands, and 13 other small adjoining islands, are connected by fringing reefs (Fig. 8). The reefs on the northwest side of Bathurst Island and on the west side of Irvine Island are headland reefs exposed to the ocean swell on the seaward shores and mainly dominated (based on ground observations) by domal faviids. Conversely, the reefs on the northeast side of Bathurst Island and the south and southeast sides of Irvine Island are classified as bayhead fringing reefs, protected from high-energy swells and the coral community is dominated (based on ground observations) by *Acropora*. In terms of geomorphic characteristics and surficial facies, the reefs on both sides appear to be similar to other fringing reefs on islands in this region. However,



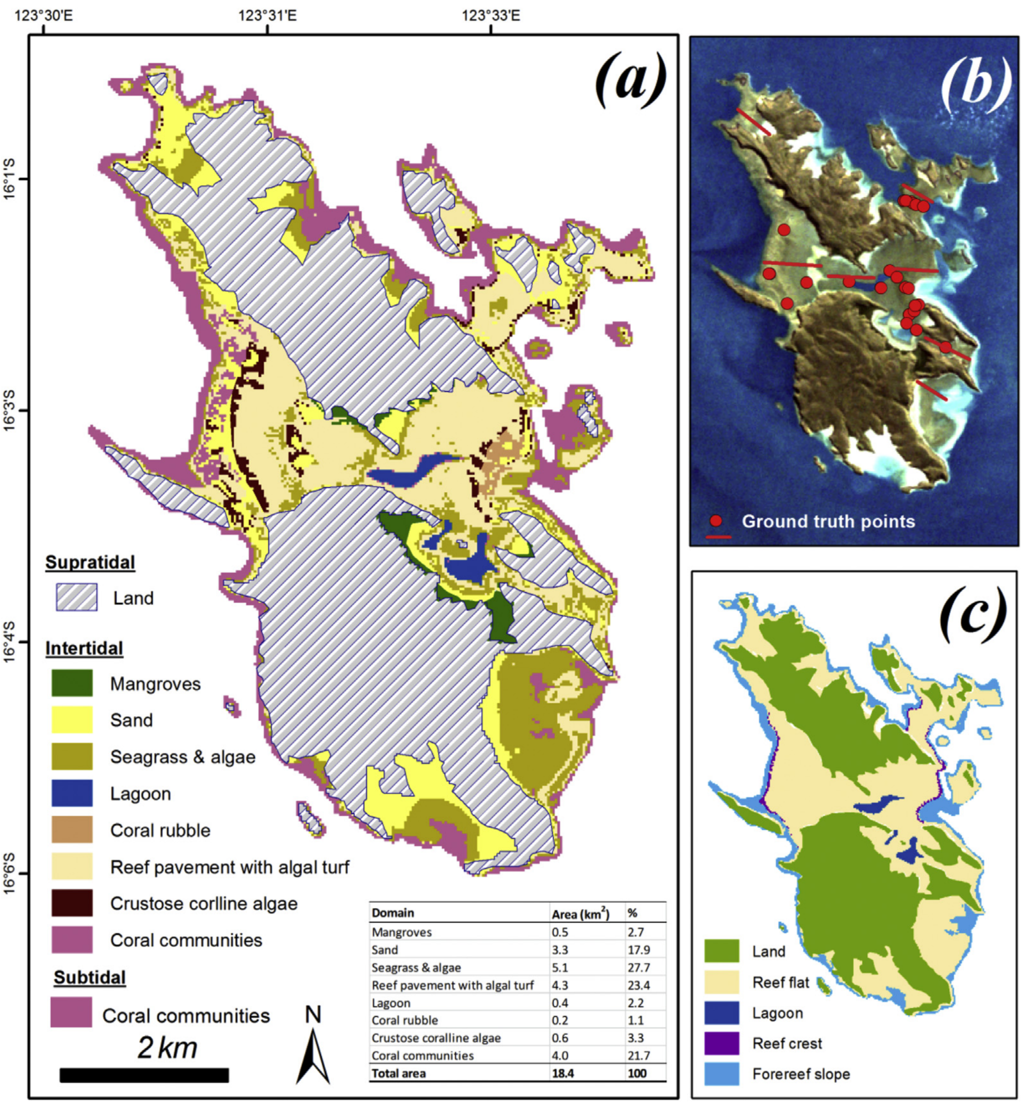
Domain	Area (km^2)	%
Mangroves	3.3	8.8
Sand	3.8	10.1
Seagrass & algae	4.6	12.3
Reef pavement with algal turf	11.1	29.6
Lagoon	0.02	0.1
Mud banks	7.1	18.9
Crustose coralline algae	0.9	2.4
Coral communities	6.7	17.9
Total area	**37.5**	**100**

Fig. 7. (a) Satellite image of Molema Island (Turtle Reef) with ground-truth point locations highlighted; (b) geomorphic zones map; (c) habitat/substrate classification map of Turtle Reef.

the extensive reef platform between Bathurst and Irvine Islands differentiates it from the other reefs. This type of fringing reef is classified as an inter-island reef and may have formed through a process of coalescence between the fringing reefs of both islands. The reef flat is entirely exposed during low tide. It is characterised by a relatively elevated centre and there is extensive coverage (23.4%) of reef pavement with algal turf. Microatolls of between 30 and 100 cm in diameter are sparse on the reef flat. Mangroves have developed on the sandy beaches of both islands, particularly on the southern island and cover less than 3% of the reef area. The carbonate sand covers approximately 18% of the reef area. Large sand banks (mainly on the western side of the reef) are trapped behind edges made by encrusting coralline algae and have a minor accumulation of rhodoliths. Many live coral communities (e.g. domal and branching *Porites* sp.) are present in the shallow lenticular pools scattered on the reef flat. There are also various living coral communities in and around three deep pools. Corals are prolific on the forereef slopes on both sides of the reef and cover 21.7% of the reef area.

3.1.5. *Tallon Island*

Tallon Island is a small, high island that has a curved (almost talon-like) shape. It is situated approximately 7 km to the east of One Arm Point and surrounded by numerous islands in a sheltered area (Fig. 1f). Two fringing reefs exist at the eastern and western sides of the island (Fig. 9). While both reefs are terraced and have



Domain	Area (km^2)	%
Mangroves	0.5	2.7
Sand	3.3	17.9
Seagrass & algae	5.1	27.7
Reef pavement with algal turf	4.3	23.4
Lagoon	0.4	2.2
Coral rubble	0.2	1.1
Crustose coralline algae	0.6	3.3
Coral communities	4.0	21.7
Total area	**18.4**	**100**

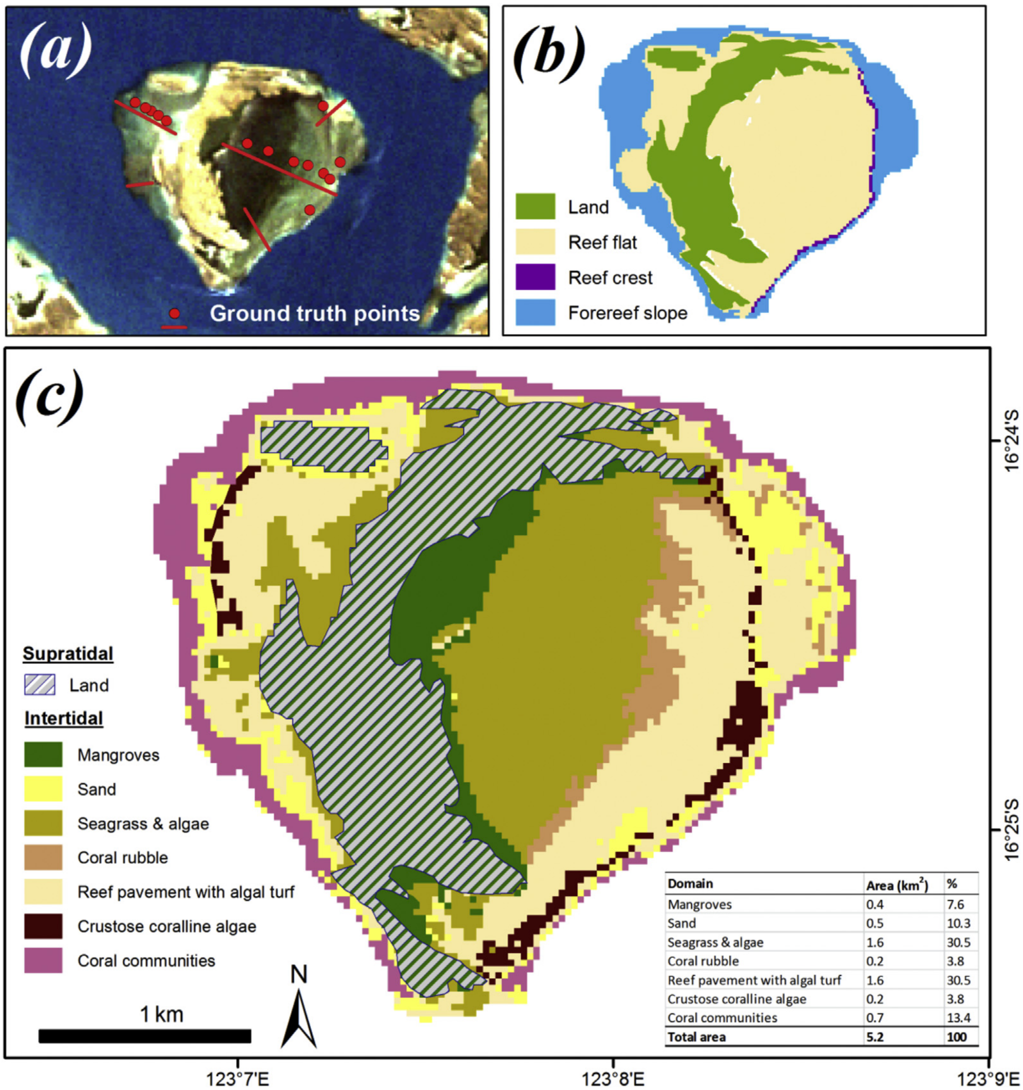
Fig. 8. (a) Habitat/substrate classification map of reefs between Bathurst and Irvine Islands; (b) satellite image of Bathurst and Irvine Islands with ground-truth point locations highlighted; (c) geomorphic zones map.

some similarities in relation to their habitats and substrates, their morphology differs. The reef on the eastern side of the island supports a dense growth of mangroves on its sandy beach that covers 7.6% of the reef area. Further, the eastern reef flat is approximately 1 km wider than the flat of the western reef and considerably higher. The eastern reef is protected from winds and swells and is considered a high intertidal and bayhead reef. Conversely, the western reef is classified as an intertidal and headland reef. Seagrass and algae cover 30.5% of both reef flats. Approximately 14% of the reef flats are covered by coarse carbonate sand and coral rubble, some of which is trapped by terraces of crustose coralline algae; this is particularly predominant in the eastern reef. A minor assemblage of rhodoliths is also present in this area. A large area of the reef flats (30.5%) is covered by reef pavement with algal turf. There are numerous shallow pools on both reef flats that are filled with coral communities (e.g. domal and branching *Porites* sp. and soft corals). Coral communities cover 13% of the reef, mostly on the forereef slope of the western reef.

3.2. Planar reefs

3.2.1. Montgomery Reef

Montgomery Reef is located in Collier Bay about 25 km off the Kimberley mainland shore (Fig. 1d). It is a large, terraced reef complex of over 380 km^2 with a central island formed of Proterozoic rocks (Wilson and Blake, 2011). The reef is an irregular oval shape and has an elongated peninsula (breakwater) that extends from the western side of the reef edge towards the northern side (Fig. 10). A small reef platform on the eastern side, consisting of five high islands, is called High Cliffy Reef. The small reef is separated from Montgomery Reef by a channel approximately 10 m deep. Montgomery Reef is a high reef platform that emerges a few metres (~4 m) above the mean low water spring (MLWS) tide level during tidal cycles. Despite its unique structure it has been classified as a high intertidal and planar reef. At the centre of the reef flat are three vegetated low islands that contain mud flats and mangroves surrounded by sand sheets. There are also four vegetated low islands on the eastern edge of the reef flat. Sand covers approximately 12% of the reef flat, particularly near the reef centre, the southern breakwater, and the reef terraces. The reef flat is covered



Domain	Area (km^2)	%
Mangroves	0.4	7.6
Sand	0.5	10.3
Seagrass & algae	1.6	30.5
Coral rubble	0.2	3.8
Reef pavement with algal turf	1.6	30.5
Crustose coralline algae	0.2	3.8
Coral communities	0.7	13.4
Total area	5.2	100

Fig. 9. (a) Satellite image of Tallon Island, with ground-truth point locations highlighted; (b) geomorphic zones map; (c) habitat/substrate classification map of Tallon Island reefs.

by a large area (42.3%) of reef pavement with algal turf. Coral rubble with seagrass and algae cover 8.5% and 8% of the reef flat, respectively. Crustose coralline algae dominate the reef crest and large areas of rhodolith banks can be found on the reef terraces. Coral communities are widespread and represent approximately 20% of the reef area and occur across many geomorphic zones. Corals can be found in and near deep lagoons and channels towards the north-western centre of the reef flat, and fill the many shallow lenticular pools on the massive reef flat. Corals are also prolific on the forereef slopes. The terraced, elevated reef flat, with its shallow pools, rhodolith banks, and crustose coralline algae near the reef crest, has many characteristics of a high intertidal reef (see Wilson, 2013).

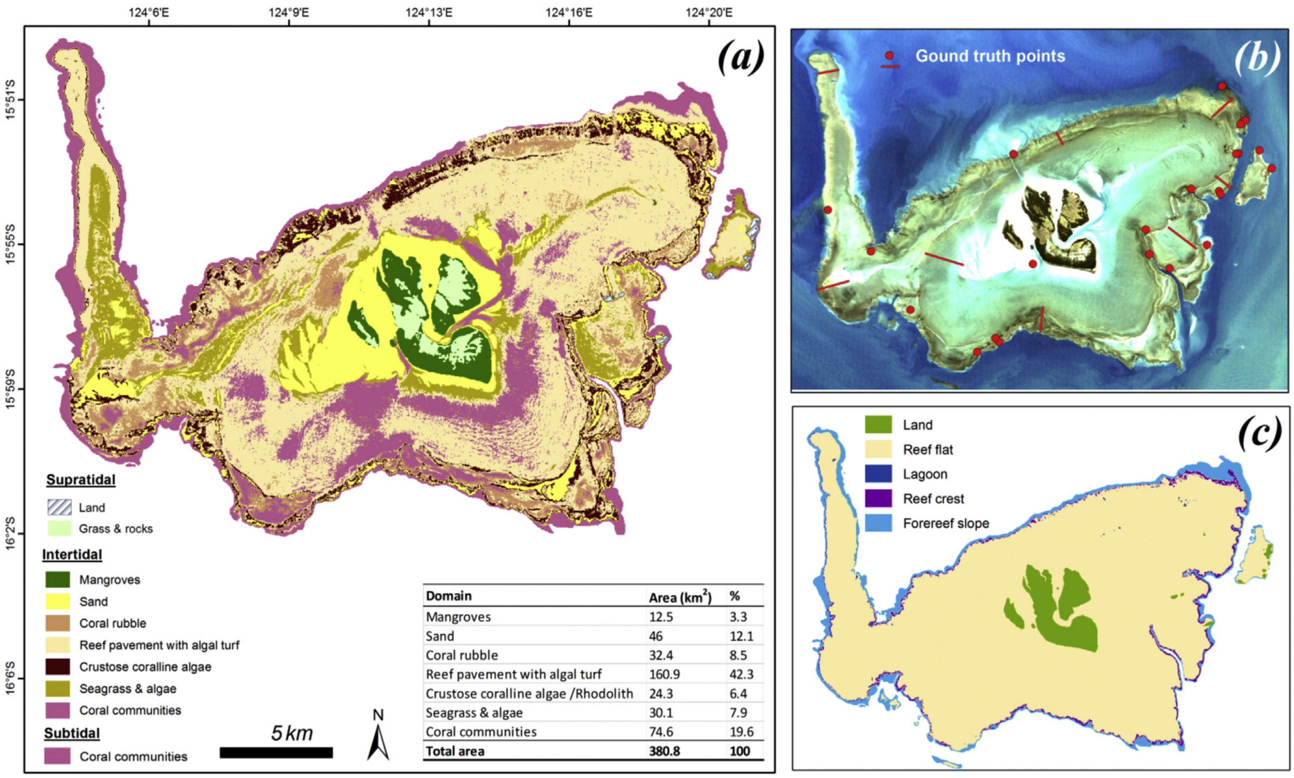
3.2.2. Adele Reef

Adele Reef is located near the edge of the inner ramp of the north-western continental shelf, about 90 km northwest of the Kimberley shore (Fig. 1e). The isolated reef covers a total area of 168 km^2 and is nearly elliptical in shape. Its long axis is oriented north-west to south-east. It has a wide, relatively deep channel on its north-western side known as 'Fraser Inlet'. Adele Reef has a vegetated low island at its centre. It is surrounded by a large sand cay that covers approximately 28% of the reef surface and is submerged during high tide. The reef is considered intertidal and planar. The reef flat is exposed during low tide and is mainly covered by coarse sand and coral rubble (24.6%) and minor algal turf (7%). Macroalgae (mostly *Sargassum* sp.) occurs near the edge of the reef flat as well as on the forereef slope. The reef has a terraced edge dominated by crustose coralline algae and a wide area of rhodolith banks lies behind this edge. Coral communities are abundant on the reef and cover a considerable area (23.5%) of the forereef slope. There are also numerous coral communities in the shallow pools of the reef flat (Fig. 11).

In contrast to the inshore reefs, Adele Reef is located in a wave-exposed, open-ocean setting. It lacks a shallow Proterozoic basement and overlies previous generations of Pleistocene reefs and old limestone foundations into which deep (>100 m) lowstand channels have been cut adjacent to the platform (Collins et al., 2015).

3.2.3. Long Reef

Long Reef is situated to the north of the Bonaparte Archipelago about 27 km off the Kimberley coast (Fig. 1b). The reef covers a total area of 195 km^2 and is elongated northeast southwest. A large area of the reef platform (approximately 40%) is covered by an intertidal sheet of carbonate sand fans and coral rubble that is submerged



Domain	Area (km^2)	%
Mangroves	12.5	3.3
Sand	46	12.1
Coral rubble	32.4	8.5
Reef pavement with algal turf	160.9	42.3
Crustose coralline algae /Rhodolith	24.3	6.4
Seagrass & algae	30.1	7.9
Coral communities	74.6	19.6
Total area	**380.8**	**100**

Fig. 10. (a) Habitat/substrate classification map of Montgomery Reef; (b) satellite image of Montgomery Reef with ground-truth point locations highlighted; (c) geomorphic zones map.

during high tide (Fig. 12). There is no central vegetated island on the reef, although a small sand cay is located on the north side of the reef that remains exposed during high tide. The reef has a number of lagoons distributed on its flat that vary in depth and width and are mostly filled with sand. Long Reef is considered an intertidal and planar reef. Algal turf on a reef pavement covers a considerable area (31.6%) of the reef flat. There are noticeable differences between the windward and leeward sides of the reef. The western (windward) side of the reef is exposed to high energy swells and has a terraced edge that is dominated by crustose coralline algae. The forereef slope on the windward side is narrow and steeply sloping; whereas the forereef slope of the leeward side is wider and slopes more gently. Macroalgae (*Sargassum* sp.) cover approximately 14% of the reef area and is prolific in deeper areas of the reef flat as well as on the forereef slopes. Coral communities are abundant on the reef, covering 13.6% of the reef area, mainly on the forereef slopes, in and around the lagoons, and in shallow pools on the reef flat (Fig. 12).

3.3. High intertidal reefs

High intertidal reefs are a unique feature of macrotidal reefs (Wilson, 2013; Collins et al., 2015) that are characterised by a high, flat-topped reef surface that may be several metres above mean low water neap (MLWN) tide and are commonly exposed during the tidal cycle (Richards and O'Leary, 2015). The surfaces have distinctive lithified algal terraces and coralline algae (rhodoliths) banks (Fig. 13), shallow coral-filled pools on reef flats, and often prolific *Porites* sp. microatoll. These reefs include both planar (e.g. Montgomery Reef) and fringing reefs (e.g. Turtle Reef, Bathurst-Irvine Reef, and East Tallon Reef).

3.4. Similarities and differences between the reefs of this study area

A total of seven substrates and habitats were identified on the major reef platforms in the study area. The distribution and coverage area of these substrates and habitats varied between reef types, however common factors found for all reefs included prolific reef growth, considerable areas covered by sand, reef pavement with algal turf, and seagrass and algae (see Table 5).

Other substrates and habitats were found to be present on particular types of reef. For example, mangroves were mainly found on fringing reefs attached to the mainland or islands. However, Montgomery Reef is an exceptional case of a planar reef because it contains Proterozoic vegetated islands that characterised by the presence of mangroves.

Crustose coralline algae are usually found on the edge of low intertidal planar reefs and high intertidal areas of both planar and fringing reefs, but are either absent or rarely found on other types of reef. For example, Adele Reef has crustose coralline algae coverage of approximately 9% near its reef crest, whereas Montgomery Reef has 6.4% coverage.

4. Discussion

The scarcity of previous research on reefs in the KIM can be mainly attributed to its remoteness. However, remote sensing used in conjunction with other relevant data sources (e.g. aerial photography, bathymetric charts, and supporting ground-truth) has provide information that is useful for the mapping of reefs. Landsat was found to be an effective space-borne sensor due to its characteristics that enable reef features to be mapped in extreme water conditions, including a long-term archive, and large scene size (i.e. 170 km north-south by 183 km east-west). However, reef

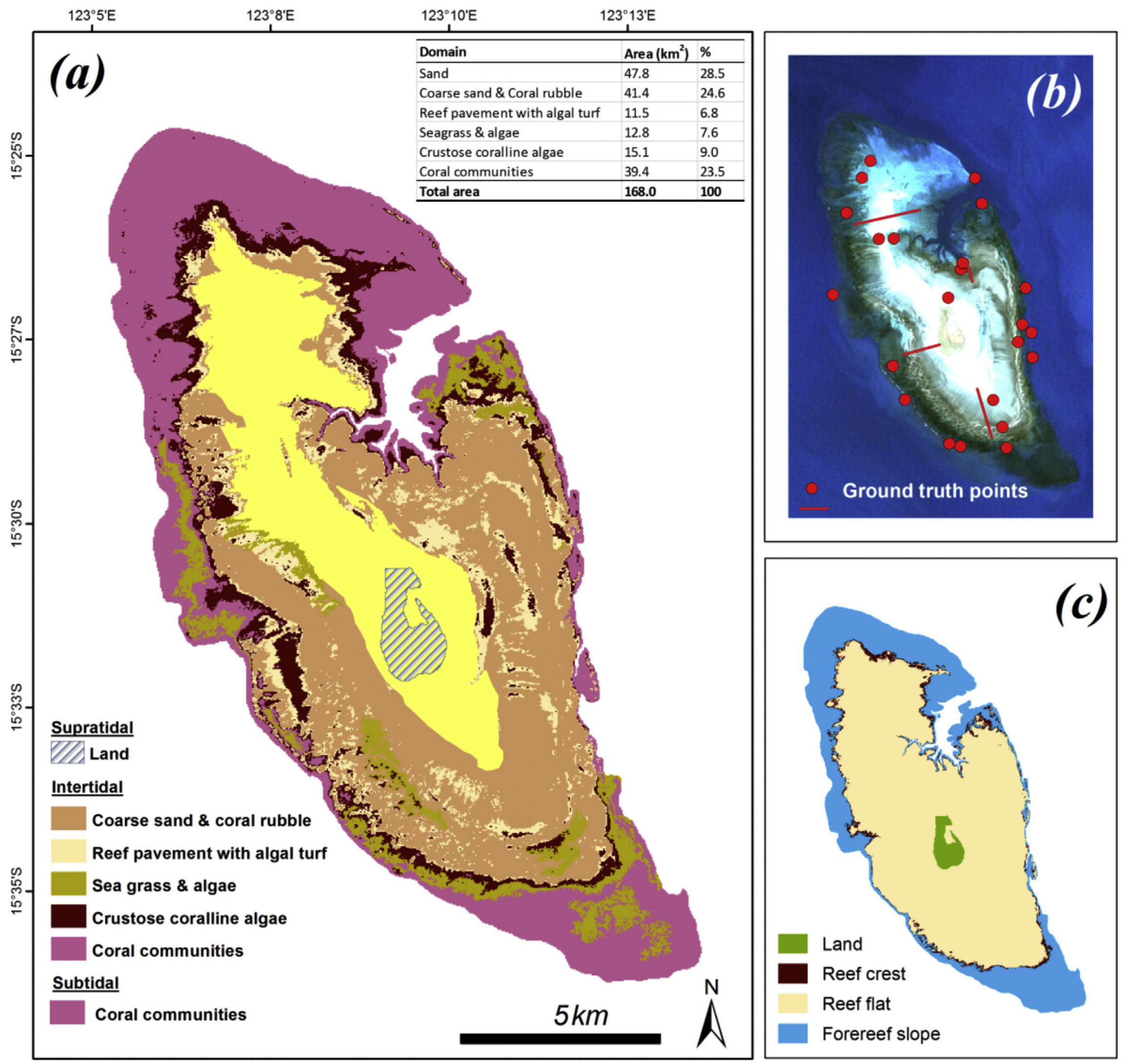


Fig. 11. (a) Habitat/substrate classification map of Adele Reef; (b) satellite image of Adele Reef with ground-truth point locations highlighted; (c) geomorphic zones map.

mapping remains challenging because it is limited by light attenuation and spectral misclassifications. The results of this study indicate that significant improvements in accuracy can be achieved in the mapping of intra-reef geomorphic zones and associated habitats and substrates for many reefs in the KIM.

In this study, examples of Kimberley reefs were chosen that illustrated the properties of fringing and planar reefs. Particular attention was given to the high intertidal reefs (i.e. fringing and planar) of the southern KIM. The methodology developed for this study was used to document the geomorphology of eight reef platforms in different geographical locations whose sizes could be mapped using Landsat images, and on which there was sufficient ground-truth information available. The reef platforms were also mapped in relation to their biosedimentary substrates and sedimentary facies, including the percentage of coverage of each substrate type.

This study shows that Landsat images can effectively be used to map the detailed geomorphology of coral reefs by applying image analysis techniques and using unsupervised classification. An overall accuracy of between 64% and 77% was obtained using a confusion matrix. The lower overall accuracy and Kappa coefficient of Cape Londonderry map was mainly due to the shortage in ground-truth points. One advantage of using an unsupervised classification method is that it can be replicated on other reefs in the region. Further, the resultant classification allows for a spatial analysis of the distribution and geometry of intra-reef components that can be used to derive classification schemes that are consistent across other reefs in the KIM.

The majority of fringing reefs observed in the study area have grown around high islands or submerged rocky outcrops. Reefs attached to islands are often wider and have more reef growth on windward sides that are exposed to the northwest and more steeply sloping reef fronts. Reefs on the leeward side are more gently sloping and reef flats tend to be narrowest where reefs are sheltered from high wave energy. The difference in width between the windward and leeward sides of the reefs appears to be consistent across most islands, particularly in the northern part of the Bonaparte Archipelago. This suggests that either exposed reefs grow faster than sheltered reefs, or start growing earlier (Wilson, 2013). Fringing reefs with a defined reef crest are best developed in the Buccaneer Archipelago (e.g. Sunday Island, and Tallon Island) and are also present northward of the Buccaneer Archipelago (Wilson, 2013). The area of a fringing reef is usually smaller than the area of the high island to which it is attached. However, the area of

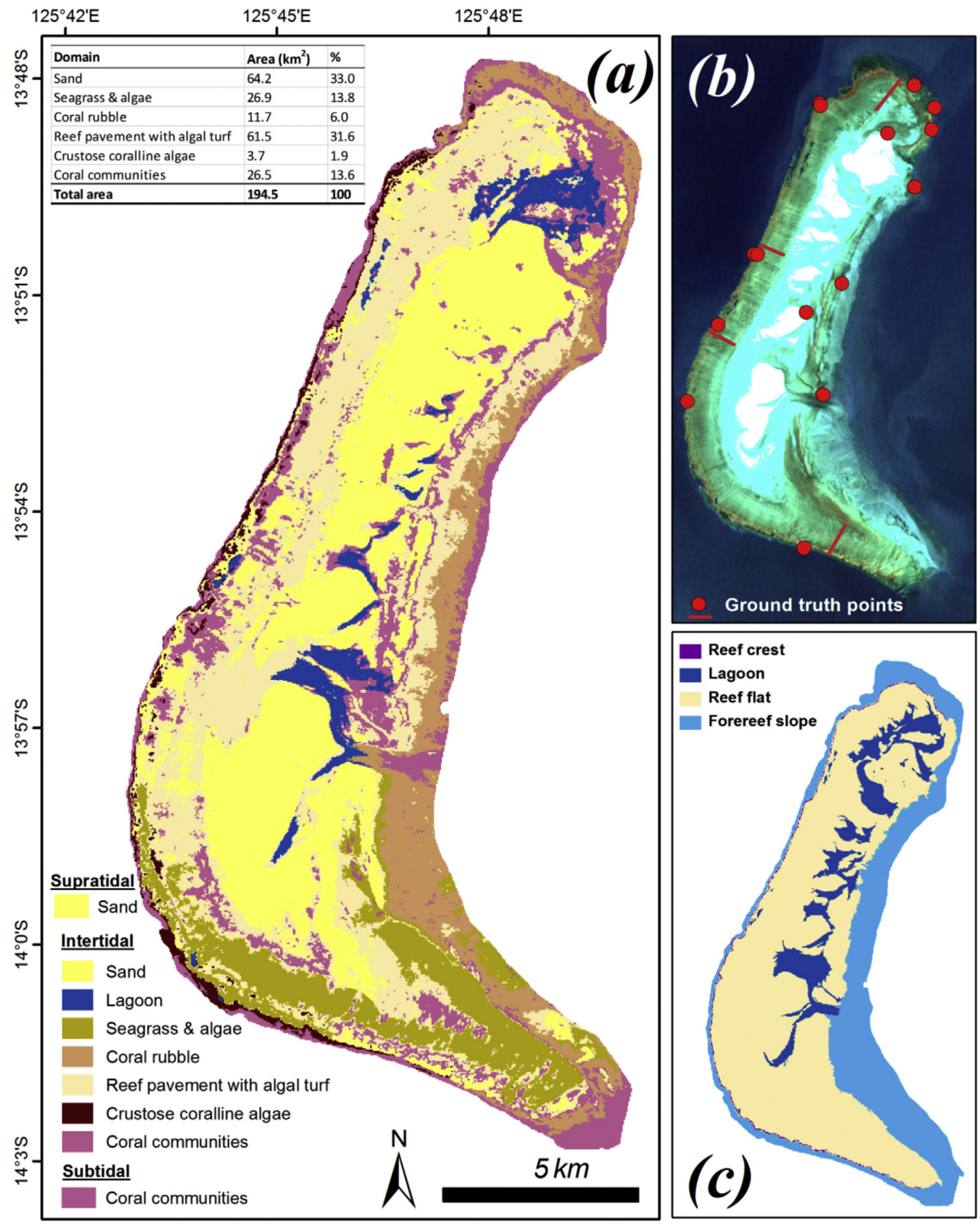


Fig. 12. (a) Habitat/substrate classification map of Long Reef; (b) satellite image of Long Reef, with ground-truth point locations highlighted; (c) geomorphic zones map.

other reefs (e.g. Tallon Island) exceeds that of their island many times.

Planar reefs have isolated features characterised by a large area and are mostly found offshore. According to Hopley's classification, these reefs are considered to be in their senile stage as most of their lagoons are infilled and the reef flat extends across the entire reef platform. Reef flats are often exposed at low tides. The majority of these reefs are covered by a massive sand sheet on the reef flat and surrounded by an intertidal reef platform or rampart. However, some other senile reefs have a central vegetated low island (e.g. Adele Reef), or an unvegetated sand cay (e.g. Long Reef).

High intertidal reefs are a remarkable feature of the KIM. The reef flat is easily distinguished as the elevation is at the position of mean sea level (MSL) rather than mean low water spring (MLWS) (a feature that allowed the reefs to be mapped in greater detail using remote sensing images). High intertidal reefs are characterised by lithified algal terraces, coralline algae with rhodolith accumulations, and *Porites* sp. microatolls (Wilson, 2013). This type of reef includes both planar reefs (e.g. Montgomery Reef) and fringing reefs (e.g. Tallon Island); these reefs are particularly prevalent in the Buccaneer Archipelago where the spring tide range exceeds 9 m (e.g. Molema Island and Bathurst-Irvine Islands). The reef platform between islands appears to have been formed by a coalescence of fringing reefs attached to the islands. A recent seismic study conducted by Collins et al. (2015) suggested that these reefs have a long growth history, including Holocene and Late Pleistocene (last interglacial) reef-building events.

The coral reefs of the KIM occur in extreme environments (including areas influenced by macrotides, highly turbid water, and complex coastal morphology). Such environments can limit

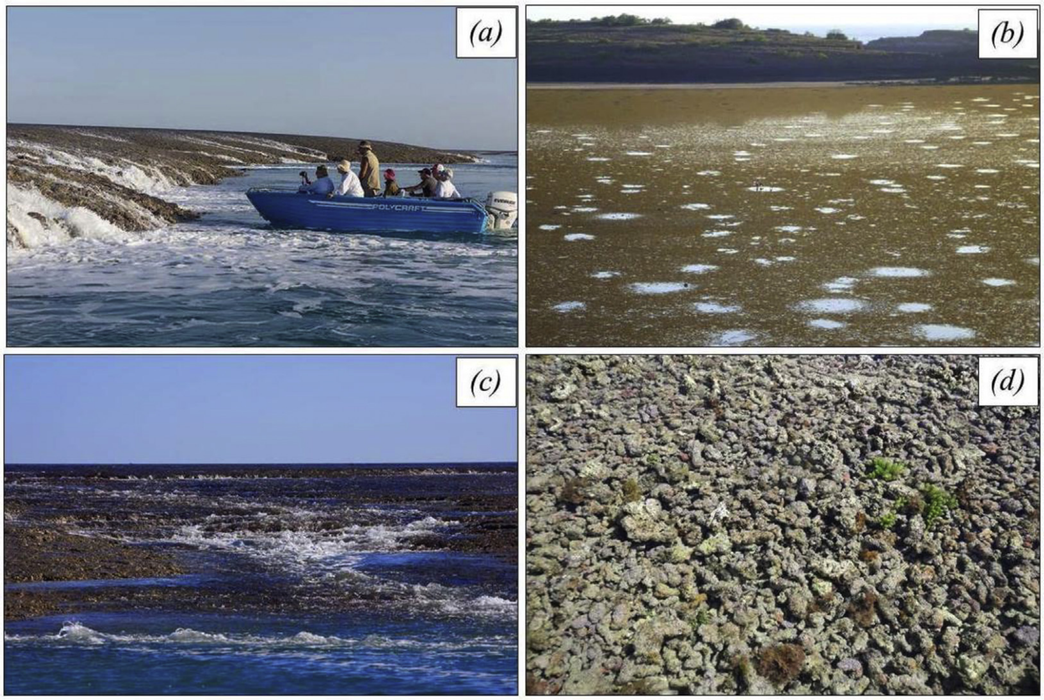


Fig. 13. Common characteristics of high intertidal reefs: (a) An elevated flat of Montgomery Reef during low tide; (b) an exposed reef flat on East Bathurst Island with many shallow lenticular pools; (c) lithified algal terraces on Montgomery Reef; (d) a rhodolith bank on East Tallon Island. (Photos courtesy of Kimberley Media, Mick O'Leary and Tubagus Solihuddin).

Table 5
Coverage area of substrates and habitats of selected reefs.

Reef Name	Lat° (S)	Reef type	Tide	Substrates and habitats								Total area (km^2)
				Man	San	Lag	SG & A	CR	RPAT	CCA	CC	
Cape Londonderry	13° 43′	Fringing	Low intertidal	6.4 (6.4%)	17.2 (17.3%)	0.1 (0.1%)	12.3 (12.4%)	4.0 (4.0%)	35.8 (35.9%)	0.0 (0%)	23.8 (23.9%)	99.6
Long Reef	13° 55′	Planar	Low intertidal	0 (0%)	64.2 (33.0%)	0 (0%)	26.9 (13.8%)	11.7 (6.0%)	61.5 (31.6%)	3.7 (1.9%)	26.5 (13.6%)	194.5
Maret Island	14° 25′	Fringing	Low intertidal	0 (0%)	1.8 (22.0%)	0 (0%)	1.1 (13.8%)	0 (0%)	1 (12.2%)	0 (0%)	4.3 (52.4%)	8.2
Adele Reef	15° 30′	Planar	Low intertidal	0 (0%)	47.8 (28.5%)	0 (0%)	12.8 (7.6%)	41.4 (24.6%)	11.5 (6.8%)	15.1 (9.0%)	39.4 (23.5%)	168.0
Montgomery Reef	15° 55′	Planar	High intertidal	12.5 (3.3%)	46 (12.1%)	0 (0%)	30.1 (7.9%)	32.4 (8.5%)	160.9 (42.3%)	24.3 (6.4%)	74.6 (19.6%)	380.8
Bathurst & Irvine Islands	16° 03′	Fringing	High intertidal	0.5 (2.7%)	3.3 (17.9%)	0.4 (2.2%)	5.1 (27.7%)	0.2 (1.1%)	4.3 (23.4%)	0.6 (3.3%)	4.0 (21.7%)	18.4
Molema Island	16° 15′	Fringing	High intertidal	3.3 (10.8%)	3.8 (12.5%)	0.02 (0.1%)	4.6 (15.1%)	0 (0%)	11.1 (36.5%)	0.9 (3.0%)	6.7 (22.0%)	30.42
Tallon Island	16° 25′	Fringing	High intertidal	0.4 (7.6%)	0.54 (10.3%)	0 (0%)	1.6 (30.5%)	0.2 (3.8%)	1.6 (30.5%)	0.2 (3.8%)	0.7 (13.4%)	5.24
Total area (km2)				23.1	184.6	0.5	94.5	89.9	287.7	44.8	180.0	905.1

Note: Percentages of the coverage are in brackets. Latitudes are ordered from north (top) to south (bottom) with reef and tide types. Description of substrate and habitat abbreviations: 'Man' = mangroves; 'San' = sand; 'lag' = lagoon; 'SG & A' = seagrass and algae; 'CR' = coral rubble; 'RPAT' = reef pavement with algal turf; 'CCA' = crustose coralline algae; and 'CC' = coral communities.

accessibility and hinder the mapping of the coastal features. Despite these challenges, many reefs have been mapped successfully using remote sensing. This study has produced a detailed analysis of reef geomorphology and key substrates and habitats, thus providing significant information on the distribution and extent of reef landforms, insights into reef growth and morphology patterns, and a description of the classification and distribution of reefs according to type. This study recognised and mapped distinctive geomorphic reef features using remote sensing for the first time.

One of the most common limitations of using remotely sensed images in mapping reefs is that it is not easy to discriminate between live coral and other habitats that consist of chlorophyll organisms such as macroalgae and seagrass (Kaczmarek et al., 2010; Zainal et al., 1993). The similarity in light spectra reflectance characteristics of these species can result in misclassifications. However, Benfield et al. (2007), Groom et al. (1996), and Mumby et al. (1998) suggested using a manual editing process (i.e. contextual editing) in circumstances where habitat distributions are known. This process was applied in the current study to improve the accuracy of the maps.

Another potential limitation of this study was the time lag between the collection of the ground-truth data and the acquisition of the satellite images. However the chronological gap in this study was relatively insignificant (few days to few weeks) except for Maret Islands, time convergence would be preferable especially where changes in reefs need to be detected (Goodman et al., 2013).

5. Conclusions

The complexity and remoteness of the Kimberley coast has limited the accessibility to the intertidal and submerged reefs. This has created particular difficulties in collecting field data. The scarcity of reef research and investigations in the KIM can mainly be attributed to the coast's harsh conditions. This lack of information has resulted in the number of reefs in the KIM being underestimated and led to the KIM not being classified as a major reef province.

The use of remote sensing is an effective means for mapping coral reef distribution. The high spatial and spectral resolution of remote sensors would be preferable for capturing greater details of reefs features. However, the multispectral and moderate spatial resolution Landsat sensor has been used to map the reefs in this study due to the water conditions of the KIM. Nonetheless Landsat is able to capture useful information about shallow reefs. The results of this study show that when used in conjunction with other relevant data sources (e.g. aerial photography, bathymetric charts and supporting ground-truth information), the Landsat sensor has enabled significantly improved mapping of the reefs.

The outcomes of this study provide a firm scientific foundation for biodiversity assessment and reef structure comparisons. Further, they facilitate the monitoring and detection of changes in these vital natural resources for conservation and management purposes and pave the way for future studies to examine major threats to reef ecosystems (e.g. the effects of climate change, tropical cyclones, and economic resource extractions).

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CHAPTER FIVE

REEFKIM: AN INTEGRATED GEODATABASE FOR SUSTAINABLE MANAGEMENT OF THE KIMBERLEY REEFS, NORTH WEST AUSTRALIA

Use of geospatial techniques to map distribution and erect a geomorphic classification of the Kimberley Reefs, as well as to map detailed intra-reef geomorphological zones and their associated habitats and substrates, was presented in the previous two chapters. This chapter exploits these outputs to address the third objective which is ‘construction of a geodatabase with information about the Kimberley reefs (ReefKIM) for better reef management’. It demonstrates the usefulness of developing an integrated geodatabase as a practical tool for scientists and managers to facilitate better monitoring and sustainable management of Kimberley reefs. It also shows how the evolution of information and communication technology can be employed to aggregate new data relevant to the Kimberely reefs from a wide range of people that can contribute to the development of this geodatabase.

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ReefKIM: An integrated geodatabase for sustainable management of the Kimberley Reefs, North West Australia

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ABSTRACT

Coral reefs of the Kimberley Bioregion are seldom studied due to limited accessibility and extreme water conditions, which make management of these vital ecosystems a challenging task. Managing reef resources requires a considerable amount of credible, consistent and continual information. We identified the geographic information system (GIS) approach to be useful in developing an integrated geodatabase by acquiring information from different sources relating to the Kimberley reefs. Based on this approach, the study aimed to create a foundation for the first comprehensive geodatabase of the Kimberley reefs, called ReefKIM. The work included compiling existing spatial and non-spatial data, as well as collecting new data to complete information gaps. The study demonstrates how new technologies can be harnessed to crowdsource data from a wide range of people though a web-based platform. ReefKIM will provide a practical tool for scientists and managers to facilitate better monitoring and sustainable management of these vital natural resources. Moreover, it will support further studies in various disciplines leading to a more detailed understanding of the Kimberley Bioregion reefs.

1. Introduction

The coral reefs of Australia's North West Kimberley Bioregion have been recently recognised as being of international significance (Wilkinson, 2008; Chin et al., 2008). The Kimberley reefs are particularly unique in that they inhabit an environment with the highest tidal range in the southern hemisphere (up to 11 m) and appear to endure high levels of turbidity and frequent cyclones. These extreme environments have resulted in coral reefs with unique geomorphological attributes which merit further study (Wilson, 2013). The remoteness of the Kimberley Bioregion has, for an inshore continental reef system, resulted in very low levels of direct anthropogenic impacts (Collins, 2011). While this remoteness has been an advantage in maintaining reef health, the cost of fieldwork and data acquisition can be prohibitively expensive, which has limited the ability of marine scientists and managers to access the region. The result is that compared to regions like the Great Barrier Reef, only a small pool of data has been collected from the Kimberley by a variety of sources including; universities, government agencies, tourism operators, commercial and recreational fishermen and most importantly, the traditional owners that inhabit the region. The result is a small amount of data spread across a large number of stakeholders making information on these reefs either rarely available or inaccessible.

There is a critical need to know what kind of data has been collected from the Kimberley coast and if they are available to share or exchange. In the first instance greater accessibility of data should prevent duplication of previous work, reduce cost, increase data quality (Chesnaux et al., 2011) and allow for multiuse datasets. In order to address these issues and more, this study aims to create a high-capacity, multi-source, easy-to-access and cost-effective geodatabase for Kimberley reefs. The database is a foundation for future marine studies in the Kimberley Bioregion. It provides researchers and managers with critical scientific data and identifies knowledge gaps that need to be addressed.

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1.1. Reef geodatabases

A geographic information system (GIS)-based database, or geodatabase, is a computer-based system that can handle a variety of information, including both locational and attribute data of a particular feature. It not only displays and produces maps but can also record and analyse descriptive characteristics of map features. Geodatabases have been developed for many coral reef regions around the world, particularly in the areas of coral reef management and conservation with the efforts of the Great Barrier Reef Marine Park Authority (GBRMPA) in the early 1990s (Hartcher and Shearin, 1996) being an early example. Since then, usage of GIS for data management has increased rapidly and expanded worldwide. The construction of the Global Coral Reef Database, also known as ReefBase or ReefGIS, was initiated in 1993 by the International Centre for Living Aquatic Resources Management (ICLARM), and is a good example of a global-scale GIS database (McManus, 1994; McManus and Ablan, 1997). Another global-scale assessment of total reef area was undertaken using GIS-based technology by Spalding and Grenfell (1997). Similarly, the map-based indicator Reefs at Risk was developed by the World Resources Institute (WRI) and uses GIS to assess potential threats to coral reef ecosystems around the world (Bryant et al., 1998). Dahdouh-Guebas (2002) applied an environmental GIS database to the sustainable development and management of tropical coastal ecosystems by collecting and integrating data from different disciplines. More recently, a regional-scale GIS database named ReefBahia was developed to assist in managing and conserving the coral reefs of Bahia in Brazil (Carvalho and de Kikuchi, 2013), and another was created to improve management of the Coral Triangle (Beare, 2014; Cros et al., 2014).

Rapid developments in information and communication technology, particularly over the last decade, have led to an exponential increase in computational and networking efficiency, which facilitates the aggregation of vast amounts of data through sophisticated, relatively affordable, and highly accurate devices, such as smartphones, tablets and portable computers (Heipke, 2010). Moreover, these devices are often equipped with high-definition digital cameras, built-in global positioning systems (GPS), internet connectivity and high-capacity memory storage, which allow for recording of data and capturing images and videos associated with essential metadata, such as location (geo-referenced), date and time. Other optional information can be entered manually or through a software application menu designed for a particular type of data in order to avoid entry errors (Briner et al., 1999).

1.2. Crowdsourcing data

New technologies have changed the way researchers and managers receive information from the field. The crowdsourcing geospatial data approach for information aggregation has been implemented worldwide for a variety of purposes, including creating and sharing geographic information volunteered by individuals through common and freely available platforms such as Wikimapia and OpenStreetMap (Goodchild, 2007; Hacklay, 2010) and assisting people during crises through programs such as Ushahidi (Okolloh, 2009). Furthermore, the crowdsourcing approach has been employed in many scientific endeavours, including Geo-Wiki, a global network of volunteers helping to improve the quality of global land cover maps (Fritz et al., 2009; Comber et al., 2013). In a recent study, Franzoni and Sauermann (2014) thoroughly discussed benefits of scientific research in open collaborative projects using the 'crowd science' or 'citizen science' approach. Rovere et al. (2012) also conveyed the advantages of crowdsourcing for the creation of databases of sea levels from the mid-Pliocene warm period.

According to Lewis et al. (2003), community participation played a significant role in re-zoning the GBRMPA. Volunteer involvement in the monitoring program Reef Watch, coordinated by the Conservation Council of South Australia for the sustainable management of marine ecosystems, has helped increase knowledge about the status of temperate reefs in South Australia (CCSA, 2009). Additionally, volunteer divers and snorkelers recorded about 180 marine species in Victoria, Australia, through the monitoring initiative Reef Watch Victoria, developed by the Victoria National Parks Association and Museum Victoria to protect Victoria's marine environment (VNPA, 2014). Another remarkable monitoring program called Eye on the Reef, managed by GBRMPA, in partnership with the Queensland Parks and Wildlife Service, enables visitors to the Great Barrier Reef to report reef observations though a web map and/or smartphone or tablet application. The data provide Marine Park managers and researchers with up-to-date information on current reef status (GBRMPA, 2014).

The main aim of this study is to establish a geodatabase of information on the Kimberley reefs in order to provide a regional picture of the reef numbers, types and status. The work included compiling existing spatial and non-spatial data and collecting new data through online GIS sources. Furthermore, the database allows for crowdsourcing of future data to fill in information gaps. The geodatabase has been developed through a partnership with the Western Australian Marine Science Institution (WAMSI) for the Kimberley Marine Research Program (KMRP) and implemented with the sponsorship of the Government of Western Australian. This geodatabase will improve our knowledge and provide decision makers with helpful information for the sustainable management of this vital reef ecosystem.

2. Methodology

Constructing a useful geodatabase requires a considerable amount of different types of data distributed across both time and space. ArcGIS 10 software developed by the Environmental Systems Research Institute (ESRI) was selected for developing the database due to its high performance and wide recognition. Procedures used in this study are illustrated in Fig. 1 (see Fig. 2).

2.1. Data sources

The information related to the study area was acquired from various sources (Table 1). Most of the datasets used in this study were available in digital formats (i.e. raster and vector); otherwise, they were digitised. Satellite images, maps, charts and other datasets covering the entire study area were compiled. The database comprises more than 90 satellite image scenes acquired between 1998 and 2014 from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) sensors. The geodatabase also contains 18 geological maps, 12 bathymetric charts and a set of 24 very high resolution orthophotographs covering the entire Kimberley coast and nearshore islands. Moreover, there are over 2500 ground truth points, about 295 km of seismic lines, 52 core points and 800 site images. Other related data were extracted from a wide range of secondary and tertiary sources, such as reports, publications, atlases, books, maps and encyclopaedias. The geodatabase was designed to allow modification of current data and addition of new information and photographs, which can be aggregated or crowdsourced through a web-map platform (e.g. Google Earth) using laptops, smartphones or tablets.

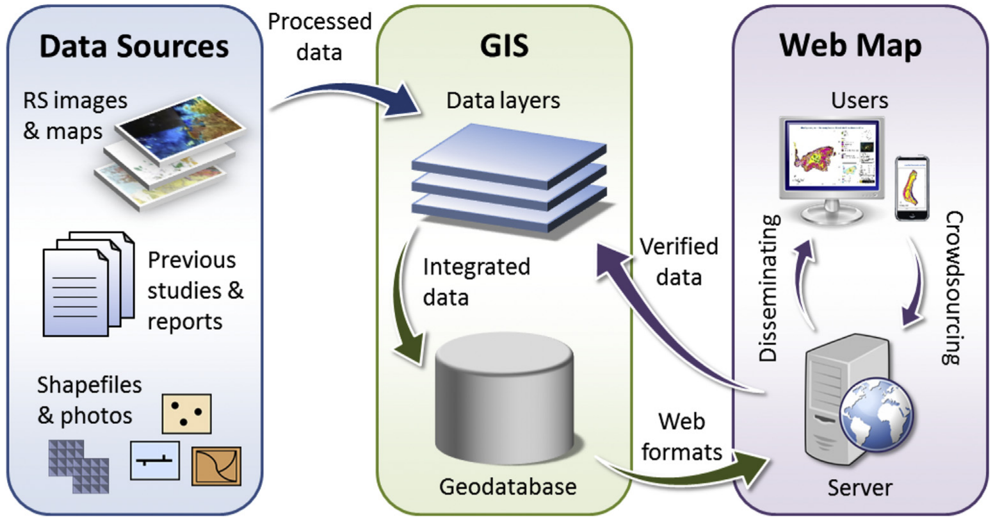


Fig. 1. Methodological scheme of data acquisition, processing, integration and storage for the Kimberley reef geodatabase (ReefKIM).

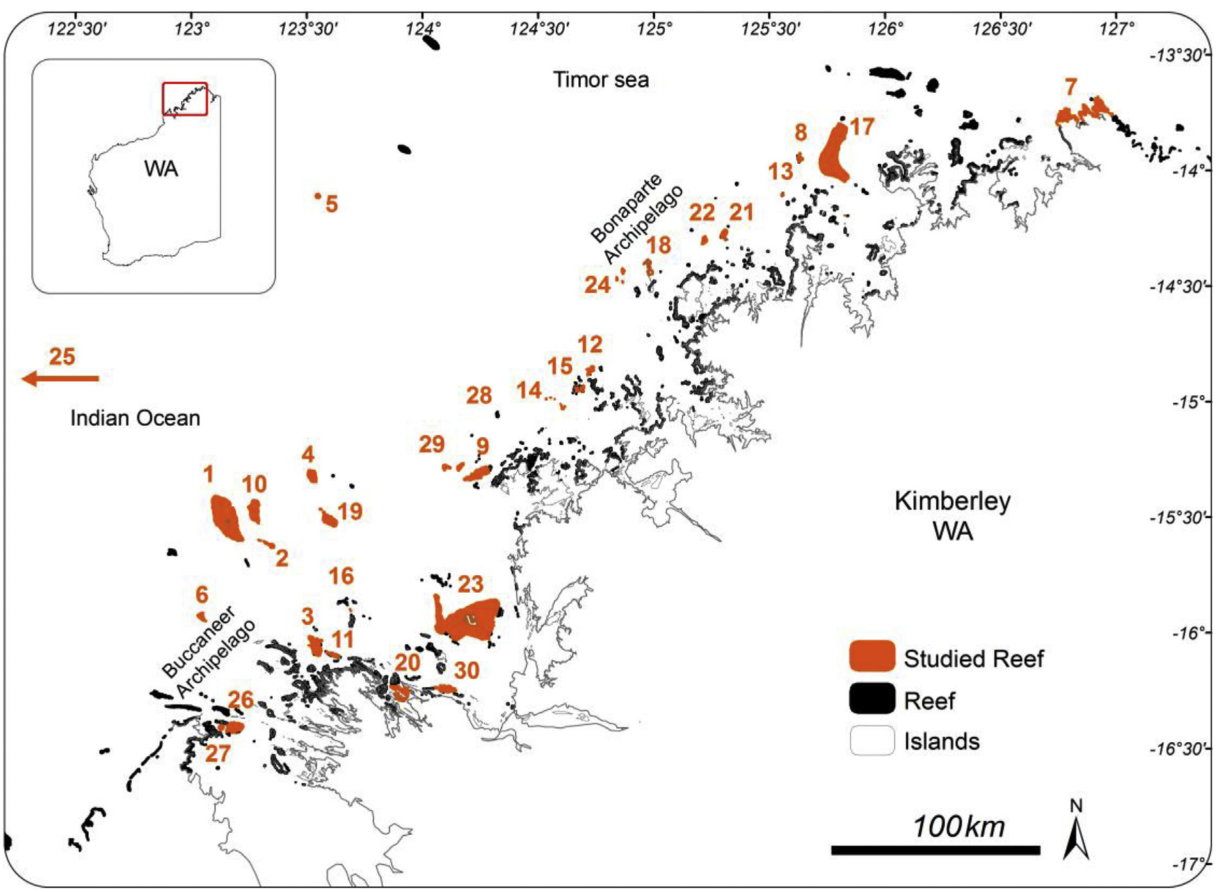


Fig. 2. Spatial distribution map of the Kimberley reefs and islands compiled in ReefKIM. The arrow on the left-hand side of the map points toward reef number 25, Scott Reef.

2.2. Data processing

Initial preparation of the data (pre-processing) is important to ensure accuracy and reliability. The satellite imagery was processed using ENVI 4.3 software prior to data extraction. ArcGIS was then used to integrate various images with other data sources. Maps and charts were geo-referenced and projected according to the Geocentric Datum of Australia (GDA 94) for consistency and homogeneity. All remotely sensed images were calibrated and atmospherically corrected. Moreover, some images were pre-processed to offset problems with band data and to recalculate DN values. Subsequently, a range of map features, including coastline, islands, reefs and areas of shoaling, were precisely digitised and geomorphological zones and associated habitats and substrates were determined.

Table 1
Datasets used in this study and their sources.

Dataset	Source of data[a]	Data format
Kimberley coastline	Satellite images (USGS, 2012), orthophotos (Landgate, Western Australia and (DPaW, 2013)).	Raster
Islands	Satellite images (USGS, 2012), orthophotos (Landgate, Western Australia and (DPaW, 2013)), bathymetric charts (AHO, 2009), geological maps (GSWA, 2013)	Raster
Coral reef	Satellite images (USGS, 2012), orthophotos (Landgate, Western Australia and (DPaW, 2013), bathymetric charts (AHO, 2009), geological maps (GSWA, 2013)	Raster
	WAM/Woodside Collection Kimberley Project 2008–2011; Brooke, 1995, 1997; Wilson, 2011, 2013	Points
Seabed geomorphology	Geoscience Australia	Polygon
Sea surface temp.	(NOAA, 2012)	Polygon
Bathymetric contours	GA, (AHO, 2009)	Polyline
Sub-bottom profiles	Collins et al., 2015	Polyline
Ground-truth	WAM/Woodside Collection Kimberley Project 2008–2012; Wilson and Blake, 2011; Wilson et al., 2011; WAMSI 1.3.1 Reef Geomorphology Project 2012–2015	Points
Reef coring	Solihuddin et al., 2015	Points
Weather and tide	(BOM, 2012)	Various

[a] Note: The data were sourced from national and international government agencies, including the Department of Parks and Wildlife (DPaW), Geoscience Australia (GA), the Western Australia Marine Science Institute (WAMSI), the Geological Survey of Western Australia (GSWA), Western Australian Museum (WAM), Australian Hydrographical Service (AHO), Australian Bureau of Meteorology (BOM), the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA).

2.3. Data integration

Because a single dataset usually does not contain all the necessary information, data integration was employed to fill in the missing information. The use of GIS data overlays enables comparisons to be made and links created between datasets with common spatial properties. Such overlays enhance data interpretation, reveal correlations and allow distribution patterns between different phenomena and zones on reefs to be identified (El-Raey et al., 1996; Bryant et al., 1998; Salm et al., 2000; Crosby et al., 2002). Further, GIS allows digitised and georeferenced non-digital data to be integrated with other data (Chapman and Turner, 2004). Integration allows for data verification, detection of changes, and data updating (Gösseln and Sester, 2005). It has also been used to combine multiple sources of data for the same object or feature in order to extract information or add value. As a result, a consistent and accurate dataset that is more informative than the original can be produced.

The resulting features were stored in vector format so that they could be presented using different colours and symbols for easy differentiation. Each feature was linked to its attributes, such as the feature name, type, area, location, date of survey, source of data and any other related information. All this data was then saved in an attribute table enabling further data analysis to improve understanding of linkages between geological substrate, reef geomorphology, reef classification and distribution.

Subsequently, all data were compiled into a data library, and information relevant to this project was extracted, rectified and entered into a database. The selected information was represented as feature classes and raster-based datasets in ArcGIS as usable data layers. This geodatabase also contains the most significant elements and conditions that influence reef growth in the region.

2.4. Data accessibility

A GIS-based database enables an administrator to control and restrict access to authorised users only, to avoid accidental loss of data. It also supports a wide range of database queries and operations. For example, users can search for information within the database using Structured Query Language (SQL). A copy of reef and island data layers was converted to an open, web based format using Keyhole Markup Language (KML), in this case to enable visualisation in Google Earth. Dissemination of data though a web-based platform allows aggregating new information though consistent crowdsourcing. These outsourced data must be rectified before being compiled into the geodatabase.

3. Results

A geodatabase of the Kimberley reefs, termed ReefKIM, was constructed. A variety of sources were used in this study to foster and maximise extraction and interpretation of data. As a result, six feature classes were derived from these datasets and saved consistently in the geodatabase. The feature classes (described in Table 2) include *reefs*, *coastline*, *islands*, *geomorphological zones*, *habitats and substrates* and *other studies and work*.

Each resulting feature class can be displayed in ArcGIS either as a solo data layer or in conjunction with other data layers according to the information that needs to be illustrated and/or calculated. For example, three feature classes (*reefs*, *islands* and *coastline*) are displayed simultaneously in Fig. 3, showing the extent of the Kimberley coastline and the distribution of reefs and islands on a regional-scale map. 853 reefs and 2413 islands were mapped along the 5300 km coastline, for which number, areas, geographic distribution and distance from coastline can be calculated. The numbered reefs highlighted in orange (in the web version) indicate the locations of 30 reefs that have been mapped in detail.

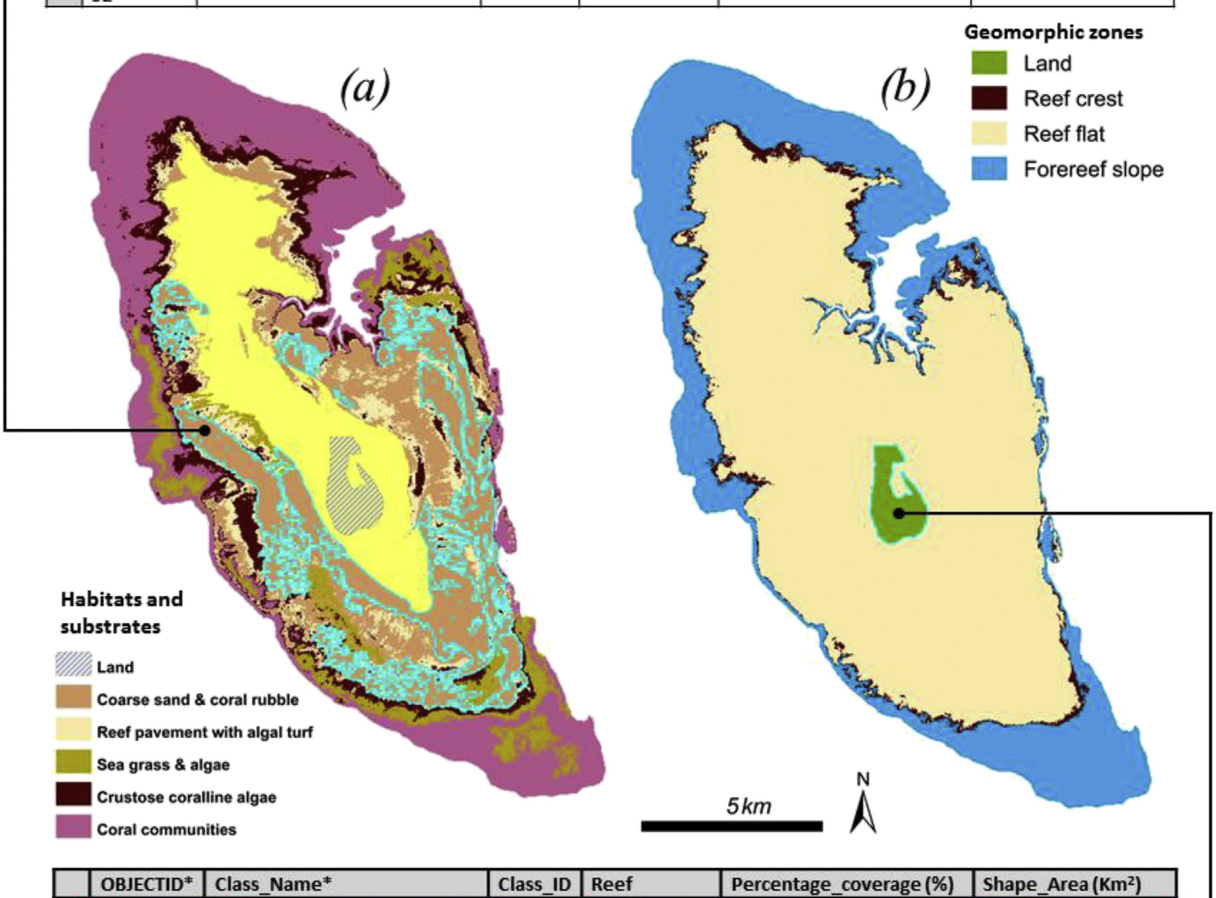
The 30 reefs are listed alphabetically in Table 3 along with sources of information used to map them in more detail. Landsat images, geological maps and bathymetric charts were used for all these reefs, while ground truth data were available for 90% of the studied reefs. However, sub-bottom profiling and coring data were only available for fewer than 23% of the reefs. Adele Reef and Cockatoo Island had the largest number of data sources. On the other hand, Beagle Reef, Cape Londonderry, Mavis Reef, and King Island had the fewest available data sources.

The geodatabase can also present information at the reef scale to display further details on individual reefs. For instance, the *geomorphic zone* feature class can include information on geomorphology, including shapes, areas and distributions, for specific reefs. Moreover, further information on associated habitats and substrate coverage for these geomorphic zones were stored in the *habitats and substrates* feature class. Fig. 3 illustrates an example of geomorphic zones and habitat and substrate maps for Adele Reef. Geomorphic zones are presented in different colours to delineate the boundaries of each zone, while related information, such as the zone's name, area, percentage of coverage and other values, is recorded in an attribute table and linked to a certain map feature.

Table 2
Resultant feature classes included in ReefKIM.

Feature class	Contents	Format
Reefs	853 reef features including sizes, shapes and types were recorded.	Vector
Coastline	A 5300 km line of the mainland coast was mapped using the mean low water neap (MLWN) level to ensure that mangroves and reef flats were not included.	Vector
Islands	Over 2400 island features (i.e. islets, exposed rocks and exposed cays) as defined by Geoscience Australia were recorded.	Vector
Geomorphological zones	Five reef geomorphologic zones (i.e. land, reef flat, lagoon, reef crest and fore-reef slope) were recorded for 30 reefs.	Vector
Habitats and substrates	Seven key habitats and substrates (i.e. mangroves, sand, seagrass and algae, coral rubble, reef pavement with algal turf, crustose coralline algae and coral communities) were recorded.	Vector
Other studies and work	This class encompasses geographic locations of all studies, work and information related to the Kimberley reefs that have been encountered and accessed (e.g. ground truth points, survey, sample collections, coring sites, sub-bottom profiles, images, etc.)	Vector

OBJECTID*	Class_Name*	Class_ID	Reef	Percentage_coverage (%)	Shape_Area (Km²)
45	Sand	01	Adele	28.5	47.82
47	Coarse sand & coral rubble	02	Adele	24.6	41.40
48	Reef pavement with algal turf	03	Adele	6.8	11.51
49	Sea grass & algae	04	Adele	7.6	12.82
50	Crustose coralline algae	05	Adele	9.0	15.14
51	Coral communities	06	Adele	23.5	39.39
52					



OBJECTID*	Class_Name*	Class_ID	Reef	Percentage_coverage (%)	Shape_Area (Km²)
13	Land	01	Adele	0.2	0.28
14	Reef crest	02	Adele	3.2	5.4
15	Reef flat	03	Adele	66.2	111.2
16	Forereef slope	04	Adele	30.5	51.2
17					

Fig. 3. Two maps of Adele reef: (*a*) intra-reef geomorphic zones and (*b*) distribution of habitats and substrates on the reef platform. Each map feature is connected to an attribute table in the geodatabase.

Table 3
Data sources used to produce geomorphic, substrate and facies maps for targeted reefs (reefs are listed in alphabetical order).

Reef	Data sources[a]									
	LS	OP	HR	GM	GT	SBP	BC	PS	CO	SI
Adele Reef	✓		✓	✓	✓	✓	✓	✓	✓	✓
Albert Reef	✓		✓	✓	✓		✓			
Bathurst and Irvine islands	✓	✓		✓	✓	✓	✓		✓	✓
Beagle Reef	✓			✓	✓		✓			
Browse Island	✓		✓	✓	✓		✓	✓		✓
Brue Reef	✓		✓	✓	✓	✓	✓			
Cape Londonderry	✓	✓		✓			✓			
Cassini Island	✓		✓	✓	✓		✓	✓		
Champagny Island	✓	✓		✓	✓		✓			
Churchill Reef	✓			✓		✓	✓	✓		
Cockatoo Island	✓	✓		✓	✓	✓	✓	✓	✓	✓
Colbert Island	✓		✓	✓	✓		✓	✓		
Condillac Island	✓	✓		✓	✓		✓			
De Freycinet Island	✓		✓	✓	✓		✓			
Hedley Island	✓		✓	✓	✓		✓	✓		
King Island	✓			✓	✓		✓			
Long Reef	✓	✓		✓	✓		✓	✓		✓
Maret Island	✓		✓	✓	✓		✓	✓		✓
Mavis Reef	✓			✓	✓		✓			
Molema Island	✓	✓		✓	✓		✓	✓		✓
E. Montalivet Island	✓	✓	✓	✓	✓		✓	✓		✓
W. Montalivet Island	✓	✓	✓	✓	✓		✓	✓		✓
Montgomery Reef	✓	✓		✓	✓	✓	✓	✓		✓
Robroy Reef	✓			✓	✓		✓	✓		
Scott Reef	✓			✓	✓	✓	✓	✓	✓	
Sunday Island	✓	✓		✓	✓		✓		✓	✓
Tallon Island	✓	✓		✓	✓		✓		✓	✓
White Reef	✓	✓	✓	✓	✓		✓	✓		
Wildcat Reef	✓	✓		✓	✓		✓	✓		
Woninjaba Island	✓	✓		✓			✓	✓		

[a] Note: Data source acronyms are LS = Landsat images, OP = orthophotos, HR = higher resolution satellite images, GM = geological maps, GT = ground truth, SBP = sub-bottom profiling, BC = bathymetric charts, PS = previous studies, CO = coring and SI = site images.

For example, in Fig. 3a, a land zone is highlighted on the map, and information related to this selected feature is shown in the bottom attribute table, revealing that land area on Adele Reef is 0.28 km^2, covering approximately 0.2% of the total reef. Similarly, Fig. 3b shows the distribution of habitats and substrates on Adele Reef with distinguishable boundaries for each feature. The highlighted feature represents the *coarse sand and coral rubble* class. The statistical information of this selected feature is presented in the top attribute table, revealing that the coarse sand and coral rubble class covers over 41 km^2, which represents more than 24% of the total reef coverage.

Information on previous studies and work on the Kimberley reefs are also presented on a reef-scale map. Fig. 4, for example, shows the locations of some available information sourced from a variety of studies and work on Adele Reef. Each source of information is represented by a distinct symbol on the map. On Adele Reef, for instance, seven sub-bottom profiles have been surveyed, and nine habitat sites have been studied. Additionally, 13 monitoring stations have been established, and eight sites have been cored. All the information is stored in the *other studies and work* feature class with links to its origin in the attribute table.

Reef data was converted to KML for visualisation in Google Earth. Fig. 5 depicts reef distribution in vivid orange across the entire Kimberley coast in Google Earth. It also demonstrates that some reefs can have map pins and name labels as visualisation tools. The layers panel on the left-hand side of the map allows users to choose (by turning on or off) the information to be displayed over the map in the map view.

Moreover, additional information crowdsourced into the map was examined. Fig. 6 shows an example of photos taken using smartphone cameras from 10 different locations and added into the map. After the photos were uploaded, their locations were marked on the map by yellow map pins, which can be clicked for further information. For instance, the pop-up window shown in Fig. 6 points to one of these yellow map pins, located on a reef flat between Bathurst and Irvine islands. The window presents the reef picture and essential information, such as the name of that site, date, time and coordinates.

4. Discussion

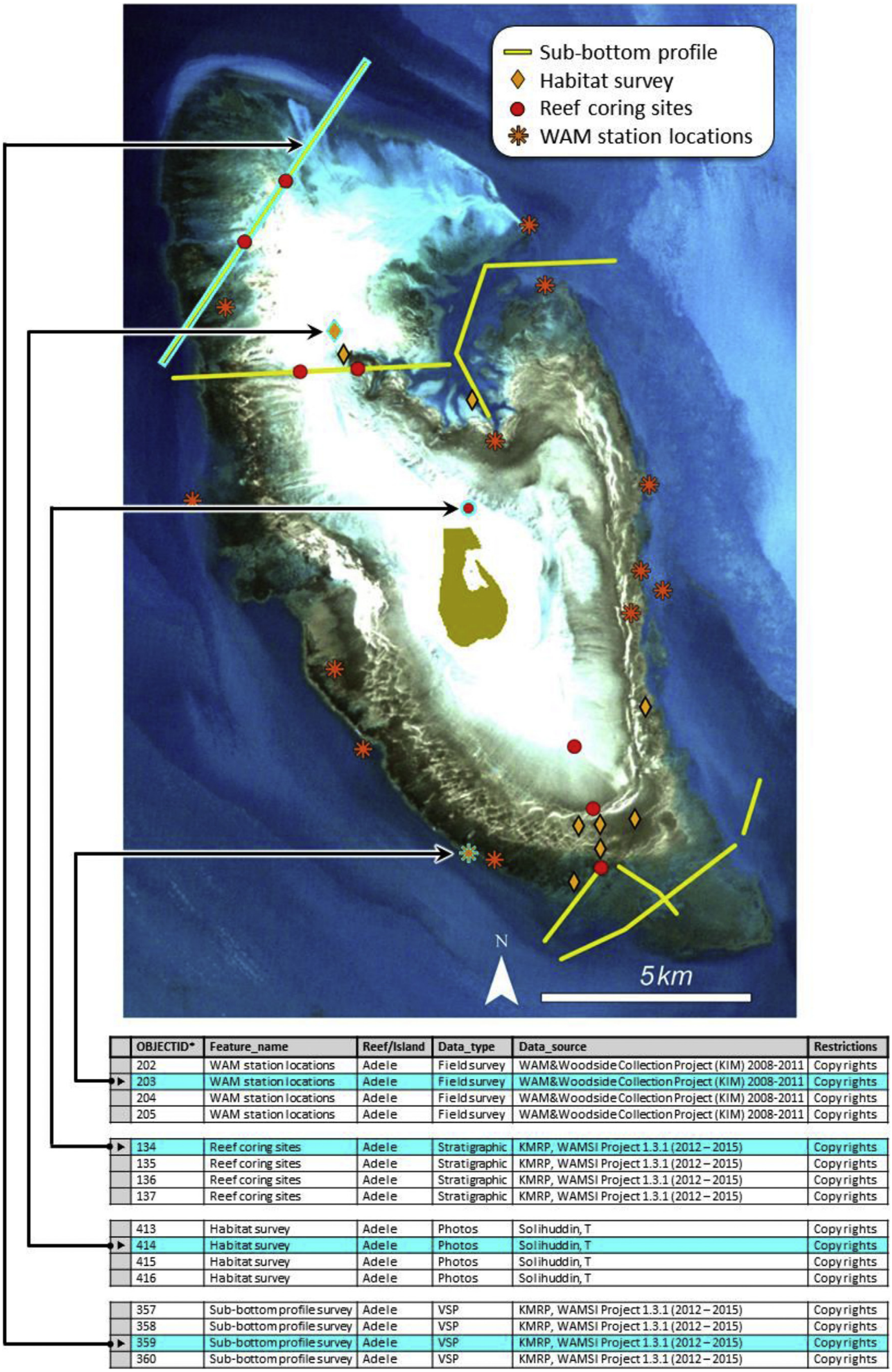
Prior to the gazetting of the KMRP, there had only been a handful of studies that investigated the coral reefs and marine environments in the Kimberley Bioregion. While additional information had been collected by scientists and managers over the course of decades, much of this information remained unpublished, or housed as internal reports making access to information difficult.

ReefKIM is the first attempt to collate and integrate this information related to the Kimberley reefs into one comprehensive geodatabase. Accordingly, the preliminary focus in this stage of ReefKIM is mainly on obtaining and recording essential information, such as reef occurrence, spatial distribution, geomorphic classification and typology and key habitats and substrates. ReefKIM users are consequently able to explore any reef system as well as individual reefs through reef-scale maps, to obtain details on reef dimension, habitats and substrate cover and other information related to management efforts. Acquiring new information will necessitate additional literature searches and the involvement of a wide range of stakeholders and other individuals.

The study developed a process for constructing an integrated geodatabase using various types and sources of datasets, fostering data fusion and maximising accessibility of important information for a better understanding of the Kimberley coral reefs. This data integration approach has resulted in significant improvements in reef mapping. It showed, for example, that the number and area of Kimberley reefs are approximately 60% greater than described by previous studies, as many areas that may comprise reefs were unmapped due to lack of information. Reef number and area are anticipated to increase considerably as more information becomes available. The data integration approach also led to the creation of detailed reef-scale maps of 30 reefs in different geographical locations within the Kimberley Bioregion. Intra-reef geomorphic zones and associated biosedimentary substrates were mapped. Such spatial analyses support marine park and coastal managers in their efforts to monitor coastal development and assess the impacts of different hazards on the coastal environment (Gayanilo et al., 1998; Freire, 2001; Puotinen, 2005, 2007; Ma et al., 2013).

During field work in the Kimberley Bioregion, it was noticed that many people connected with the marine environment (e.g. rangers, fishermen, pearl farmers, traditional owners, nature photographers and tourists) possess valuable information, such as site images, underwater videos and photos and aerial photography of marine fauna and flora, including reefs. This information has had a significant role in the verification of satellite images when reef habitats and substrates have been mapped. Optimistically, these people were willing to share their knowledge for the sake of conservation of this vital ecosystem.

Some information in the geodatabase can be made accessible to the public through a web-based interactive map allowing the selection, query and addition of information. This reef map can be used as a platform for crowdsourcing information from other participants to help implement reef monitoring. ReefKIM, as with many newly constructed geodatabases, requires frequent updates and insertion of new information to increase efficiency and



	OBJECTID*	Feature_name	Reef/Island	Data_type	Data_source	Restrictions
	202	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
▶	203	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
	204	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
	205	WAM station locations	Adele	Field survey	WAM&Woodside Collection Project (KIM) 2008-2011	Copyrights
▶	134	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	135	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	136	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	137	Reef coring sites	Adele	Stratigraphic	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	413	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
▶	414	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
	415	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
	416	Habitat survey	Adele	Photos	Solihuddin, T	Copyrights
	357	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	358	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
▶	359	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights
	360	Sub-bottom profile survey	Adele	VSP	KMRP, WAMSI Project 1.3.1 (2012 – 2015)	Copyrights

Fig. 4. Satellite image of Adele Reef showing locations of previous studies and works on this reef with links to their origins in attribute tables.

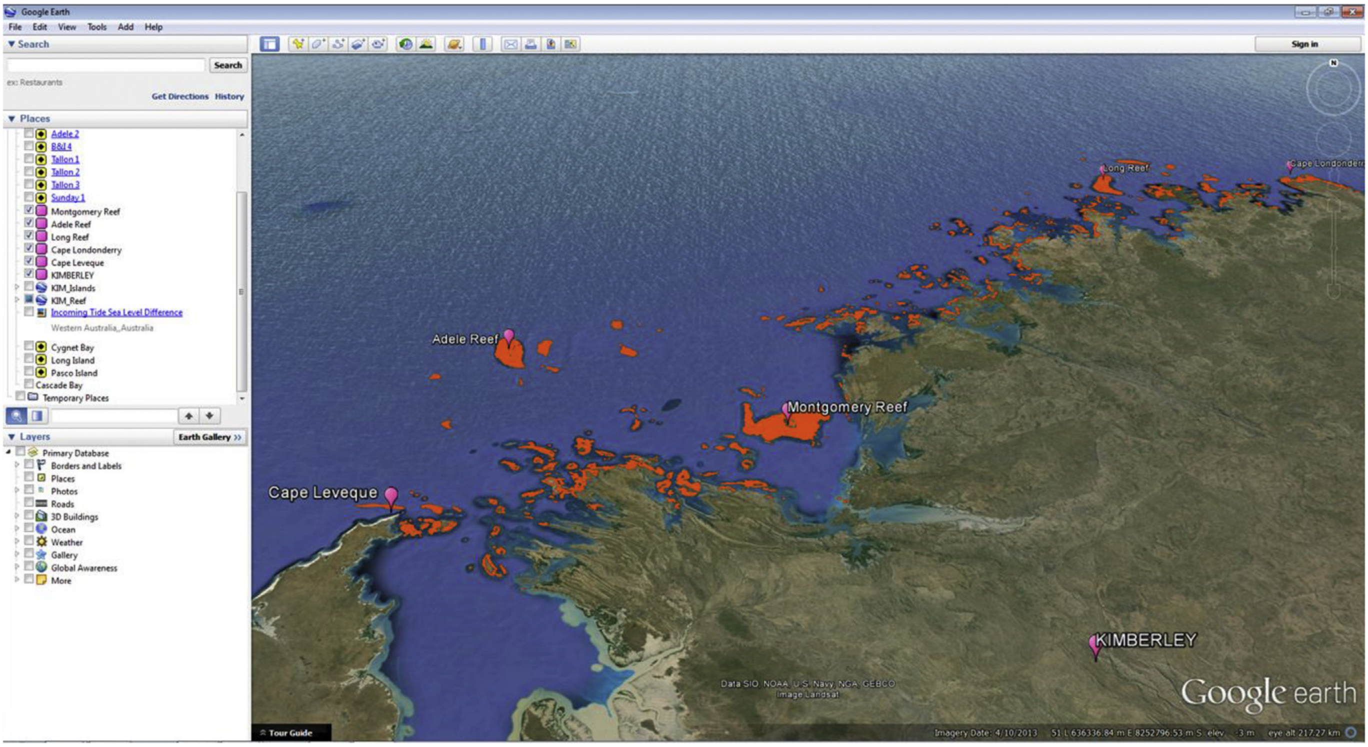


Fig. 5. Screenshot of an oblique view of the Kimberley Bioregion. Reefs are shown in vivid orange in Google Earth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

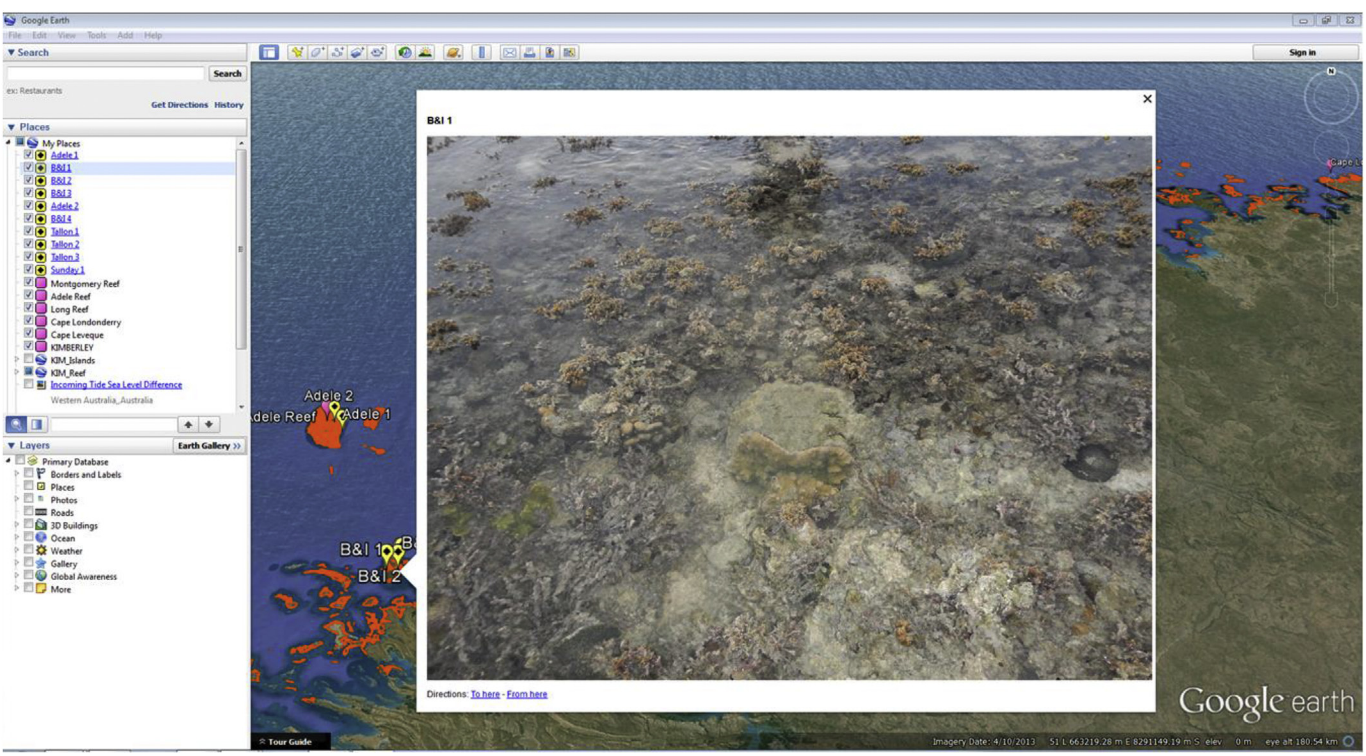


Fig. 6. Screenshot showing photo locations (as yellow map pins). A pop-up window displays a reef photo with relevant information. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

effectiveness at long-term monitoring. Google Earth was employed to examine reef data visualisation due to its capabilities in handling various types of imagery and other geographic information and viewing and searching for specific locations. Furthermore, this platform enables crowdsourcing of information, through which users can easily contribute to the development of this geodatabase by adding and sharing their knowledge.

Crowdsourcing is a promising approach for filling knowledge gaps and enhancing the understanding of such complex reef ecosystems. Both scientists and managers need a tremendous number of data points to be collected, which may not be feasible with small teams. However, the task may be more achievable if a large number of people are involved. Each data entry can be verified, labelled according to its reliability, referenced and acknowledged. Crowdsourcing will help produce more reliable information as the project progresses. The management efforts of the GBRMPA and its associated ecosystems are considered a model example of the contemporary reef management process. ReefKIM will allow the best practices from these efforts to be replicated for the Kimberley.

ReefKIM's data is expected to enable the detection of changes and quantification of current reef conditions at the regional and national levels, helping keep managers and conservation organisations informed and equipped to implement the required policy changes (Ma et al., 2011, 2013). In addition to being a management tool, ReefKIM can be also useful in pinpointing future research priorities (cf. GBRMPA).

5. Conclusions

ReefKIM is a GIS-based database constructed upon previous and current work, incorporating a wide range of datasets, including remote sensing images, bathymetric charts, site photos and many geological and biological datasets into one inclusive geodatabase. It is intended to provide researchers with an overview of essential information on the Kimberley reefs, where many reefs have yet to be mapped. It also constitutes a significant decision-making tool, as it can provide managers with practical support for the implementation of their plans and will help shape the direction of future management policies of coral reefs in the Kimberley region.

The database was designed to be developed in collaboration with other regional and national institutions as well as individuals through a web-based map. The crowdsourcing approach allows many people already in the field, such as researchers, rangers, fishermen, tourists and traditional owners, to become involved in mapping and share their valuable knowledge.

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CHAPTER SIX

GENERAL CONCLUSIONS

This chapter summarises the key outcomes in relation to the main aim and objectives of this study (as outlined in Chapter 1). The main aim of this study was to gain a regional understanding of the geomorphology of the Kimberley reefs and, more specifically, to bridge gaps in knowledge in relation to the fringing and nearshore reefs in the KIM. Three specific objectives were proposed to address this aim. First, to compile the first dedicated reef census map and develop a geomorphic classification scheme for the Kimberley reefs. Second, to map the intra-reef geomorphology and derive information on key habitats and substrates. Finally, to construct a geodatabase of information on the Kimberley reefs (ReefKIM) that contains details of the reefs' most significant features and highlights areas in which management could be improved.

Accordingly, previous studies on the Kimberley reefs were reviewed in Chapter 1, 3 and 4, and it was shown that the KIM encompasses a vast diversity of coral reefs that form the main geomorphic features of the region's coast. These reefs have adapted to survive in an extreme marine environment (*i.e.* high tides and turbid waters) and in conditions that would normally be considered inappropriate for the development of coral reefs. The complex geological setting and macrotidal regimes of the Kimberley coast provide a suitable substrate and environment for coral reefs to develop on the wide shallow continental shelf and in close proximity to the region's many high islands. However, due to the tropical climate of the Kimberley region and the orographic structure of the coast, huge volumes of fresh water and terrestrial sediments enter the sea through river mouths and estuaries, preventing coral reef settlement around these areas. Thus, fringing reefs have developed intermittently along the mainland coast and the coastlines of islands with a similar topography.

6.1 Usefulness of geospatial technologies in the study of coral reefs

The complexity and remoteness of the Kimberley coast has limited the accessibility to the intertidal and submerged reefs. This has created particular difficulties in collecting field data. The scarcity of reef research and investigations in the KIM can mainly be attributed to the coast's harsh conditions. This lack of information has resulted in the number of reefs in the KIM being underestimated and led to the KIM not being classified as a major reef province.

Geospatial techniques and their application to coral reef mapping were reviewed in Chapter 2 and employed in this study to explore the existence and extent of reefs in the KIM (see Chapters 3, 4 and 5). The use of remote sensing is an effective means for mapping coral reef distribution. The high spatial and spectral resolution of remote sensors would be preferable for capturing greater details of reefs feautres. However, the multispectral and moderate spatial resolution Landsat sensor has been used to map the reefs in this study due to the water conditions of the KIM. Nonetheless Landsat is able to capture useful information about shallow reefs. The results of this study show that when used in conjunction with other relevant data sources (*e.g.* aerial photography, bathymetric charts and supporting ground-truth information), the Landsat sensor has enabled significantly improved mapping of the reefs.

The mapping of the Kimberley reefs demonstrates a strong morphological complexity and clear regional patterns. It also provides essential information about the extent of reef landforms and a description of the classification and distribution of reefs by type. Fringing reefs have been identified as the dominant reef type and are widely distributed throughout the KIM. Additionally, their distribution is strongly correlated with the distribution of islands. It was also found that tidal range affected the distribution of reef geomorphologies. Planar reefs were found to be isolated and usually located some distance from the mainland coast. In terms of area, following fringing reefs, planar reefs are the next most dominant type of reef in the KIM. Consequently, a prominent reef morphotype (*i.e.* high intertidal) was defined for the first time in Chapter 3. However, a lack of adequate information meant that patch and shoal types could not be studied in detail. This study was therefore limited to shallow fringing and planar reefs. However, it revealed that the number of Kimberley reefs and their area are considerably greater than previously thought. As shown in Chapter 3, the total combined reefal area of the Kimberley reefs is approximately 1,950 km^2. Further, the actual reef area is anticipated to be at least twice this size. Thus, the KIM could be one of the largest continental shelf reef provinces in the world.

Despite the challenging conditions of the Kimberley coast, Landsat images were also effectively used (on a reefal scale) to illustrate the properties of 30 reef platforms (*i.e.* fringing and planar) situated at different geographical locations across the KIM (see Appendix B). This study presents a detailed analysis of the geomorphology, key substrates and habitats of eight reefs where more ground information is avalable (see Chapter 4). It was found that by applying unsupervised classification and using available ground-truth information for contextual editing, detailed geomorphology maps of coral reefs and their associated habitats and substrates could be obtained with relatively high accuracies (*i.e.* 64–77%) using a confusion matrix. This classification method can be applied to other reefs in the region to derive consistent classification schemes for the KIM.

Fringing reefs attached to islands are usually found to have wider reef flates on the windward side and have more steeply sloping forereefs. Conversely, reefs on the leeward side are mainly gently sloping and narrower. This pattern is consistent across most of the islands, particularly in the northern part of the KIM and across the Bonaparte Archipelago. Elevated reef flats were identified as another feature of fringing reefs attached to islands, particularly towards the south of the Kimberley coast and for the many islands clustered in the Buccaneer Archipelago. Notably, the areas of some of those reefs exceed the areas of the high islands to which they are attached.

6.2 Crowdsourcing and its application to coral reef data collection

Remotely sensed information was used to derive and analyse the spatial patterns of coral reef distribution and map their intra-reef geomorphology and associated habitats and substrates. Scientists and marine park managers require a tremendous amount of *in situ* data to be continually collected. However, it is often infeasible for research and exploration teams to collect such data. Crowdsourcing offers a more effective method for gathering data, as individuals permanently connected with the marine environment (*e.g.* rangers, commercial and recreational fishers and traditional owners) can crowdsource on a regular basis through user-friendly web-based interactive maps and/or smartphone/tablet applications. This approach was examined in Chapter 5 and outputs from the mapped reefs were harnessed to construct a comprehensive geodatabase of the KIM entitled 'ReefKIM'. The main purpose of ReefKIM is to compile various types and sources of reef and marine environment-related information, thus fostering data fusion and maximising the accessibility of important information to better understand the Kimberley reefs. Crowdsourcing (also known as the 'citizen science' approach) is a promising method for filling knowledge gaps and enhancing understanding of complex reef ecosystems. It also has facilitated significant improvements in reef mapping.

6.3 Implications for future studies

This study presents the most comprehensive dataset available on reef typology and distribution of the KIM. The Department of Parks and Wildlif (DPaW) has incorporated the resulting information into their database theough the Western Australian Marine Science Institution (WAMSI) (see Appendix E). Results continue to be processed and work is being conducted to prepare a technical infrastructure (*i.e.* a web-based platform and a smartphone application). The results of this study provide the first detailed spatial analysis of the KIM and thus make available a reliable, spatially constrained data set that can be used in biodiversity assessments and reef structure comparisons. Further, these results provide scientists and reef managers with quality information relevant to the monitoring, conservation and management of these vital natural resources. The geospatial approach outlined in this study is applicable to any shallow reef in the KIM and can be replicated by other researchers elsewhere. It will also pave the way for future studies addressing issues beyond the scope of the present research.

The use of geospatial techniques appears to be feasible in mapping shallow reefs, however the high-turbidity water prevented the remote sensors from detecting submerged reefs. Different approaches (*e.g.* the use of a Multibeam echosounder, LiDAR or underwater video) are required to investigate these relatively deep reefs. If such technologies are incorporated, the reef distribution map for the Kimberley will become increasingly comprehensive.

The Kimberley reefs are predominantly considered pristine. However, they are not protected from serious threats such as accelerated natural and anthropogenic disturbances in the region. Thus, active management of this natural resource is required to balance the socioeconomic development of the Kimberley coast and the conservation of its coral reefs.

ReefKIM is dynamic and was designed to continually accommodate new datasets. Thus, it will enable reef managers to detect changes and to quantify current reef conditions. Additionally, ReefKIM will assist in keeping managers and conservation organisations informed and enable them to implement any policy changes required. As a management and decision support tool, ReefKIM can also be used to identify future research priorities (*cf.* GBRMPA).

Given the rapid progress of advanced technologies, the methods for obtaining accurate data will become more readily available and accessible. Future work on the Kimberley reefs should consider the advantages of using higher resolution satellite imagery, as this could significantly improve the accuracy of mapping the habitat and substrate complexities of the reefs.

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APPENDICES

APPENDIX A: CO-AUTHOR CONTRIBUTION STATEMENT

To Whom It May Concern

I, Moataz Nael S Kordi, contributed to all aspects of the research publication including, but not limited to, primary data collection, data processing and analysis, figure drafting and writing for the publications entitled:

1) Kordi, M.N., Collins, L.B., O'Leary, M., and Stevens, A. (2016). ReefKIM: An integrated geodatabase for sustainable management of the Kimberley Reefs, North West Australia. Ocean & Coastal Management, 119, 234-243

2) Kordi, M.N., and O'Leary, M. (2016) A Spatial Approach to Improve Coastal Bioregion Management of the North Western Australia. Ocean & Coastal Management, 127, 26-42

3) Kordi, M.N., and O'Leary, M. (2016). Geomorphic Classification of Coral Reefs in the North Western Australian Shelf, Regional Studies in Marine Science, 7, 100–110.

4) Kordi, M.N., Collins, L.B., and Stevens, A. (2015). A Large Scale Geomorphological and Surficial Cover Map of Nearshore Reefs in the Kimberley Coast, WA. In Proceedings from Coast to Coast Conference 2014, Mandurah, Western Australia. ISBN-10: 0994357206 pp 15 – 20

5) Kordi, M.N., Collins, L.B., and Stevens, A. (2015). Geomorphic Patterns, Habitats and Substrates of Macrotidal Reefs from the Kimberley, North West Australia. In Proceedings from 2015 WAMSI Research Conference, Perth, Western Australia pp 72

A realistic breakdown of the contribution by each author is as follows:

Moataz Kordi	85%
Prof. Lindsay Collins	5%
Dr. Michael O'Leary	8%
Ms Alexandra Stevens	2%

I, as co-author, endorse that the level of contributions indicated above are accurate.

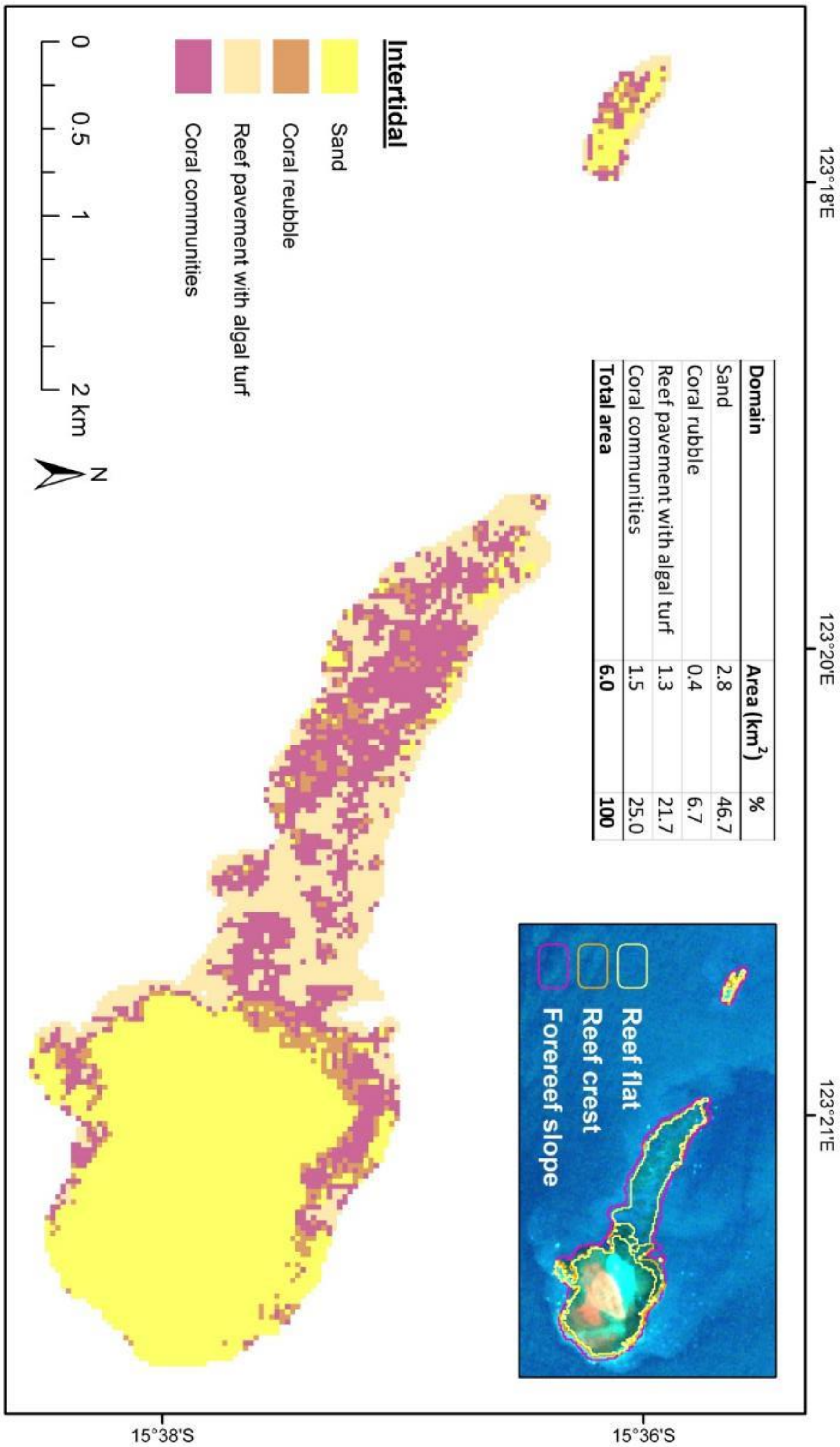
Prof. Lindsay Collins ____________________

Dr. Michael O'Leary ____________________

Ms Alexandra Stevens ____________________

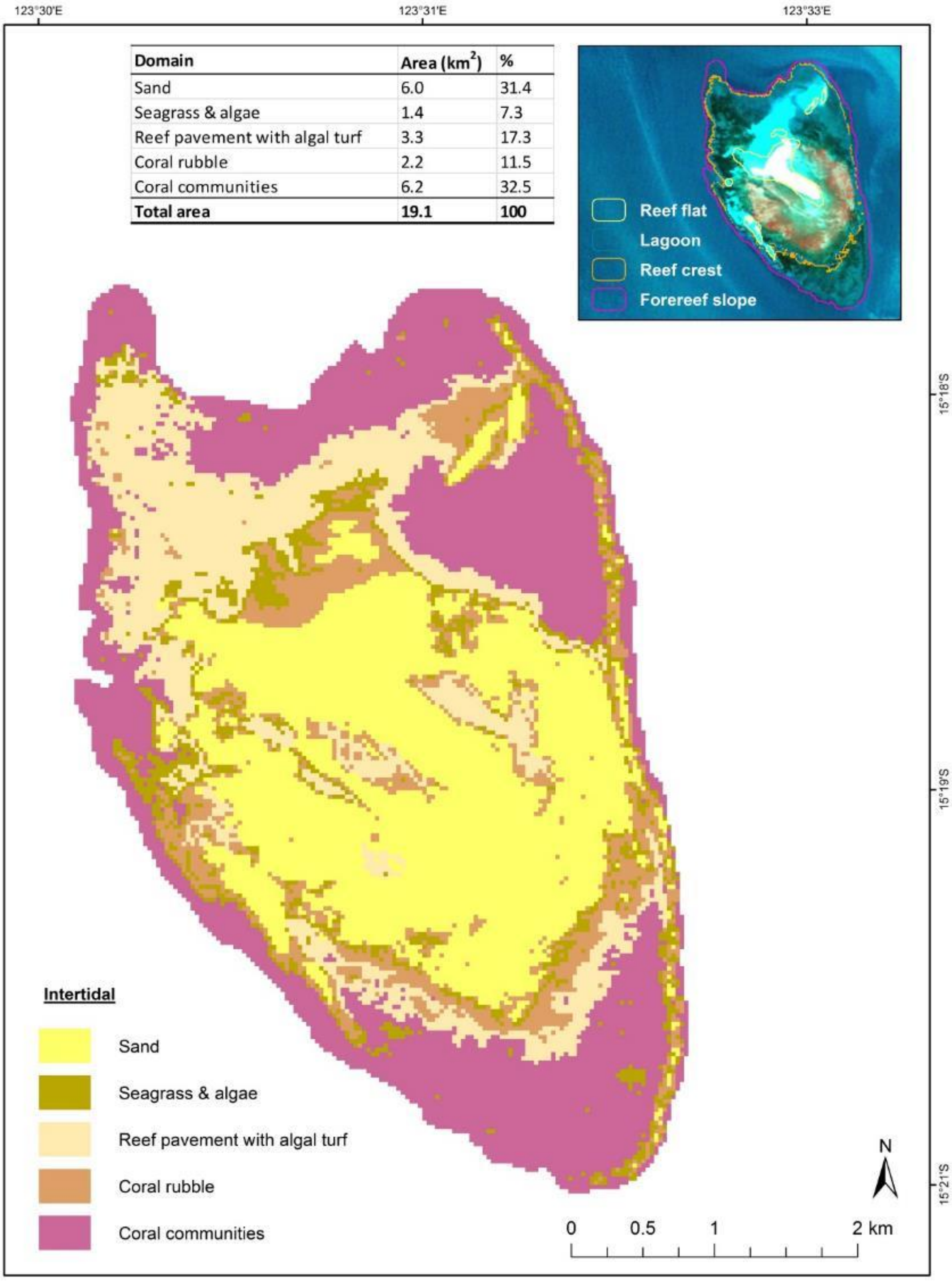
APPENDIX B: GEOMORPHIC, HABITAT AND SUBSTRATE MAPS

Albert Reef



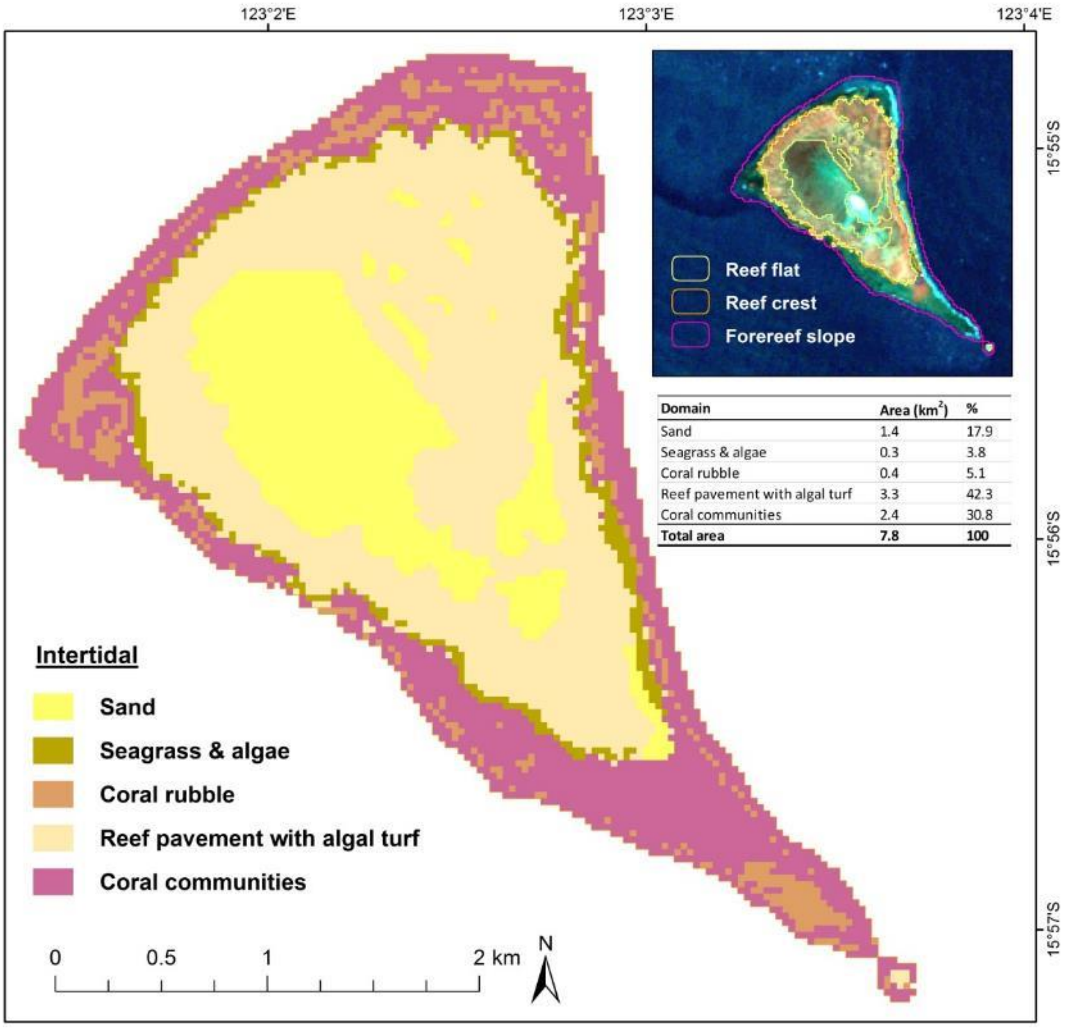
Domain	Area (km^2)	%
Sand	2.8	46.7
Coral rubble	0.4	6.7
Reef pavement with algal turf	1.3	21.7
Coral communities	1.5	25.0
Total area	**6.0**	**100**

Beagle Reef



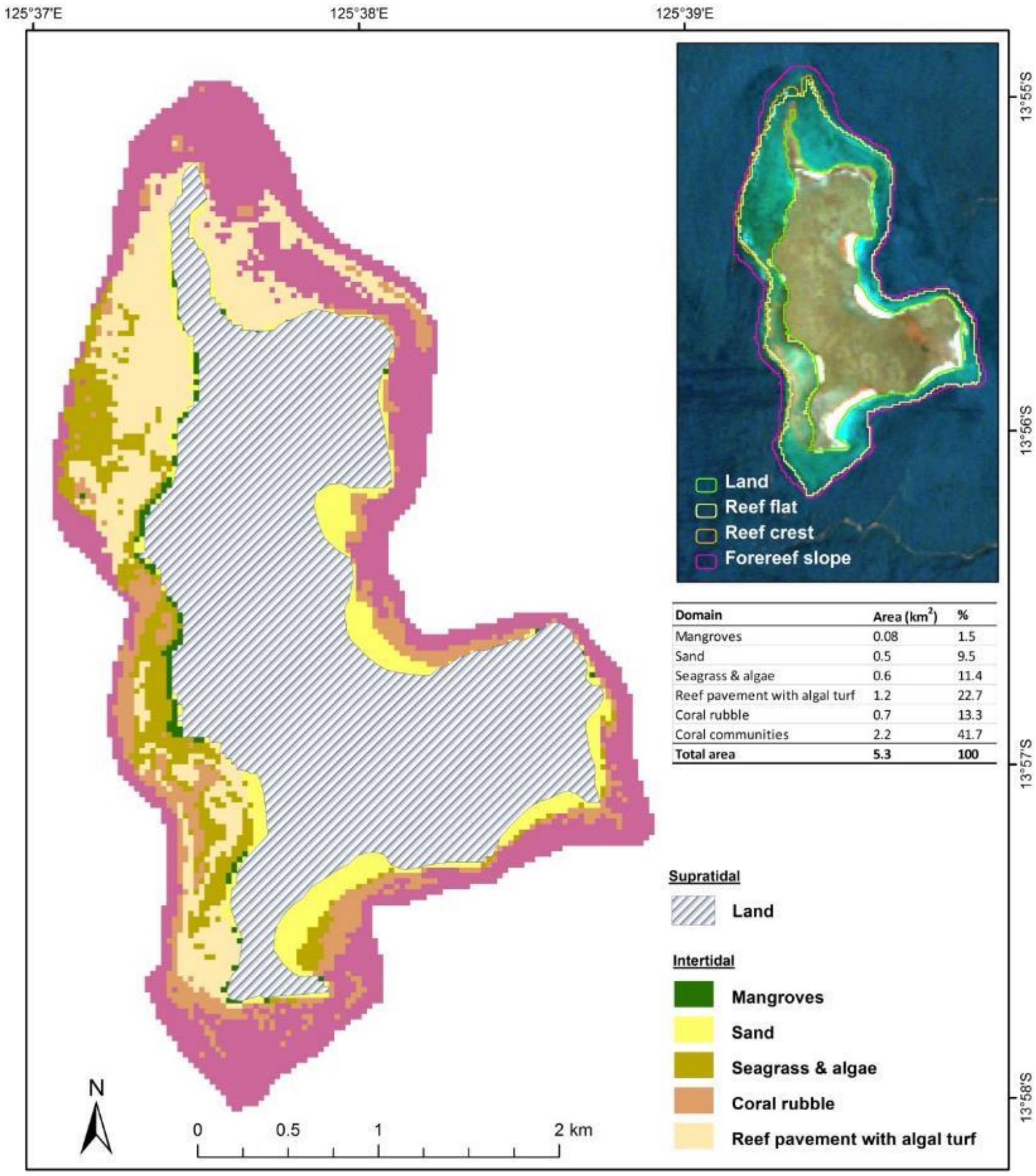
Domain	Area (km^2)	%
Sand	6.0	31.4
Seagrass & algae	1.4	7.3
Reef pavement with algal turf	3.3	17.3
Coral rubble	2.2	11.5
Coral communities	6.2	32.5
Total area	**19.1**	**100**

Brue Reef



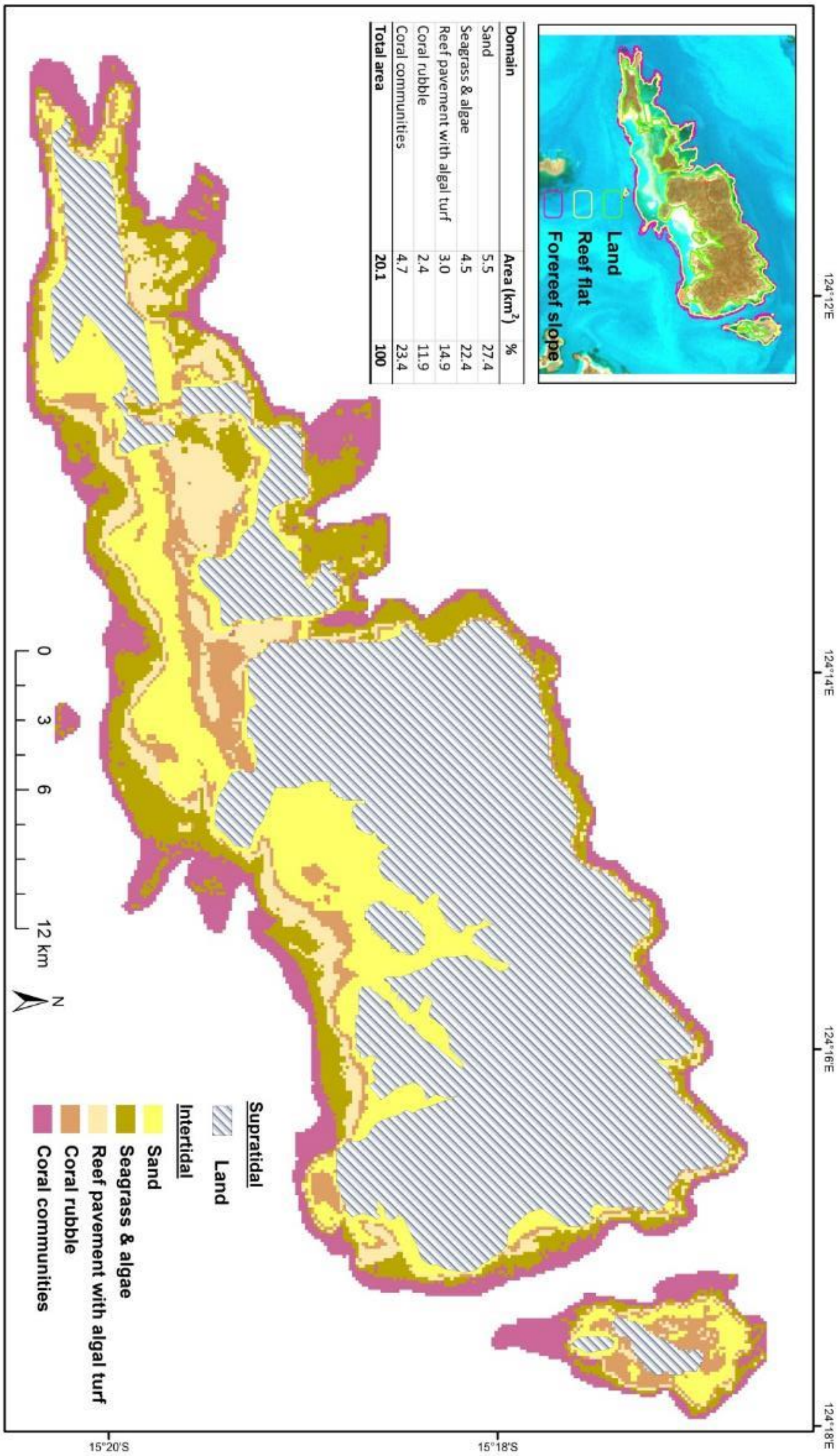
Domain	Area (km^2)	%
Sand	1.4	17.9
Seagrass & algae	0.3	3.8
Coral rubble	0.4	5.1
Reef pavement with algal turf	3.3	42.3
Coral communities	2.4	30.8
Total area	**7.8**	**100**

Cassini Island



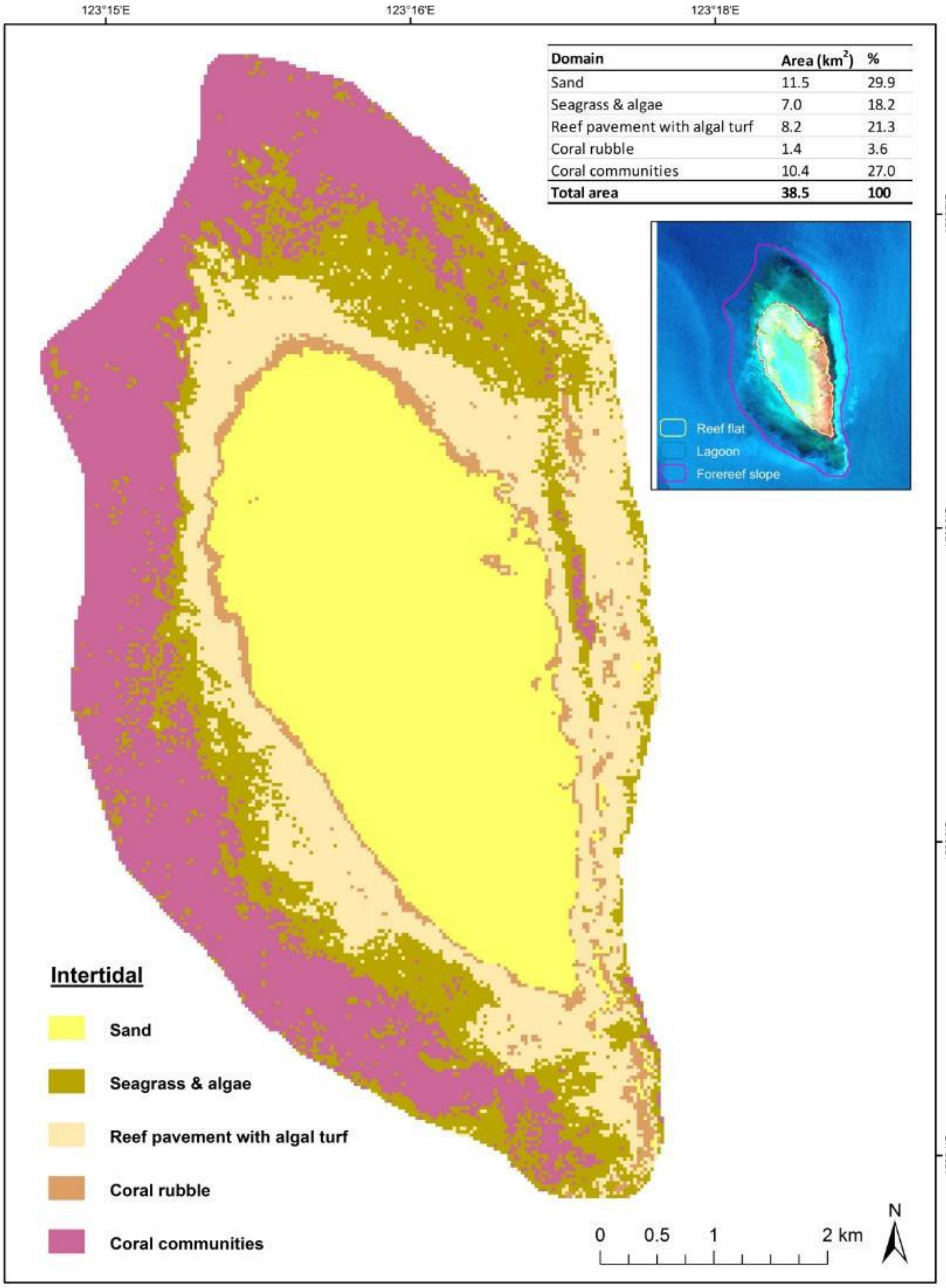
Domain	Area (km^2)	%
Mangroves	0.08	1.5
Sand	0.5	9.5
Seagrass & algae	0.6	11.4
Reef pavement with algal turf	1.2	22.7
Coral rubble	0.7	13.3
Coral communities	2.2	41.7
Total area	**5.3**	**100**

Champagny Island



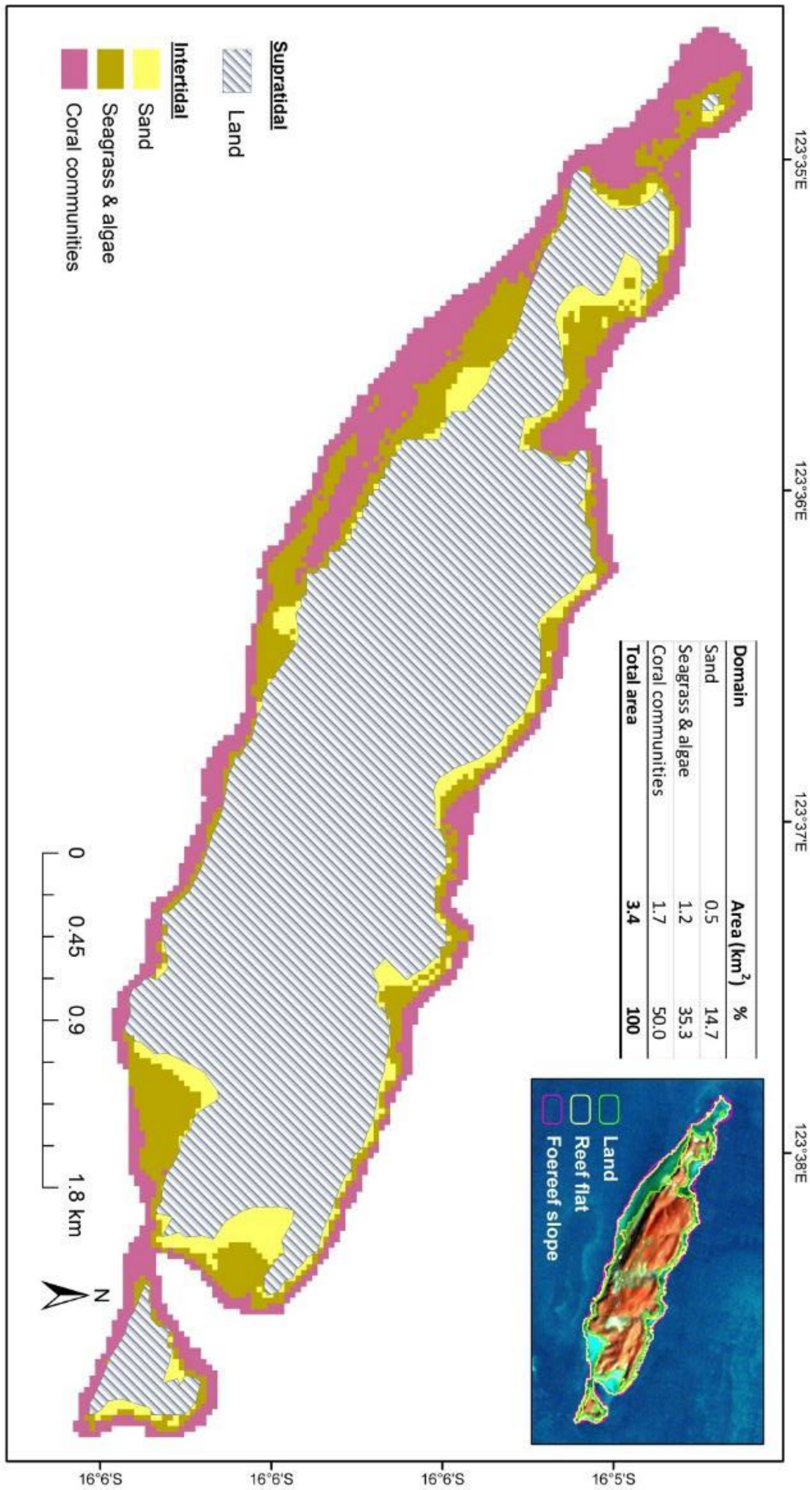
Domain	Area (km^2)	%
Sand	5.5	27.4
Seagrass & algae	4.5	22.4
Reef pavement with algal turf	3.0	14.9
Coral rubble	2.4	11.9
Coral communities	4.7	23.4
Total area	**20.1**	**100**

Churchill Reef

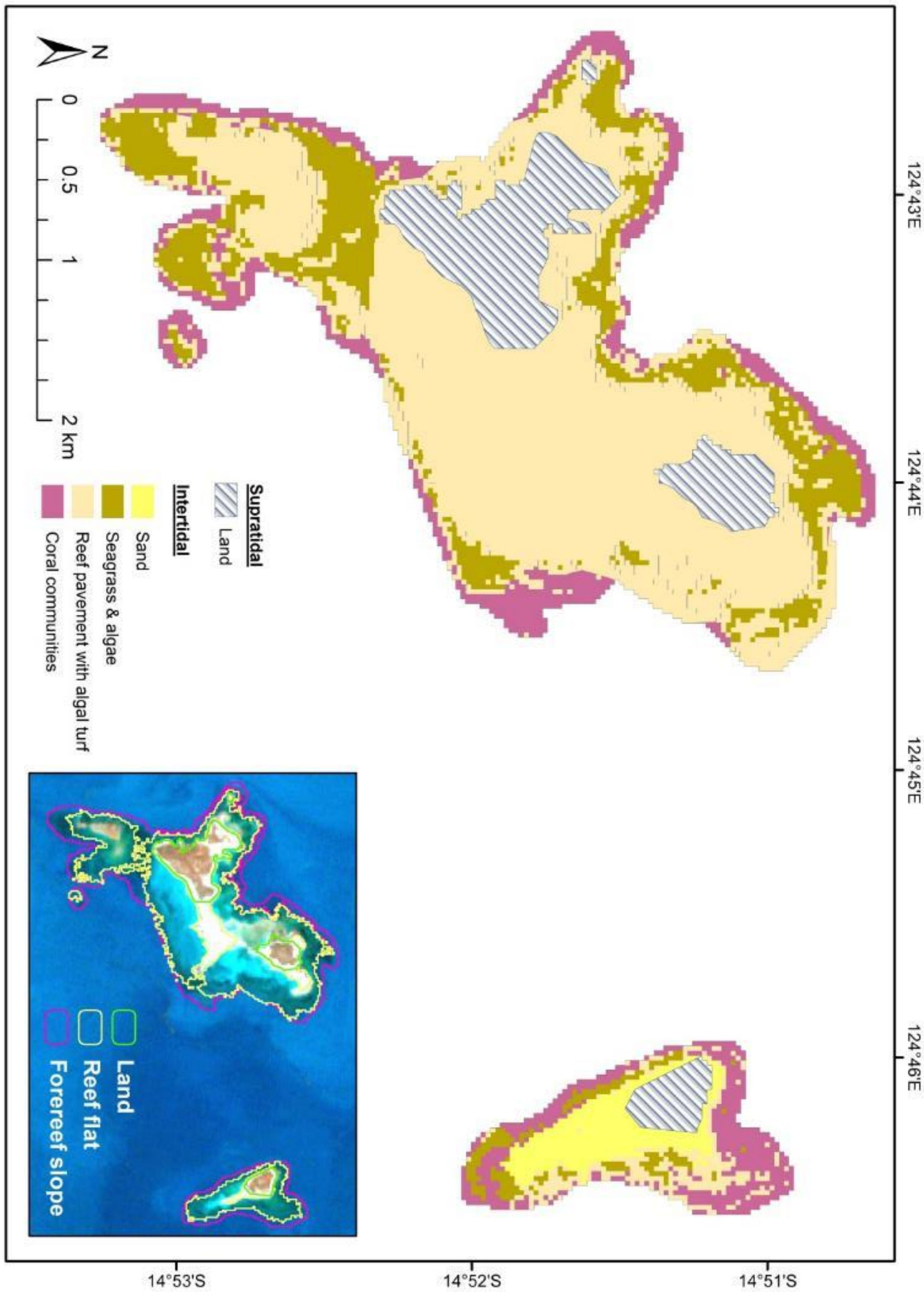


Domain	Area (km^2)	%
Sand	11.5	29.9
Seagrass & algae	7.0	18.2
Reef pavement with algal turf	8.2	21.3
Coral rubble	1.4	3.6
Coral communities	10.4	27.0
Total area	**38.5**	**100**

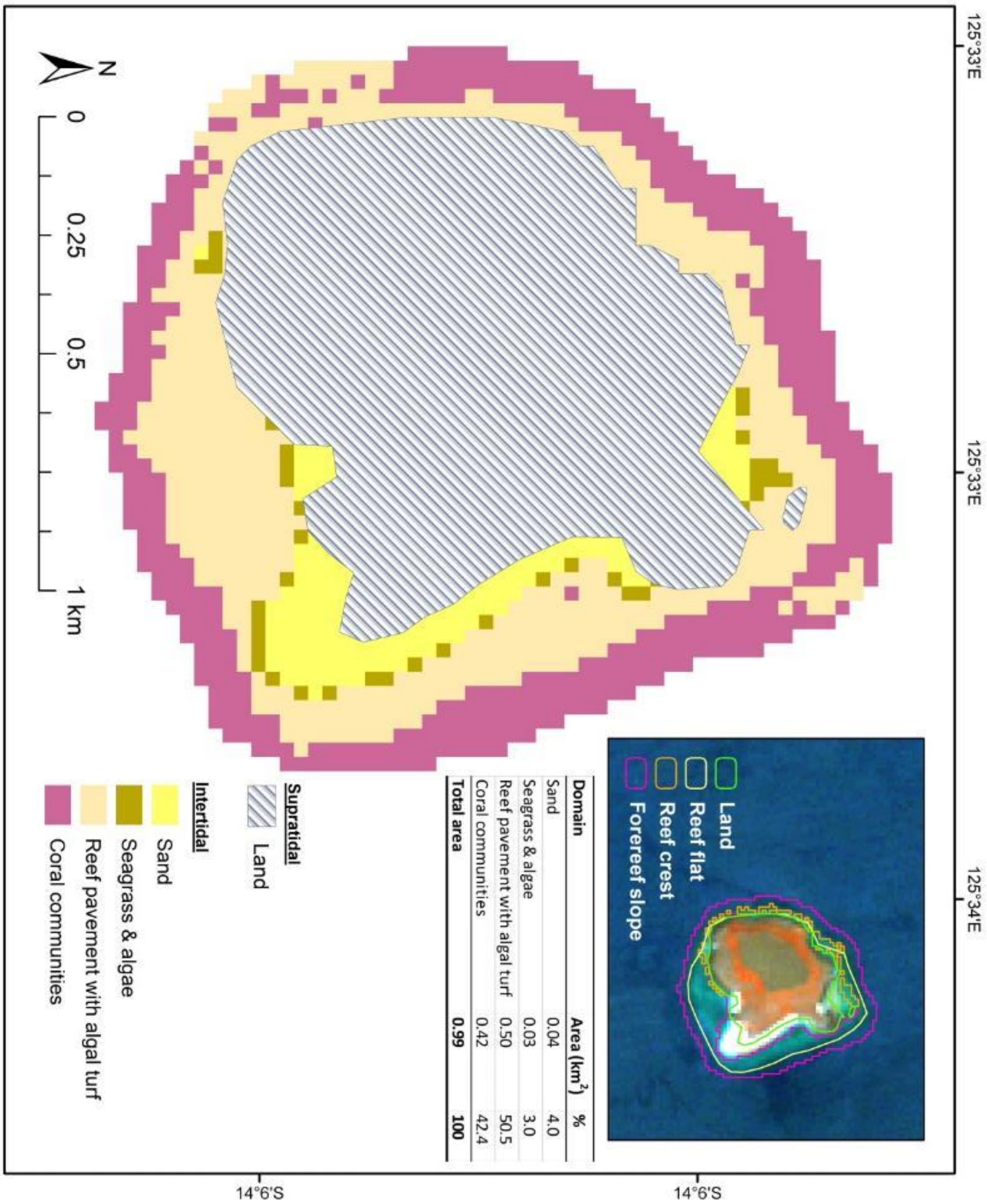
Cockatoo Island



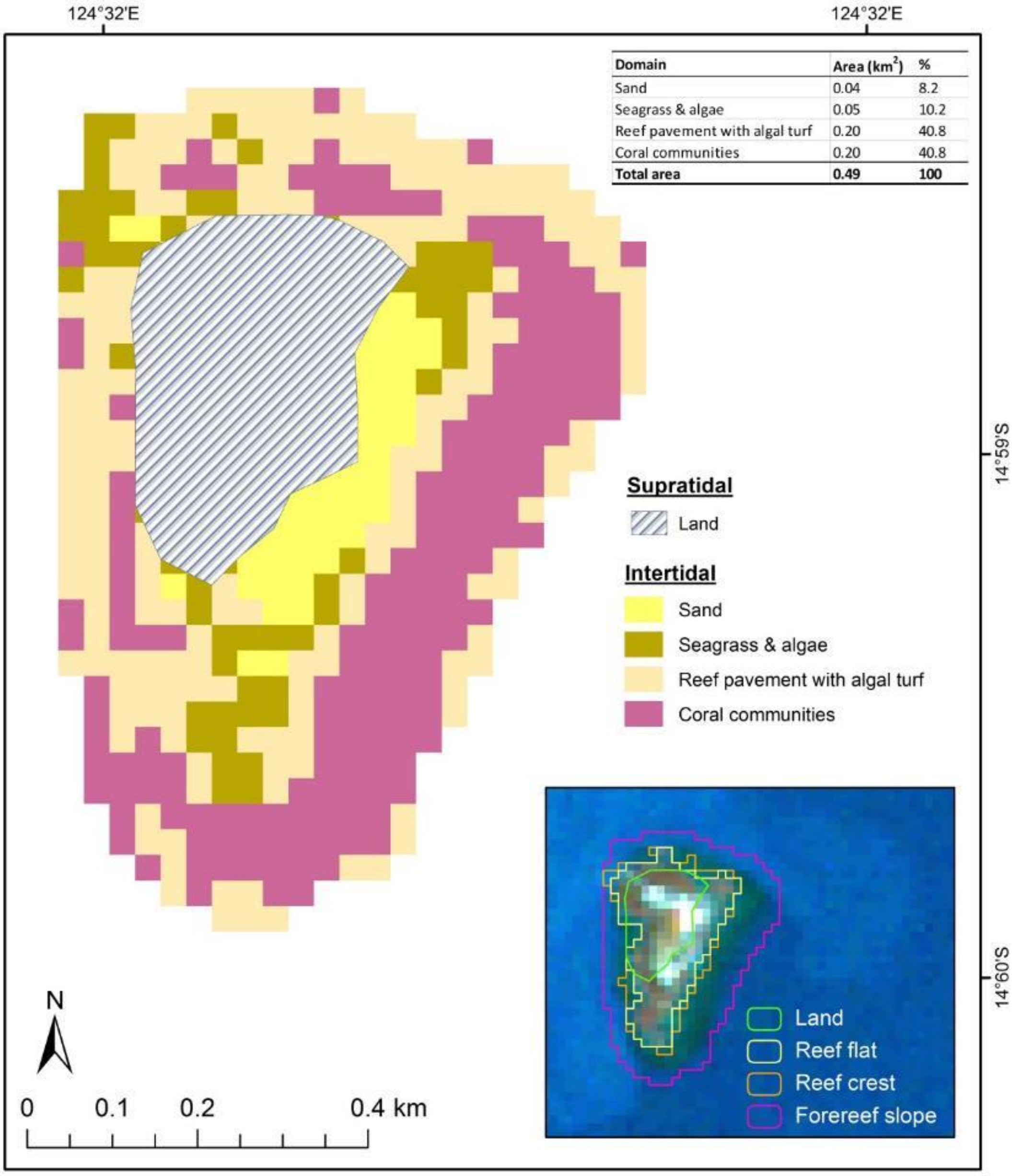
Colbert Island



Condillac Island

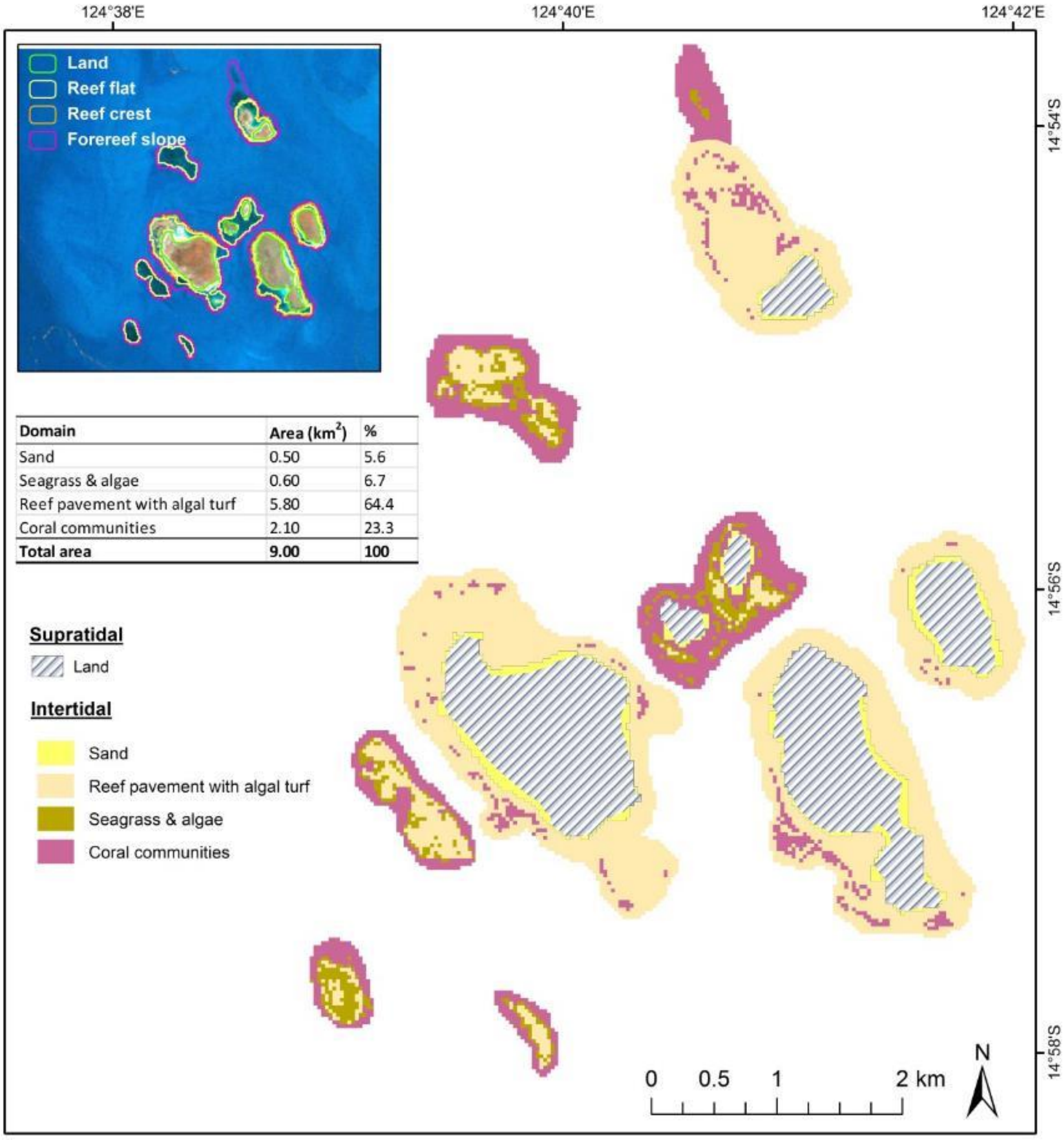


De Freycinet Island



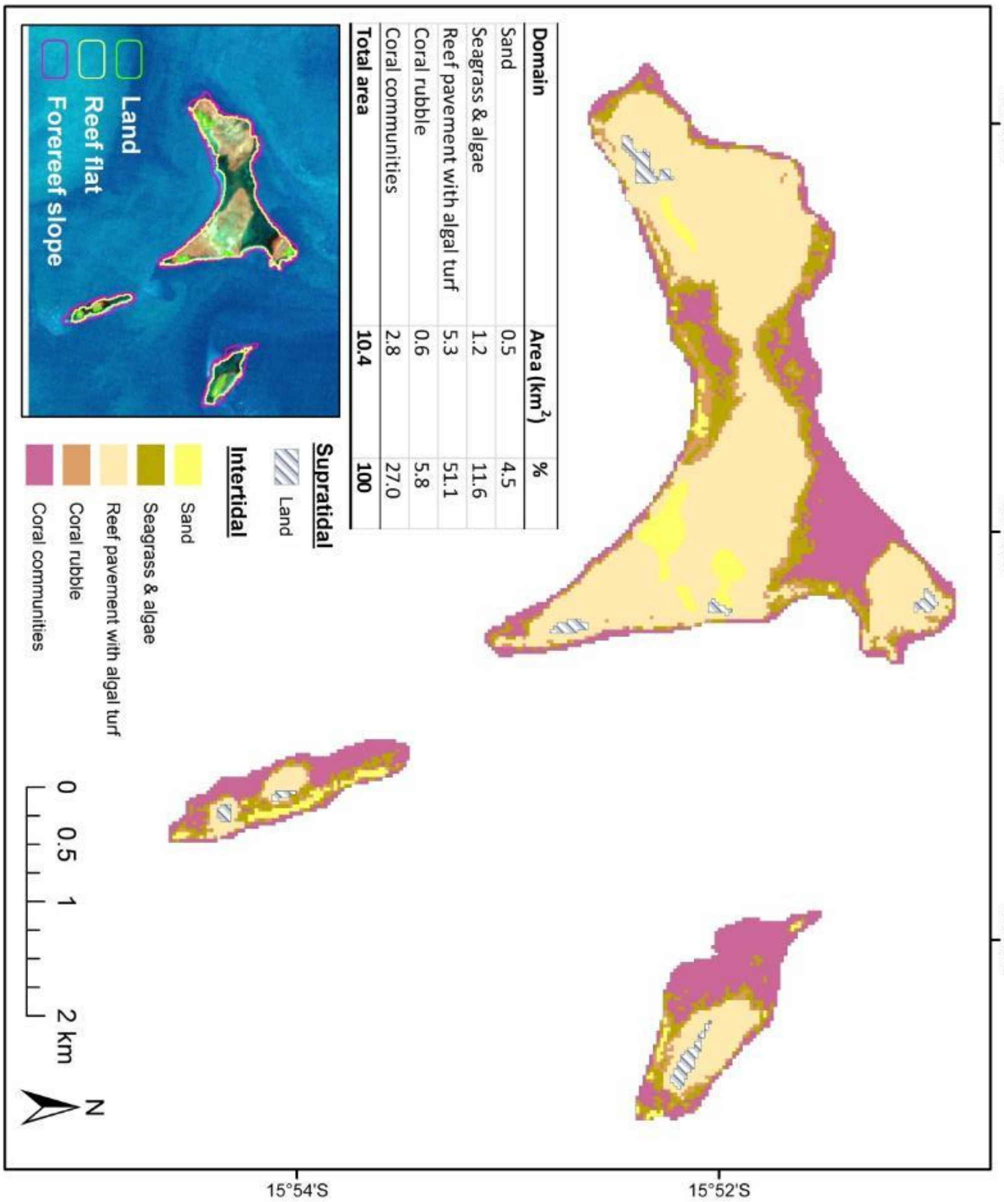
Domain	Area (km²)	%
Sand	0.04	8.2
Seagrass & algae	0.05	10.2
Reef pavement with algal turf	0.20	40.8
Coral communities	0.20	40.8
Total area	**0.49**	**100**

Hedley Island



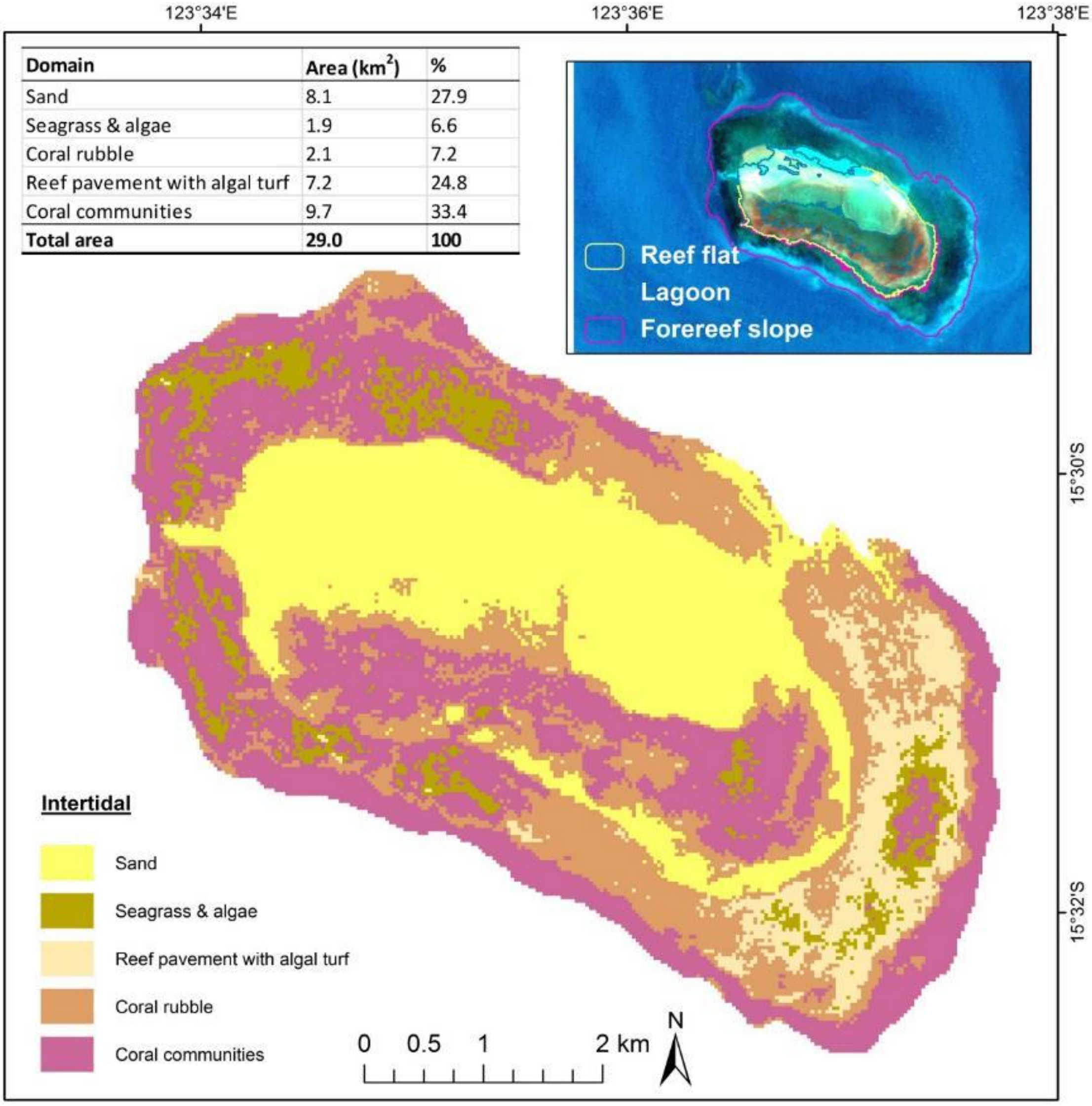
Domain	Area (km^2)	%
Sand	0.50	5.6
Seagrass & algae	0.60	6.7
Reef pavement with algal turf	5.80	64.4
Coral communities	2.10	23.3
Total area	**9.00**	**100**

King Island



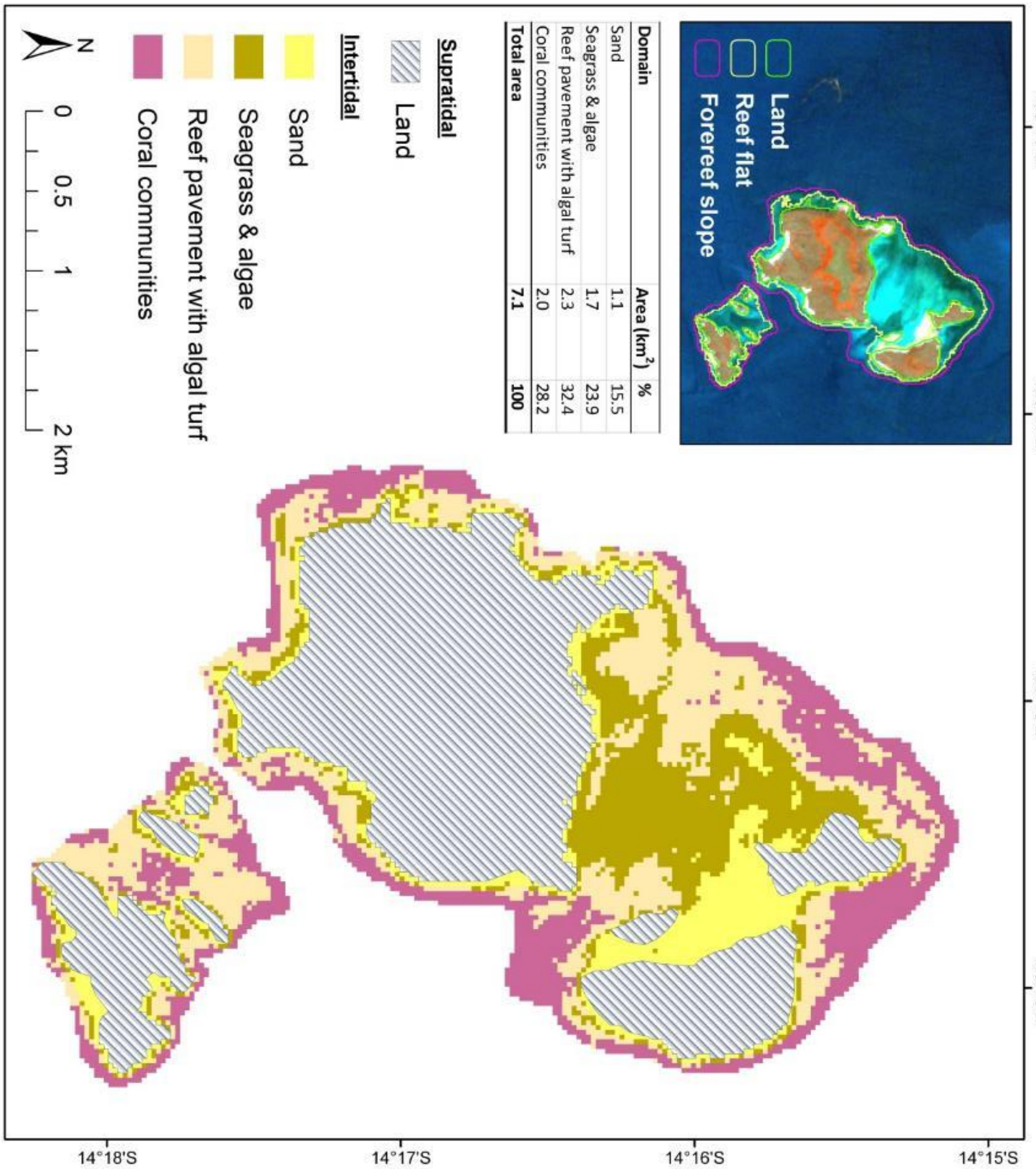
Domain	Area (km^2)	%
Sand	0.5	4.5
Seagrass & algae	1.2	11.6
Reef pavement with algal turf	5.3	51.1
Coral rubble	0.6	5.8
Coral communities	2.8	27.0
Total area	**10.4**	**100**

Mavis Island



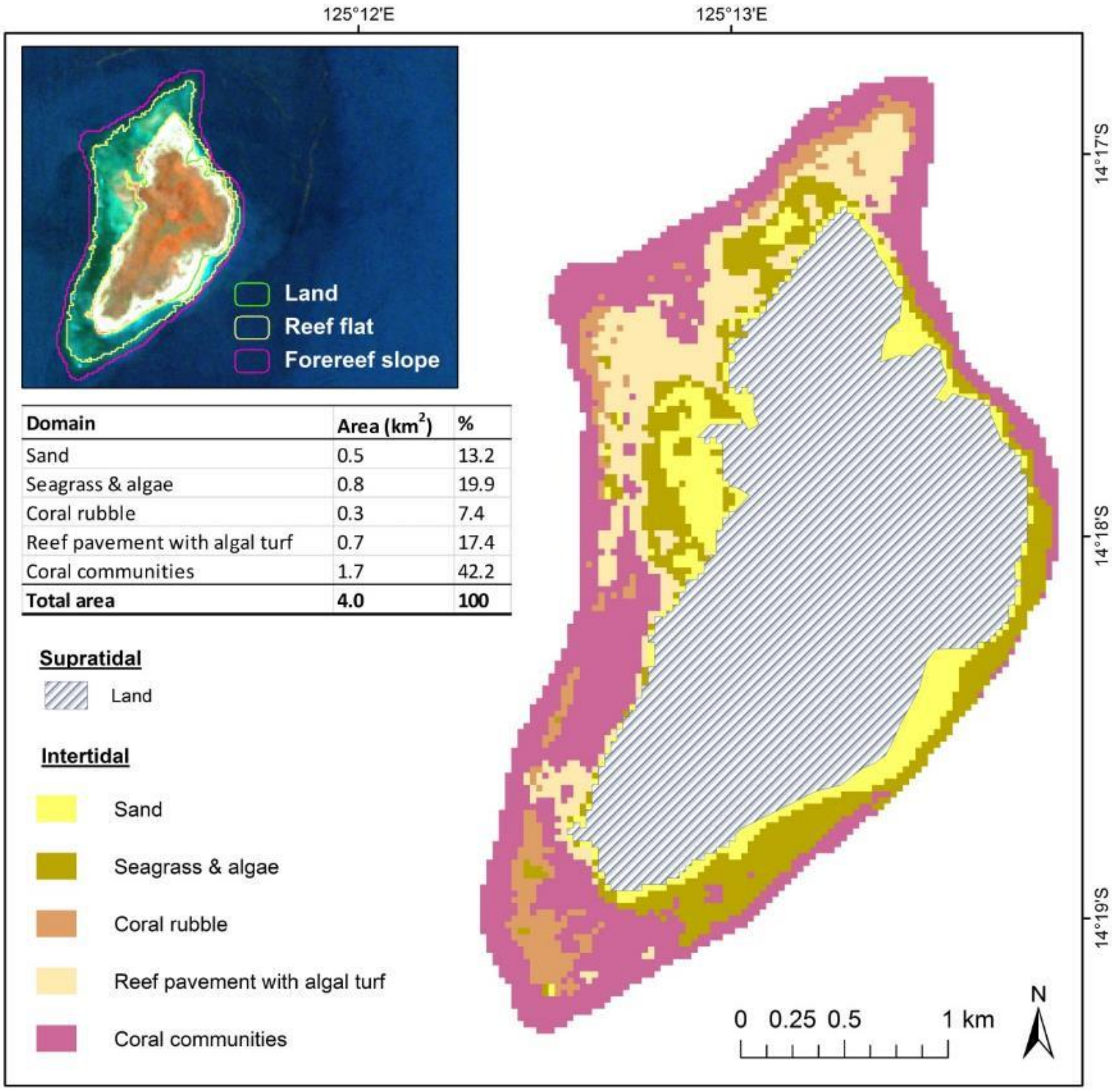
Domain	Area (km^2)	%
Sand	8.1	27.9
Seagrass & algae	1.9	6.6
Coral rubble	2.1	7.2
Reef pavement with algal turf	7.2	24.8
Coral communities	9.7	33.4
Total area	**29.0**	**100**

East Montalivet Island



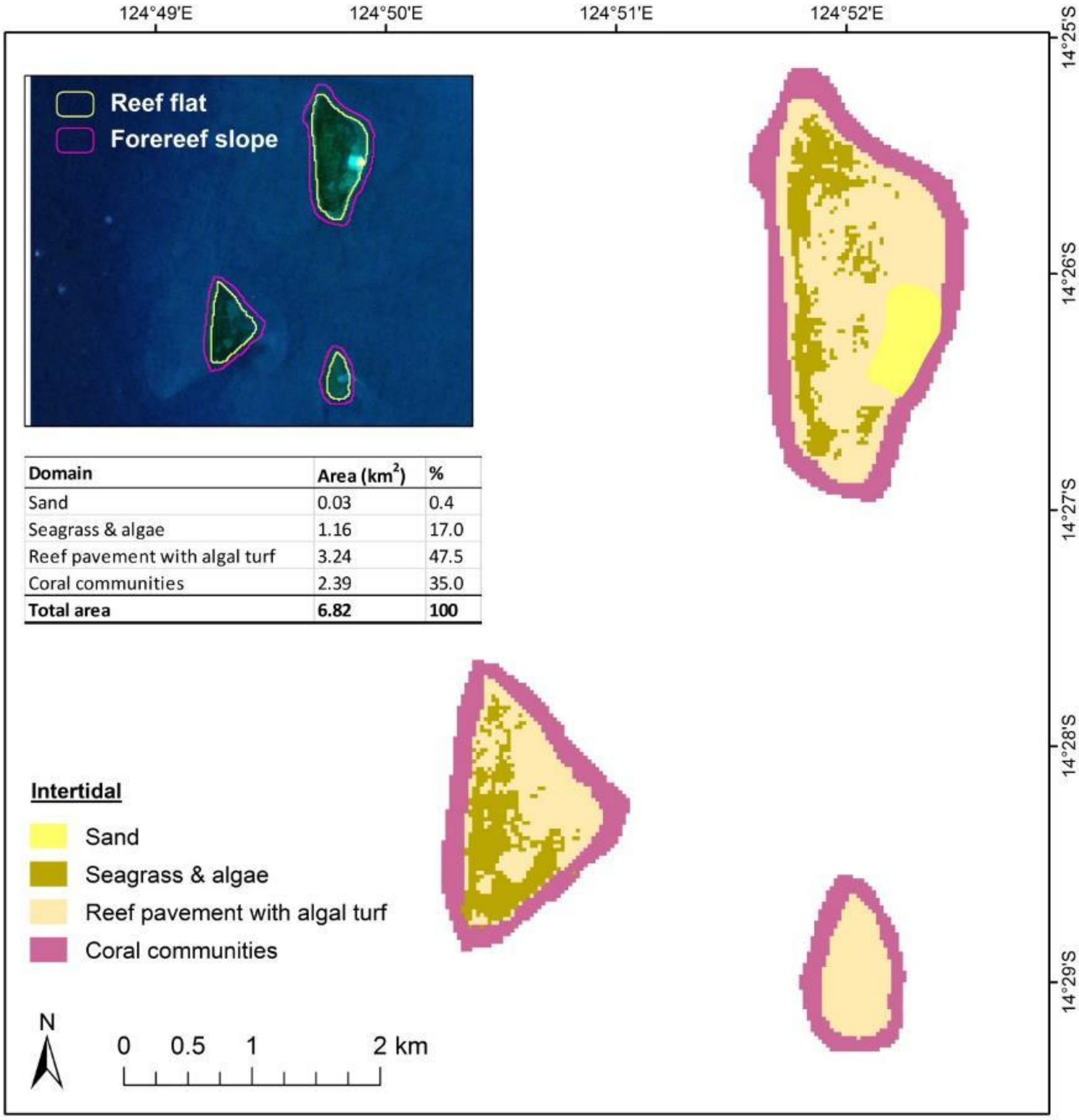
Domain	Area (km^2)	%
Sand	1.1	15.5
Seagrass & algae	1.7	23.9
Reef pavement with algal turf	2.3	32.4
Coral communities	2.0	28.2
Total area	**7.1**	**100**

West Montalivet Island



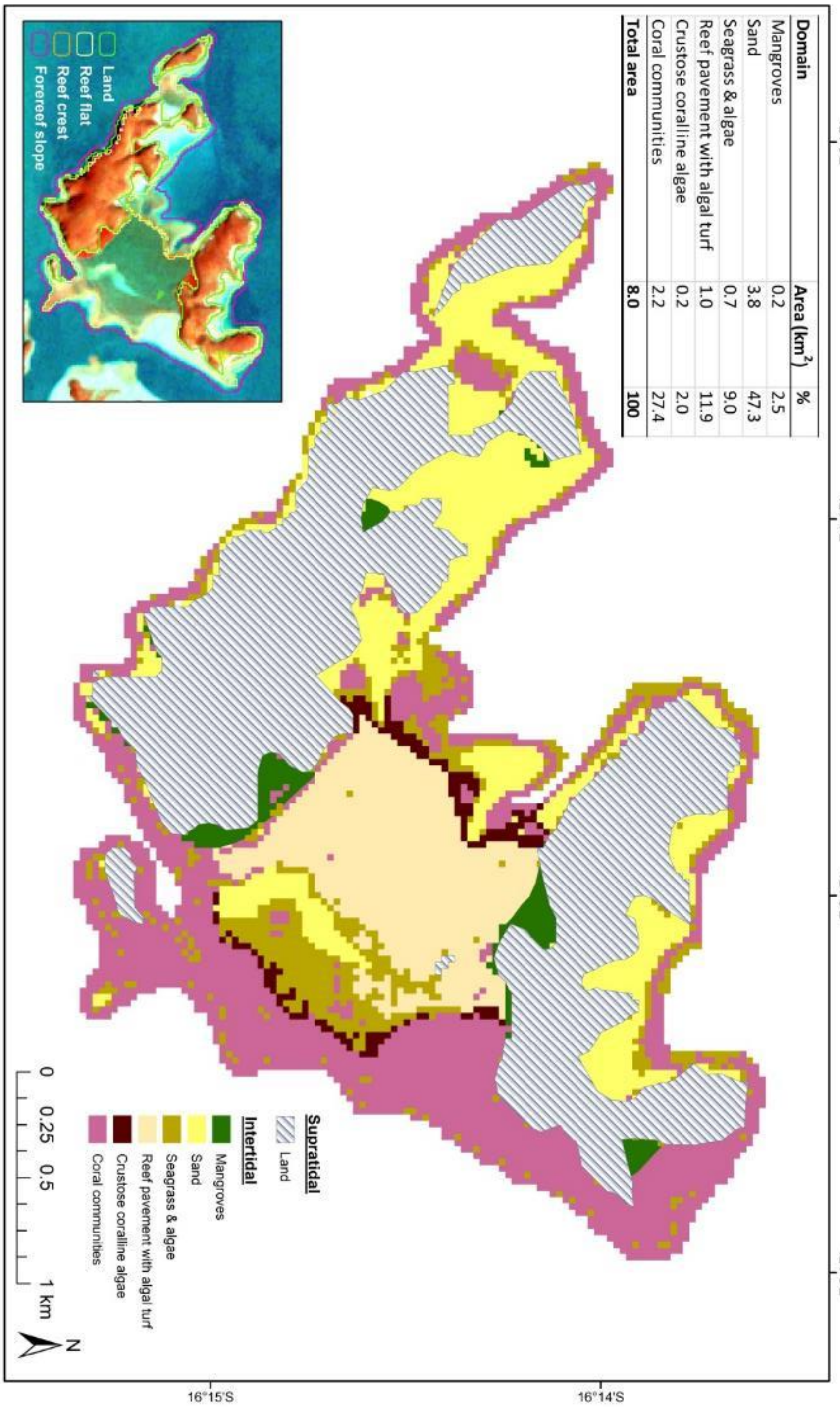
Domain	Area (km^2)	%
Sand	0.5	13.2
Seagrass & algae	0.8	19.9
Coral rubble	0.3	7.4
Reef pavement with algal turf	0.7	17.4
Coral communities	1.7	42.2
Total area	**4.0**	**100**

Robroy Reefs



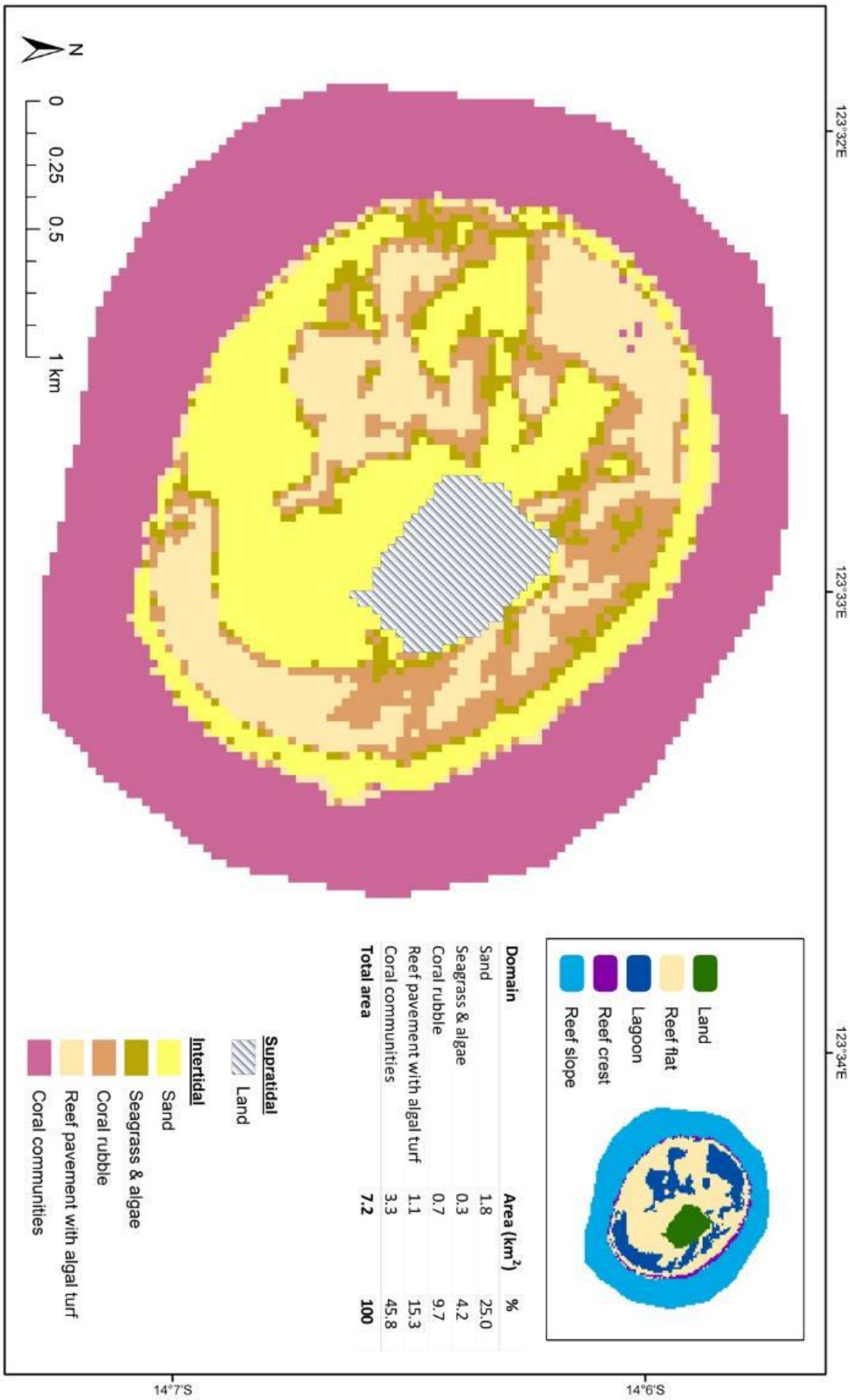
Domain	Area (km^2)	%
Sand	0.03	0.4
Seagrass & algae	1.16	17.0
Reef pavement with algal turf	3.24	47.5
Coral communities	2.39	35.0
Total area	**6.82**	**100**

Woninjaba Islands

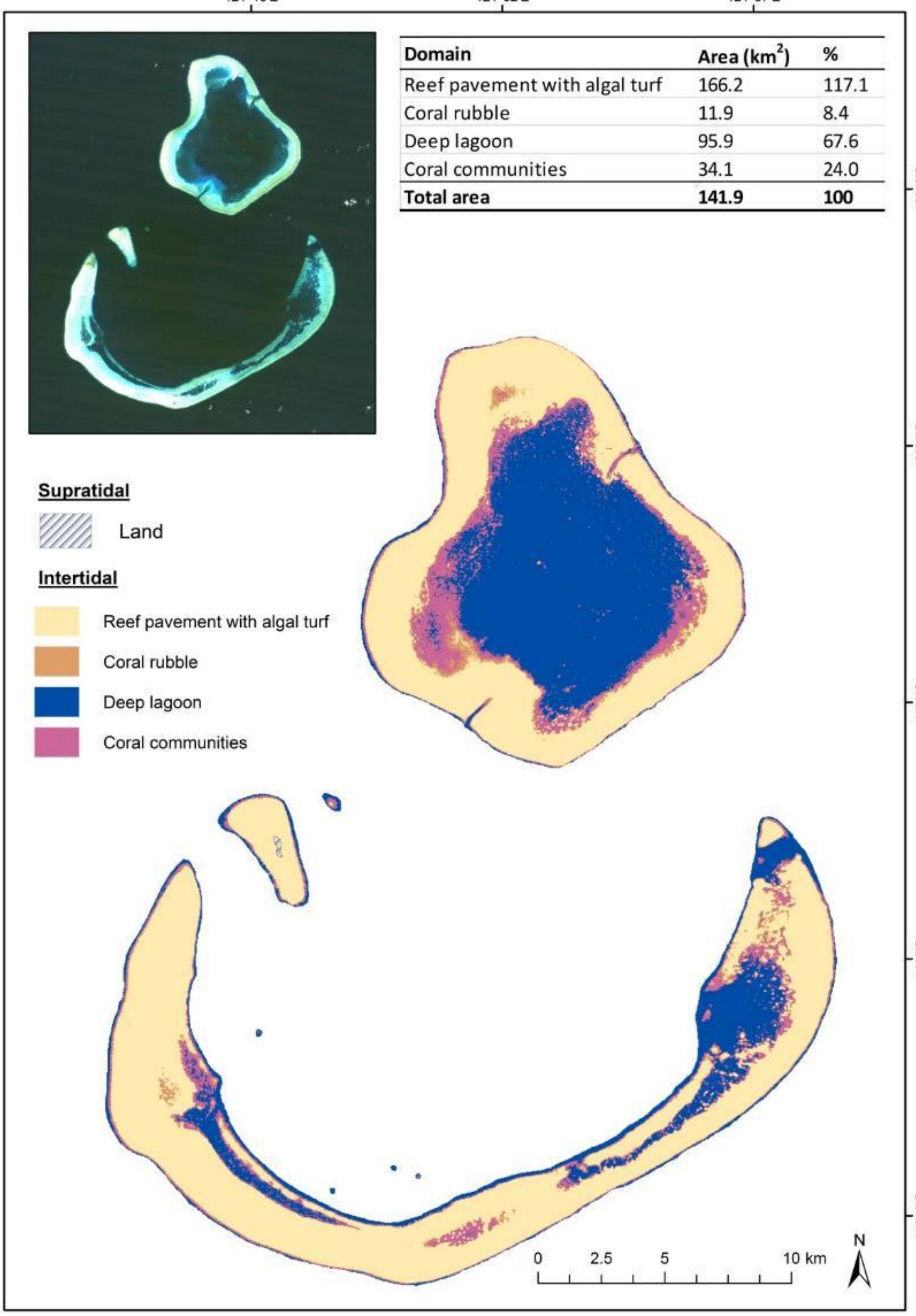


Domain	Area (km^2)	%
Mangroves	0.2	2.5
Sand	3.8	47.3
Seagrass & algae	0.7	9.0
Reef pavement with algal turf	1.0	11.9
Crustose coralline algae	0.2	2.0
Coral communities	2.2	27.4
Total area	**8.0**	**100**

Browse Island

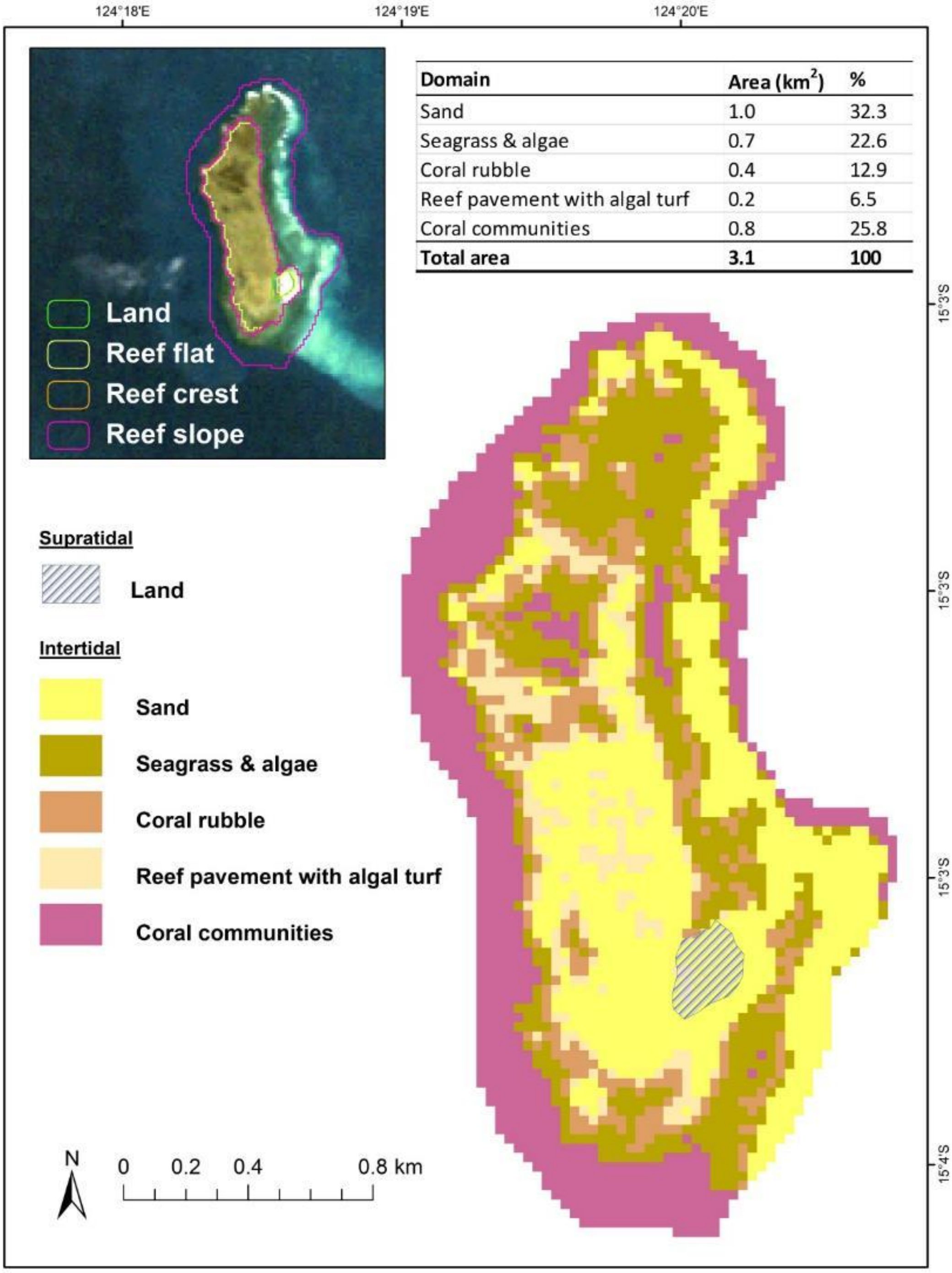


Scott Reef



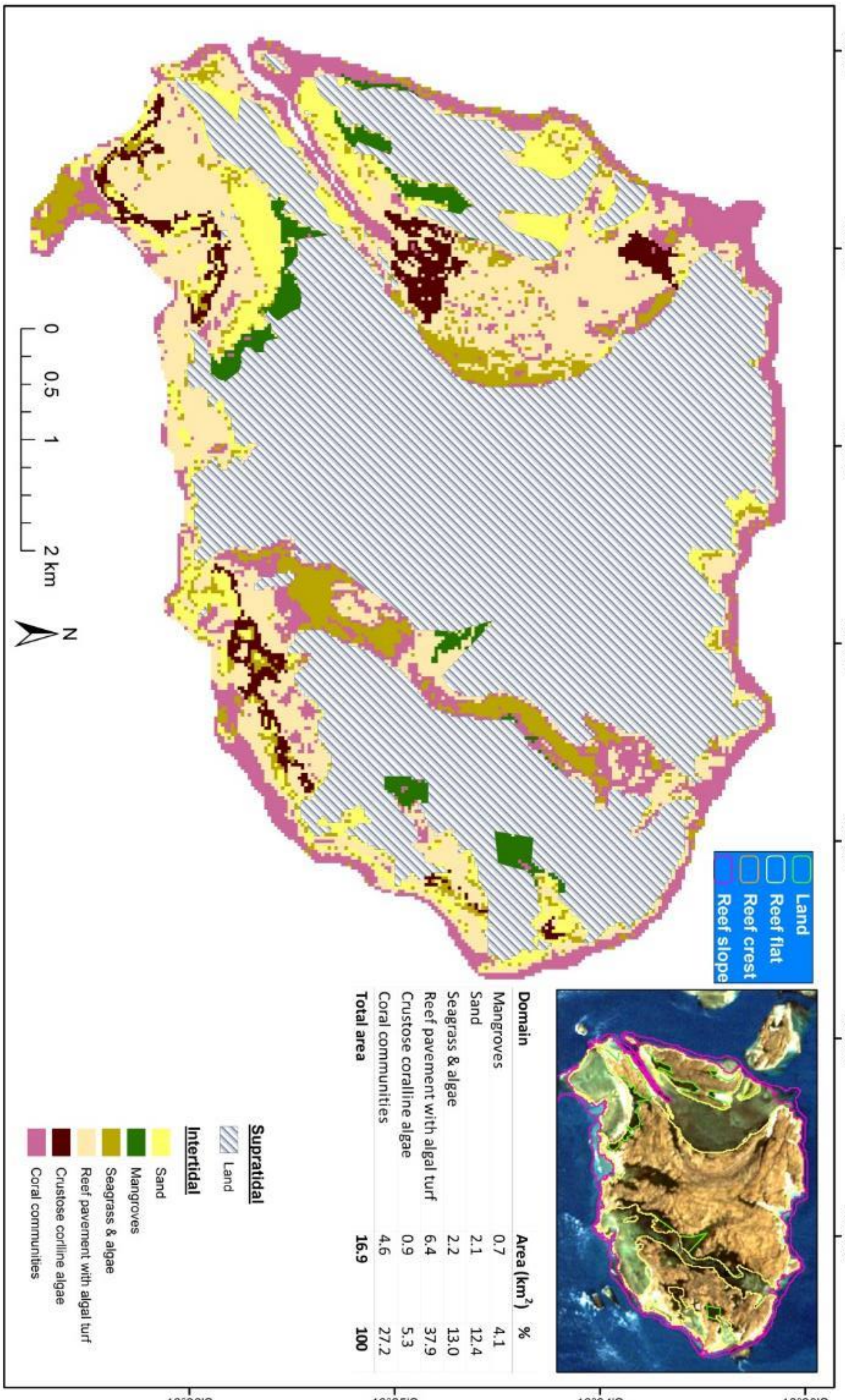
Domain	Area (km^2)	%
Reef pavement with algal turf	166.2	117.1
Coral rubble	11.9	8.4
Deep lagoon	95.9	67.6
Coral communities	34.1	24.0
Total area	**141.9**	**100**

White Island



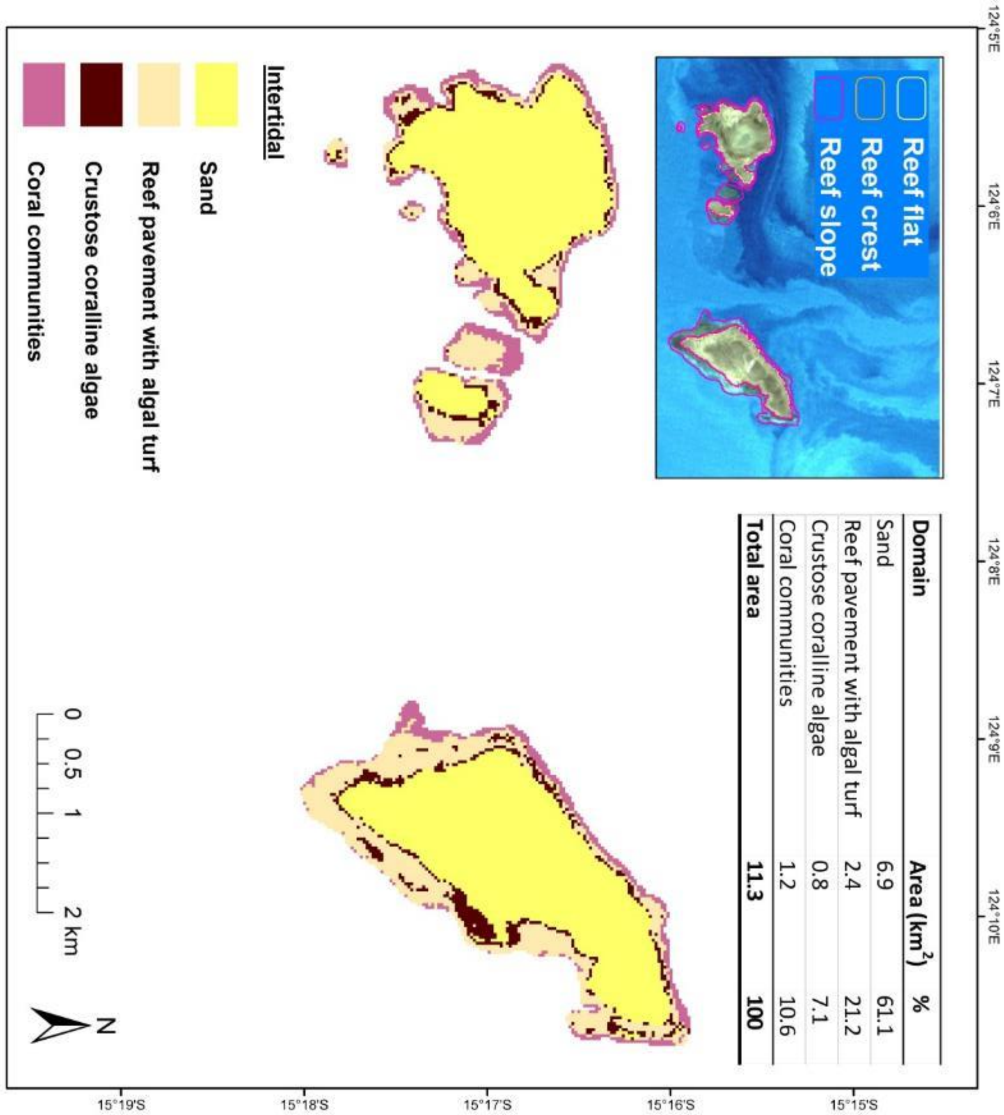
Domain	Area (km^2)	%
Sand	1.0	32.3
Seagrass & algae	0.7	22.6
Coral rubble	0.4	12.9
Reef pavement with algal turf	0.2	6.5
Coral communities	0.8	25.8
Total area	**3.1**	**100**

Sunday Island



Domain	Area (km^2)	%
Mangroves	0.7	4.1
Sand	2.1	12.4
Seagrass & algae	2.2	13.0
Reef pavement with algal turf	6.4	37.9
Crustose coralline algae	0.9	5.3
Coral communities	4.6	27.2
Total area	**16.9**	**100**

Wildcat Reef



APPENDIX C: REEFS INFORMATION HELD IN THE GEODATABASE (REEFKIM)

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
1	Fringing	Headland	Leveque Islet	Low Intertidal	-16.38	2.51	0.30	0.36
2	Fringing	Bayhead	One Arm Point	Low Intertidal	-16.38	4.28	0.71	0.02
3	Patch	Unbroken margin	Rip Reef	Low Intertidal	-16.65	3.05	0.66	5.55
4	Fringing	Headland	Evans Rocks	Low Intertidal	-16.45	1.64	0.11	5.85
5	Fringing	Headland	Jackson Island	Low Intertidal	-16.44	0.90	0.04	5.74
6	Fringing	Headland	Jackson Island	Low Intertidal	-16.44	0.47	0.02	5.24
7	Fringing	Headland	Lone Rock	Low Intertidal	-16.45	1.06	0.06	9.05
8	Fringing	Circum-Island	NW Twin Is	Low Intertidal	-16.27	8.63	2.22	8.93
9	Fringing	Circum-Island	SE Twin Is	Low Intertidal	-16.29	6.86	1.40	8.40
10	Planar	Coralgal	Witcomb Reefs	Low Intertidal	-16.29	8.92	4.16	17.68
11	Patch	Coralgal	Vickery Reefs	Low Intertidal	-16.32	3.94	1.05	6.03
12	Planar	Sand Lagoon	Brue Reef	Low Intertidal	-15.93	13.14	7.85	45.15
13	Patch	Irregular margin	Macleay Island	Low Intertidal	-15.97	0.76	0.04	17.23
14	Fringing	Circum-Island	Macleay Island	Low Intertidal	-15.95	31.40	2.38	17.41
15	Patch	Irregular margin	Gibbings Reefs	Low Intertidal	-15.93	2.10	0.29	22.33
16	Patch	Irregular margin	Gibbings Reefs	Low Intertidal	-15.94	2.60	0.28	21.99
17	Fringing	Bayhead	Mclntyre Island	Low Intertidal	-15.99	3.75	0.18	19.79
18	Patch	Unbroken margin	Lena Reef	Low Intertidal	-15.98	0.90	0.06	21.33
19	Patch	Irregular margin	Dickie Rock	Low Intertidal	-16.39	2.10	0.23	4.65
20	Patch	Irregular margin	Amur Reef	Low Intertidal	-16.47	1.16	0.07	16.83
21	Patch	Irregular margin	Talbot Bay	Low Intertidal	-16.19	1.40	0.12	2.83
22	Patch	Irregular margin	Talbot Bay	Low Intertidal	-16.20	1.01	0.05	2.41

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
23	Patch	Irregular margin	Talbot Bay	Low Intertidal	-16.20	0.73	0.04	2.28
24	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.20	15.45	2.59	2.46
25	Fringing	Circum-Island	Woninjaba Islands	Low Intertidal	-16.24	10.23	0.46	1.30
26	Fringing	Bayhead	Woninjaba Islands	Low Intertidal	-16.24	6.76	0.35	1.82
27	Fringing	Inter-Island	Woninjaba Islands	High Intertidal	-16.24	27.04	4.77	1.76
28	Fringing	Headland	Yampi Peninsula	Low Intertidal	-16.27	2.04	0.12	0.00
29	Fringing	Headland	Yampi Peninsula	Low Intertidal	-16.26	16.33	1.32	0.00
30	Fringing	Headland	Traverse Island	Low Intertidal	-16.26	1.87	0.17	1.60
31	Fringing	Inter-Island	Woninjaba Islands	Low Intertidal	-16.24	38.16	4.22	2.10
32	Fringing	Inter-Island	Woninjaba Islands	Low Intertidal	-16.26	5.17	0.54	2.01
33	Fringing	Inter-Island	Woninjaba Islands	Low Intertidal	-16.27	8.83	0.90	2.51
34	Fringing	Headland	Yampi Peninsula	Low Intertidal	-16.30	4.73	0.35	0.00
35	Fringing	Circum-Island	Rankin Island	Low Intertidal	-16.31	4.76	0.29	2.80
36	Patch	Unbroken margin	Mulgudna Island	Low Intertidal	-16.05	4.74	0.53	16.14
37	Patch	Irregular margin	Mulgudna Island	Low Intertidal	-16.05	3.43	0.24	14.34
38	Patch	Irregular margin	Collier Bay	Low Intertidal	-16.02	0.99	0.07	13.13
39	Patch	Unbroken margin	Station Reef	Low Intertidal	-16.04	4.50	0.50	26.04
40	Patch	Irregular margin	Collier Bay	Low Intertidal	-16.05	0.71	0.03	25.49
41	Fringing	Inter-Island	Caesar Island	Low Intertidal	-16.06	10.63	2.10	15.39
42	Patch	unclassified	Collier Bay	Low Intertidal	-16.07	9.35	3.47	16.71
43	Planar	Coralgal	Montgomery Reef	Low Intertidal	-15.91	16.47	5.02	7.68
44	Planar	Coralgal	Mongomery Reef	High Intertidal	-15.95	177.32	352.43	8.38
45	Patch	unclassified	Collier Bay	Low Intertidal	-16.00	2.90	0.43	16.95

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
46	Patch	unclassified	Collier Bay	Low Intertidal	-16.04	1.90	0.15	16.22
47	Planar	Coralgal	Cockell Reefs	Low Intertidal	-15.77	23.14	9.66	32.45
48	Patch	unclassified	Cockell Reefs	Low Intertidal	-15.79	5.85	1.31	30.71
49	Patch	unclassified	Cockell Reefs	Low Intertidal	-15.80	2.81	0.31	29.02
50	Patch	unclassified	Cockell Reefs	Low Intertidal	-15.76	5.12	0.45	28.25
51	Patch	unclassified	Cockell Reefs	Low Intertidal	-15.77	1.56	0.17	41.12
52	Planar	Sand Lagoon	Mavis Reef	Low Intertidal	-15.51	21.44	23.44	65.80
53	Planar	Sand Lagoon	Albert Reef	Low Intertidal	-15.62	13.47	6.01	63.50
54	Patch	unclassified	Albert Reef	Low Intertidal	-15.60	3.36	0.49	68.98
55	Planar	Sand Lagoon	Churchill Reef	Low Intertidal	-15.47	28.48	38.53	76.93
56	Planar	Sand Lagoon	Adele Reef	Low Intertidal	-15.50	87.23	168.51	72.88
57	Fringing	Headland	Scobell Rocks	Low Intertidal	-15.90	3.67	0.35	24.57
58	Fringing	Inter-island	King Island	Low Intertidal	-15.87	15.83	3.36	27.58
59	Fringing	Headland	Conway Island	Low Intertidal	-15.85	2.32	0.23	30.67
60	Patch	unclassified	Challis Rocks	Low Intertidal	-15.87	6.43	0.55	28.48
61	Fringing	Headland	Wilson Point	Low Intertidal	-15.55	17.81	1.19	0.00
62	Fringing	Headland	Wilson Point	Low Intertidal	-15.53	2.58	0.16	0.20
63	Patch	unclassified	Rice Rocks	Low Intertidal	-15.48	1.58	0.19	4.35
64	Patch	unclassified	Rice Rocks	Low Intertidal	-15.49	1.40	0.14	4.11
65	Fringing	Headland	Bumpus Island	Low Intertidal	-15.51	2.38	0.15	4.05
66	Fringing	Headland	Slate Island	Low Intertidal	-15.54	11.69	0.99	1.64
67	Fringing	Headland	Rankin Island	Low Intertidal	-16.32	7.24	0.73	0.07
68	Fringing	Headland	Collier Bay	Low Intertidal	-15.73	8.41	0.65	0.00

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
69	Fringing	Headland	Collier Bay	Low Intertidal	-15.80	6.08	0.88	0.00
70	Planar	Coralgal	Cascade Bay	Low Intertidal	-16.58	9.02	1.41	6.92
71	Fringing	Bayhead	One Arm Point	Low Intertidal	-16.46	15.14	3.25	0.00
72	Fringing	Headland	Cape Leveque	Low Intertidal	-16.38	31.34	5.49	0.00
73	Fringing	Headland	Augustus Island	Low Intertidal	-15.39	7.21	2.54	8.78
74	Fringing	Headland	Augustus Island	Low Intertidal	-15.38	7.44	0.60	9.35
75	Fringing	Headland	Augustus Island	Low Intertidal	-15.38	4.06	0.58	9.38
76	Fringing	Headland	Augustus Island	Low Intertidal	-15.37	9.66	1.11	10.95
77	Fringing	Headland	Augustus Island	Low Intertidal	-15.35	22.85	3.70	11.96
78	Fringing	Headland	Augustus Island	Low Intertidal	-15.28	0.83	0.04	16.38
79	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.20	2.30	0.36	24.77
80	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.18	3.57	0.66	26.92
81	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.18	1.78	0.24	15.43
82	Patch	unclassified	Dries	Low Intertidal	-15.24	3.27	0.74	2.25
83	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.21	1.02	0.07	4.51
84	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.20	1.58	0.09	5.43
85	Patch	unclassified	York Sound	Low Intertidal	-15.10	0.87	0.04	2.16
86	Fringing	Bayhead	York Sound	Low Intertidal	-15.12	8.44	0.60	0.00
87	Fringing	Bayhead	York Sound	Low Intertidal	-15.13	4.64	0.45	0.00
88	Fringing	Headland	York Sound	Low Intertidal	-15.11	11.60	1.36	0.00
89	Fringing	Headland	York Sound	Low Intertidal	-15.09	20.69	2.48	0.00
90	Patch	unclassified	York Sound	Low Intertidal	-15.08	0.89	0.05	0.81
91	Fringing	Headland	York Sound	Low Intertidal	-15.04	22.39	2.43	0.00

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
92	Fringing	Headland	York Sound	Low Intertidal	-15.00	5.61	0.66	0.00
93	Fringing	Headland	York Sound	Low Intertidal	-14.99	2.44	0.12	0.00
94	Fringing	Headland	York Sound	Low Intertidal	-14.98	5.55	0.55	0.00
95	Fringing	Headland	York Sound	Low Intertidal	-14.99	5.00	0.48	0.00
96	Fringing	Headland	Ena Island	Low Intertidal	-14.97	5.15	0.41	0.90
97	Fringing	Headland	York Sound	Low Intertidal	-14.93	2.98	0.24	5.23
98	Fringing	Headland	Anderdon Islands	Low Intertidal	-14.92	2.20	0.19	6.40
99	Fringing	Headland	Anderdon Islands	Low Intertidal	-14.92	13.65	1.53	6.62
100	Fringing	Headland	Anderdon Islands	Low Intertidal	-14.92	2.21	0.22	7.51
101	Fringing	Headland	York Sound	Low Intertidal	-14.96	3.43	0.55	4.56
102	Fringing	Headland	York Sound	Low Intertidal	-14.96	4.68	0.20	3.18
103	Fringing	Headland	York Sound	Low Intertidal	-14.96	1.78	0.20	2.74
104	Patch	unclassified	York Sound	Low Intertidal	-14.99	2.10	0.31	2.16
105	Fringing	Headland	York Sound	Low Intertidal	-14.98	2.52	0.10	1.23
106	Fringing	Headland	Anderdon Islands	Low Intertidal	-14.94	6.84	0.34	3.32
107	Fringing	Headland	York Sound	Low Intertidal	-14.95	27.91	3.33	0.00
108	Fringing	Headland	Anderdon Islands	Low Intertidal	-14.92	5.74	0.32	1.17
109	Fringing	Headland	York Sound	Low Intertidal	-14.94	16.16	1.23	0.00
110	Fringing	Headland	York Sound	Low Intertidal	-14.92	15.64	1.48	0.00
111	Fringing	Headland	Anderdon Islands	Low Intertidal	-14.91	7.35	0.58	0.56
112	Fringing	Headland	York Sound	Low Intertidal	-14.97	9.48	0.72	0.00
113	Fringing	Headland	York Sound	Low Intertidal	-14.85	4.31	0.27	0.00
114	Fringing	Headland	York Sound	Low Intertidal	-14.87	5.91	0.43	0.00

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
115	Fringing	Headland	Kartja Island	Low Intertidal	-14.87	13.00	0.97	1.68
116	Fringing	Headland	York Sound	Low Intertidal	-14.83	53.23	4.56	0.00
117	Fringing	Headland	York Sound	Low Intertidal	-14.79	13.60	1.54	0.00
118	Fringing	Headland	York Sound	Low Intertidal	-14.80	6.62	0.27	2.03
119	Fringing	Headland	Cape Pond	Low Intertidal	-14.74	65.55	5.63	0.00
120	Patch	unclassified	Cape Pond	Low Intertidal	-14.74	0.58	0.01	1.70
121	Fringing	Headland	Tournefort Island	Low Intertidal	-14.81	9.25	1.65	12.09
122	Fringing	Headland	Cape Pond	Low Intertidal	-14.74	3.92	0.76	4.08
123	Fringing	Headland	Bonaparte Island	Low Intertidal	-14.86	6.94	0.90	28.72
124	Fringing	Inter-Island	Cotton Island	Low Intertidal	-14.91	5.68	0.36	28.70
125	Fringing	Headland	Cotton Island	Low Intertidal	-14.91	0.75	0.04	28.46
126	Fringing	Headland	Buffon Island	Low Intertidal	-14.92	21.54	2.31	24.70
127	Fringing	Headland	Museums Island	Low Intertidal	-14.94	1.41	0.09	24.10
128	Fringing	Headland	Museums Island	Low Intertidal	-14.96	12.62	0.95	21.45
129	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.95	1.54	0.08	22.02
130	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.95	1.38	0.08	22.01
131	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.95	0.95	0.04	21.59
132	Fringing	Headland	Whitley Island	Low Intertidal	-14.93	6.27	0.40	27.65
133	Fringing	Inter-Island	McCulloch Island	Low Intertidal	-14.93	6.04	0.66	29.23
134	Fringing	Headland	Hedley Island	Low Intertidal	-14.95	2.50	0.40	28.09
135	Fringing	Headland	Hedley Island	Low Intertidal	-14.94	0.65	0.03	29.23
136	Fringing	Headland	Keraudren Island	Low Intertidal	-14.95	12.31	1.05	26.57
137	Fringing	Headland	Iredale Island	Low Intertidal	-14.91	3.13	0.44	30.96

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
138	Fringing	Headland	Hedley Island	Low Intertidal	-14.94	7.51	0.92	29.54
139	Fringing	Headland	Iredale Island	Low Intertidal	-14.90	2.29	0.27	32.66
140	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.99	1.29	0.06	19.82
141	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.96	2.10	0.11	18.36
142	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.98	0.88	0.06	16.52
143	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.98	1.71	0.11	16.74
144	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.97	5.15	0.32	17.04
145	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.00	2.31	0.14	13.62
146	Fringing	Headland	Coronation Islands	Low Intertidal	-14.95	10.97	0.61	13.36
147	Fringing	Headland	Coronation Islands	Low Intertidal	-14.93	8.54	0.61	15.65
148	Fringing	Inter-Island	Coronation Islands	Low Intertidal	-14.90	9.76	0.75	16.00
149	Fringing	Headland	Coronation Islands	Low Intertidal	-14.91	4.44	0.20	13.74
150	Fringing	Headland	Coronation Islands	Low Intertidal	-14.89	2.67	0.12	13.74
151	Fringing	Headland	Coronation Islands	Low Intertidal	-14.90	1.35	0.08	13.10
152	Fringing	Headland	Coronation Islands	Low Intertidal	-14.90	0.76	0.04	12.41
153	Fringing	Headland	Coronation Islands	Low Intertidal	-14.91	1.44	0.05	11.96
154	Fringing	Headland	Coronation Islands	Low Intertidal	-14.91	0.97	0.05	10.81
155	Fringing	Headland	Coronation Islands	Low Intertidal	-14.92	1.59	0.06	12.99
156	Fringing	Headland	Coronation Islands	Low Intertidal	-14.93	0.79	0.03	10.27
157	Fringing	Headland	Coronation Islands	Low Intertidal	-14.95	29.00	2.58	7.30
158	Fringing	Headland	Coronation Islands	Low Intertidal	-14.97	18.08	1.69	10.68
159	Patch	unclassified	Osborn Reef	Low Intertidal	-15.15	1.75	0.19	46.10
160	Patch	unclassified	Rainbow Shoals	Low Intertidal	-15.21	2.76	0.50	37.83

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
161	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.31	4.02	0.51	0.10
162	Fringing	Headland	York Sound	Low Intertidal	-14.99	14.60	1.27	1.49
163	Fringing	Headland	York Sound	Low Intertidal	-15.02	2.02	0.13	4.85
164	Fringing	Headland	York Sound	Low Intertidal	-15.03	0.90	0.05	4.57
165	Fringing	Headland	York Sound	Low Intertidal	-15.04	0.76	0.04	4.54
166	Patch	unclassified	Brunswick Bay	Low Intertidal	-14.98	2.33	0.29	32.46
167	Fringing	Headland	De Freycinet Island	Low Intertidal	-14.99	3.09	0.17	32.72
168	Patch	unclassified	Champangy Island	Low Intertidal	-15.35	1.66	0.17	27.85
169	Patch	unclassified	Champangy Island	Low Intertidal	-15.37	3.71	0.92	27.21
170	Patch	unclassified	Scott Strait	Low Intertidal	-14.63	7.86	2.21	3.22
171	Patch	unclassified	Scott Strait	Low Intertidal	-14.65	1.00	0.05	3.08
172	Fringing	Headland	Bigge Island	Low Intertidal	-14.50	1.58	0.07	18.91
173	Fringing	Headland	Bigge Island	Low Intertidal	-14.64	4.29	0.41	13.84
174	Fringing	Headland	Queen Island	Low Intertidal	-14.60	6.02	0.36	16.45
175	Fringing	Headland	Bigge Island	Low Intertidal	-14.57	3.38	0.19	18.04
176	Fringing	Headland	Cape Pond	Low Intertidal	-14.72	2.76	0.28	5.43
177	Patch	unclassified	Cape Pond	Low Intertidal	-14.69	0.74	0.04	6.42
178	Fringing	Headland	Scott Strait	Low Intertidal	-14.61	4.91	0.53	0.00
179	Fringing	Headland	Scott Strait	Low Intertidal	-14.59	18.92	1.36	0.00
180	Fringing	Headland	Scott Strait	Low Intertidal	-14.58	1.21	0.05	0.00
181	Fringing	Headland	Scott Strait	Low Intertidal	-14.58	1.08	0.04	1.69
182	Fringing	Headland	Scott Strait	Low Intertidal	-14.58	2.67	0.24	1.07
183	Fringing	Headland	Scott Strait	Low Intertidal	-14.56	6.84	0.34	1.74

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
184	Fringing	Bayhead	Scott Strait	Low Intertidal	-14.56	5.06	0.33	0.00
185	Fringing	Headland	Scott Strait	Low Intertidal	-14.53	1.00	0.06	0.00
186	Fringing	Bayhead	Scott Strait	Low Intertidal	-14.50	1.42	0.07	1.24
187	Fringing	Bayhead	Scott Strait	Low Intertidal	-14.50	0.77	0.02	1.88
188	Fringing	Headland	Scott Strait	Low Intertidal	-14.50	1.95	0.10	2.17
189	Fringing	Headland	Scott Strait	Low Intertidal	-14.50	5.04	0.69	0.95
190	Fringing	Headland	Montague Sound	Low Intertidal	-14.46	4.50	0.50	6.67
191	Fringing	Inter-Island	Montague Sound	Low Intertidal	-14.48	14.43	2.38	8.57
192	Fringing	Headland	Montague Sound	Low Intertidal	-14.48	4.13	0.25	9.66
193	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.44	2.76	0.29	14.80
194	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.42	9.12	0.85	15.09
195	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.43	6.09	0.44	13.01
196	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.41	4.24	0.28	14.00
197	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.41	2.18	0.18	15.18
198	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.40	3.47	0.46	16.51
199	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.42	1.80	0.20	12.48
200	Fringing	Headland	Prudhoe Islands	Low Intertidal	-14.43	4.15	0.53	11.15
201	Fringing	Headland	Clerk Island	Low Intertidal	-14.40	1.52	0.09	13.00
202	Fringing	Headland	Bishop Island	Low Intertidal	-14.41	5.56	0.33	10.72
203	Patch	unclassified	Montague Sound	Low Intertidal	-14.41	1.95	0.25	10.74
204	Fringing	Headland	Montague Sound	Low Intertidal	-14.41	1.33	0.07	11.87
205	Fringing	Headland	Montague Sound	Low Intertidal	-14.40	2.70	0.17	12.13
206	Patch	unclassified	Montague Sound	Low Intertidal	-14.39	3.52	0.75	12.41

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
207	Fringing	Headland	Montague Sound	Low Intertidal	-14.39	5.46	0.51	13.31
208	Fringing	Headland	Montague Sound	Low Intertidal	-14.42	1.54	0.10	9.79
209	Fringing	Headland	Montague Sound	Low Intertidal	-14.41	6.39	0.68	11.99
210	Fringing	Headland	Cleghorn Island	Low Intertidal	-14.37	4.70	0.21	15.47
211	Fringing	Headland	Montague Sound	Low Intertidal	-14.36	1.53	0.07	16.42
212	Fringing	Headland	Montague Sound	Low Intertidal	-14.36	1.80	0.07	17.07
213	Fringing	Headland	Montague Sound	Low Intertidal	-14.38	0.75	0.03	14.97
214	Fringing	Headland	Tancord Island	Low Intertidal	-14.34	2.32	0.13	18.15
215	Fringing	Headland	Hawick Island	Low Intertidal	-14.34	0.81	0.04	18.29
216	Fringing	Headland	Hawick Island	Low Intertidal	-14.33	1.52	0.06	18.87
217	Fringing	Headland	Warn Island	Low Intertidal	-14.33	1.64	0.12	19.38
218	Fringing	Headland	East Montalivet Island	Low Intertidal	-14.30	4.45	0.42	23.27
219	Fringing	Headland	East Montalivet Island	Low Intertidal	-14.29	1.94	0.15	24.63
220	Fringing	Headland	East Montalivet Island	Low Intertidal	-14.29	1.13	0.07	24.64
221	Fringing	Inter-Island	East Montalivet Island	Low Intertidal	-14.27	13.74	3.48	25.42
222	Fringing	Headland	East Montalivet Island	Low Intertidal	-14.28	0.82	0.04	26.51
223	Fringing	Headland	East Montalivet Island	Low Intertidal	-14.29	2.83	0.21	25.13
224	Fringing	Headland	Sand Cay	Low Intertidal	-14.24	2.33	0.13	27.03
225	Fringing	Headland	West Montalivet Island	Low Intertidal	-14.30	18.64	2.60	26.13
226	Patch	unclassified	Albert Reef	Low Intertidal	-14.26	6.48	2.28	33.73
227	Patch	unclassified	Ingram Reef	Low Intertidal	-14.12	4.29	1.29	35.37
228	Planar	Coralgal	Jamieson Reef	Low Intertidal	-14.06	8.83	5.20	30.83
229	Fringing	Headland	Condillac Island	Low Intertidal	-14.11	0.66	0.03	14.77

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
230	Fringing	Headland	Condillac Island	Low Intertidal	-14.10	2.15	0.15	15.71
231	Fringing	Headland	Randall Island	Low Intertidal	-14.14	7.39	1.29	10.07
232	Fringing	Headland	Baudin Island	Low Intertidal	-14.13	6.26	0.50	11.45
233	Fringing	Inter-Island	Monge Island	Low Intertidal	-14.20	6.55	1.39	2.54
234	Fringing	Headland	Montague Sound	Low Intertidal	-14.33	1.38	0.04	0.71
235	Fringing	Headland	Montague Sound	Low Intertidal	-14.35	3.14	0.42	1.40
236	Fringing	Headland	Montague Sound	Low Intertidal	-14.36	3.65	0.44	0.42
237	Fringing	Headland	Montague Sound	Low Intertidal	-14.35	4.81	0.49	0.00
238	Fringing	Headland	Montague Sound	Low Intertidal	-14.38	3.23	0.29	0.00
239	Fringing	Headland	Montague Sound	Low Intertidal	-14.43	32.17	3.49	0.00
240	Fringing	Headland	Montague Sound	Low Intertidal	-14.50	10.19	1.11	0.00
241	Fringing	Headland	Montague Sound	Low Intertidal	-14.51	2.20	0.16	0.00
242	Fringing	Headland	Montague Sound	Low Intertidal	-14.51	1.93	0.12	0.00
243	Fringing	Headland	Montague Sound	Low Intertidal	-14.52	5.16	0.47	0.00
244	Fringing	Headland	Montague Sound	Low Intertidal	-14.54	1.29	0.07	0.00
245	Fringing	Headland	Montague Sound	Low Intertidal	-14.53	5.28	0.28	0.00
246	Fringing	Headland	Montague Sound	Low Intertidal	-14.52	1.61	0.10	0.45
247	Fringing	Headland	Montague Sound	Low Intertidal	-14.54	2.68	0.13	0.00
248	Fringing	Inter-Island	Montague Sound	Low Intertidal	-14.49	17.27	2.43	1.53
249	Fringing	Headland	Montague Sound	Low Intertidal	-14.51	0.76	0.04	0.00
250	Fringing	Headland	Montague Sound	Low Intertidal	-14.51	3.02	0.16	0.00
251	Fringing	Circum-Island	Katers Island	Low Intertidal	-14.46	54.80	7.00	1.29
252	Fringing	Headland	Montague Sound	Low Intertidal	-14.43	16.08	2.45	7.05

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
253	Fringing	Headland	Montague Sound	Low Intertidal	-14.42	3.03	0.26	9.81
254	Fringing	Headland	Water Island	Low Intertidal	-14.35	4.08	0.20	9.71
255	Fringing	Headland	Montague Sound	Low Intertidal	-14.48	2.09	0.12	4.76
256	Fringing	Headland	Montague Sound	Low Intertidal	-14.48	0.77	0.04	4.42
257	Fringing	Circum-Island	Maret Islands	Low Intertidal	-14.42	45.17	4.61	32.19
258	Fringing	Headland	Cambe Island	Low Intertidal	-14.44	1.35	0.09	29.66
259	Fringing	Headland	Berhier Island	Low Intertidal	-14.49	16.28	1.45	29.32
260	Fringing	Headland	Corvisart Island	Low Intertidal	-14.54	7.83	1.48	25.31
261	Fringing	Inter-Island	Albert Islands	Low Intertidal	-14.52	20.57	3.42	31.91
262	Fringing	Headland	Albert Islands	Low Intertidal	-14.52	0.79	0.03	34.38
263	Patch	unclassified	Robroy Reefs	Low Intertidal	-14.48	2.61	0.37	41.41
264	Patch	unclassified	Robroy Reefs	Low Intertidal	-14.47	3.97	0.90	44.14
265	Planar	Coralgal	Robroy Reefs	Low Intertidal	-14.43	7.40	2.42	44.30
266	Fringing	Headland	Institut Islands	Low Intertidal	-14.20	6.93	1.56	3.11
267	Fringing	Headland	Laplace Island	Low Intertidal	-14.19	7.13	0.52	4.78
268	Fringing	Headland	Lavoisier Island	Low Intertidal	-14.22	2.59	0.16	1.53
269	Fringing	Inter-Island	Desoartes Island	Low Intertidal	-14.17	15.58	2.86	6.67
270	Fringing	Headland	Institut Islands	Low Intertidal	-14.15	5.50	0.46	8.65
271	Fringing	Headland	Fenelon Island	Low Intertidal	-14.13	13.64	2.08	11.63
272	Fringing	Headland	Institut Islands	Low Intertidal	-14.11	1.98	0.29	14.64
273	Fringing	Headland	Institut Islands	Low Intertidal	-14.10	1.09	0.03	17.56
274	Fringing	Headland	Bird Island	Low Intertidal	-14.09	6.41	1.91	17.20
275	Fringing	Headland	Institut Islands	Low Intertidal	-14.09	2.80	0.20	18.59

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
276	Fringing	Headland	Oliver Island	Low Intertidal	-14.09	5.12	0.64	19.01
277	Fringing	Headland	Institut Islands	Low Intertidal	-14.10	1.63	0.03	19.30
278	Fringing	Headland	Oyster Rock	Low Intertidal	-14.07	1.26	0.04	22.26
279	Fringing	Bayhead	Corneille Island	Low Intertidal	-14.19	4.33	0.48	9.26
280	Fringing	Headland	Corneille Island	Low Intertidal	-14.18	3.81	0.25	9.98
281	Fringing	Circum-Island	Lagrange Island	Low Intertidal	-14.21	11.23	4.23	7.35
282	Fringing	Headland	Institut Islands	Low Intertidal	-14.22	0.94	0.06	8.66
283	Fringing	Headland	Institut Islands	Low Intertidal	-14.23	1.11	0.07	8.43
284	Fringing	Headland	Institut Islands	Low Intertidal	-14.23	0.67	0.03	8.89
285	Fringing	Headland	Kingsmill Islands	Low Intertidal	-14.17	1.76	0.23	13.04
286	Fringing	Headland	Kingsmill Islands	Low Intertidal	-14.16	7.36	0.81	14.26
287	Fringing	Headland	Parry Island	Low Intertidal	-14.33	11.22	1.87	2.78
288	Fringing	Headland	Waimesly Bay	Low Intertidal	-14.36	1.58	0.10	1.39
289	Fringing	Headland	Berthoud Island	Low Intertidal	-14.28	1.26	0.07	11.49
290	Fringing	Headland	Racine Island	Low Intertidal	-14.26	6.31	0.45	10.34
291	Fringing	Headland	Racine Island	Low Intertidal	-14.25	1.01	0.07	10.89
292	Fringing	Headland	Pascal Island	Low Intertidal	-14.07	5.61	0.84	17.59
293	Fringing	Headland	Low Rock	Low Intertidal	-14.06	2.79	0.20	11.10
294	Planar	Sand Lagoon	Long Reef	Low Intertidal	-13.93	76.05	194.31	14.40
295	Fringing	Headland	Rothery Reef	Low Intertidal	-13.77	5.67	1.50	26.17
296	Fringing	Headland	Cassini Island	Low Intertidal	-13.93	1.81	0.16	33.83
297	Fringing	Circum-Island	Cassini Island	Low Intertidal	-13.95	17.14	1.58	29.75
298	Patch	unclassified	Fury Rock	Low Intertidal	-13.98	2.65	0.51	1.09

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
299	Fringing	Headland	Hecla Island	Low Intertidal	-13.98	6.37	0.96	1.21
300	Fringing	Headland	Cape Bougainville	Low Intertidal	-14.00	1.90	0.26	0.38
301	Fringing	Headland	Cape Bougainville	Low Intertidal	-14.00	157.01	31.12	0.00
302	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.93	0.89	0.05	0.00
303	Patch	unclassified	Eyre Reef	Low Intertidal	-13.87	4.13	1.14	2.47
304	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.92	3.50	0.63	0.00
305	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.91	4.68	0.48	0.00
306	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-13.95	19.15	2.87	0.00
307	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.95	4.02	0.55	0.93
308	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.98	2.03	0.21	0.00
309	Fringing	Headland	Cape Bougainville	Low Intertidal	-14.01	6.74	1.09	0.00
310	Fringing	Headland	Cape Bougainville	Low Intertidal	-14.01	1.82	0.25	0.35
311	Fringing	Headland	Long Island	Low Intertidal	-13.98	1.42	0.15	6.96
312	Fringing	Inter-Island	Eclipse Island	Low Intertidal	-13.92	73.58	25.91	7.30
313	Fringing	Headland	Mary Island	Low Intertidal	-13.98	16.31	5.00	2.53
314	Patch	unclassified	Vansittart Bay	Low Intertidal	-14.07	1.17	0.09	2.44
315	Fringing	Headland	Vansittart Bay	Low Intertidal	-14.16	2.53	0.13	1.57
316	Fringing	Headland	Vansittart Bay	Low Intertidal	-14.17	1.92	0.15	0.53
317	Fringing	Bayhead	Vansittart Bay	Low Intertidal	-14.18	5.05	0.41	0.00
318	Fringing	Headland	Jar Island	Low Intertidal	-14.15	2.34	0.35	2.38
319	Fringing	Bayhead	Vansittart Bay	Low Intertidal	-14.15	1.83	0.08	0.00
320	Fringing	Headland	Vansittart Bay	Low Intertidal	-14.14	5.48	0.47	0.00
321	Fringing	Headland	Cape Bougainville	Low Intertidal	-14.08	3.84	0.36	0.00

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
322	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-14.08	2.18	0.22	0.00
323	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.22	2.06	0.17	0.00
324	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.23	3.66	0.34	0.00
325	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.24	8.37	1.01	0.00
326	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.22	1.25	0.09	4.23
327	Fringing	Headland	Borda Island	Low Intertidal	-14.24	22.69	2.96	2.24
328	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.25	1.12	0.08	3.25
329	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.48	2.51	0.42	4.55
330	Fringing	Headland	Bignell Island	Low Intertidal	-14.49	2.31	0.17	3.78
331	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.53	1.27	0.05	0.00
332	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.52	0.84	0.04	0.21
333	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.53	20.74	2.88	0.00
334	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.55	1.39	0.09	0.84
335	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.45	1.19	0.09	2.07
336	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.44	1.24	0.10	2.96
337	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.45	2.37	0.16	2.97
338	Fringing	Inter-Island	Waimesly Bay	Low Intertidal	-14.42	6.98	1.45	0.49
339	Planar	Coralgal	W Holothuria Reef	Low Intertidal	-13.56	6.29	2.60	47.97
340	Planar	Coralgal	East Holothuria Reef	Low Intertidal	-13.58	38.38	49.99	32.03
341	Planar	Coralgal	East Holothuria Reef	Low Intertidal	-13.59	7.02	1.41	32.40
342	Fringing	Circum-Island	Guichen Reef	Low Intertidal	-13.73	4.62	1.11	18.84
343	Fringing	Headland	Troughton Island	Low Intertidal	-13.75	13.08	3.59	15.89
344	Patch	unclassified	W Holothuria Reef	Low Intertidal	-13.58	1.42	0.12	41.90

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345	Fringing	Circum-Island	Jones Island	Low Intertidal	-13.76	14.68	7.52	25.33
346	Fringing	Headland	Osborne Islands	Low Intertidal	-14.33	8.41	0.96	8.32
347	Fringing	Circum-Island	Osborne Islands	Low Intertidal	-14.35	44.14	3.73	2.99
348	Fringing	Bayhead	Osborne Islands	Low Intertidal	-14.38	9.13	0.88	0.11
349	Fringing	Headland	Steep Head Island	Low Intertidal	-14.44	13.84	1.03	1.54
350	Fringing	Headland	Admiralty Gulf	Low Intertidal	-14.18	2.11	0.16	0.40
351	Fringing	Headland	Eclipse Archipelago	Low Intertidal	-13.93	3.47	0.42	5.32
352	Fringing	Headland	Eclipse Archipelago	Low Intertidal	-13.92	5.34	1.24	4.62
353	Fringing	Headland	Scorpion Island	Low Intertidal	-13.85	2.34	0.21	11.09
354	Fringing	Headland	Scorpion Island	Low Intertidal	-13.87	7.16	1.11	8.32
355	Fringing	Headland	Napier Broome Bay	Low Intertidal	-14.00	6.40	0.62	1.62
356	Fringing	Headland	Galley Point	Low Intertidal	-13.97	5.31	0.47	0.00
357	Fringing	Headland	Galley Point	Low Intertidal	-13.97	1.05	0.06	0.01
358	Fringing	Headland	Cape Talbot	Low Intertidal	-13.89	7.99	0.53	0.00
359	Fringing	Headland	Cape Talbot	Low Intertidal	-13.86	8.88	0.60	0.00
360	Fringing	Headland	Cape Talbot	Low Intertidal	-13.82	7.47	0.45	0.00
361	Fringing	Headland	Cape Londonderry	Low Intertidal	-13.76	50.33	32.61	0.00
362	Fringing	Headland	Cape Londonderry	Low Intertidal	-13.80	6.13	0.52	0.00
363	Fringing	Headland	Cape Londonderry	Low Intertidal	-13.75	36.38	18.10	0.00
364	Fringing	Headland	Cape Londonderry	Low Intertidal	-13.72	50.72	28.74	0.00
365	Fringing	Headland	Stewart Island	Low Intertidal	-13.69	3.46	0.51	5.67
366	Fringing	Bayhead	Deep Bay	Low Intertidal	-14.11	9.76	1.58	0.00
367	Fringing	Bayhead	West Bay	Low Intertidal	-14.09	6.15	1.68	0.00

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
368	Fringing	Circum-Island	Napier Broome Bay	Low Intertidal	-14.02	3.64	0.51	5.10
369	Fringing	Circum-Island	Napier Broome Bay	Low Intertidal	-14.01	2.77	0.27	3.33
370	Fringing	Headland	Napier Broome Bay	Low Intertidal	-13.99	1.38	0.13	3.19
371	Planar	Sand Lagoon	Beagle Reef	Low Intertidal	-15.32	16.79	18.62	88.23
372	Patch	unclassified	Mavis Reef	Low Intertidal	-15.48	3.23	0.77	72.76
373	Patch	unclassified	Mavis Reef	Low Intertidal	-15.47	2.80	0.55	74.66
374	Shoal	unclassified	Fox Shoal	Subtidal	-15.37	4.31	1.17	79.16
375	Patch	unclassified	Dingo Reef	Low Intertidal	-15.32	2.47	0.45	89.51
376	Shoal	unclassified	Adele Shoal	Subtidal	-15.70	7.90	1.33	61.09
377	Shoal	unclassified	Barcoo Shoal	Subtidal	-15.65	11.85	7.57	77.48
378	Shoal	unclassified	Lorinna Shoal	Subtidal	-14.41	3.44	0.89	22.49
379	Shoal	unclassified	Branch Banks	Subtidal	-13.63	18.02	18.75	28.84
380	Shoal	unclassified	Otway Bank	Subtidal	-13.67	20.76	14.15	23.77
381	Shoal	unclassified	Koojarra Shoal	Subtidal	-13.78	4.67	1.28	16.57
382	Shoal	unclassified	Tancred Bank	Subtidal	-14.09	8.21	2.28	7.85
383	Shoal	unclassified	Alarm Shoal	Subtidal	-16.32	35.38	15.62	2.26
384	Shoal	unclassified	Pit Shoal	Subtidal	-16.27	26.06	13.51	11.71
385	Shoal	unclassified	Ferret Reef	Subtidal	-16.26	2.98	0.60	10.02
386	Shoal	unclassified	Anchor Shoal	Subtidal	-16.34	22.31	13.38	6.73
387	Shoal	unclassified	Otway Shoal	Subtidal	-16.34	9.32	1.82	16.50
388	Fringing	Bayhead	Anjo Peninsula	Low Intertidal	-13.98	15.78	1.50	0.00
389	Fringing	Bayhead	Anjo Peninsula	Low Intertidal	-13.95	1.10	0.08	0.06
390	Fringing	Headland	Institut Islands	Low Intertidal	-14.20	1.81	0.17	14.72

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
391	Fringing	Headland	Jussieu Island	Low Intertidal	-14.71	2.62	0.18	17.68
392	Fringing	Headland	Jussieu Island	Low Intertidal	-14.71	2.53	0.09	17.73
393	Fringing	Inter-Island	Turtle Reef	High Intertidal	-16.26	56.38	25.24	0.00
394	Planar	Coralgal	Eclipse Archipelago	Low Intertidal	-13.80	14.94	6.35	19.11
395	Planar	Coralgal	Eclipse Archipelago	Low Intertidal	-13.81	14.59	7.02	20.52
396	Fringing	Bayhead	Governor Islands	Low Intertidal	-13.95	3.02	0.13	2.08
397	Fringing	Headland	Governor Islands	Low Intertidal	-13.94	3.61	0.27	3.64
398	Fringing	Headland	Deep Bay	Low Intertidal	-14.14	14.66	1.36	0.00
399	Fringing	Headland	Anjo Peninsula	Low Intertidal	-13.99	39.36	9.57	0.00
400	Fringing	Headland	Eclipse Archipelago	Low Intertidal	-13.95	10.73	6.96	2.44
401	Fringing	Headland	Vansittart Bay	Low Intertidal	-14.06	66.92	19.10	0.00
402	Fringing	Headland	Cape Voltaire	Low Intertidal	-14.29	36.21	7.63	0.00
403	Fringing	Headland	Cape Voltaire	Low Intertidal	-14.28	2.16	0.13	0.68
404	Patch	unclassified	Cape Voltaire	Low Intertidal	-14.28	0.87	0.05	0.69
405	Fringing	Headland	Cape Voltaire	Low Intertidal	-14.25	18.51	1.74	0.00
406	Fringing	Headland	Cape Voltaire	Low Intertidal	-14.25	30.89	3.22	0.00
407	Fringing	Headland	Cape Voltaire	Low Intertidal	-14.28	10.27	0.82	0.00
408	Fringing	Headland	Montague Sound	Low Intertidal	-14.33	12.34	0.98	0.00
409	Fringing	Headland	Scott Strait	Low Intertidal	-14.56	24.39	1.86	0.00
410	Fringing	Headland	Scott Strait	Low Intertidal	-14.57	3.91	0.20	0.25
411	Fringing	Headland	Scott Strait	Low Intertidal	-14.57	4.12	0.20	0.00
412	Patch	unclassified	Scott Strait	Low Intertidal	-14.62	0.59	0.02	2.80
413	Fringing	Headland	Scott Strait	Low Intertidal	-14.64	19.33	1.77	0.58

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
414	Fringing	Headland	Scott Strait	Low Intertidal	-14.68	6.30	0.51	1.59
415	Fringing	Headland	Scott Strait	Low Intertidal	-14.68	4.86	0.29	0.60
416	Fringing	Headland	York Sound	Low Intertidal	-14.78	3.55	0.21	0.44
417	Fringing	Headland	York Sound	Low Intertidal	-14.87	3.51	0.16	0.35
418	Fringing	Headland	York Sound	Low Intertidal	-14.88	2.23	0.08	1.13
419	Patch	unclassified	Montague Sound	Low Intertidal	-14.42	1.29	0.10	9.99
420	Fringing	Inter-Island	Bigge Island	Low Intertidal	-14.46	7.61	0.82	13.65
421	Fringing	Inter-Island	Bigge Island	Low Intertidal	-14.46	13.90	1.81	13.90
422	Fringing	Headland	Bigge Island	Low Intertidal	-14.45	24.66	2.56	16.05
423	Fringing	Headland	Bigge Island	Low Intertidal	-14.46	6.09	0.53	18.33
424	Fringing	Headland	Bigge Island	Low Intertidal	-14.48	20.32	2.02	17.58
425	Fringing	Headland	Bigge Island	Low Intertidal	-14.62	62.78	11.26	7.75
426	Fringing	Inter-Island	Cape Pond	Low Intertidal	-14.67	20.82	3.70	4.94
427	Fringing	Headland	Bigge Island	Low Intertidal	-14.64	12.80	1.85	4.70
428	Fringing	Headland	York Sound	Low Intertidal	-14.78	23.36	3.59	12.01
429	Fringing	Headland	York Sound	Low Intertidal	-15.09	7.07	0.40	2.38
430	Fringing	Headland	York Sound	Low Intertidal	-15.08	1.23	0.08	4.66
431	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.14	31.99	2.11	0.00
432	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.20	5.77	0.79	0.00
433	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.23	9.40	0.95	0.00
434	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.23	6.05	0.60	3.40
435	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.21	8.24	0.78	2.68
436	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.21	12.29	0.96	4.26

REEF ID	**REEF TYPE**	**REEF SUBCLASS**	**REEF NAME**	**REEF FLAT ELEVATION**	**LATITUDE (°S)**	**PERIMETER (km)**	**AREA (km^2)**	**DIST FROM MAINLAND (km)**
437	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.24	0.59	0.02	2.00
438	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.24	0.28	0.00	2.39
439	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.23	1.61	0.12	2.59
440	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.24	29.06	3.05	1.68
441	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.22	2.32	0.16	4.40
442	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.22	0.80	0.02	3.96
443	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.21	0.54	0.02	4.37
444	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.19	1.58	0.04	6.36
445	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.19	0.25	0.00	6.87
446	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.18	1.96	0.22	8.20
447	Fringing	Inter-Island	Brunswick Bay	Low Intertidal	-15.17	16.84	2.33	9.17
448	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.16	1.72	0.20	11.18
449	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.18	4.17	0.64	11.00
450	Patch	unclassified	Jungulu Island	Low Intertidal	-15.27	0.58	0.02	24.95
451	Patch	unclassified	Jungulu Island	Low Intertidal	-15.27	0.64	0.02	24.81
452	Patch	unclassified	Jungulu Island	Low Intertidal	-15.28	0.42	0.01	23.54
453	Patch	unclassified	Jungulu Island	Low Intertidal	-15.26	0.79	0.03	27.37
454	Fringing	Headland	Miawaja Island	Low Intertidal	-15.24	1.61	0.10	29.02
455	Fringing	Headland	Etisus Island	Low Intertidal	-15.24	6.39	0.37	26.17
456	Fringing	Inter-Island	Miawaja Island	Low Intertidal	-15.23	30.89	2.83	27.20
457	Fringing	Headland	Pyrene Island	Low Intertidal	-15.25	9.50	0.48	25.39
458	Fringing	Headland	Jungulu Island	Low Intertidal	-15.28	56.26	5.05	19.71
459	Fringing	Inter-Island	Okenia Island	Low Intertidal	-15.25	26.99	15.42	19.09

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
460	Fringing	Headland	Okenia Island	Low Intertidal	-15.23	2.87	0.16	22.66
461	Patch	unclassified	Jungulu Island	Low Intertidal	-15.29	2.87	0.41	19.60
462	Patch	unclassified	Jungulu Island	Low Intertidal	-15.29	0.94	0.04	20.71
463	Patch	unclassified	Jungulu Island	Low Intertidal	-15.29	0.62	0.02	20.22
464	Patch	unclassified	Jungulu Island	Low Intertidal	-15.28	0.23	0.00	21.10
465	Patch	unclassified	Jungulu Island	Low Intertidal	-15.29	0.15	0.00	21.03
466	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.78	0.04	18.27
467	Patch	unclassified	Augustus Island	Low Intertidal	-15.30	0.50	0.01	18.44
468	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.38	0.01	18.02
469	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.13	0.00	17.94
470	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.74	0.03	17.11
471	Patch	unclassified	Augustus Island	Low Intertidal	-15.30	0.48	0.01	18.20
472	Patch	unclassified	Augustus Island	Low Intertidal	-15.30	0.49	0.01	18.17
473	Patch	unclassified	Augustus Island	Low Intertidal	-15.30	0.12	0.00	18.21
474	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.26	0.00	18.15
475	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.60	0.02	17.78
476	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.15	0.00	17.66
477	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.37	0.01	17.30
478	Patch	unclassified	Augustus Island	Low Intertidal	-15.32	0.51	0.02	16.54
479	Fringing	Headland	Augustus Island	Low Intertidal	-15.32	14.76	1.31	16.25
480	Fringing	Headland	Jungulu Island	Low Intertidal	-15.32	5.63	0.45	16.77
481	Fringing	Headland	Augustus Island	Low Intertidal	-15.28	3.55	0.17	17.39
482	Fringing	Headland	Lucas Island	Low Intertidal	-15.21	18.30	1.79	17.59

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
483	Fringing	Headland	Olaseron Island	Low Intertidal	-15.23	13.44	1.25	13.90
484	Fringing	Headland	Olaseron Island	Low Intertidal	-15.24	19.97	2.29	15.44
485	Fringing	Headland	Jungulu Island	Low Intertidal	-15.27	6.47	0.50	26.61
486	Fringing	Inter-Island	Champangy Island	Low Intertidal	-15.29	8.92	1.61	27.58
487	Fringing	Inter-Island	Champangy Island	Low Intertidal	-15.32	82.98	16.29	27.09
488	Fringing	Circum-Island	Heywood Island	Low Intertidal	-15.34	46.71	6.21	19.86
489	Fringing	Headland	Heywood Island	Low Intertidal	-15.33	10.35	0.70	22.92
490	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.12	5.48	0.29	22.33
491	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.13	2.49	0.09	22.68
492	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.16	2.52	0.19	16.46
493	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.02	17.14	1.65	6.65
494	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.02	1.13	0.05	9.34
495	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.02	2.91	0.27	11.15
496	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.01	5.72	0.47	12.10
497	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.02	10.69	0.84	10.72
498	Fringing	Inter-Island	D'Arcole Islands	Low Intertidal	-15.02	17.97	1.83	14.27
499	Fringing	Headland	D'Arcole Islands	Low Intertidal	-15.03	9.27	1.21	15.09
500	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.02	1.88	0.08	26.45
501	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.03	4.71	0.46	25.62
502	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.02	2.69	0.12	26.86
503	Fringing	Headland	Entrance Island	Low Intertidal	-15.28	15.93	1.11	3.65
504	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.30	67.31	9.90	0.00
505	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.28	2.95	0.26	1.41

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
506	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.29	2.90	0.20	1.35
507	Patch	unclassified	Brunswick Bay	Low Intertidal	-15.30	1.98	0.25	0.83
508	Planar	Coralgal	Wildcat Reefs	Low Intertidal	-15.28	11.77	5.18	38.23
509	Patch	unclassified	Rainbow Shoals	Low Intertidal	-15.26	1.32	0.05	35.03
510	Patch	unclassified	Rainbow Shoals	Low Intertidal	-15.25	1.32	0.12	35.06
511	Patch	unclassified	Rainbow Shoals	Low Intertidal	-15.23	0.47	0.01	36.75
512	Patch	unclassified	Rainbow Shoals	Low Intertidal	-15.23	0.35	0.01	36.42
513	Planar	Coralgal	Wildcat Reefs	Low Intertidal	-15.28	11.52	4.33	42.20
514	Patch	unclassified	Wildcat Reefs	Low Intertidal	-15.29	0.56	0.02	43.89
515	Patch	unclassified	Wildcat Reefs	Low Intertidal	-15.30	0.62	0.03	44.00
516	Patch	unclassified	Entrance Island	Low Intertidal	-15.28	3.31	0.36	6.85
517	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.90	0.05	8.38
518	Patch	unclassified	Augustus Island	Low Intertidal	-15.30	0.60	0.02	7.64
519	Patch	unclassified	Augustus Island	Low Intertidal	-15.31	0.95	0.06	7.52
520	Patch	unclassified	Augustus Island	Low Intertidal	-15.34	0.88	0.05	5.95
521	Patch	unclassified	Olaseron Island	Low Intertidal	-15.22	0.56	0.02	14.49
522	Patch	unclassified	Collier Bay	Low Intertidal	-15.89	2.54	0.26	1.59
523	Patch	unclassified	Collier Bay	Low Intertidal	-15.90	2.28	0.21	2.32
524	Patch	unclassified	Collier Bay	Low Intertidal	-15.92	1.86	0.11	4.02
525	Patch	unclassified	Collier Bay	Low Intertidal	-15.93	1.62	0.10	5.16
526	Fringing	Circum-Island	Collier Bay	Low Intertidal	-16.31	3.19	0.28	1.72
527	Fringing	Headland	Collier Bay	Low Intertidal	-16.01	16.61	1.34	24.01
528	Patch	unclassified	Collier Bay	Low Intertidal	-16.00	3.07	0.38	28.63

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
529	Patch	unclassified	Collier Bay	Low Intertidal	-16.00	3.88	0.48	28.47
530	Patch	unclassified	Collier Bay	Low Intertidal	-16.01	0.63	0.02	28.55
531	Patch	unclassified	Collier Bay	Low Intertidal	-16.02	1.04	0.03	28.06
532	Patch	unclassified	Collier Bay	Low Intertidal	-15.90	0.76	0.04	8.62
533	Patch	unclassified	Collier Bay	Low Intertidal	-15.90	0.80	0.05	8.79
534	Patch	unclassified	Collier Bay	Low Intertidal	-15.90	0.17	0.00	8.89
535	Patch	unclassified	Collier Bay	Low Intertidal	-15.90	0.11	0.00	9.08
536	Patch	unclassified	Collier Bay	Low Intertidal	-15.90	0.08	0.00	9.14
537	Fringing	Bayhead	E Tallon Island	High Intertidal	-16.41	9.57	2.79	5.42
538	Fringing	Inter-Island	E Sunday Island	Low Intertidal	-16.42	29.07	3.45	12.22
539	Fringing	Inter-Island	SW Sunday Island	High Intertidal	-16.43	9.29	2.15	7.86
540	Fringing	Inter-Island	W Sunday Island	High Intertidal	-16.41	25.16	4.93	7.81
541	Fringing	Inter-Island	Salural Island	Low Intertidal	-16.39	11.06	1.23	7.24
542	Fringing	Inter-Island	Poolngin Island	Low Intertidal	-16.39	10.31	0.82	8.64
543	Fringing	Circum-Island	Rees Island	Low Intertidal	-16.38	3.87	0.73	6.39
544	Fringing	Inter-Island	Waterlow Island	Low Intertidal	-16.42	17.86	7.02	0.62
545	Fringing	Inter-Island	Jackson Island	Low Intertidal	-16.43	33.52	5.66	1.64
546	Fringing	Inter-Island	One Arm Point	Low Intertidal	-16.45	5.41	0.30	0.74
547	Fringing	Inter-Island	Apex Island	Low Intertidal	-16.39	8.89	1.02	1.58
548	Patch	unclassified	Apex Island	Low Intertidal	-16.40	0.77	0.04	3.07
549	Patch	unclassified	Apex Island	Low Intertidal	-16.40	1.04	0.07	2.55
550	Fringing	Headland	Apex Island	Low Intertidal	-16.39	2.00	0.08	3.26
551	Fringing	Headland	Sr Graham Moore Is.	Low Intertidal	-13.88	37.48	12.45	4.51

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
552	Patch	unclassified	Eclipse Archipelago	Low Intertidal	-13.78	1.31	0.08	23.01
553	Patch	unclassified	Eclipse Archipelago	Low Intertidal	-13.78	0.77	0.04	22.62
554	Patch	unclassified	Eclipse Archipelago	Low Intertidal	-13.79	4.32	0.47	22.64
555	Fringing	Headland	D'Arcole Islands	Low Intertidal	-14.86	27.84	6.11	31.31
556	Patch	unclassified	D'Arcole Islands	Low Intertidal	-14.92	2.85	0.37	31.50
557	Patch	unclassified	D'Arcole Islands	Low Intertidal	-14.95	2.51	0.23	29.49
558	Patch	unclassified	D'Arcole Islands	Low Intertidal	-14.93	0.89	0.05	26.19
559	Patch	unclassified	D'Arcole Islands	Low Intertidal	-14.88	0.51	0.02	31.06
560	Patch	unclassified	D'Arcole Islands	Low Intertidal	-14.97	1.34	0.09	27.70
561	Patch	unclassified	D'Arcole Islands	Low Intertidal	-14.96	1.24	0.08	29.06
562	Fringing	Headland	White Island	Low Intertidal	-15.06	7.42	2.18	42.67
563	Fringing	Inter-Island	Collier Bay	Low Intertidal	-16.07	30.91	12.36	17.48
564	Fringing	Inter-Island	Collier Bay	Low Intertidal	-16.15	28.48	3.28	10.55
565	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.20	44.89	9.38	0.94
566	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.20	19.95	1.59	1.34
567	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.19	1.11	0.05	3.20
568	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.19	0.75	0.04	2.94
569	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.25	60.70	8.26	0.59
570	Fringing	Circum-Island	Talbot Bay	Low Intertidal	-16.28	9.00	0.71	3.58
571	Fringing	Circum-Island	Talbot Bay	Low Intertidal	-16.29	4.20	0.29	2.85
572	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.31	3.54	0.19	0.85
573	Fringing	Headland	Talbot Bay	Low Intertidal	-16.28	1.90	0.06	3.95
574	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.31	2.87	0.22	1.01

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
575	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.32	4.52	0.27	0.63
576	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.33	3.95	0.15	0.72
577	Fringing	Headland	Talbot Bay	Low Intertidal	-16.34	1.13	0.04	0.54
578	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.34	4.80	0.29	0.16
579	Patch	unclassified	Talbot Bay	Low Intertidal	-16.34	0.52	0.02	0.62
580	Fringing	Circum-Island	Talbot Bay	Low Intertidal	-16.32	1.78	0.06	0.77
581	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.33	3.27	0.14	0.70
582	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.35	3.97	0.12	0.27
583	Fringing	Headland	Talbot Bay	Low Intertidal	-16.31	0.61	0.01	0.97
584	Fringing	Inter-Island	Iron Islands	Low Intertidal	-16.18	14.46	2.04	0.39
585	Fringing	Bayhead	Iron Islands	Low Intertidal	-16.19	2.61	0.15	0.65
586	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.18	22.54	1.77	0.00
587	Fringing	Bayhead	Yampi Sound	Low Intertidal	-16.16	3.45	0.13	0.17
588	Fringing	Headland	Koolan Island	Low Intertidal	-16.13	50.92	2.99	0.38
589	Fringing	Circum-Island	Cockatoo Island	Low Intertidal	-16.09	32.66	2.75	5.66
590	Fringing	Bayhead	Usborne Island	Low Intertidal	-16.11	4.25	0.17	5.22
591	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	1.52	0.07	4.01
592	Patch	unclassified	Buccaneer Archipelago	Low Intertidal	-16.12	0.70	0.03	3.79
593	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	2.34	0.10	3.75
594	Fringing	Inter-Island	Bathurst & Irvine Islands	High Intertidal	-16.05	93.46	16.07	8.02
595	Fringing	Headland	Tanner Island	Low Intertidal	-16.09	1.44	0.03	9.03
596	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.05	3.48	0.37	12.22
597	Fringing	Circum-Island	Gibbing Island	Low Intertidal	-16.15	26.76	3.41	2.88

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
598	Fringing	Headland	Nares Point	Low Intertidal	-16.15	33.00	2.91	0.00
599	Fringing	Headland	Yampi Sound	Low Intertidal	-16.16	25.77	2.86	0.00
600	Fringing	Headland	Yampi Sound	Low Intertidal	-16.16	8.56	0.48	0.00
601	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.15	7.95	0.29	0.00
602	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.16	23.32	2.51	0.00
603	Fringing	Headland	Woodhouse Point	Low Intertidal	-16.16	52.28	4.01	0.00
604	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.20	4.74	0.26	0.13
605	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.19	46.11	2.98	0.00
606	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.22	10.96	0.46	0.00
607	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.23	28.89	1.63	0.00
608	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.21	4.23	0.22	0.86
609	Fringing	Headland	Arbidej Island	Low Intertidal	-16.20	21.49	1.89	1.70
610	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.20	8.99	0.48	2.47
611	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.17	2.09	0.12	0.75
612	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.23	11.56	0.34	1.87
613	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.25	4.35	0.17	1.32
614	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.25	1.12	0.08	1.36
615	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.26	28.50	1.76	0.11
616	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.26	2.07	0.04	0.16
617	Fringing	Headland	Chambers Island	Low Intertidal	-16.27	47.62	3.21	0.06
618	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.26	1.65	0.05	0.09
619	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.26	1.10	0.02	0.17
620	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.28	17.58	0.89	0.00

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621	Fringing	Inter-Island	Hidden Island	Low Intertidal	-16.23	60.90	5.66	4.05
622	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.28	36.59	4.10	9.66
623	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.28	10.25	1.52	14.58
624	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.31	12.38	0.97	10.49
625	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.29	4.76	0.42	6.85
626	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.30	1.12	0.05	6.55
627	Fringing	Headland	Aveling Island	Low Intertidal	-16.34	26.07	3.42	0.25
628	Patch	unclassified	Buccaneer Archipelago	Low Intertidal	-16.35	0.66	0.03	0.40
629	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.22	18.89	1.18	4.52
630	Patch	unclassified	Buccaneer Archipelago	Low Intertidal	-16.21	1.74	0.12	6.21
631	Patch	unclassified	Buccaneer Archipelago	Low Intertidal	-16.22	0.62	0.02	6.18
632	Fringing	Inter-Island	Powerful Island	Low Intertidal	-16.07	81.28	13.53	13.96
633	Fringing	Inter-Island	Bowles Rock	Low Intertidal	-16.05	4.32	0.60	19.14
634	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.08	3.99	0.18	15.54
635	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.12	5.03	0.45	12.68
636	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.13	4.10	0.25	13.12
637	Fringing	Inter-Island	Finch Island	Low Intertidal	-16.15	38.10	5.13	10.05
638	Fringing	Inter-Island	Gagg Island	Low Intertidal	-16.17	13.77	1.23	13.33
639	Fringing	Inter-Island	Gagg Island	Low Intertidal	-16.19	8.72	1.25	10.51
640	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.19	2.49	0.15	8.18
641	Fringing	Inter-Island	Sir Frederick Island	Low Intertidal	-16.12	29.39	2.81	15.09
642	Fringing	Inter-Island	Bedford Island	Low Intertidal	-16.14	53.06	4.74	21.89
643	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.04	11.16	0.94	24.40

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644	Fringing	Inter-Island	Tide rip Islands	Low Intertidal	-16.31	27.86	2.79	20.23
645	Fringing	Headland	High Island	Low Intertidal	-16.35	24.26	1.71	15.29
646	Fringing	Inter-Island	Folly Island	Low Intertidal	-16.38	10.25	0.48	5.84
647	Fringing	Inter-Island	Sir richard Island	Low Intertidal	-16.41	16.21	1.16	0.07
648	Fringing	Circum-Island	Mermaid Island	Low Intertidal	-16.44	25.68	2.32	9.53
649	Fringing	Headland	Wyborn Islets	Low Intertidal	-16.46	2.41	0.08	10.02
650	Fringing	Inter-Island	McMahon Islet	Low Intertidal	-16.50	5.12	0.25	6.11
651	Fringing	Inter-Island	Pasco Island	Low Intertidal	-16.51	22.72	2.08	2.77
652	Fringing	Circum-Island	Long Island	Low Intertidal	-16.57	52.34	5.02	7.57
653	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.60	9.70	0.44	9.23
654	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.66	4.76	0.11	1.26
655	Fringing	Headland	Tournefort Island	Low Intertidal	-14.80	0.07	0.00	12.77
656	Fringing	Headland	York Sound	Low Intertidal	-14.80	0.07	0.00	12.77
657	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.30	1.19	0.05	0.00
658	Fringing	Headland	Brunswick Bay	Low Intertidal	-15.30	1.19	0.05	0.00
659	Fringing	Headland	Bigge Island	Low Intertidal	-14.65	2.29	0.12	4.79
660	Fringing	Headland	Bigge Island	Low Intertidal	-14.65	2.29	0.12	4.79
661	Fringing	Headland	Bigge Island	Low Intertidal	-14.65	1.84	0.12	5.48
662	Fringing	Headland	Bigge Island	Low Intertidal	-14.65	1.84	0.12	5.48
663	Fringing	Headland	Jungulu Island	Low Intertidal	-15.31	0.41	0.00	22.71
664	Fringing	Headland	Jungulu Island	Low Intertidal	-15.31	0.41	0.00	22.71
665	Fringing	Headland	One Arm Point	Low Intertidal	-16.43	0.62	0.00	7.97
666	Patch	unclassified	Osborn Reef	Low Intertidal	-15.17	5.22	1.65	44.61

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
667	Fringing	Headland	Red Island	Low Intertidal	-15.22	1.76	0.23	36.84
668	Fringing	Headland	Talbot Bay	Low Intertidal	-16.32	2.09	0.20	0.00
669	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.31	7.22	1.47	0.00
670	Patch	unclassified	Talbot Bay	Low Intertidal	-16.30	1.42	0.08	2.21
671	Patch	unclassified	Talbot Bay	Low Intertidal	-16.29	1.47	0.09	2.49
672	Patch	unclassified	Talbot Bay	Low Intertidal	-16.29	0.65	0.03	2.86
673	Patch	unclassified	Talbot Bay	Low Intertidal	-16.29	0.26	0.00	2.68
674	Fringing	Bayhead	West Bay	Low Intertidal	-14.10	9.28	1.61	0.05
675	Fringing	Headland	Guy Point	Low Intertidal	-14.09	6.50	0.36	0.03
676	Fringing	Bayhead	Galley Point	Low Intertidal	-13.99	9.35	1.15	0.00
677	Fringing	Bayhead	Vansittart Bay	Low Intertidal	-14.15	2.59	0.19	0.02
678	Fringing	Bayhead	Vansittart Bay	Low Intertidal	-14.15	3.70	0.18	0.11
679	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-14.06	7.14	0.59	0.00
680	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-14.07	9.55	0.45	0.00
681	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-13.99	13.94	1.00	0.00
682	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-14.01	18.13	1.81	0.00
683	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-13.99	11.89	1.10	0.00
684	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.99	16.99	1.41	0.00
685	Fringing	Bayhead	Cape Bougainville	Low Intertidal	-13.91	8.86	1.31	0.00
686	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.90	6.91	1.11	0.00
687	Fringing	Headland	Cape Bougainville	Low Intertidal	-13.91	2.08	0.11	0.00
688	Fringing	Headland	Middle Osborne Island	Low Intertidal	-14.30	14.17	3.18	3.45
689	Fringing	Bayhead	One Arm Point	Low Intertidal	-16.42	31.20	10.12	0.00

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
690	Fringing	Inter-Island	W Tallon Island	Low Intertidal	-16.41	7.34	1.97	4.94
691	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.36	8.42	2.69	12.83
692	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.37	4.26	0.69	16.70
693	Fringing	Headland	Collier Bay	Low Intertidal	-16.40	4.39	0.48	1.78
694	Fringing	Headland	Collier Bay	Low Intertidal	-16.39	1.69	0.17	2.04
695	Fringing	Headland	Collier Bay	Low Intertidal	-16.38	20.10	12.23	0.67
696	Fringing	Headland	Collier Bay	Low Intertidal	-16.34	3.26	0.36	2.99
697	Fringing	Headland	Collier Bay	Low Intertidal	-16.34	0.88	0.05	2.56
698	Fringing	Headland	Collier Bay	Low Intertidal	-16.33	2.21	0.24	0.61
699	Fringing	Headland	Collier Bay	Low Intertidal	-16.34	0.84	0.04	0.80
700	Fringing	Headland	Collier Bay	Low Intertidal	-16.33	1.06	0.07	0.57
701	Fringing	Headland	Collier Bay	Low Intertidal	-16.29	1.33	0.11	6.02
702	Fringing	Circum-Island	Collier Bay	Low Intertidal	-16.29	2.28	0.34	5.63
703	Fringing	Circum-Island	Collier Bay	Low Intertidal	-16.28	3.55	0.54	4.80
704	Fringing	Circum-Island	Collier Bay	Low Intertidal	-16.27	3.05	0.63	4.55
705	Fringing	Headland	Collier Bay	Low Intertidal	-16.27	0.72	0.03	4.66
706	Fringing	Circum-Island	Collier Bay	Low Intertidal	-16.30	3.14	0.47	1.80
707	Fringing	Circum-Island	Collier Bay	Low Intertidal	-16.31	2.68	0.44	1.72
708	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.42	1.26	0.07	1.04
709	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.42	1.86	0.16	0.09
710	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.41	12.04	2.75	0.97
711	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.42	0.40	0.01	0.62
712	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.42	0.37	0.01	0.83

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
713	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	1.10	0.07	1.59
714	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.37	9.69	2.56	1.95
715	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	2.99	0.20	3.67
716	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	3.79	0.37	4.09
717	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.34	1.52	0.09	3.08
718	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.33	5.63	0.42	2.48
719	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.35	0.98	0.06	4.60
720	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.33	1.64	0.11	3.52
721	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.37	2.29	0.18	2.19
722	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.37	0.58	0.02	2.06
723	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.37	0.51	0.02	2.67
724	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.37	6.13	0.50	0.62
725	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.38	1.33	0.05	0.59
726	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.38	0.53	0.01	0.12
727	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.38	0.35	0.01	1.05
728	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.40	0.72	0.03	0.48
729	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.40	0.26	0.00	0.59
730	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.39	0.35	0.01	0.56
731	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.40	0.68	0.03	1.53
732	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.39	1.36	0.12	2.12
733	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.39	1.73	0.14	3.60
734	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.32	0.80	0.04	12.53
735	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.33	1.52	0.10	10.50

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
736	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.34	9.10	1.88	9.21
737	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.35	3.34	0.27	10.17
738	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	1.10	0.07	8.93
739	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	1.21	0.06	10.28
740	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	4.90	0.85	7.46
741	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.38	1.40	0.13	9.60
742	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.37	6.09	1.07	10.63
743	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.37	2.20	0.22	13.21
744	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.40	5.03	0.65	15.03
745	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.39	1.23	0.08	16.89
746	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.39	2.41	0.26	17.60
747	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.39	1.06	0.07	18.35
748	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.45	2.14	0.30	5.79
749	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.46	2.42	0.17	4.16
750	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.46	3.42	0.47	2.25
751	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.47	2.85	0.37	1.60
752	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.53	1.30	0.09	2.63
753	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.51	1.21	0.06	1.56
754	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.53	8.12	2.22	0.50
755	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.52	12.90	5.41	0.00
756	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.50	2.88	0.46	0.35
757	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	1.57	0.06	0.06
758	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.49	6.44	1.73	0.38

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
759	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.48	0.86	0.04	0.89
760	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.49	1.62	0.12	0.42
761	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	1.17	0.04	0.55
762	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	0.68	0.03	0.53
763	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	0.50	0.02	0.24
764	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	0.86	0.05	0.22
765	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.49	0.47	0.01	0.48
766	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.49	0.76	0.04	0.21
767	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.36	4.09	0.85	0.69
768	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.35	5.58	1.40	0.06
769	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.35	5.74	1.19	0.79
770	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.35	0.36	0.00	0.84
771	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.35	0.41	0.01	0.88
772	Fringing	Circum-Island	Talbot Bay	Low Intertidal	-16.34	9.45	2.02	1.49
773	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.35	0.72	0.04	0.74
774	Fringing	Bayhead	Talbot Bay	Low Intertidal	-16.35	0.29	0.01	1.10
775	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.48	0.30	0.01	1.62
776	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.48	0.31	0.01	1.67
777	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.47	0.28	0.01	1.55
778	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.47	0.42	0.01	1.49
779	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.51	1.70	0.11	0.17
780	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.45	3.00	0.20	0.81
781	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.45	0.46	0.01	1.32

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
782	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.45	0.81	0.03	1.40
783	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.44	0.46	0.01	1.46
784	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	0.65	0.03	2.56
785	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.49	0.75	0.02	2.75
786	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	0.46	0.01	3.14
787	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.50	4.40	0.51	3.39
788	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.50	0.70	0.03	5.50
789	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.49	0.65	0.02	5.91
790	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.49	4.03	0.34	6.37
791	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.48	0.92	0.05	8.52
792	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.26	1.68	0.16	8.54
793	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.26	0.52	0.01	8.83
794	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.28	1.77	0.10	8.87
795	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.29	1.33	0.06	10.73
796	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.29	0.44	0.01	10.51
797	Fringing	Headland	One Arm Point	Low Intertidal	-16.35	2.73	0.40	0.45
798	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.58	4.41	1.03	13.10
799	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.31	4.93	0.26	23.98
800	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.30	2.82	0.14	24.36
801	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.04	13.35	4.21	30.32
802	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.18	2.25	0.29	22.74
803	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.17	0.77	0.03	21.91
804	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.16	1.00	0.04	25.01

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
805	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.16	1.13	0.08	25.71
806	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.17	0.58	0.02	24.97
807	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	1.35	0.11	28.40
808	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.16	1.02	0.05	21.29
809	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.16	0.73	0.02	20.01
810	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.15	0.28	0.00	19.18
811	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.16	0.62	0.02	14.56
812	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.17	0.96	0.04	16.47
813	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.18	0.67	0.03	11.84
814	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.17	0.95	0.05	9.79
815	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.15	0.37	0.01	9.79
816	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.15	0.55	0.02	9.62
817	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.14	1.11	0.07	9.49
818	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.13	1.46	0.09	10.39
819	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.13	1.03	0.05	11.15
820	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	0.63	0.03	19.56
821	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	0.32	0.01	20.21
822	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	0.55	0.02	20.44
823	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.12	0.58	0.02	20.75
824	Fringing	Headland	Talbot Bay	Low Intertidal	-16.13	5.49	0.55	7.79
825	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.15	3.92	0.52	4.46
826	Fringing	Inter-Island	Talbot Bay	Low Intertidal	-16.14	3.19	0.30	5.21
827	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.03	0.42	0.01	28.10

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
828	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.20	0.43	0.01	7.91
829	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.20	0.42	0.01	12.30
830	Fringing	Headland	E Sunday Island	Low Intertidal	-16.43	0.53	0.02	14.36
831	Fringing	Headland	E Sunday Island	Low Intertidal	-16.43	0.38	0.01	14.49
832	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.40	0.70	0.03	16.49
833	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.61	1.81	0.10	1.63
834	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.60	5.47	1.46	1.64
835	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.61	0.62	0.01	1.81
836	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.63	3.33	0.47	0.50
837	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.63	1.15	0.05	0.92
838	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.63	1.45	0.10	0.94
839	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.62	0.80	0.03	1.95
840	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.62	0.39	0.01	2.30
841	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.62	0.28	0.01	1.56
842	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.61	0.71	0.03	2.09
843	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.61	1.48	0.11	2.26
844	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.62	0.31	0.00	1.37
845	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.62	1.22	0.10	0.72
846	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.62	1.22	0.07	0.37
847	Fringing	Circum-Island	Buccaneer Archipelago	Low Intertidal	-16.62	23.00	13.63	0.17
848	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.56	0.95	0.03	0.70
849	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.57	0.21	0.00	1.76
850	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.58	1.19	0.07	0.40

REEF ID	REEF TYPE	REEF SUBCLASS	REEF NAME	REEF FLAT ELEVATION	LATITUDE (°S)	PERIMETER (km)	AREA (km^2)	DIST FROM MAINLAND (km)
851	Fringing	Headland	Buccaneer Archipelago	Low Intertidal	-16.58	3.15	0.33	0.24
852	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.59	9.83	4.16	0.33
853	Fringing	Inter-Island	Buccaneer Archipelago	Low Intertidal	-16.60	3.73	0.81	0.16

APPENDIX D: RESPONSE TO REVEIWERS

Ms. Ref. No.: RSMA-D-16-00063
Title: Mapping and Geomorphic Classification of Reefs in the North Western Australian Shelf.
Regional Studies in Marine Science

Dear Dr. Jason Michael Hall-Spencer,

Thank you for your email and for reviewers' constructive comments concerning our manuscript entitled "Mapping and Geomorphic Classification of Reefs in the North Western Australian Shelf". Based on these comments, we have revised the manuscript carefully and made all the requested correction and changes which we hope meet with approval. Revised portions are marked in the Tracked Changes version (TC_manuscript). The responds to the reviewer's comments are in shown blue as flowing:

Reviewer 1:

Title: Suggest changing to Geomorphic Classification of Coral Reefs in the North Western Australian Shelf.
Done

Intro:
L4. Distribution of coral reefs is constrained to the photic zone (~50 m)… which is not "very deep water". Reword
Changed

L47 Other relevant references worth considering include:

Roelfsema, C., Phinn, S., Jupiter, S., Comley, J., Albert, S., 2013. Mapping coral reefs at reef to reef-system scales, 10s-1000s km2, using object-based image analysis. International Journal of Remote Sensing, 1-22.

Leon, J.X., Woodroffe, C.D., 2013. Morphological characterisation of reef types in Torres Strait and an assessment of their carbonate production. Marine Geology, 338, 64-75.

Madden, R.H.C., Wilson, M.E.J., O'Shea, M., 2013. Modern fringing reef carbonates from equatorial SE Asia: An integrated environmental, sediment and satellite characterisation study. Marine Geology, 344, 163-185.
Done

- L115 Which coordinate system was employed? GDA94 is just the datum
In fact the Geocentric Datum of Australia (GDA94) is a coordinate system for Australia. It supersedes the older coordinate systems Australian Geodetic Datum 1984 (AGD84).

Reviewer 2:

It might be better moving the aim of this study (L89-97) before introducing the study area (L59). Introduce the study area as part of the methods section.
Done

Table 1: including spatial resolution where possible
Done

L130 Include references to support this
Done

L138 Reword last sentence to actually include the bands and spatial resolution of the aerial photos… or refer to Table 1
Done

Figure 4: Should show the actual mapping process workflow…
Done

Table 2: Better as a map?
Due to the very small features of some islands, they cannot be seen if they are presented on a map. However, information on islands number and distribution also can be found on the map in Figure 5.

Table 3: Better as a histogram?
It can be presented either as a table or histogram. However, it was decided to present it in a table format just for diversification in data view as the article contains many figures.

L230 Section 3.2 should not be part of results but Methods (2.4).
Done.

Discussion is great but could be better if conclusions are presented separately
Done

We really hope these modifications can meet with your approval.

Yours Sincerely,
Moataz Kordi

Ms. Ref. No.: OCMA-D-15-00424
Title: A Spatial Approach to Improve Coastal Bioregion Management of the North Western Australia.
Ocean & Coastal Management

Dear Dr. Victor N de Jonge,

Thank you for your email and for reviewers' constructive comments concerning our manuscript entitled "A Spatial Approach to Improve Coastal Bioregion Management of the North Western Australia". Based on these comments, we have revised the manuscript carefully and made the all requested corrections and changes which we hope meet with approval. Revised portions are marked in the Tracked Changes version (Reviewed_Manuscripts_TC).

Yours Sincerely,
Moataz Kordi

Reviewer #1:
In this manuscript, the authors use remote sensing to classify the main habitats and substrates of reefs in the Kimberly Bioregion in Western Australia. Due to the large extent of the area and lack of data, the use of Landsat imagery, combined with ground truthing data and orthophotos, is presented as a viable technique for providing information on the composition of reefs. The manuscript is well written with excellent graphics. While the approach is not novel, there is certainly value in providing this kind of information for monitoring changes over time and certainly in this area. There were some sections that need to be improved and I would therefore recommend that this manuscript be accepted with minor changes.

Introduction: Clear and concise.

Methods: I found that this section was missing some crucial information on the remote sensing technique. The authors need to expand on what bands were used in the study, what corrections were performed and importantly, why they chose Landsat TM above Landsat 8 or other finer resolution imagery. Similarly, the description of the ground truthing was also vague and missing many important details. The details regarding the remote sensing and subsequent ground truthing are essential for the reader to understand the validity of the technique and credibility of the results. The method should be repeatable and therefore all the necessary details need to be included.
Done

Results: The authors should describe the confusion matrix. From the table given, it appears that there was a large overlap in the user's accuracy between classes. All the descriptions of the habitats and substrates hang on the accuracy of the remote sensing technique so it is really important to explain what is going on at this point. Were the ground truthing data and orthophotos used to improve the classification before describing the reef characteristics? I would suggest presenting Table 3.2 earlier in the results section with a description of the table contents.
Done

Discussion and methods: This section was good, but I felt that the accuracy of the results in the confusion matrix had once again been overlooked. Remote sensing is not a perfect approach and certainly not when using a 30m spatial resolution. The authors could really expand on this and describe how accurately the individual classes were classified and why.
Done

Overall: The manuscript was easy to read and nicely written. The title suggested more emphasis on management than what was actually given in the paper.

Reviewer #2:
In general, the manuscript is good and of high quality. It is a well conducted study, however it is quite descriptive and thus the manuscript would benefit from a stronger clarification of the aims of the study and highlight the significance of results of the study for the scientific community.
While the general aim of the study it is mentioned briefly in the abstract it needs to be explained in further detail in the text. For example, at the end of the introduction add a paragraph at line 56 "The general objective of the study was to …" and then list the specific aims of the study (1), (2), and (3). Followed by a short description of the presumed implications of the results for e.g. management, etc.
The manuscript provide a proper description and background of the Kimberley area, using different applied methods. The manuscript is very well written, however there are a couple of changes that needs to be addressed before re-submission.

References:
References are well presented and relevant literature has been used for references, however at some places references could be added, e.g. at line 82.
Line 80 Remove semicolon: Purkis and; Zainal, 1994).
Line 82 Remove semicolon: Spalding et al., 2001; Tupper et al, 2011; 82 Wilkinson, 2008;)
Done

Grammar and writing:
The writing is of high quality with very few typos, however the manuscript would benefit of a couple of changes in the text, which preferably should be changed before print, for example:

line 2, 8, 14, etc unless bioregion is part of the name, avoid capital "B" (see Collins et al. 2015 reference).
line 98 in situ should be in italic
line 123-124 Repeated sites from line 116-118. If the remote sensing was carried out at the same sites as the ground-truth data, it may be confusing to list the names of the reefs again in the following paragraph.
line 129 add comma after "conditions".
line 167 i.e. should not be in italic.
line 231 i.e. should not be in italic.
line 234 e.g. should not be in italic.
line 242 i.e. should not be in italic.

line 247 repetition? (remove "map" from "a map legend")
line 280 add "ocean" before swell.
line 281 "5-7 km" instead of "5 - 7 km" for consistency.
line 285 suggested rephrasing: "...the habitats and substrates on the reef flats resemble other fringing reefs in this category."
line 301 "Turtle reefs" with double quotation. Is it "Turtle reef" or "Turtle reefs" (see e.g. line 118)?
line 324 add "ocean" before swell.
line 340 Please clarify: Porites sp. or Porites ssp.
line 405 Sargassum sp.?
line 431 Sargassum sp.?
line 445 See comment above: Please clarify: Porites sp. or Porites ssp.
line 450 remove Italic from the sentence.
line 472 e.g should not be in italic.
line 475 i.e. should not be in italic.
line 481 i.e. should not be in italic.
line 515 The reef flat
line 536 Long and slightly odd paragraphs due to the usage of brackets. Perhaps divide into two sentences instead would be better.
line 567 "extractions" instead of "extraction", for consistency.
Done

Graphs and tables:
While the information in the tables are good and provide relevant information, references to figures do not need to be in italic, e.g. line 261. Please avoid using italic numbering or letters when not necessary (including in the figures).
table 2.1 "Macroalgae" instead of "macro algae"
Done

Ms. Ref. No.: OCMA-D-15-00280
Title: ReefKIM: an integrated geodatabase for sustainable management of the Kimberley Reefs, North West Australia
Ocean & Coastal Management

Dear Dr. Victor N de Jonge,

Thank you for your email and for reviewers' constructive comments concerning our manuscript entitled "ReefKIM: an integrated geodatabase for sustainable management of the Kimberley Reefs, North West Australia". Based on these comments, we have revised the manuscript carefully and made the requested correction and changes which we hope meet with approval. Revised portions are marked in the Tracked Changes version (TC_manuscript). The main corrections and changes in the paper and the responds to the reviewer's comments are in blue as flowing.

Reviewer 1:

- Introduction and Discussion
Several studies have surveyed sustainable management, especially application of Geographical Information Systems and Information Systems in ecosystem conservation and management in other countries (Ma et al., 2011, 2013) in the way of Marine Protected Areas, such as (Ma et al., 2013). The results and conclusion of Ma et al (2013) would be helpful for the discussion in this manuscript.
References were added.

- Methodology
This part is clear and well addressed, my only concern is that in "2.3. Data integration", the author noted that they use data integration to fill in the missing information. The review wonders what kind of integration do the author use for creating this database, data verification, detection of changes, or data updating, or all of them? Could that be more specific?
More explanations about the integration process were added.

Reviewer 2:

- Only a few minor revisions are suggested.
Done

Reviewer 3

- In the results there are 10 photographs 'crowdsourced' but no information about this. In the discussion it appears that crowdsourcing hasn't yet been done - only that it could be (and will be in the future) (I tried finding ReefKIM online through a google search and didn't come across it).
The 10 images were for testing purpose. Those images were crowdsourced by the project team members using 4 different devices including digital camera with built-in

gps, smartphones and tablets. All information associated with these images are stored in the image properties and they can be displayed upon request.
ReefKIM has been tested and ready to be launched online once the governmental procedures are completed and the official approvals are obtained.

- Likewise, in the introduction it also mentions that some of the most-important data is with the traditional owners that inhabit the region. Yet there isn't any mention of these 'traditional knowledge' data in the results or discussion.
Traditional owners of the land possess many information such as historical information on ancient inhabitants of the land, old names of the islands and thousands of the photos of marine species. Many of these photos and information were already used in this study to interpret remote sensing images.

- If my expectations hadn't been raised about the crowd-sourcing aspect and gathering traditional knowledge, I wouldn't have been disappointed. I think the manuscript well and truly stands on its own in relation to the development of the geodatabase through all the biophysical data. It is a massive area and massive dataset to integrate and will be extremely valuable to management planning in the Kimberley Region. My suggestion would be to reduce the crowd-sourcing aspect in the introduction (to one paragraph) and reduce it in the discussion also to about 1 paragraph (about potential application and future direction). This would then lead into another paper once the crowdsourcing aspect has actually been trailed and tested.
Crowdsourcing approach is an essential part of this project, the geodatabase has been designed and tested to be able to receive new information though users. However, our role as researchers at this stage is to provide marine park managers and decision-makers with reliable and up-to-date information. It is also important to facilitate and develop new means to collect information from users. Once the platform is launched and new data is being collected, assessment can be made in the next stage.

- L9. This study doesn't actually 'demonstrate' crowdsourcing through a web-based platform. I would delete this sentence
Please see response above.

- L 36 'increasing' should be 'increase'
Done

- L104 I would change this sentence to 'This geodatabase will improve…..of this vital reef ecosystem'
Done

- L144 'was' should be 'were'
Done

L147 to 152 Data integration. I believe this section needs some additional explanation about the integration process. For example, if there are two datasets with overlapping information were they somehow merged or was one used preferentially over the other?
More explanations about the integration process were added.

- L158 ..reef geomorphology, reef classification and distribution
Done

- L165-166 I would change this sentence to make it clearer. Perhaps '…enables an administrator to control and restrict access to authorized users only, to avoid accidental loss of data.'
Done

- L174-175 This sentence isn't clear 'A variety of sources fostered using data fusion….'
Done

L200 Table 3. For the purpose of a general journal paper I think the rows in this table could be reduced to a single line stating the number of reefs (out of 30) with features. For example LS = 30, SI = 12 etc.). The more complete table could be placed in supplementary information.
The suggestion is much appreciated. However, as long the paper is relatively short it may easier and more informative for readers to keep the table as is.

- L248 to 259. Is this actually from crowdsourcing or did the authors take the 10 photos as part of the study in order to test the ability to attach photos etc.? If it is actual crowdsourced information that other people have added in, then shouldn't there be some additional metadata provided with the photograph? Such as who provided the photograph, date it was taken, Lat Long etc. and also provide an indication of the uptake in the results (did just one person contribute photographs or 10 different people?). If it was actually crowdsourced these results would be interesting and should be included.
Please see response above.

- There was no social information given in the examples (especially anything about traditional knowledge which is indicated as being of critical importance in the introduction.
At this stage, the main aim of the project is to determine reef locations and its major habitat and substrate types for management purposes. Other social and historical knowledge can be added to the geodatabase in the future.

- The second paragraph of the discussion should be more positive about what has been achieved in this study: A geodatabase has been constructed using key physical information integrated, and this can be used at the regional to individual reef to site scale……
Done

- The third paragraph does this - I would probably just delete the 2nd paragraph or move it towards the end of the discussion.
Done

- L290 in prep b?
Done

- L293 'can be made available' or 'is available'? If it is only 'can be made' then the crowdsourcing component is aspirational and hasn't actually been conducted as part of this study.
Detailed information will be accessible to users upon request.

- L295 to help implement reef monitoring?
Done

We really hope these modifications can meet with your approval.

Yours Sincerely,
Moataz Kordi

APPENDIX E: LETTER FROM THE DEPARTMENT OF PARKS AND WILDLIF

Government of Western Australia
Department of Parks and Wildlife
Science and Conservation Division

Your ref:
Our ref: Waples0616
Enquiries: Kelly Waples
Phone: 9219 9796
Email: Kelly.waples@dpaw.wa.gov.au

To whom it may concern

Dear Sir/Madam

Kimberley georeferenced database (ReefKIM)

This letter is to acknowledge the value of the ReefKIM database produced as part of the geomorphology project conducted through the Western Australian Marine Science Institution by Moataz Kordi and the research team.

Until recently there has been very limited information on the Kimberley island and reef system, despite the recognized conservation value of this region. The project led by Mr Kordi provides a precise georeferenced perimeter maps of all reefs and islands across the Kimberley. In addition, this project used remote sensing technology to develop habitat characterization maps for 30 individual reefs across the region. This information highlights the value of the Kimberley based on the extent of reef area and on the unique structure of the reef system.

Managers from the Department of Parks and Wildlife will be able to use this database in marine protected area planning processes and to support research and monitoring activities. The ReefKIM database is a valuable tool that is now available to underpin management decision making processes.

Yours sincerely

Dr Kelly Waples
A/Marine Science Program Leader

21 June 2016

Marine Science Program
Locked Bag 104, Bentley Delivery Centre, Western Australia 6983
Phone: (08) 9219 9754 Email: holly.raudino@dpaw.wa.gov.au
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