1.0 Chapter I

INTRODUCTION

1.1 Overview

Intertidal reefs may undergo considerable change in the near future due to the combined impacts of climate change and increasing human occupation in coastal areas (Jackson and McIlvenny, 2011). Within the marine environment, the impacts of climate change can be classified into three categories: ocean acidification, water temperature changes and sea level rise (IPCC, 2014). The focus of the present research is on the effects of sea level rise on biodiversity conservation of intertidal rocky reef ecosystems. Recent satellite-altimeter data and tide-gauge data have shown sea levels rising at over 3mm/yr. (Church et al., 2008). The intertidal reef supports very diverse communities with a high level of endemism, especially along the Eastern coast of Australia (Zann, 2000) and is situated in a vulnerable position for the predicted changes in sea level.

Habitat loss and modification is a critical factor in conserving ecosystem biodiversity (Antoniadou et al., 2010, Hewitt et al., 2005) and potentially can create cascade effects at higher trophic levels (Skilleter and Warren, 2000). Inventory and monitoring of coastal ecosystems is a critical first step in assessing and understanding changes brought about by human activity or by climate change. However, in Australia, this process is hampered by the vast coastline and the fact that even basic data are unavailable in many regions (Banks et al., 2005, Gladstone, 2007, Smith, 2005, 2008). Potential solutions can be found in the use of remote sensing and modelling tools (Andrew and O'Neill, 2000, Banks and Skilleter, 2002, Brown and Collier, 2008, Pech et al., 2004, Populus et al., 2004).

The Solitary Islands Marine Park (SIMP) is located on the subtropical north coast of NSW, Australia, in an area that is recognized as an important hotspot for marine biodiversity conservation, since it is an overlap zone between tropical and temperate biota (Smith 2005; 2008). The prediction of the spatial distribution of species from survey data has been recognized as a significant component of conservation planning (Austin, 2002, Pearson and Dawson, 2003). This project aims to develop a predictive model for species richness with the ultimate goal of predicting the effects of habitat loss or modification due to sea level rise on intertidal rocky reef biodiversity.

1.2 Climate change

The amount of global warming predicted by the Intergovernmental Panel on Climate Change (IPCC) over the next hundred years is 1.4-5.8° Celsius (Stoker et. al., 2013). Barnett et al. (2005) suggests that the ocean warming in the past 40 years is induced by human activity increasing CO_2 emissions in the atmosphere (Figure 1.1).

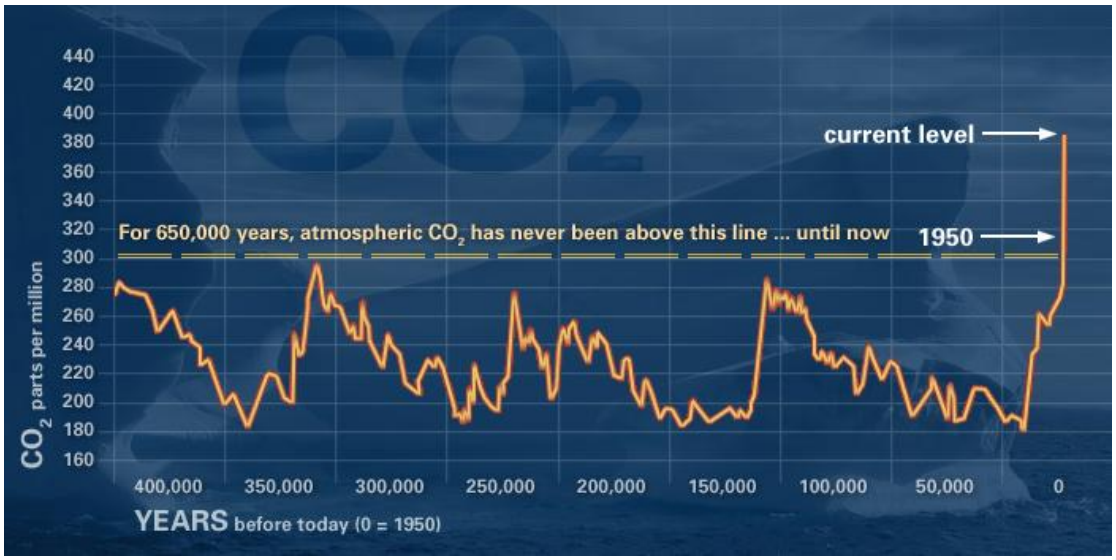

Figure 1.1 The comparison of atmospheric samples contained in ice cores and more recent direct measurements, providing evidence that atmospheric CO_2 has increased since the Industrial Revolution (Source: NOAA in http://frontierscientists.com).

Sea levels have varied over 120m during glacial/interglacial cycles, but in the past several thousand years there has been little change. Only during the 19th century and early 20th century could the increase in SLR be detected (Church et al., 2008, Russell et al., 2000). Recent sea level rises are a result of ocean thermal expansion and the melting of glaciers and ice caps while ice sheets are potentially the largest contributor in the longer term (Cazenave et al., 2009, Church et al., 2008, Horton et al., 2008, Shepherd and Wingham, 2007).

The effects of climate change in the oceans have not been dramatic up to now due to the high thermal inertia of the system (Edwards, 2006, Horton et al., 2008, Meehl et al., 2005). Sea levels are currently rising at the upper limit of the projections of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (TAR IPCC) (Stoker et. al., 2013), and there is a strong concern about large ice sheet contributions, especially if greenhouse gas emissions continue to increase (Church et al., 2008). Edwards (2006) and Shepherd et al.

(2007) state that sea levels have risen abruptly in the past. Church and White (2006) have detected an acceleration of 0.013mm per year. According to Church et al. (2001) an upper limit of 0.88m of SLR is expected over the next hundred years. Future sea level rise is not expected to be globally uniform due to ocean circulation, wind pressure patterns and geological uplift (Church et al., 2001, Levitus et al., 2005, Nicholls et al., 2007, Meehl et al., 2007, Senior et al., 2002). Flooding of coastal wetlands and low lying islands, storm damage, eroding shorelines, groundwater contamination by salt water and also changes in the salinity of estuaries are all real possibilities of even a small increase in sea level. Important resources for island and coastal populations such as beaches, freshwater, fisheries, rocky shores, coral reefs and wildlife habitat are also at risk (Nicholls et al., 2007). Other effects that must be kept in mind when evaluating sea level rise impacts are storm surges and spring tides (Senior et al., 2002).

Climate models indicate that the increase in temperature over Greenland is thought to be one to three times higher than the global average. Ice sheet models project that a local warming of more than 3°C, if sustained, would lead to a complete melting of the Greenland ice sheet, adding around 7m to the sea level (Gregory and Huybrechts, 2006, Murray, 2006). Also, the West Antarctic Ice Sheet (WAIS) could potentially contribute 6m to SLR. The entire Antarctic ice sheet holds enough water to raise global sea levels by 62 meters (Shepherd and Wingham, 2007). As the predictive sea level rise models have a high level of uncertainty, and do not take into account the ice sheet contributions there is a concern that the projections of mean sea level by 2100 could be quite underestimated (Church et al., 2001 and Senior et al., 2002).

1.3 Intertidal Rocky Reefs

Rocky shores are complex ecosystems of high diversity located at the land–sea edge occupying one third of the world's coastline (Johnson, 1988) (Figure 1.2). Around 80% of the world's intertidal reefs are composed of platforms backed up by high cliffs (Emery and Kuhn, 1982) suggesting that even small changes in sea level could have a great impact on the availability of intertidal area along the rocky reefs which in turn would promote a significant change in the coastal landscape. As one of the most accessible and diverse marine habitats, rocky shores are important features for education, recreation and harvesting (Garcia and Smith, 2012, Murray et al., 2006) and the consequences of habitat loss include the availability of resources this ecosystem offers for the coastal inhabitants.

Figure 1.2. Intertidal reef ecosystem overview at Arrawarra Headland. (Photo credits: Jaqueline Thorner)

The intertidal reef area is displayed as a mosaic of different habitats that have been created by the interaction of natural elements such as rock formations, tidal patterns, oceanic swell and weather conditions (Menge and Branch, 2001). The energy of waves along with the chemical content of the water is what erodes the rock platforms (Johnson and Baarli, 1999). Due to their geological nature, erosion processes are relatively slow, especially if compared to other intertidal habitats such as estuaries, beaches and mangroves, hindering the transformation of

the rocky coastline by the effects of climate-change-driven sea level rise in a short-term span (Jackson and McIlvenny, 2011). The intertidal reef habitats can be classified in many different ways according to the features observed on each particular coastline (Figure 1.3-1.5). The most common classifications include boulder fields, rock pools and platform (Banks and Skilleter, 2002, Chapman, 2002, Smith, 2005, Underwood and Skilleter, 1996).

Figure 1.3. Rock pool habitat with Mullaway Headland in the background. (Photo credits: Jaqueline Thorner)

Figure 1.4. Boulder field habitat at Arrawarra Headland during biodiversity surveys. (Photo credits: Ana Markic)

Figure 1.5. Platform habitat at Flat Top Point. (Photo credits: Jaqueline Thorner)

Most habitats that compose the intertidal reef ecosystem are created by erosion processes, where deep pools are generated from the erosion of the rock platform by boulders, which is a slow process for such habitat to be created. Boulder fields, however, are the habitat most easily to be recreated by the erosion process acting along the cliffs. Shallow pools, on the other hand, originate from the shape of the rock platform where water accumulates in the lower parts of the intertidal area (Johnson and Baarli, 1999). The physical features of each habitat type provide specific conditions that in turn support different assemblages of species which have a direct influence on the local biodiversity (Menge and Branch, 2001). However, the lack of technical tools to quantify habitats at an appropriate resolution has been one of the main reasons hampering fine-scale studies along the whole intertidal area (Fraschetti et al., 2005).

The tidal movement creates a volatile habitat that is constantly changing, challenging the most resilient species to survive such dynamic conditions. Along the vertical gradient, desiccation is the main factor in regulating the species distribution in the upper section of the shore, whereas biological factors (e.g. predation and competition) control the distribution of species in the lower level of the shore. In contrast, the horizontal gradient is primarily affected by wave action creating variable exposure levels along the shore (Menge and Branch, 2001).

1.4 Remote sensing

Predicting the magnitude of climate change impacts on intertidal rocky reefs relies not only on accurate predictions of sea level rise, but also on the development of technologies to map and quantify habitats and environmental processes at appropriate spatial scales. Potential solutions can be found in the use of remote sensing, allowing collection of habitat data over larger areas with the required accuracy and efficiency (Andrew and O'Neill, 2000, Banks and Skilleter, 2002, Brown and Collier, 2008, Guichard et al., 2000, Pech et al., 2004, Populus et al., 2004).

In the last decades, new forms of multispectral sensors have permitted the acquisition of digital imagery along most of the electromagnetic spectrum. It is now possible to acquire easily, and at a relatively low cost, high quality digital data to support qualitative and quantitative studies (Brock et al., 2002, Chust et al., 2008, Hall et al., 2009, Robertson et al., 2004, Stockdonf et al., 2002, Petzold et al., 1999). The conservation of fine-scale spatial heterogeneity is a critical factor in marine reserve planning (Ackerly et al., 2010). To date, LIDAR (Light Detection and Ranging) has the finest horizontal resolution and greatest vertical accuracy and is the only technology suitable for analyzing sea-level changes in the range predicted for the next century (Runting et al., 2013, Church et al., 2001).

Airborne LIDAR consists of three main components: a laser scanner unit, a Global Positioning System (GPS) receiver, and an Inertial Measurement Unit (IMU) integrated to a high-resolution digital camera attached to an aircraft flying at low height, typically at 1000m (Figure 1.6). The laser scanning unit actively transmits pulses of light toward an object of interest, and receives the light that is scattered and reflected by the objects, creating highly accurate digital terrain models (x,y = ±30cm; z = ±10cm resolution) geo-referenced by the information provided by a differential kinematic GPS (Liu, 2008).

New technologies in digital aerial photography can provide unprecedented definition (0.1m per pixel) allowing the visualization of detailed spatial information which, coupled with the already established LIDAR technology (Brock and Purkis, 2009), can reveal important features such as elevation and area of specific habitats at centimeter to meter scale (Thorner et al., 2013).

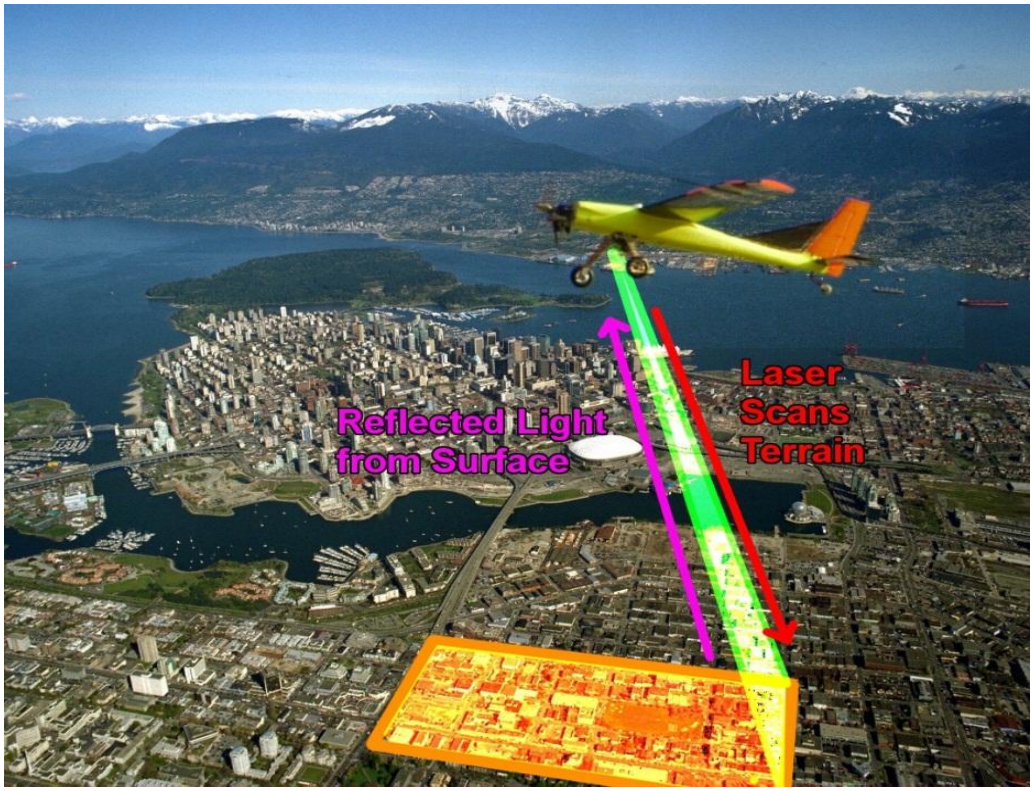

Figure 1.6. Airborne LIDAR data collection concept. Photo credits: [http://stratus-aero.com]

Habitat mapping has been used as a tool to provide spatial information for environmental management supporting the design of marine protected areas (Baker and Harris, 2011). The application of new technologies that can accelerate the acquisition of spatial data can improve the decision-making process, which can be crucial to the effectiveness of biodiversity conservation in a changing world where sudden changes in the environment can be analyzed and underpinned in an ecosystem-based approach to set conservation priorities at short notice.

1.5 Biodiversity conservation

Climate change is currently one of the main threats to the biodiversity of our planet. If environmental patterns change to the point that a species can no longer thrive in sites where it is currently found, its population will decline, unless it can either adapt to these changes or migrate to new, more suitable sites (Armsworth et al., 2004). Biodiversity is an extremely valuable resource that has been lost at an accelerating rate as a result of human activity (Armsworth et al., 2004, Benkendorff and Davis, 2002). The conservation of diversity should be undertaken at ecosystem, species and genetic levels (Banks and Skilleter, 2002).

Figure 1.7. Intertidal reef biodiversity, *Hydatina physis* (Linnaeus 1758) at Mullaway Headland upper shallow pool habitat. (Photo credits: Ana Markic)

Habitat loss and change is potentially one of the greatest threats to biodiversity conservation in a changing world, and a challenge for environmental management through static systems such as marine reserves. However, the intertidal rocky reefs are the most accessible of the

marine environments (Benkendorf and Davis, 2002) and increasingly exposed to human impacts (Smith, 2008). The sections of the shore with the most human activity, also the most sheltered, contain the greatest levels of biodiversity. The difficulty in acquiring biodiversity data adds to the necessity of basic information to set conservation targets and has led several studies to analyze the effectiveness of habitats (Banks et al., 2005, Banks and Skilleter, 2002) and taxonomic groups (Gladstone, 2002, Benkendorff and Davis, 2002, Smith, 2005) as surrogates for biodiversity.

The choice of a reduced set of target organisms that act as surrogates for broader diversity has been used in marine ecosystems with considerable success by several scientists (Adams and Chandler, 2002, Brock et al., 2002, Banks and Skilleter, 2002, Magierowski and Johnson, 2006, Sarkar et al., 2005, Terlizzi et al., 2009, Ward et al., 1999, Warwick and Light, 2002). In particular, molluscs appear to be useful, general surrogates for marine conservation studies (Benkendorff and Davis, 2002) and shelled gastropods and bivalves are considered the best surrogates for total biodiversity in the Solitary Islands Marine Park (Smith, 2005) (Figure 1.7). On the Southeastern Australian coast, 95% of mollusc species are considered endemic to Australia (Zann, 2000). The level of endemism can be relevant to environmental management when considering the risk of extinction as a consequence of a widespread event such as sea level rise, since it could affect the whole extent of a species distribution area (Harley et al., 2006).

1.6 Ecological modelling

In ecology, the numbers of species, or species richness, has long been associated with area, where the larger area sampled the more species are likely to be found (Arrhenius, 1921). The measurement of total biodiversity is a laborious task, if not impossible to complete, especially over larger areas hampering the knowledge required to successfully manage ecosystems (Smith, 2005). Several non-parametric estimators for species richness have been developed from the basic need of species-area information for ecological research (Connor and McCoy, 1979, Smith and Belle, 1984, Ugland et al., 2003). Species accumulation curves are dependent on species identity and are concerned with accumulation rates of new species over the sampled area (Ugland et al., 2003). In the marine environment, a very high species richness is observed where a pattern of few abundant species associated with a great number of rare species results in the species accumulation curves to be non-asymptotic, requiring a very large sampled area in order to reflect a reliable estimate of the number of species (Gotelli and Colwell, 2001, Gray, 2001). Ugland et al., (2003) described a method of estimating species richness that can be applied to any spatial extent, regardless of the area sampled. The model consists of a Total-Species accumulation curve (TS), which is created through the average of subsets of samples, instead of the randomization of all samples used in the traditional method of plotting a species accumulation curve (Colwell et al., 2004). Subsequently, the application of a semi-logarithmic function to the curve creates a linear model which derives an equation. This equation is used as a basis for extrapolating the species richness estimate to the desired area extent. Both the species accumulation curve and the semi-logarithmic function described are independent of the underlying species abundances. Several authors have applied the TS-curve model for extrapolation of species richness with success on marine benthic ecosystems (Gingold et al., 2010, Reichert et al., 2010, Labrune et al., 2008). There is a lot of uncertainty involved in extrapolating species richness for areas larger than sampled (Ugland et al., 2003). Nevertheless, it is sometimes a necessity, especially when setting conservation priorities, due the unavailability of biodiversity data. The use of predictive models for species distribution can add relevant information to the management of intertidal reefs in respect to changes generated by climate-change-driven sea level rise where habitat loss and modification are the main consequences affecting biodiversity conservation.

1.7 Study Area

The coastal landscape of New South Wales, Australia is comprised of islands, headlands, beaches, estuaries and river mouths. The headlands along the coast are formed by a rocky reef base relatively flat in the protected intertidal areas, where most of the diversity is found, sheer cliffs on the wave exposed sections and at higher-ground cliffs and bushland (Figure 1.8). The Solitary Islands Marine Park (SIMP), located on the subtropical mid-north-coast of NSW, is comprised of 24 headlands, supporting a significant area of intertidal rocky shore (26% of the park) (Marine Parks, 2002).

Figure 1.8. Aerial view of the intertidal reef at Arrawarra Headland . (Photo credits: Roger Dwyer)

Rocks on the islands and headlands generally range from north to south, parallel to the coast, and consist of metamorphic greywacke deposits (Korsch and Harrington, 1981) which is hard-wearing and provides a stable base for the development of diverse marine assemblages (e.g. Smith, 2005). Weathering and erosion have selectively removed softer strata, leaving more resilient rocky outcrops (Mau, 1997) which form the basis of the headland's formation (Figure 1.9). Variations in sea level have also influenced the geomorphology of the marine park, with the sea level being considerably lower during the last glacial period around

20,000–15,000 years ago. Different erosional and depositional forces acted on the rocks and sediments of this area during that time (Johnson and Baarli, 1999).

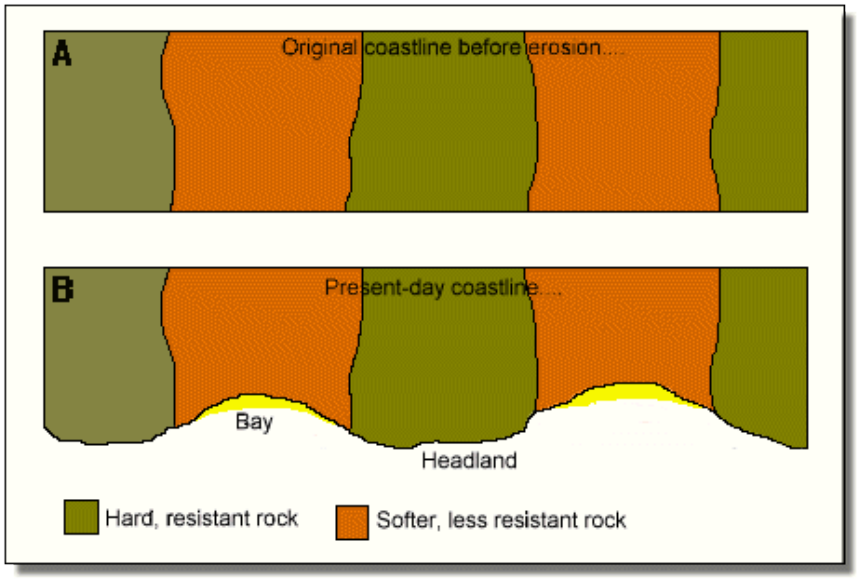

Figure 1.9. Headlands development over time (Source: georesources.co.uk).

The five headlands chosen for this research were: Arrawarra Headland (153°12'07''E-30°3'33''S); Oceanview Headland (153°12'14"E-30°04'01"S); Mullaway Headland (153°12'15''E-30°4'33''S); Woolgoolga Headland (153°12'17"E-30°06'30"S); and Flat Top Point (153°12'26"E-30°07'48"S) (Figure 1.10). The headlands intertidal reefs comprise cliffs, bedrock and scree with variable wave-driven erosional patterns and areas of sand accumulation. In the SIMP zoning plan, Arrawarra Headland is classified as a Sanctuary zone and Flat Top Point as a Special Purpose zone, which have the highest level of protection for biodiversity conservation. The region has a 2-m, semi-diurnal tidal cycle, a Mean Sea Level of 0.9m, Mean Low Tide Level of 0.4m and Mean High Tide Level of 1.4m (Foremann, 1977) and is renowned for the overlap of tropical and temperate currents (Malcolm et al., 2011), which result in high biodiversity comprising tropical, temperate and endemic species (Smith, 2005, Smith et al., 2008, Malcolm et al., 2010, Harrison and Smith, 2012).

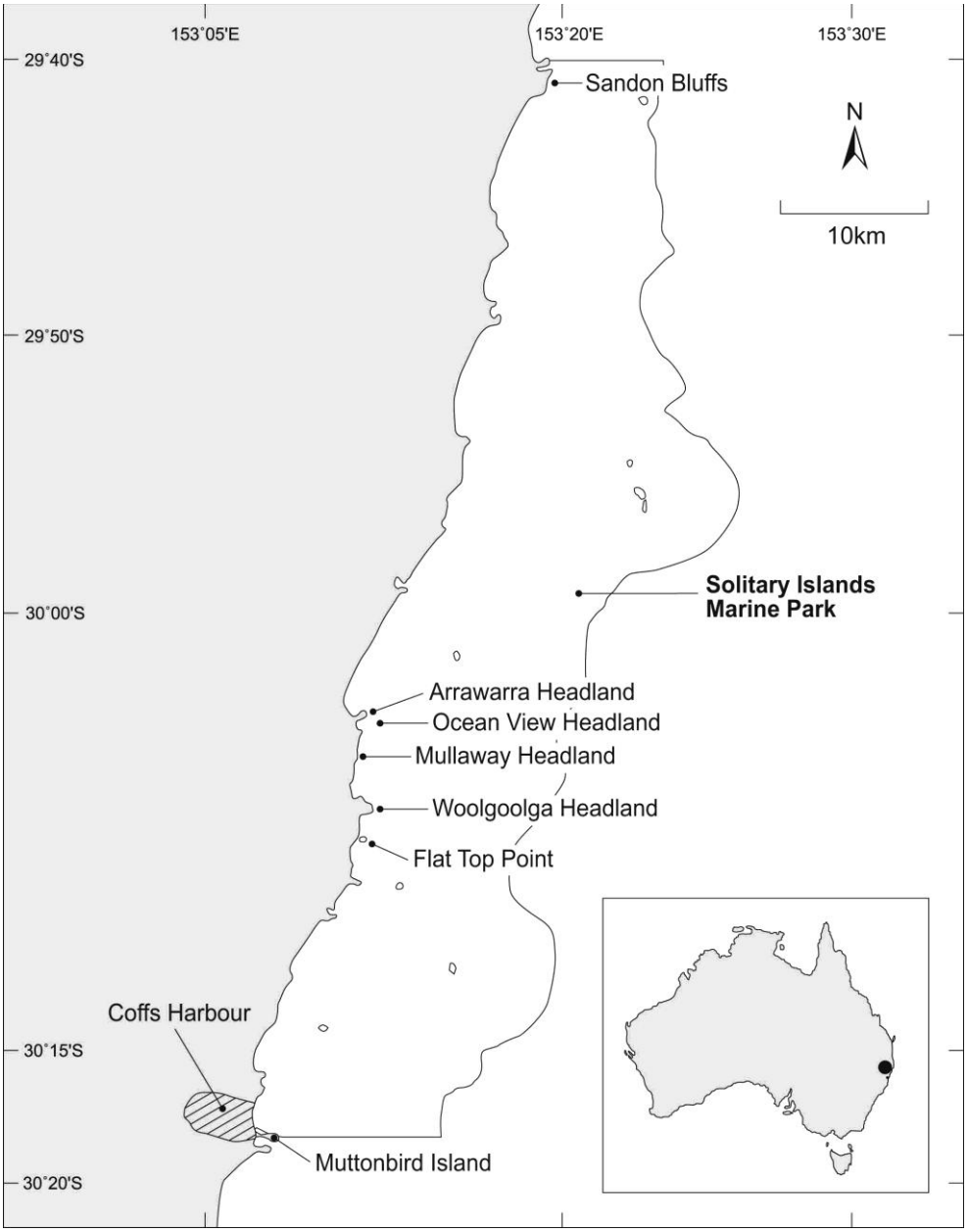

Figure 1.10. Map of the Solitary Islands Marine Park, NSW, Australia, showing the five headlands used in this study (Arrawarra, Ocean View, Mullaway, Woolgoolga and Flat Top Point).

1.8 Aims of the Research

Problem

Biodiversity is an invaluable asset that can be irreversibly lost through extinction. South-eastern Australian intertidal reefs contain a high level of diversity and endemism which is at risk with the effects of climate change. The predicted sea level rise for the next century, of around one meter (Stoker et. al., 2013), is likely to have a great impact on intertidal areas, possibly hampering the effectiveness of marine reserves in respect to biodiversity conservation.

Research Question

Can we improve the biodiversity conservation of intertidal rocky reefs in a changing world with the use of remote sensing and modeling tools?

Objectives

i. To classify and quantify intertidal reef habitats through the development of habitat mapping techniques using remote sensing tools;

ii. To model predicted sea level rise impacts for the next century on intertidal rocky reefs;

iii. To describe the fine-scale patterns of a taxonomic surrogate group for invertebrate biodiversity (mollusc) along the intertidal rocky reef;

iv. To design, test and apply a predictive model for species richness for intertidal rocky reefs;

v. To analyze the possible impacts of predicted sea level rise on intertidal rocky reefs biodiversity using ecological modelling tools.

These aims were achieved through four publications in this thesis presented as chapters in manuscript format to facilitate publication in peer-reviewed journals. As such, there may be repetition, particularly amongst the introduction and methods sections of each chapter.

2.0 Chapter II Fine-scale 3D habitat mapping as a biodiversity conservation tool for intertidal rocky reefs.

FINE SCALE 3D HABITAT MAPPING AS A BIODIVERSITY CONSERVATION TOOL FOR INTERTIDAL ROCKY REEFS

Jaqueline Thorner, Lalit Kumar and Stephen David Anthony Smith

Published in Journal of Coastal Research (2013), 29 (5), 1184-1190.

3.0 Chapter III Impacts of climate-change-driven sea level rise on intertidal rocky reef habitats will be variable and site specific.

IMPACTS OF CLIMATE-CHANGE-DRIVEN SEA LEVEL RISE ON INTERTIDAL ROCKY REEF HABITATS WILL BE VARIABLE AND SITE SPECIFIC

Jaqueline Thorner, Lalit Kumar and Stephen D.A. Smith

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4.0 Chapter IV Patterns of molluscs distribution on intertidal rocky reefs in a subtropical marine park.

PATTERNS OF DISTRIBUTION OF MOLLUSCS ON INTERTIDAL ROCKY REEFS IN A SUBTROPICAL MARINE PARK

Jaqueline Thorner, Lalit Kumar and Stephen David Anthony Smith

5.0 Chapter V Is intertidal rocky reef biodiversity resilient to coastal squeeze: a modelling approach.

IS INTERTIDAL ROCKY REEF BIODIVERSITY RESILIENT TO COASTAL SQUEEZE: A MODELLING APPROACH

Jaqueline Thorner, Karl Inne Ugland , Lalit Kumar and Stephen David Anthony Smith

6.0 Chapter VI

SYNTHESIS

This study aimed on developing and testing tools to improve biodiversity conservation management on intertidal rocky reef ecosystem under climate-change-driven sea level rise conditions. The ability to quantify intertidal habitats has been a challenge that has prevented many advances in ecological research on intertidal reefs (Fraschetti et al., 2005). The basic features of the rocky shore, where habitats are distributed as a mosaic, have hampered the ability to measure and map the intertidal reef with the necessary accuracy to yield useful results to spatial ecology studies (Runting et al., 2013). However, the access to the state-of-the-art technology of remote sensing and software capable of translating the information obtained by the modern sensors to useful data for scientific applications, brought into light many opportunities for the development of novel techniques invaluable to the conservation of biodiversity in a changing world. I was able to create a habitat mapping technique at the centimeter to meter scale specific to the rocky shore environment which was of crucial importance given the complex structure of this ecosystem (Chapter 2).

Laser scanning technology or LIDAR (light detection and ranging) has been available for the last decades (Brock and Purkis, 2009). However, the progress of the intertidal reef habitat quantification at fine-scale was accomplished in this research mainly by the availability of new technologies in digital photography, which the unprecedented resolution of 10cm/pixel allowed the visualization in detail of the patchy distributed habitats of the rocky shore ecosystem. The features quantified by this technique generated results never accomplished before.

The intertidal rocky shore comprises a relatively narrow area located at the land-sea edge but nevertheless, it occupies 30% of the world's coastline (Johnson, 1988). The habitat mapping process through the use of modern remote sensing tools has developed a cost/time effective solution to map the relatively small areas of intertidal reefs along large extensions of the coast. The habitat mapping at the resolution of 10cm/pixel, added to the three-dimensional resolution provided by the LIDAR, which is to date, the only effective technique for modelling the sea level rise at the range expected for the next Century (Runting et al., 2013), represents an invaluable advancement to the spatial ecology research on intertidal rocky reefs.

By conducting studies at fine-scale, it has been possible to assess the vulnerability of different intertidal reefs to habitat loss that has not been revealed by the broad-scale sea level rise modelling (kms of coastline) (Jackson and McIlvenny, 2011). The intertidal reef habitats will have a variable pattern of change as the sea level rises. However, at the range of one meter sea level rise, the majority of the intertidal reef area will be lost. Mean size and number of shallow pools will also show a variable, and headland-specific, change as the sea level rises and the lower section of the shore will show an increase of area relatively to the upper shore in most headlands, despite the overall reduction in intertidal area (Chapter 3).

The initial idea that comes up when thinking of sea level rise impacts on rocky shores is that as the coastline is eroded by the coastal processes new intertidal reef habitats are going to be created to replace the inundated areas. This perception might be wrong since the sheltered areas of the intertidal zone, where the greatest diversity of habitats is found, are often backed up by high cliffs. In doing so, the intertidal area is at risk of losing permanently the diversity of habitats depending on the local geomorphology of the coastline even under a small rise in the sea level.

My research emphasized the link between the biodiversity distribution patterns and the loss of specific habitat's area (Chapter 4). The structure of the assemblages has shown strong patterns of variation between habitats and headlands. In general, the patterns of community structure in boulder field and platform habitats seem to be very similar between the two southern headlands analyzed in this study and significantly different from the remaining headlands. In contrast, among the three northern headlands, significant variations in the upper shallow pool habitat were present. These results reveal specific local patterns of distribution of species related to habitat type which lead to a conclusion that, although variations exist between different habitats, similar habitats can also provide different conditions due to variation in the particular features of each headland significantly influencing the biodiversity distribution along the rocky shore at local scale (Raffaelli and Hawkins, 1999).

There was a significant difference in species richness between upper and lower shore habitats where lower boulder fields and platform habitats were richer than the upper counterparts, which supports the classical model for intertidal rocky shores, where the vertical gradient has a negative correlation with species richness (Menge and Branch, 2001), this may help to ameliorate the potential loss of biodiversity associated with the overall decline in intertidal

area since the lower shore extent is likely to increase relatively to the upper shore as the sea level rises. However, most of the "new" lower shore areas have a reduced proportion of boulder fields and rock pools, if compared to platform habitat, which are associated with high diversity (Smith, 2005). Shallow pools do not significantly differ between the upper and lower shore in respect to species richness. These results may be relevant to environmental management in regard to climate change impacts, especially sea level rise scenarios were habitat loss and modification are likely to impact biodiversity conservation in marine reserves (Hannah, 2008, McLeod et al., 2008, Mora and Sale, 2011).

Shallow pool habitat had the highest number of species and at the same time showed significant differences between shore levels for species composition but no significant differences for species richness suggesting that this habitat type has the capacity of satisfying the survival requirements of many species. The habitats featuring the highest number of species are likely to suffer the greatest area loss, especially boulder fields and rock pools, impacting considerably the biodiversity on intertidal reefs. A point that must be made is that most of species found inhabiting boulder fields and rock pools can survive in sub-tidal areas, alleviating the consequences of habitat loss on species richness. Nevertheless, rock pools and boulder fields support many species of exclusively intertidal habitat that would not survive in a platform habitat. All the habitat generalists found in this study, which are exclusively intertidal species, would not have a problem in surviving the consequences of habitat loss. However, the changes in habitat area could be reflected in the abundance levels, increasing the species density, which in turn could have consequences for the biological factors such as predation and production (Jackson and McIlvenny, 2011).

The use of ecological modelling tools revealed the vulnerability of intertidal reef biodiversity to the sea level rise in an objective way (Chapter 5). Ugland's TS-method estimates a total species richness of 185 for the total area of the five mapped intertidal rocky reefs at the Solitary Islands Marine Park. The application of the TS-model not only clearly identified a strong heterogeneity in species composition among habitats, supporting the habitat classification approach, but also indicated the hotspots for species richness at local level (headlands). Flat Top Point and Arrawarra Headland are currently granted the highest level of protection for biodiversity conservation within the Marine Park, Sanctuary Zone and Special Purpose Zone respectively, selected through previous surveys at headland level (not discriminating habitat types) which supports the model accuracy in detecting biodiversity

hotspots (Marine Parks, 2002). Predicting species richness are challenging tasks due to the impossibility of completely measuring the true number of species of any environment (Benkendorff and Davis, 2002). It always will have an element of uncertainty. Nevertheless, despite the information obtained through the use of models not be perfect, it would not be available otherwise. The necessity of setting targets for biodiversity conservation must be based on the best available tools to provide a foundation to work on. Therefore, based on the results of this research we confirm that modelling tools can be a useful cost/time effective way to predict changes in species richness on intertidal reefs by habitat loss.

Future Directions

Intertidal rocky shore fauna have shown shifts in species ranges at the rate of 50km within a decade in response to the climatic change, which demonstrate a much more rapid rate than the terrestrial counterparts (Helmuth et al., 2006). The communities are not going to shift as a whole, different species will find different ways of adapting to the new situation and species compositions could change under different climatic conditions (Hawkins et al., 2009). The complexity of components affecting the distribution of species in rocky shores under climate change scenarios, such as habitat loss, thermal stress and acidification added to the natural variations, anthropogenic pressure and uncertainties in predictions make it nearly impossible to forecast the consequences for the community structure, especially with the lack of knowledge at local scale (Kappelle et al., 1999, Jackson and McIlvenny, 2011, Thompson et al., 2002). Unexpected break down of biological interactions (e.g. predation and recruitment), due to the reduction in habitat area, could have a higher impact on the biodiversity than is possible to estimate by only applying predictive models since the communities could have a threshold where the functional relationship between species would collapse (Fortuna and Bascompte, 2006). The estimates from the model assume that the species interactions within the ecosystem are going to be maintained despite the reduction of habitat area. This assumption may fail in fragile ecological networks (Montoya and Sole, 2001); however, given the resilience of the intertidal fauna to daily abiotic changes promoted by the tidal movement and wave exposure, it may prove to be quite a robust ecological system that could be adaptable to the new environmental conditions. In analyzing the whole mechanism of species-area relationship it is logical that the richest habitats and headlands have also the greatest loss of species as the habitat area is lost emphasizing the importance of protecting biodiversity hot-spots.

The gathering of knowledge required to set effective conservation priorities should focus on:

i) Detecting unknown biodiversity hotspots and setting conservation targets that provide a sizeable area of protection around them;
ii) Investigating what factors promote the existence of a hotspot;
iii) Discovering thresholds of minimum habitat area capable of maintaining a similar community structure for this ecosystem;

iv) Monitoring the intertidal reef biodiversity responses to environmental change and set conservation targets taking in consideration fine-scale parameters.

Another point that needs to be addressed is the interaction of responses to sea level rise between different intertidal habitats, such as sandy beaches and estuaries, since coastal processes like erosion might have very specific developments according to the local geomorphology (Harley et. al., 2006).

Marine protected areas cannot be expected to remain static and are likely to change over time so strategies that could be flexible enough to include sudden change in predictions of sea level rise would back-up the conservation goals more effectively. The greatest challenge for coastal managers will be to evaluate how to deal with the lack of predictability for climate change factors (Hannah, 2008, McLeod et al., 2008), since changes occur slowly and the effects also interact with other impacts already imposed on the environment such as pollution and anthropogenic disturbance (Kappelle et al., 1999, Smith et al., 2008). Since the actual conservation planning is based on current sea levels further investigation needs to take place to reveal if present sanctuary zones are going to be effective for ongoing conservation in a changing environment. There is a need to determine if targets that prioritize sites where habitat loss will be lower will actually translate into similar representation for the biota. This also needs to be considered in terms of other factors determining ecosystem functioning (e.g. various processes that can vary over a range of spatial scales) (Hawkins et al., 2009). Environmental management in a changing world must, therefore, not only take into account new scenarios expected to arise over the next decades, but also be flexible enough to handle sudden change in predictions, which can hamper long-term biodiversity conservation (Agardy et al., 2003).

Concluding Remarks

Eighty percent of the world's oceanic coastlines comprise of rock platforms backed by steep cliffs (Emery and Kuhn, 1982); this description is very similar to the headland formation for much of the Australian coastline (Hails, 1965) suggesting profound changes in the landscape are going to be seen as the sea level rises. The results from this research have shown that fine-scale habitat heterogeneity indeed influence the distribution patterns of species on intertidal reefs suggesting that specific knowledge about community structure at local level is indispensable to successfully detecting biodiversity hotspots in order to set effective conservation priorities (Banks et al., 2005). Predicting species richness are challenging tasks due to the impossibility of completely measuring the true number of species of any environment (Colwell et al., 2004). It always will have an element of uncertainty. Nevertheless, despite the information obtained through the use of models not be perfect, it would not be available otherwise. The necessity of setting targets for biodiversity conservation must be based on the best available tools to provide a foundation to work on (Ugland et al, 2003). Therefore, based on the results of this research we conclude that remote sensing and ecological modelling tools can be useful tools to predict changes in species richness on intertidal reefs by habitat loss, effectively supporting conservation management in a changing world.

7.0 REFERENCES

Ackerly, D., Loarie, S., Cornwell, W., Weiss, S., Hamilton, H., Branciforte, R. and Kraft, N. 2010. The geography of climate change: implications for conservation biogeography. *Diversity and Distributions,* 16**,** 476-487.

Adams, J. and Chandler, J.H. 2002. Evaluation of LiDAR and medium scale photogrammetry for detecting soft-cliff coastal change. *Photogrammetric Record* 17(99), 405-418.

Agardy, T., Bridgewater, P., Crosby, M. P., Day, J., Dayton, P. K., Kenchington, R., Laffoley, D., Mcconney, P., Murray, P. A. and Parks, J. E. 2003. Dangerous targets? Unresolved issues and ideological clashes around marine protected areas. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 13**,** 353-367.

Algar, A. C., Kharouba, H. M., Young, E. R. and Kerr, J. T. 2009. Predicting the future of species diversity: macroecological theory, climate change, and direct tests of alternative forecasting methods. *Ecography,* 32, 22-33.

Allen T.J. 1999. Building pathways for marine invertebrate conservation. *In:* Ponder W. and Lunney D. (eds), The Other 99%. The Conservation and Biodiversity of Invertebrates. *Transactions of the Royal Zoological Society of New South Wales* (Mosman, Australia).

Akumu, C. E., Pathirana, S., Baban, S. and Bucher, D. 2011. Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. *Journal of Coastal Conservation,* 15**,** 15-22.

Anderson, M. J. 2001. A new method for non-parametric multivariate analysis of variance. *Austral Ecology,* 26**,** 32-46.

Andrew, N.L., Mapstone, B.D., 1987. Sampling and the description of patterns in marine ecology. *Oceanography and Marine Biology Annual Review* 25, 39-90.

Andrew, N. and O'neill, A. 2000. Large-scale patterns in habitat structure on subtidal rocky reefs in New South Wales. *Marine and Freshwater Research,* 51**,** 255-263.

Antoniadou, C.; Voultsiadou, E. and Chintiroglou, C., 2010. Benthic colonization and succession on temperate sublittoral rocky cliffs. *Journal of Experimental Marine Biology and Ecology* 382, 145-153.

Armsworth, P. R., Kendall, B. E. and Davis, F. W. 2004. An introduction to biodiversity concepts for environmental economists. *Resource and Energy Economics,* 26, 115-136.

Arrhenius, O. 1921. Species and area. *Journal of Ecology,* 9, 95-99.

Austin, M. 2002. Spatial prediction of species distribution: an interface between ecological theory and statistical modelling. *Ecological modelling,* 157**,** 101-118.

Baker, E. K. and Harris, P. T. 2011. Habitat Mapping and Marine Management. *Seafloor Geomorphology As Benthic Habitat: GeoHAB Atlas of Seafloor Geomorphic Features and Benthic Habitats***,** 23.

Baltsavias, E.P., 1999. A comparison between photogrammetry and laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 83–94.

Banks, S.A. and Skilleter, G.A., 2002. Mapping intertidal habitats and an evaluation of their conservation status in Queensland, Australia. *Ocean and Coastal Management* 45, 485-509.

Banks, S. A., Skilleter, G. A. and Possingham, H. P. 2005. Intertidal habitat conservation: identifying conservation targets in the absence of detailed biological information. *Aquatic conservation: marine and freshwater ecosystems,* 15**,** 271-288.

Banks, S. A. and Skilleter, G. A. 2007. The importance of incorporating fine-scale habitat data into the design of an intertidal marine reserve system. *Biological conservation,* 138**,** 13-29

Barnett, T. P., Pierce, D. W., Achutarao, K. M., Gleckler, P. J., Santer, B. D., Gregory, J. M. and Washington, W. M. 2005. Penetration of human-induced warming into the world's oceans. *Science,* 309**,** 284-287.

Benkendorff, K. and Davis, A. 2002. Identifying hotspots of molluscan species richness on rocky intertidal reefs. *Biodiversity and Conservation,* 11**,** 1959-1973.

Blaalid, R., Carlsen, T., Kumar, S., Halvorsen, R., Ugland, K. I., Fontana, G. and Kauserud, H. 2012. Changes in the root-associated fungal communities along a primary succession gradient analysed by 454 pyrosequencing. *Molecular Ecology,* 21, 1897–1908.

Bray, M. J. and Hooke, J. M. 1997. Prediction of Soft-Cliff Retreat with Accelerating Sea-Level Rise. *Journal of Coastal Research,* 13**,** 453-467.

Brock, J.C.; Wright, C.W.; Sallenger, A.H.; Krabill, W.B. and Swift, R.N., 2002. Basis and methods of NASA airborne topographic mapper LiDAR surveys for coastal studies. *Journal of Coastal Research* 18(1), 1-13.

Brock, J.C. and Purkis, S.J., 2009. The emerging role of LiDAR remote sensing in coastal research and resource management. *Journal of Coastal Research* SI (53), 1-5.

Brooks, S. M. and Spencer, T. 2011. Shoreline retreat and sediment release in response to accelerating sea level rise: Measuring and modelling cliffline dynamics on the Suffolk Coast, UK. *Global and Planetary Change,* 80**,** 165-179.

Brown, C. J. and Collier, J. S. 2008. Mapping benthic habitat in regions of gradational substrata: an automated approach utilising geophysical, geological, and biological relationships. *Estuarine, Coastal and Shelf Science,* 78**,** 203-214.

Browne, M. A. and Chapman, M. G. 2011. Ecologically informed engineering reduces loss of intertidal biodiversity on artificial shorelines. *Environmental science and technology,* 45, 8204-8207.

Canning-Clode, J., Valdivia, N., Molis, M., Thomason, J. and Wahl, M. 2008. Estimation of regional richness in marine benthic communities: quantifying the error. *Limnology and Oceanography,* 6, 580-590.

Cazenave, A., Dominh, K., Guinehut, S., Berthier, E., Llovel, W., Ramillien, G., Ablain, M. and Larnicol, G. 2009. Sea level budget over 2003–2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo. *Global and Planetary Change,* 65**,** 83-88.

Chapman, M. G. and Underwood, A. J. 1994. Dispersal of the intertidal snail, nodilittorina pyramidalis, in response to the topographic complexity of the substratum. *Journal of Experimental Marine Biology and Ecology,* 179**,** 145-169.

Chapman, M. 2002. Patterns of spatial and temporal variation of macrofauna under boulders in a sheltered boulder field. *Austral Ecology,* 27**,** 211-228.

Chapman, M. 2006. Intertidal seawalls as habitats for molluscs. *Journal of Molluscan Studies,* 72**,** 247-257.

Chapman, M. G. and Underwood, A. J. 2009. Evaluating Accuracy and Precision of Species-Area Relationships for Multiple Estimators and Different Marine Assemblages. *Ecology,* 90, 754-766.

Chapman, M. and Underwood, A. 2011. Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. *Journal of Experimental Marine Biology and Ecology,* 400, 302-313.

Church, J. A.; Gregory, J.M.; Huybrechts, P.; Kuhn M.; Lambeck, K.; Nhuan, M.T.; Qin, D. and Woodworth, P.L., 2001. Changes in Sea Level. *In:* Houghton, J.T; Ding, Y.; Griggs, D.J.; Noguer, M.; Van der Linden, P.J.; Dai, X.; Maskell, K. and Johnson, C.A. (eds.): *Climate Change 2001: The Scientific Basis: Contribution of Working*

Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press (Cambridge, New York), pp. 639-694.

Church, J. A. and White, N. J. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters,* 33**,** L01602.

Church, J. A., White, N. J., Aarup, T., Wilson, W. S., Woodworth, P. L., Domingues, C. M., Hunter, J. R. and Lambeck, K. 2008. Understanding global sea levels: past, present and future. *Sustainability Science,* 3, 9-22.

Chust G.; Galparsoro, I.; Borja, A.; Franco, J. and Uriarte, A., 2008. Coastal and estuarine habitat mapping, using LiDAR height and intensity and multi-spectral imagery. *Estuarine, Coastal and Shelf Science* 78(4), 633-643.

Colwell, R. K., Mao, C. X. and Chang, J. 2004. Interpolating, Extrapolating, and Comparing Incidence-Based Species Accumulation Curves. *Ecology,* 85, 2717-2727.

Congalton, R.G. 1991. A review of assessing the accuracy of classification of remotely sensed data. *Remote Sensing of Environment* 37:35-46.

Connor, E. F. and Mccoy, E. D. 1979. The statistics and biology of the species-area relationship. *American Naturalist,* 791-833.

Cooper, H. M., Chen, Q., Fletcher, C. H. and Barbee, M. M. 2012. Assessing vulnerability due to sea-level rise in Maui, Hawai'i using LiDAR remote sensing and GIS. *Climatic Change***,** 1-17.

Davidson, I. C., Crook, A. C. and Barnes, D. K. 2004. Quantifying spatial patterns of intertidal biodiversity: is movement important? *Marine Ecology,* 25**,** 15-34.

Davidson, I. 2005. Structural gradients in an intertidal hard-bottom community: examining vertical, horizontal, and taxonomic clines in zoobenthic biodiversity. *Marine Biology,* 146**,** 827-839.

Edwards, R. J. 2006. Sea levels: change and variability during warm intervals. *Progress in Physical Geography* 30, 6, 785-796

Emery, K. O., and Kuhn, G. G. 1982. Sea cliffs: their processes, profiles, and classification. *Geological Society of America Bulletin*, *93*(7), 644-654.

ESRI 2010. ArcGIS Desktop. Redlands, CA: Environmental Systems Research Institute.

Fahrig, L. 2001. How much habitat is enough? *Biological conservation,* 100, 65-74.

Fish, M., Cote, I., Horrocks, J., Mulligan, B., Watkinson, A. and Jones, A. 2008. Construction setback regulations and sea-level rise: mitigating sea turtle nesting beach loss. *Ocean and Coastal Management,* 51**,** 330-341.

Firth, L. B., Thompson, R. C., White, F. J., Schofield, M., Skov, M. W., Hoggart, S. P., Jackson, J., Knights, A. M. and Hawkins, S. J. 2013. The importance of water-retaining features for biodiversity on artificial intertidal coastal defence structures. *Diversity and Distributions*.

Foggo, A., Attrill, M. J., Frost, M. T. and Rowden. A. A. 2003. Estimating marine species richness: an evaluation of six extrapolative techniques. *Marine Ecology Progress Series*, 248, 15-26.

Foremann, M. G. G. 1977. Manual for tidal heights analysis and prediction. *Pacific Marine Science Report*, 77-10**,** 58pp.

Fraschetti, S., Terlizzi, A. and Benedetti-Cecchi, L. 2005. Patterns of distribution of marine assemblages from rocky shores: evidence of relevant scales of variation. *Marine Ecology Progress Series*, 296.

Garcia, A. and Smith, J. R. 2012. Factors influencing human visitation of southern California rocky intertidal ecosystems. *Ocean & Coastal Management*.

Gilman, E., Ellison, J. and Coleman, R. 2007. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. *Environmental monitoring and assessment*, 124**,** 105-130.

Gingold, R., Mundo-Ocampo, M., Holovachov, O. and Rocha-Olivares, A. 2010. The role of habitat heterogeneity in structuring the community of intertidal free-living marine nematodes. *Marine biology*, 157, 1741-1753.

Gladstone, W. 2002. The potential value of indicator groups in the selection of marine reserves. *Biological Conservation*, 104**,** 211-220.

Gladstone, W. 2007. Requirements for marine protected areas to conserve the biodiversity of rocky reef fishes. *Aquatic conservation: marine and freshwater ecosystems*, 17**,** 71-87.

Gotelli, N. J. and Colwell, R. K. 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. *Ecology letters*, 4, 379-391.

Gray, J. S. 2000. The measurement of marine species diversity, with an application to the benthic fauna of the Norwegian continental shelf. *Journal of Experimental Marine Biology and Ecology*, 250, 23-49.

Gray, J. S. 2001. Marine diversity: the paradigms in patterns of species richness examined. *Scientia Marina*, 65, 41-56.

Gregory, J. and Huybrechts, P. 2006. Ice-sheet contributions to future sea-level change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 364**,** 1709-1732.

Guichard, F. and Bourget, E. 1998. Topographic heterogeneity, hydrodynamics, and benthic community structure: a scale-dependent cascade. *Marine Ecology Progress Series,* 171**,** 59-70.

Guichard, F., Bourget, E. and Agnard, J. P. 2000. High-resolution remote sensing of intertidal ecosystems: A low-cost technique to link scale-dependent patterns and processes. *Limnology and oceanography***,** 45(2), 328-338.

Guisan, A. and Zimmermann, N. E. 2000. Predictive habitat distribution models in ecology. *Ecological modelling,* 135, 147-186.

Gutierrez, R.; Gibeaut, J.C.; Smyth, R.C.; Hepner, T.L. and Andrews, J.R., 2001. Precise airborne LiDAR surveying for coastal research and geo-hazards applications. *International Archives of Photogrammetry and Remote Sensing, XXXIV-3/W4* (Annapolis, MD), pp. 22-24.

Hails, J. 1965. A critical review of sea-level changes in Eastern Australia since the Last Glacial. *Australian Geographical Studies,* 3**,** 63-78.

Hall, R.K.; Watkins, R.L.; Heggem, D.T.; Bruce Jones, K.; Kaufmann, P.R.; Moore, S.B. and Gregory, S.J., 2009. Quantifying structural physical habitat attributes using LiDAR and hyperspectral imagery. *Environmental Monitoring Assessment* 159, 63–83.

Hannah, L. 2008. Protected areas and climate change. *Annals of the New York Academy of Sciences,* 1134**,** 201-212.

Hanski, I. 2011. Habitat loss, the dynamics of biodiversity, and a perspective on conservation. *AMBIO: A Journal of the Human Environment,* 40**,** 248-255.

Harley, C. D., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J., Thornber, C. S., Rodriguez, L. F., Tomanek, L. and Williams, S. L. 2006. The impacts of climate change in coastal marine systems. *Ecology letters,* 9**,** 228-241.

Harrison, M.A., Smith, S.D.A., 2012. Cross-shelf variation in the structure of molluscan assemblages on shallow, rocky reefs in subtropical, eastern Australia. *Marine Biodiversity,* 42: 203-216

Hawkins, S., Sugden, H., Mieszkowska, N., Moore, P., Poloczanska, E., Leaper, R., Herbert, R. J., Genner, M., Moschella, P. and Thompson, R. 2009. Consequences of climate-driven biodiversity changes for ecosystem functioning of North European rocky shores. *Marine Ecology Progress Series,* 396, 245-259.

He, F. and Legendre, P. 2002. Species Diversity Patterns Derived from Species-Area Models. *Ecology,* 83, 1185-1198.

Helmuth, B., Mieszkowska, N., Moore, P. and Hawkins, S. J. 2006. Living on the Edge of Two Changing Worlds: Forecasting the Responses of Rocky Intertidal Ecosystems to Climate Change. *Annual Review of Ecology, Evolution, and Systematics,* 37, 373-404.

Hewitt, J. E., Thrush, S. F., Halliday, J. and Duffy, C. 2005. The importance of small-scale habitat structure for maintaining beta diversity. *Ecology,* 86, 1619-1626.

Hortal, J., Borges, P. A. V. and Gaspar, C. 2006. Evaluating the performance of species richness estimators: sensitivity to sample grain size. *Journal of Animal Ecology*, 75, 274–287.

Horton, R., Herweijer, C., Rosenzweig, C., Liu, J., Gornitz, V. and Ruane, A. C. 2008. Sea level rise projections for current generation CGCMs based on the semi-empirical method. *Geophysical Research Letters,* 35**,** L02715.

Jackson, A.C. and McIlvenny, J., 2011. Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts *Journal of Experimental Marine Biology and Ecology,* 400(1), 314 – 321.

Johnson, M.E., 1988. Why are ancient rocky shores so uncommon? *Journal of Geology,* 96, 469-480.

Johnson, M. E. and Baarli, B. G. 1999. Diversification of rocky-shore biotas through geologic time. *Geobios,* 32**,** 257-273.

Kappelle, M., Van Vuuren, M. M. and Baas, P. 1999. Effects of climate change on biodiversity: a review and identification of key research issues. *Biodiversity and Conservation,* 8**,** 1383-1397.

Kingsford, M. and Battershill, C., 1998. *Studying temperate marine environments: A handbook for ecologists*. Canterbury University Press.

Kirwan, M. L., Guntenspergen, G. R., D'alpaos, A., Morris, J. T., Mudd, S. M. and Temmerman, S. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters,* 37**,** L23401.

Korsch, R. J. and Harrington, H. J., 1981. Stratigraphic and structural synthesis of the New England Orogen. *Journal of the Geological Society of Australia*, 28(1-2), 205-226.

Kostylev, V.E.; Todd, B.J.; Fader, G.B.J.; Courtney, R.C.; Cameron, G.D.M. and Pickrill, R.A., 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. *Marine Ecology Progress Series* 219, 121-137.

Labrune, C., Grémare, A., Amouroux, J.-M., Sardá, R., Gil, J. and Taboada, S. 2008. Structure and diversity of shallow soft-bottom benthic macrofauna in the Gulf of Lions (NW Mediterranean). *Helgoland Marine Research,* 62, 201-214.

Lambshead, P. J. D. and Boucher, G. 2003. Marine nematode deep-sea biodiversity – hyperdiverse or hype? *Journal of Biogeography,* 30, 475-485.

Levitus, S., Antonov, J. and Boyer, T. 2005. Warming of the world ocean, 1955–2003. *Geophysical Research Letters,* 32**,** L02604.

Liu, X. 2008. Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography,* 32**,** 31-49.

Magierowski, R. H. and Johnson, C. R. 2006. Robustness of surrogates of biodiversity in marine benthic communities. *Ecological Applications,* 16**,** 2264-2275.

Malcolm, H. A., Jordan, A. and Smith, S. D. A. 2010. Biogeographical and cross-shelf patterns of reef fish assemblages in a transition zone. *Marine Biodiversity,* 40**,** 181-193.

Malcolm, H. A., Davies, P. L., Jordan, A. and Smith, S. D. A. 2011. Variation in sea temperature and the East Australian Current in the Solitary Islands region between 2001–2008. *Deep Sea Research Part II: Topical Studies in Oceanography,* 58**,** 616-627.

Marine Parks 2002. Solitary Islands Marine Park Zoning Plan. *Marine Parks Authority, New South Wales, NSW, Australia*.

Mau, R. 1997. A Preliminary Survey of Continental Shelf Habitats of the Solitary Islands Marine Park, New South Wales. *Unpubl. Honours thesis, Southern Cross University, Lismore, Australia*.

McLeod, E., Salm, R., Green, A. and Almany, J. 2008. Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment,* 7**,** 362-370.

McGuinness, K. 1984. Species–area curves. *Biological Reviews,* 59, 423-440.

McQuaid, C. D. and Dower, K. M. 1990. Enhancement of habitat heterogeneity and species richness on rocky shores inundated by sand. *Oecologia,* 84**,** 142-144.

McQuaid, C. and Lindsay, T. L. 2000. Effect of wave exposure on growth and mortality rates of the mussel Perna perna: bottom up regulation of intertidal populations. *Marine Ecology Progress Series,* 206**,** 147-154.

Meager, J. J., Schlacher, T. A. and Green, M. 2011. Topographic complexity and landscape temperature patterns create a dynamic habitat structure on a rocky intertidal shore. *Marine Ecology Progress Series,* 428**,** 1-12.

Meehl, G. A., Washington, W. M., Collins, W. D., Arblaster, J. M., Hu, A., Buja, L. E., Strand, W. G. and Teng, H. 2005. How much more global warming and sea level rise? *Science,* 307**,** 1769-1772.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, A., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M. and Noda, A. 2007. Global climate projections. *Climate change***,** 747-845.

Menge, B. A. And Branch, G. M. 2001. Rocky intertidal communities. *Marine community ecology***,** 221-251.

Mora, C. and Sale, P. F. 2011. Ongoing global biodiversity loss and the need to move beyond protected areas: a review of the technical and practical shortcomings of protected areas on land and sea. *Marine Ecology Progress Series,* 434**,** 251-266.

Morris, J. T., Sundareshwar, P., Nietch, C. T., Kjerfve, B. and Cahoon, D. 2002. Responses of coastal wetlands to rising sea level. *Ecology,* 83**,** 2869-2877.

Murray, T. 2006. Climate change: Greenland's ice on the scales. *Nature,* 443**,** 277-278.

Murray, S.N.; Ambrose, R.F. and Dethier, M.N. 2006. *Monitoring Rocky Shores*. University of California Press. 219p.

Nicholls, R. J., Wong, P. P., Burkett, V., Codignotto, J., Hay, J., Mclean, R., Ragoonaden, S., Woodroffe, C. D., Abuodha, P. and Arblaster, J. 2007. Coastal systems and low-lying areas. in Parry, ML, Canziani, OF, Palutikof, JP, van der Linden, PJ, and Hanson, CE (ed) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge, UK, Cambridge University Press, 2007, 315-356.

NSW Government, 2012. Solitary Islands Marine Park – Recreational and commercial activities. Available from: *http://www.mpa.nsw.gov.au/simp-activities.html (20 February 2012)*

Olabarria, C. and Chapman, M.G., 2001. Comparison of patterns of spatial variation of microgastropods between two contrasting intertidal habitats. *Marine Ecology Progress Series* 220:201-211.

Pearson, R. G. and Dawson, T. P. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global ecology and biogeography,* 12, 361-371.

Pech, D., Condal, A. R., Bourget, E. and Ardisson, P.-L. 2004. Abundance estimation of rocky shore invertebrates at small spatial scale by high-resolution digital photography and digital image analysis. *Journal of Experimental Marine Biology and Ecology,* 299**,** 185-199.

Pethick, J. 2001. Coastal management and sea-level rise. *Catena,* 42**,** 307-322.

Petzold, B.; Reiss, P. and Stössel, W., 1999. Laser scanning-surveying and mapping agencies are using a new technique for the derivation of digital terrain models . *ISPRS Journal of Photogrammetry and Remote Sensing* 54(2-3), 95-104.

Populus, J.; Laurentin, A.; Rollet, C.; Vasquez, M.; Guillaumont, B. and Bonnot-Courtois, C., 2004. Surveying coastal zone topography with airborne remote sensing for benthos mapping. *EARSeLe Proceedings* 3, pp. 105-117.

Raffaelli, D. and Hawkins, S. 1999. *Intertidal Ecology.* Kluwer Academic Publishers.

Reichert, K., Ugland, K. I., Bartsch, I., Hortal, J., Bremner, J. and Kraberg, A. 2010. Species richness estimation: Estimator performance and the influence of rare species. *Limnology and Oceanography Methods,* 8, 294-303.

Robertson,V.W.; Whitman, D.; Zhang, K. and Leatherman, S.P., 2004. Mapping shoreline position using airborne laser altimetry. *Journal of Coastal Research* 20(3), 884-892.

Runting, R. K., Wilson, K. A. and Rhodes, J. R. 2013. Does more mean less? The value of information for conservation planning under sea level rise. *Global Change Biology,* 19**,** 352-363.

Russell, G. L., Gornitz, V. and Miller, J. R. 2000. Regional sea level changes projected by the NASA/GISS atmosphere-ocean model. *Climate Dynamics,* 16**,** 789-797.

Sarkar, S., Justus, J., Fuller, T., Kelley, C., Garson, J. and Mayfield, M. 2005. Effectiveness of environmental surrogates for the selection of conservation area networks. *Conservation Biology,* 19**,** 815-825.

Scrosati, R. and Heaven, C. 2007. Spatial trends in community richness, diversity, and evenness across rocky intertidal environmental stress gradients in eastern Canada. *Marine Ecology Progress Series,* 342**,** 1-14.

Scrosati, R. A., Knox, A. S., Valdivia, N. and Molis, M. 2011. Species richness and diversity across rocky intertidal elevation gradients in Helgoland: testing predictions from an environmental stress model. *Helgoland Marine Research,* 65**,** 91-102.

Senior, C., Jones, R., Lowe, J., Durman, C., Hudson, D., Senior, C., Jones, R., Lowe, J., Durman, C. and Hudson, D. 2002. Predictions of extreme precipitation and sea–level

rise under climate change. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences,* 360**,** 1301-1311.

Shepherd, A. and Wingham, D. 2007. Recent sea-level contributions of the Antarctic and Greenland ice sheets. *Science,* 315**,** 1529-1532.

Skilleter, G.A. and Warren, S., 2000. Effects of habitat modification in mangroves on the structure of mollusc and crab assemblages. *Journal of Experimental Marine Biology and Ecology* 244, 107-129.

Smith, E. P. and Belle, G. V. 1984. Nonparametric Estimation of Species Richness. *Biometrics,* 40, 119-129.

Smith, S.D.A., James, K.A., 2003. Rapid assessment of rocky shore biodiversity in the Byron Bay region. *Report to the NSW Marine Parks Authority*. National Marine Science Centre, Coffs Harbour, Australia. 60 pp.

Smith, S.D.A., 2005. Rapid assessment of invertebrate biodiversity on rocky shores: where there's a whelk there's a way. *Biodiversity and Conservation* 14, 3565 – 3576.

Smith, S. D. 2008. Interpreting molluscan death assemblages on rocky shores: are they representative of the regional fauna? *Journal of Experimental Marine Biology and Ecology,* 366**,** 151-159.

Smith, S.D.A.; Rule, M.J.; Harrison, M. and Dalton, S.J., 2008. Monitoring the sea change: Preliminary assessment of the conservation value of nearshore reefs, and existing impacts, in a high-growth, coastal region of subtropical eastern. *Marine Pollution Bulletin* 56 (3), 525-534.

Smith, S. D. 2009. A state-wide assessment of marine, intertidal, molluscan death assemblages for NSW. *Report to the NSW Department of Environment, Climate Change and Water. National Marine Science Centre, Coffs Harbour.* 30pp.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. and Miller, H. 2007. *Climate change 2014*: *The physical science basis*. Taylor & Francis.

Sousa, W. P. 1979. Disturbance in Marine Intertidal Boulder Fields: The Nonequilibrium Maintenance of Species Diversity. *Ecology,* 60**,** 1225-1239.

Sousa, W. P. 1984. The Role of Disturbance in Natural Communities. *Annual Review of Ecology and Systematics,* 15**,** 353-391.

Stockdonf, H.F.; Sallenger, A.H.; List, J.H. and Holman, R.A., 2002. Estimation of shoreline position and change using airborne topographic LiDAR data. *Journal of Coastal Research,* 18 (3), 502-513.

Stocker, T., Dahe, Q., and Plattner, G. K. E. 2013. Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013, *The Physical Science Basis*.

Terlizzi, A., Anderson, M. J., Bevilacqua, S., Fraschetti, S., Włodarska-Kowalczuk, M. and Ellingsen, K. E. 2009. Beta diversity and taxonomic sufficiency: Do higher-level taxa reflect heterogeneity in species composition? *Diversity and Distributions,* 15**,** 450-458.

Thompson, R., Crowe, T. and Hawkins, S. 2002. Rocky intertidal communities: past environmental changes, present status and predictions for the next 25 years. *Environmental conservation,* 29, 168-191.

Thorner, J., Kumar, L. and Smith, S. D. A. 2013. Fine scale 3D habitat mapping as a biodiversity conservation tool for intertidal rocky reefs. *Journal of Coastal Conservation,* 29 (5), 1184-1190.

Thorner, J., Kumar, L. and Smith S. D. A. 2014. Impacts of climate-change-driven sea level rise on intertidal rocky reef habitats will be variable and site specific. *PLoS ONE* 9(1): e86130.

Ugland, K. I., Gray, J. S. and Ellingsen, K. E. 2003. The species–accumulation curve and estimation of species richness. *Journal of Animal Ecology,* 72, 888-897.

Underwood, A. J. and Skilleter, G. A. 1996. Effects of patch-size on the structure of assemblages in rock pools. *Journal of Experimental Marine Biology and Ecology,* 197**,** 63-90.

Underwood, A. 2000. Experimental ecology of rocky intertidal habitats: what are we learning? *Journal of Experimental Marine Biology and Ecology,* 250**,** 51-76.

Vermeij, G. 1973. Morphological patterns in high-intertidal gastropods: adaptive strategies and their limitations. *Marine Biology,* 20**,** 319-346.

Ward, T., Vanderklift, M., Nicholls, A. and Kenchington, R. 1999. Selecting marine reserves using habitats and species assemblages as surrogates for biological diversity. *Ecological Applications,* 9**,** 691-698.

Warwick, R. and Light, J. 2002. Death assemblages of molluscs on St Martin's Flats, Isles of Scilly: a surrogate for regional biodiversity? *Biodiversity & Conservation,* 11**,** 99-112.

Webster, T.L., Forbes, D.L., Dickie, S. and Shreenan, R., 2004. Using topographig LiDAR to map flood risk from strom-surge events for Charlottetown, Prince Edward Island, Canada. *Canadian Journal of Remote Sensing* 30(1):64-76.

Wentworth, C. K., 1922. A scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30**,** 377-392.

Willis, J. K. and Church, J. A. 2012. Regional sea-level projection. *Science*, 336**,** 550-551.

World Register of Marine Species (WoRMS). Available online at: http://www.marinespecies.org/. [Accessed on 1 March 2014].

Worm, B. and Duffy, J. E. 2003. Biodiversity, productivity and stability in real food webs. *Trends in Ecology and Evolution*, 18, 628-632.

Zann H.P. 2000. The Marine Environment. Technical Annex 1. *State of the Marine Environment report for Australia*. Department of the Environment, Sport and Territories (Canberra, Australia).

Zhou, G.; Song, C.; Simmers, J. and Cheng, P., 2004. Urban 3D GIS From LiDAR and digital aerial images. *Computers and Geosciences* 30(4), 345-353.

Appendix

CONTENT

SPECIES LIST (Source: World Register of Marine Species – WoRMS)

Class Gastropoda	**Intertidal/Sub-tidal**
Family Aplustridae	
Hydatina physis (Linnaeus, 1758)	I
Family Architectonicidae	
Heliacus variegatus (Gmelin, 1791)	I/S
Family Buccinidae	
Cominella eburnea (Reeve, 1846)	I/S
Engina australis (Pease, 1871)	I/S
Engina zonalis (Lamarck, 1822)	I/S
Family Cerithidae	
Cacozeliana granarium (Kiener, 1842)	I/S
Clypeomorus petrosa (Wood, 1828)	I
Family Chilodontidae	
Herpetopoma aspersum (Philippi, 1846)	I/S
Family Columbelidae	
Euplica varians (Sowerby I, 1832)	I
Mitrella tayloriana (Reeve, 1859)	I
Mitrella scripta (Linnaeus, 1758)	I/S
Pardalinops testudinaria (Link, 1807)	I/S
Family Conidae	
Conus coronatus (Gmelin, 1791)	I/S
Conus ebraeus (Linneaus, 1758)	I/S
Conus sponsalis (Hwass in Bruguiere, 1792)	I/S
Family Cypraeidae	
Monetaria annulus (Linnaeus, 1758)	I
Monetaria caputserpentis (Linnaeus, 1758)	I/S
Erronea errones (Linnaeus, 1758)	I
Melicerona felina (Gmelin, 1791)	I/S

Monetaria moneta (Linnaeus, 1758)	I
Family Epitoniidae	
Epitonium jukesianum (Forbes, 1852)	I/S
Epitonium lamellosum (Lamarck, 1822)	I/S
Opalia australis (Lamarck, 1822)	I/S
Family Fasciolariidae	
Nodopelagia brazieri (Angas, 1877)	I/S
Family Fissurellidae	
Amblychilepas nigrita (G. B. Sowerby I, 1835)	I/S
Diodora lineata (G. B. Sowerby I, 1835)	I/S
Montfortula rugosa (Quoy and Gaimard, 1834)	I
Scutus antipodes (Montfort, 1810)	I/S
Tugali parmophoidea (Quoy and Gairmard, 1834)	I/S
Family Hipponicidae	
Antisabia foliacea (Quoy and Gaimard, 1835)	I/S
Family Liottidae	
Australiotia botanica (Hedley, 1915)	I
Family Littorinidae	
Afrolittorina praetermissa (May, 1909)	I
Austrolittorina unifasciata (Gray, 1826)	I
Bembicium nanum (Lamarck, 1822)	I
Nodilittorina pyramidalis (Quoy and Gaimard, 1833)	I
Family Lottiidae	
Notoacmea sp. (Iredale, 1915)	I
Patelloida mufria (Hedley, 1915)	I/S
Family Muricidae	
Bedeva paivae (Crosse, 1864)	I
Cronia aurantiaca (Hombron and Jacquinot, 1848)	I/S
Cronia contracta (Reeve, 1846)	I/S

Lepsiella reticulata (Blainville, 1832)	I
Drupella margariticola (Broderip, in Broderip & Sowerby, 1833)	I/S
Tenguella marginalba (Blainville, 1832)	I
Morula nodicostata (Pease, 1868)	I
Oppomorus noduliferus (Menke, 1829)	I
Phyllocoma speciosa (Angas, 1871)	I/S
Thais orbita (Gmelin, 1791)	I/S
Family Nacellidae	
Cellana conciliata (Iredale, 1940)	I
Cellana tramoserica (Holten, 1802)	I/S
Family Nassaridae	
Nassarius pauper (Gould, 1850)	I/S
Family Naticidae	
Notocochlis gualteriana (Recluz, 1844)	I/S
Family Neritidae	
Nerita albicilla (Linnaeus, 1758)	I
Nerita melanotragus E. A. Smith, 1884	I
Nerita chamaeleon (Linnaeus, 1758)	I
Nerita plicata (Linnaeus, 1758)	I
Nerita sp. (Linnaeus, 1758)	I
Family Patellidae	
Scutellastra peronii (Blainville, 1925)	I
Family Phenacolepadidae	
Cinnalepeta cinnamomea (Gould, 1846)	I/S
Family Planaxidae	
Hinea brasiliana (Lamarck, 1822)	I
Family Ranellidae	
Gyrineum lacunatum (Mighels, 1845)	I/S

Family Rissoinidae	
Rissoina crassa (Angas, 1871)	I/S
Family Siphonariidae	
Siphonaria diemenensis (Quoy and Gaimard, 1833)	I
Siphonaria funiculata (Reeve, 1856)	I
Family Strombidae	
Canarium mutabile (Swainson, 1821)	I/S
Family Triphoridae	
Triphorid sp.	I/S
Family Trochidae	
Austrocochlea porcata (A. Adams, 1853)	I
Bankivia fasciata (Menke, 1830)	I/S
Cantharidella picturata (A. Adams and Angas, 1864)	I
Clanculus clangulus (W. Wood, 1828)	I
Eurytrochus strangei (A. Adams, 1853)	I
Phasianotrochus eximius (Perry, 1811)	I/S
Family Turbinidae	
Astralium tentoriiforme (Jonas, 1845)	I/S
Turbo militaris (Reeve, 1848)	I/S
Lunella undulata (Lightfoot, 1786)	I/S
Family Vermetidae	
Dendropoma sp. (Morch, 1861)	I/S
Class Bivalvia	**Intertidal/Sub-tidal**
Family Arcidae	
Anadara trapezia (Deshayes, 1839)	I/S
Barbatia pistachia (Lamarck, 1819)	I/S
Family Carditidae	
Cardita aviculina (Lamarck, 1819)	I/S
Family Chamidae	

Chama asperella (Lamarck, 1819)	I
Family Galeommatidae (Gray, 1840)	I/S
Family Gryphaeidae	
Hyotissa hyotis (Linnaeus, 1758)	I/S
Parahyotissa numisma (Lamarck, 1819)	I/S
Family Lasaeidae	
Lasaea australis (Lamarck, 1818)	I/S
Family Lucinidae	
Codakia rugifera (Reeve, 1835)	I/S
Family Mytilidae	
Musculus varicosus (Gould, 1844)	I/S
Trychomya hirsuta (Lamarck, 1819)	I/S
Family Noetiidae	
Arcopsis afra (Gmelin, 1791)	I/S
Family Ostreidae	
Saccostrea glomerata (Gould, 1850)	I/S
Family Pinnidae	
Pinna bicolor (Gmelin, 1791)	I/S
Family Psammobiidae	
Heteroglypta contraria (Deshayes in Maillard, 1863)	I/S
Family Pteriidae	
Isognomon nucleus (Lamarck, 1819)	I
Pinctada imbricata fucata (Gould 1850)	I/S
Family Veneridae	
Irus crenatus (Lamarck, 1818)	I/S
Venerupis anomala (Lamarck 1818)	I/S