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An empirical evaluation of the relationship between coral reef calcium carbonate production and wave energy using geospatial techniques at Lizard Island, Great Barrier Reef, Australia

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Abstract

Coral reefs are complex, dynamic ecosystems occurring over a range of spatial and temporal scales. They provide a range of goods and services to mankind, including shoreline protection and support a large portion of marine life. The value of coral reefs exemplifies the need to empirically evaluate the complex interactions operating on them to efficiently manage these systems in light of anthropogenic induced climate change. This study was on Lizard Island's coral reef system, situated within the northern lagoon of the Great Barrier Reef, Australia. Carbonate production is an important process, which underpins reef development and island security. Wave energy is one of the most important physical processes influencing coral reef carbonate production by flushing nutrients around the system, and removing metabolic waste. Other important functions include mechanically breaking down and transporting calcium carbonate. The empirical relationship between carbonate production and wave energy has not been addressed in the current literature and warrants a comprehensive investigation. The aim of this thesis was to employ a unique geospatial approach to combine *in situ* field observations, remote sensing and modelling techniques to develop a spatially continuous distribution model of coral reef calcium carbonate production and to empirically evaluate its relationship against a spatially continuous model of wave energy. Census-based methods and video samples were used to quantify carbonate production using published carbonate production rates of various benthic organisms. Individual benthic models of carbonate producing components included live coral, carbonate sand, green calcareous macroalgae and encrusting calcified algae. Regression analysis used surrogates derived from a digital elevation model of the seafloor and satellite imagery from Worldview-2 to predict the distribution of each component. The spatially continuous carbonate production model was the combined result of each benthic component layer, using their respective carbonate production rates as a weight. Comparing carbonate production and wave energy datasets was performed using global techniques and a series of transects, traversing across the entire reef platform. Results suggest that carbonate production increases with wave energy. However, transect comparisons suggest that a threshold of carbonate production occurs when wave energy exceeds 300 J/m2. These empirical results further the scientific understanding of coral reef ecosystems and can be incorporated into environmental models to predict the impacts of increased wave energy on reef and island development due to rapid climate change.

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An empirical evaluation of the relationship between coral reef calcium carbonate production and wave energy using geospatial techniques at Lizard Island, Great Barrier Reef, Australia

By Alexander Pescud

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The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledges, and has not been submitted in part, or otherwise, for any other degree or qualification.

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1 INTRODUCTION

The empirical relationship between coral reef calcium carbonate production and wave energy has not been established in the current literature and merits a detailed investigation in the light of future climate change. Investigating the relationship between complex ecological and physical processes operating on coral reefs, at the landscape scale, will provide valuable insight into the future response of coral reef systems to changes of extrinsic factors including atmospheric, oceanic and anthropogenic forcing. A geospatial approach combines ecological field data, remote sensing and statistical modelling techniques to exploit and investigate the ecological and physical processes operating on coral reefs. This chapter provides an overview of calcium carbonate production on coral reefs and the methods used to quantify overall carbonate production, the influence of hydrodynamics on carbonate production, an understanding of spatial and temporal scales associated with coral reefs, a review of the application of geospatial technology to the study of coral reefs and a statement of the aims of the present study.

1.1 Introduction

The complex interactions between chemical, biological, and physical processes that govern the development, evolution and stability of coral reef systems over decadal to millennial timescales have inspired a range of definitions to be formulated to describe a coral reef (Kleypas et al. 2001). The definition of a coral reef should incorporate biological and geological components (Wood 1999) and also include environmental components. Therefore, a coral reef should be defined as a tract of corals growing on a massive, three dimensional, wave-resistant, carbonate structure, built almost entirely by skeletons of successive generations of corals and other calcifying organisms over decadal to millennial timescales, over the relict topography of former surfaces (Done 2011). This definition highlights that coral reefs are robust features over geological time scales and recognises that they are the end product of the biological processes, such as carbonate production, which operate over ecological timescales. Investigating the interaction between the complex processes operating on coral reefs over ecological timescales is an important step toward understanding the dynamics of coral reefs systems (Kench 2011).

Changes of intrinsic factors such as biological and physical processes, will force dynamic change within the reef system to an uncertain degree (Perry 2011). This thesis explores the interaction between two intrinsic processes operating on coral reefs (calcium carbonate production and wave energy). This will be done in an empirical manner and yield data that can be used to predict dynamic change within coral reef systems.

Non-empirical statements have been made about the relationship between carbonate production and wave energy. Mallela (2007) suggest that high wave energy regions are associated with high carbonate production. This is a qualitative stipulation that this thesis attempts to test quantitatively.

Coral reefs are generally located between 28°S and 28°N of the equator throughout the Indo-Pacific and Atlantic regions. The distribution of coral reefs across the globe is largely a result of environmental parameters restricting reef-building organisms to certain environmental niches. These parameters include temperature, salinity, light, nutrients and aragonite saturation state (Kleypas et al. 1999; Kench et al. 2009). Light penetration through the water column allows for photosynthetic processes to take place by reef building organisms (Veron 2011). Reef building components on coral reefs rely on photosynthesis to keep pace with sea level rise (Neumann & Macintyre 1985).

Coral reefs are economically and culturally valuable. The Great Barrier Reef, located along the northeast coast of Australia, contributes AU$6.9 billion per year through the provision of goods (e.g., fisheries, aquarium fish, seafood, jewelry) and services (e.g. coastal protection, mangrove and seagrass growth promotion, recreation, tourism and employment) (Access Economics 2009). The value of coral reefs clearly exemplifies the need to understand these systems to manage impacts of climate change.

Kench et al. (2009) recently introduced the term eco-morphodynamics, which can be used to explore the complex relationships interacting between ecological and physical processes on coral reefs. Eco-morphodynamics is the interaction and co-adjustment of physical and ecological processes that is mediated by calcium carbonate production, transfer and deposition within a coral reef system (Kench 2011). Eco-morphodynamics provides a valuable framework for understanding the interactions between ecological and

physical processes, for instance carbonate production and wave energy, which past research has not empirically attempted to evaluate.

Calcium carbonate ($CaCO_3$) production is a fundamental process underpinning reef platform development and provides a source of carbonate sediment to associated sedimentary landforms (Perry et al. 2008). Organisms, which produce carbonate sediment for both framework accumulation and detrital material, include corals, coralline algae, rhodoliths, calcareous green algae (*Halimeda*), molluscs, benthic foraminifera, calcareous epibionts and bioeroders (Montaggioni & Braithwaite 2009).

Wave energy is one of the most important physical factors influencing the morphology of coral reef components (Chappell 1980) and the ecological processes within the coral reef system (Gourlay 2011). The empirical relationship between carbonate production and wave energy on coral reefs has not yet been established in current literature and is the central theme of this thesis. Defining an empirical relationship will enable a further understanding of the eco-morphodynamic relationships operating on coral reefs and provide insight into the future responses of coral reefs to environmental change.

1.2 Calcium carbonate production by coral reefs

1.2.1 Introduction and importance of calcium carbonate production

The formation and development of coral reefs, and associated sedimentary landforms is the result of complex geological, biological, chemical and morphological processes operating on them over decadal to millennial timescales (Darwin 1842; Wood 1999; Woodroffe 2002). Calcium carbonate production is a key constructional component of a coral reef system, which underpins the accumulation of reef framework and provides a source of carbonate sediment to associated sedimentary landforms such as reef islands, beaches and sand aprons (Woodroffe et al. 2007; Perry et al. 2008). The composition of coral reef platforms and associated sedimentary landforms is predominantly calcium carbonate, derived almost entirely from ecological processes (Kench et al. 2009). The types of individual biological components living on coral reefs determine the rate at which calcium carbonate sediment is produced (Hart & Kench 2007), as individual components have varying rates of carbonate production (Montaggioni & Braithwaite 2009). Corals and

other calcareous organisms produce calcium carbonate by the process of calcification. Calcification is the process by which corals and other calcareous organisms derive calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions from the surrounding saturated seawater and convert it to calcium carbonate (Kinzie & Buddemeier 1996). Carbonate production underpins reef framework accumulation (Wood 1999) and the formation and development of low-lying reef islands (McLean & Woodroffe 1994; Yamano et al. 2000), which are both of critical importance to the survival and development of coral reef ecosystems (Gourlay 1988).

1.2.2 Reef platform and island development

A reef platform is the three dimensional carbonate structure built up over millennial timescales by corals and other carbonate producing components (Done 2011). Carbonate production is a critical process operating on coral reefs that underpins reef platform development (Kench et al. 2009). The development of a reef platform is the combined result of five processes, including (1) primary framework growth, (2) secondary framework growth, (3) erosion by physical and biological processes, (4) internal sedimentation and (5) cementation (Wood 1999). These five processes operate in sequence (Woodroffe 2002), with carbonate production initiating primary and secondary framework growth (Perry 2011). The cumulative result of these five processes allows coral reefs to either keep pace with, catch up to, or give up to rates of sea-level rise (Neumann & Macintyre 1985).

Reef islands are low-lying accumulations of reef-derived sediment that have built up on reef platforms over millennial timescales (McLean & Woodroffe 1994; Hopley et al. 2007). Reef islands are the build up of carbonate sediment on top of a reef platform (Hopley et al. 2007). Carbonate production is a process that underpins island development and provides additional sediment supply to these landforms (Woodroffe et al. 2007). The factors that operate over geological timescales (e.g. atoll formation) are important drivers of reef island formation (Hopley et al. 2007). The existence and maintenance of reef islands are important to various Aboriginal and Torres Strait Island cultures (Aston 1995) as well as providing permanent and seasonal habitats for a wide variety of flora and fauna (Gourlay 1988).

The reef-derived sediments, which compose the reef islands, originate from the carbonate production by adjacent reef communities (Woodroffe et al. 2007). The two types of reef islands are sandy *cays* and shingle *motu*, which are generally found in low-energy and high-energy environments respectively (Stoddart & Steers 1977). The modes of long-term formation and development (possible initiating around 3500 years before present) of reef islands have generated much speculation amongst the literature (McLean & Woodroffe 1994). Chivas et al. (1986) investigated the evolution of Lady Elliot Island, which is a coral cay located on the Great Barrier Reef. Radiocarbon dating of *Tridacna* shells from shingle ridges determined that island growth has consistently accumulated sediment and continues to build up at a gradual rate since 3200 years before present. Woodroffe et al. (2007) support this claim when they investigated the depositional chronology of Warraber Island, which is a small sand cay in the Torres Strait. Accelerator mass spectrometry radiocarbon dating of sand grains from various parts of the island indicated continual accretion of sediment from the adjacent reef since 3000 years before present. Hopley et al. (2007) argue that the formation of reef islands, on the Great Barrier Reef, occurred during a rapid deposition period around 3500 years before present and only minor additions and modifications have been made ever since. Suggestions by Mclean et al. (1978) indicate that reef islands accreted during one or more episodes during the Holocene high-energy window (3500-3000 years before present). In either case, reef islands are considered dynamic sedimentary landforms underpinned by carbonate production and oceanographic processes (McLean & Woodroffe 1994). Reef islands are composed of carbonate sediment, which is derived from the surrounding reef system. Carbonate production on reefs is therefore an important factor influencing the volume, dynamics and morphology of reef islands. By focusing attention on the interactions between ecological factors (e.g. carbonate production) and physical processes (e.g. wave energy), which underpin island development, it is possible to further our understanding of how these processes will operate in the future and in turn, influence reef island development (Gourlay 1988).

1.2.3 Measuring overall community calcium carbonate production

Estimates of carbonate production by individual benthic cover types have been made in past research (Chave et al. 1972; Kinsey 1985; Boucher et al. 1998; Chisholm 2000) and are commonly expressed in kilograms of calcium carbonate produced per meter squared per year (kg $CaCO_3$ m^{-2} a^{-1}) (Table 1.1). Quantifying carbonate production of modern coral reefs at the landscape scale has proven to be a difficult task (Montaggioni & Braithwaite 2009). The three main approaches to the measurement of carbonate production on coral reef platforms are the alkalinity-anomaly approach (Smith and Kinsey 1976), biological census-based method (Chave et al. 1972; Harney & Fletcher 2003; Moses et al. 2009) and stratigraphic evidence using drill cores (Davies & Hopley 1983). Each approach has its advantages and disadvantages. The most suitable method to adopt to estimate carbonate production will depend on the research aims and what the research wants to accomplish (Kench et al. 2009). Table 1.1 summarises the published carbonate production rates of various benthic cover types derived from the alkalinity-anomaly technique, census-based method and stratigraphic evidence.

Table 1.1: Estimations of gross calcium carbonate production on reef systems, benthic cover types and reef zones

Location	$CaCO_3$ production rate (kg $CaCO_3$ m^{-2} a^{-1})	Method	Description	Reference
Great Barrier Reef, Australia	0.5 - 10	Alkalinity-anomaly	Gross carbonate production ranges from 0.5 kg $CaCO_3$ m^{-2} a^{-1}, for sand and rubble regions, 4 kg $CaCO_3$ m^{-2} a^{-1} by algal encrusted pavement and 10 kg $CaCO_3$ m^{-2} a^{-1} for a coral/algal substrate.	(Kinsey 1985)
Six different reef flat environments ranging from latitudes 23°S to 25° N	0.5 – 4.5	Alkalinity-anomaly	Shallow seaward reef flat environments typically produce between 3.6 and 4.5 $CaCO_3$ m^{-2} a^{-1}. Top of coral pinnacle produced 3.7 $CaCO_3$ m^{-2} a^{-1} and protected environments (i.e. lagoon) produce between 0.5 and 1.5 $CaCO_3$ m^{-2} a^{-1}.	(Smith & Kinsey 1976)
Warraber Island, Torres Strait	1.66	Census-based	0-4 m deep inter-tidal reef flat	(Hart & Kench 2007)
Cane Bay, ST. Croix, U.S. Virgin Island	1.21	Census-based	Fringing reef shelf, 0-40 m deep including reef flat, slope and shelf. Corals were considered the dominant carbonate producing organisms (1.13 kg $CaCO_3$ m^{-2} a^{-1}), while coralline algae and other organisms including molluscs, foraminifera and echinoderms produced 0.02 and 0.06 kg $CaCO_3$ m^{-2} a^{-1} respectively.	(Hubbard et al. 1990)
Kailua Bay, Oahu, Hawaii	1.22	Census-based	Gross carbonate production by corals and encrusting coralline algae.	(Harney & Fletcher 2003)
Discovery Bay, Jamaica	5.2	Census-based	Gross productivity by corals (*A. palmate*, *A. cercicornis*, *M. annularis and Agarcia*) was 3.08 kg $CaCO_3$ m^{-2} a^{-1}. Coral and non-coral on the fore-reef terrace and fore-reef slope produced 5.2 kg $CaCO_3$ m^{-2} a^{-1}.	(Land 1979)
Hypothetical reef system	5	Census-based	Lagoon	(Chave et al. 1972)
Hypothetical reef system	3	Census-based	Reef flat	(Chave et al. 1972)
Hypothetical reef system	9	Census-based	Algal ridge	(Chave et al. 1972)
Hypothetical reef system	60	Census-based	Upper slope	(Chave et al. 1972)
Hypothetical reef system	8	Census-based	Lower slope	(Chave et al. 1972)
Great Barrier reef, Australia	0.5 – 4.5	Stratigraphic evidence	(See Table 1.2)	(Hopley 1982)

The alkalinity-anomaly approach was developed by Smith and Kinsey (1976) and is based on the mass balance of calcium carbonate precipitation from seawater. Estimating the carbonate production by coral reefs is accomplished by measuring the reduction in the total alkalinity of the water multiplied by an estimate of the water flushing through the reef system. This method has successfully been used to measure carbonate production on various reef systems. The LIMER expedition (1975) investigated calcification rates over different reefal zones at Lizard Island on the Great Barrier Reef, Australia. Smith and Harrison (1977) adopted the alkalinity-anomaly approach to measure the carbonate production of windward reef slope on Enewetak Atoll. This approach provides a single, integrated measure of carbonate production across the total benthic community (Kinsey 1985).

Smith and Kinsey (1976) argue that the alkalinity-anomaly approach avoids potential inaccuracies that are associated with the biological census-based method. They further argue that stratigraphic evidence could reveal inaccuracies associated with physical dispersion and concentration of detrital material that the alkalinity approach avoids. The convenient and nondestructive manner of the alkalinity approach is favorable when studying coral reefs. Technological advancements will increase the precision of collected data by the alkalinity-anomaly approach, which provide a useful tool to estimate carbonate production on coral reefs (Chisholm & Gattuso 1991). However, even though the alkalinity-anomaly approach provides real-time data on the carbonate production at a specific site (Smith & Kinsey 1976), it is unable to quantify the carbonate production associated with individual benthic components living on the reef platform (Mallela & Perry 2007; Perry 2011).

The census-based method can be used to quantify the carbonate production associated with individual groups of organisms by estimating the overall carbonate production based on reef cover type and carbonate production rates associated with each individual benthic component (Harney & Fletcher 2003). This approach is widely adopted to quantify carbonate production on coral reefs (Hart & Kench 2007; Moses et al. 2009) and is the basis for carbonate budget investigations (Perry 2011). The census-based approach assumes that the whole is equal to the sum of the parts (Atkinson & Grigg 1984; Moses et al. 2009) and that the production of carbonate sediment on coral reefs is an additive emergent process (Hatcher 1997).

Many studies have adopted census-based methods to investigate carbonate production on coral reefs throughout the Caribbean (Land 1979; Scoffin et al. 1980; Hubbard et al. 1990; Mallela & Perry 2007), Indo-pacific regions (Edinger et al. 2000; Harney & Fletcher 2003) and on hypothetical reef systems (Chave et al. 1972). Census-based studies have been used to explore the changes in marine environmental conditions and associated impacts on carbonate production (Eakin 1996; Mallela & Perry 2007). The census-based approach was adopted by Eakin (1996) to investigate carbonate production at Uva Island in the eastern Pacific before and after the influence of thermal stress related to pre- and post-El Niño climate fluctuations. Findings suggest that the reef has changed from a depositional environment to an erosional environment due to the decrease in carbonate production. Mallela and Perry (2007) used the census-based method to explore the relationship between carbonate production and the influence of terrestrial runoff on two coral reefs at Rio Bueno, Jamaica. Their results suggested that increased fluvial influence, including pollution, reduces carbonate production on reef front sites. Census-based methods have also been employed to regionally (Vecsei 2001) and globally (Kleypas 1997; Vecsei 2004) estimate coral reef carbonate production. The census-based approach provides a valuable tool to understand the structural and functional processes operating on coral reef systems at a range of spatial scales (Harney & Fletcher 2003).

Estimations of carbonate production can be made using drill cores from a coral reef platform by assessment of stratigraphy and radiocarbon dating techniques (Davies & Hopley 1983). Coral reef framework is particularly amendable to radiometric dating, which can be used to derive carbonate production values at different geomorphic zones on a coral reef (Woodroffe 2002). Table 1.2 summarises carbonate production rates, derived from drill cores, at different geomorphic locations on reef systems within the Great Barrier Reef, Australia.

Table 1.2: Calcification rates from stratigraphic studies based on Hopley (1982) (adapted from Woodroffe 2002).

Reef Environment	**Carbonate production rate (kg $CaCO_3$ m^{-2} a^{-1})**
Outer slope	1.4
Algal rim	4.0
Reef flat coral zone	4.5
Sand flats	0.3
Lagoonal patch reef	1.5
Deep lagoon	0.5

The data collected by drill cores provides estimations of carbonate production over millennial timescales (Perry 2011) as opposed to the alkalinity-anomaly and the census-based approach, which provide present day estimates of carbonate production (Smith & Kinsey 1976; Hart & Kench 2007). The drill core approach provides useful long-term evidence of coral reef development and evolution. However, it doesn't consider the highly variable ecological processes that are operating in the present time and is also limited to the location of the drill core, which does not capture spatial variability (Perry et al. 2008).

Selecting the most appropriate method to measure carbonate production on a coral reef depends on the questions and aims of the investigation (Perry et al. 2012). This thesis employed the census-based approach as it was the most ideal method to (1) quantify carbonate production at the landscape scale (Vecsei 2001), (2) distinguish between individual carbonate producing benthic components on coral reefs (Atkinson & Grigg 1984) and (3) to investigate the distribution of carbonate production over ecological timescales (Perry et al. 2008; Kench et al. 2009). For these reasons, the census-based approach was employed to estimate overall carbonate production on Lizard Island's coral reef system.

1.3 Hydrodynamics: influence on calcium carbonate production

Hydrodynamics is the study of water motion including waves, currents and tides, and the forces that cause the motion (Gourlay 2011). The existing literature investigating water motion on coral reefs has helped to developed a comprehensive understanding of coral reef ecology and biogeochemical dynamics (Hearn 2011a). While there is an expanding body of literature dedicated to understand hydrodynamic conditions on coral reefs (Hearn 2011b), there have been no attempts to empirically evaluate the relationship between carbonate production and wave energy. These two processes are fundamental to the development of coral reefs and their associated sedimentary landforms and warrant a comprehensive investigation to define and empirical relationship.

Waves are generated by wind blowing on the oceans surface and are termed swell when they propagate away from the area of formation. The amount of wave-energy is dependent on the strength and duration of the wind blowing, and the presence of storm activity

(Woodroffe & Leon 2010). Coral reef systems develop under various wave energy conditions ranging from sheltered low-energy to cyclone-exposed regions (Anthony 2009). Wave energy is considered one of the most important physical influences shaping the morphology (Chappell 1980) and influencing the ecology on modern coral reefs (Gourlay 2011). Higher wave energy optimizes mixing and nutrient uptake by corals and calcareous organisms (Grigg 1998). In contrast, extreme high-wave energy can cause damaging effects to corals and calcareous organisms including toppling, overturning, fragmentation, tissue damage, smothering from mobilised sediment and bleaching (Anthony 2009). These extreme high-wave energy conditions, due to storms, are important for generating detritus material for reef framework and island development (Braithwaite et al. 2000), however, they disturb the growth of living corals and other calcareous organisms (Grigg 1998).

Tides are low frequency waves, which fluctuate level caused by the gravitational forces of the sun and moon (Woodroffe 2002). Tides produce currents that transport nutrients and flush water around coral reef platforms (Veron 2011). Regions of continual nutrient supply and flushing are ideal for coral and calcareous organisms.

The amount of water motion on coral reefs will impact benthic community morphology, zonation and survival (Chappell 1980; Done 2011). Table 1.3 highlights the hydrodynamic processes that influence coral reef carbonate production and also the impact of water quality, temperature and salinity.

Table 1.3: Hydrodynamic processes influencing carbonate production on coral reefs.

Hydrodynamic process	Influence on coral reef carbonate production	Reference
Wave energy	Significantly higher rates of carbonate production occur in high wave energy environments. Wave energy and its dissipation by the benthos enable higher rates of carbonate production productivity compared to low wave energy settings. Mechanical erosion of coral and other calcareous benthic components is associated with higher wave energy. Waves enable the circulation of nutrients and carbonate sediment around the reef platform. Mechanical breakdown of corals and other calcareous organisms is an essential procedure for reef framework accretion.	(Mallela 2007) (Hearn et al. 2001)
Currents	Currents supply nutrients to coral reefs and circulate nutrients around the reef platform.	(Done 2011)
Tides	A large tidal range in shallow clear waters provides an optimal environment for corals and calcareous benthic components due to the light availability combined with the continuous flushing and nutrient transport. Tidal currents locally provide nutrient renewal for carbonate production producing organisms.	(Veron 2011)
Extreme events	Hurricanes, tsunamis, and storms increase mechanical forcing on coral reefs and are key erosional processes that can cause major destruction to reef platforms. Removing and damaging carbonate production producers on the reef platform the will, in turn, reduce the carbonate production for that site.	(Woodroffe 2002) (Montaggioni & Braithwaite 2009)
Water quality and nutrients	The transport of nutrients to corals and calcareous organisms is by wave energy and currents. Decrease of carbonate production has been correlated with increased terrestrial riverine inputs such as turbidity, light attenuation, sedimentation, and nutrient inputs. High nutrient concentrations potentially lead to an ecological shift in the community on coral reefs. High nutrients can initiate macroalgae to dominate, while low nutrient concentrations are distinctive of high coral cover, hence, increased carbonate production areas.	(Mallela 2007) (Perry et al. 2008) (Done 1992)
Sea surface temperature	Carbonate production by coral reefs is generally restricted to between 18°C and 33-34°C. Production rates decline linearly as a function of latitude towards the outer limits of the tropical belt (30°S and 30°N).	(Grigg 1982) (Montaggioni & Braithwaite 2009) (Kleypas et al. 1999)
Salinity	Benthic components producing carbonate production generally are restricted to marine salinity levels of 35-36 particle salinity units (psu), but some can tolerate levels up to 46 psu.	(Montaggioni & Braithwaite 2009)

Relatively few studies have attempted to define a relationship between overall calcium carbonate production along environmental gradients (low stress – high stress), especially hydrodynamic forcing. A study conducted at four sites within the Rio Bueno embayment, north Jamaica, investigated the distribution and abundance of encrusting calcareous organisms along a gradient of terrestrial disturbance (e.g. turbidity, light attenuation, sedimentation, and nutrient inputs). The study suggested that the abundance of calcareous encrusting organisms decreases when exposed to higher concentrations of terrestrial input and increases with proximity away from the terrestrial input. A conclusion was also stated that increased abundance of encrusters inhabit higher wave energy regions, which in turn suggests increased carbonate production at higher wave energy regions (Mallela 2007). Mallela and Perry (2007) contradict this claim, that terrestrial influence negatively effects carbonate production, by quantifying community carbonate production using census-based methods at two sites within the Rio Bueno embayment, north Jamaica. They found an increase of net carbonate production at the site closer to the terrestrial influence and a lower net carbonate production at the site impacted by no terrestrial influence. They concluded that the overall carbonate production of an area is a function of its parts, and in the case of Rio Beuno embayment, corals are the dominant carbonate producers, not calcareous encrusters. The increased abundance of live coral will produce higher amounts of carbonate sediment. Martindale (1992) explored the zonation and morphological growth forms of important carbonate producers, including calcified epidonts (crustose coralline algae, bryozoans, foraminiferans and serpulid worms) in relation to environmental factors such as water turbulence and incident light. Results suggest a distinct zonation of benthic components, indicating that higher abundance of calcified epidonts (and in turn increased carbonate production) correlates with higher exposure to both water turbulence (wave energy) and light. Fabricius and De'ath (2001) estimated the spatial distribution of crustose coralline algae on 144 different reefs of the Great Barrier Reef and compared it with the amount of fluvial influence. They found a decrease in percentage cover of crustose coralline algae (and hence decrease in carbonate production) associated with an increase in turbid conditions (close proximity to rivers). These studies investigate carbonate production in relation to hydrodynamic impacts. However, they did not define empirical relationships between carbonate production and wave energy. Measuring empirical relationship between carbonate production and wave energy is a necessary investigation to further our understanding of hydrodynamic processes influencing the ecology of coral reefs.

1.3.1 Climate change: implications for coral reef calcium carbonate production

Coral reefs are vulnerable ecosystems to rapid climate change. The environmental processes operating on coral reefs have and will persist to be altered by climate change (Hoegh-Guldberg et al. 2007). Various aspects of changing environmental conditions associated with climate change are summarised in Table 1.4. Understanding the extent of these impacts will assist the implementation of effective management strategies.

Table 1.4: Changes to environmental conditions associated with rapid climate change.

Environmental process	Influence of climate change on coral reefs	Reference
Wind/Waves	Modest changes in frequency and intensity of wind energy can have a major impact on the wave climate. Projections of 2-5% increase of wind energy will produce higher energy waves to transfer over reef systems.	(CSIRO & Bureau of Meteorology 2007)
Sea surface temperature	The IPCC 2007 suggests a rise of is sea temperature over the 21st century. Extended periods of elevated sea surface temperatures cause coral bleaching that could introduce macroalgae and bacterial slime to take over a reef system.	(Veron 2008)
Ocean acidification	Increase anthropogenic CO_2 within the ocean causes acidification, which can decrease coral calcification and coral growth up to 40%.	(Hoegh-Guldberg et al. 2007)
Severe weather	Cyclone intensities are increasing with warming oceans. A recent study by De’th et al. 2012 suggests that cyclones are responsible for 48% loss of coral cover.	(De'ath et al. 2012)
Sea-level rise	Thermal expansion of the oceans and melting of ice caps will increase the rate of sea-level rise over the 21st century. The fourth assessment report by the IPCC 2007 indicates a potential sea level rise of 0.22 to 0.44 m by the mid-2090s under A1B scenario.	(IPCC 2007)

1.4 Scales underpinning coral reef systems

Coastal environments are dynamic systems that adjust to the surrounding environmental conditions over a range of spatial and temporal timescales (Wright & Thom 1977; Franklin 1995). Understanding the structural (benthic assemblages, geomorphological zonation) and functional (wave energy) properties of coral reef systems requires observations and analysis at the landscape scale, which is defined at 10s to 1000s km^2 (Perry et al. 2008). The factors influencing the geomorphology and ecological zonation on coral reefs operates at smaller scales and includes the hydrodynamic conditions, sediment

production, transport and deposition (Done 2011). The recent introduction of the term *eco-morphodynamics* enables ecologists and geomorphologists to conceptualise these processes that operate on coral reefs across the spatial and temporal scales over which they exist (Kench et al. 2009). Observing phenomena through a range of spatial and temporal scales is necessary as certain patterns and processes are revealed at different scales (Franklin 1995; Fortin & Dale 2005).

The spatial scales in which coral reefs operate range from microscopic to global scales and the temporal processes operate over instantaneous to geological time scales (Hatcher 1997). Figure 1.1 illustrates the various scales associated with coral reef development. Instantaneous processes include carbonate production by corals and calcareous organisms, which aggregate over millennial timescales to construct fringing, barrier and atoll reef systems. All processes are connected and interact over a range of scales. Any impact occurring within a certain scale will propagate through to the other scales (Van Gardingen et al. 1997). For instance, an ecological shift form a coral dominated reef system to an algae dominated reef system, due to environmental disturbance over decadal timescales, will reduce reef growth and impact the reef over geological times as it may not be able to keep pace with sea level rise (Perry et al. 2008). Geospatial analysis enables investigation of coral reef processes over a range of spatial scales from carbonate production by individual benthic components to geomorphological zonation of benthic components at the landscape scale. Geospatial analysis is a valuable tool to understand coral reef systems over a range of scales, which is desirable for coastal management (Yang 2009).

Observing relationships between phenomena and processes across a variety of spatial scales is an important approach to adopt. Investigating relationships across global scale (the entire reef system) and local scale (transects across wave energy gradients) will expose intricate relationships that would otherwise be imbedded in datasets and not revealed (Fortin & Dale 2005). This thesis employs both global and local scale comparison techniques to thoroughly explore the empirical relationships between carbonate production and wave energy across the reef platform. Adopting this approach will ensure patterns and relationships embedded within the datasets are exposed.

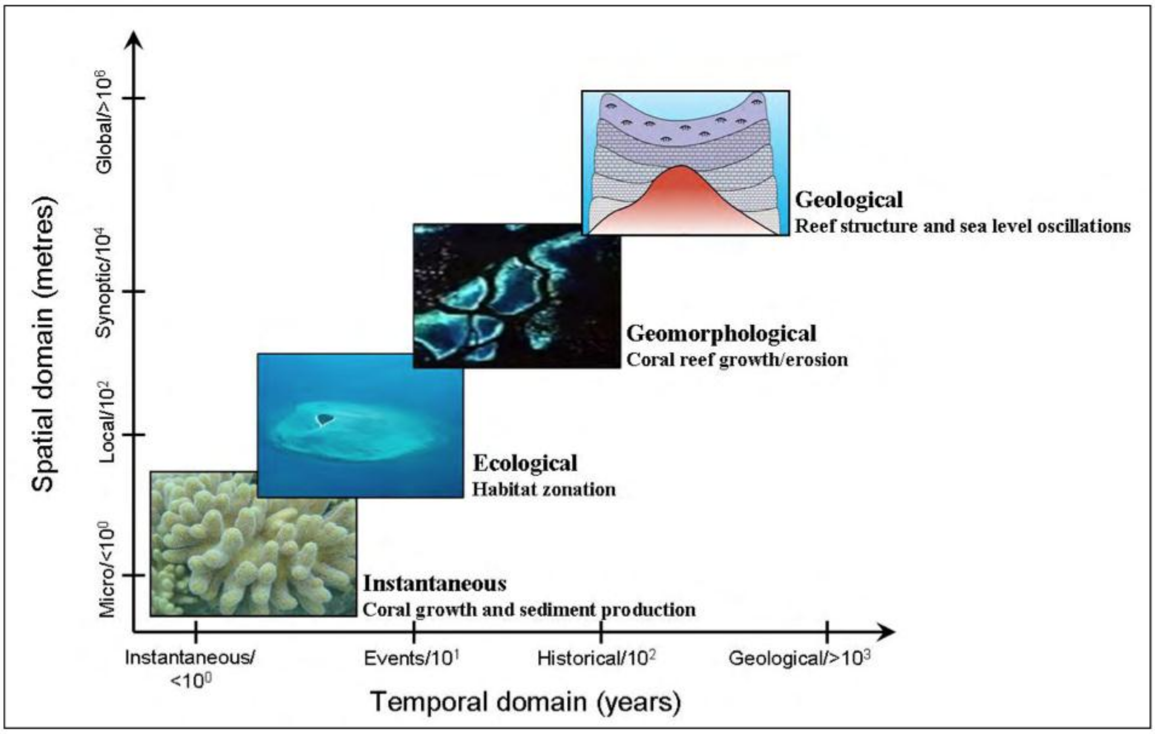


Figure 1.1: Spatial and temporal scales of coral reef systems. Source: (Leon 2010).

1.5 Geospatial applications to the study of coral reefs

Building a model of these processes and interrogating the relationships between carbonate production and wave energy is possible by adopting a geospatial approach. This unique approach combines fieldwork observations, remotely sensed data and modelling techniques within computer software, which then enables analysis and interpretation of the phenomena under observation at various spatial scales (Woodroffe & Leon 2010).

1.5.1 In situ field investigation

Field surveys are an essential requirement of geospatial modelling and Geographic Information System investigations. Creating a model requires the abstraction and representation of phenomena such as carbonate production and wave energy, which in turn requires detailed field observation as a link to reality. Three important steps to undertake a geospatial modelling exercise include the identification of features (e.g. individual benthic components), spatially locating each feature (ground referencing) and finally to generate sufficient additional data to undertake validation procedures and accuracy assessment (Green et al. 2000).

Spatially referenced data is an essential requirement of a coastal modelling process (Mumby et al. 2004). *In situ* data collection requires the use of a Global Positioning Systems (GPS), which allocates precise geographic coordinates to the feature under observation through triangulation using a network of satellites (Jensen 2007). GPS can be used to collect (1) measurements of prominent features *in situ* to assist geometric correction and (2) to assign positions to field data (Green et al. 2000).

1.5.2 Remote sensing of coastal environments

Coral reefs are dynamic structures controlled by a range of physical, chemical and biological processes operating over various spatial and temporal scales. The most appropriate scale to observe a reef process requires an understanding of the spatial and temporal scales in which processes of interest to the analyst operate (Mumby et al. 2004). Remote sensing can be applied to study coral reefs at scales ranging from 10s to 1000s km^2, which is an appropriate scale to observe the heterogeneous nature of a coral reef landscape (Perry et al. 2008).

Remote sensing is the collection of data without coming into physical contact with the target (Jensen 2007). Imaging sensors are mounted on platforms such as aircrafts, satellites, ships and buoys to collect electromagnetic radiation (EMR) or acoustic sound waves reflected or emitted by Earth’s surface (Andréfouët 2011). Figure 1.2 illustrates the remote sensing process undertaken by a passive satellite sensor. Solar radiation penetrates through the atmosphere and water column and reflects unique spectral signature associated with different benthic component types, such as coral or seagrass (Hochberg et al. 2004).

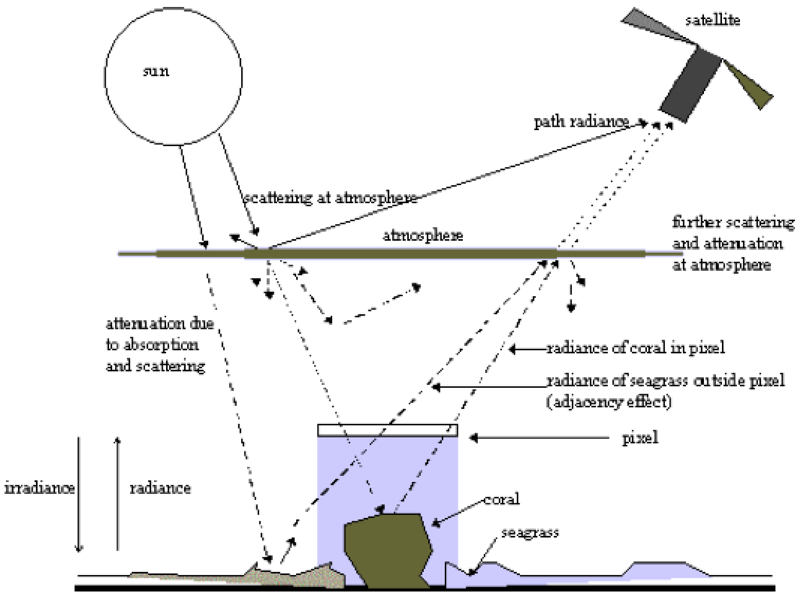


Figure 1.2: Schematic representation illustrating the atmospheric interface and the passage of electromagnetic radiation from the sun to the satellite sensor (source: Edwards 1999, page. 81).

Optical sensors and acoustic sensors are widely used to study coral reefs (Hochberg & Atkinson 2003). The advantages and disadvantages of optical and acoustic remote sensing of coral reefs are outlined in Table 1.5. Optical satellite sensors can penetrate up to 30 meters water depth, with blue wavelengths (400 nm) of the electromagnetic spectrum penetrating further into the water than red wavelengths (600 nm) (Mumby et al. 2004).

Table 1.5: Advantages and disadvantages of optical and acoustic remote sensing to observe coral reefs.

Optical sensor		**Acoustic sensor**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Synoptic coverage of large spatial areas	Restricted to non-cloudy days to observe benthic environment	Greater depth of penetration	Sensor platforms (e.g. boat) are restricted to depths >5m
Penetrates shallow marine environments (0 – 30 m)	Limited penetration through water column when there is suspended sediment	Unrestrained by optical water properties	Does not provide spatial continuity over large areas
Ability to discriminate between benthic cover types (spectral signatures)	Constrained by optical water properties (dissolved organic matter and suspended sediment)	Measurement of seafloor structure	Unable to observe pigmentation of benthic components

Justifying the ideal remote sensor to use in an application is important, due to the wide variety of sensor types to choose from (Mumby et al. 2004). The synoptic coverage of satellite sensor images provides useful spatial data for environmental models and captures the heterogeneity in the landscape (Woodcock et al. 1997). Satellite imagery has been

widely adopted in coral reef research (Hochberg & Atkinson 2003) and has the ability to scale-up coral reef carbonate production (Andréfouët & Payri 2000). Table 1.6 summarises the remote sensing applications currently being used to study coral reefs.

Worldview-2 (WV-2) is a remote sensing satellite that has unique spectral bands that enable penetration of the water column using the shorter visible wavelengths of the electromagnetic spectrum (400 nm – 900 nm). WV-2 satellite imagery includes the panchromatic band and 8 multispectral bands with high spatial resolution of 0.5 m (Figure 1.3). WV-2 satellite imagery was selected to use in this investigation as its spectral diversity allows for detailed observation of benthic components living on the seafloor (Collin et al. 2012). The unique coastal band (400-450 nm), blue band (450-510 nm) and green band (510-580 nm) allows for deeper penetration of the water column and higher spatial resolution compared to other commercially available satellite sensors. Longer wavelength bands become absorbed by the water column and are therefore not good for underwater applications.

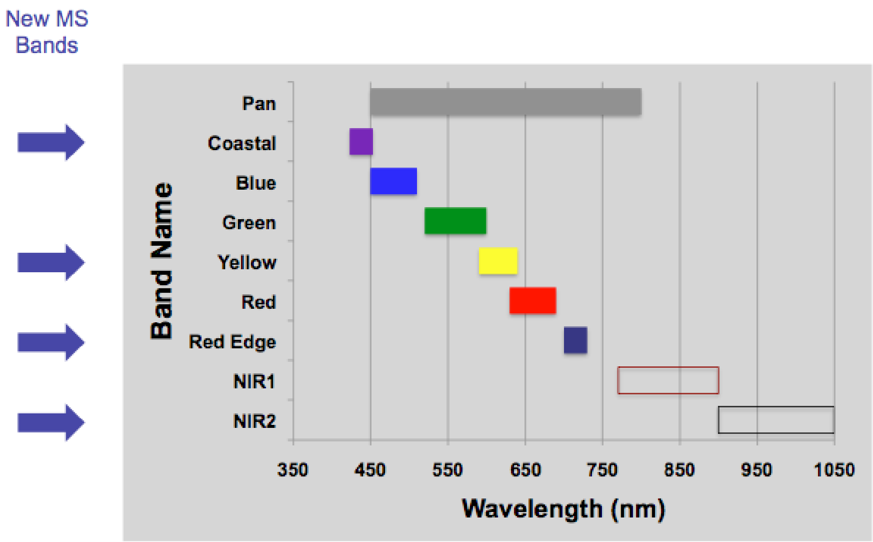


Figure 1.3: Spectral wavebands of the Worldview-2 satellite (source: Satellite Imaging Corporation 2012).

Table 1.6: Overview of the most common remote sensing platforms, sensor types, and applications to study coral reefs (adapted from Mumby et al. 2004; Andrefouet 2011).

Platform	**Aircraft**			**Satellite**			
Sensor technology	Laser	Hyperspectral	Photography	Hyperspectral	Multispectral (High resolution)	Multispectral (Medium resolution)	Multispectral (Low resolution)
Example of sensor	Lidar, LADS	AVIRIS, CASI, ATM	SLR camera	Hyperion	Ikonos, Quickbird, WV-2	Landsat TM, SPOT, IRS	SeaWIFS, MODIS, OCM
Reef community	✓	✓	✓	?	✓	✓	n
Coral species and algal cover	?	✓?	n	?	✓?	n	n
Reef community (>5 classes)	✓?	✓	✓	?	✓?	✓?	n
Reef community (<5 classes)	✓	✓	✓	?	✓	✓	n
Occurrence of bleaching	?	?	✓?	?	?	n	n
Location of shallow reefal areas	✓	✓	✓	?	✓	✓	✓?
Structural complexity (rugosity)	?	?	?	?	?	n	n
Bathymetry	✓	✓	✓?	?	✓	✓	✓?

Note: ✓indicates routinely possible; ✓? Indicates demonstrated in limited cases only; ? indicates untested but a possibility in the future; n indicates not possible at this time. LADS = Laser Airborne Depth Sounder, AVIRIS = Airborne Visible/Infrared Imaging Spectrometer, CASI = Compact Airborne Spectrographic Imager, ATM = Airborne Thematic Mapper, SLR = Single Lens Reflex, TM = Thematic Mapper, SPOT = Systematic Probatoire de l'Observations de la Terre, IRS = Indian Remote Sensing Satellite, SeaWiFS = Sea Wide Field-of-view Sensor, MODIS = Moderate Resolution Imaging Spectroradiometer, OCM = Ocean Colour Monitoring, WV-2 = WorldView-2.

1.5.3 Modelling coral reefs adopting a geospatial approach

A model is an abstraction and description of the real world or part of it (McDonnell & Kemp 1995) in which we can construct tentative assumptions that may be useful in understanding complex environmental processes operating over a range of spatial and temporal scales (Box 1976). The distribution of corals and calcareous organisms on a coral reef platform are the direct result of physical and ecological processes operating on them (Hatcher 1997). Modelling the distribution of benthic components on coral reefs is possible using physical environmental variables as predictors of benthic cover type. The distribution and processes influencing their distribution are conceptualised and represented within a computer system as vector and/or raster based datasets (Burrough & McDonnell 1998).

The structural and functional components of coral reef environments exist in spatio-temporal patches that can be observed, analysed and modelled at various scales (Perry et al. 2008). Understanding patterns at the landscape scale enables scientific research to assist engineers and decision makers to effectively manage coral reef ecosystems (Woodroffe & Leon 2010). Conceptualising processes that operate on coral reefs, at the landscape scale, is an observational science rather than an experimental science. Observational sciences do not manipulate the levels of explanatory variables in a lab setting, which is the approach adopted in the experimental sciences, but rather, they employ gradients across space and measures the levels of explanatory variables (Haining 2003).

Both structural and functional phenomenon exists within geographic location and can enter into scientific explanation in two ways. Firstly, location as place, where varying levels of input variables influence a particular location. Secondly, location as space, which focuses on the positioning of objects in relation to the surrounding objects and questions whether variability can be described by the location of an object with respect to the surrounding objects (Haining 2003). The ability to expose statistical patterns, to understand the relationships between controlling processes and benthic component distribution focuses on the core principle of geography: near things are more related than distant things (Tobler 1970).

Geographic Information Systems provide a digital environment for data integration, synthesis and modelling. Various spatial analysis techniques are useful to understand coastal environments and conceptualise geographic phenomena. Yang (2009) provides a summary of the spatial analysis techniques appropriate for coastal ecosystem research. The major techniques enabling the analysis of spatial data include basic spatial analysis (e.g. buffering, neighborhood function, map overlay and distance modelling), spatial pattern analysis (e.g. spatial autocorrelation, quadrat analysis, nearest-neighbour analysis, landscape metrics and spatial interpolation), statistical spatial analysis (e.g. regression analysis, clustering analysis, principle component analysis, artificial neural networks and fuzzy logic system) and spatial modelling (e.g. statistical models, cellular automata models and agent-based models).

The distribution of benthic components across a reef platform have recently been explored using spatial statistics and ordinary least square regression (Hamylton et al. 2012). Other studies have also utlilised statistical analysis techniques, remote sensing and fieldwork investigations to build models of coral reef ecosystems (Garza-Pérez et al. 2004; Arias-González et al. 2012).

Exploring the relationships between benthic component distribution (dependent variable) and physical predictors (independent variable), such as depth, slope and topographic complexity is the basis of ecological modelling, which enables synoptic distribution and abundance models of benthic cover type to be created (Mellin et al. 2010).

Explaining the cause of the spatial distribution of carbonate production can be attributed to the distribution of live coral and calcareous algae and the underlying physical processes such as, depth, slope and bathymetric complexity (Haining 2003). The spatial distribution of carbonate production can be assessed against important processes, which influence its distribution, such as wave energy. Wave energy is a controlling factor of live coral distribution, which in turn will control carbonate production distribution.

1.6 Aims

Coral reefs are threatened by rapid climate change over the coming decades (Kleypas et al. 1999). Changing environmental conditions will impact the complex processes occurring on coral reefs to an uncertain degree. A better understanding of the processes occurring on coral reefs will enable effective management plans to be implemented for preservation of these fragile ecosystems.

Calcium carbonate production is an important element of coral reef systems and a process, which underpins island development, beach nourishment and reef accretion (Perry 2011). The response of carbonate production on coral reefs to a change in surrounding environmental conditions, due to rapid climate change, is uncertain. Wave energy is a key process occurring on coral reefs (Gourlay 2011) and influences the distribution of carbonate producing benthic components, such as coral (Kench et al. 2009).

This thesis attempts to further understand the complex interactions between carbonate production and wave energy operating on coral reef systems at the landscape scale. A geospatial approach has been adopted to create spatially continuous models of benthic cover type, gross carbonate production and investigate the relationships between carbonate production and wave energy using global and local comparisons. The lack of empirical research dedicated to understand the interaction between dynamic processes on coral reefs at the landscape scale has influenced this investigation. The aims of this research are to:

1. Adopt a geospatial approach to model the spatial distribution of carbonate producing benthic components on Lizard Island's reef system using *in situ* video footage, satellite imagery, benthic terrain variables and ordinary least square regression.
2. Model the overall distribution of coral reef calcium carbonate production on Lizard Island, Great Barrier Reef, Australia.
3. Investigate the empirical relationship between coral reef calcium carbonate production and wave energy using a range of global and local comparison techniques.

2 METHODOLOGY

2.1 Introduction

Investigating the relationship between reef calcium carbonate production and wave energy will help to further understand the complexity and dynamics of the processes occurring on coral reefs. In this investigation, a geospatial approach is adopted to create a spatial distribution model of overall reef calcium carbonate production on a coral reef and compare it with a spatially continuous wave energy model across an entire reef system. Global comparisons and local comparisons between the two models explore these important relationships.

This chapter outlines the geospatial approach used to model and explore the relationship between calcium carbonate production and wave energy. Figure 2.1 is an overall schematic that illustrates the steps taken to build the spatially continuous distribution models of benthic cover, overall carbonate production and outlines the comparison methods used to investigate the relationship between carbonate production and wave energy.

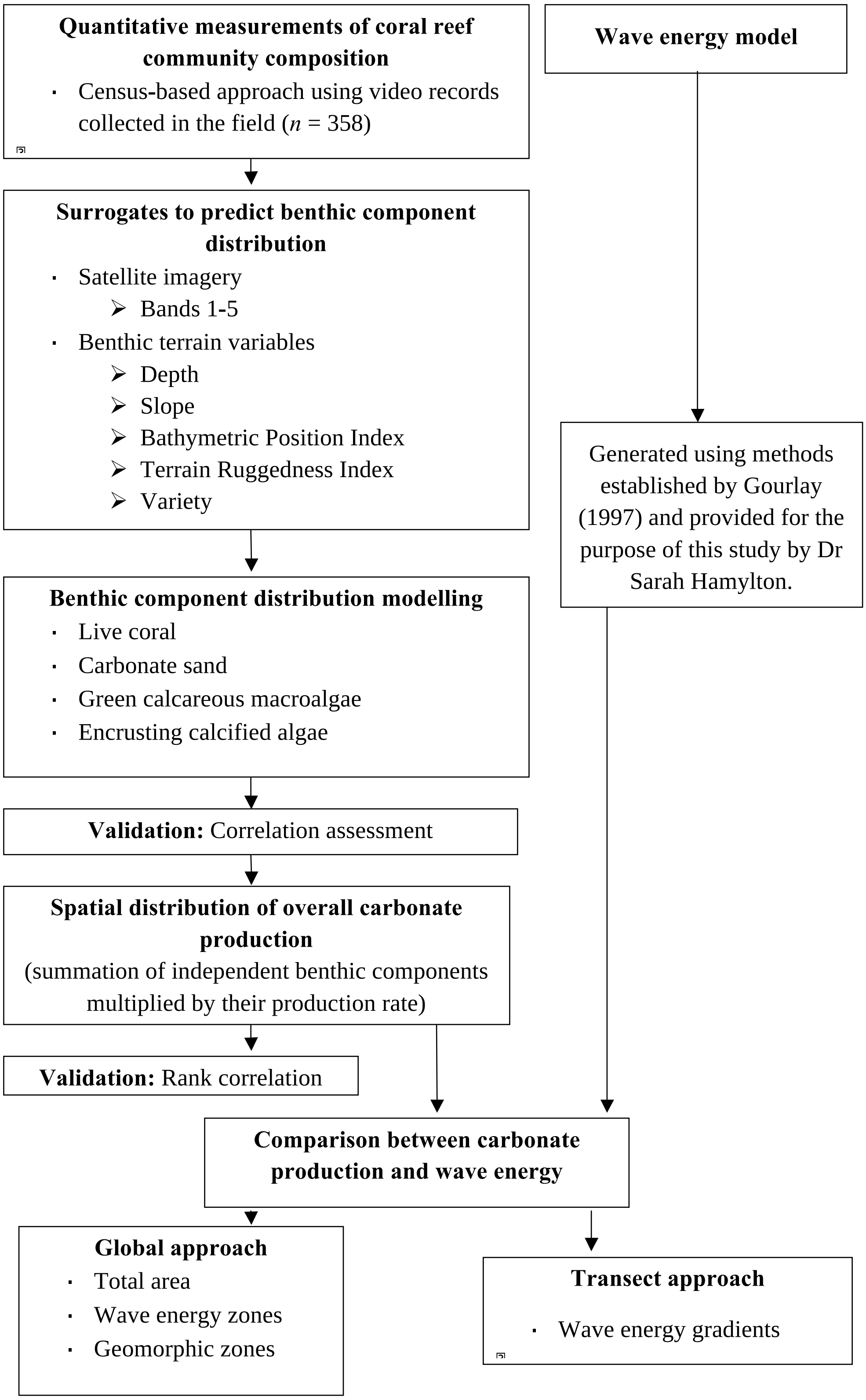


Figure 2.1: Flow diagram of the overall methodology employed to model the relationship between coral reef calcium carbonate production and wave energy (*n* = number of video samples).

2.2 Study site

Lizard Island (14°40′S, 145°27′E) is situated within the relatively shallow (< 40 m depth) lagoon of the Northern Great Barrier Reef province (NGBR), off the northeast coast of Australia (Figure 2.2). Lizard Island is composed of three late Permian, granite, continental islands (Rees et al. 2006) connected by fringing and barrier type coral reef systems (Flood 1984). Coral reef platforms surround the three terrigenous islands and a semi-enclosed, small lagoon (Kinsey 1977) with a maximum depth of 14 meters.

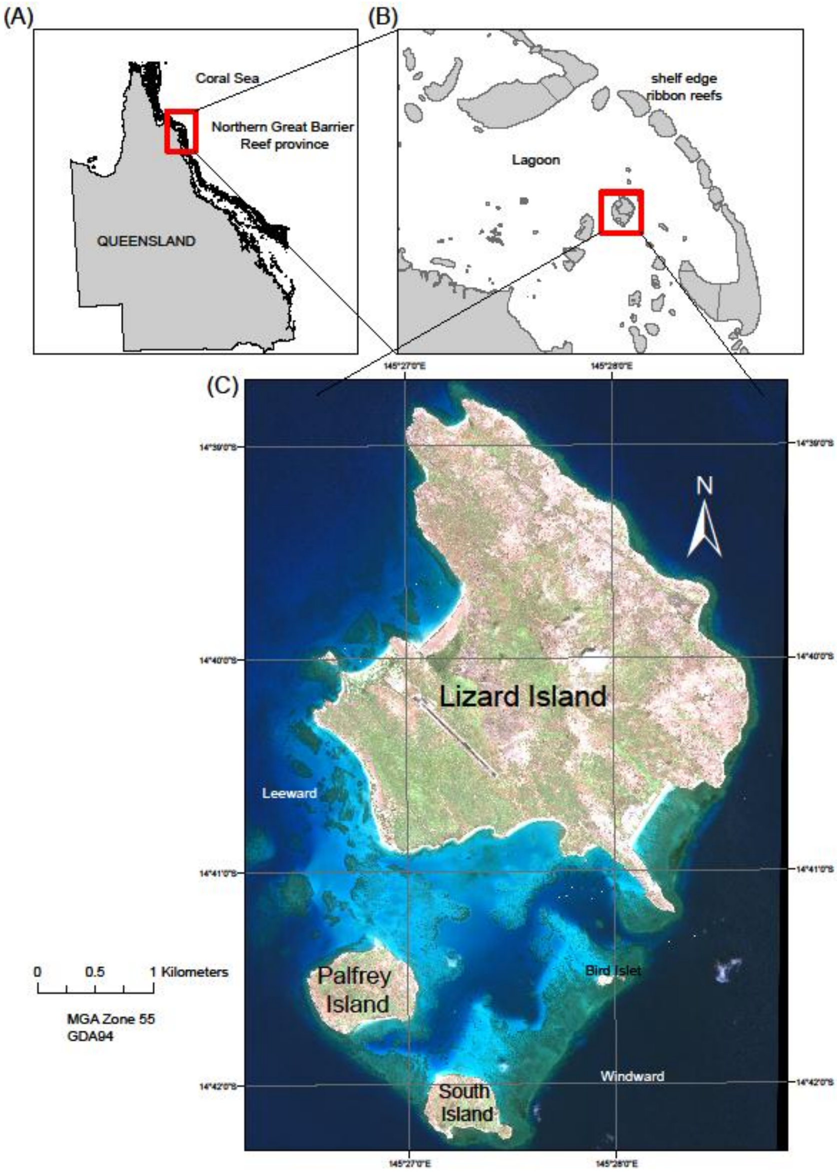


Figure 2.2: Location of Lizard Island within the Great Barrier Reef, Australia. (A) Illustrates the location of the NGBR province off the coast of Queensland, Australia. (B) Shows the outer ribbon reefs and (C) illustrates the continental islands and the reef system at Lizard Island.

No continental rivers discharge into this part of the Great Barrier Reef and sandy quartz beaches have developed in the bays and inlets of the island (Flood 1984). The series of patch and ribbon reefs that have developed on the edge of the Australian continental shelf (Figure 2.2B) restrict propagation of large period oceanic swells to Lizard Island. The wave climate at Lizard Island is, therefore, almost exclusively produced by the prevailing southeasterly winds (Madin et al. 2006) which blow for eight months of the year. Published estimates of carbonate production in different reef environments and by individual components on Lizard Island's coral reef system are summarised in Table 2.1.

Table 2.1: Estimates of calcium carbonate production rates within various locations Lizard Island's coral reef system.

<table>
<tr><th>Environment</th><th>Carbonate production rate
(kg $CaCO_3$ m^{-2} a^{-1})</th><th>Method</th><th>Reference</th></tr>
<tr><td>Complete reef system</td><td>1.80</td><td>Alkalinity-anomaly approach</td><td>(Kinsey 1985)</td></tr>
<tr><td>Windward reef flat</td><td>3.47 – 3.83</td><td rowspan="5">Alkalinity-anomaly approach</td><td rowspan="5">(LIMER 1975)</td></tr>
<tr><td>Coral pinnacle/
outer seaward reef fringes</td><td>3.65</td></tr>
<tr><td rowspan="3">Central to leeward reef flat</td><td>0.91</td></tr>
<tr><td>3.10</td></tr>
<tr><td>4.56</td></tr>
<tr><td>Algal pavement</td><td>3.80</td><td rowspan="4">Alkalinity-anomaly approach</td><td rowspan="4">(Smith & Kinsey 1976)
(Boucher et al. 1998)</td></tr>
<tr><td>Coral-algal cover</td><td>3.60</td></tr>
<tr><td>Top of coral pinnacle</td><td>3.70</td></tr>
<tr><td>Lagoon</td><td>1.00</td></tr>
<tr><td>Benthic foraminifera
(Marginopora vertebralis)</td><td>0.78</td><td>Incubation
(short-term and long-term)</td><td>(Smith & Wiebe 1977)</td></tr>
<tr><td>Windward crustose coralline algae</td><td>1.50 – 10.30</td><td>Alkalinity-anomaly approach</td><td>(Chisholm 2000)</td></tr>
</table>

2.3 Quantitative measurements of coral reef community composition: census-based approach

2.3.1 Fieldwork: collection of video samples

Performing a census-based approach to measure coral reefs gross carbonate production requires the collection of *in situ* video snapshots of the benthic environment around Lizard Island. Dr. Hamylton and Prof. Woodroffe collected 364 video snapshots on a field expedition to Lizard Island from the 7th- 17th December 2011.

At each point of interest, a 30 second underwater video snapshot was taken after the underwater video camera was rapidly deployed and lowered on a cable from the boat and held so that it drifted within close proximity (<50 cm) to the sea floor. The geographical position of each video snapshot was recorded using a GPS. A total of 364 video snapshots of oblique underwater footage were collected (see Figure 2.3). This type of field survey method enabled large areas and types of coral reef to be visually recorded and generated a dataset that was applied in further analysis.

The satellite imagery used in this investigation has high spatial resolution and warrants an intensive sampling method such as underwater video (Green et al. 2000). Underwater video sampling was therefore determined to be the most appropriate field sampling method to adopt for the census-based approach.

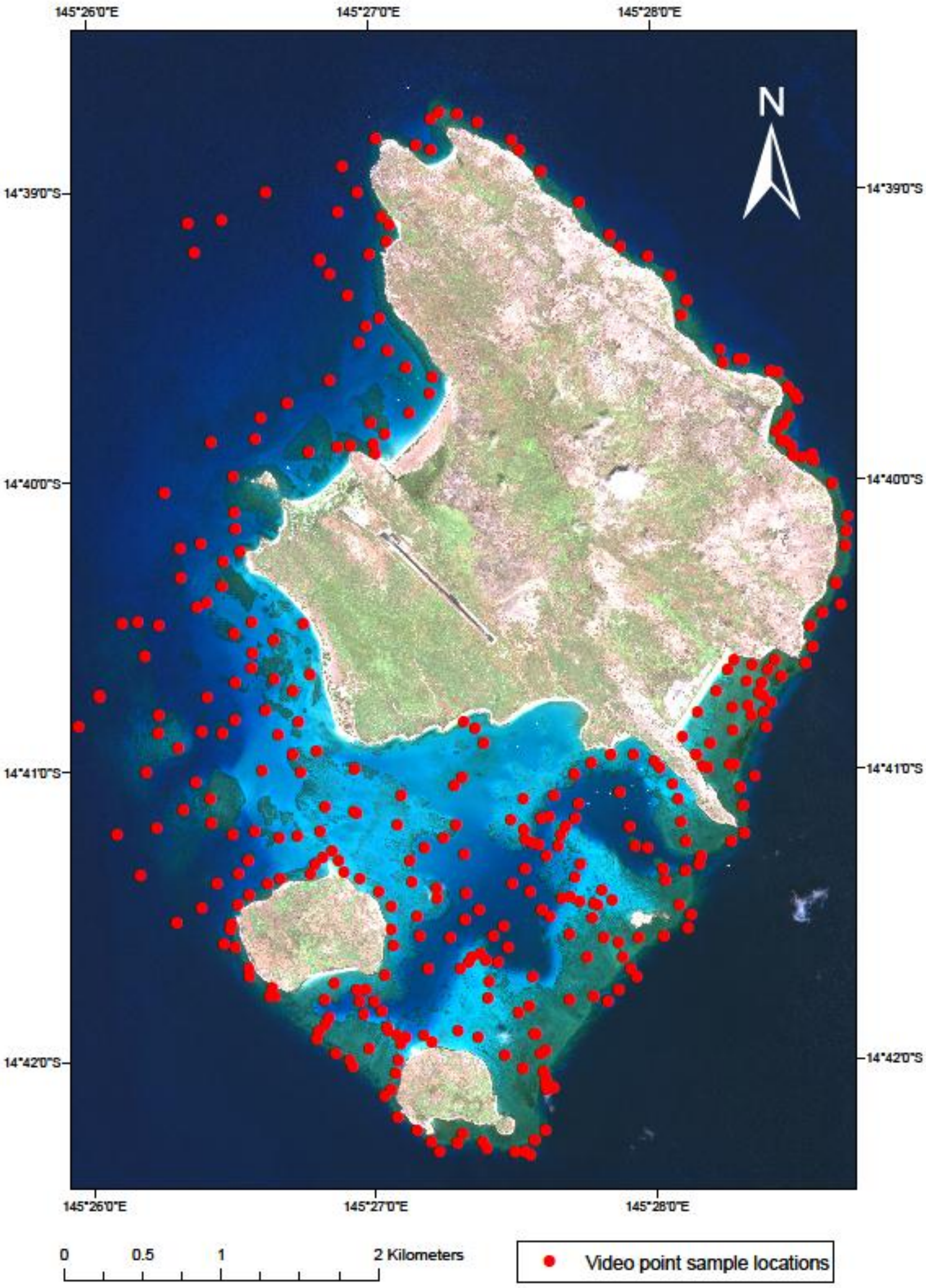


Figure 2.3: Location of video point sample sites surveyed around Lizard Island.

2.3.2 Visual interpretation of video samples

A video sample analysis was undertaken to create a robust data set containing percentage cover of benthic components present on Lizard Island's reef system. Six video snapshots showed poor visibility of the reef system and were discarded from the analysis. The remaining 358 video snapshots were individually examined and the percentage cover of

each benthic component was recorded in a table in Microsoft Excel. Observed benthic components that made a contribution to calcium carbonate production included live coral, carbonate sand, green calcareous macroalgae and encrusting calcified algae (Figure 2.4). Seagrass, dead coral and rubble percentage cover was recorded but not used in further analysis. Each individual video snapshot summed up to 100% and contained some or all of the benthic components shown in Figure 2.4 and Appendix A. A classification table of benthic component types existing on Lizard Island's reef system was created to ensure consistent classification of each video snapshot (see Appendix A). The analysis of all video footage was undertaken over a short period of time (3-4 days) by the author of this thesis to ensure consistent classification.

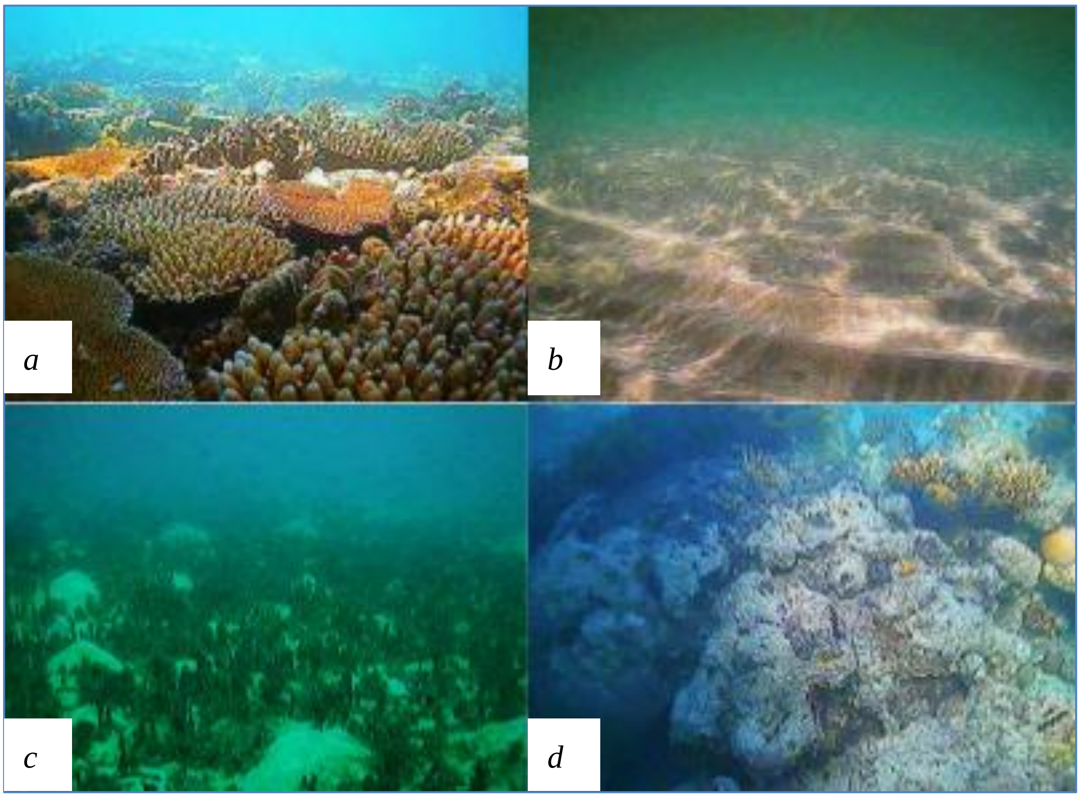


Figure 2.4: Video footage sample of benthic cover type of the four major carbonate producing components on Lizard Island including (*a*) live coral, (*b*) carbonate sand, (*c*) green calcareous macroalgae and (*d*) encrusting calcified algae.

2.3.3 Gross carbonate production of each video sample

Gross calcium carbonate production of each video snapshot was determined using a census-based approach (Harney & Fletcher 2003). Carbonate production was estimated as

the sum of recently published carbonate production rates of each benthic component (Table 2.2) multiplied by their abundance in each video sample. This approach has successfully been adopted in past research to measure gross carbonate production on coral reefs from various parts of the world (Harney & Fletcher 2003; Hart & Kench 2007; Moses et al. 2009; Shi et al. 2009; Perry et al. 2012).

Carbonate production rates for each benthic component type were selected from existing literature. Accurate measurements of carbonate production rates for Lizard Island's benthic components were selected from the most recently published carbonate production rates, within closest proximity to Lizard Island (Table 2.2). A shapefile was created using ArcCatalogue software containing the geographic locations of each video snapshot, benthic component percentages and carbonate production values of each point. This exercise was conducted for the purpose of validating the overall community model of calcium carbonate production.

Table 2.2: Selected estimates rates of calcium carbonate production for each benthic component at Lizard Island's coral reef system.

Benthic component	Carbonate production rate (kg $CaCO_3$ m^{-2} a^{-1})	Justification	Reference
Live coral	3	Average rate derived from coral calcification research in the Torres Strait region and Lizard Island's coral pinnacle/seaward reef fringes.	(Hart & Kench 2007) (LIMER 1975)
Carbonate sand	0.24	Estimated using *in situ* incubation chambers from a barrier type reef Moorea, French Polynesia.	(Boucher et al. 1998)
Green calcareous macroalgae	1.8	Average rate of calcified green macroalgae calcification estimated from Kailu Bay, Oahu, Hawaii	(Harney & Fletcher 2003)
Encrusting calcified algae	1.494	Measured rate of crustose coralline algae from the windward reef at Lizard Island	(Chisholm 2000)

2.4 Surrogates to predict benthic component distribution

Surrogates including spectral reflectance acquired from satellite sensors and benthic terrain variables have the potential to predict the distribution of benthic components on coral reef systems. The surrogates used to predict the distribution of benthic components are discussed in detail in the following sections.

2.4.1 Satellite imagery

Remote sensing has proven to be a very useful and efficient tool to study coral reefs (Andréfouët & Payri 2000) and was therefore adopted in this investigation for modelling purposes. The most suited satellite remote sensing tool for this investigation was the Worldview-2 satellite imagery because of its unique spectral bands primarily built to penetrate the water column with greater precision than other commercially available satellite sensors.

A pan sharpened Worldview-2 image, acquired in October 2011, was pre processed for atmospheric and water column correction (by Dr. Hamylton) and provide spectral reflectance data that were used in regression analysis to predict the distribution of benthic carbonate producers on Lizard Island's coral reef system. Spectral information from the coastal, blue, green and yellow wavebands were extracted from the satellite image and added to the point shapefile containing the benthic cover percentages and the carbonate production values using the 3D analyst tool in ArcGIS.

2.4.2 Benthic terrain variables

A digital elevation model (DEM) is a digital representation of the elevation of locations on the land surface (McDonnell & Kemp 1995) and in the case of this investigation, a DEM is a digital representation of the underwater bathymetry surrounding Lizard Island. The DEM was used to derive benthic terrain variables of the coral reef system surrounding Lizard Island.

The DEM was supplied by Dr. Javier Leon. The two meter resolution, continuous DEM was constructed using a shallow water bathymetric model, multi-beam, single-beam and

Australian Hydrographic Office chart spot depths along with LiDAR (light detection and ranging) topographic elevation data. The DEM was used to derive independent environmental variables as inputs for regression analysis to predict the distribution of benthic cover types on Lizard Island's coral reef system.

Using the DEM various terrain parameters were derived and investigated as potential proxies for the actual distribution of benthic carbonate producing components around Lizard Island. Depth, slope, Bathymetric Position Index (BPI), Terrain Ruggedness Index (TRI) and variety were derived from the DEM and used for predictive distribution modelling.

2.4.2.1 Depth

Various organisms on coral reefs rely on photosynthesis to survive and grow, keeping pace with sea level rise. For this reason, water depth is a major influence on the coral reef components distribution. As water depth increases, less sunlight will penetrate, resulting in a limited source of energy for photosynthesizing organisms living on coral reefs. Depth was calculated from the supplied DEM (Figure 2.6a).

2.4.2.2 Slope

The slope on a coral reef system has a strong influence on the distribution of benthic components such as coral and has successfully been used in past predictive habitat models (Guinan et al. 2009). Slope is a first derivative of a DEM and was calculated using spatial analyst tools in ArcGIS. The slope represents the rate of change of elevation for each DEM cell (Figure 2.6b).

2.4.2.3 Bathymetric Position Index

BPI is a calculated metric that defines the elevation of locations with reference to the overall landscape. It is a local statistical operator that works by comparing the value of a pixel to its neighbours by iteratively placing a window over each pixel and applying

Equation 1. It has been recognised as a support tool for marine habitat mapping (Guinan et al. 2009). The BPI map provides valuable geomorphological information such as slopes, depressions, crest lines, flat areas and was considered an important variable to predict the distribution of benthic components on Lizard Island's coral reef system. The following algorithm creates a BPI raster layer using the DEM and user defined radii (Lundblad et al. 2006)

$$\mathrm{BPI}(\mathit{scalefactor}) = \mathrm{int}((\mathit{bathy} - \mathrm{focalmean}(\mathit{bathy}, \mathrm{annulus}, \mathit{irad}, \mathit{orad}) + 0.5) \qquad \text{Equation 1}$$

where the *scalefactor* is defined by the outer radius in map units multiplied by the DEM data resolution. The inner annulus-shaped analysis neighbourhood is denoted by *irad* and the outer by *orad*. The term *bathy* represents the digital elevation model used in the analysis.

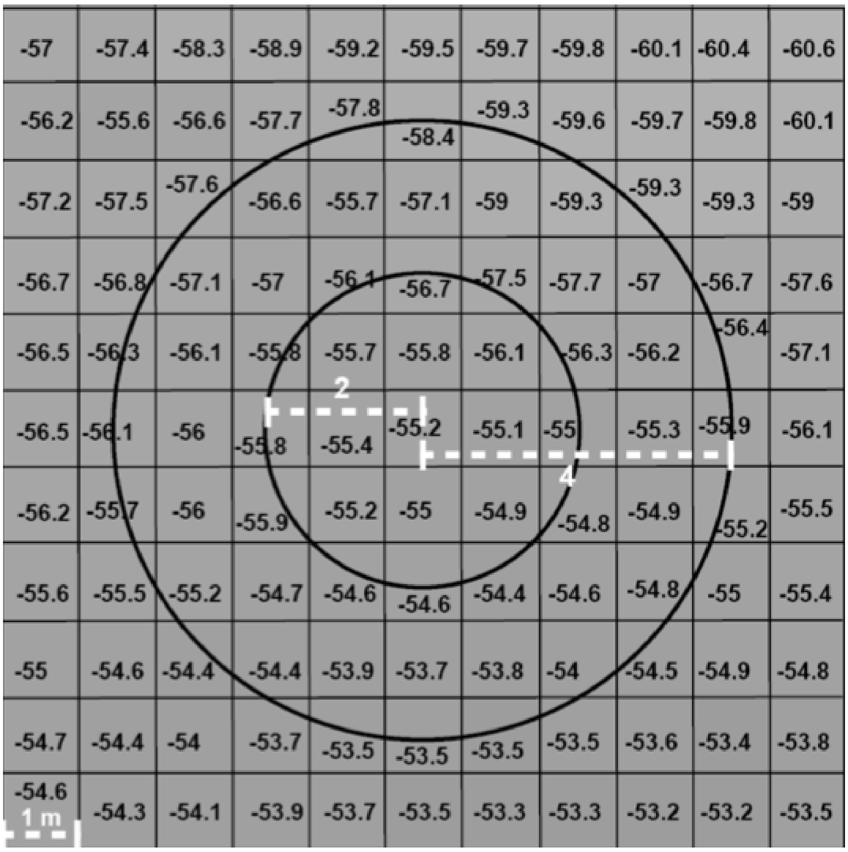


Figure 2.5: Example of the variables used to create a BPI layer using a bathymetric raster layer. For this example, the *irad* = 2 and the *orad* = 4.

BPI was calculated from the DEM (negative bathymetry data) and resulted in negative BPI values for depressions, positive values for crests and zero values for flat areas and

constant slopes (Weiss 2001; Lundblad et al. 2006). Broad scale and fine scale BPI were determined by the size of the annulus neighbourhood. A smaller annulus neighbourhood (*irad*=1 and *orad*=5) resulted in a fine scale BPI and a larger annulus neighbourhood (*irad*=1 and *orad*=2), similar to Figure 2.5, resulted in a broad scale BPI. A smaller annulus neighbourhood producing the fine scale BPI is thought to detect more localised variation in the bathymetry compared to the broad scale BPI (Weiss 2001). Both broad scale (Figure 2.6c) and fine scale (Figure 2.6d) BPI were calculated and used as inputs into a regression analysis.

2.4.2.4 Terrain Ruggedness Index

Terrain Ruggedness Index (TRI) is a simple index created from the DEM and results in a layer depicting valuable relief features. The TRI is calculated using the aspect variation (a_v) and average slope (a_s) as shown in Equation 2. Aspect variation and average slope layers were created using focal statistics in ArcGIS.

$$TRI = ((a_v a_s)/(a_v + a_s))/100 \qquad \text{Equation 2}$$

TRI is a similar measure to rugosity but much simpler to construct using AcrGIS software. Areas with abrupt depth changes and slope direction gave a high TRI value, while smooth or gentle rolling terrain gave a low TRI value (Nellemann & Cameron 1996) (Figure 2.6e).

2.4.2.5 Variety

The variety layer determined the number of unique values in the DEM on a cell-by-cell basis. This was applied within a focal window. It is a measure of the terrain and was used as an input independent variable to predict benthic component distribution around Lizard Island (Figure 2.6f).

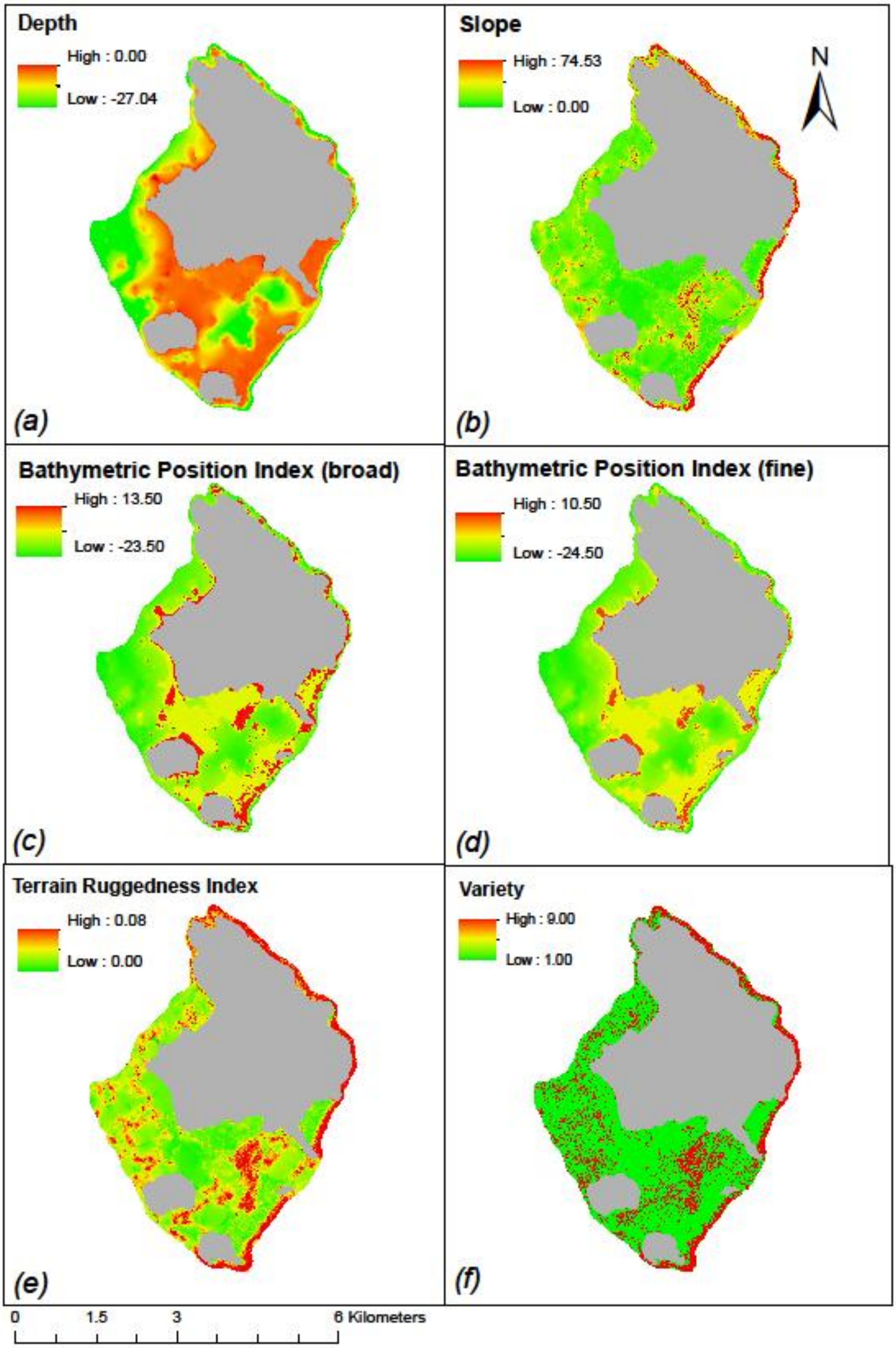


Figure 2.6: Benthic terrain variables used to predict the distribution of carbonate producing benthic components (*a*) depth, (*b*) slope, (*c*) Bathymetric Position Index (broad), (*d*) Bathymetric Position Index (fine), (*e*) Terrain Ruggedness Index and (*f*) variety.

2.5 Benthic component distribution modelling

Developing distribution models of benthic components on coral reef platforms requires underlying ecological concepts and a conceptual framework. The formulation of a conceptual framework enables a selection of explanatory variables for the predictive distribution models. The distribution of benthic components on the basis of benthic terrain variables are believed to be the causal, driving force for their distribution and abundance (Hamylton et al. 2012). Deriving benthic variables (depth, slope, topographic complexity or slope characteristics) from a DEM is possible without losing precision of the data (Guisan & Zimmermann 2000). ArcGIS and GeoDa software packages were employed to derive benthic terrain variables from the DEM. The selected explanatory variables to predict the distribution of benthic components on Lizard Island are outlined in Table 2.3. The influence of each explanatory variable to predict benthic component distribution was performed using ordinary least square regression analysis.

Table 2.3: Conceptual framework to predict the distribution of benthic components on coral reefs.

Environmental variables	Benthic cover type/s	Influence on spatial distribution	Reference
Depth	Live coral Macroalgae Carbonate sand	Increased depth limits light penetration through the water column affecting the photosynthesising organisms that produce carbonate sediment. Deeper depth is ideal for green calcareous macroalgae	(Hubbard et al. 1990) (Freile & Hillis 1997) (Kleypas et al. 1999) (Kench et al. 2009) (Hamylton et al. 2012)
Slope	Live coral Carbonate sand	Slope influences hydrodynamic regime on a reef system and therefore, the food source for sessile suspension feeders. Carbonate sand is transported off slopes to be deposited in sinks	(Burrough & McDonnell 1998) (Guinan et al. 2009)
BPI	Live coral Macroalgae	Highlights bathymetric variation, related to the distribution on benthic cover types. Higher coral cover located at higher BPI values.	(Guinan et al. 2009)
Rugosity	Live coral Macroalgae	Rugosity highlights changes in geomorphological features and therefore, the type of benthic cover associated with that region.	(Brown et al. 2002) (Edwards et al. 2003) (Guinan et al. 2009)
Spectral reflectance	Live coral Macroalgae Carbonate sand	Benthic cover types have different spectral reflectance characteristics. As a result, components can be differentiated from each other.	(Andréfouët & Payri 2000) (Hochberg & Atkinson 2003) (Mumby et al. 2004)

A modelling approach was adopted whereby all environmental variables created in section 2.4 were tested in the regression analysis. The specific combinations of variables that produced an overall R^2 value greater or equal to 0.7 were selected for further investigation. This represented a different combination of variables for modelling the distribution of each benthic component.

2.5.1 Benthic component models

ArcGIS was used to create a point shapefile containing 358 points and variables including carbonate producing benthic components estimated from the *in situ* video data (live coral, carbonate sand, green calcareous macroalgae and encrusting calcified algae), satellite imagery (WV-2 bands 1, 2, 3, 4 and 5) and benthic terrain variables (depth, slope, aspect, BPI, TRI and variety). GeoDa software was used to perform a classic ordinary least square (OLS) regression analysis with the intent to predict the dependent variable (e.g. benthic component, such as live coral) using independent variables (e.g. depth, slope etc.). The dataset created by the regression analysis was expanded into a continuous distribution model of benthic components using raster calculator in ArcGIS. Figure 2.7 shows an example of the process to build the individual benthic models in raster calculator. Benthic component models were treated individually, each using a variation of independent variables and video snapshot points.

Validations of the output benthic models are an essential procedure (Green et al. 2000). To validate each benthic component model, the predicted values from the regression analysis were plotted against the observed percentages from the video analysis. The coefficient of determination (R^2) assessed the correlation between the two datasets.

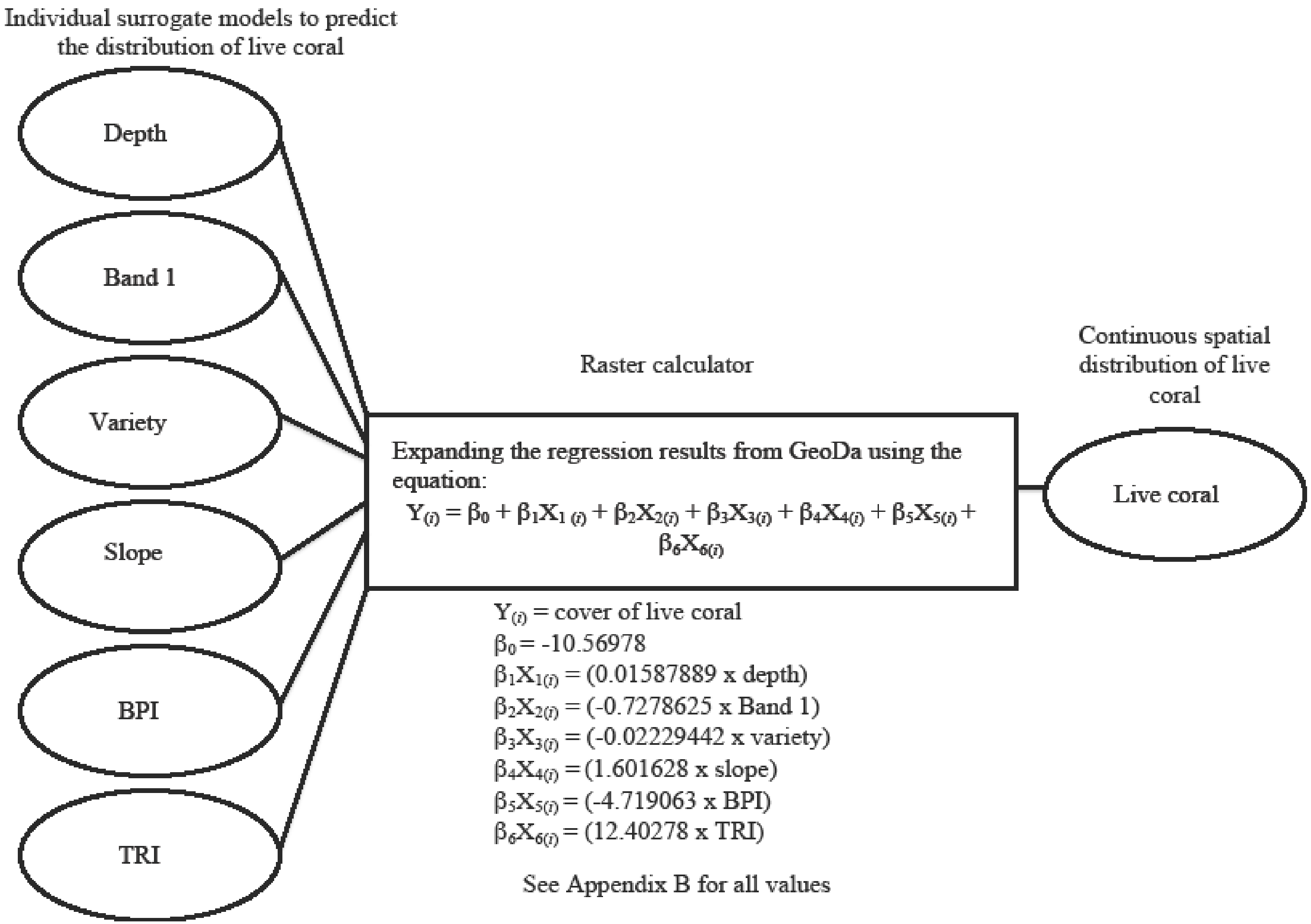


Figure 2.7: Example of a benthic component distribution model developed in this thesis using the regression results to expand the dataset into a spatially continuous model.

2.6 Spatial distribution of overall calcium carbonate production

The carbonate production distribution model was derived from combining benthic component maps using the assumption that the sum of all parts is equal to the whole (Andréfouët & Payri 2000). The sum of all benthic components producing calcium carbonate will produce a map of gross carbonate production (Harney & Fletcher 2003). Carbonate production rates were used as a weight when adding each benthic component map together (Equation 3).

$$C = 3M_c + 0.24M_s + 1.8M_g + 1.494M_e \qquad \text{Equation 3}$$

C represents the distribution model of gross calcium carbonate production, M_c represents the modelled distribution of live coral, M_s represents the modelled distribution of carbonate sand, M_g represents the modelled distribution of green calcareous macroalgae and M_e represents the modelled distribution of encrusting calcified algae.

The carbonate production map was validated using the rank correlation method (Kendall & Gibbons 1990). The rank correlation method measured the general correlation coefficient, Γ, which highlighted the amount of similarity between the observed carbonate production values from the video analysis (see section 2.3.3) and the modelled carbonate production values. Equation 4 was used to calculate the general correlation coefficient (Γ) to validate the carbonate production model.

$$\Gamma = \frac{\sum_{i,j=1}^{n} a_{ij} b_{ij}}{\sqrt{\sum_{i,j=1}^{n} a_{ij}^2 \sum_{i,j=1}^{n} b_{ij}^2}} \qquad \text{Equation 4}$$

In order to validate the carbonate production model, both the observed carbonate production values from the video analysis and the modelled carbonate production values were given a rank with respect to the video point locations and compared. When perfect correlation between rankings exists, Γ is equal positive one. If Γ equals negative one, then there is perfect negative correlation between the rankings. Any value in between negative

one and positive one will indicate the amount of agreement between the rankings (Kendall & Gibbons 1990).

2.7 Comparison between calcium carbonate production and wave energy

To investigate the relationship between calcium carbonate production and wave energy on coral reefs requires a valid model of each process. The carbonate production model was validated using the approach described in section 2.6 and Dr. Hamylton supplied a validated wave energy model for the purpose of the investigation. The wave energy model (Figure 2.8) was developed using the equations outlined by Gourlay (1997).

Defining the empirical relationship between the carbonate production and wave energy datasets was possible using global analysis of the entire reef system and transects, which traversed across wave energy gradients. Adopting a global approach analysed all data points and exposed spatial patterns embedded within the datasets over the entire reef system. Global comparison techniques explored the relationship between carbonate production and wave energy over the entire reef system, within wave energy zones and within geomorphic zones of Lizard Island's reef system.

Exploring the empirical relationship along wave energy gradients was conducted across four separate transects, traversing across the entire reef system. Investigating the relationship between the datasets using transects across environmental gradients (e.g. low wave energy to high wave energy) enabled spatial patterns to become apparent, which would otherwise be hidden using a global statistical analysis (Fortin & Dale 2005). These two types of statistical analysis techniques ensured that the important patterns between carbonate production and wave energy were exposed.

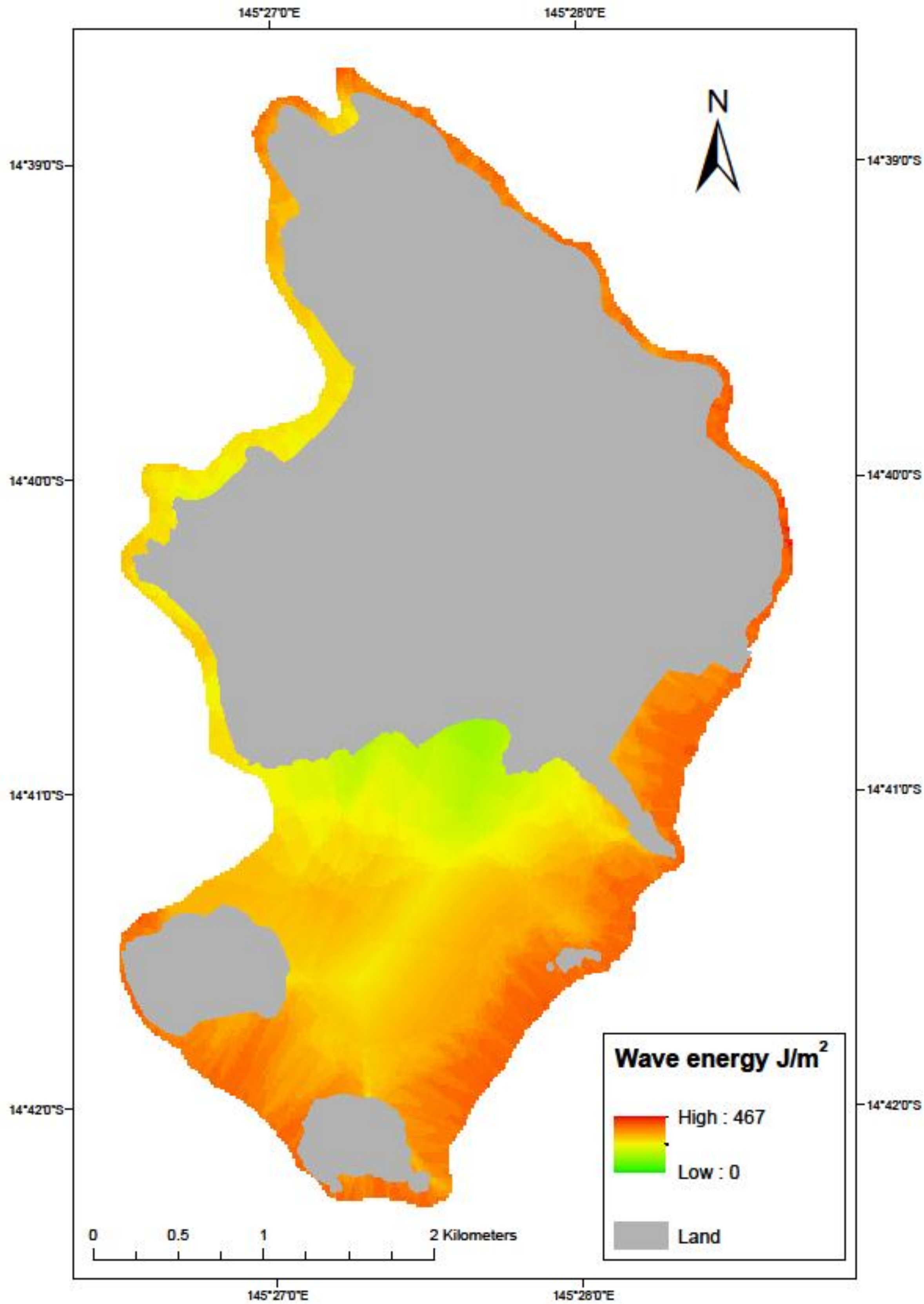


Figure 2.8: A model of wave energy distribution across the reef system at Lizard Island.

2.7.1 Global comparison

Global comparison between carbonate production and wave energy was undertaken using three steps. The first step used a synoptic grid point shapefile, which covered the entire wave energy model, which contained 23605 data points each spaced 15 meters apart. The second step separated the wave energy model into intervals and the third step investigated their relationship between the different geomorphic zones on Lizard Island's coral reef system.

2.7.1.1 Overall comparison of datasets

The first step compared the relationship between carbonate production and wave energy across the entire reef system. A point file was built on the basis of the wave energy resolution (15 meters) and consisted of 23605 points. Values of carbonate production and wave energy were extracted at each point using 3D analyst tools in ArcGIS. Relationships between the data were determined by plotting carbonate production and wave energy against each other in Microsoft Excel. The correlation between the two complete datasets was explored using variations in trendlines and R^2 values.

2.7.1.2 Comparison using wave energy zones

The second step reclassified the wave energy model into eight wave energy zones and converted the raster layer into a vector format using conversion tools in ArcGIS. A database query was undertaken to select the carbonate production and wave energy data points located within each wave zone region. Carbonate production values and wave energy values were then extracted from each point using 3D analyst tools and graphed in Microsoft Excel. Box plots were then created to investigate the standard deviations, ranges and mean values of each zone.

2.7.1.3 Comparison between geomorphic regions

The main geomorphic zones of a typical reef system are comprised of different carbonate producing benthic components. These include the reef front, reef crest, reef flat and lagoon (Woodroffe 2002) The third step examined carbonate production values associated with broad geomorphic regions on Lizard Island's coral reef system. The Zonation of each geomorphic zone on Lizard Island's reef system (Figure 2.9) was digitized in ArcGIS and determined on the basis of past research (LIMER 1975; Rees et al. 2006) and the DEM. Data values of carbonate production were extracted from each geomorphic zone. The relationship between carbonate production and geomorphic zonation were investigated in Microsoft Excel using box plots consisting of standard deviations, ranges and mean values.

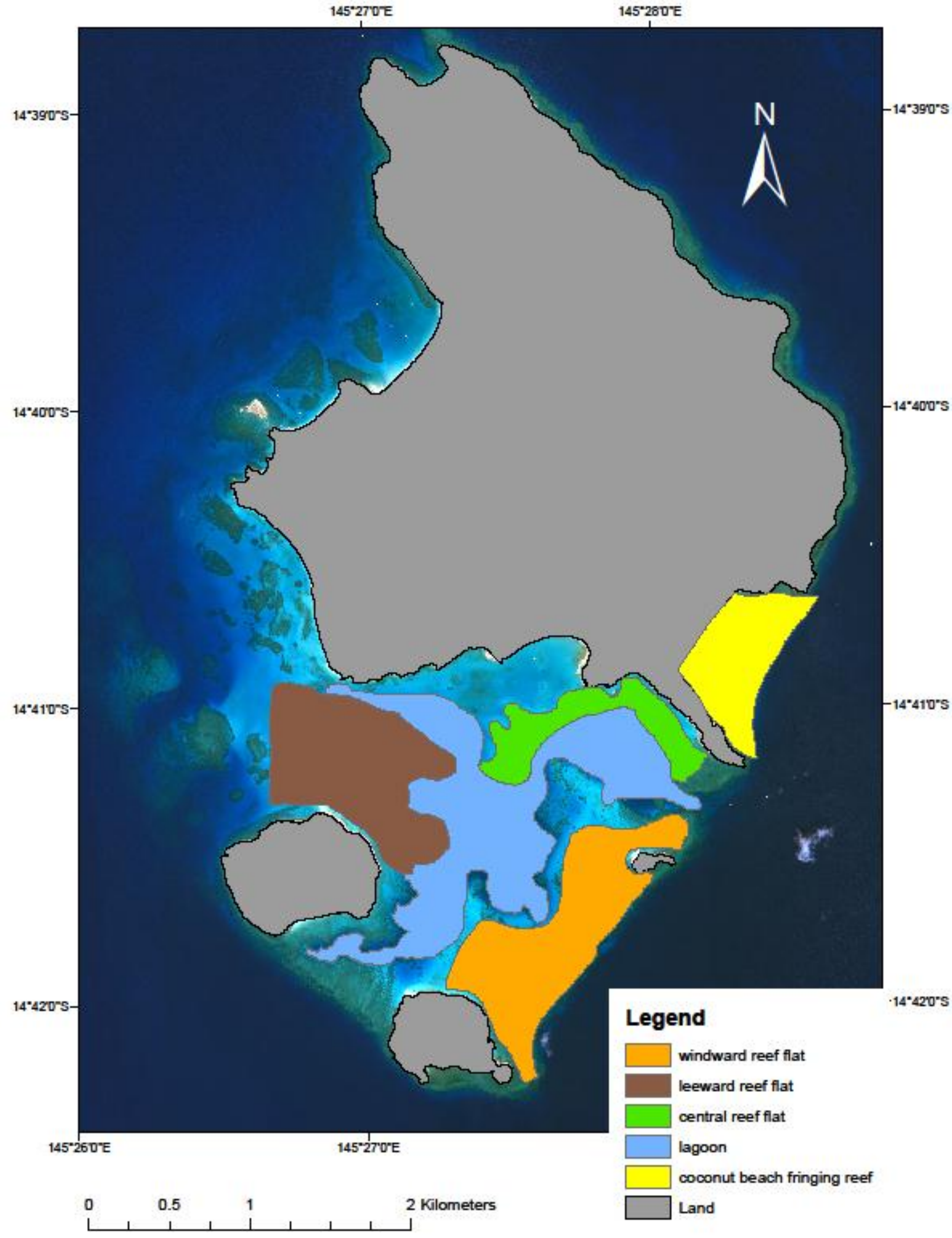


Figure 2.9: Geomorphic zones on Lizard Island's coral reef system.

2.7.2 Transect comparison

The transect comparison approach is another technique used to investigate the relationships between coral reef carbonate production and wave energy. Transects are widely used to examine landscapes (LIMER 1975), as they capture variation of processes across gradients that are important to understanding ecological dynamics of a system (Fortin & Dale 2005). Transects were made up of evenly spaced points and were placed along wave energy gradients (Figure 2.10). The optimal distance at which points were placed on transects was determined using a semivariogram (Figure 2.11).

In geographic space, near things are related to near things (Tobler 1970), which causes entities, within close proximity to each other, to have spatial dependency. The semivariogram indicated the distance between sample points at which spatial independency is reached, eliminating internal redundancy. It does so by plotting a measure of the similarity of values observed at point sample locations (*y*-axis) against the distance between locations (*x*-axis). The point at which the two no longer co-vary can be considered the distance in geographic space at which they are no longer influencing each other. Figure 2.11 shows the semivariogram, which suggests a distance of 3 meters between points would be sufficient enough to ensure spatial independency (Burrough & McDonnell 1998).

Values were extracted from the wave energy and carbonate production layer using 3D analyst tools. The datasets were then plotted against each other and their correlation assessed using trendlines and R^2 values. Various types of relationships were explored including linear, power, exponential and polynomial functions. Also, the relationship was visually assessed from the graph.

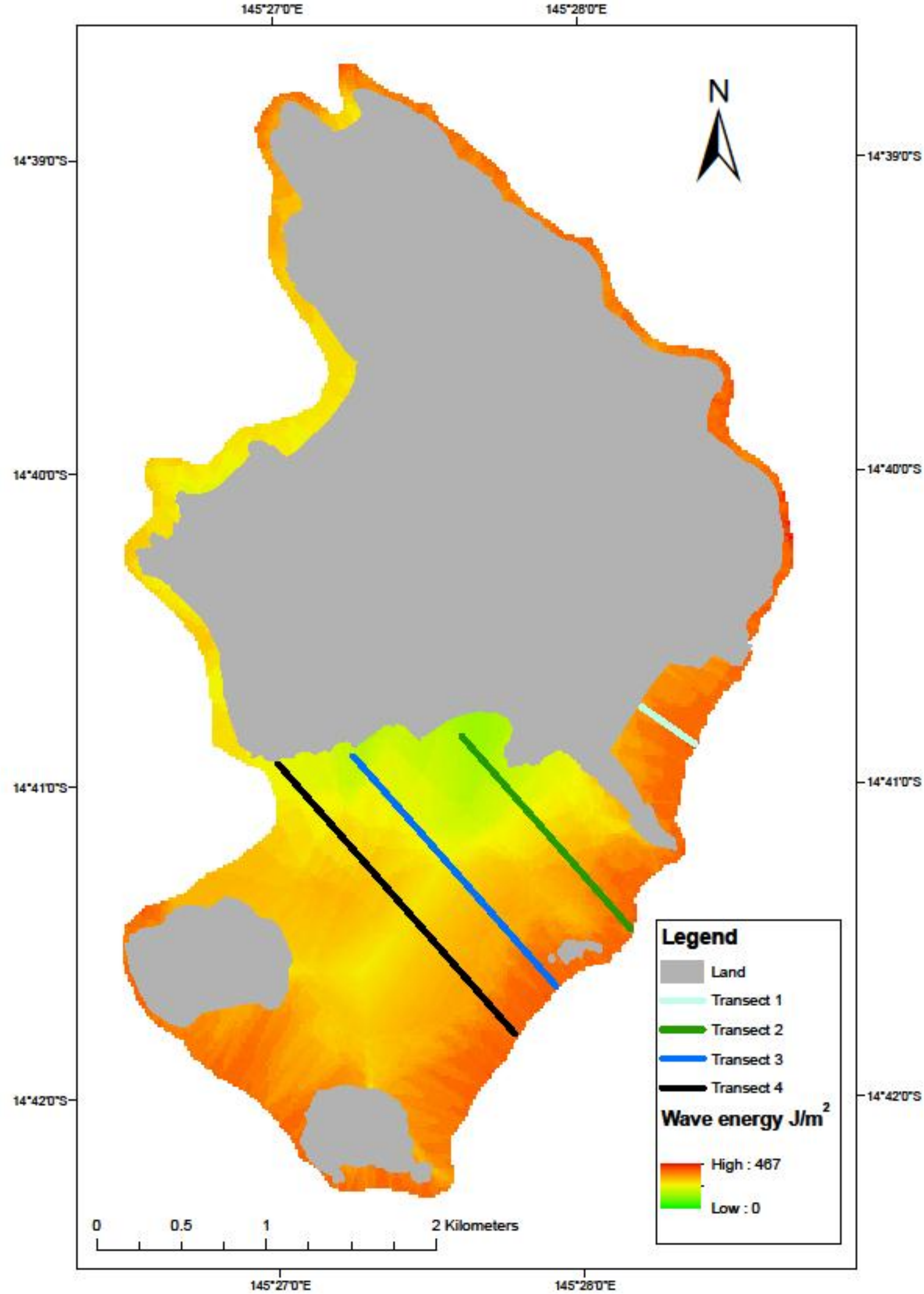


Figure 2.10: Transect locations established along wave energy gradients across the coral reef platform at Lizard Island.

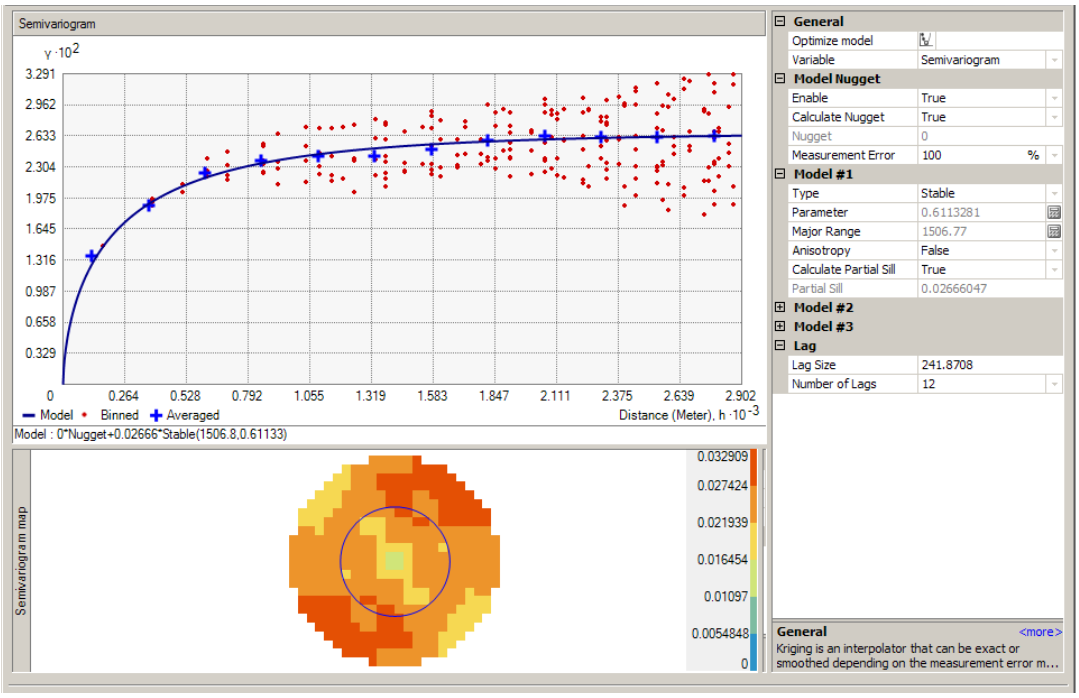


Figure 2.11: Semivariogram derived from the carbonate production model. Suggesting that spatial dependency is absent beyond a distance of 2.902 meters between points.

3 RESULTS

3.1 Introduction

This chapter presents the results obtained by following the methodology outlined in chapter 2. The results highlighted in this chapter are the benthic component distribution models, the spatial distribution model of calcium carbonate production and the global and local scale comparisons between carbonate production and wave energy.

3.2 Benthic components distribution models

Regression analysis was used to predict the distribution of carbonate producing components on Lizard Island's coral reef system. All benthic distribution models produced a statistically significant result $p < 0.001$, providing a basis for rejection of the null hypothesis that each explanatory variable used in each model had no influence on the models performance. Table 3.1 summarises the results obtained from the regression analyses (see Appendix B for full regression diagnostics). The carbonate sand model performed the best with an R^2 value of 0.91. Suggesting that 91% of variation in the independent validation dataset was explained by the model. This was followed by encrusting calcified algae ($R^2 = 0.88$), live coral ($R^2 = 0.84$) then green calcareous macroalgae ($R^2 = 0.79$).

Table 3.1: Statistical regression results for each benthic component distribution model (*n* = number of observations).

Coverage	*n*	R-squared	F-statistic	P-value
Live coral	116	0.84	93.11	<0.001
Carbonate sand	214	0.91	291.44	<0.001
Green calcareous macroalgae	56	0.79	37.26	<0.001
Encrusting calcified algae	144	0.88	172.73	<0.001

The benthic distribution models are visually represented in Figure 3.1. Live coral (Figure 3.1a) dominated the eastern fringe of Lizard Island's reef system. High percentages of coral cover are found on the southeasterly reef crest/slope and patch reefs have developed on the leeward reef flat. There is a relatively high percentage of live coral in and around the lagoon.

Carbonate sand (Figure 3.1b) dominated the shallow areas proximal to the shoreline and was present on both the windward and leeward reef flat. Percentage cover of carbonate sand is lowest on the easterly reef crests and reef slopes. Low cover of carbonate sand is found in the lagoon compared to the surrounding reef flats.

Dense cover of green calcareous macroalgae is represented in the lagoon and on the deeper westerly side of the leeward reef flat (Figure 3.1c). There is minimal cover of green calrareous macroalgae in the shallow regions of the windward and leeward reef flats.

The distribution of encrusting calcified algae (Figure 3.1d) is limited to the easterly fringes of the reef system. Moderate production values were found in the lagoon and on the leeward reef flat associated with patch reefs. Encrusting calcified algae was found in areas where live coral was dominant.

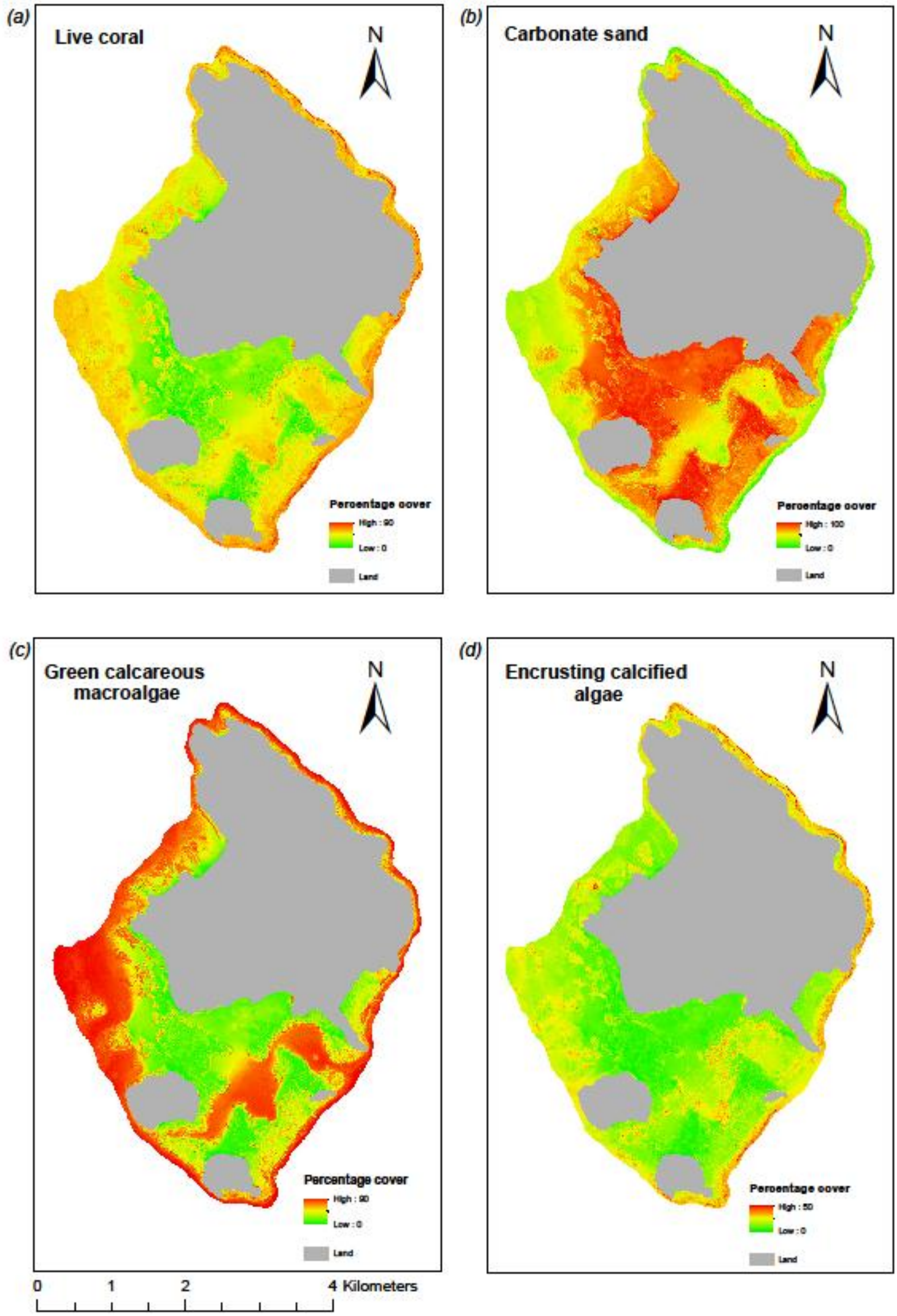
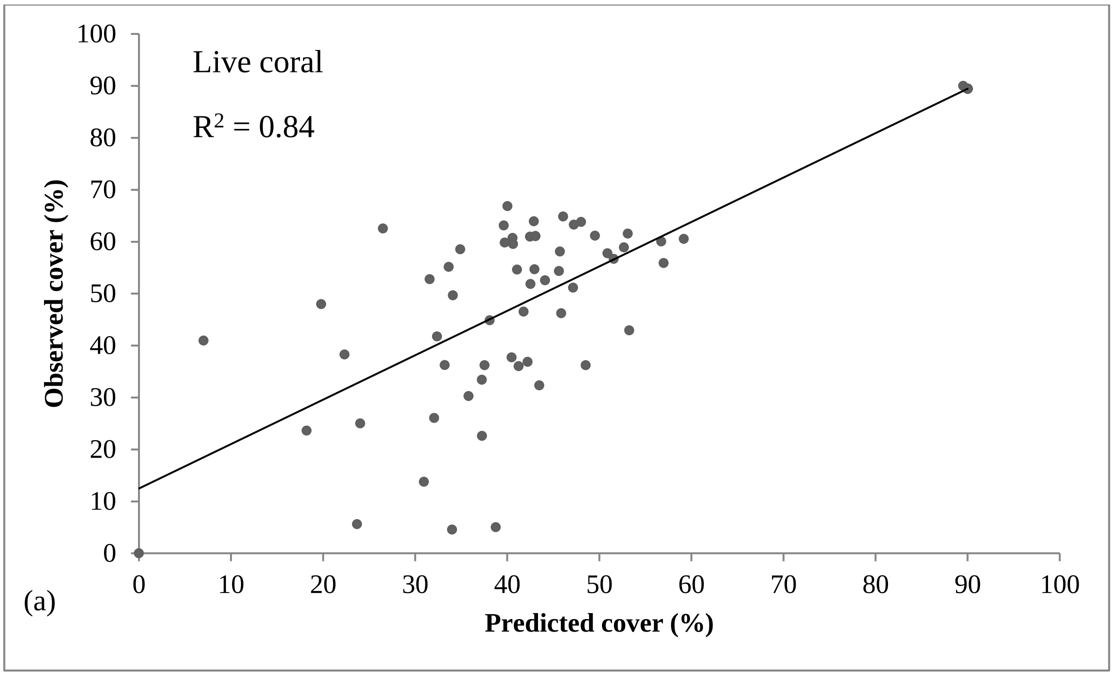
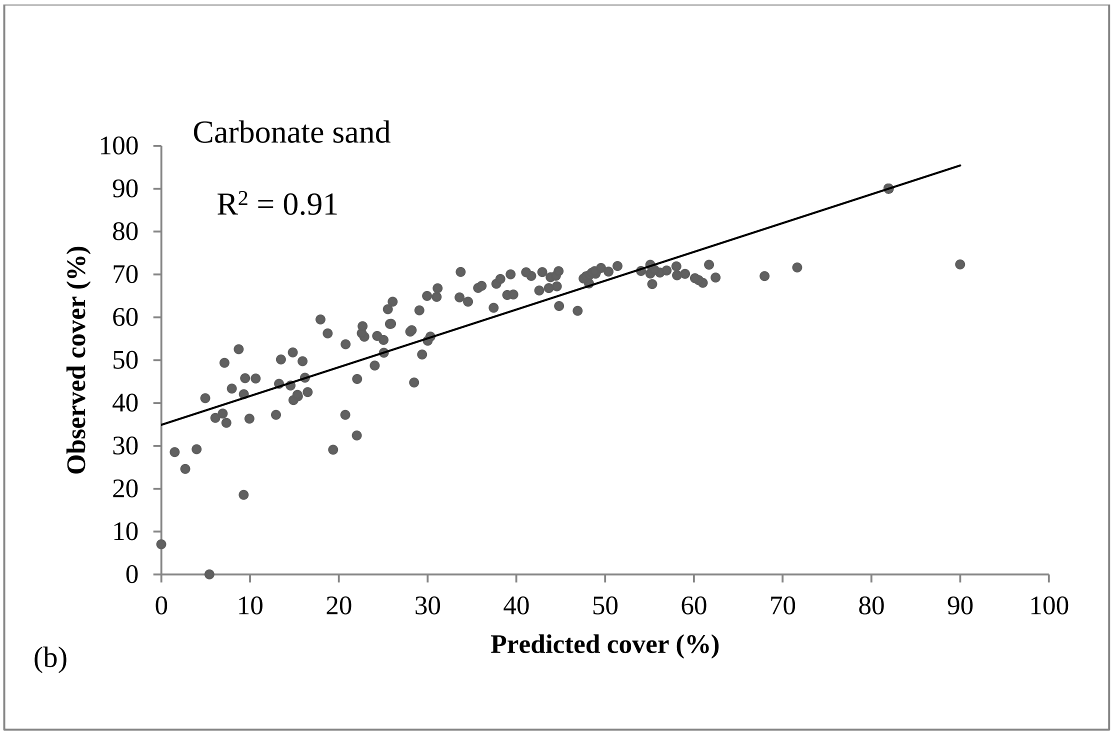
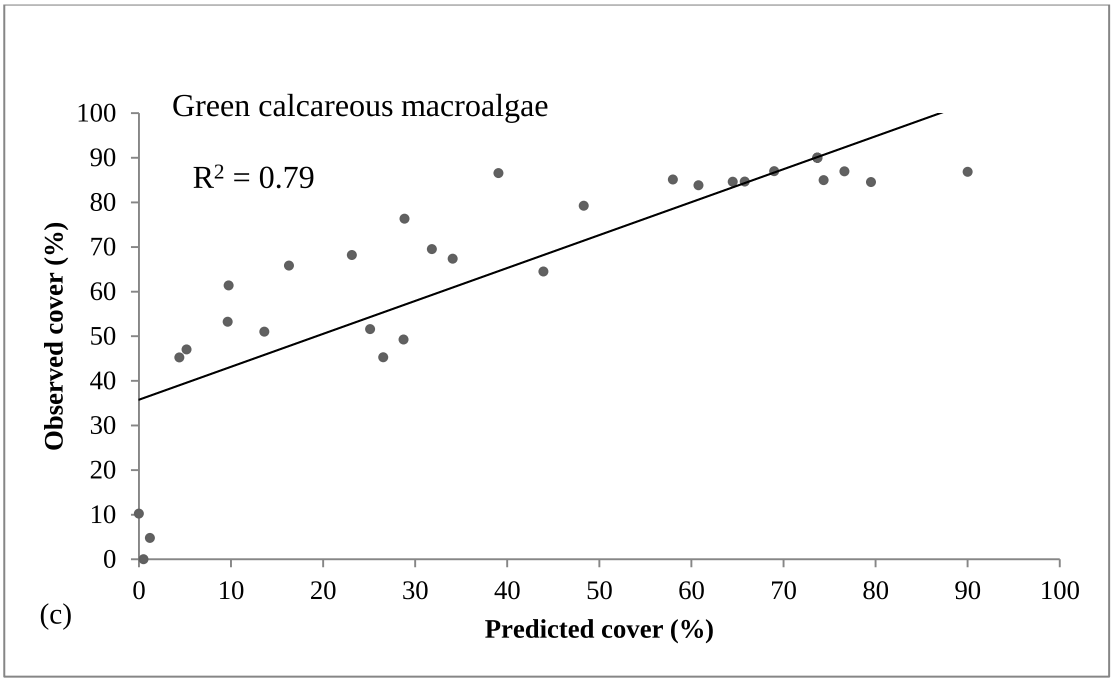


Figure 3.1: Distribution models of each carbonate producing benthic component on Lizard Island's coral reef system (*a* = live coral, *b* = carbonate sand, *c* = green calcareous macroalgae and *d* = encrusting calcified algae).

Model validations for each benthic component model are presented in figure 3.2. Each validation highlights that the surrogates to predict each benthic component distribution were useful in terms of the models performance and can be used for further analysis and interpretation.







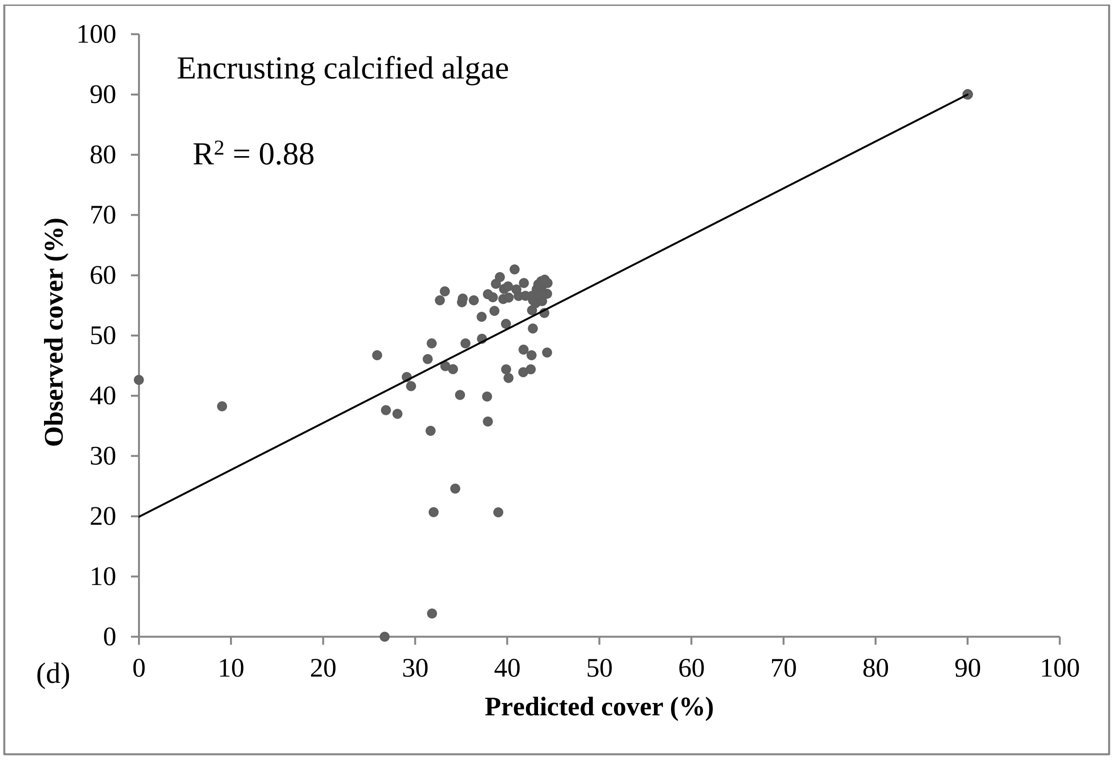


Figure 3.2: Validations of each benthic model. Predicted values are plotted against observed percentage coverage of each benthic component (a = live coral, b = carbonate sand, c = green calcareous macroalgae and d = encrusting calcified algae).

3.3 Spatial distribution of carbonate production

The spatial distribution model of calcium carbonate production (Figure 3.3) indicated highest production values on the northeasterly and southeasterly fringes of the reef system. The lagoon showed relatively high values of production compared to the surrounding reef flats. Model validation was undertaken using the rank correlation method, which revealed a high level of correspondence between field datasets and modelled values of carbonate production ($\Gamma = 0.81$).

The windward reef flat shows similar carbonate production values to coconut beach (located on the eastern side of the island) where high values taper off to lower values when heading in a westerly direction.

Low values of carbonate production dominated the leeward reef flat with the occasional high value for patch reefs. The most westerly areas off the leeward reef flat revealed moderate carbonate production values.

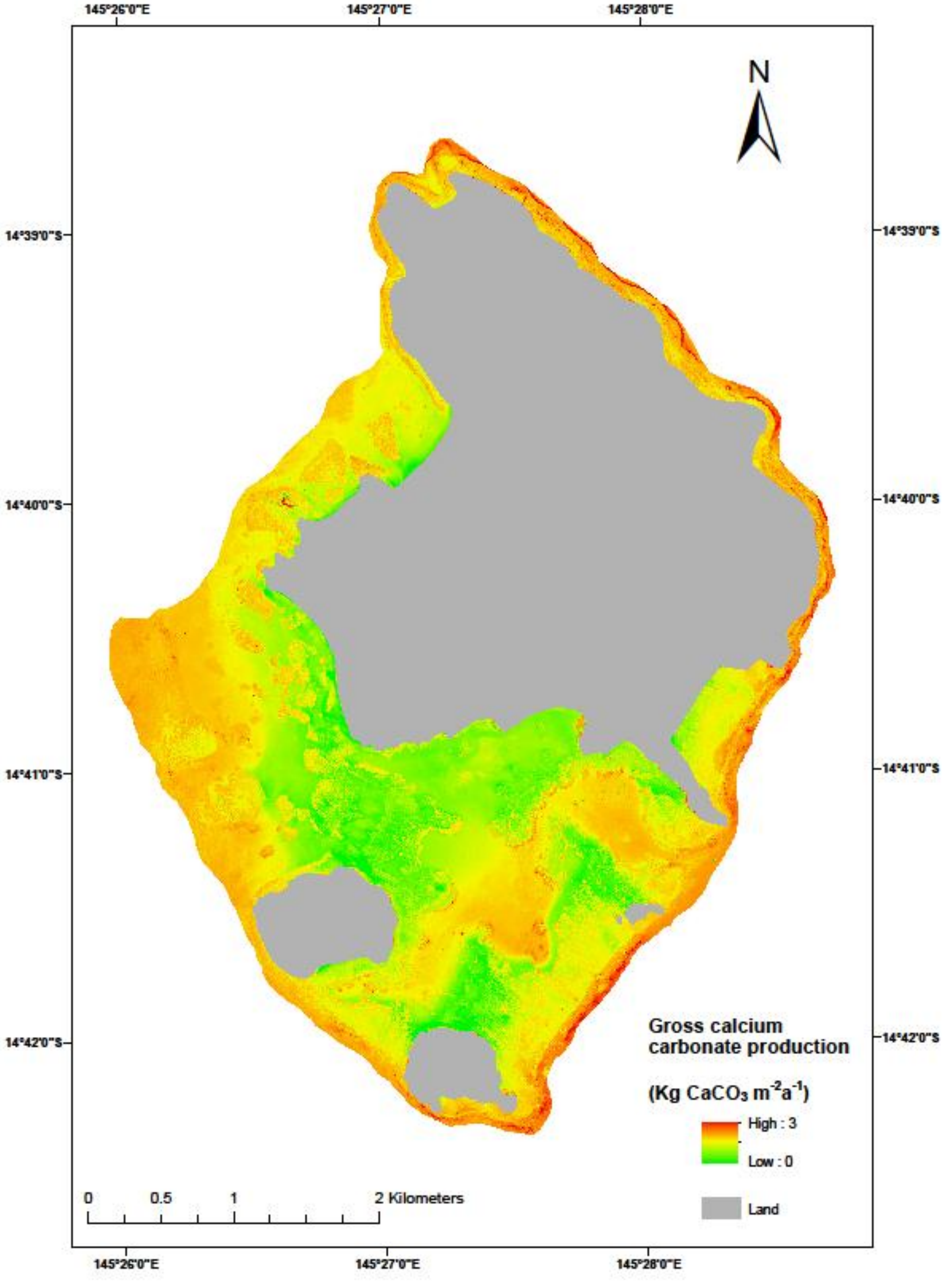


Figure 3.3: Spatial distribution of calcium carbonate production on Lizard Island's coral reef system.

3.4 Global comparison: carbonate production and wave energy

Three global comparison methods were undertaken in this analysis. Not all comparisons produced a significant result. Total coral reef system, wave energy zones and geomorphic zone comparisons are presented below.

3.4.1 Total coral reef system comparison

A point file containing 23605 points was used to extract surface information from the carbonate production model and the wave energy model. The extracted data is compared in Figure 3.4. There is a slight linear trend, which indicates carbonate production values increase as wave energy increases but the correlation is weak (R^2 = 0.19). The mean carbonate production value was 1.84 kg $CaCO_3$ m^{-2} a^{-1} and values range from 0.72 kg $CaCO_3$ m^{-2} a^{-1} to 3.36 kg $CaCO_3$ m^{-2} a^{-1}.

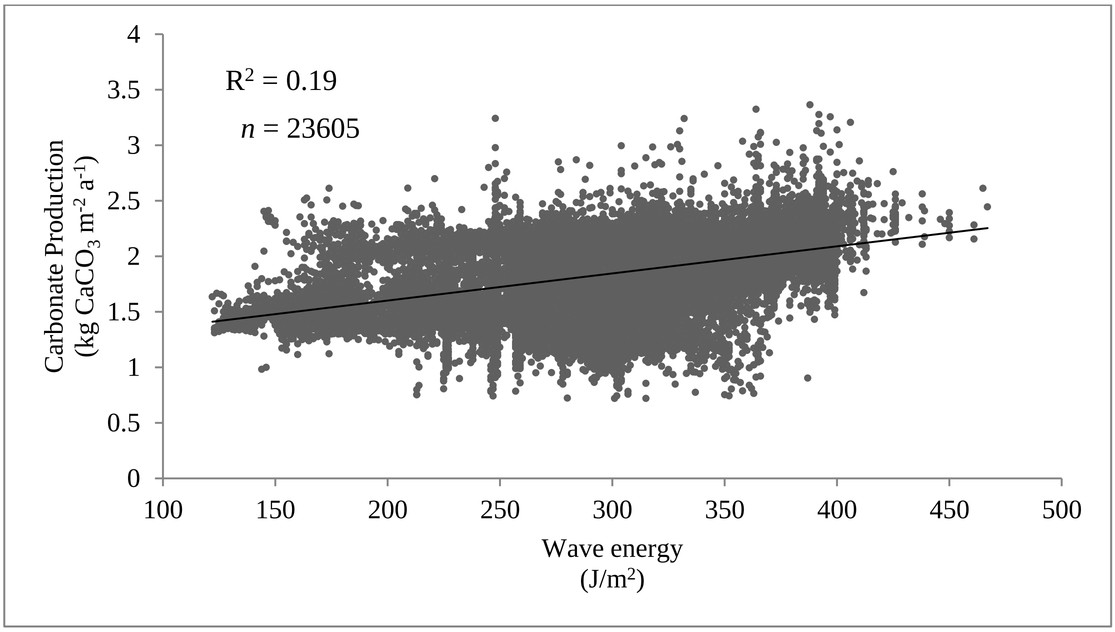


Figure 3.4: A regression of wave energy against carbonate production across the entire reef system. *n* = number of extracted points.

3.4.2 Wave energy zone comparison

The reef platform was divided up into eight wave energy zones, separated by 40 J/m^2 intervals and carbonate production values were extracted from each region. Figure 3.5 shows the range, standard deviation and number of points used in each wave energy zone. The mean carbonate production (±standard deviation) within low wave energy zones (100-140 J/m^2) was 1.44 (±0.08) kg $CaCO_3$ m^{-2} a^{-1}, which was significantly lower that high wave energy zones (380-420 J/m^2) producing 2.15 (±0.21) kg $CaCO_3$ m^{-2} a^{-1}.

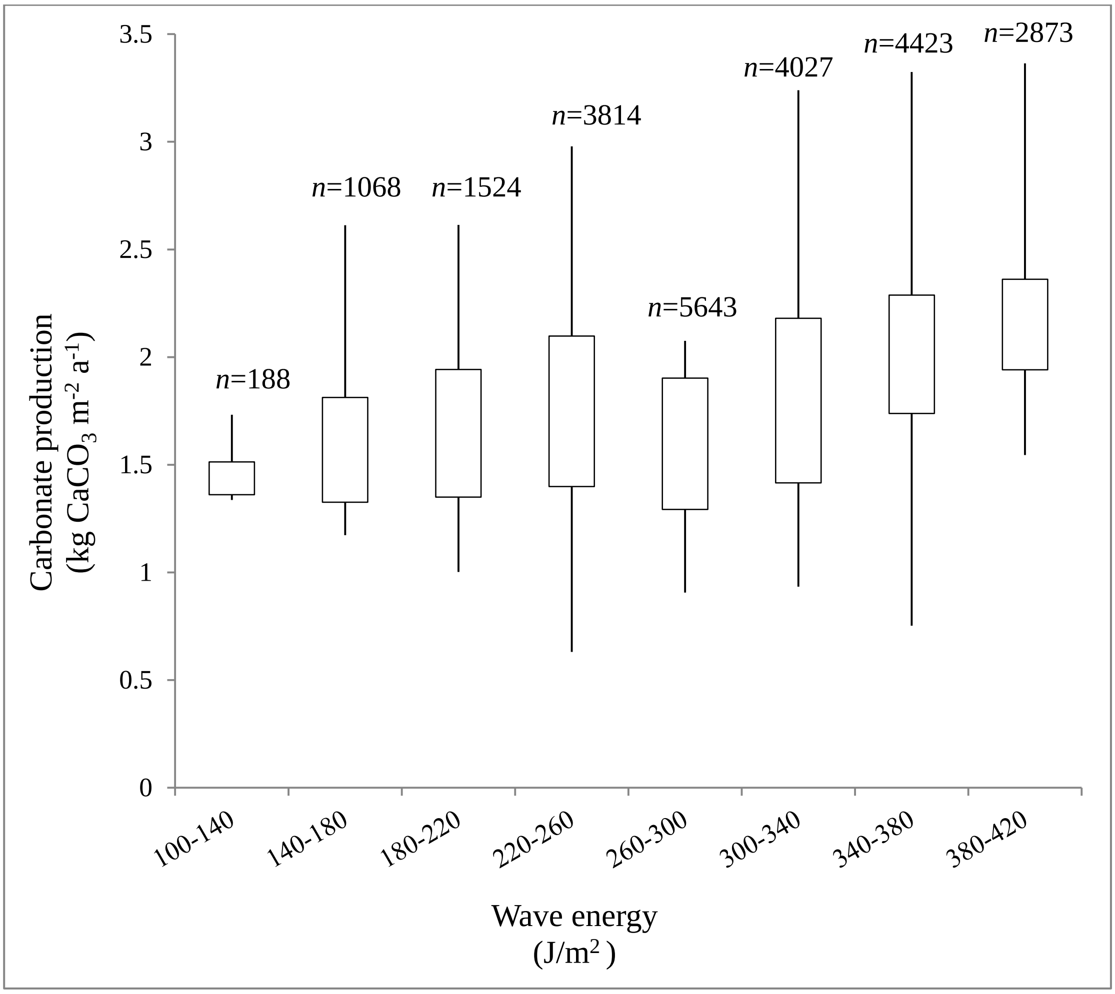


Figure 3.5: A box plot of carbonate production values compared with wave energy across eight different wave energy zones. The boxes represent standard deviation, the mean is in the center of each box, lines represent the range of carbonate production and *n* denotes the number of points extracted from each wave zone.

3.4.3 Geomorphic zone comparison

Carbonate production within each major geomorphic zone on Lizard Island's coral reef system is shown in Figure 3.6. The standard deviation, range and number of points (*n*) used in each zone are presented. The locations of each geomorphic zone are shown in chapter 2 (Figure 2.6). The average (±standard deviation) carbonate production value on coconut beach reef flat and the windward reef flat produced the highest carbonate production values of 2.00 (±0.26) kg $CaCO_3$ m^{-2} a^{-1}, and 1.81 (±0.32) kg $CaCO_3$ m^{-2} a^{-1}, respectively. The lagoon region produced high values of carbonate production of 1.87 (±0.26) kg $CaCO_3$ m^{-2} a^{-1}, due to the high abundance of green calcareous macroalgae. The leeward reef flat areas produced the lowest carbonate production values of 1.31 (±0.26) kg $CaCO_3$ m^{-2} a^{-1} and the central reef flat produced 1.70 (±0.30) kg $CaCO_3$ m^{-2} a^{-1}. The carbonate sand flat regions produced 0.90 kg $CaCO_3$ m^{-2} a^{-1}.

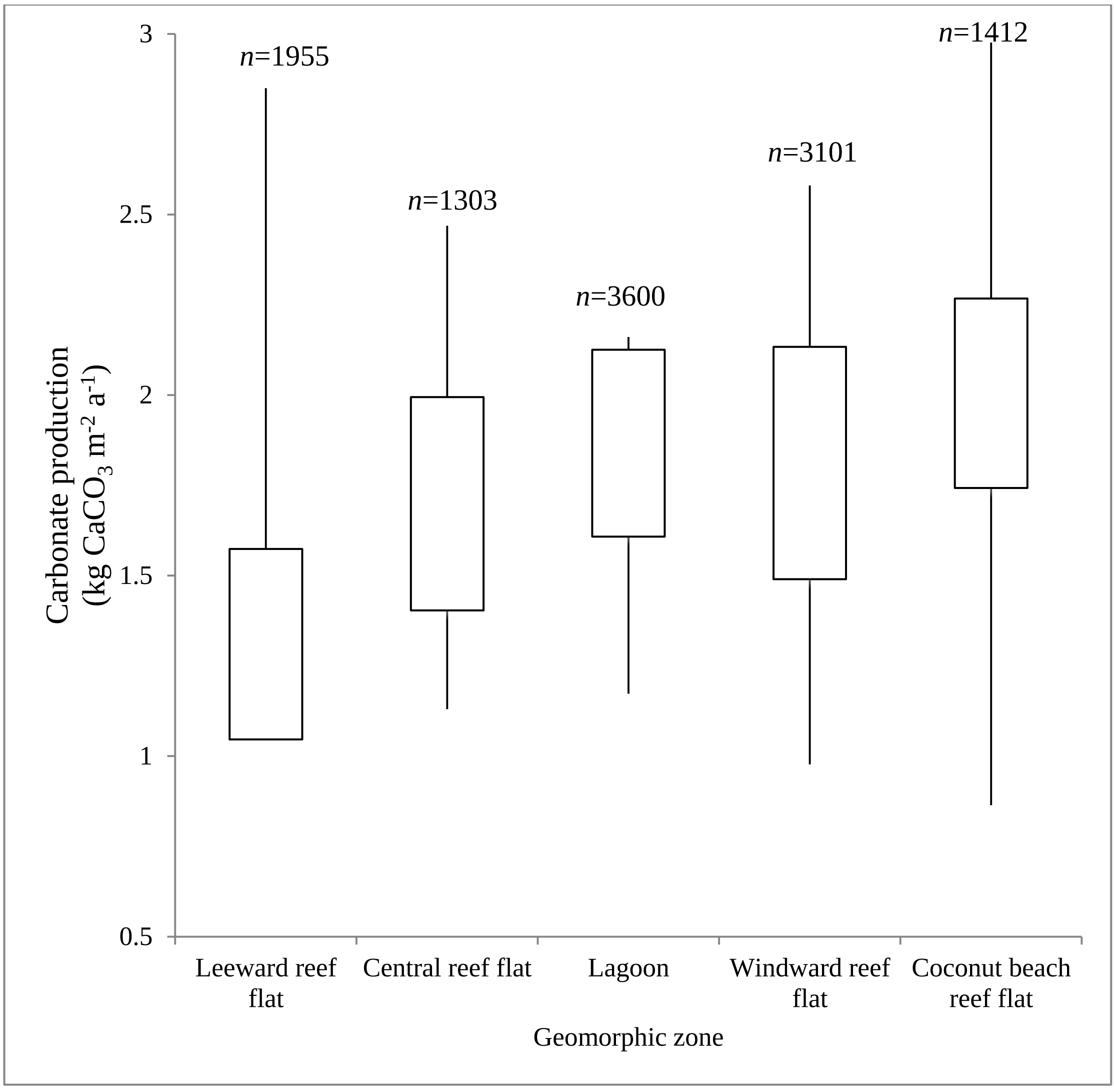


Figure 3.6: Box plot of carbonate production values associated with each geomorphic zone on Lizard Island's coral reef system. The boxes represent standard deviation, the mean is in the center of each box, lines represent the range of carbonate production values and *n* equals the number of points extracted from each geomorphic zone.

3.5 Transect comparison along wave energy gradients

The results for each transect comparison are presented in Figures 3.7 – 3.10. Each transect refers to the transect locations illustrated in Chapter 2 (Figure 2.7). Transect 1 had the shortest length (410 m), traversing over a typical fringing reef system. Transects 2, 3 and 4 traversed across the whole complex reef system, ranging from 1500 m to 2000 m, through different geomorphic zones. These longer transects highlighted complex patterns of carbonate production associated with wave energy.

3.5.1 Transect 1

Transect one represents a typical fringing reef system. The trend in Figure 3.7 highlights a significant increase of carbonate production with the increase of wave energy. An R^2 value of 0.73 was achieved when this relationship was characterised by a second order polynomial function.

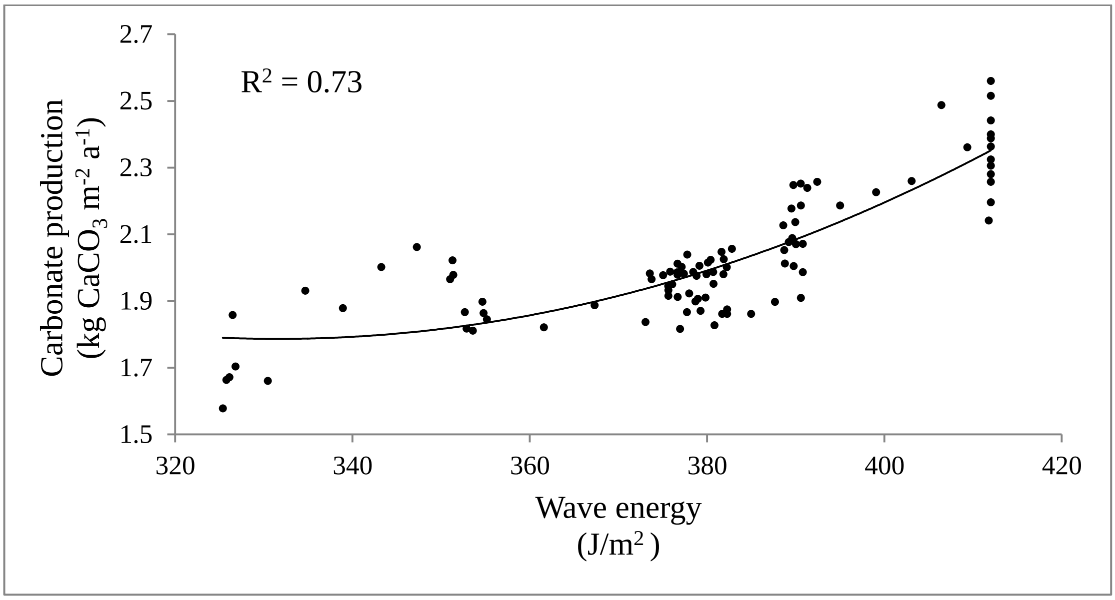


Figure 3.7: Transect 1 comparison between carbonate production and wave energy.

3.5.2 Transect 2

Transect 2 traversed across various geomorphic zones along a wave energy gradient. The result of this comparison is showed in Figure 3.8. A second order polynomial trendline was used to assess the correlation between carbonate production and wave energy. The trendline suggests that carbonate production increases with wave energy until 300 J/m^2, followed by a decrease in carbonate production. There is a peak of carbonate production when wave energy equals, approximately 160 J/m^2, possibly caused by the coral pinnacle on the lagoons edge.

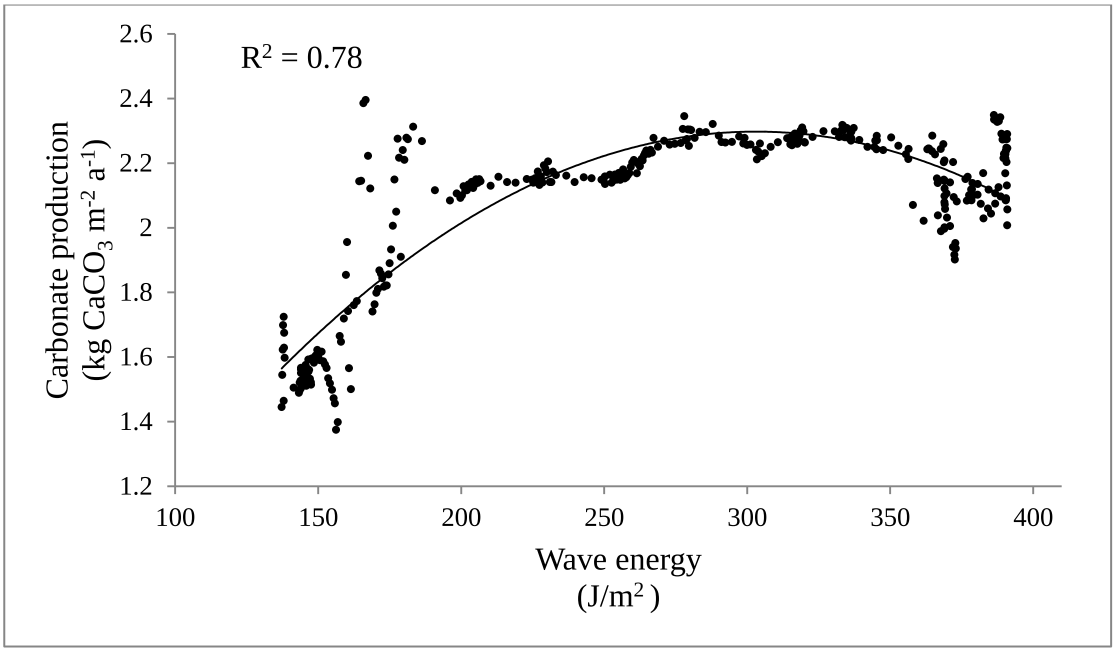


Figure 3.8: Transect 2 comparison between carbonate production and wave energy.

3.5.3 Transect 3

Transect 3 traversed across the entire fringing/barrier type reef system. Comparison between carbonate production and wave energy along transect 3 is presented in Figure 3.9. This transect revealed much more complex patterns compared to transects 1 and 2. Transect 3 showed a weak linear relationship (R^2 = 0.16) between carbonate production and wave energy. There was a slight peak of carbonate production at 170 J/m^2 and major peak at 250 J/m^2, which is caused by the coral pinnacle on the lagoons edge and the high abundance of calcareous macroalgae within the lagoon. The overall linear trend suggests a slight increase of carbonate production occurs with increasing wave energy.

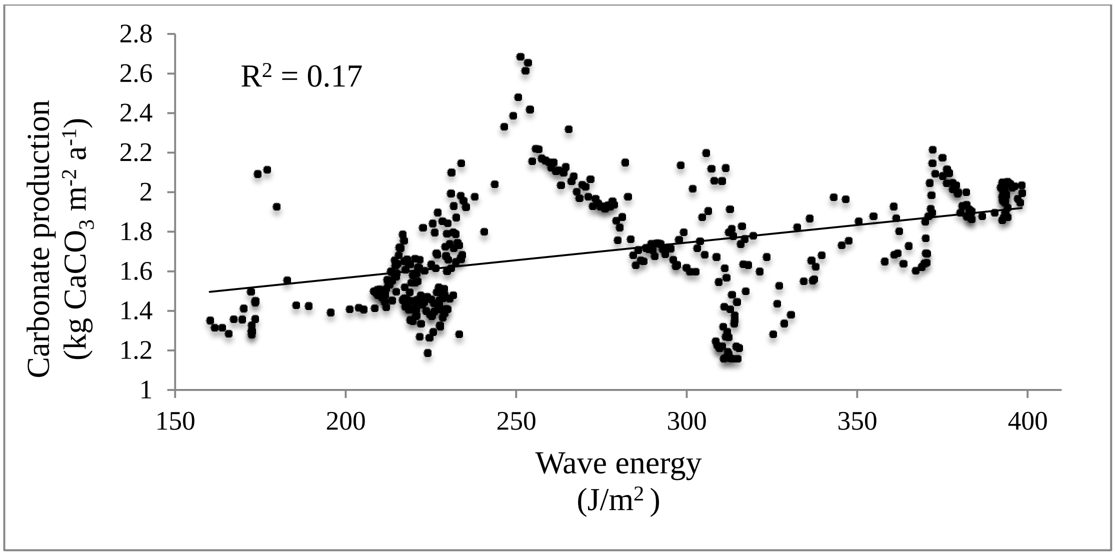


Figure 3.9: Transect 3 comparison between carbonate production and wave energy.

3.5.4 Transect 4

Transect 4 traverses across the entire reef platform. Figure 3.10 compares the carbonate production values against the wave energy values and fits a second order polynomial trendline to the data. An R^2 value of 0.37 suggests slight correlation between datasets. The trendline implies that carbonate production increases with wave energy until wave energy reaches 320 J/m^2, then starts to decrease. This results is similar to transect 2. There is a peak of carbonate production at 320 J/m^2 of wave energy possibly due to coral patches on the lagoons edge.

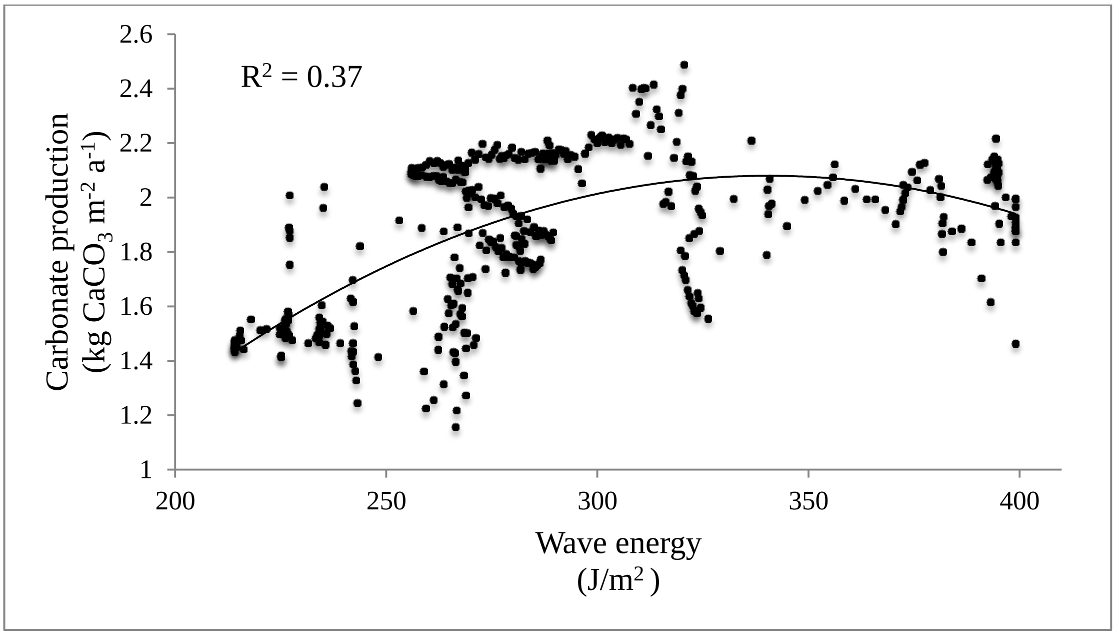


Figure 3.10: Transect 4 comparison between carbonate production and wave energy.

4 DISCUSSION

4.1 Introduction

The geospatial analysis outlined in this thesis, successfully modelled the spatial distribution of individual benthic components and generated a continuous spatial distribution model of calcium carbonate production on Lizard Island's coral reef system. Investigating the empirical relationship between carbonate production and wave energy was possible using both a global analysis of the reef system and local analysis using transects, which traversed across the entire reef platform. This chapter discusses the results obtained in this investigation and highlights their importance to understanding the dynamics of coral reef ecosystems. Limitations of the methodology and future recommendations are provided.

4.2 Benthic component distribution models

Corals, calcareous green macroalgae, encrusting calcified algae and carbonate sand are considered the main carbonate producing benthic components on Lizard Island's reef system (LIMER 1975). Seagrass is considered to contribute to carbonate production on a reef system (Perry & Beavington-Penney 2005) and was observed in 10 of the 364 video samples. The minimal abundance of seagrass observed on Lizard Island did not warrant for an individual model to be built, therefore, seagrass was excluded from the analysis.

The distribution and zonation of these benthic cover types, on the reef platform at Lizard Island, have only been examined to a relatively small extent. Pichon and Morrissey (1981) examined the structure and zonation of corals and algae on a small portion of the reef platform surrounding South Island (see Figure 2.2) at eight stations along a single transect. Nelson (1992) investigated the patterns in benthos cover, diversity and spatial arrangement at four sites on sheltered and exposed fringing reefs on Lizard Island reef system. Each of the four sites, were divided into three subsites perpendicular to the reef crest and each subsite was further divided into five areas of reef zonation including bottom, slope, crest, outer reef flat and inner reef flat. Three ten meter long transects examined the diversity and cover of the benthos within each reefal zone. LIMER (1975) carried out alkalinity-anomaly analysis of the benthic cover types along three separate

transects on the shallow reef platform. They noted the type of benthic components present along each transect, which included coral, calcareous algae, sand and rubble. The spatially continuous benthic cover models of live coral (R^2 = 0.84), carbonate sand (R^2 = 0.91), green calcareous macroalgae (R^2 = 0.79), and encrusting calcified algae (R^2 = 0.88), generated in this thesis, extend the previous investigations described here by quantitatively predicting the distribution and abundance of each benthic component across the entire reef system. The approach adopted in this thesis, to construct a spatially continuous model of each benthic component, was possible using spectral reflectance from satellite imagery and benthic terrain variables as predictors of benthic cover type distribution.

Spectral reflectance from the seafloor is an important parameter to predict the type of benthic component present at a particular geographic location (Hochberg et al. 2004). Coral, algae and sand each have a unique spectral signature, which can be differentiated using satellite imagery (Andréfouët et al. 2001). The models produced in this thesis successfully utilised spectral reflectance as a parameter to predict the distribution of each carbonate producing benthic component on Lizard Island (see Appendix B). This finding highlights that satellite imagery is an important tool to synoptically predict benthic cover distribution and abundance on coral reef platforms. It also provides coastal managers with a valuable monitoring tool. The combination of benthic terrain variables and satellite imagery made the benthic models successful.

The distribution models of individual benthic cover type produced in this thesis followed a conceptual framework of ecological parameters that were considered to be the causal, driving forces of their distribution and abundance (Guisan & Zimmermann 2000). The DEM was used to derive accurate benthic terrain variables including depth, slope, Bathymetric Position Index, Terrain Ruggedness Index and variety of Lizard Island’s reef system. Building models of topographic complexity to predict benthic cover distribution is a valuable method in ecological and spatial modelling (Garza-Pérez et al. 2004; Arias-González et al. 2012). The conceptual framework adopted to predict benthic component distribution on Lizard Island followed theoretical assumptions of biotic elements of coral reef systems (Table 2.3).

Water depth is a controlling factor of corals and macroalgae distribution (Kleypas et al. 1999). Reef-building corals and their symbiotic relationship with zooxanthellae rely on

solar energy to photosynthesize and produce calcium carbonate (Veron 2011). Light diminishes with depth (Chappell 1980) and, therefore, will restrict the distribution of calcifying organisms to the photic zone. Depth was a successful predictor used in the regression analysis to predict the distribution of live coral ($P < 0.01$), carbonate sand ($P < 0.001$) and green calcareous algae ($P < 0.001$), although depth was a weak indicator of encrusting calcified algae distribution ($P < 0.85$).

Slope of the seafloor influences the hydrodynamic regime controlling the distribution of food sources for coral and calcareous benthic components (Guinan et al. 2009). These sessile organisms adapt to the slope conditions, where food supply is abundant. Slope was a powerful predictor of live coral, carbonate sand, green calcareous macroalgae and encrusting calcified algae distribution.

High abundance of live coral has been found to correlate with higher Bathymetric Position Index values (Guinan et al. 2009). This terrain variable was successfully applied in regression analysis, contributing as a significant indicator for not only live coral distribution, but also carbonate sand, green calcareous macroalgae and encrusting calcified algae.

Terrain Ruggedness Index (TRI) is a similar measure of rugosity, which was developed by Nellemann and Cameron (1996) to investigate the distribution of Calving Caribou (*Rangifer tarandus granti*), within the Arctic Coastal Plain of Alaska. They found a strong correlation between Caribou abundance and TRI values. A spatially continuous model of Terrain Ruggedness Index is relatively simple to create using derivatives from a Digital Elevation Model. The results obtained in this thesis suggest that the TRI is a useful variable to predict the distribution of carbonate producing benthic components on coral reef platforms.

Predictive marine habitat mapping is "*the use of spatially continuous environmental data sets to represent and predict biological patterns on the seafloor (in a continuous or discontinuous manner)*" (Brown et al. 2011). The majority of habitat map procedures adopt supervised or unsupervised classification techniques, which use environmental data layers as proxies for the distribution and abundance of the biological components. Supervised and unsupervised classification techniques distinguish benthic cover types on

the basis of pixel signatures from satellite imagery (Moses et al. 2009; Collin et al 2012). The geospatial approach outlined in this thesis differs from the standard pixel-based classification approach as it employs regression analysis, video footage, satellite imagery and benthic terrain variables to produce continuous benthic cover models. The data produced by this approach produces multiple predictive layers that contain much more detail than a standard pixel-based habitat map. The individual benthic models produced in this thesis can identify percentage abundance of benthic cover type for individual pixels, compared to the supervised or unsupervised habitat maps, which segment the reef system into classes and identify one dominant class per pixel (Brown et al. 2011).

4.3 Calcium carbonate production at Lizard Island

The unique geospatial analysis employed in this study allowed for a synoptic, reef scale quantification of carbonate production. This in turn provides a new approach to quantify carbonate production at the landscape scale using satellite imagery and census-based methods. Recent census-based investigations employ a range of procedures to estimate carbonate production, which are distinguishable from this thesis.

Mallela and Perry (2007) mapped the substrate type and benthic organisation at two sites using ten meter long transects within Rio Bueno embayment, north Jamaica. Carbonate production at each site was estimated on the basis of benthic component type and coverage. This study only focused on two specific sites of the embayment to explore the influence of terrestrial impact, which does not explore the spatially heterogeneous nature of carbonate production across an entire reef system (Kleypas et al. 2001). Hart and Kench (2007) employ aerial photography and seven transects, ranging from 0.6 to 3.5 km in length, around Warraber Island, Torres Strait, to construct ecological zonation maps. Carbonate production of ecological zones were based on published carbonate production rates multiplied by the area of each zone. The spatially continuous carbonate production model, developed in this thesis, used census-based estimations and satellite imagery to capture the heterogeneous nature of carbonate production. The spatially extensive nature of this study extended beyond Mallela and Perry (2007) and provided a more reliable predictive habitat mapping approach compared to Hart and Kench (2007).

Gross carbonate production of Lizard Island's reef system was estimated at 1.84 kg $CaCO_3$ m^{-2} a^{-1}, similar to Kinsey (1985), estimating 1.81 kg $CaCO_3$ m^{-2} a^{-1}. Values of carbonate production ranged from 0.72 kg $CaCO_3$ m^{-2} a^{-1} over carbonate sand dominated areas to 3.36 kg $CaCO_3$ m^{-2} a^{-1} where live coral was highly abundant. These values were comparable to the values derived from the alkalinity-anomaly approach conducted by LIMER (1975).

A two-week field expedition, conducted by the LIMER (1975) determined the calcification rates from the reef community along three transects at Lizard Island using the alkalinity-anomaly technique. Transects were located over the windward reef flat, the leeward reef flat and the coral pinnacle located at the entrance of the lagoon. Estimations of calcification rates ranged from 0.91 to 4.56 kg $CaCO_3$ m^{-2} a^{-1}. These ranges were similar to the values generated in this thesis, which ranged from 0.72 to 3.36 kg $CaCO_3$ m^{-2} a^{-1}. The transect located on the windward reef flat conducted by LIMER (1975) estimated carbonate production values ranging from 3.47 to 3.83 kg $CaCO_3$ m^{-2} a^{-1}. Carbonate production values, for the windward reef flat estimated in this thesis, were lower, ranging from 0.9 to 2.6 kg $CaCO_3$ m^{-2} a^{-1} (see Figure 3.6). The lower values possibly reflect the influence of ocean acidification and coral bleaching associated with rapid climate change (Hoegh-Guldberg et al. 2007). Ocean acidification impacts reef carbonate producing organisms by lowering the pH, which reduces carbonate production. The weaker skeletons are more susceptible to breakage by physical erosion. Reduced calcification rates also correlate with coral bleaching, which in turn, causes implications of reef accretion processes and lowers carbonate production (Veron 2008). Increase frequency of coral bleaching events, due to periods of elevated sea temperatures, have been recorded between 1975 and the present day (Spencer 2011). Coral bleaching reduces live coral cover, which in turn, reduces overall community production. The lower carbonate production values on the windward reef flat could be associated with ocean acidification and coral bleaching, which poses a major threat to coral reef accretion and the stability of reef islands.

Comparison of the overall values of carbonate production determined in this study with other studies on other reef systems around the world, should be approached with caution, as each individual study adopts a slightly different methodological approach to quantify carbonate production. Hubbard et al. (1990) employed a census-based approach to

quantify carbonate production of a reef system at St. Croix, U.S, Virgin Islands. Gross carbonate production was estimated along three transects and up-scaled to the overall reef system. The estimated carbonate production by the overall reef system was 1.15 kg $CaCO_3$ m^{-2} a^{-1}. Hart & Kench (2007) employed a census-based approach to quantify carbonate production of a reef system at Warraber Island, Torres Strait, Australia. Gross carbonate production was estimated along seven transects using 1 m^2 quadrats at 37 sites, determining a carbonate production value of 1.66 kg $CaCO_3$ m^{-2} a^{-1} for the entire reef system. The geospatial approach adopted in this thesis yielded an overall carbonate production value of 1.84 kg $CaCO_3$ m^{-2} a^{-1} for the entire reef system at Lizard Island. This value is similar to Kinsey (1985), which was 1.80 kg $CaCO_3$ m^{-2} a^{-1} and higher than reef systems at St. Croix and Warraber Island.

Mean carbonate production values within each geomorphic region of Lizard Island's reef system are illustrated in Figure 3.6. These values correspond to similar values determined by stratigraphic evidence estimated by Hopley (1982). For instance, windward reef flats were much higher carbonate producing regions (4.5 $CaCO_3$ m^{-2} a^{-1} by Hopley (1982) and 3.6 $CaCO_3$ m^{-2} a^{-1} in this study) compared to carbonate sand dominated regions (0.3 $CaCO_3$ m^{-2} a^{-1} by Hopley (1982) and 0.72 $CaCO_3$ m^{-2} a^{-1} in this study). The windward reef flat and coconut beach reef flat at Lizard Island's reef system (Figure 3.6) produced high rates of carbonate production. This was expected as fore reef zones are considered an important carbonate production area of any reef system (Vecsei 2001). Although windward and sand regions correlated well with Hopley (1982), there was considerable difference in carbonate production values within the lagoon region.

Relatively high rates of carbonate production were found in the lagoon at Lizard Island. An examination of the benthic cover models in Figure 3.1, illustrates that green calcareous macroalgae dominates the lagoonal areas elsewhere. High productivity, corresponding with the abundance of *Halimeda*, has been documented in lagoonal areas. Freile and Hillis (1997) measured the carbonate production rate of *Halimeda Incrassata* flourishing in a lagoonal environment in Pico Feo, San Blas, Panama. They measured carbonate production using algal density, total biomass and carbonate production mass. The estimated carbonate production rate by *Halimeda* was 2.3 kg $CaCO_3$ m^{-2} a^{-1}. They concluded that green calcareous macroalgae is an important carbonate producing benthic component and can dominate lagoonal settings. *Halimeda* appears to be of similar

functional importance within the lagoon at Lizard Island. The values within the lagoon derived in this thesis range from 0.9 to 2.1 kg $CaCO_3$ m^{-2} a^{-1}. These values correspond to the low producing sandy areas and the higher producing *Halimeda* regions.

4.4 The relationship between carbonate production and wave energy

The empirical relationship between carbonate production and wave energy is defined in Figures 3.4, 3.5, 3.7, 3.8, 3.9 and 3.10. Figures 3.4 and 3.5 provide a global comparison between datasets and Figures 3.7 to 3.10 employed transects to compare datasets. Significant results were found comparing wave energy zones using the range and standard deviations of carbonate production values within each wave energy zone (Figure 3.6). Results suggest that carbonate production increases when wave energy increases. This finding is similar to Mallela (2007) who commented on a similar association between carbonate production and wave energy.

Transect comparison between carbonate production and wave energy revealed important findings, which can be used to further understand intricate relationships between carbonate production and coral reef hydrodynamics. A second order polynomial trendline was used to assess correlation between carbonate production and wave energy datasets along transect 2 and transect 3 (Figure 3.8 and 3.10 respectively). Transect 2 displayed an R-squared values of 0.78, which suggested that the relationship between carbonate production and wave energy could characterised adequately as a second order polynomial function. Transect 4 displayed an R-squared value of 0.37, which was not a strong correlation but does show a similar threshold of carbonate production. The trendlines on both transects highlight a threshold of carbonate production when wave energy exceeds 300 J/m^2. Carbonate production increased to values of 2.0 to 2.2 kg $CaCO_3$ m^{-2} a^{-1} with wave energy and then starts to decrease when wave energy exceeds values of 300 J/m^2. This finding suggests that although water movement is useful to transport nutrients (Anthony 2009) and remove metabolic waste (Veron 2011) for carbonate producers such as corals, too much water movement results in the mechanical forces physically breaking corals and other calcareous elements resulting in a decrease of carbonate production values. This threshold is an important empirical finding. This provides a quantitative

extension of our understanding of the relationship between fundamental processes operating within coral reef systems.

Figure 4.1 represents the eco-morphodynamic model of coral reef systems. This model highlights the close interconnections between extrinsic and intrinsic processes and also the complex interaction between individual intrinsic processes. The empirical evidence highlighted in this thesis provides empirical values to be assigned to both carbonate production and wave energy shown in Figure 4.1. For instance, if ocean forcing increased wave energy over reef platforms, the empirical results found in this thesis can be used to estimate the likely reductions of carbonate production and its further influence on reef growth, reef island development and sand apron development. A practical application to incorporate the empirical threshold values determined in Figure 3.8 and 3.10 can be done by integrating future projections of wind energy provided by the CSIRO and Bureau of Meteorology (2007) (Table 1.4). For example, Figure 3.8 suggested that carbonate production values are 2.2 kg $CaCO_3$ m^{-2} a^{-1} when wave energy levels are 300 J/m^2. Beyond this wave energy threshold, carbonate production starts to decrease. If wind energy increases by 5% by the year 2100, wave energy will also increase. Predictions suggest that by the year 2100, community carbonate production by coral and calcareous organisms at Lizard Island will decrease if wave energy increases beyond the critical wave threshold of 300 J/m^2. This will lead to further implications reef development and island formation, as they are underpinned by carbonate production (Chivas et al. 1986; Woodroffe et al. 2007).

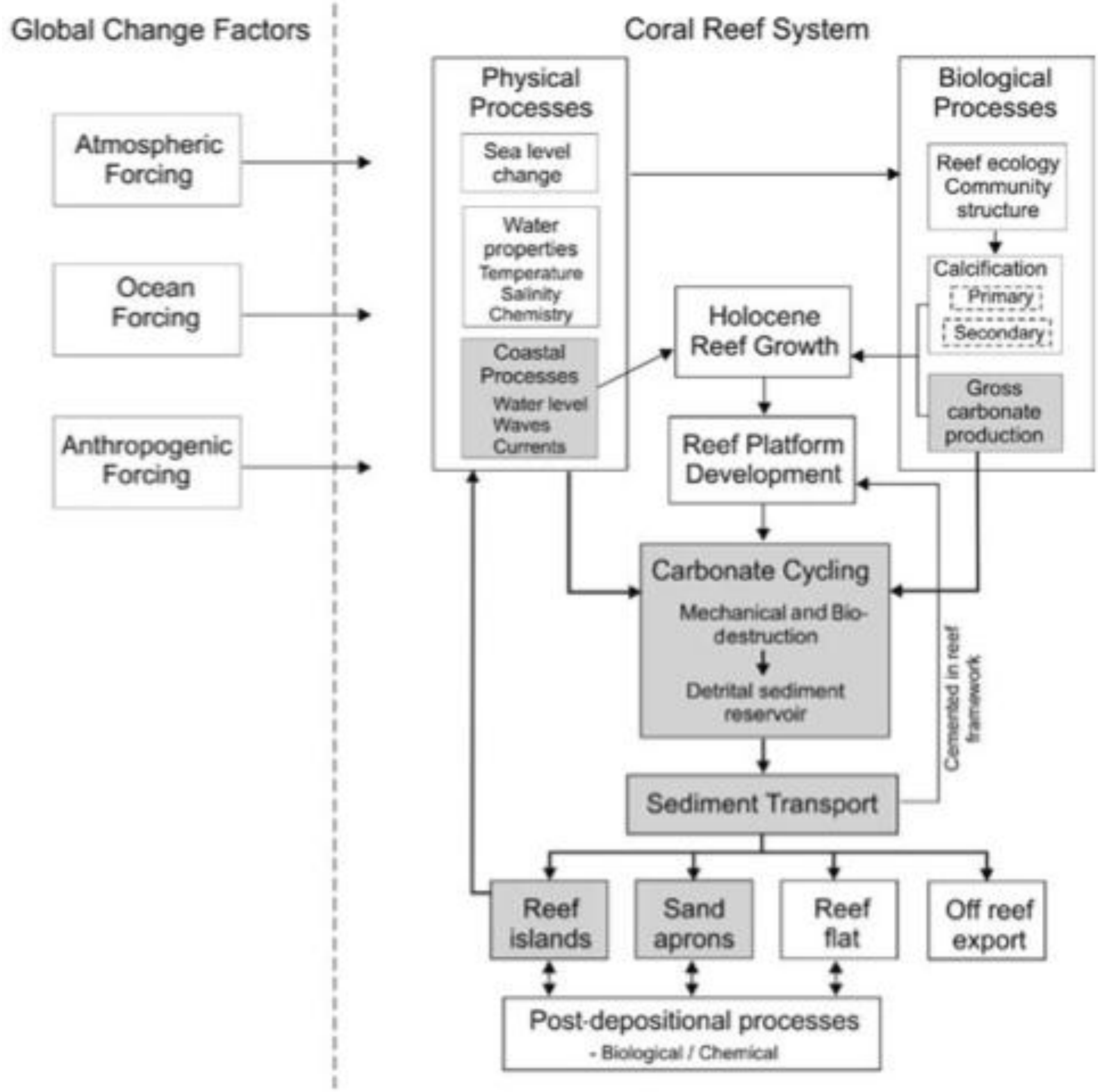


Figure 4.1: Structural and functional processes of the eco-morphodynamic model of coral reef systems. Highlights the global influences on the coral reef system, which is composed of various physical and biological processes (source: Kench et al. 2009).

4.5 Significance of the results: implications for coastal management

Formulating effective management strategies for the coastal zone requires a detailed understanding of the interconnections between the natural environment and human activities (Nwilo 2005). Managing the impacts of development and anthropogenic activities requires a comprehensive understanding of process operating within the coastal ecosystem (Wang et al. 2009). The geospatial approach outlined in this thesis provides a

valuable tool to understand the processes operating within coral reef ecosystems at the relevant spatial scale for coastal management (Yang 2009). Defining the empirical relationship between carbonate production and wave energy, and highlighting wave energy thresholds, makes a significant contribution to the knowledge base on which coastal management strategies are formulated.

Coral reef dynamics operate over various scales and are difficult systems to conceptualise and represent digitally in a modelling framework (Yang 2009). The geospatial analysis performed in this thesis provided an important, unique methodology to further understand the dynamics of coral reef dynamics and their associated hydrodynamics, which is a reliable and useful step forward in coral reef research. However, limitations and uncertainty were present and are examined in detail in the following section.

4.6 Limitations of the study

4.6.1 Limitations of the dataset: foraminifera and erosional processes

The benthic components examined in this thesis were important contributors to the overall carbonate production, which aid reef development and island formation (LIMER 1975). Live coral, carbonate sand, green calcareous macroalgae and encrusting calcified algae where easily observed in the video snapshots. Another important carbonate producing benthic component that was not incorporated into the investigation was foraminifera, which could not be identified in the video footage, as they are too small. Studies have defined calcification rates of benthic foraminifera present on Lizard Island reef flat, *Marginopora vertebralis*, which were estimated within a laboratory setting using the alkalinity-anomaly technique (LIMER 1975). They found that the foraminifera decalcification rate at night (0 to -100 μg $CaCO_3$ $g^{-1}h^{-1}$) that is similar rate to the carbonate deposition in light (0 to 100 μg $CaCO_3$ $g^{-1}h^{-1}$), concluding that the foraminifera have very little overall carbonate production rates. The extent of their contribution to the overall carbonate production of the reef system requires further investigation. Yamano et al. (2000) examined the importance of foraminifera to the development and maintenance of a coral sand cay at Green Island, Australia. They found that although foraminifera have a much lower carbonate production rates than corals and calcareous macroalgae, they are the single most important contributor to the sediment mass of the Island. Carbonate

production rates by benthic foraminifera in the algal turf and foraminifera zone on the reef flat at Green Island Australia was 0.48 ± 0.28 kg $CaCO_3$ m^{-2} a^{-1}. Foraminifera were not included in the dataset in the geospatial analysis outlined in this thesis because their abundance could not be quantified using this census-based approach Their importance in terms of the overall carbonate budget varies across sites. Further investigations should consider foraminifera in carbonate production studies, as they are important contributors to the development of reef platforms (Langer 2008) and island formation (Yamano et al. 2000).

Reef growth and island development are the end result of the constructive and destructive processes operating on coral reefs over millennial timescales (Kench et al. 2009). This thesis considers the constructional processes of a coral reef system and excluded the biological and physical destructive processes. Biologically destructive processes include bioerosion, which occurs when reef-associated faunas directly degrade the primary and secondary reef framework (Edinger et al. 2000). Destructive physical processes include storms and cyclones, which causes breakage of corals, producing coral rubble (Woodroffe 2002). Conceptualising and representing both constructive and destructive processes on coral reefs enables the development of an overall net production of carbonate production, which has been termed a carbonate budget (Perry et al. 2008; Hart & Kench 2009). Including destructive processes in the dataset was beyond the scope of this thesis, as this thesis was concerned with quantifying gross carbonate production rather than net carbonate production. Hughes (1999) provide a useful study, which quantified the export of coral fragments from Lizard Island and could be incorporated into a carbonate budget study on Lizard Island. Incorporation of bioerosion and physical erosion into the dataset is beneficial to understanding the carbonate budget at Lizard Island, as reef health and reef state could be conceptualised (Perry et al. 2008)

4.6.2 Human error

This investigation employed a census-based method, which relied on quantitative measurements of benthic component percentage coverage. Classification of individual benthic cover type in each video snapshot will vary slightly among interpreters. All video samples were analysed by the same interpreter, over a short time period, thereby taking

practical steps to minimise human error. To limit inconsistency is an important aspect of video classification (Green et al. 2000). Consistent classification of each benthic type followed a strict classification scheme, which resulted in robust assumptions of the type of benthic component being classified (see Appendix A).

4.6.3 Error and uncertainty associated with modelling

All models are subject to error (Box, 1976). The benthic distribution models developed in chapter 2 were validated using the coefficient of determination (R^2), which assessed proportion of observed variation that was explained by the model. Each model produced an R^2 value greater than 0.75, which is considered a good correlation to assess the models performance (Zhang et al. 1995). The spatial distribution of calcium carbonate production was calculated by summing the benthic cover models using their individual carbonate production rate as a weight. The rank correlation method assured the carbonate production model was valid against actual carbonate production values (Kendal et al. 1990). The exercise of adding benthic cover models to build an overall carbonate production model could propagate error throughout each step. This modelling process provides valuable information and is sufficient to use synoptically investigate coral reef ecosystems, however, error and uncertainty must be quantified (Bruce 2005).

Uncertainty, associated with models, arises from the initial exercise to conceptualise complex, geographic phenomena in a digital manner within a finite computer based system (Bruce 2005). All modelling exercises inherently involve some form of uncertainty that can be assessed and quantified. Quantifying uncertainty can be perceived as an intrinsic property of knowledge, rather than a consequence of empirically failing to achieve perfect accuracy (Couclelis 2003). Quantifying error associated with the geospatial approach to model benthic habitats and carbonate production is important to evaluate the reliability of the output data. All sources of error associated with the carbonate production model produced in this thesis have not been quantified. Although significant correlation assessment validated the benthic models and carbonate production model, errors associated with other aspects of the investigation have not been quantified. Additional error sources that can be quantified include (1) digitizing of the geomorphic zones in section 2.7.1, (2) seasonal error, which influences macroalgae growth (LIMER

1975), and (3) carbonate production rate error. Identifying the amount of uncertainty and error associated with models and the methodology is important for strengthening the empirical relationship between carbonate production and wave energy. Furthermore, this analysis would profit from an exercise to ascertain the cumulative error that propagated across the multiple steps associated with model development (Figure 2.1).

4.7 Future recommendations

This thesis provides baseline data of gross carbonate production at a particular point in time on Lizard Island's reef system. Future studies should incorporate biological and physical erosion to construct a more complete carbonate budget of Lizard Island's reef system, which will provide important information to assess reef health and reef state (Perry et al. 2008). Investigations should attempt to incorporate a different field sampling methodology that would allow foraminifera to be sampled and included in analysis.

The influence of wave energy on carbonate production was assessed in this thesis, which is only one of many intrinsic hydrodynamic processes operating within the reef system. Future investigations should focus on other important hydrodynamic processes such as currents, tides or water properties including temperature, chemistry and salinity (Kench et al. 2009). Furthermore, attempts should be made to extend empirical evaluations to the relationship between carbonate production and external, global factors including atmospheric, oceanic and anthropogenic factors. Understanding the complex relationships between carbonate production and coral reef processes is possible adopting the geospatial analysis outlined in this thesis. Applying this geospatial methodology to other reef sites globally, including the Caribbean, Indian Ocean and the Eastern Pacific offers a unique approach to understand their dynamics and processes over large spatial scales relevant for management purposes.

This geospatial approach provides detailed, synoptic data of coral reef carbonate production, which can be used to develop reef scale, carbonate production models for all reef systems around the world. Employing this geospatial approach at Rio Bueno bay, North Jamaica will enable spatially continuous understanding of carbonate production,

compared to the site specific areas employed by Mallela and Perry (2007), who investigated the influence of terrestrial runoff.

Quantifying all sources of uncertainty associated with this geospatial approach is an important process to strengthen the empirical relationship defined in this thesis, and furthermore, to provide robust data sets, which should be implemented in management strategies (Yang 2009). Quantification of error associated with digitizing exercises, seasonal variation of benthic cover and carbonate production rates is an essential requirement for future investigations employing this methodology.

5 CONCLUSION

The geospatial approach outlined in this thesis offers coral reef researchers, managers, geomorphologists and ecologists a valuable tool to conceptualise processes operating on reefs over large spatial scales. Building spatially continuous models of benthic cover types and overall carbonate production, provides an opportunity to understand benthic component distribution, carbonate production distribution and interactions between various processes. Investigating the empirical relationship between carbonate production and wave energy is of critical importance, as they are both fundamental processes that underpin reef development, reef island formation and stability (Kench et al. 2009). Understanding this relationship provides valuable outcomes, which can be used to predict the impacts of higher wave energy conditions associated with anthropogenic induced climate change. The geospatial approach outlined in this thesis provides a novel methodology to quantify coral reef calcium carbonate production using census-based methods. The spatially continuous carbonate production model developed, in this thesis, offers baseline data of carbonate production on Lizard Island's reef platform.

The aims of this study were to model the distribution of coral reef calcium carbonate production on Lizard Island, Great Barrier Reef and furthermore, to investigate the empirical relationship between carbonate production and wave energy using global and transect comparison techniques. These aims were accomplished, providing new knowledge of coral reef environments and allowing robust conclusions to be drawn. Key conclusions are summarised below.

- Video footage of the benthic environment provides detailed visualisation of the seafloor, which can be used in a census-based method to estimate coral reef community carbonate production.
- Worldview-2 satellite imagery and benthic terrain variables (including depth, slope, BPI, TRI and variety) derived from a Digital Elevation Model of the seafloor, offer powerful predictors of the distribution of coral reef benthic components including live coral, carbonate sand, calcareous green macroalgae and encrusting calcified algae

- Ordinary least square regression enabled carbonate producing benthic components to be predicted and mapped into a spatially continuous data model. The coefficient of determination (R^2) values of each benthic model including live coral (R^2 = 0.84), carbonate sand (R^2 = 0.91), calcareous green macroalgae (R^2 = 0.79) and encrusting calcified algae (R^2 = 0.88) yielded results that indicated a high correspondence to field datasets.
- Calcium carbonate production on coral reefs can be accurately modelled across an entire reef system using census-based techniques along with a combination of remote sensing, fieldwork and geospatial analysis.
- Gross carbonate production of the entire reef platform at Lizard Island was 1.84 kg $CaCO_3$ m^{-2} a^{-1}.
- Windward reef flats at Lizard Island are the highest carbonate production areas, which complies with the findings made by Vecsei (2001) that these areas are important carbonate producing regions.
- The transect located on the windward reef flat conducted by LIMER (1975) estimated carbonate production values ranging from 3.47 to 3.83 kg $CaCO_3$ m^{-2} a^{-1}. Carbonate production values, for the windward reef flat estimated in this thesis, were lower, ranging from 0.9 to 2.6 kg $CaCO_3$ m^{-2} a^{-1}. The reduction in carbonate production values on the windward reef flat at Lizard Island since 1975 is possibly associated with ocean acidification and coral bleaching events.
- Employing both global and local comparisons between carbonate production and wave energy revealed important patterns and relationships, which can be used to understand and manage coral reefs.
- A positive trend of increased carbonate production values with increased wave energy was empirically confirmed, using global scale analysis.
- At the local scale, transect comparisons revealed an environmental threshold. As wave energy increased to 300 J/m^2, carbonate production values also increased. When wave energy exceeded 300 J/m^2, carbonate production values started to decrease. This suggests that although wave energy is an important process to transport nutrients (Anthony 2009) and remove metabolic waste (Veron 2011) for carbonate producers such as corals, too much water movement results in the mechanical forces physically breaking corals and other calcareous elements resulting in a decrease of carbonate production values.

Coral reefs are crucial coastal environments supporting a range of marine and terrestrial life. The ability of coral reefs to persist through anthropogenic stressors depends on the scientific understanding of the system to create effective management strategies. Outlining effective methodological approaches to synoptically model coral reef processes, as demonstrated in this thesis, provides a foundation for future research and an opportunity to empirically evaluate relationships between fundamental processes underpinning coral reef systems.

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Appendix A

Video classification scheme

Benthic class	Benthic assemblage	Benthic assemblage (% cover)
Live Coral		• Live coral (100%)
Encrusting calcified algae		• Encrusting calcified algae (80%) • Live coral (10%) • Dead coral/ rubble (10%)
Green calcareous macroalgae *(Halimeda)*		• Green calcareous macroalgae (85%) • Carbonate sand (15%)
Carbonate Sand		• Carbonate sand (100%)

Seagrass		• Seagrass (90%) • Carbonate sand (10%)
Dead coral/rubble		• Dead coral/rubble (100 %)

Appendix B

Ordinary Least Square regression results

Live Coral

```
Regression
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set                  :  Live coral
Dependent Variable        :      LOG_LC  Number of Observations:  116
Mean dependent var        :   -0.932048  Number of Variables   :    7
S.D. dependent var        :     2.67191  Degrees of Freedom    :  109


R-squared                 :    0.836747  F-statistic           :      93.1127
Adjusted R-squared        :    0.827761  Prob(F-statistic)     :1.39463e-040
Sum squared residual:         135.196   Log likelihood        :     -173.479
Sigma-square              :     1.24033  Akaike info criterion :      360.957
S.E. of regression        :      1.1137  Schwarz criterion     :      380.232
Sigma-square ML           :     1.16548
S.E of regression ML:           1.07957
```

Variable	Coefficient	Std.Error	t-Statistic	Probability
CONSTANT	-10.56978	2.436915	-4.33736	0.0000323
DEPTH	0.01587889	0.005019376	3.163518	0.0020200
BAND_1	-0.7278625	0.4833987	-1.505719	0.1350317
VARIETY	-0.02229442	0.06009188	-0.3710055	0.7113505
SLOPE	1.601628	0.6230426	2.570655	0.0114993
BPI_BROAD	-4.719063	9.456723	-0.4990168	0.6187746
TRI	12.40278	9.697055	1.279025	0.2036039

Carbonate sand

```
Regression
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set                  :  sand
Dependent Variable        :    LOG_SAND  Number of Observations:  214
Mean dependent var        :   -0.490578  Number of Variables   :    8
S.D. dependent var        :     6.54366  Degrees of Freedom    :  206


R-squared                 :    0.908283  F-statistic           :      291.434
Adjusted R-squared        :    0.905166  Prob(F-statistic)     :            0
Sum squared residual:         840.438   Log likelihood        :     -450.023
Sigma-square              :      4.0798  Akaike info criterion :      916.046
S.E. of regression        :     2.01985  Schwarz criterion     :      942.974
Sigma-square ML           :     3.92728
S.E of regression ML:           1.98174
```

Variable	Coefficient	Std.Error	t-Statistic	Probability
CONSTANT	27.89516	4.568616	6.105822	0.0000000
DEPTH	-0.120868	0.01158714	-10.43122	0.0000000
BAND_1	0.08163596	0.004853385	16.82042	0.0000000
BAND_3	0.877905	0.6379074	1.376226	0.1702460
VARIETY	0.05001036	0.09098947	0.549628	0.5831707
SLOPE	-7.267418	2.279863	-3.187656	0.0016577
BPI_BROAD	-10.63309	18.8078	-0.5653555	0.5724471
TRI	12.4329	18.6124	0.6679902	0.5048883

Green calcareous macroalgae

```
Regression
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set              :  G_Cal_mac
Dependent Variable    :   LOG_CAL_M  Number of Observations:   56
Mean dependent var    :    -4.00699  Number of Variables   :    6
S.D. dependent var    :     6.57084  Degrees of Freedom    :   50



R-squared             :    0.788421  F-statistic           :     37.2637
Adjusted R-squared    :    0.767263  Prob(F-statistic)     :9.85501e-016
Sum squared residual:       511.566  Log likelihood        :      -141.4
Sigma-square          :     10.2313  Akaike info criterion :       294.8
S.E. of regression    :     3.19864  Schwarz criterion     :     306.952
Sigma-square ML       :     9.13511
S.E of regression ML:       3.02244
```

Variable	Coefficient	Std.Error	t-Statistic	Probability
CONSTANT	0.0453447	0.6040593	0.07506663	0.9404546
DEPTH	-0.06869567	0.007989474	-8.598272	0.0000000
BAND_1	0.07836662	0.007557863	10.36889	0.0000000
BAND_3	-2.058762	2.805228	-0.7339017	0.4664363
VARIETY	0.3583623	0.2979287	1.202846	0.2347012
SLOPE	0.3905016	0.1739829	2.244483	0.0292574

Encrusting calcified algae

```
Regression
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set              :  en_cal_al
Dependent Variable    :   LOG_EN_AL  Number of Observations:  144
Mean dependent var    :    0.957157  Number of Variables   :    7
S.D. dependent var    :      4.3898  Degrees of Freedom    :  137



R-squared             :    0.883245  F-statistic           :     172.733
Adjusted R-squared    :    0.878132  Prob(F-statistic)     :           0
Sum squared residual:       323.986  Log likelihood        :    -262.711
Sigma-square          :     2.36486  Akaike info criterion :     539.422
S.E. of regression    :     1.53781  Schwarz criterion     :     560.211
Sigma-square ML       :      2.2499
S.E of regression ML:       1.49997
```

Variable	Coefficient	Std.Error	t-Statistic	Probability
CONSTANT	-9.88866	4.52068	-2.187427	0.0304077
DEPTH	0.001446861	0.00735551	0.1967043	0.8443506
BAND_1	-0.6621533	0.5659633	-1.169958	0.2440494
VARIETY	-0.1504119	0.05949655	-2.528077	0.0126037
SLOPE	15.56013	5.881567	2.645576	0.0091087
BPI_BROAD	6.705726	14.35985	0.4669776	0.6412608
TRI	-18.47726	12.88606	-1.433895	0.1538802