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Long term dynamics of coral reefs in the inshore southern Great Barrier Reef

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Abstract

Coral reefs are declining on local, regional and global scales, showing evidence of long-term losses of abundance, diversity and structure. Threats to coral reefs arise from the cumulative and interacting effect of multiple stressors. Runoff and climate change are the major risk factors affecting coral reefs in the Great Barrier Reef (GBR). The degradation of this ecosystem has accelerated since European settlement in the coastline of Queensland due to land use changes resulting in augmented runoff into the GBR lagoon. Inshore coral reefs on the GBR are particularly at high risk since they are exposed to local runoff while also being impacted by global warming. However, there is a lack of direct evidence linking European settlement, anthropogenic and natural stressors, and changes in coral community structure. In order to understand this link and best manage the multiple stressors impacting on coral reefs of the GBR, it is crucial to compare the rate of change of modern coral communities with the long-term baseline of coral community change. The overarching aim of this project is to build baseline knowledge of the historical response of coral reefs to disturbances. A case study in the Keppel Islands (inshore southern GBR) will be presented, specifically aiming to 1) determine historical changes in coral reef communities following European settlement across millennial timescales; 2) reconstruct the history of high coral mortality events along a water quality gradient from the Fitzroy River; 3) describe spatial and temporal patterns of reef accretion in the late Holocene. To achieve this, live, dead and fossil coral assemblages as well as reef sediments will be investigated. Recently dead and fossil corals will be dated by high-precision U-series to reconstruct the extent and timing of coral community structure change, high coral mortality events and rates of reef accretion. Additionally, coral reef dynamics will be correlated with historical records of environmental variables including major floods and mass bleaching episodes in order to assess their relative importance. Finally, the historical input of terrigenous sediments on the reefs will be reconstructed to identify the recent anthropogenic influence. This project will be the first to provide a long-term reconstruction of coral reef dynamics from sediment cores of the southern GBR. It will also contribute to the crucial understanding required to manage the cumulative impact of multiple stressors on the GBR and the ecosystem goods and services it provides.

1 AIMS, SIGNIFICANCE AND EXPECTED OUTCOMES

1.1 BACKGROUND

1.1.1 IMPORTANCE AND THREATS TO CORAL REEFS

Coral reefs are dynamic ecosystems with extraordinary features and great significance for the global diversity and human societies. Corals are essential to the contemporary reef ecosystems because they create the largest carbonate structure built by a living organism (Veron, 2000). The complexity of the reef framework not only originates diverse habitats and supports a huge number of marine species (Birkeland, 1997) but also provides food, coastal protection, recreation and tourism for millions of people (Moberg and Folke, 1999; Wilkinson, 2008). Despite coral reefs being crucial for the wellbeing of humanity (Costanza et al., 1997; Moberg and Folke, 1999), their ability to supply goods and services on a sustained basis continues to decline worldwide (Hughes et al., 2003; Pandolfi et al., 2003; Wilkinson, 2008).

Evidence shows that loss of abundance, diversity and habitat structure in coral reef ecosystems started before 1900. This degradation process has accelerated in the last few decades and is unprecedented in palaeoecological records (Pandolfi et al., 2003; Aronson et al., 2004). The causes of coral reefs decline can be attributable to the cumulative and interactive impact of multiple stressors (Hughes, 1994; Aronson et al., 2002b). These include overfishing, pollution, bleaching, cyclones, diseases, coastal development and climate change (Hallock et al., 1993; Jackson et al., 2001; Nott and Hayne, 2001; Aronson et al., 2002b; Sutherland et al., 2004; Pandolfi et al., 2005). In order to ensure coral reefs persistence, management of such stressors requires biological knowledge in regions with the greatest biodiversity and/or under threat (Fisher et al., 2011).

The GBR in Australia is the largest continuous coral reef system on earth; it extends 15º of latitude (~2,300km) and covers 348,000km^2 (Hopley et al., 2007). The GBR comprises around 2,400 mid-outer shelf reefs built over the Holocene upon Pleistocene foundations, plus around 600 fringing and patch inshore reefs (Hopley et al., 2007).The GBR is a World Heritage Area and one of the national icons of Australia, raising a tourism income estimated over $5 billion in 2006/07 (Great Barrier Reef Marine Park Authority [GBRMPA], 2009). Although reefs in the GBR are considered to be among the best protected and closest to pristine in the world (Pandolfi et al., 2003), they have been strongly impacted by natural and anthropogenic stressors (Nott and Hayne, 2001; Fabricius, 2005; De'ath et al., 2009).

Catchment runoff and climate change have been identified as the highest risk threats to coral reef ecosystems in the GBR (GBRMPA, 2009). Human development and catchment deterioration are higher in the central and southern GBR than in the northern GBR (Fabricius et al., 2005; Clark et al., 2012). In turn, the inshore reefs are mostly affected by decreased water quality because of their proximity to rivers and urban development (Fabricius et al., 2005; Jupiter et al., 2008). This impact can also vary locally between neighboring reefs because of the complex dynamics of the sediments in the water (Golbuu et al., 2011). Recent studies suggest that the ecological consequences of reduced water quality include decreases in coral cover and diversity (Golbuu et al., 2011), colony abundance, richness and recruitment (reviewed by Fabricius, 2005); and higher risk for the reefs to become dominated by algae typical of degraded reefs (Albert et al., 2008). Thermal bleaching is another factor clearly affecting inshore reefs in the GBR during the last decades (Berkelmans et al., 2004). Ecological implications of bleaching events include significant reduction in cover of susceptible coral species, changes in community composition and coral mortality (Sweatman et al., 2011). In addition, excessive carbon dioxide emissions due to human activities have driven ocean acidification and global warming which also appears to play a role in coral reefs decline (Hoegh-Guldberg et al., 2007; Wei et al., 2009; Pandolfi et al., 2011). Coral skeletal records have shown reduction in coral calcification in the GBR since 1990 (Cooper et al., 2008; De'ath et al., 2009) and such changes were attributed to the interaction between ocean acidification and global warming.

1.1.2 Research Problem

Management of stressors to coral reef ecosystems in the GBR must comprehensively consider the cumulative impacts of multiple stressors and the scale at which they impair ecosystem services (GBRMPA, 2009). However, problems arise because human activities add novel stressors to the ecosystem or alter those of environmental nature (Done, 1992b; Hughes, 1994; Jackson et al., 2001) making difficult to isolate them. In order to understand the role of individual stressors as drivers of ecosystem decline and evaluate the social and ecological costs, an historical framework can be used (Pauly, 1995). Corals are suitable organisms for palaeoecological research (Jackson, 1992); they are the dominant constituent of coral reefs ecosystem, are sensitive to perturbation, and offer a relatively good fossil record (Pandolfi and Minchin, 1996). Unfortunately, palaeoecological research on coral reefs is scarce with the majority of studies carried out in the Caribbean region and less work focused on the GBR (for a comprehansive review of palaeoecological studies see Pandolfi, 2011).

Human development since European settlement in the Queensland coastline of Australia by mid-18th century is a well-known event, which can be used as a reference to understand historical changes in coral reef communities. Some recent studies have covered geological timescales and have attempted to link anthropogenic impacts since European settlement and coral decline on inshore reefs of northern and central GBR (McCulloch et al., 2003; Pandolfi et al., 2003; Fabricius et al., 2005; DeVantier et al., 2006; Wooldridge et al., 2006; Done et al., 2007). Although evidence suggests that increased sediment loads after European settlement have led to coral reefs degradation (McCulloch et al., 2003; Jupiter et al., 2008) and potential replacement of coral species (Roff, 2010), there is not much information on the variability in coral reef communities (changes and mortality events) along a water quality gradient from centennial to millennia scales in the southern GBR.

In order to help fill the existing information gap in reef corals palaeoecological research in the southern GBR, this research proposal will present a case study in the Keppel Islands. A number of stressors acting at different spatial scales threat coral reefs in the Keppel Islands. First, the risk of degradation imposed by global warming on coral communities is particularly high because these communities are dominated by *Acropora* species (Van Woesik and Done, 1997) which are highly susceptible to thermal stress. In 2006 a mass bleaching episode affected the Keppel Islands causing bleaching in up to 95% of corals and leading to an average of 36% of coral mortality (Weeks et al., 2008). However, these communities showed a remarkable recovery after the event (Diaz-Pulido et al., 2009) and signs of acclimatization to thermal stress (Jones et al., 2008). Second, *Acropora* species are also especially vulnerable to changes in water quality (e.g. due to floods, Van Woesik et al., 1995). The Fitzroy River (largest catchment discharging to the GBR) mouth is located ca 40km south from the Keppel Islands. Distance from the river source can be used as a proxy to define a water quality gradient in a direction pointing inshore–offshore and South-North (due to the prevailing SE swell). The Fitzroy River affects the reefs by episodic (~every 10yrs) discharge of large fresh water flood plumes and by chronic high turbidity (Webster and Ford, 2010). The soft sediments carried by the river are regularly re-suspended by wind and tides resulting in high turbidity with negative effects on corals (Van Woesik, 1991). Finally, corals in the Keppel Islands are affected by variations in seawater salinity caused by the combination of heavy rainfall and extreme low tides (Berkelmans and Oliver, 1999; Berkelmans et al., 2004).

In summary, although the Keppel Islands have become increasingly studied in the last decades, the information is still fragmentary and considerably poor in terms of palaeoecological research. The inshore southern GBR region is impacted both by global natural/human-induced stressors, such as mass bleaching resulting from global warming (Diaz-Pulido et al., 2009), and by local/anthropogenic stressors, such as decreased water quality due to river runoff (Jupiter et al., 2008).Therefore, the Keppel Islands (inshore southern GBR near the Fitzroy River) provide an excellent case study to investigate the effects of the major natural and anthropogenic stressors on historical changes in coral reef communities and decline. This project will complement recent studies done by our research group in the Keppel Islands (e.g., Rodriguez-Ramirez A., PhD thesis in preparation).The time frame period targeted by this research proposal (~1-2 thousand years to the present) will provide novel and significant scientific information to understand the long-term dynamics of inshore reefs at the GBR and to inform conservation and management strategies to GBRMPA.

The overarching aim of this project is to build a baseline of the long-term dynamics of coral reefs, including ecological changes, coral mortality events and rates of reef accretion of past coral communities to major anthropogenic and natural disturbances. Specifically, I aim to: 1) determine historical changes in coral reef communities following European settlement across millennial timescales; 2) reconstruct the history of high coral mortality events along a water quality gradient from the Fitzroy River; 3) describe spatial and temporal patterns of reef accretion in the late Holocene.

In the first aim, general responses for the Keppel Islands region will be assessed while in the second and third aim the influence of a local water quality gradient will be included. For aim 1, a comprehensive approach to assess changes in past community structure, measured from sediment cores will be presented and associated to the timing of European settlement. This will be compared with present-day coral assemblages evaluated by photo transects. For aim 2, a reconstruction of coral mortality events based on collection of corals from surface death assemblages and high precision U-series dating will be completed along a water quality gradient from the Fitzroy River source. This will be related to multiple local and global stressors inferred from secondary information, such as instrumental records and geochemical proxies from massive *Porites,* etc. (Rodriguez-

Ramirez et al, PhD thesis in preparation). For aim 3, a spatial and temporal reconstruction of the sediments deposition pattern (estimated by the ratio carbonate/terrigenous sediment) and historical reef accretion will be carried out.

1.2 AIMS

Aim 1

Determine historical changes in coral reef communities following European settlement across millennial timescales, in the Keppel Islands (inshore southern GBR).

Coral reef ecosystems can exist in multiple stable states (Knowlton, 1992) and stressors can drive transitions between states (i.e. “phase shifts”). Accumulated stressors can lead to longer and more frequent phase shifts (Hoegh-Guldberg et al., 2007; Diaz-Pulido et al., 2009) that eventually become persistent (i.e. new stable state with no return to pre-disturbance conditions).

While persistent shifts associated with anthropogenic and natural disturbances (and their interaction) are difficult to identify over short-term periods (Done, 1992a; Hughes, 1994; Done et al., 2007), long-term data sets may capture past transitions in direct response to particular disturbances. Over the last 1-2 millennia, the Earth has experienced environmental conditions (e.g. Medieval Warm Period and the Little Ice Age) which magnitude of change was probably larger than seen since European settlement. Thus, assessment of ecological disturbance over this longer period may enable to identify and separate the anthropogenic impact from the long-term natural variability. Evidence is lacking to link European settlement with historical changes in coral community structure in the Keppel Islands. Therefore, this project aims to reconstruct the ecological changes in coral reef communities over the last 1-2 millennia, with especial focus on changes associated to European settlement.

Hypothesis: Coral community structure in the Keppel Islands changed significantly following European settlement.

The hypothesis will be addressed by answering the following research questions:

- What was the timing of significant changes in coral community structure over the last 1-2 millennia?

- Are all (if any) post-European community structure changes also recorded in the pre-European 1-2 millennial history?
- Did the spatial and/or temporal scale of community structure changes remain the same before and after European settlement? Or are the recent changes larger/smaller and/or faster/slower than in the pre-European period?

Aim 2

Reconstruct the history of high coral mortality events along a water quality gradient from the Fitzroy River across decadal timescales in the Keppel Islands (inshore southern GBR).

Humans can add novel stressors or alter the temporal and spatial scales of those of natural occurrences, impacting on the normal cycles of coral mortality and recovery and impairing their capacity to return to pre-disturbance conditions. The impact of this interaction between multiple anthropogenic and natural stressors is of great concern because it can cause irreversible ecological change (Done et al., 2007).

Global warming is a natural/global stressor that may interact with decreased water quality, an anthropogenic/local stressor, impacting inshore coral reefs. In the Keppel Islands, the independent impacts of mass bleaching and water quality changes (due to floods) are well known to have resulted in events of high coral mortality (Van Woesik, 1991; Diaz-Pulido et al., 2009). On the other hand, Jupiter et al. (2008) found that recovery capacity of inshore coral reefs influenced by a nearby river (in the southern GBR) was low and high for respectively close and distant reefs. Therefore, a water quality gradient may allow investigation of the impact of different degrees of the interaction between bleaching and water quality on inshore coral reefs. However, historical information on frequency and accurate timing of high mortality events for the Keppel Islands is limited, and research on the interactive impact of those stressors is lacking.Thus, this project aims to reconstruct historical mortality events over a water quality gradient and relate such events to runoff and bleaching episodes.

Hypothesis: The frequency of high mortality events varies along a water quality gradient, with reefs in better quality waters showing less frequent mortality events due to their higher capacity to recover following disturbance.

The hypothesis will be addressed by answering the following research questions:

- What was the timing of high mortality events of coral communities?
- Can the frequency of high mortality events inform about the capacity of a reef to recover following disturbance?
- If so,
    - what is the variability along a water quality gradient?
    - can that variability inform about changes in the strength of the interaction between multiple stressors along a water quality gradient?
- What is the correlation between the timing of high mortality episodes and major disturbance events (flooding and bleaching) along the water quality gradient?

Aim 3

Describe the spatial and temporal patterns of reef accretion in the late Holocene, in the Keppel Islands (inshore southern GBR).

Inshore reefs along the GBR are commonly under the influence of terrigenous (Done, 1982; McCulloch et al., 2003; Fabricius, 2005) and carbonate (reefal) sediments, both of which leave a signature in the depositional records. Reefs in the Keppel Islands are particularly influenced by the Fitzroy River which exports to the GBR lagoon more than two million tonnes of sediments every year, only second to the Burdekin River (Neil et al., 2002). Evidence shows that the sediment load significantly increased following European settlement in Queensland coastline, and increased sediments are considered to be a threat to coral reefs (McCulloch et al., 2003; Jupiter et al., 2008). However, the link between increased sediments and coral decline is not conclusive mainly because of the lack of an ecological baseline prior to European settlement.

Perry et al.(2008; 2009) investigated radiometrically dated reef cores in the inshore GBR and found no evidence of coral decline in reef environments characterized by the dominant accumulation of fine-grained terrigenous sediments. The authors suggested that coral communities that succeed establishing themselves in near-threshold conditions may already possess the capacity to cope well with the human-induced decrease in water quality. Because coral reefs in the Keppel Islands are under high influence of terrigenous sediments (Radke et al., 2010; Webster and Ford, 2010) but show high capacity to recover from disturbance (Diaz-Pulido et al., 2009), these reefs could be in line with Perry et al.´s suggestion (2008; 2009). However, other studies found contrasting results with significant changes in coral communities in environments with similar influence of anthropogenic stressors (Roff, 2010; Lybolt et al., 2011). In addition, Perry and Smithers (2011) argued that reef accretion transitions can happen regardless of human impacts. In order to better manage coral reefs and predict their ecological future trajectories it is crucial to recognize when changes (in reef accretion and coral community structure) are due to natural cycles and to understand how those changes interact with anthropogenic stressors. This study will reconstruct reef accretion with higher precision than commonly achieved in previous studies (e.g. Perry and Smithers, 2011), presenting a palaeoecological case study in an area that has been so far overlooked, i.e. the Keppel Islands.

Hypothesis: Reef accretion and sediment composition significantly changed following European settlement.

The hypothesis will be addressed by answering the following research questions:

- What were the rates of coral reef accretion in the Keppel Islands over the last millennia?
- What is the millennial historical balance of carbonate and terrigenous deposition and grain size distribution on reefs located along the water quality gradient and how did it change since European settlement?
- What is the correlation (if any) between changes in the balance of carbonate and terrigenous sediments deposition and trends of reefs accretion?

1.3 SIGNIFICANCE

This research will provide key and novel information on the long-term dynamics of coral reef communities. Such information will help predict the response of other coral reef systems to the impact of multiple interacting stressors on crucial ecosystem processes, including coral community structure change, high coral mortality events and reef accretion.

Novelty and innovation

This project will be the first to use sediment cores in a palaeoecological reconstruction of coral reefs in the southern GBR. It will also be the first using carbonate/terrigenous contents and sediment grain size within the cores to investigate the influence of the Fitzroy River on coral reef dynamics in the Keppel Islands. This research will apply the latest high-precision U-Series dating techniques to reconstruct coral community structure and reef accretion with higher precision than commonly achieved by radio carbon dating (e.g. Perry et al., 2008; 2009). Furthermore, a Nu Plasma multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) will be used which represents an improvement compared to thermal ionization mass spectrometry (TIMS, which was used in previous palaeoecological research in the central GBR [Roff, 2010; Clark et al., 2012] and Moreton Bay [Lybolt, 2012]) because MC-ICP-MC allows U-series dating with samples 5-10 times smaller while increasing 5 times samples throughput.

Filling information gaps

This case study in the Keppel Islands will help fill a crucial information gap on palaeoecological baselines of coral reefs in the southern GBR region by reconstructing the long term history of coral community structure, reef accretion, and shorter term high coral mortality events. This research will help understand how past periods of comparable climate change (e.g. Medieval Climatic Optimum, ~9-14th centuries AD) affected past coral reef communities, thereby, facilitating predictions of their response to projected scenarios of climate change (Pandolfi et al., 2011). This research will also inform how European settlement contributed to coral reef communities decline. Furthermore, by linking historical changes in coral communities with the factors that caused such changes, this project will provide important information on the identity of the past and present major drivers of change (natural and anthropogenic).

Management relevance

The historical baseline provided by this project will constitute a reference for the conservation and/or restoration of coral reefs, and for the assessment of the success of implemented management actions. Understanding the historical response of corals in times of a changing climate will help policy makers in the preparation for the projected climate change and continuing urban development (IPCC, 2007). Information on the relative role of global versus more localized stressors can be used by managers to decide at what spatial scale management actions should be taken in order to achieve effective goals. Ultimately, this project will have socioeconomic significance because of its relevance to the management of GBR ecosystem services.

Finally, this project fits within the national research priorities of the Australian Government (Australian Government, 2006) and is relevant to four of the scientific information needs identified by the GBRMPA (2009).

1.4 Expected Outcomes

The main outcomes of this project will include: 1) baseline knowledge of the historical response of coral reefs to multiple and accumulated stressors; 2) a detailed chronological reconstruction of coral community structure change at local (reef) and regional (Keppel Islands) scales over the last millennia; 3) link past and recent ecological shifts in coral reef communities with European settlement identifying the role of humans in current coral reef structure; 4) short term (decadal) records of high coral mortality events at local and regional scales; 5) identification of major disturbance events and their correlation with high coral mortality along a water quality gradient; 6) long-term records of coral reef accretion; 7) long-term records of the historical balance of carbonate and terrigenous sediments and the grain size distribution on reefs along a water quality gradient; 8) crucial information tools for the management of the GBR and the ecosystem goods and services it provides.

1.5 Tentative List of Thesis Chapters/Papers for Publication

I intend to submit three papers (chapters 2-4 listed below) containing the outcomes of this project to peer-reviewed international journals, including: Coral Reefs; Geology and Palaeogeography, Palaeoclimatology, Palaeoecology. Results will also be communicated in national and international conferences (e.g. Australian Coral Reef Society 2013/14, Australian Marine Science Association 2014). My PhD thesis will be organized in the following 5 chapters:

- Chapter 1: General introduction.
- Chapter 2: The foot print of European settlement in the millennial history of coral reefs in the inshore southern Great Barrier Reef, a case study in the Keppel Islands.
- Chapter 3: Drivers and chronology of high coral mortality along a water quality gradient in the inshore southern Great Barrier Reef, a case study in the Keppel Islands.
- Chapter 4: Spatial and temporal patterns of reef accretion in the Keppel Islands, inshore southern Great Barrier Reef.
- Chapter 5: General discussion.

2 Research Plan and Methods

2.1 Study area

The Keppel Islands (23º10´S, 151º00´E, Fig. 1) are a group of 16 small continental islands (<1500 ha) within the shallow waters of Keppel Bay in the southern GBR. Keppel Bay encompasses three coastal towns, a number of creeks and the estuary of the prominent Fitzroy River, which crosses Rockhampton city only 50 km upstream the bay. Draining an area over 142,500 km^2, the Fitzroy basin is the largest in the GBR catchment and second largest in Australia (Rolfe et al., 2006). Moreover, it is second (after the Burdekin River) in terms of sediment discharge into the GBR lagoon (annual average over two million tons).

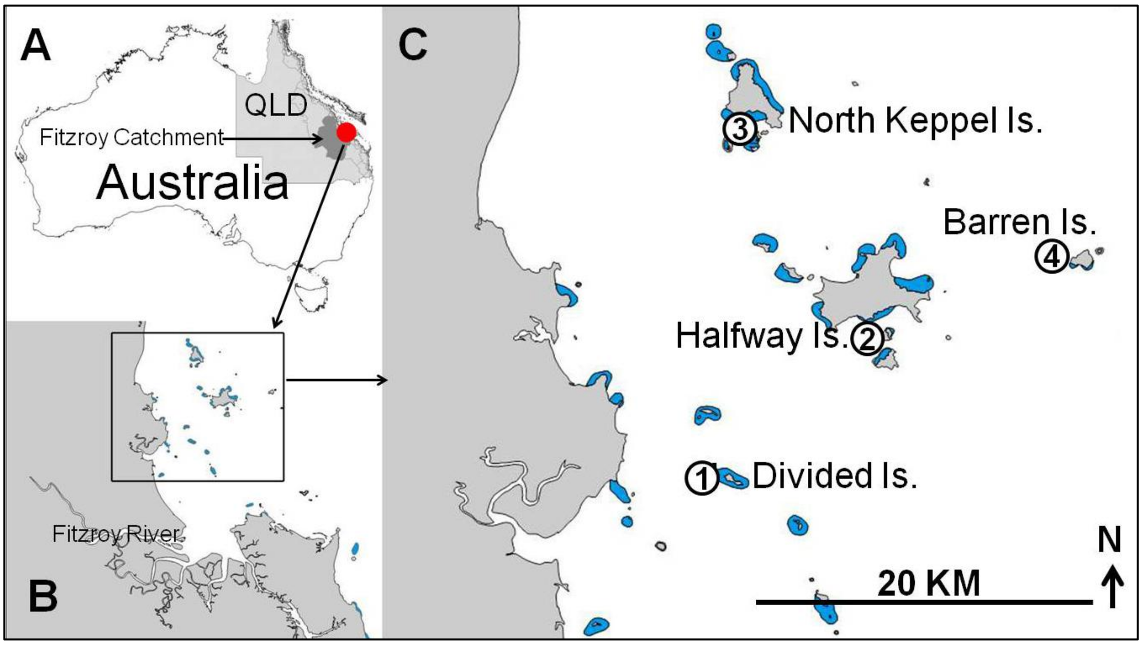


Fig. 1: Regional setting (A) of the Keppel Islands (B), affected by the largest catchment in Queensland (Fitzroy), showing four candidate islands along a water quality gradient (C). Locations 2-4 were already visited during a first fieldtrip; locations 1&4 will be confirmed or changed in a second fieldtrip.

2.2 General sampling design

Sampling methods and field strategies will be consistent with previous work by research group members (Roff, 2010; Clark et al., 2012). A stratified sampling design will be used (Fig. 2). Four locations (each location equivalent to an Island, Fig.1C, 1-4) along a water quality gradient from the Fitzroy River source will be selected. Within each location, three sites will be randomly chosen. Sites will be sheltered from the predominant SE swells and located on the reef slope at 5 m depth. Each site will be separated at least 100 m from each other.

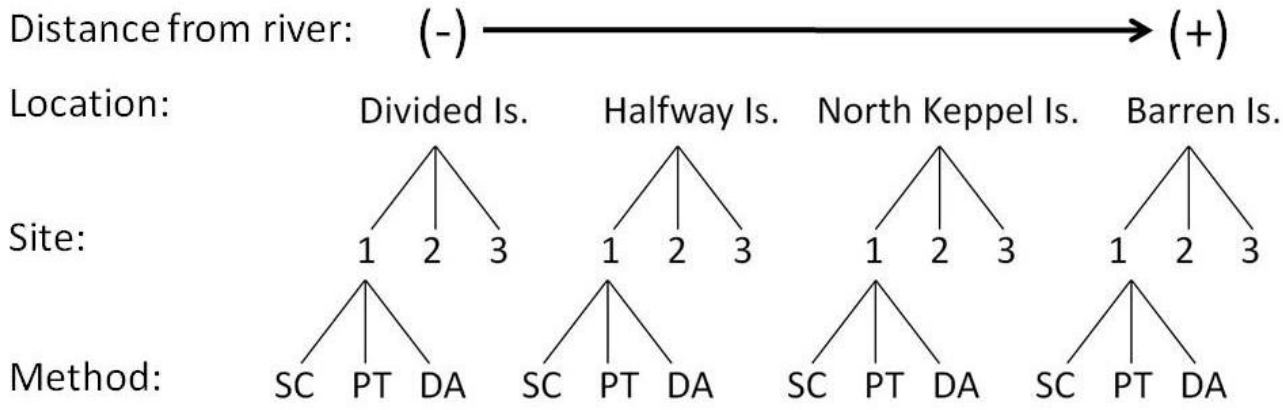


Fig. 2: Stratified sampling design. Three sampling methods (SC: sediment cores; PT: photo transects, DA: death assemblages) will be used in each of three sites per each of four locations along a water quality gradient from the Fitzroy River source.

2.3 METHODS AND DATA ANALYSIS FOR AIM 1

In order to trace historical changes in coral reef communities, assemblages of all coral taxa contained in sediment cores (collected through the reef matrix) will be analysed. Species variability in terms of growth strategies and response to disturbance will be captured by this method. Photo transects on benthic substrate will be used to link present-day live coral assemblages with historical changes in coral community structure.

Sediment cores

Sediment cores will be collected on SCUBA using a manual percussion technique (modified from Aronson et al., 2002a). A novel idea by a group member (Ian Butler, personal communication) will be applied in this project to improve the coring method previously used in the group (e.g. Roff, 2010; Lybolt et al., 2011). It consists of using a manually operated lift jack to retrieve the sediment cores under the water, which will save time, air (on SCUBA) and reduce the risk of physical injury of the divers. Four sediment cores (two cores of 5m and two of 2m) will be extracted haphazardly within each site using aluminum pipes of 10cm in diameter and 0.2cm wall thickness (n=48= 4 locations x 3 sites x 4 cores). Each sediment core will be sealed underwater and transported to the laboratory at The University of Queensland (UQ). Compression of the sediment in the cores will be calculated as the length of core filled with sediments *in situ* before extraction and then divided by the length of the pipe that penetrated into the benthos. Recovery will be calculated as the length of pipe filled with sediments before extraction (measured in the field) divided by the length of pipe filled with sediments after extraction (measured in the laboratory).

Laboratory methods will follow Roff (2010). Cores will be longitudinally sectioned using a rotary saw. One half of each core will be first photographed, to document the visual characteristics, and then transversally sectioned from base to top in 5cm segments (smallest sampling unit within a sediment core). Each segment will be divided in two size fractions using a 4mm mesh and logged for analysis of coral skeletons and sediments composition (see section 2.5). The other half of each core will be scanned using medical computer axial tomography (CAT) and then archived at 2-4 ºC. CAT sagittal images will be imported to Adobe Illustrator CS5 (Adobe) to make a log of each core outlining the identity of coral colonies. Within each 5cm core segment, the fraction retained by the 4mm mesh will be used for coral assemblage composition analysis. Coral fragments will be identified to the lowest taxonomic level possible using a dissecting microscope when necessary.

A high-precision dating method (U-series) will be applied to determine the ages of coral fragments within the cores. Each sediment core will be dated at the top and bottom in order to establish their linear age-to-depth relationship (Collins et al., 2006). In this way, the reconstruction of coral community structure between cores separated in space will be possible because the analysis will be framed within comparable time periods. In addition, the precise timing of significant changes in coral community structure (shifts) over the last millennia will be traced by dating several coral fragments within core intervals before and after those shifts. Variability in ages within a core interval and time reversals (if any) due to sediment reworking will be determined. It is anticipated that an average of five dates per core would be needed for the 5m cores, and two dates per core for the 2m cores, making up a total of 168 dates (the top of the core is assumed to be zero age). Ages of dead corals will be obtained using a MC-ICP-MS following adapted methods described by Clark (2012). From each coral, a subsample of ~0.2g of relatively pristine material will be dated in the Radiogenic Isotope Facility (RIF) at UQ.

Data analysis

In order to determine the natural baseline of changes in coral community structure over time and space, and detect significant changes potentially induced by European settlement, coral assemblages will be analysed in a number of ways. All of the 5cm segments of a core will be compared to determine the position within a core where shifts in coral communities can be identified, this is, marked transitions in coral taxa composition (including loss of a taxa). In order to estimate loss/replacement of coral taxa (as defined in DeVantier et al., 2006), diversity of the coral assemblages (taxa richness, Shannon-

Wiener index of diversity and Pielou´s [1969] index of evenness) in the different facies of the cores will be compared to that of live coral assemblages obtained using photo transects (see next section). The age-depth relationship within cores will be obtained using a weighted least squares general linear model and calculating the coefficient and slope for each core (using R stats package, 2010) which will provide an age estimate (yr) per section per core. A power analysis will be performed to determine if the estimated five/two dates per 5m/2m core respectively are sufficient. Coral assemblages will be compared across different cores and sites. Transitions in taxonomic composition and morphology will be quantified using a modified moving window analysis (MWA) fed with measures of both dissimilarity (Panis and Verheyen, 1995) and Euclidean distances (Duda and Hart, 1973; Flores-Sintas et al., 2001) between consecutive core sections and significant dissimilarities will be detected using the analysis of similarities (ANOSIM) procedure (Clarke, 1993). The ANOSIM (Clarke, 1993) will be used to compare shifts in coral assemblages and determine their composition over time.

Photo transects

In order to investigate live coral assemblages, at each site four transects of 20 m will be placed parallel to the reef margin at 5m depth (separation between transects = random distance from 1-20m). Twenty sequential not overlapping $1m^2$ photographs will be taken along each transect (using a Canon G12 camera into a Patima underwater housing equipped with an Epoque/Ikelite external ~21mm lens and 2 strobes Sea&Sea YS-110a). Each transect will constitute a sample unit (total n=48=4 locations x 3 sites x 4 transects). An “L-shaped” stick will be used to keep the distance between the camera and the substratum constant, to assure consistency in size of photographs and to obtain right angle between the camera lens and substratum. The photographs will be firstly corrected for distortion using Adobe Photoshop Lightroom v.3.6 and then analysed with Coral Point Count with Excel extensions (CPCe - Kohler and Gill, 2006) to characterize the composition and cover of live coral assemblages. Identification of corals will include growth form and taxonomy to the lowest level possible.

Data analysis

In order to compare live coral assemblages among transects, sites and locations, differences in taxonomic composition among samples will be calculated using the Bray-Curtis dissimilarity coefficient (BC, Bray and Curtis, 1957). This coefficient is one of the most robust and effective for the analysis of taxonomic composition data (Faith et al., 1987). Significant differences of growth form and taxonomic composition across different transects, sites and locations will be tested applying the (non-parametric) ANOSIM procedure (Clarke, 1993) to the BC values.

Diversity of live coral assemblages will be determined using three parameters, i.e. taxa richness, Shanon-Wiener index of diversity and Pielou´s (1969) index of evenness. Spatial differences in diversity due to site and location will be tested using a two-way ANOVA.

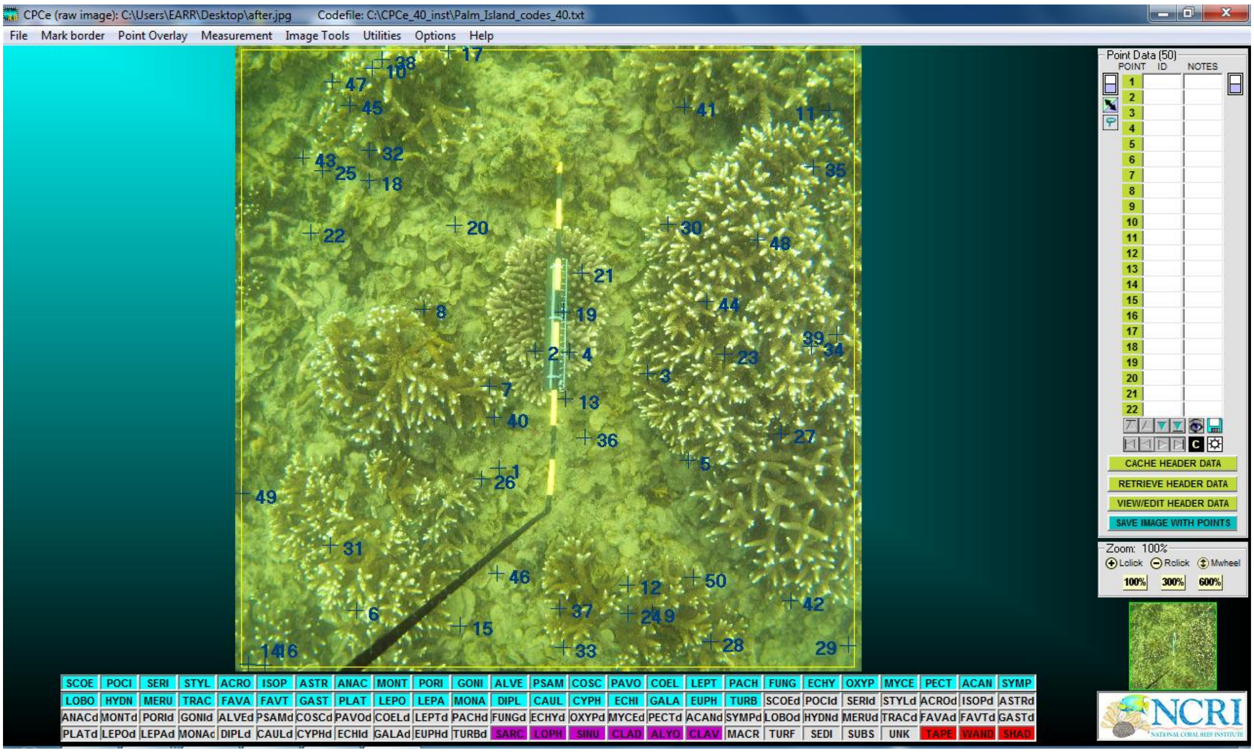


Fig. 3: PC screen capture showing a 1m^2 photo imported into CPCe software (Kohler and Gill, 2006) for characterization of coral assemblages composition and cover.

2.4 METHODS AND DATA ANALYSIS FOR AIM 2

Coral death assemblages will be analysed to reconstruct the history of high mortality events along a water quality gradient. Death assemblages will be defined as accumulations of dead corals from *in situ* colonies and loose coral rubble composing the top 10cm layer of sediments (as in Pandolfi and Minchin, 1996). Sampling methods and field strategies will follow previous work by group members (Roff, 2010; Clark et al., 2012) and sampling will be performed following the stratified design described in section 2.2 (see also Fig. 2).

Death assemblages will be sampled along each photo transect (described in section 2.3). SCUBA divers will manually collect samples at each of four randomly selected points along each transect. One sample will be composed of a calico bag (30cm x 46cm) filled with coral fragments collected from the top layer of sediments (10cm) and/or from *in situ* dead colonies (total n=192= 4 locations x 3 sites x 4 transects x 4 collection points). To reconstruct the timing of high mortality events of coral communities over different spatial scales, 10 randomly selected coral fragments will be dated from each site along the water quality gradient (total dates=120= 4 locations x 3 sites x 10 fragments). Coral fragments will be sectioned lengthwise and a 2-3 g subsample will be extracted from the cleanest section of the growing margin. Then, the coral material will be dated as described for aim 1 (section 2.3).

The chronological reconstruction of high mortality events of this aim will be related to secondary information on local and global stressors. Three sources of information on major disturbances will be used: 1) historical records of Fitzroy River floods using geochemical proxies of massive *Porites* (Rodriguez-Ramirez A., PhD thesis in preparation); 2) historical records of major floods (back until 1859) and anomalous increase of sea surface temperature available in the Bureau of Climatology and 3) peer-reviewed journal articles reporting bleaching and flooding episodes (e.g. Van Woesik, 1991; Diaz-Pulido et al., 2009). By correlating the information of high mortality with major stressors along the water quality gradient, it may be possible to determine the relative importance of those stressors across the gradient. This objective is optional because it will depend on the error margins of the dates of coral mortality relative to the length of the environmental episodes that caused such mortality events. For instance, if the error margins of U-series ages were at a decadal scale, it may be impossible to relate coral mortality with episodes that occurred in a single year. This consideration is valid for the following section too.

Data analysis

Data will be analyzed using descriptive statistics (mean, confidence intervals) and temporal variation plots of ages of coral mortality. Patterns of mortality will be interpreted from plots of corrected ^{230}Th ages. Peaks of mortality will be identified from plots of relative probability using Isoplot 3.0 (Ludwig, 2008) and they will be compared across the water quality gradient to identify potential correlation with the influence of the river. Differences in mortality ages over reefs across the water quality gradient and sites within a location will be tested with a two-way ANOVA (general linear Model using the least-square procedure). Local and/or regional effects on mortality events will be distinguished by combining results from both probability plots and ANOVA.

2.5 METHODS AND DATA ANALYSIS FOR AIM 3

Samples of sediments collected from cores (section 2.3) will be analysed to determine the spatial and temporal patterns of carbonate and terrigenous deposition. Considering that carbonates and terrigenous material account for >99% of bulk sediment (Page and Dickens, 2005), an accurate measurement of carbonates provides estimations for both components (Heap et al., 2001). Therefore, carbonate concentrations will be determined using acid digestion by the 'carbonate bomb' method (Müller and Gastner, 1971). Samples will be obtained from sediment core segments (see section 2.3). A preliminary analysis will determine how many (5cm) segments of a sediment core will be sampled. A total amount of 200-300mg of powdered sediment will be weighed and reacted with excess 10% HCl. In addition, to establish sediment source, grain size analysis will be performed using a Malvern laser particle sizer (available at the School of Chemical Engineering, UQ). Recent studies have reported that fine sand and muddy sand predominantly constitute the bulk of benthic sediments in the Fitzroy River estuary (Brooke et al., 2008; Packett et al., 2009).

To estimate the accretion rates in the reef matrix, coral fragments from the sediment cores (section 2.3) will be dated at the top and bottom in order to establish the linear age-to-depth relationship (Collins et al., 2006). For the long cores, three additional fragments along the core will be also dated to obtain a better adjusted model of accretion rates. The U-series dating technique (MC-ICP-MS) will be applied to coral fragments (as per sediment cores in section 2.3).

Data analysis

Profiles of terrigenous/carbonate concentrations versus core depth, age, and grain size will be analysed to identify spatial and temporal patterns in sediment deposition. Data of instrumental records of river discharge will be correlated with terrigenous/carbonates concentrations to assess the influence of the Fitzroy River on reef sediments in recent times. ANOVA analysis will be applied to test for differences in terrigenous/carbonates concentrations over spatial and temporal scales.

The age-depth relationship and the temporal constraint of reef accretion rates within cores will be obtained using a weighted least squares general linear model and calculating the coefficient and slope for each core (using R, 2010) which will provide an average accretion rate (mm yr^{-1}) and age estimate (yr) per section per core. In addition, exploratory analysis such as correlations will be used to asses associations between patterns of terrigenous/carbonates and accretion rates.

3 FIELDWORK PROGRESS

Logistics

The first of the two scheduled fieldtrips to the Keppel Islands required two weeks (completed in February/March 2012) and a team of eight scientific divers, including researchers with previous experience in the area and methodologies. The collected samples were kept at room temperature until transported by ground to UQ facilities and stored at 4ºC.

Aims

The general aim of fieldtrip 1 was both to collect samples and explore the Keppel Islands to evaluate their suitability for this research. Specifically, the objective was to collect samples from two sites in each of three different locations, and to explore as many other locations as possible. We planned to use three sampling methods, i.e. photo transects, death assemblages, and sediment cores. We aimed to collect twenty sediment cores, based on previous fieldwork experience by other group members and because of permit restrictions, which also limited sampling to “habitat protection zones” (blue zone, GBRMPA).

Outputs

Samples were collected in three locations, i.e. North Keppel, Halfway and Barren islands. In regards to photo transects and death assemblages collection, both North Keppel and Halfway islands were fully sampled following the methods described above (2.3 2.4 respectively) but no other location was sampled. In regards to the sediment coring, one short and two long cores were collected from each of three sites in North Keppel and Halfway, except for one core in Halfway due to bad weather. Thus, nine sediment cores were collected in North Keppel Island (average length [av.] ~3.4m) and eight in Halfway Island (av.~3.6m). In Barren Island, only three very short cores were collected (av.~0.5m). Table 1 shows the length and number of sediment cores collected in fieldtrip 1.

Three other locations, i.e. Miall, Middle and Great Keppel islands, were explored to assess their suitability for this project. In every location, branching *Acropora* species were the dominant components of the reef. The locations closer to the Fitzroy River mouth could not be explored because of extremely low visibility, which is characteristic of summer time in the area. These locations, and particularly Divided Island, will be visited and potentially sampled in a future fieldtrip.

Table 1: Pooled number of sediment cores collected in North Keppel, Halfway and Barren islands for different ranges of length of compacted sediments (measured in the field).

Length range (m)	**#**
< 1	3
2 to 3	3
3 to 4	9
4 to 5	5
total	**20**

Preliminary discussion and conclusions

North Keppel and Halfway islands were suitable for all three methods used in this project. However, the site visited in Barren Island appeared to have a hard substrate layer underneath the sediments relatively close to the benthos surface. This is presumed because sediment cores did not penetrate further than 1.25m in average and the bottom end of the aluminium tubes always showed severe damage when retrieved. I did not account for how the physical damage at the bottom of the tubes affected apparent tubes penetration (Lp, Table 5, Appendix 1). Therefore, the derived estimates of sediment compaction and compression (Lc and C% respectively, Table 5, Appendix 1) of Barren Island should be interpreted with caution until the cores are opened and the actual sediment length within the core can be measured. It is very likely that those extremely short cores (which were the only ones possible to collect) will not provide a long enough historical record of the dynamics of these coral reefs. If this is the case, other sites around Barren Island or a different location will be sampled in the second fieldtrip.

Despite the difficulty to penetrate sediment cores, Barren Island appears to be an interesting location because its coral assemblages were almost entirely alive (by March 2012). In contrast, both North Keppel and Halfway islands showed different degrees of coral degradation, including sites entirely composed of dead coral assemblages, both as detached rubble and standing *in situ* colonies. Interestingly, the same reefs in North Keppel Island were visited in July 2010 by two researchers that were present during the fieldtrip of February-March 2012 too. They reported that in July 2010 the reefs appeared to be healthier than in March 2012 (Fig. 4). Personal communication with the local skipper of the chartered dive boat suggested that these reefs had declined following the floods of

December 2010-January 2011. If such perceptions could be confirmed through analysis and dating of the collected samples, then it would strongly imply that the floods of December 2010-January 2011 impacted on coral reefs from North Keppel and Halfway islands but not Barren Island. Thus, Barren Island may be a potential location to control for the effects of water quality, still being expected to be affected by mass bleaching episodes.

The explored sites in Miall Island did not allow deep penetration when probed with an aluminium stick (3m long x diameter ~1cm). Middle and Great Keppel islands could not be tested for penetration because the probe was accidentally lost. However, visual inspection of coral assemblages indicated that these locations appeared to be similar to North Keppel and Halfway islands, with dead coral assemblages covering from part to all the reefs. Thus, Middle and Great Keppel islands will be considered as potential sampling locations and a new application for a permit including these "green zones" will be made.

Fieldwork 1 achieved slightly below half of the total samples required overall for this project (50% photo transects, 50% death assemblages, 40% sediment cores). A second fieldtrip (2 weeks, 8 people) should be sufficient to collect the remaining samples, especially because I will build upon experience/lessons learnt in the first trip. Fieldtrip 2 is planned for winter 2013 in order to ensure maximum visibility, allowing sampling in locations that were too turbid during fieldtrip 1.

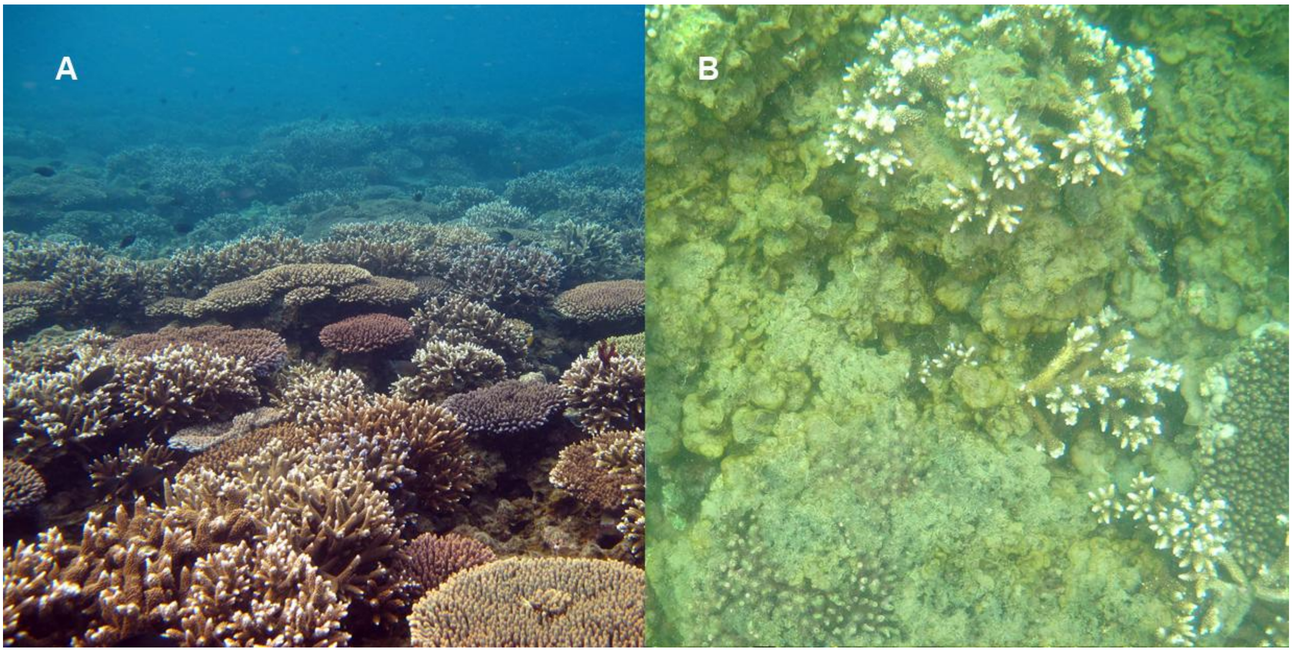
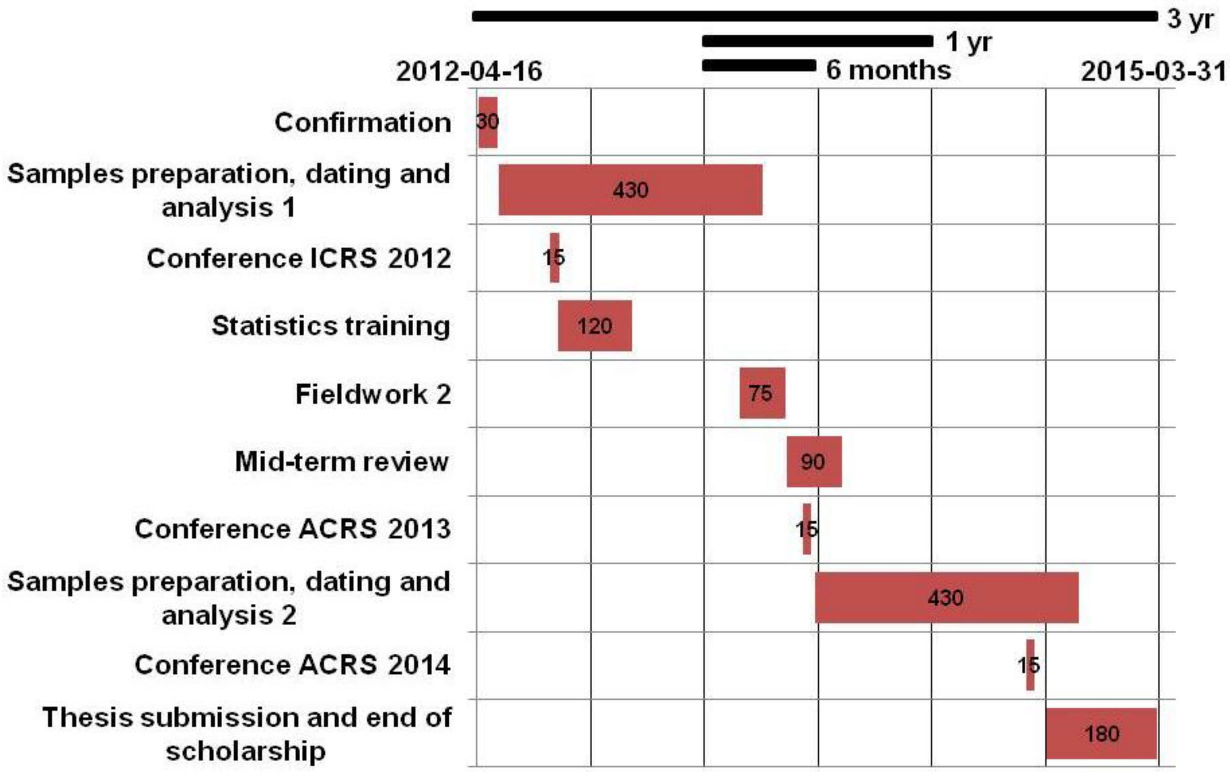


Fig. 4: Coral reefs in North Keppel Island. A: July 2010; B: March 2012.

4 PROPOSED TIMETABLE

I am funded by an AusAID scholarship (total ~$259,289.86, Australian Government) which includes the costs of both UQ tuition fees and living allowance until March 2015. Since this project started, I have received different types of training (see section 6) and completed one of the two scheduled fieldtrips. The timeline for the almost 3 remaining years of this project is described in Table 2.

Table 2: Timetable for the remaining project time showing tasks and approximate duration in days (numbers within red bars) including the time required to prepare each task.



5 PROJECT BUDGET

This project is fully funded by a NERP grant lead by Prof. Jian-xin Zhao and co-lead by Prof. John Pandolfi. Costs will be optimized since much of the resources required for this project (e.g. equipment, facilities, fieldtrips, etc.) will be shared with other projects within the same NERP research umbrella. Table 3 details the main estimated costs of this project.

Table 3: Project detailed costs.

Description	Cost
Fieldwork (fk) 1* food	2,150
fk 1* accommodation	5,400
fk 1* transport	4,300
fk 1* diving operation	8,600
fk 1 consumables	2,600
U-series dating (290 samples)	29,000
fk 2* estimate (based on fk 1)	23,000
Total	**75,050**

*based on 8 people for 2 weeks.

6 Required Skills

This project will require a number of skills. Table 4 lists skills I have already acquired. However, I still need to improve my knowledge in coral taxonomy and statistical analysis. In regards to coral taxonomy, I plan to learn both independently and aided by experienced group members. In regards to statistical analysis, I plan to attend statistical workshops at UQ and regular undergraduate courses.

Table 4: Skills already acquired.

	Qualification obtained
Sc. SCUBA diving	ADAS scientific diver
Boat handling	Recreational marine driving licence, Queensland TMR
VHF radio operation	VHF marine radio operator, Australian Maritime College, ACMA
4WD vehicles driving	4WD training at UQ
U-series dating	Personalized training at UQ RIF lab

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8 APPENDIX 1: SEDIMENT CORING DATA SHEET

Table 5: Sediment coring data sheet: Distance between islands was > 1km and between sites within an island > 100m. d: water depth; Li: length inside the tube underwater (UW); Le: Length from top to the substrate surface UW; Lt: total length of the tube UW; Lp: Length of the part of the core that penetrated into the substrate; Lc: compaction = Lt - Li; C%: compression = Lc / Lp x 100.

Island	site	GPS	sample name	d (m)	Li (cm)	Le (cm)	Lt (cm)	Lp (cm)	Lc (cm)	C% (%)
North Keppel Island (NKI)	S1	23° 5'9.22"S, 150°53'46.80"E	NKI.S1.C01	4.4	103	35	496	461	393	85
		23°05'09.2"S, 150°53'47.2"E	NKI.S1.C02	4.3	104	60	449	389	345	89
		23° 5'8.07"S, 150°53'51.00"E	NKI.S1.C03	3.8	94	33	351	318	257	81
	S2	23° 5'6.66"S, 150°53'56.79"E	NKI.S2.C01	5.9	113	38	526	488	413	85
		23° 5'6.74"S, 150°53'56.86"E	NKI.S2.C02	5.9	108	43	455	412	347	84
		23° 5'6.59"S, 150°53'57.49"E	NKI.S2.C03	4.5	135	38	362	324	227	70
	S3	23° 5'10.14"S, 150°53'42.38"E	NKI.S3.C01	5.8	108	40	469.5	429.5	361.5	84
		23° 5'10.28"S, 150°53'42.67"E	NKI.S3.C02	6.7	101	35	502	467	401	86
		23° 5'10.27"S, 150°53'42.95"E	NKI.S3.C03	6.6	98	45	411	366	313	86
Halfway (HW)	S1	23°12'05.0"S, 150°58'09.9"E	HW.S1.C01	6	70	55	462	407	392	96
		23°12'05.0"S, 150°58'09.9"E	HW.S1.C02	6	73	70	467	397	394	99
		23°12'04.9"S, 150°58'09.7"E	HW.S1.C03	6	67	52	467	415	400	96
	S2	23°12'0.95"S, 150°58'10.17"E	HW.S2.C01	6.6	130	40	558.5	518.5	428.5	83
		23°12'1.05"S, 150°58'9.74"E	HW.S2.C02	6.9	87	49	543.5	494.5	456.5	92
		23°12'0.81"S, 150°58'9.70"E	HW.S2.C03	6	55	51	371	320	316	99
	S3	23°11'56.56"S, 150°58'4.90"E	HW.S3.C01	5.3	101	48.5	429	380.5	328	86
		23°11'56.85"S, 150°58'5.26"E	HW.S3.C02	6.2	141	53	345	292	204	70
Barren Island (BI)	S1	23°9'47.12"S, 151° 4'26.13"E	BI.S1.C01	5.1	123	40	186	146	63	43
		23° 9'47.42"S, 151° 4'26.35"E	BI.S1.C02	4.4	148	40	203	163	55	34
	S2	23° 9'47.73"S, 151° 4'29.97"E	BI.S1.C03	3.5	76	48	116	68	40	59

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