

**School of Science
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**Coral reef soundscapes: The use of passive acoustic
monitoring for long-term ecological survey**

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**This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University**

April 2018

Declaration of authorship

I, **Jamie Neish McWilliam**, declare that to the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

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

The research presented and reported in this thesis was conducted in compliance with the National Health and Medical Research Council Australian code for the care and use of animals for scientific purposes 8th edition (2013). The proposed research study received animal ethics approval from the Curtin University Animal Ethics Committee, Approval Number # AEC_2013_28.

A handwritten signature in blue ink that reads "Jamie Neish McWilliam". The signature is written in a cursive style with a horizontal line above the name.

17/05/2017

'The earth has music for those who listen'

Shakespeare

'In the beginner's mind there are many possibilities. In the expert's mind there are few'

Shunryu Suzuki

Acknowledgements

I would like to thank Rob McCauley, Miles Parsons and Christine Erbe for their help and feedback throughout this project and allowing me the freedom to develop my ideas and carry out extended bouts of fieldwork.

My heartfelt thanks goes out to all the researchers and assistants who helped me out at Lizard Island. Working with such a mixture of people from different backgrounds was one of the highlights of this project. A special mention goes to Bridie Allan and the James Cook University crew for accompanying me on numerous adventurous field trips around the Island. There was never a dull moment and your ability to make light of anything got me through many of the long days.

I would like to especially thank Professor Mark McCormick for his invaluable advice and help in the field from the first day I arrived fresh-faced (later to become a vivid red) and throughout my time on Lizard Island.

I am indebted to Dr Lyle Vail and Dr Anne Hogget and the station's staff (Bruce, Mary-Anne and John) for their advice, assistance with equipment (especially during the 'interesting' weather periods), and your patience for my endless list of questions.

Back on dry land, a big thanks to all the fellow prisoners at the CMST Dungeon, Shyam, Marta, Matt, Tristan (code Guru), Sarah Marley (for being Scottish), Sven (unbeatable), Arti, Bec and Monse for laughs, general discussions and inappropriate trips to the pub. Thanks goes to Nico, Allison, Jono, Steve, Ashley, Henry for keeping me grounded in the world outside academia. A special mention goes to Alex Lim for all his support and advice.

Life out at sea doesn't come cheap and so I am grateful for the generous support from the Lizard Island Reef Research Foundation (Lizard Island Doctoral Fellowship), the Australian Acoustical Society (Education Grant) and the Holsworth Wildlife Research Endowment.

Finally, I want to acknowledge the support my family (adopted, immediate and extended) has given me. To Alasdair, my older brother for much needed music suggestions and the educational video links that have got me through the long analysis and writing stages. Lastly, I would like to thank my Mum and Dad, for supporting me through all these adventures with a healthy dose of optimism and tea.

Statement of candidate contributions

This thesis is presented as a series of four manuscripts in scientific journal format linked together by a general introduction and an overall discussion.

I designed the methodology, carried out the primary data collection, analysis and write-up for each of the manuscripts with support, feedback and guidance from my supervisors and collaborators.

Dr Christine Erbe and Dr Robert McCauley both assisted in developing code for analyses of collected acoustic data. Dr Miles Parsons provided analytical and statistical advice for analysis of acoustic data and provided logistical support during field work.

Thesis chapters were written by me, with feedback from Dr Rob McCauley, Dr Christine Erbe and Dr Miles Parsons.



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Abstract

Coral reefs provide ecosystem services to millions of people and are a habitat for almost one third of the world's named marine fish species. As the world's human population and the demand for natural resources expand, the states of most terrestrial and marine ecosystems continues to decline at an alarming rate. In the past century, coral reefs have suffered significant rates of deterioration, through a combination of stressors, including invasive species, climate change related disturbances and pollution. More recently, El Niño events, combined with several major storm events have been connected with extensive bleaching and significant coral mortality, particularly in Australia's Great Barrier Reef (GBR).

The designation of marine protected areas (MPAs) worldwide, covering nearly 3% of the world's oceans, is an example of the world's commitment towards safeguarding the future of marine ecosystems. However, to meet the demands and goals of marine management policies, there is a need for implementation of well-structured management plans. Fundamentals of effective management, conservation, research of ecosystems and natural resources are built on the ability to track patterns in space and time. This is where long-term monitoring and research can provide critical ecological insight.

Passive acoustic monitoring (PAM) is used to investigate environmental systems through the medium of sound. It permits natural physical, biological and anthropogenic sound sources to be monitored over long time frames and offers an additional approach to visual surveys of coral reefs. However, the full management applicability of PAM remains undetermined.

The aims of this research were to categorise biological reef sounds, identify and investigate temporal patterns of fish choruses, quantify the contribution of anthropogenic (ship) noise and determine how large disturbance events may influence soundscapes over time on Australia's Great Barrier Reef.

Lizard Island, situated in the GBR, was chosen as the primary location to conduct field work. The GBR supports over 1500 species of fish, 400 species of hard corals and an enormous variety of other life forms, making it an ideal location for investigating how PAM may have potential as a long-term coral reef monitoring tool. Lizard Island has been, and continues to be, a key location for coral reef research. Over the last 30 years, the Island's renowned research station has helped to support and foster a wealth of marine research projects.

Long-term monitoring in coral reefs has always been a significant challenge due to reefs being logistically difficult and expensive to access, highly heterogeneous and a demanding environment for equipment. This has meant that many surveys have been restricted to fine resolution 'snapshot' studies, so that our understanding of larger scale ecosystem dynamics over longer time scales is

more limited. Therefore, the combination of logistical support and access to relevant data that Lizard Island research station provides was a deciding factor for choosing this location.

The coral reefs surrounding Lizard Island in the GBR have a diverse soundscape that contains an array of bioacoustic phenomena, particularly biological choruses produced by soniferous fish. Six fish choruses identified around Lizard Island exhibited notable spatial and temporal patterns from 2014 to 2016. Several environmental variables had a significant influence on the timing and received levels of several of the fish choruses. Two out of the six detected choruses exhibited spectral and temporal characteristics similar to choruses produced by planktivorous fish species previously documented at these sites and elsewhere. Three of the six choruses appear to be undocumented and could hold information on the presence, abundance and dispersal patterns of important fish species, which may have long-term management applications. Several choruses displayed high site fidelity, indicating that particular sites may represent important habitat for fish species, such as fish spawning aggregations sites.

The contribution and subsequent impacts that anthropogenic noise may have in marine ecosystems, particularly in coral reefs, has gained substantial attention in the last decade. Vessels (commercial, recreational and research) are the key sources of anthropogenic noise in coral reef soundscapes around Lizard Island. Significant spatial differences in research vessel activity were present around Lizard Island, which led to several vessel traffic hotspots, in areas of high activity. Daily activity of commercial vessels was similar throughout the year, but a notable rise in recreational vessel density occurred during the start of the austral wet season, which coincides with peak biophonic activity in the form of fish choruses. The long-term noise contributions of research vessels were apparent at sites that had high levels of research boat activity, but were not observed at sites with low activity. Noise from commercial vessels raised soundscape sound levels at low frequencies (< 500 Hz) at five of the six field sites. With commercial ship numbers and size continuing to increase, it is expected that vessel noise will be a growing contributor to coral reef soundscapes. Combined with elevated environmental disturbances from climate change, this is likely to be an important additional threat to coral ecosystems.

Lizard Island was exposed to a Category 4 cyclone in March 2015, which resulted in widespread damage to several areas of reef around the Island. The following year, large parts of the GBR experienced severe bleaching; including around Lizard Island which, resulted in substantial mortality of corals. Fish choruses were still present at sites that sustained significant cyclone damage, but a change in chorus energy attributes was observed. Sound recordings taken close to the start of the bleaching event did not reveal any discernible short-term changes to the soundscape. Recordings taken around Lizard Island in November and December 2016 contained five of the six choruses recorded pre-bleaching, also similar to those measured in the previous two years, which implies at least some short-term resilience. However, the long-term impact of these destructive disturbance events and how soundscapes and their key constituents will be affected is

yet to be determined. A notable drop in low-frequency noise in 2016, post-bleaching, corresponds with a reduction in vessel activity in the same area, suggesting PAM may provide an indication of potential socio-economic impacts.

These findings highlight the utility of PAM for long-term monitoring and management of coral reefs, which is highly relevant in light of recent global disturbance events, particularly coral bleaching. Comparison of current and historical soundscape recordings made around Lizard Island over 25 years ago revealed long-term site fidelity of fish choruses. This indicates that soundscapes should be strongly considered as a long-term coral reef monitoring tool, with fish choruses showing potential as an ecological indicator of coral reef condition.

Future research should focus on extricating the temporal patterns associated with bioacoustic activity and determining the potential environmental drivers of biological choruses. Utilising and developing automatic signal processing techniques in pattern recognition would help progress this. This could then support technique development for direct identification of vocalising species, which would strongly increase the management applicability of PAM. Research efforts should also be made towards expanding soundscape monitoring across the GBR, with a focus on sampling areas that contain a range of live coral coverage.

Chapter 1

General introduction

1.1 Coral Reefs

Coral reefs provide ecosystem services to millions of people and are a habitat for almost one third of the world's named marine fish species (Moberg and Folke, 1999; Roberts et al., 2002). As the world's human population and the demand for natural resources expand, the states of most terrestrial and marine ecosystems continue to decline at an alarming rate (Geist and Lambin, 2002; Pandolfi et al., 2003, 2011; Hooper et al., 2012). Approximately one in four species of rays, sharks and skates is threatened with extinction due to overfishing, tropical reefs have lost over 50% of reef building corals in the last three decades, and if current ocean temperature predictions are correct, by 2050 coral reefs may no longer be able to function (Tanzier et al., 2015). A decline in diversity has been linked with exponential declines in ecosystem stability, water quality and recovery potential (Worm et al., 2008). This degradation has accelerated over the past 50 years at an unparalleled rate, increasing the risk of ecosystem collapse (Sato and Lindenmayer, 2018). We are moving swiftly towards projected ecological tipping points or thresholds, which when crossed, lead to alternate shifts in ecosystem states that are hard if not impossible to reverse (Scheffer et al., 2001). The significant decline observed in Caribbean coral reefs after the widespread black sea urchin (*Diadema antillarum*) mortality in 1983 is a key example of a shift in ecosystem state (Mumby et al., 2007).

Coral reefs, in particular the GBR, have suffered disturbing rates of deterioration in the past century due to a combination of stressors, including invasive species, climate change related disturbances and pollution (Bellwood et al., 2004; Fabricius, 2005; De'ath et al., 2012; Hughes et al 2017).

In the last 20 years, El Niño events, combined with several major storm events (Category 4 or 5 cyclones), have been connected with extensive bleaching and significant coral mortality throughout the GBR. The most significant bleaching event to date began in northern reefs in early 2016 and then affected central areas in 2017 (Fig. 1.1).

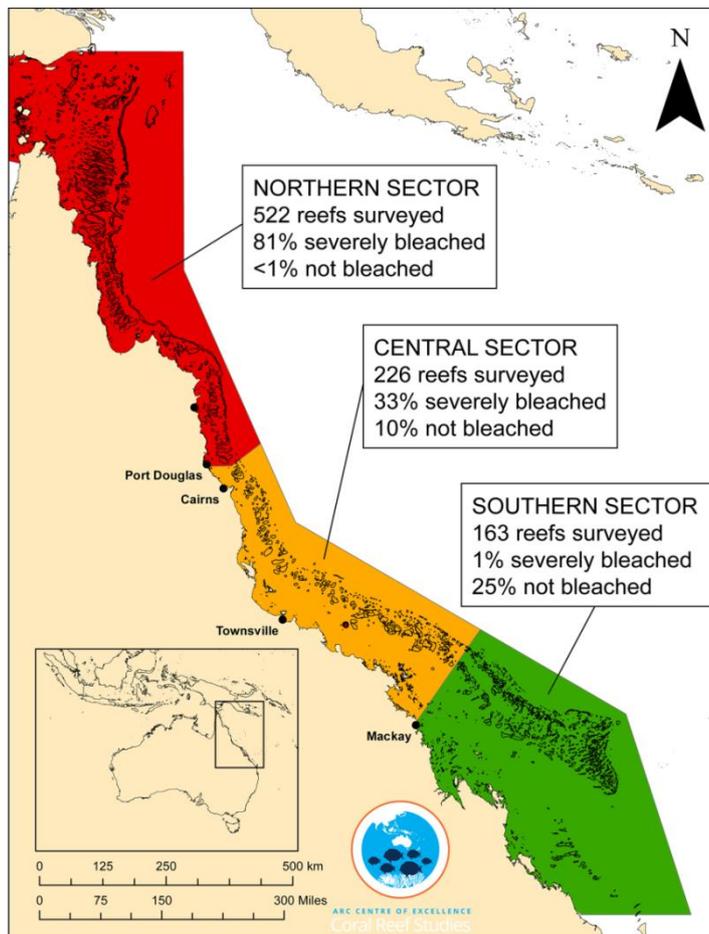


Figure 1.1 Map of the Great Barrier Reef showing results of aerial surveys for 911 reefs in 2016 (A) and results from aerial surveys in 2016 and 2017 Credit: Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies / Tom Bridge and James Kerry (A) Terry Hughes (B).

The designation of more than 11,212 marine protected areas (MPAs) worldwide, covering around 3% of the world's oceans, is an example of the world's commitment towards safeguarding the future of marine ecosystems (data accessed from www.mpatlas.org). However, to meet the demands and goals of marine management policies, there is a need for implementation of well-structured management plans, particularly for large MPAs (Voyer et al., 2012). Fundamentals of effective management, conservation, research of ecosystems and natural resources are built on the ability to track patterns in space and time. An important question is 'How do organisms react to environmental changes?' This is where long-term monitoring and research can provide critical ecological insight (Lindenmayer and Likens, 2009).

1.2 Long-term monitoring and marine soundscapes

Long-term monitoring in coral reefs has always been a significant challenge due to reefs being logistically difficult and expensive to access, highly heterogeneous and a demanding environment for equipment (Mumby et al., 1999). This has meant that many surveys have been restricted to fine resolution 'snapshot' studies, so that our understanding of larger scale ecosystem dynamics over longer time scales is more limited (Mumby et al., 1999; Lammers et al., 2008; Underwood, 2009). Recent technological advances and development of conceptual frameworks has enhanced spatio-temporal sampling and processing capabilities. Passive acoustic monitoring (PAM) can be used to investigate environmental systems through the medium of sound, monitoring natural physical, biological and anthropogenic sound sources over long time periods (months to years). PAM presents an affordable, non-invasive way to monitor ecosystem processes, which can reveal information on weather, ecosystem community structure (Lillis et al., 2014), anthropogenic activities (Erbe et al., 2014) and community processes such as fish spawning (Schärer et al., 2012a, 2012b). It has also been used to track large-scale fish movements, which has improved our understanding of fish dispersal patterns and ecological connectivity (Costa et al., 2014). This knowledge can then be used to help guide effective mitigation measures and support marine spatial plans.

Our oceans are home to a rich and diverse array of underwater sounds, where the properties of water enable certain frequencies of sound energy to travel substantial distances (Urlick, 1983). Many marine organisms use underwater sound for navigation, foraging and reproduction either producing communication signals or listening for signals of interest (Mann and Lobel, 1997; Hawkins and Amorim, 2000; McCauley and Cato, 2000; Popper et al., 2003; Leis et al., 2011). Hundreds of fish species are known to produce sound (Kaatz et al., 2002). Soniferous fish produce sounds either independently or as a chorusing group. These sounds are prominent throughout Australian waters and have been associated with feeding and spawning activities (Cato, 1978; McCauley and Cato, 2000; Parsons et al., 2009).

Many of the animals inhabiting reefs are soniferous, which makes coral reefs an ideal ecosystem to monitor using sound (Myrberg, 1997; Lammers et al., 2008; Schärer et al., 2012a, 2012b; Tricas and Boyle, 2014). PAM has been a key area of marine research for over half a century and a large body of relevant research already exists, yet only a few studies have investigated PAM from an ecosystem perspective (Staaterman et al., 2014; Erbe et al., 2015). Renewed research interest in large-scale terrestrial and marine ecosystems has initiated a move towards an ecosystem based management approach, directed at the conservation of natural resources and biodiversity (Pijanowski et al., 2011).

Now, an emerging field known as soundscape ecology, provides a conceptual mechanism to process spatially explicit, long-term data collected using PAM, and presents an opportunity to evolve and deepen our understanding of marine ecosystems (Farina, 2014; Harris and Radford, 2014). A key principal of this field of study is that soundscapes are an integral part of the natural environment, rather than just inconsequential 'noise' (Pijanowski et al., 2011). In the context of this work, the soundscape is defined as 'the resulting combination of overlapping sounds from biophonic, geophonic and anthropophonic sources, which are fundamentally linked to the structure and functions of the geographic seascape' (adapted from Pijanowski et al., 2011).

Biophony or biophonic sources refer to biological sounds. In marine environments, the main sources of biological sounds are marine mammals, soniferous fish and invertebrates (notably the snapping shrimp). The geophony consists primarily of wind, wave and rain generated sounds, but includes sounds produced from earthquakes and breaking ice. The anthropophony is composed of sounds created by human generated sounds (i.e. propellers, engines, airguns, sonar, trawling gear) (Farina, 2014).

Biological sound production in the marine environment is incredibly diverse, with soniferous species spread across several different genera, from mammals to invertebrates and fish (Ladich and Fine, 2006). One of the dominant biological sounds in shallow waters (< 60 m depth) of the tropics, subtropics and temperate regions is snapping shrimps (Family: Alpheidae) (Au and Banks, 1998; Lammers et al., 2008; Kennedy et al., 2010; Au et al., 2012; Coates et al., 2012). Snapping shrimps produce an extremely broadband sound with energy focused around 2–5 kHz and ranging upwards of 200 kHz, the broadest spectrum of any animal (Au et al., 2012). Despite its widespread prevalence in the marine environment, we have a limited understanding of the function of snapping shrimp snap signals (Lillis et al., 2017).

Signals may be used for deterring predators, stunning prey and other conspecific territorial interactions (Nolan and Salmon, 1970). Limited scientific research on snapping shrimp is partly due to the cryptic nature of these invertebrates, which makes them difficult to locate and study. A number of papers cite the potential for snapping shrimp clicks or snaps as an indicator of environmental quality, condition or habitat type (Watanabe et al., 2002; Radford et al., 2010;

Coates et al., 2012; Bohnenstiehl et al., 2016). However, it is still unknown whether snapping shrimps are solely responsible for the broadband clicks and snaps observed in shallow water ecosystems as there may be other organisms capable of producing similar acoustic signals (Finfer et al., 2007).

Fish are thought to use sound primarily for reproduction and territorial strategies, but this extends to predator-prey interactions such as a fright response or distress signals (Moulton, 1962; Ladich, 1997; Amorim, 2006). Reproductive examples include the damselfish *Dascyllus albisella*, which produces a pulsed sound during courtship behaviour in an attempt to attract a mate (Mann and Lobel, 2007) and the Nassau grouper *Epinephelus striatus*, that produces a tonal sound during courtship behaviours (Schärer et al., 2012b). Territorial examples include the blue-eyed damselfish *Plectroglyphidodon johnstonianus*, a coralivore that produces agonistic sounds towards neighbouring conspecifics that encroach on its territory (Tricas and Boyle, 2014) and plainfin midshipman *Porichthys notatus*, that produces short broadband agonistic grunts while choosing a nesting site (Brantley and Bass, 1994). With many hundreds of species actively producing sound, fish have evolved some of the most diverse sound production apparatus among vertebrates (Ladich and Fine, 2006). Sound can be produced in several ways, including drumming, stridulation and hydrodynamic movements (Tavolga, 1971; Amorim, 2006). Stridulatory sounds are generated by striking or rubbing hard parts of the body together, producing broadband sounds from 50 Hz to 10 kHz (Fish, 1954; Kaatz and Lobel, 1999). Drumming involves activating sonic muscles to apply vibration patterns to the swim bladder (Tavolga, 1964). Hydrodynamic sounds are broadband noise generated by water turbulence when a fish changes speed or direction while swimming (Tavolga, 1964).

The capacity to control muscular vibration in and around the swim bladder permits more structured sounds to be generated, with the ability to produce pure tone, amplitude modulated, frequency modulated, pulsed, or harmonic sounds (Kaatz, 2002). The ability to alter the temporal aspects of the call, such as pulse repetition rate or call duration, allows more complex levels of information to be conveyed. Therefore, temporal patterning in fish sounds is of key importance in communication (Amorim, 2006; Lobel, 2010).

The swim bladder also functions as an auditory organ when the swim bladder is connected to the ear by either ossicles or diverticula (Popper and Fay, 1999). Measurements of fish hearing sensitivity have established that most species of fish have a hearing range over a relatively narrow range of frequencies (Popper and Schilt, 2008). This ranges from approximately 50 Hz to 1500 Hz, with sensitivity focused in the lower frequencies (<1 kHz). There are cases where sensitivity can reach up into the tens of kilohertz, but this appears to be a rare occurrence (Popper and Fay, 1993). Fishes that do not have a swim bladder are likely to be more sensitive to particle motion than sound pressure (Casper and Mann, 2007).

Underwater, sound waves have both a pressure and particle motion component, of which the latter is used primarily by many fish and most invertebrates for detecting sound (Fay, 1984; Packard et al., 1990; Budelmann, 1992; Lu et al., 1996). Our understanding of the mechanisms of hearing through particle motion detection is generally well established through acoustic studies (Chapman and Hawkins; 1973; Popper et al., 2001). However, access to appropriate particle motion sensors has hampered progress in determining the ecological implications and roles that particle motion may have in the marine environment (Nedelec et al., 2016; Popper and Hawkins, 2018). Due to these limitations, particle motion measurements were not conducted in this thesis, but the importance of particle motion has been acknowledged.

1.3 Ecological application of soundscapes

A soundscape ecology approach presents a promising, complementary method to monitor and evaluate environmental changes in marine systems over broad temporal and spatial scales that can enhance data from other sources. This approach will help facilitate the identification of spatial patterns present in marine communities, thereby, contributing to progressing ecosystem based management practices (Brown et al., 2011). Soundscape research has provided a systematic approach to measuring potential anthropogenic activity in marine ecosystems. For example, it has been found that anthropogenic noise may be linked to seal hearing loss (Jones et al., 2017), disruption in fish orientation behaviour (Holles et al., 2013) and increased fish mortality by predation (Simpson et al., 2016a). This is particularly relevant for marine reserves and parks, where a key goal is to protect these areas from destructive anthropogenic activities.

Soundscape ecology has been gaining significant interest from the scientific community, over the last decade. A search of the scientific literature for studies that are associated with the term 'soundscape' shows there has been a steadily increasing rate of citation (Fig. 1.2).

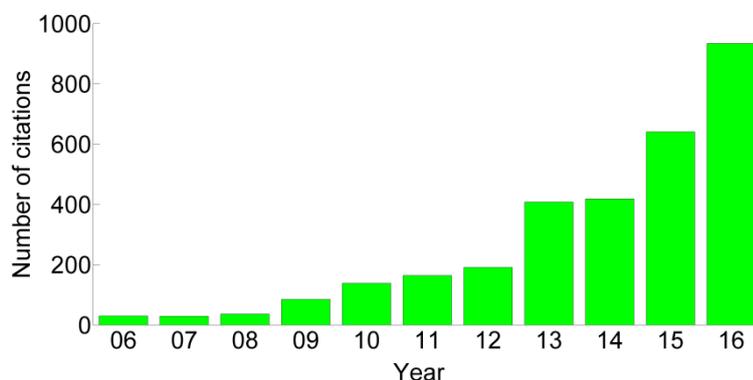


Figure 1.2 Web of Science search results for papers with the word 'Soundscape' in the title within one of the following categories (Acoustics, Oceanography, Biodiversity conservation, environmental studies, marine fresh water biology, zoology evolutionary biology and fishes).

Several studies have demonstrated the potential application of acoustic features as indicators of condition or biological composition within marine ecosystems, such as live coral cover or biological diversity (Kennedy et al., 2010; Staaterman et al., 2013; Piercy et al., 2014; Bertucci et al., 2016; Harris et al., 2016). There is evidence that underwater coastal habitats have distinct acoustic signatures and these may be used by marine organisms to identify suitable habitat to settle (Radford et al., 2010). Marine studies using coral reef noise have found evidence that pelagic fish larvae actively seek out generated reef noise (Tolimieri et al., 2000, 2004; Simpson et al., 2004, 2005, 2008, 2010; Radford et al., 2011).

1.4 Key knowledge gaps and research challenges

While these studies provide evidence to support the application of soundscape survey for long-term monitoring of coral reefs, we still do not have a clear understanding of many aspects of reef soundscapes, particularly in terms of their spatial and temporal variation. Most reef studies are unrepeated or restricted to snapshot data, which has limited our short and long-term understanding of coral reef soundscapes (Table 1.1). Much of the bioacoustic activity on coral reefs occurs after sunset (Cato, 1978; McCauley and Cato, 2000; McCauley, 2012; Parsons et al., 2016a), yet many of the reef soundscape studies were confined to the daytime, therefore failing to capture an important acoustic time period. Reef soundscapes have been shown to elicit complex periodicities over a range of temporal scales including tidal, diel, lunar and seasonal (McCauley, 2001, 2012; Staaterman et al., 2013) and notably, some of the same sources exhibit different temporal patterns at different locations (Parsons et al., 2016a). Therefore, snapshot studies can lead to potentially unrepresentative and misleading conclusions regarding the underlying characteristics of marine soundscapes.

Table 1.1 Duty cycle and durations of selected reef associated soundscape studies

Paper	Duty cycle - Daily (%)	Total recording duration (days)
Lammers, 2008	3.33	30*
Radford et al., 2008	8.33	12
Kennedy et al., 2010	0.14	30*
Radford et al., 2010	0.69	12
McCauley, 2012	22.22	1095*
Staaterman et al., 2013	2.40	2
Staaterman et al., 2014	4.00	412
Piercy et al., 2014	0.14	nsp
Radford et al 2014	8.33	2
Kaplan et al., 2015	0.21	103
Kaplan et al., 2015	2.08	103
Bertucci et al., 2015	0.21	89
Nedelec et al., 2015	0.63	nsp
Pine et al., 2015	C	3
Bertucci et al., 2016	8.33	2
Buscaino et al., 2016	6.67	364
Harris et al., 2016	13.33	3
Parsons et al., 2016a	33.33	330
Rice et al., 2017	C	151
Rossi et al., 2017	0.35	13
McPherson et al., 2016	57.70	93
Sánchez-Gendríz & Padovese 2017	C	30

C: Continuous, nsp: not specified, *approximately

There is still a tendency to focus on only one component of soundscapes, usually the biophony, while overlooking the relative influence of the geophony and anthropophony. Boat presence, with few exceptions (MacGillivray et al., 2014; Erbe et al., 2015; McPherson et al., 2016; Pine et al., 2016) is usually mentioned, but is limited, to a statement on their presence rather than formal analysis (Radford et al., 2010; Nedelec et al., 2015; Piercy et al., 2014).

Widespread acoustic energy generated from human activities has resulted in increased ambient noise levels being reported in some of the world oceans, particularly in localised areas near ports (McDonald et al., 2006). Considerable changes in soundscapes are likely to continue with expansion of global shipping reaching into previously remote areas. Ensuing impacts that anthropogenic noise may have in marine ecosystems, particularly coral reefs, has gained

substantial attention in the last decade (Hawkins and Popper, 2016). Recent research investigating the influence of anthropogenic activity in coral reef species has discovered that noise from small boats can alter settlement behaviour of coral reef fish larvae (Simpson et al., 2016b). However, the lack of investigations on the contribution and potential influence of large ships remains a key area of research yet to be explored, particularly in regard to continued growth of shipping activity in the marine environment. The impact of disturbance events (pollution and climate change) on coral reefs, revealed through soundscape survey, has also received limited attention and in instances where this topic has been considered, a limited sampling period makes deductions on impacts problematic (Rossi et al., 2017).

The application of acoustic indices as potential indicators of marine biodiversity has also gained significant attention in the last 5 years (Staaterman et al., 2014; Kaplan et al., 2015), but more research is required to determine how robust these indices are in marine soundscapes, as they were originally developed for terrestrial ecosystems and have received mixed opinions on their efficacy in marine environments (Parks et al., 2014; Staaterman et al., 2014; Bertucci et al., 2016; Harris et al., 2016). From a long-term monitoring context, categorisation of sounds into the three components of biophony, anthropophony and geophony is essential; a single number is likely to be too coarse a level of analysis for acoustically understudied and complex natural systems, e.g. coral reefs (Sueur et al., 2014; Parsons et al., 2016c). A better understanding of the spatio-temporal acoustic patterns and the key contributors to coral reef soundscapes is required before investigating the potential of acoustic indices. Therefore, the utilisation of acoustic indices has not been explored in this thesis.

1.5 Aims and Objectives

The aim of this thesis is to explore the potential application of coral reef soundscapes for long-term ecological survey of coral reefs, using PAM as the principal measurement tool. This will be achieved by investigating several linked coral soundscape topics with the following objectives:

1. Categorise key biological reef sounds
2. Identify and explain temporal patterns of fish choruses
3. Investigate the contribution of anthropogenic (vessel) noise around a coral reef
4. Investigate how large disturbance events may influence coral soundscapes

To complete these objectives, Lizard Island, situated in the GBR, was chosen as the primary location to conduct field work. The GBR supports over 1500 species of fish, 400 species of hard corals and an enormous variety of other species, making it an ideal location for investigating the potential of PAM as a long-term coral reef monitoring tool. The GBR is an international hub for tropical marine research and arguably one of the world's best-studied tropical marine ecosystems (Fabricius and De'ath, 2004). For the last 30 years, Lizard Island has been a key area of coral reef

research due to its location (direct access to the surrounding reef) and research facilities. The island's renowned research station supports a vast body of research (more than 60 scientific papers a year are published relating to Lizard Island). As an emerging multi-disciplinary field of study, soundscape ecology relies on incorporating other fields of study to progress research, particularly when results and approaches are compatible and complementary. Therefore, the combination of logistical aid and access to data and information directly relevant to this study (spatially and temporally) was a deciding factor for choosing this location.

In 2014, six field sites were established around Lizard Island. However, one of the field sites (Eagle Island) ceased to be sampled in 2015 and 2016 due to logistical challenges after Cyclone Nathan. Therefore, Eagle Island data are included in Chapters 2 and 3, and omitted from the remaining chapters due to its short sampling duration.

1.6 Research significance

While a number of studies have investigated coral reef soundscapes, acoustic recordings have generally been spatially and temporally limited, where field sites are rarely resampled on an annual basis. In contrast, this study comprises a series of months-long continuous acoustic datasets collected over three years, making it an important resource. Categorisation of key biological sounds is an important progressive step for investigating the long-term monitoring application of reef soundscapes. In this body of work, identifying and describing prominent temporal and spatial acoustic patterns in respect to ecological processes such as fish spawning or feeding provides detailed environmental information, which is relevant to reef management. To date, there have been very few studies concerned with quantifying contribution of vessel noise in the GBR and beyond (MacGillivray et al., 2014). Finally, this work includes a study comparing reef soundscapes after two major disturbance events, a category four cyclone and the worst coral bleaching event ever recorded at Lizard Island.

Combined, these findings provide valuable information to reef scientists, policy makers and managers. It is also expected that this work may later help in assisting and enhancing reef biodiversity monitoring initiatives at reduced costs, complementing other survey strategies.

1.7 Thesis structural overview

This body of work is presented as four data chapters, with each chapter addressing one of the four main thesis objectives along with specific research questions outlined at the start of each chapter. Efforts have been made to minimise repetition, but some degree of reiteration is unavoidable as each chapter has been largely produced as a stand-alone scientific paper.

Chapter 2 - Soundscape diversity in the Great Barrier Reef: Lizard Island, a case study with a focus on fish choruses

A key step in investigating the long-term monitoring application of soundscapes is developing a baseline soundscape description and establishing the key bioacoustic contributors. The purpose of this chapter is to progress a foundational knowledge of GBR soundscapes by classifying prominent fish contributors of coral reef soundscape around Lizard Island.

This chapter has been published in the peer-reviewed journal *Bioacoustics* as:

McWilliam, J.N., McCauley, R.D., Erbe, C., & Parsons, M.J.G. (2017). Soundscape diversity in the Great Barrier Reef: Lizard Island, a case study. *Bioacoustics*, 1-17. DOI: 10.1080/09524622.2017.1344930

Chapter 3 - Biophonic periodicity on coral reefs in the Great Barrier Reef: Patterns and drivers

This study builds and expands on the findings from Chapter 2, identifying patterns in classified fish choruses and the potential drivers of these observed patterns, enabling a more detailed understanding of bioacoustic temporal patterns in reef soundscapes.

This chapter has been published in the peer-reviewed journal *Scientific Reports* as:

McWilliam, J.N., McCauley, R.D., Erbe, C., & Parsons, M.J.G (2017). Patterns of biophonic periodicity on coral reefs in the Great Barrier Reef. *Scientific Reports*, 7(1), 17459. DOI:10.1038/s41598-017-15838-z

Chapter 4 - Lost in the noise? Anthropogenic activity around Lizard Island in the Great Barrier Reef

This chapter continues with a spatio-temporal focus, introducing one of the key contributors to marine soundscapes, anthropogenic noise. The aim here being to assess the contribution of anthropogenic noise to the coral reef soundscape around Lizard Island and investigate the current and future implications, when considering the continuing growth of shipping in the GBR.

This chapter has been split into two separate journal papers with one in preparation for submission to the peer-reviewed journal *Global Change Biology*. The second paper in prep has yet to be assigned to a journal.

Chapter 5 - Long-term changes and acute stressors in a coral reef soundscape

The final chapter explores the long-term soundscape patterns captured over a three-year period around Lizard Island using two major disturbance events as a case study (cyclone and coral bleaching). Potential changes to the soundscape are investigated along with consultation of several historic soundscape recordings taken over 25 years ago, revealing the enduring spatio-temporal patterns of several fish choruses categorised in Chapter 2. A case is also put forward for the consideration of fish choruses for potential inclusion in a suite of coral reef ecological indicators.

This chapter is in prep. for submission to the journal *Proceedings of the Royal Society B*.

The thesis concludes with a review of thesis objectives, discussion of the key research findings, project limitations, future research opportunities and significance of work.

Chapter 2

Soundscape diversity in the Great Barrier Reef: Lizard Island, a case study with a focus on fish choruses

Passive acoustic monitoring can provide valuable information on coral reefs, and examining the acoustic attributes of these ecosystems has the potential to provide an insight into their status and condition. From 2014 to 2016, a series of underwater recordings were taken at field sites around Lizard Island in the Great Barrier Reef, Australia. Six individual fish choruses were identified where each chorus displayed distinct acoustic characteristics. Choruses exhibited diurnal activity and some field sites displayed consistently higher diversity of choruses and levels than others, suggesting that particular locations are important aggregation areas for soniferous fish species. During peak activity, choruses were a prominent component of reef soundscapes, where received levels of a chorus reached upwards of 120 dB re 1 μ Pa rms over the 450–650 Hz band, equating to a 40 dB increase above ambient noise levels of \approx 80 dB re 1 μ Pa rms. Two out of the six detected choruses exhibited spectral and temporal characteristics similar to choruses produced by planktivorous fish species previously documented at these sites and elsewhere. Three of these choruses appear to be undocumented and could hold information on the presence, abundance and dispersal patterns of important fish species, which may have long-term management applications. Future research should focus on extricating the temporal patterns associated with bioacoustic activity and determining the potential environmental drivers of biological choruses. Additionally, developing appropriate techniques for direct identification of vocalising species would strongly increase the management applicability of passive acoustic monitoring.

2.1 Introduction

Coral reefs are finely balanced, highly sensitive ecosystems that are susceptible to comparatively minor changes in environmental conditions (Hoegh-Guldberg, 1999). Currently, coral reefs, such as the Great Barrier Reef (GBR), are one of the most endangered types of ecosystem on the planet, due to a combination of overfishing, pollution, extreme weather events and climate change (Hoegh-Guldberg, 1999; Wooldridge, 2009). Recent coral bleaching events have caused degradation of large areas of the GBR and this disturbance continues to threaten this World Heritage site (Ainsworth et al., 2016). Within these complex environments, fish can contribute significantly to ecosystem resilience; that is the capacity for an ecosystem to withstand perturbation without changing self-organised processes and structures (Holling, 1973; Burkpile and Hay, 2008). For example, herbivorous fish can promote coral growth by inhibiting algal development, while their exclusion can result in microalgae dominance, reducing coral survival rates (Mumby et al., 2006; Hughes et al., 2007). Thus, long-term monitoring of the spatio-temporal patterns in fish species composition, abundance and distribution can be indicative of the reef's current condition and potential future.

The GBR is one of the most studied marine ecosystems in the world. For several decades, many hundreds of visual-based surveys have been conducted across this reef system (Sweatman et al., 2011). In contrast, passive acoustic monitoring has been widely overlooked and under-utilised. Passive acoustic monitoring has only been conducted in a handful of locations for short time periods and consequently, knowledge of GBR soundscapes, the array and composition of acoustic environments around the reef, remains limited (McCauley and Cato, 2000; McCauley, 2001). Sound travels well underwater and is an integral part of underwater ecosystems, essential to numerous species' survival. Many animals use acoustics to forage, navigate and communicate, including marine mammals (McDonald and Fox, 1999; Tyack, 2000; Mellinger et al., 2007), invertebrates (Moulton, 1957; Fish, 1964; Versluis et al., 2000; Popper et al., 2001; Bohnenstiehl et al., 2016) and fish (Fish et al., 1952; Fish, 1954; Moulton, 1958; Tavolga, 1958; Fish and Mowbray, 1970; Tavolga, 1971; Fish and Cummings, 1972; Horch and Salmon, 1973; Hawkins and Myrberg, 1983; Bass and Ladich, 2008; Parsons et al., 2013a, 2016a).

Monitoring coral reef soundscapes, particularly the biological contributors, and understanding how they relate to the fish assemblage and surrounding habitat presents a promising complementary approach to studying reef ecosystems (Kennedy et al., 2010; Radford et al., 2010; Nedelec et al., 2015; Staaterman et al., 2015; Freeman and Freeman, 2016). Over 1000 species of fish have been observed to vocalise (Kaatz et al., 2002; Kasumyan, 2008) and several studies have discovered that Australian marine soundscapes, including coral reefs, contain noteworthy fish choruses (Cato, 1978, 1980, 1992; McCauley and Cato, 2000; McCauley, 2001; Erbe et al., 2015; Parsons et al., 2016a, 2016b). In order to establish a foundational knowledge of GBR

soundscapes, key bioacoustic contributors must first be understood. This paper takes the first steps towards this by identifying and listing the acoustic characteristics of key bioacoustic contributors.

2.2 Aim of Study

The aim of this work was to classify prominent fish contributors of a coral reef soundscape around Lizard Island in the GBR.

2.3 Methodology

2.3.1 Study site: Lizard Island overview

Lizard Island (14° 40'S, 145° 29.8'E) is a continental granite island, situated in the World Heritage listed Great Barrier Reef, 270 km north of Cairns, around 30 km off the coast. The surrounding seascape can be considered as shallow water, with depths typically less than 30 m. There are three other smaller islands nearby, Palfrey, South Island and Bird, which together form the Lizard Island Group (Fig. 2.1). Each smaller island is encircled by coral reef and a thin fringing reef surrounds much of the main island. A more extensive reef encompasses the Blue Lagoon between Lizard and South Island, with depths in the lagoon reaching up to 12 m. Maximum tidal range at Lizard is ± 3 m, with the entrances to the lagoon and waters around North Point experiencing current speeds exceeding 30 cm/s during tidal cycles (Frith et al., 1986).

2.3.2 Sound recording system and deployment procedures

Between 2014 and 2016, a series of underwater audio recordings were acquired at various times at six sites around Lizard Island (Fig. 2.1) Recordings were made using SoundTrap 202 digital sound recorders set to sample at 48 ksps (manufacturer's specifications of a flat response within ± 3 dB between 20 Hz and 60 kHz). Each device was piston-phone calibrated at 250 Hz with a known level of 121 dB re 1 μ Pa by OceanInstruments^{NZ}. Recorders were time synchronised to local time (AEST). SoundTrap clock resynchronisation and clock-drift readings to an accuracy of ≈ 1 s were carried out for each subsequent deployment with a Garmin 60Csx GPS unit and a laptop computer.

Recording sites were chosen to represent the diversity of seascapes present around Lizard Island. The location of each site was recorded using a Garmin 60Csx GPS, accurate to ± 3 m. SoundTraps were attached to weighted mounts and diver-deployed to the seabed on sandy substrates, at least 3 m from reef structures. Sites consisted of a variety of patch reef habitat in a range of water depths (Table 2.1). A sub-surface marker consisting of two concrete breeze blocks and a rope attached to a buoy was placed ≈ 5 m from each SoundTrap, to help find the equipment in turbid

conditions. Recorders were retrieved and redeployed every \approx 10–14 days to download data and recharge the battery.

Table 2.1 Lizard Island field sites characteristics

Site	Depth (m)	Seabed characteristics	Substrate	Rugosity
North Point (NP)	18–21	Gradually sloping site extending from surface to 24 m over a distance of 300 m	Coarse sand	Medium
Shipping channel (SC)	25–30	Flat bottom	Coarse to fine sand	Low
Eagle Island (EI)	19–22	Flat bottom ~200 m from reef ledge	Coarse sand	Low
Big Vicky's (BV)	7–10	Mosaic of coral reef and sand patches	Coarse sand	High
Lagoon (L)	6–9	Mosaic of coral reef and sand patches	Coarse sand	High
South Island (SI)	13–16	Gradually sloping profile with mosaic of coral reef and sand patches	Coarse sand	Medium

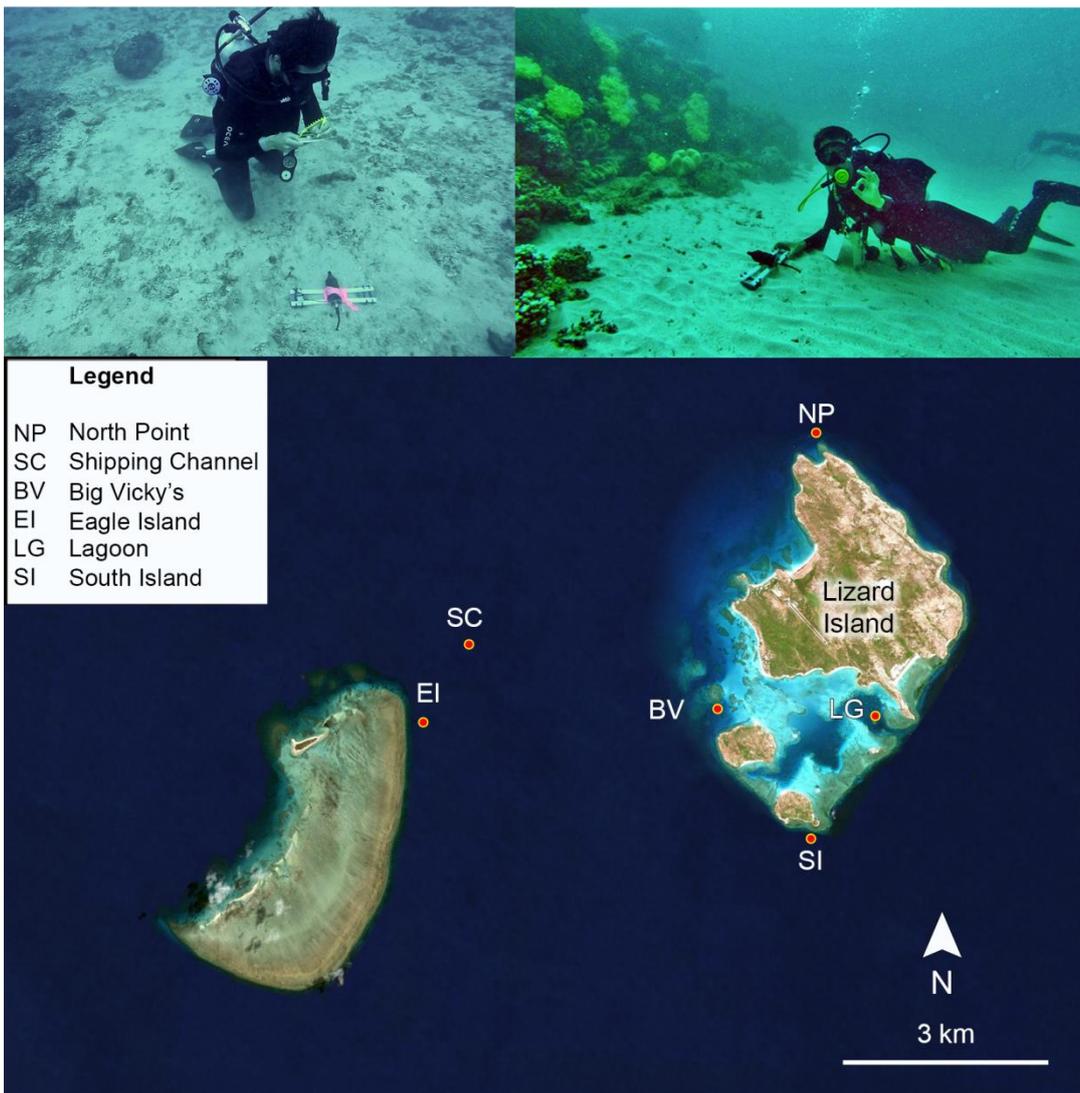


Figure 2.1 Deployment of SoundTraps (top) and location of field sites around Lizard Island (bottom). See Table 2.1 for site names.

2.3.3 Audio recording analysis

Inspection of the acoustic datasets was carried out employing a combination of long-term spectrogram visual analysis and audio scrutiny of recordings using headphones. Calibrated power spectral density (PSD) averages were calculated from 300 s windows and used to create long-term spectrograms. The PSD for each sample was then stacked to form a continuous dataset with time on the x-axis and frequency on the y-axis (logarithmic or linear scale), with the colour denoting intensity. These were displayed and inspected using the Graphical User Interface (GUI) toolbox, CHaracterisation Of Recorded Underwater Sound (CHORUS; Gavrilov & Parsons 2014), in the MATLAB software environment (The Mathworks Inc., Boston, MA). CHORUS has been designed to analyse long-term underwater sound recordings. The GUI allows the user to adjust spectrogram length from a single day to several months and display the individual 300 s windows. Local sunrise and sunset (the points when the upper edge of the sun's disk touches the horizon) times were

calculated with a custom MATLAB routine, which employs an algorithm developed from expressions by Dogget et al. (1978).

Sounds were deemed to originate from fish based on their similarity to frequency, energy level, duration and timing of other reported calls and choruses (e.g. Parsons et al., 2016a). In some cases, characteristics were sufficiently similar to suggest a same source species as those in previous reports, while in others, the characteristics merely provided weight of evidence that they were calls originating from fish. Once the source was classified as fish, the duration, spectral content and frequency of the spectral peak of each chorus were determined. In choruses where discrete, observable fish sounds could be identified, individual calls with high signal-to-noise ratios were selected and analysed in the audio program Audacity™ using a 1024 Hanning analysis window. The following measurements were taken:

- Call duration (ms)
- Individual pulse length (ms)
- Pulse interval duration (ms)
- Peak frequency (Hz) [512 Hanning window, - Hz frequency resolution]
- Broadband root-mean-square received levels (dB re 1 μ Pa rms)

For presentation purposes band-pass filters (Butterworth) were applied on an individual call basis to facilitate inspection of the call structure in the waveform using custom-made code developed with the programming software MATLAB® (see appendix for details). Received levels were noted for individual calls containing the highest signal-to-noise ratios, where possible. As the source range was not identified, these are not equivalent to source levels, however, they can provide an indication of minimum potential source level for the call type which can be valuable information for relating caller numbers to overall chorus levels (Parsons et al., 2016a).

Fish choruses were categorised as separate types based on their spectral content (bandwidth and spectral peak frequency of calls and choruses), time of commencement and cessation of chorus (determined by the times when there was a 3 dB increase above ambient levels in energy for a minimum of 30 min in the selected chorus bandwidth, e.g. 400–700 Hz), duration and pulse repetition rate of individual calls (where identifiable), and by visual inspection for frequency partitioning between two choruses.

Other biological sounds including calls suspected to originate from fish, dolphins and snapping shrimp noise were also identified during analysis of long-term recordings.

2.4 Results

Inspection of sound recordings taken around Lizard Island across a two-year period revealed a diverse array of sounds, including container ships, small vessels, wind, rain, and several notable

sources, likely of biological origin. These bioacoustic inputs featured regularly around Lizard Islands, where many distinct fish choruses were present in the soundscape, and increased received sound pressure levels to varying degrees (Table 2.2).

2.4.1 Biological choruses - composition and spatio-temporal patterns

Six choruses were identified across all the selected field sites, occupying a frequency band from 20 to 2000 Hz. Several of the choruses significantly raised sound levels within this bandwidth for several hours, particularly post-sunset (Table 2.2). The most common of these, Chorus I, was observed at a number of areas around the island from 2014 to 2016 (Table 2.3). This chorus displayed the highest received sound pressure levels of all choruses, with peak levels exceeding 120 dB re 1 μ Pa rms over 400 to 700 Hz bandwidth (Fig. 2.2).

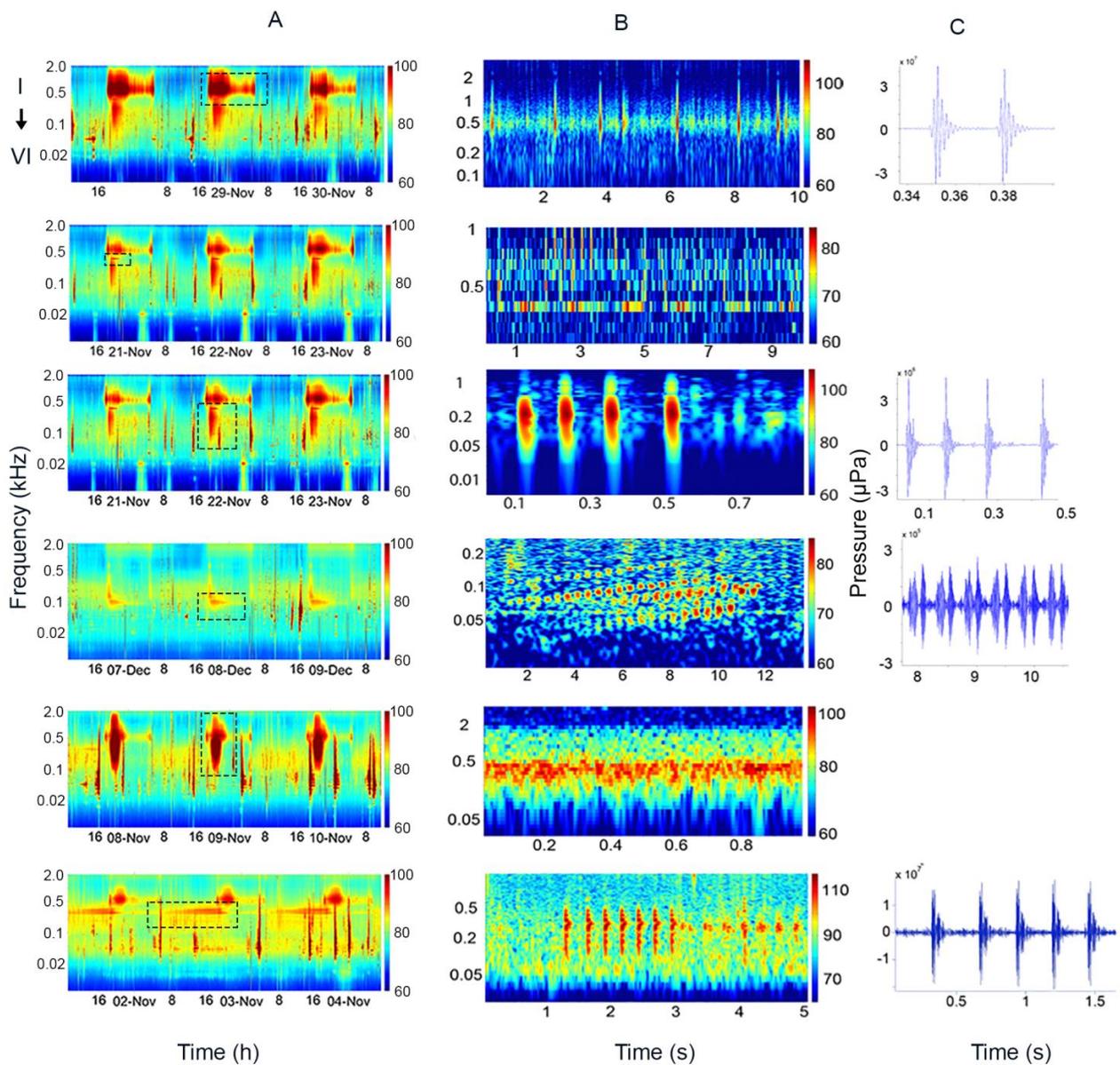


Figure 2.2 Spectrograms (A) of fish choruses (rows 1-6) with expansions of individual calls (or groups of calls where individuals could not be discerned) (B), and waveforms of individual fish calls (C). Dashed boxes

identify each chorus. Spectrograms of individual calls include expansions in both time and frequency to maximise the content of the call within the spectrogram.

Chorus I comprised exclusively short-duration calls of 40 ± 0.04 ms (mean \pm SD), with energy spread across a broad frequency range and a spectral peak frequency of 601 ± 49 Hz for individual calls (Figure 2.2, Table 2.2). The chorus displayed a distinct diurnal pattern with calling commencing just prior to sunset (± 10 min), with a few individual calls per minute and quickly (typically during a 15 min period) building to more than a hundred overlapping calls, during peak chorus activity. There were no instances where the chorus was observed during the day. This pattern was consistent at all sites where Chorus I was present.

Chorus II covered a narrow frequency band (Table 2.2). Inspection of the chorus waveform showed no discernible individual signals. Audio scrutiny with headphones revealed a drone-like hum sound that reached a maximum of 15–20 dB above background received levels. The chorus started abruptly in the evening, between 60 and 90 min post-sunset, and displayed a sharp peak in received levels before dropping below background noise levels after ≈ 2.5 h. Chorus II was recorded at South Island, Eagle Island and North Point sites with Eagle Island displaying the most prominent levels for this Chorus (Table 2.3).

Chorus III comprised low-frequency calls of multiple pulses with energy from 150 to 280 Hz and a spectral peak frequency of approximately 226 ± 23 Hz (Fig. 2.2). Chorus activity began approximately 1 h post-sunset and lasted for a period of just over 1 h, with the highest levels occurring approximately 1.5 h post-sunset.

Chorus IV consisted of a series of calls between 70 and 150 Hz with distinct upper and lower frequency components (Table 2.2, Fig. 2.2). Calling commenced at sunset and reached a peak 1 h post-sunset, continuing for 10–11 h, before diminishing to background levels ≈ 2 h pre-sunrise (Fig. 2.2). Chorus activity was present at Eagle Island, the Shipping Channel (SC) and Big Vicky's.

Audio analysis and examination of Chorus V's waveform revealed no discernible individual signals. Chorus energy was broadband in content with energy centred at its lower frequencies, below 500 Hz (Table 2, Fig. 2.2). It was present at southerly sites and was a very notable contributing sound source with levels recorded at >35 dB above background levels. At its maximum level this chorus exceeded 120 dB re $1\mu\text{Pa}$ rms (150–500 Hz) and masking of Chorus I was evident (Fig. 2.3). The chorus started at ≈ 0.5 h post-sunset, ramping up >20 dB over a 90 min period, reaching maximum levels 2 h post-sunset. Chorus levels then decreased to background levels ≈ 3.5 h post-sunset. The Chorus was observed at the South Island and Big Vicky's site for a short three-week period starting on the 6th November, 2015.

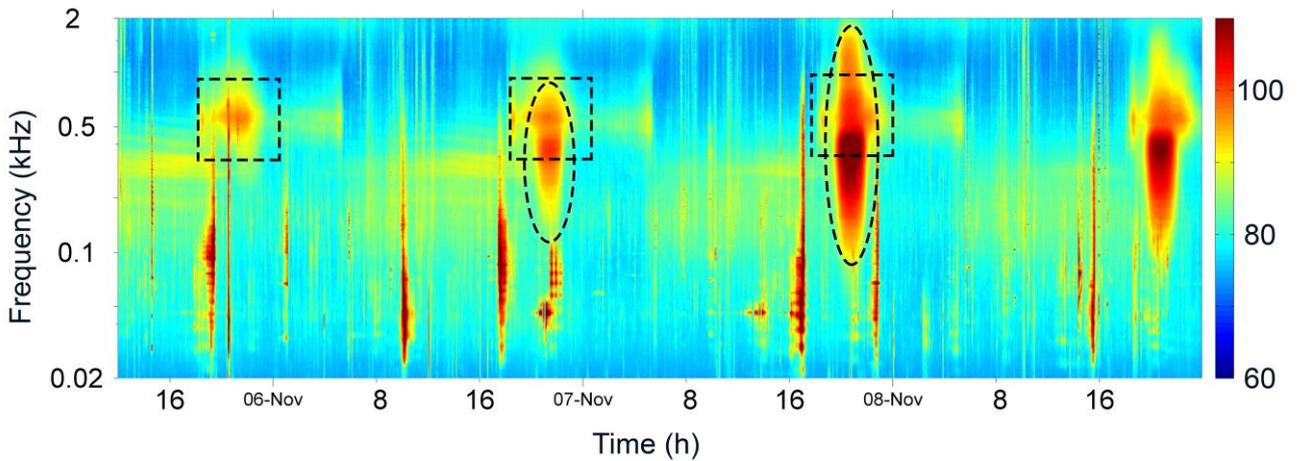


Figure 2.3 Spectrogram showing overlap of two fish choruses. Chorus I (square) and Chorus V (circle).

Chorus VI was composed of calls which were formed by a series of single pulses. Calls were 146 ± 25 ms in duration with spectral energy from 260 to 350 Hz (Table 2.2). The chorus began in the early morning, 1–2 h prior to sunrise and continued for approximately 12–14 h, around sunset. The chorus was detected at the South Island site and in the Shipping Channel (SC site) with the latter displaying activity from the chorus until the end of February in 2015.

Several other calls, suspected to be made by fish, were routinely observed during audible scrutiny and spectrogram analysis of acoustic recordings, though they were not common enough to form choruses (Fig. 2.4). Snapping shrimp were also heard in recordings and observed in long-term spectrograms at all field sites, where they elevated sound pressure levels in the higher frequency bands (~5 – 15 kHz (Fig. 2.5) On several occasions, suspected dolphin calls were recorded at the NP site, though these did not appear to occur on a regular basis (Fig 2.6).

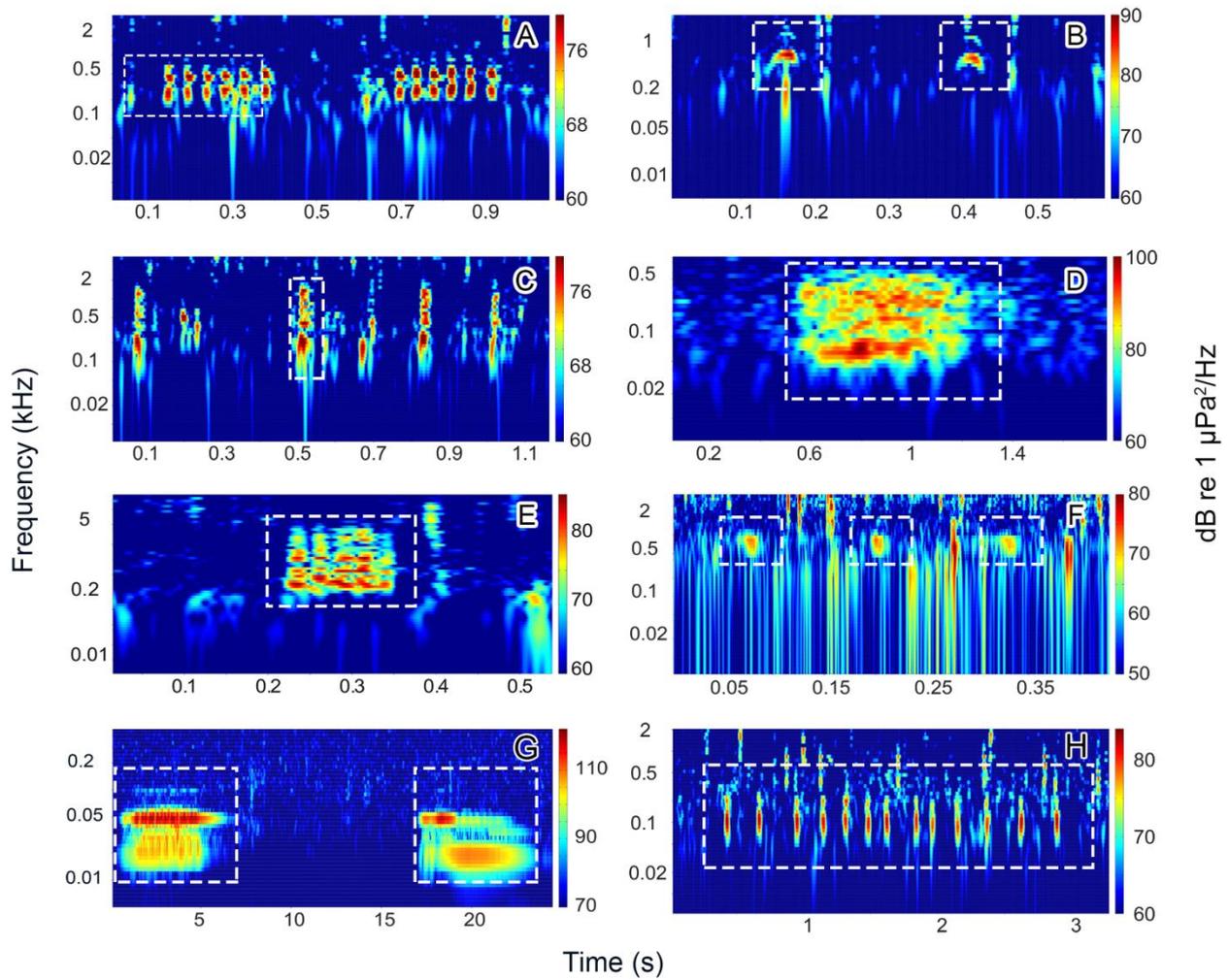


Figure 2.4 Additional calls, suspected to be produced by fish, recorded at various Lizard Island sites. The call shown in spectrogram B is suspected to be produced by the Damselfish (*Pomacentrus amboinensis*).

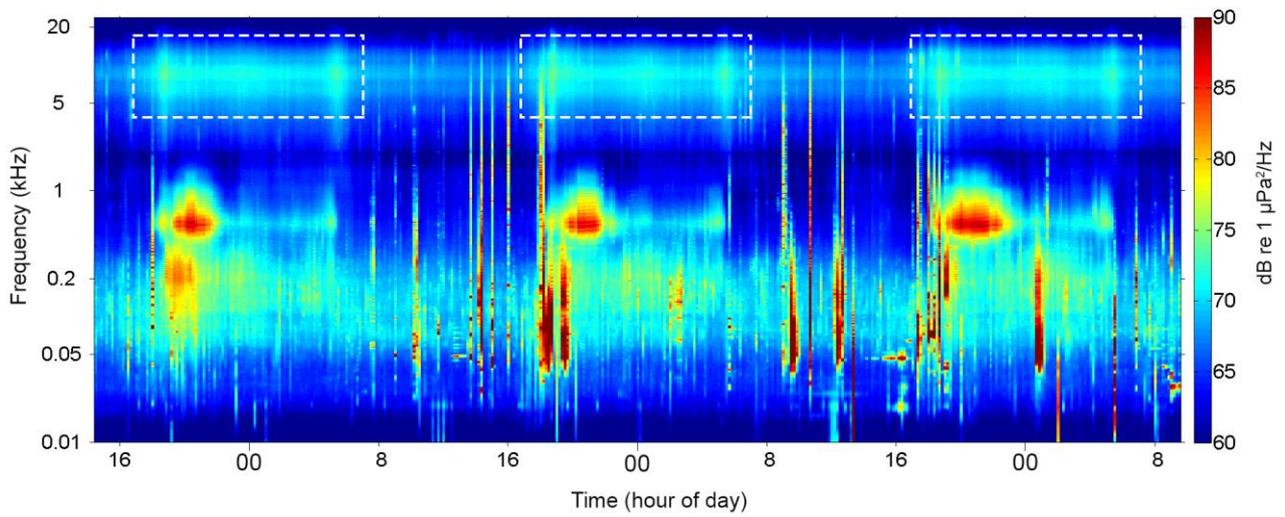


Figure 2.5 Three day spectrogram from NP site in November 2014 showing contribution of snapping shrimp to the soundscape in upper frequency bands (white dashed rectangles).

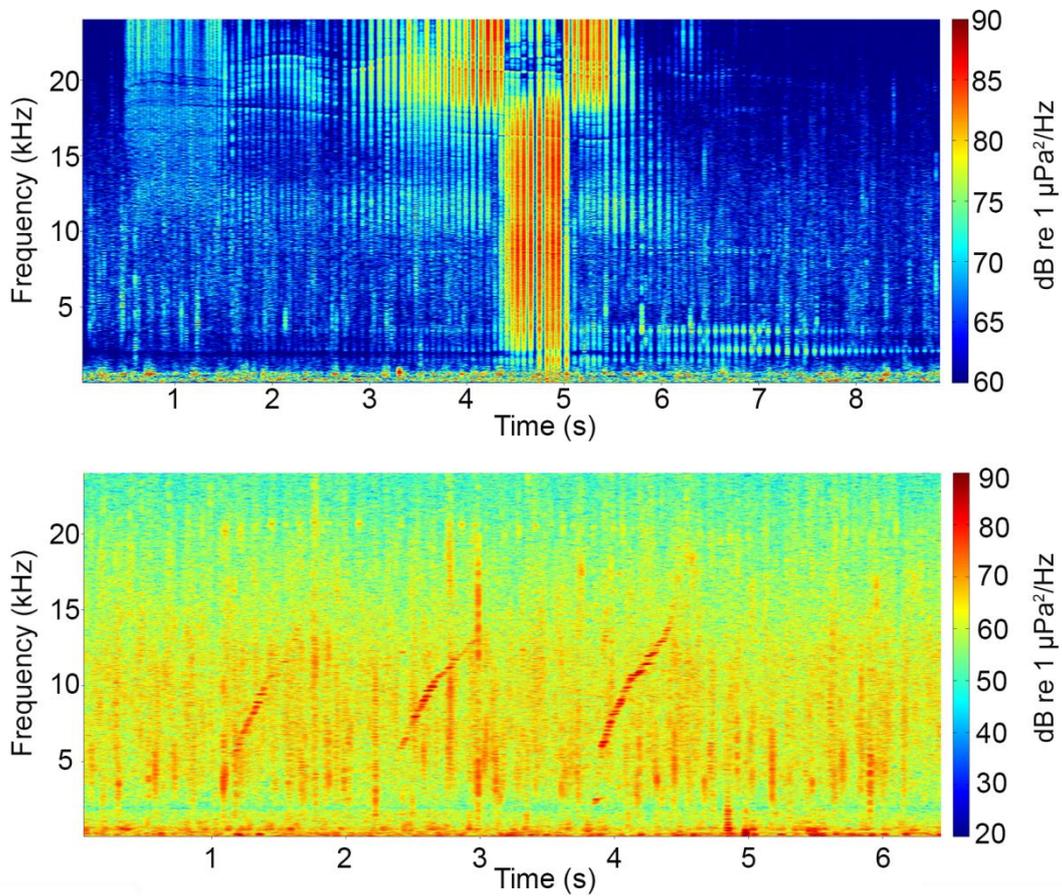


Figure 2.6. Spectrogram of suspected dolphin echolocation clicks (top) and call upsweeps (bottom) recorded at NP site in November 2014.

Table 2.2 Description of prominent biological fish choruses (mean \pm standard deviation [SD]).

Chorus	Individual calls										
	Freq. band (Hz)	Max RL (dB re 1 μ Pa rms)	Duration (h)	Post sunset peak (h)	Max RL (dB re 1 μ Pa rms)	Max peak to peak (Pa)	Spectral peak freq (Hz)	Pulse rate (ms)	No. pulses in calls	Call duration (s)	Sample size (n)
I	400–1800	120–125	12–13	+2.5	140 \pm 6.1	279 \pm 110	601 \pm 49	0.02 \pm 0	2 \pm 0	0.4 \pm 0*	30
II	340–360	100	\approx 2.5	+0.5	-	-	-	-	-	-	-
III	20 – 280	105–108	\approx 1	+0.5	121 \pm 5	15 \pm 7	226 \pm 23	-	-	83.3 \pm 9.4*	113
IV	70 – 150	98–100	10–11	+1	101 \pm 2	4 \pm 2	112 \pm 8 146 \pm 5	0.39 \pm 0.03	12 \pm 4	4.66 \pm 1.87	30
							88 \pm 5 101 \pm 4	0.37 \pm 0.02	9 \pm 3	3.54 \pm 1.18	30
V	150 – 400	115–120	\approx 3	+2	-	-	-	-	-	-	-
VI	260–350	90–100	12–14	+18.5	109 \pm 4	5 \pm 2	249 \pm 16	0.231 \pm 0.01	7	1.612 \pm 0.04	30

- information could not be determined as individual calls or pulses could not be resolved, *ms

Table 2.3 Total recording periods and sites where different chorus types were present.

	Recording Periods					
	2014		2015		2016	
	Date	Duration (days)	Date	Duration (days)	Date	Duration (days)
NP	29/10–08/11	10 ^c	26/09–15/12	80 ^c	12/11–27/11	22 ^{***}
	10/11–17/11	7 ^c	08/03–17/03	9 ^c	20/11 – 28/11	8 ^c
	18/11–30/11	12*			07/04–06/05	30 ^c
SC	1/12–31/12	30 ^{**}	1/01–5/07	216 ^c	--	--
EI	31/10 – 8/11	8 ^c	--	--	--	--
BV	28/11–30/11	3 ^c	27/09–16/12	81 ^c	26/11–4/12	9 ^c
			06/03–17/03	11 ^c	06/04–05/05	30 ^c
LG	18/11–19/11	2 ^c	26/09–13/12	79 ^c	26/11–5/12	10 ^c
			07/03–14/03	7 ^c	07/04–07/05	31 ^c
SI	22/11 - 27/11	5 ^c	29/09–15/12	78 ^c	29/11–3/12	5 ^c
					07/04–23/04	17 ^c
Chorus Type						
	I	II	III	IV	V	VI
NP	✓	✓	✓	✓		
SC		✓		✓		✓
EI	✓	✓		✓		✓
BV				✓	✓	
LG						
SI	✓			✓	✓	✓

^c continuous, *16.67% duty cycle (dc), ** 20% dc, *** 93% dc, -- no recordings

2.5 Discussion

Six study sites located around Lizard Island contained several distinct bioacoustic signals in the form of six predominant biological fish choruses. Between them, the choruses occupied a broad frequency band, displaying energy from approximately 20 Hz to 2000 Hz, contributing significantly to the ambient noise levels. During peak activity, each chorus dominated its respective frequency band, indicating that this is an important time for vocalising fish. Call received levels from each chorus were low compared with source levels of some Australian fish (McCauley, 2001; Parsons et al., 2012, 2013b, 2016a), but also compared to the chorus levels themselves, suggesting that overall, a large number of calls per minute were emitted. This in turn indicates that the choruses were produced by either a large number of individuals calling slowly, or individuals that produce calls repetitively and in quick succession, for prolonged periods. The calling repetition rates observed for individual fish suggest that the former was the case here. The reported received levels also provide information for future studies at these sites. As source levels of individuals and to an extent each species are thought to be comparatively consistent, (Connaughton et al., 2000; Parsons et al., 2012) the reported received levels of individual calls provide an indication of the caller range. When combined with the estimated calling rate and the chorus levels it is then possible to estimate the likelihood of any day-to-day change in chorus level as being a result of fewer fish, or greater range from the hydrophone (McCauley, 2001). Targeted passive acoustic monitoring is often limited by the number of underwater recording systems that can be deployed, thus the ability to identify even relative changes in range can improve confidence in long-term monitoring of chorus levels by assisting in understanding whether these changes are a result of changing callers numbers or range.

Choruses were detected at various locations around the island with some sites containing greater chorus diversity and higher chorus received levels than others, indicating that particular spots are important areas for vocalising fish. Similar to choruses at other locations, each chorus displayed distinct diurnal patterns, with peak levels here occurring primarily post-sunset (McCauley and Cato, 2000; McCauley, 2001; Erbe et al., 2015, Parsons et al., 2016b). Several other suspected fish calls and dolphin calls were observed around Lizard Island and while not meeting the chorus classification criteria (Cato, 1978), together, they demonstrate the broad diversity of biological sounds found around Lizard Island. Reporting biological calls, particularly those in little studied, pristine or critical habitats, is important for future monitoring of coral reefs. Classification of calls holds potential application for investigating the presence and distribution of vocalising species in these ecosystems, once the source animal has been identified. This in turn could aid future species-specific research and management projects.

2.5.1 Source of choruses and other biological sounds

Spectral maxima of Chorus I were between 450 and 650 Hz with energy spread from 400 Hz to \approx 1.8 kHz. This spectral pattern compares directly with the individual calls and chorus described by McCauley (2001) as the 'popping chorus'. This chorus was recorded at a number of locations along the Queensland coast, Northern Territory and NW Western Australia in the early 1990's and is suspected to be produced by nocturnal planktivorous fish of the families *Priacanthidae*, *Holocentridae* or *Pempheridae* (McCauley and Cato, 2000; McCauley, 2001; McCauley, 2012). Individual calls that compose Chorus I match several of the call characteristics of the bigeye fish *Pempheris adspersa* including spectral content, individual call duration and time of peak calling presented by Radford et al. (2015). Several species in the *Pempheridae* family are commonly observed around Lizard Island around rock/ coral ledges including, *Pempheris analis*, *P. oualensis* and *P. schwenkii*. Chorus VI consists of a series of knocking sounds. The spectral content and call duration closely resemble the knocking calls described by McCauley (2001). In January 1991, McCauley (2001) recorded rates of knocking calls at roughly 100 per 10 min in the area between Eagle Island and Lizard Island. This site is close to sites (\pm 3 km) where knocking calls were recorded from 2014–2016. Chorus VI was present at the Shipping Channel field site (SC) in January 2015, demonstrating an apparent spatial and temporal overlap with the knocking calls described by McCauley (2001). The source of the knocking call has not yet been determined, but is thought to be produced by a planktivorous fish (McCauley, 2001). The source of Chorus IV is suspected to be the Batfish (*Platax sp.*), which are commonly found all around Lizard Island. A Batfish chorus with call type and spectral content that closely resembles Chorus IV is described by Parsons et al. (2016b), where measurements of approximate spectral peak frequencies, call duration, and time of peak calling displayed strong similarities. No previous reports have been found that document the three remaining choruses (II, III and V) described in this paper. This highlights the importance of documenting their characteristics and occurrence, particularly in a World Heritage area, that is experiencing a state of decline (Hughes et al., 2017).

Of the individual calls reported, Call type B displayed acoustic characteristics similar to calls described by Parmentier et al. (2016) of the Ambon damselfish, *Pomacentrus amboinensis*, which is commonly found within coral reefs around Lizard Island (Hixon and Jones, 2005; Hoey and McCormick, 2006). Call distribution and patterns by damselfish could be a useful indicator for long-term tracking of damselfish distribution and activity rates. Damselfish have the capacity to strongly modify benthic algae community structure and consequently, influence ecosystem dynamics (Lobel, 1980; Sammarco, 1983). This highlights the importance of reporting significant contributors to the soundscape for later identification. Outbreaks of species-specific diseases, while uncommon, can occur over short timescales, yet have significant long-term effects on the local population (Lamb et al., 2016). Identifying the timing of such events can be problematic if they occur at remote sites, however, long-term changes in vocalisations can elucidate this. It is

therefore important to document call types in case later identification provides information on changes in the fish assemblage composition.

Dolphins have been observed on several occasions around Lizard Island by researchers conducting field work. The presence of dolphins at the NP site at a time, when many fish choruses were active was an interesting observation and may indicate an important area for this species, potentially for feeding purposes. It has been reported that sound producing fishes may constitute a large component of some cetacean's diets (Burros and Myrberg, 1987). However, further analysis detecting dolphin calls within long-term recordings would be required to establish the spatial and temporal presence of dolphins around Lizard Island.

2.5.2 Biological function of choruses

While the sources of some choruses have not been verified, their temporal characteristics indicate nocturnal fish species, which become active post-sunset. Nocturnal vocal behaviour is often associated with feeding or spawning (Fish and Mowbray, 1970).

2.5.2.1 Feeding

Key food sources for planktivorous fish are zooplankton and fish larvae/eggs. These may be important factors that determine why North Point and South Island are areas possessing higher peak chorus levels than the other sites. Shallow reef outcrops, like the one that composes North Point are often associated with gyres forming nearby (Johannes, 1978). These systems of rotating currents are associated with areas of upwelling and high productivity that attract zooplankton in high concentrations (Cushing, 1971; Alldredge and King, 1977), anecdotally seen on echosounders in this area of Lizard Island. Chorus I displayed a sudden increase in activity at sunset and a noticeable decrease in activity prior to dawn. Nocturnal feeding often occurs in response to a combination of planktonic vertical migration post-sunset, which results in an increase in biomass, and reduced predation pressures from piscivorous fish (Yahel, et al., 2005). The periods of Chorus I activity, combined with the site potential for upwelling, suggest feeding as an associated function, similar to McCauley (2001). Fish choruses may also be associated with an additional biological function; maintaining group cohesion. In the absence of light, sound would be one of the primary senses for orientation. A recent study investigating con-specific vocalisation of bigeye fish (*Pempheris adspersa*) discovered that group cohesion increased significantly when exposed to playback of conspecific calls (van Oosterom et al., 2016).

2.5.2.1 Spawning

It is hypothesised that Chorus V and VI are possibly associated with reproductive activity. Peak activity strongly coincides spatially with spawning sites of a number of coral reef species, some of which are of high ecological or commercial interest (Robertson et al., 1983). Tropical fish species

commence spawning to coincide with new/full moon and spring tides, which facilitates the flushing of larvae away from shallow water areas, reducing the risk of larval predation by zooplanktivores (Johannes, 1978). Coral trout, *Plectropomus leopardus*, for example, are known to spawn in this area around the new moon period from October to December (Johannes, 1978; Samoily, 1997; Zeller, 1998), coinciding with peak activity of Chorus V. Coral trout are part of the *Serranidae* family and while there are no reports to date of coral trout calling, a number of *Serranidae* are notable sound producers including the yellowfin Grouper, *Mycteroperca venenosa*, Goliath Grouper, *Epinephelus itajara*, and the Nassau grouper, *Epinephelus striatus* (Gerhardinger et al., 2006; Schärer et al., 2012a, 2012b).

Spawning around underwater promontories, usually the foremost outcrops or island peninsulas helps to position eggs close to nearshore gyres. These circular currents while initially retaining eggs and larvae in the area, later sweep eggs away from shallow water predators (Randall and Randall, 1963; Billings and Munro, 1974). Gyres also increase the chance of oceanic larvae of being returned to their native reef on local currents. A larval recruitment study at Lizard Island determined that 15–60% of juveniles may be returning to their natal reef (Jones et al., 1999). North Point and South Island sites can be considered as seaward extensions of fringing reef and this may explain why they have high bioacoustic activity.

2.6 Conclusions and future research

Recent global disturbance events, particularly coral bleaching, highlight the pressing need for developing robust ecosystem indicators. The long-term survival of the World Heritage listed GBR will require careful management practices, which are guided by a greater understanding of reef ecosystems (Gray, 1997; Mumby and Stenek, 2008; Giakoumi et al., 2015). Fish populations are fundamental to functioning coral reefs and have subsequently been shown to be indicators of coral reef resilience (Dulvy et al., 2004; Burkpile and Hay, 2008; Green and Bellwood, 2009). Fish choruses appear to be a widespread and diverse part of Australian marine soundscapes and therefore, are a promising potential reef monitoring indicator (McCauley, 2012; McCauley and Cato, 2016; Parsons et al., 2016b). However, little is known about many of the vocal fish species that inhabit the GBR. This study provides baseline knowledge on marine soundscapes within a high-profile World Heritage Site. Lizard Island coral reef soundscapes contain a diverse array of bioacoustic signals, particularly biological choruses produced by vocalising fish. Six individual choruses were identified around Lizard Island. Strong diurnal activity was present in nearly all of the choruses with some field sites displaying consistently higher chorus diversity and levels than others, suggesting that particular locations are important aggregation areas for soniferous fish (Luczkovich et al., 2008). Three of these choruses appear to be undocumented and could hold valuable information on the presence, abundance and dispersal patterns of fish species.

Sound is an integral, but unrepresented part of marine ecosystems. While a growing number of studies are helping to improve our understanding of marine soundscapes and bring awareness to the importance of passive acoustics in ecosystem monitoring (Simpson et al., 2005; Radford et al., 2010,14; Staaterman et al., 2013; Kaplan et al., 2015; Bertucci et al., 2016), these are often based on short-term datasets. Long-term passive acoustic datasets enable tracking of bioacoustic activity with disturbance events and may help reveal how these events impact coral reef biological communities over time, through on-going monitoring of soundscape composition. Therefore, gaining knowledge of fish chorus presence and patterns develops our understanding of marine soundscapes and consequently our comprehension of reef ecosystems (Rountree et al., 2006; Lammers et al., 2008; Van Parijs et al., 2009). The findings of this study could be highly relevant to other scientific research projects and marine managers, especially in light of the recent widespread coral bleaching. Future research should focus on determining the temporal patterns associated with bioacoustic activity and identifying the potential environmental drivers of biological choruses. Developing automated techniques to directly identify vocalising species would also increase the management applicability of passive acoustic monitoring. However, analysis of large datasets remains a significant bottleneck to widespread implementation of PAM data due to the labour intensive nature of analysis (Ranjard et al., 2017). While there are several promising methods such as hidden Markov models, we are still in the developmental stages of automatic signal processing of bioacoustic data (Alonso et al., 2017). Automatic detection rates vary considerably and require extensive supervised learning that is usually based on datasets that are manually selected, evaluated by experts and where the data is of high quality (Potamitis et al., 2014). Therefore, automation is specific to the selected dataset being analysed and this makes wider adoption of automated processing challenging.

Chapter 3

Biophonic periodicity on coral reefs in the Great Barrier Reef: Patterns and drivers

The coral reefs surrounding Lizard Island in the GBR have a diverse soundscape that contains an array of bioacoustic phenomena, notably biological choruses produced by soniferous fish. Six fish choruses identified around Lizard Island exhibited notable spatial and temporal patterns from 2014 to 2016. Several choruses displayed high site fidelity, indicating that particular sites may represent important 'habitat hotspots' for fish species, such as fish spawning aggregations sites. Choruses displayed a broad frequency spectrum of periodicities, from diel to annual, which provides new insights into the ecology of vocalising reef fish species and the surrounding ecosystem. Several environmental variables, including temperature and moonlight, had a significant influence on the timing and received levels of several of the fish choruses. These findings highlight the utility of PAM for long-term monitoring and management of coral reefs, which is highly relevant in light of recent global disturbance events, particularly coral bleaching.

3.1 Introduction

Environmental rhythms strongly influence the presence, diversity and dispersal of organisms in marine ecosystems, where cyclical patterns are a fundamental part of natural systems (Danilevsky et al., 1970). Marine ecosystems contain a plethora of diverse and complex phenomena, which occur on a range of temporal scales and relate to patterns in tides, temperature and season (Munro, 1990). Nearly all species have evolved temporal adaptations to increase the population's chances of survival. One such adaptation and well-known phenomenon is the spawning aggregation of fishes, defined by Claydon (2004) as 'any temporary aggregation formed by fishes that have migrated for the specific purpose of spawning'.

Globally, 164 species of reef fishes across 26 families have been identified as forming spawning aggregations (Claydon, 2004; de Mitcheson et al., 2011; Erisman et al., 2015). The commencement of spawning in fish has been shown to be influenced by a combination of environmental cues, notably water temperature (Samoilys, 1997), tidal regimes (Choat and Robertson, 1975; Thresher; 1984) and lunar phase (Colin, 1991; Tucker et al., 1993). These may act synergistically or antagonistically to stimulate changes in behaviour (Boch et al., 2011). Fish spawning behaviour is also strongly influenced by circadian and circalunar rhythms, where solar and lunar photoperiods are key triggers of gonadal activation and diurnal breeding in many tropical reef species (Lobel, 1978; Robertson, 1983; Fox et al., 2015; Numata and Helm, 2015).

Several species that form spawning aggregations produce sound during mating, including *Pomacentridae* (Lobel and Mann, 1995; Gladstone, 2007), *Gadidae* (Hawkins and Rasmussen, 1978), *Serranidae* (Colin, 1992; Rowell et al., 2012, 2015; Schärer et al., 2012a) and *Sciaenidae* (Luczkovich et al., 1999; Holt, 2008). Sound has been shown to play an important role in aggregations as a species-specific recognition signal, orientation mechanism, and stimulant of sexual activity and synchronous reproductive efforts of the entire colony/aggregation (Tavolga, 1971; Kaatz, 2002).

When numerous fish collectively produce sound they can raise the ambient noise levels significantly, producing what has been termed a chorus. A fish chorus is defined as the continuous sound produced by vocalising fish that significantly raises the background noise level (BNL) in a characteristic frequency band by >3 dB for an extended period (\approx 1 h or more) (Cato, 1978).

Biological sound production in the marine environment is incredibly diverse, with soniferous species spread across several different genera, from mammals to invertebrates and fish

Australian coral reefs have been shown to emanate a wealth of biological sounds from invertebrates (notably the snapping shrimp), mammals and fish, which form characteristic fish choruses (McCauley and Cato, 2000; McCauley, 2001; McPherson et al., 2016; Parsons et al., 2016a). Around Lizard Island in the GBR, six fish choruses were recently identified across six field

sites (McWilliam et al., 2017). Occupying a broad frequency band from 50 to 2000 Hz, several of these choruses exhibited distinct temporal patterns, where strong diurnal activity was present in five of the six choruses (McWilliam et al., 2017). Four of the six were predominantly detected at distinct times in hours of darkness while two were also found during the day. Field sites in the north and south of the island displayed consistently higher chorus diversity and levels than other sites, suggesting that particular locations are important aggregation areas for soniferous fish (Luczkovich et al., 2008). Three of these choruses appear to be undocumented and could hold valuable information on the presence, abundance and dispersal patterns of fish species.

3.2 Aim of study

The aim of this study is to determine the periodicities of selected fish choruses and their environmental drivers around Lizard Island in order to:

- elaborate areas of essential fish habitat,
- better understand existing spatio-temporal patterns, and
- provide a means of comparison with future monitoring, particularly post environmental change or increases in anthropogenic pressure.

3.3 Methodology

3.3.1 Study area

Lizard Island (14°40.88'S, 145°27.82'E) is a continental island located 270 km north of Cairns, approximately 30km off the coast within the World Heritage listed GBR. There are three other smaller islands: Palfrey, South Island and Bird Island nearby, which make up the Lizard Island Group (Fig. 3.1). Coral reef borders the smaller islands and a narrow band of fringing reef surrounds much of Lizard Island. Between Lizard and South Island, a more extensive reef encompasses the Blue Lagoon, with water depths up to 12 m. The maximum tidal range at Lizard is ± 3 m. Current speeds vary around the island group with the entrances to the lagoon and waters around North Point experiencing current speeds, which can exceed 30 cm/s during tidal cycles (Frith et al., 1986).

The island is subjected to south-easterly trade winds from April to September with maximum monthly wind speeds averaging 42 km/h for this period (Frith et al., 1986). In October and November, wind speeds drop considerably, averaging 28 km/h and become more variable in direction. Gusty north-westerly winds are interposed with calm periods in November and December.

3.3.2 Data collection

A series of underwater audio recordings were obtained at various times over a three-year period from six field sites around Lizard Island (Fig. 3.1). Recordings were made using a) SoundTrap 202 (Ocean Instruments, New Zealand) digital sound recorders with a 48 kps sample rate (manufacturer's specifications of a flat response within ± 3 dB between 20 Hz and 60 kHz) and b) an underwater sound recorder [USR] (developed by the Centre for Marine Science and Technology (CMST) at Curtin University and the Defence Science and Technology Organisation) with a calibrated omni-directional, HTI 96-min hydrophone (HighTech Inc., MS, USA) with a 18 kps sample rate.

Every device was piston-phone calibrated with a known level of 121 dB re 1 μ Pa at 250 Hz by the manufacturer, while the CMST USR was calibrated with a white noise generator at -90 dB re 1 V²/Hz. For each subsequent deployment, a Garmin 60C_{sx} GPS unit and a laptop with internet connection were used to ensure continuing SoundTrap clock accuracy and to minimise clock-drift readings. Field recording sites were selected to be representative of the variety of seascapes found around Lizard Island. Site locations were recorded with a Garmin 60C_{sx} GPS, accurate to ± 3 m.

Sound recorders were fastened to weighted mounts and diver-deployed to the seabed on sandy substrates, at a minimum distance of 3 m from reef structures. Recorders were collected and redeployed every 10-14 days for data acquisition and battery recharge. A second SoundTrap was deployed for a period of around 5 minutes prior to retrieval of the first SoundTrap to provide adequate cross-over time. Spectrograms of the overlapping *.wav files were visually and audibly inspected to determine an appropriate cross-over point in SoundTrap wav files, i.e. where diver and handling noise were lowest (minimal). To aid equipment relocation in turbid conditions, a sub-surface marker composed of two concrete breeze blocks and a rope attached to a sub-surface buoy were placed ≈ 5 m from each SoundTrap.

The USR was deployed off the side of one of Lizard Island's research vessels (Kirsty K). The logger was gently lowered to the seafloor by a rope pulley system, followed by a 100 m rope line with a 60 kg sacrificial dump weight in order to maximise the distance of the hydrophone from potential sources of extraneous noise. An acoustic release coupled to sub-surface buoys was attached to the dump-weights for surface-based retrieval of the USR.

To support the long-term data, opportunistic boat-based and seabed recordings were collected, at a number of locations around the islands ranging from approximately 10–20 minutes to several hours in duration. For seabed recordings, a SoundTrap, was deployed using the same procedure outlined above for the long-term recordings. Boat based recordings were carried out using an HTI-96-Min hydrophone (HighTech Inc., MS, USA) and a HR-5 Recorder (Jammin Pro) with a 48 kps sample rate. The hydrophone was placed at 5–10 m below the surface depending on water depth

and the boat was allowed to drift during recordings so that extraneous noise sources were minimised, e.g. from the anchor chain or engine.

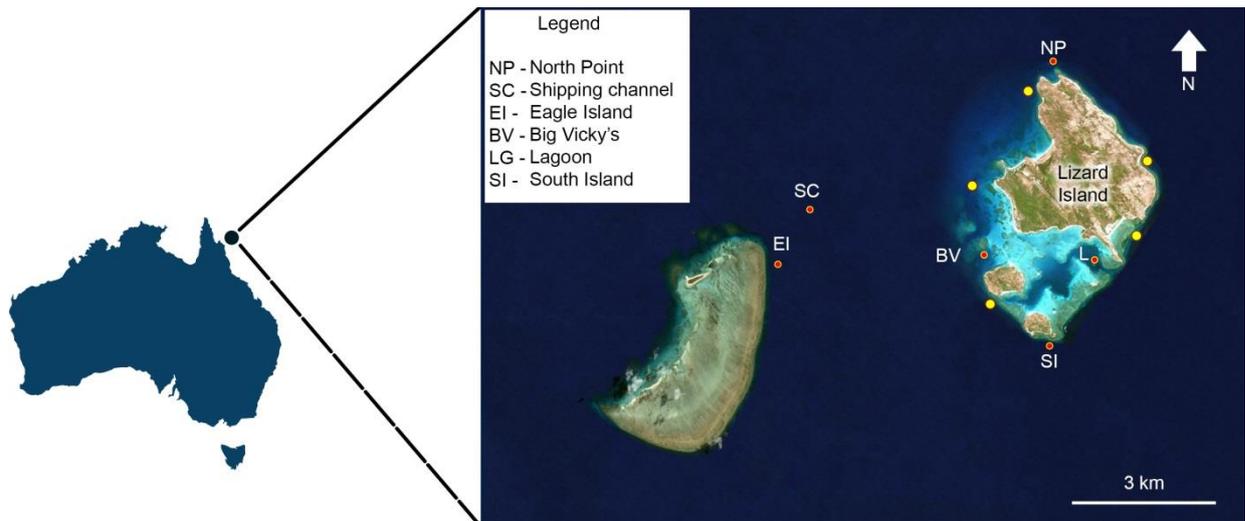


Figure 3.1 Location of field sites around Lizard Island. Red dots denote long-term sites and yellow dots denote location of opportunistic recordings. Long-term site depths (m): NP [18-21], BV [7-10], LG [6-9], SI [13-16], SC [25-30], EI [19-22].

3.3.3 Audio analysis

Acoustic datasets were analysed using a combination of long-term spectrogram visual analysis and audio inspection of recordings with high-quality headphones. Calibrated power spectral density (PSD) averages were computed over 300 s windows and joined chronologically to create long-term spectrograms with time on the x-axis and frequency on the y-axis (logarithmic or linear scale), with colour representing power. A Graphical User Interface (GUI) toolbox, CHaracterisation Of Recorded Underwater Sound (CHORUS; Gavrilov & Parsons 2014) was used to display and inspect the spectrograms in the MATLAB software environment (The Mathworks Inc. Boston, MA). CHORUS was designed to analyse long-term underwater sound recordings. The GUI allows the spectrogram adjustment from a single day to several months. Local sunrise and sunset times (when the upper edge of the sun's disk touches the horizon) were determined with a custom MATLAB routine, which utilises an algorithm developed from expressions by Dogget et al. (1978).

McWilliam et al. (2017) identified signals contributing to six different choruses as originating from fish, based on their similarity in frequency content, energy level, duration and temporal patterns of other reported calls and choruses (e.g. McCauley, 2001; Parsons et al., 2016a), on occasion with sufficient similarity to infer the source species. This study elaborates on the spatio-temporal patterns exhibited by those six choruses utilising the measured duration (start and end time established as the times when ambient energy levels were raised by 3 dB and then maintained for a minimum of 1 h in the designated chorus bandwidth, e.g. 400-700 Hz), spectral content and frequency of spectral peak of each chorus. Each of these descriptors was measured directly from

the long-term spectrograms in CHORUS. The pulse repetition rate of individual calls (where identifiable) and evidence of frequency partitioning between two choruses were determined by visual analysis of spectrograms or waveforms and contributed to categorising each fish chorus. This study also includes two additional chorus types not identified in the previous chapter, which were distinguished using these methods.

3.3.4 Environmental variables

The time difference (ΔT) between the chorus descriptor and environmental factors was determined for the following combinations:

- Peak chorus time vs peak level
- Peak chorus level vs tide height
- Peak level vs chorus duration
- Peak chorus time vs peak tide time
- Peak level vs water temperature
- Peak level vs wind speed
- Peak level vs sunlight
- Peak level vs moonlight
- Peak tide time vs time of sunset

* Peak chorus level refers to the highest received level across the selected frequency bands (e.g. 340 – 360 Hz), i.e. peak band level.

Hourly tidal prediction measurements were taken from the Maritime Safety Queensland Blue Book (Government of Queensland, 2016) and imported into MATLAB. Five minute tidal predictions were estimated using the `interp1.m` function, employing a cubic spline order to incorporate the sinusoidal pattern of tidal levels (Orr et al., 2005). Wind speed, water temperature, sunlight and rainfall readings were collected from the Facility for Automated Intelligent Monitoring of Marine Systems (FAIMMS) Sensor network run by the Australian Integrated Marine Observing System (IMOS). Temperature readings were measured using a Sensus Ultra temperature sensor (ReefNet Inc.) in 10.1 m depth (14°41'17.41"S, 145°26'33.00"E). Datasets and instrument information is freely available from the IMOS online data portal (www.imos.gov.au). In 2015, HOBO Pendant® Temperature/Light data loggers were deployed at each field site while the FAIMMS network was temporarily offline. Wind speed and direction measurements were obtained from the IMOS Lizard Island weather station. In 2015 and 2016, two additional autonomous anemometers (LEWL-PRO) were deployed north and south of Lizard Island to compare localised wind speeds around field sites. Anemometers were programmed to take a wind speed and direction measurement every five minutes. Moonlight levels were estimated using an astronomy and astrophysics package for MATLAB (Ofek, 2014; McCauley and Cato, 2016). Lunar periods in relation to chorus peak levels

were collected from online open access datasets (<https://www.timeanddate.com>) and processed in MATLAB.

3.3.5 Temporal comparison

To account for the strong lunar influence on fish chorus levels, inter-annual comparison of fish choruses was carried out by aligning time series to the day of either the previous full or new moon (McCauley and Cato, 2016). Short-term comparisons could then be conducted by comparing consecutive lunar periods and diel patterns were investigated by zero-ing data to either sunrise, sunset or tidal peaks. Correlation coefficients were computed in MATLAB to investigate potential relationships between fish choruses and environmental variables.

3.4 Results

3.4.1 Spatial patterns of choruses

From 2014 to 2016, fish choruses exhibited distinct and regular spatial patterns around Lizard Island (Fig. 3.2). North Point (NP), Eagle Island (EI) and South Island (SI) displayed the highest diversity of fish choruses (a total of four). Chorus I was observed at three sites, NP, EI and SI, where the NP site consistently displayed the highest chorus levels (Table 3.2). This chorus was not detected at the remaining field sites, Big Vicky's (BV), Lagoon (LG) and Shipping Channel (SC) during any of the recording periods. Chorus II was recorded at three locations, NP, SC and EI, with highest recorded levels at the SC site. Chorus III appeared only at NP throughout the entire monitoring period, appearing to be exclusively active in this area of Lizard Island (Fig. 3.2). Chorus IV was the most spatially widespread chorus and was only absent from the LG field site throughout the 2014–2016 monitoring period. Chorus V was detected at two sites, BV and SI. Chorus VI was observed at three sites, SC, EI and SI (Fig. 3.2).

The six choruses identified were some of the most notable bioacoustic contributors to the Lizard Island soundscape. In addition to these, a large number of discrete calls, suspected to be produced by fish, were also consistently observed during analysis (McWilliam et al., 2017). While most of these calls did not occur at a sufficient rate to produce a chorus, two additional choruses, not reported in McWilliam et al. (2017) have been detected and included in this study. These choruses were detected at the BV and LG sites. These two choruses had relatively low peak SPLs, and remained active for periods ranging from 1 to 3 h (Table 3.3). Chorus VII occupied a narrow higher frequency band, peaking around sunset, whereas Chorus VII's energy was spread across lower frequency bands and was most active around sunrise (Table 3.3).

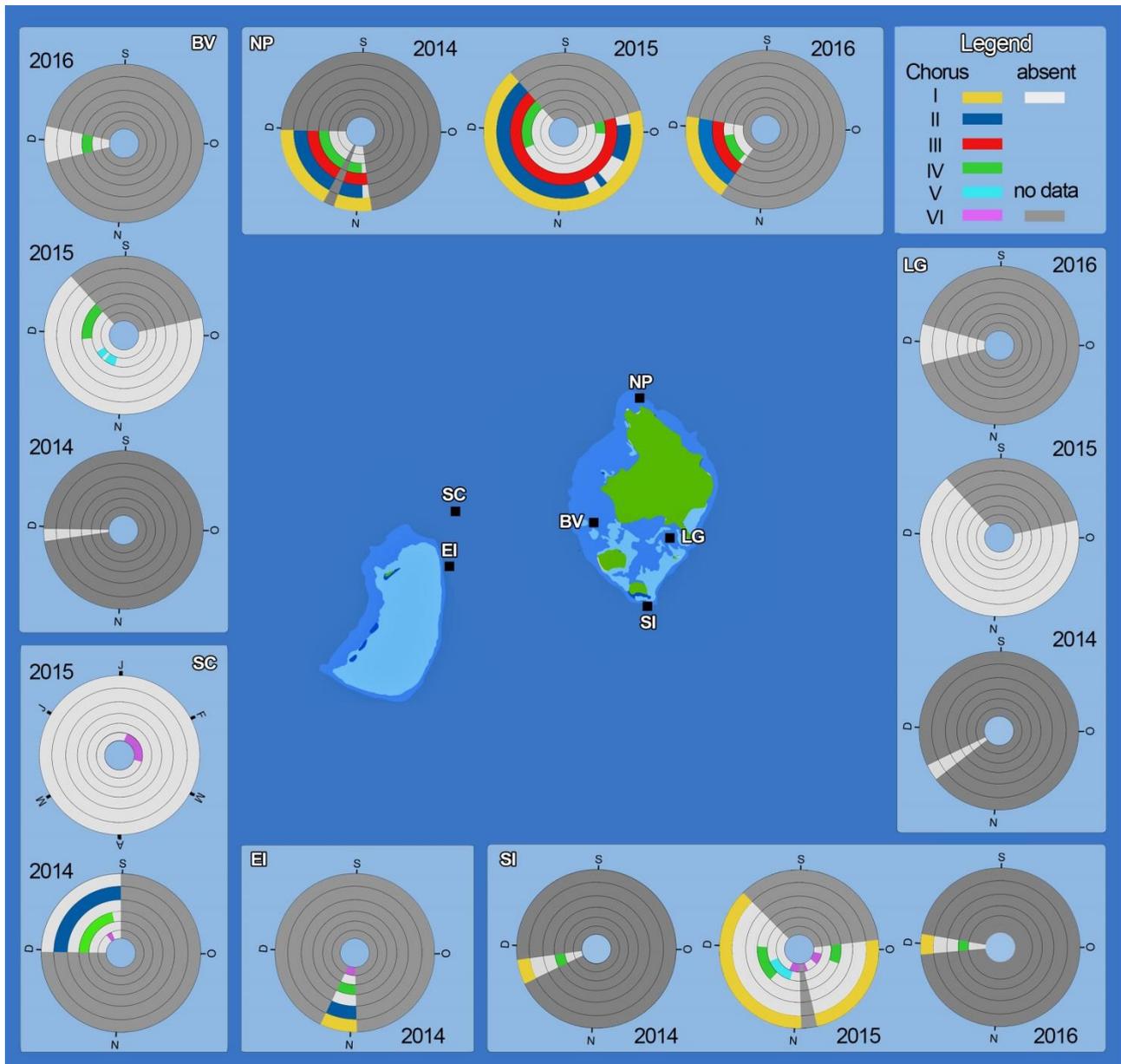


Figure 3.2 Circular Gantt diagrams of fish choruses identified around Lizard Island. Gantt chart units - calendar days with letters representing months of the year. S > D (September to December), J > J (January to July). Fish choruses are colour coded from outer to inner: Chorus I to VI (yellow to purple), no chorus (white), no data (dark grey).

3.4.2 Temporal variation

The choruses displayed a diverse assortment of patterns across several temporal ranges, including diel, tidal, lunar and annual time scales.

Inspection of chorus levels in the six choruses revealed notable diel cycles (Fig. 3.3). A considerable increase in chorus levels post-sunset was observed in all cases with the exception of

Chorus VI, which was predominantly present during hours of sunlight. A low signal-to-noise ratio in some of the fish choruses meant that the daily duration of each chorus could not always be measured, particularly in the case of Choruses IV and VI.

Chorus I levels spiked significantly (>30 dB above background levels) around sunset, dropped to ≈100-105 dB re 1μPa for ≈6 h, then spiked again just prior to sunrise (Fig. 3.3). Daily chorus duration remained largely consistent (≈11-12 h) across the different sites (Table 3.1) and there were no instances where Chorus I was observed during the day. Chorus II began abruptly around sunset (±20 min), building to a sharp peak (up to 20 dB above background levels) before dropping below discernible levels after ≈2 h at NP and EI and ≈3 h at SC (Table 3.1). Chorus III was observed exclusively at NP and commenced around 1 h post-sunset with a duration of ≈1 h. Chorus IV began at sunset, reaching maximum levels one hour later, before calling activity gradually diminished and later dropped to background levels roughly 2 h after sunrise (Fig. 3.3). Chorus V, observed at BV and SI for a three-week period in November, 2015, always commenced after sunset, ramping up (> 25 dB) to a peak over a ≈90-min period. With each consecutive day during this 21-day period, the start of Chorus V shifted to a later time in the evening, with the difference in start time shifting by 120 min (from ≈19:30 to 21:30) over the three-week period in which it was detected. Chorus VI began ≈1-2 h before sunrise and dropped below observable levels in the early morning, though accurate times were difficult to discern due to low SNR.

Table 3.1 Mean chorus durations (hours) with standard deviations (SD) and the number of nights (n) observed. Chorus IV and VI durations are absent due to their low signal-to-noise ratio.

I	NP			SI			EI		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2014	11.89	0.63	29	11.32	0.34	5	10.99	0.18	8
2015	11.75	0.39	80	11.26	0.47	72			
2016	11.83	0.34	21	10.86	0.32	4			
2014–16	11.79	0.45	130	11.24	0.47	81			
II	NP			SC			EI		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2014	1.79	0.70	29	2.90	0.83	29	1.86	0.42	8
2015	1.82	0.62	47						
2016	2.01	0.47	21						
2014–16	1.85	0.62	97						
III	NP								
	Mean	SD	n						
2014	1.64	1.08	29						
2015	1.49	0.56	76						
2016	1.71	0.34	16						
2014–16	1.56	0.70	121						
V	BV			SI					
	Mean	SD	n	Mean	SD	n			
2015	1.82	0.39	14	2.09	0.51	16			

Table 3.2 Peak chorus levels (dB re 1 μ Pa) of fish choruses at field sites from 2014 – 2016.

	NP				SI			BV			EI		
	I	II	III	IV	I	IV	V	IV	V	VI	I	II	IV
Mean	108.2	90.7	103.1	95.6	102.9	89.3	111.6	92.6	98.8	89.8	94.2	89.4	92.7
Max	121.9	98.4	116.1	100.6	115.3	90.1	120.8	94.8	104.1	91.9	96.4	90.5	94.2
Min	94.3	80.4	92.4	92.5	96.8	88.3	103.2	90.0	92.8	86.9	92.4	87.7	90.6
SD	6.8	4.0	4.3	2.7	4.4	0.7	5.3	1.4	4.5	0.8	1.4	1.1	1.2
n	130	130	121	19	80	4	16	23	14	85	8	8	8

Table 3.3 Acoustic characteristics of two additional choruses.

Site	n	Chorus	Duration (h)	Peak level [Hz] (SD)	Time after sunset (SD)	Frequency range (Hz)
BV	77	VII	1 – 1.5	89.8 \pm 0.09	00:30 \pm 9	550 – 650
LG	78	VII	1 – 1.5	92.4 \pm 0.12	00:30 \pm 7	550 – 650
LG	8	VIII	2 – 3	95.6 \pm 0.47	12:30 \pm 37	100 – 400

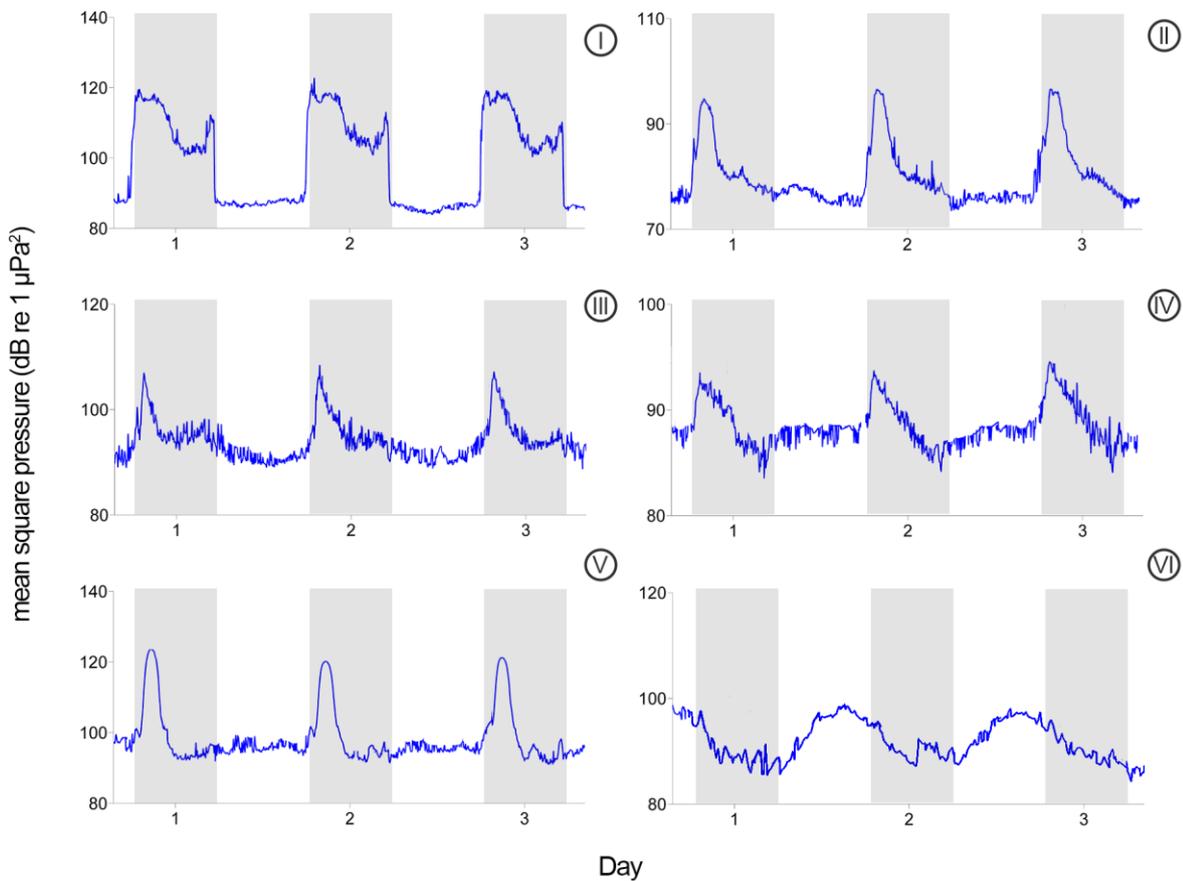


Figure 3.3 Example of daily periodicities over three days of fish choruses (I – VI) around Lizard Island. Mean square pressure for Chorus I to VI is in frequency bands 400–700, 340–360, 20–280, 90–150, 150– 500, 260–350, respectively. unshaded area (day-time), shaded (night-time).

3.4.2.1 Tidal and lunar

Tidal periodicities were only observed in a few choruses. Daily Chorus V peak levels predominantly occurred after a local tide maxima (Fig. 3.4), 81% of the time ($n = 16$) at SI and BV, where the chorus was present.

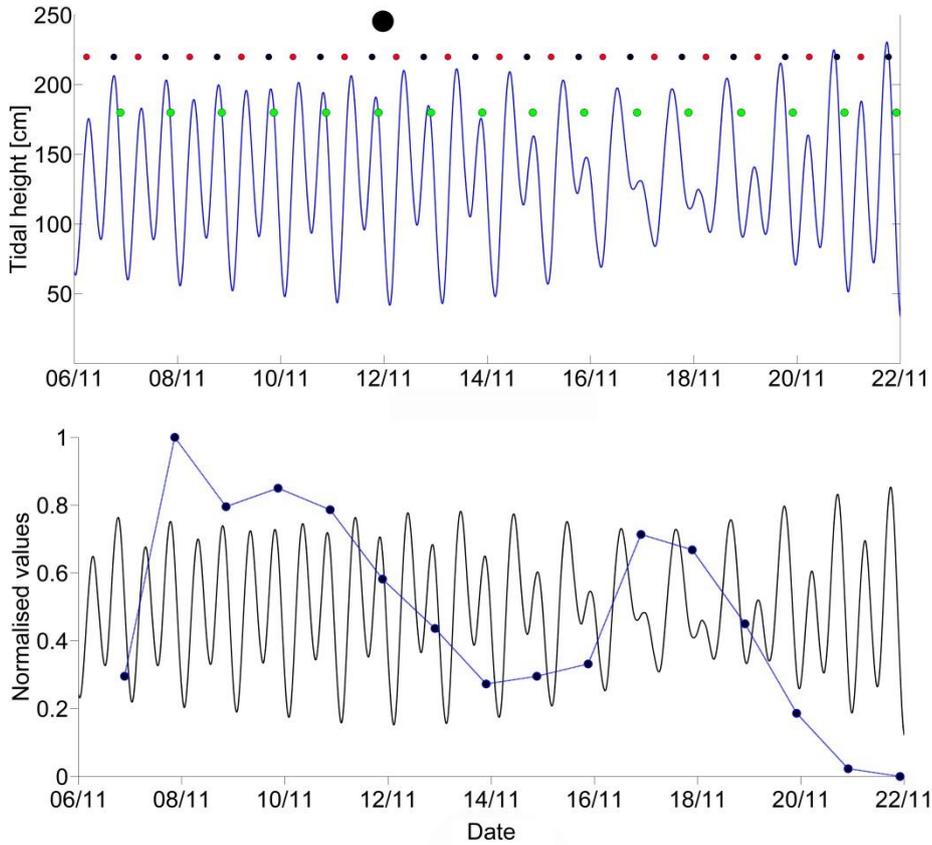


Figure 3.4 Time of the peak Chorus V levels (green dots) in relation to tide height at SI (top) over a 16-day period in 2015, with sunrise and sunset marked by red and black dots, respectively. Normalised (0-1) peak Chorus V levels (black dots connected by blue lines) with normalised tidal heights (0-1) at SI (bottom). Full moon (large black dot).

At the LG site, a discrete and previously unidentified chorus was detected on several occasions. This chorus displayed apparent tidal influences where the chorus coincided with distinct lunar and tidal periods, appearing to reach maximum levels around neap tides, or seven days after spring tides (Fig. 3.5).

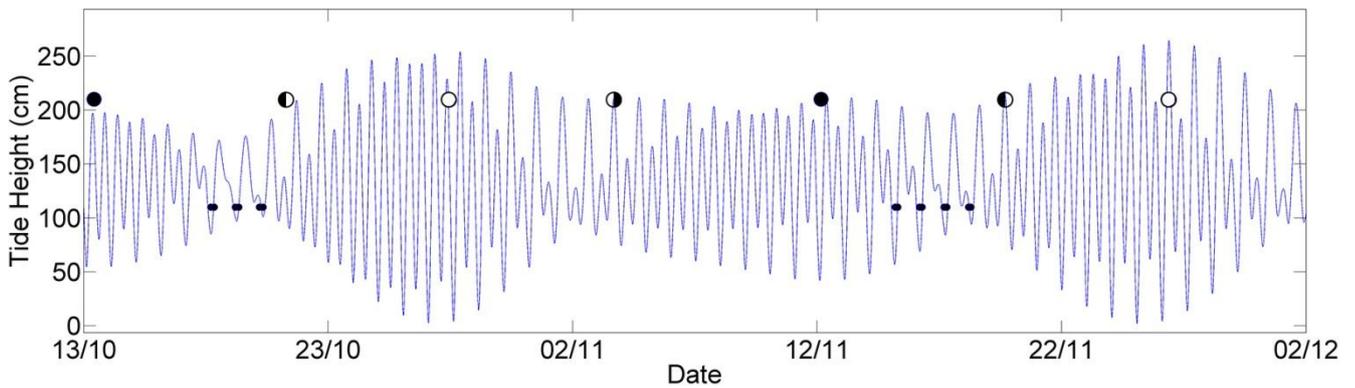


Figure 3.5 Peak times of previously unidentified fish chorus at the LG site (small black circles) in 2015. New moon (large black circles), first quarter (black/white circles), full moon (white circles) and third quarter (white/black circles).

Similar to the chorus in Figure 3.5, lunar periodicities were evident in several of the choruses (I, II and III), with levels increasing around the new moon and decreasing around the full moon. Chorus I, for example, exhibited a negative correlation between days after the new moon and chorus levels in October, which switched to a positive correlation in the subsequent months (Fig. 3.6).

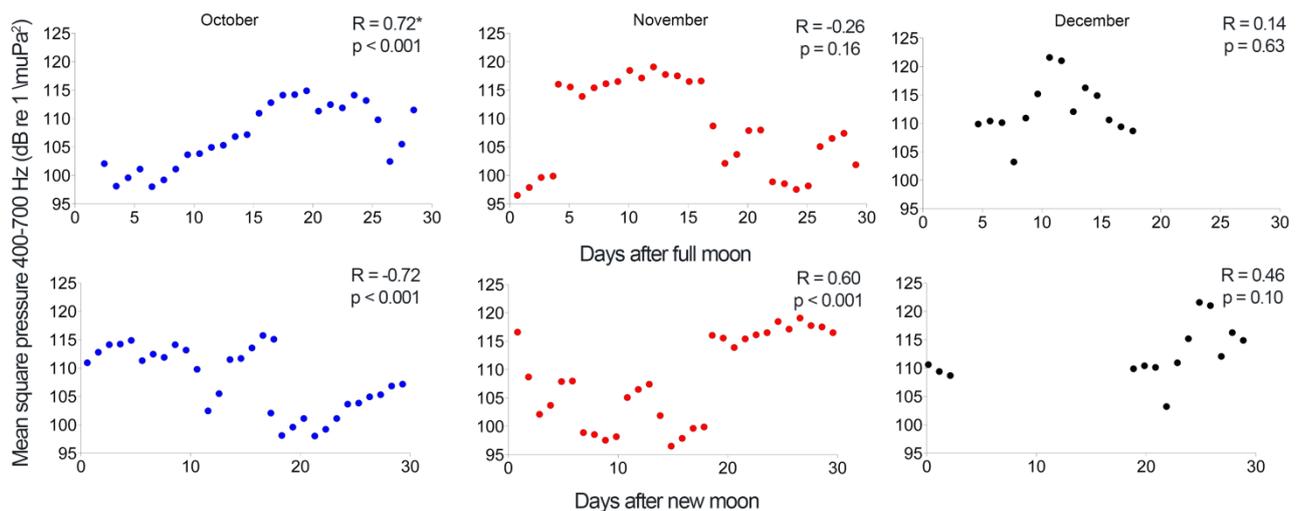


Figure 3.6 Scatter plot of chorus I peak levels in relation to lunar period with correlation coefficients.

*three outliers removed from analysis.

3.4.2.2 Seasonal

Lizard Island has a tropical climate consisting of an austral summer-wet season and a winter-dry season. Seasonal periodicity was seen in Choruses I to VI across all field sites, with a trend of increasing chorus acoustic presence and activity levels from September onwards, into the summer months (November – January), then decreasing towards the end of the summer months. Intermittent individual calls from these choruses could occasionally be heard during the end of the summer-wet season and start of the winter-dry season (March 2014 and April-May 2015) across sites around Lizard Island, but levels did not form a chorus by definition. Long-term recordings from

the SC site (December 14 – July 15) also revealed a comparable pattern of chorus activity to the other field sites. Three choruses (II, IV and VI) were present in December before two of them disappeared prior to January. Chorus VI continued to be observed throughout early January to late February but was not observed after this period, all the way through until July.

3.4.2.3 Annual

Choruses detected in multiple years displayed consistent diel patterns (start/end times), levels (mean square pressure), and comparable durations (Table 3.1). Table 3.1 (mean and SD) shows that chorus durations remain highly consistent over long time scales (2014–2016).

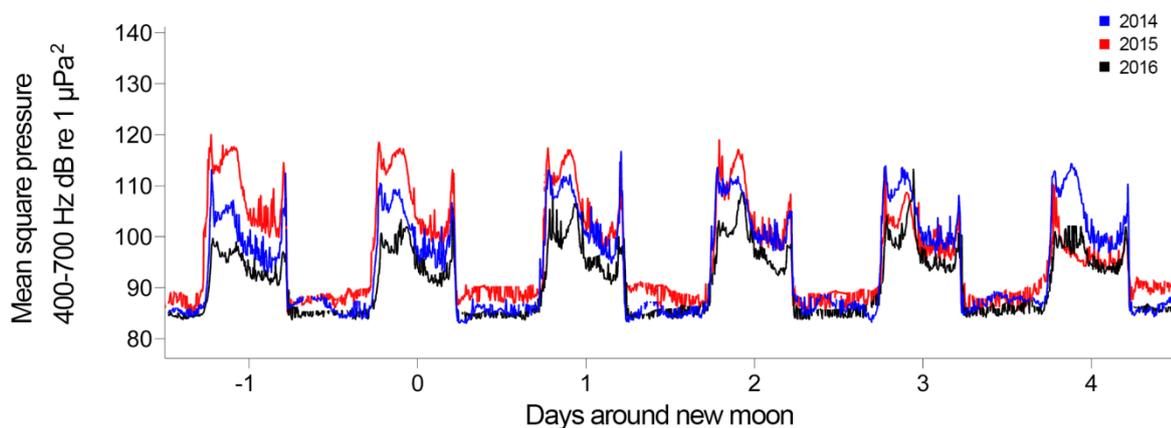


Figure 3.7 Chorus I levels at the NP site around the November new moon period for each year of recording. Day 1 begins on the first midnight after new moon and time intervals continue on a standard 24h cycle. Mean square pressure (MSP) averaged over 300 s windows.

3.4.2.4 Chorus frequency bands

The frequency bands that choruses occupied did not deviate over the recording period with the exception of those of Chorus II at NP, which shifted in the final recording year. In 2016, this chorus shifted frequency bands to $\approx 360\text{-}380$ Hz, up from $\approx 340\text{-}360$ Hz, observed in 2014 and 2015. All other choruses continued to occupy the same frequency bands.

3.4.3 Environmental variables

The correlation between chorus descriptors and environmental variables displayed evidence of chorus and site-specific relationship (Table 3.4).

Table 3.4 Correlation coefficients of potential environmental drivers and fish choruses.

site	n	Pk chorus time vs level	Pk chorus level vs tide height	Pk chorus time vs pk tide time	Pk level vs chorus duration	Pk level vs temperature	Pk level vs wind speed	Pk level vs sunlight	Pk level vs moonlight
NP CI 2014	29	0.74***	0.13	0.18	-0.07	0.74***	0.26	-0.49***	-0.17
NP CI 2015	80	0.29**	0.28	0.52***	0.06	0.14	-0.30**	0.28	-0.22*
NP CI 2016	21	0.76***	0.08	0.49*	0.23	-0.39	-0.24	0.3	-0.54**
SI CI 2015	72	0.53	0.51	0.53**	-0.37	0.54	-0.47	†	0.04
NP CII 2014	29	0.77***	0.24	0.33	0.82***	0.32	-0.42*	-0.31	-0.70***
NP CII 2015	80	0.42	0.26	0.42	0.60***	0.32**	-0.35**	†	-0.45***
NP CII 2016	21	0.77	-0.09	0.21	0.37	-0.47	0.09	0.36	-0.72***
SC CII 2014	29	-0.02	0.3	-0.18	0.59***	-0.14	0.14	-0.11	-0.34
NP CIII 2014	29	0.63	0.18	0.3	0.02	0.51**	0.16	-0.41	-0.48*
NP CIII 2015	76	-0.02	0.01	0.38***	0.09	0.02	0	†	-0.55***
NP CIII 2016	16	0.93***	0.57	0.51	-0.68	0.64	-0.71	0.29	0.41
NP CIV 2015	19	0.82***	0.16	-0.01		0.72***	0.43	†	-0.28
SC CIV 2014	26	-0.19	-0.13	0.1	0.65	0.21	-0.17	-0.49	-0.40*
BV CIV 2015	17	0.77***	0.47	0.51		0.85***	0.17	†	0.09
BV V 2015	14	-0.31	-0.41	0.37	0.91***	0.1	-0.27	-0.27	-0.18
SI V 2015	16	-0.65*	-0.13	0.15	0.84***	-0.19	-0.57*	-0.18	-0.67***

*** p < 0.001, ** p < 0.01, * p < 0.05 † limited data (missing env. variable measurements)

At individual sites, several of the choruses, displayed a positive relationship with water temperature. Chorus I peak levels for 2014 at NP were significantly correlated with water temperature ($r = 0.74$, $p < 0.001$). In 2015, Chorus II and IV peak levels at NP and BV were also positively correlated with temperature (Table 3.4). Temperature was positively correlated with Chorus III in 2014, 2015 and 2016, but in the second recording year the positive correlation was not significant. All choruses (peak SPL's) were, to varying degrees, negatively correlated with moonlight levels with three exceptions (Chorus I at SI in 2015, Chorus III at NP in 2015 and Chorus IV, BV in 2015) [Table 3.4]. Chorus II, displayed the strongest (negative) correlations with moonlight (2014–2016), followed by Chorus V at SI in 2015 (Table 3.4)

Chorus I was negatively correlated with moonlight at NP throughout recording years, but showed a much weaker positive correlation at SI in 2015 ($r = 0.04$). Wind speed and peak chorus levels showed a largely negative relationship in 9 out of 16 chorus site measurements (stronger winds equalling lower chorus levels), where the correlation was strongest at NP for Choruses I-III and Chorus V at SI (Table 3.4).

Sunlight levels, taken as daily averages, were positively and negatively correlated with peak levels for Choruses I–V. However, correlation was only statistically significant for Chorus I at North Point in 2014. Time of chorus peak relative to sunset was significantly correlated with peak chorus level in several choruses, particularly Chorus I from 2014 to 2016, illustrating that peak chorus levels occurred consistently at a similar time of the evening (Table 3.4). However, Chorus V peak levels did not occur at a similar time each night but shifted to later times in the evening, peaking on a falling tide. As a result, there was limited correlation between the time of peak chorus and the chorus levels alone.

A weak positive correlation between peak chorus levels and tide height was seen in four of the six choruses but none were found to be significant. Peak tide time and chorus level showed a stronger relationship, with significant correlations for Choruses I and III, but not for Chorus V. Peak chorus level and chorus duration were significantly correlated in two of the six choruses, Choruses II and V. The chorus peak mean square pressure levels were higher when the chorus continued for a longer period of time.

3.5 Discussion

3.5.1 Spatio-temporal patterns

The fish choruses detected in long-term recordings around Lizard Island have shown various levels of spatial delineation and distinct temporal patterns. Three of these choruses have previously been speculated to originate from bigeye fish *Pempheris adspersa* (or other *Pempheridae*, Chorus I), Batfish (*Platax sp.*, Chorus IV) or members from the *Sciaenidae*, *Scorpaenidae*, *Callionymidae* (stinkfishes) and *Aridae* (catfishes) (Chorus VI), while the sources of Choruses II, III and V currently appear undocumented (McCauley, 2001; Radford et al., 2015; Parsons et al., 2016a; McWilliam et al., 2017). The delineation of spatio-temporal patterns for such a variety of species in such a small area emphasises the importance of documenting their characteristics and occurrence, particularly in a World Heritage area, that is subjected to environmental pressures (Hughes et al., 2017).

The consistency and regularity of these choruses suggests high site fidelity around Lizard Island, with several sites simultaneously hosting multiple choruses, providing evidence that particular areas have significant biological importance for vocalising fish. A number of studies have shown that reef fish can maintain long-term site fidelity, with some spawning sites exhibiting multi-decadal use (Colin, 1996; Aguilar-Perera, 2006) and a recent global baseline of fish spawning aggregations found that up to approximately 90% of aggregation records were from reef pass channels, promontories and outer reef-slope drop-offs (de Mitcheson et al., 2008).

Several aggregation sites of spawning coral trout (*Plectropomus leopardus*) have been identified around Lizard Island and notably, individuals displayed strong fidelity to their chosen aggregation site (Zeller, 1998). Behaviours like these may in part explain NP's higher levels of chorus diversity, as the area contains multiple seascape features thought to be favourable to aggregating fish (Domeier and Colin, 1997). Anecdotal evidence from the opportunistic, short-term recordings (omitted from the long-term analysis) made on the east side of the island, confirmed the presence of Chorus II, making the absence of Chorus II at SI and BV an interesting observation. Chorus III was only observed at the NP site, in contrast to Chorus IV, which exhibited a widespread presence around the island. These differences in chorus presence imply a single aggregation site for the former and that several distinct aggregations form around the Island group in the latter. Chorus V was observed at BV and SI, displaying the highest chorus levels at SI. This suggests that this area in particular, is favoured as an aggregating zone for this species. Chorus VI appeared to be confined to deeper sites, with the exception of NP. Levels were highest at SC, suggesting a species that aggregates in open water areas, or a species that produces a chorus at Eagle Island that is loud enough to be detectible further away (1–2 km) in open water areas.

None of the six choruses were observed at the LG site on the east of the island. This is likely to be due to a combination of acoustic and ecological parameters. The site's shallow water depths can cause acoustic signals to attenuate more quickly than the deeper sites, therefore reducing the sampling area compared with deeper sites (Fine and Lenhardt, 1983). The site is also virtually isolated from the open sea with the exception of a narrow (75 m) channel entrance. From an ecological perspective, if choruses are associated with fish spawning, the lagoon, with its sheltered, shallow habitats, and large numbers of resident predators, would not be considered advantageous for egg survival. Historical spawning aggregation records document several locations around Lizard Island, including SI, but omit the LG, providing weight to this hypothesis (Robertson, 1983; Zeller, 1998). Through all analysis, the gaps in sampling periods, presented in this study necessitate that conclusions on spatial patterns of choruses should be treated with a degree of caution until further recordings can be made.

3.5.2 Larger spatial context of fish chorus patterns

All six choruses exhibited regular diel periodicity across the recording period, and the majority of chorus activity occurred at night. This provides strong evidence that five out of the six choruses are produced by nocturnal fish species. Diel periodicity in fish choruses has been observed in several other locations including the Southern Atlantic, (Sánchez-Gendríz & Padovese, 2016) the central Pacific, (Kaplan et al., 2015) the Mediterranean, (Buscaino et al., 2016) the east Indian Ocean, the west Pacific the Timor Sea (Cato, 1978; Parsons et al., 2016a), the Arabian Sea (Mahanty et al., 2015) and the North Atlantic, (Luczkovich et al., 2008) several of which begin early evening, increasing at sunset, peaking a few hours after sunset and ending by sunrise (Luczkovich et al., 2008; Mann and Grothues, 2009; McCauley, 2012; Parsons et al., 2016b).

3.5.3 Tidal

The weak correlation with tidal patterns, especially for Chorus I, whose daily peak levels did not display any changes in daily tidal regimes, suggest tide has little influence on the aggregation function. However, while not statistically significant, Chorus V displayed a clear tidal influence, where peak chorus levels occurred consistently on falling tide at both sites it was present. Chorus V was present for a short three-week period in November, where peak levels were highest around the spring tides. This may be indicative of a reproductive strategy, where timing of spawning coincides with strong ebbing tides, in order to maximise tidal flushing of eggs to offshore waters (Johannes, 1978). Colin (2010) found further evidence of tidal influence by discovering fish spawning took place shortly after high tides that occurred in the late afternoon. Large numbers of fish have also been observed migrating to outer reef edges and forming spawning aggregations 1.5 – 4 h after the high tide, showing a similar tide-related pattern seen in Chorus V (Robertson, 1983).

3.5.4 Lunar

Many coral fish species are thought to exhibit moon-related reproductive patterns because periodic variations of photoperiod and water temperature are less distinct in equatorial and tropical zones (Thresher, 1984). Most of the choruses displayed negative correlation of chorus peak levels with moonlight, indicating that activity is higher around the new moon when lunar light levels are minimal. Change in moonlight intensity has been found to be a stimulating cue for gonadal development and gamete release in fish, where moonlight levels can inhibit activity in some species and promote it in others (Takemura et al., 2010). Previous studies of fish spawning aggregations around Lizard Island found several instances where these events occurred around the new moon (Robertson, 1983; Ferreira, 1995; Zeller, 1998). Evidence of moon phase influence on fish choruses has also been noted in other areas, including off Darwin, at Scott Reef and around the Maret Islands in north Australia (McCauley, 2012; Parsons et al., 2016a, 2016b).

Lunar and semi-lunar periodicity was not a pronounced feature in five out of the six choruses in 2015 when analysing the recording period as a single event. However, when recording periods were split into months, these became more visible. The change from negative to positive correlation with Chorus I levels from October to November and December may indicate the commencement of a peak in spawning activity for this species. Spawning at a time with low lunar light levels is a reproductive strategy used by several species to decrease predation pressures and enhance egg survival through tidal dispersal (Taylor, 1984; Robertson et al., 1990). In contrast to the other choruses, the previously unidentified chorus at the LG site, active for a total of six days after the full moon, showed a strong lunar pattern. However, the limited presence of many of the choruses, e.g. Chorus V for just over three weeks, means that it is not always possible to elucidate lunar patterns without longer datasets. Therefore, larger sample sizes are required to determine

the significance of these patterns, particularly for those which only appear for a few days in a few months. Currently, such datasets are not yet available at Lizard Island.

3.5.5 Seasonal

Over the year, fish choruses displayed strong seasonal periodicity, displaying an intermittent presence. Chorus activity at sites around Lizard Island was considerably higher in months of the austral wet season (November and December) than the earlier months at the end of the dry season. Chorus activity was minimal at all the long-term field sites near the beginning and middle of the austral dry season (March to July). A chorus found in the northern GBR, described by McCauley (2001), which closely resembles Chorus VI in duration, frequency and timings also displayed strong seasonal periodicity, with similar high calling rates over the wet season. A recent review of fish that form spawning aggregations found that the spawning season of most species typically last for less than three months of the year (de Mitcheson et al., 2008). This seasonal periodicity is thought to have evolved as a reproductive strategy, to ensure optimum spawning conditions and has been observed in several coral reef fishes, particularly in relation to temperature thresholds (Colin, 1992; Samoily, 1997). Temperature has been shown to have a pronounced influence on fish behaviour and physiology, particularly reproduction (Davies et al., 1986; Colin, 1992; Pankhurst and Van Der Kraak, 1997). Several species that form spawning aggregations (*Serranidae*) have strong associations with water temperature, such as coral trout (*Plectropomus leopardus*) which spawns along the Great Barrier Reef once water temperatures reach 26 °C (Samoily, 1997) or the Nassau grouper (*Epinephelus striatus*) when ambient water temperatures are between 25 and 25.5°C (Colin, 1992). Sound production is also functionally related to ambient water temperature because the majority of fish are ectothermic so that muscle activity, used for generating sound, is influenced by temperature (Mann and Grothues, 2009). Fish chorus activity was also found to be significantly related with temperature in northern Australia (Parsons, et al., 2016).

Inter-annual variations in chorus levels are likely to be related to a combination of environmental conditions. In particular, the relative timing of temperature cycles, tidal periods and lunar phases, which have been shown in this study and previous work to have pronounced effects on vocalising fish (Parsons, 2010, 2016; McCauley 2012) can have a combined effect. Interestingly, most of the fish choruses were present at the same sites each year suggesting that species are either resident reef populations or transients that annually migrate to specific locations around Lizard Island.

3.5.6 Wind and rain

Some environmental variables can have a confounding effect on either the sound production or detection, or both, predominantly through the generation of geophysical noise or water movement (Terhune and Ronald, 1975). Wind speed appeared to have a strong negative relationship with peak chorus levels for the majority of choruses. Currents in shallow water areas around Lizard

Island are predominantly driven by the wind (Frith et al., 1986). Wind-driven current fluctuations may influence fish choruses in several ways. High levels of water movement may require insupportable levels of energy consumption to form large fish aggregations and smaller aggregations therefore have lower chorus levels. Strong currents may reduce fertilisation success rates in spawning aggregation by removing eggs before they are fertilised. Wind may affect the dispersal patterns of marine fauna like fish larvae and zooplankton, on which soniferous planktivorous fish feed so that calling rates and levels are minimised to conserve energy in the absence of food (Lasig, 1983; Kingsford and Finn, 1997). Rain was omitted from the statistical analysis as an explanatory variable due to limited rainfall at Lizard Island during the main recording periods.

3.5.7 Potential chorus sources

A major aggregation site for coral trout is located on the west side of BV, close to the recording site, where spawning activity was highest during new moon periods in November (Zeller, 1998). This coincides closely with Chorus V spatial and temporal activity, making it plausible that coral trout are the source of this chorus. While no direct recordings of coral trout vocalising have been reported, several members of the *Serranidae* family are known sound producers (Fish and Mowbray, 1970; Nelson et al., 2011). The frequency band of Chorus V was approximately 150–500 Hz. The low frequency band indicates that the chorus was produced by a large vocalising fish as to produce sounds at lower frequencies generally requires a greater body size (McCauley and Cato, 2016). The spectral content of a call, including the spectral peak, is related to a combination of swimbladder size, sonic muscle size and the mechanism by which the muscle impinges on the swimbladder (McCauley and Cato, 2000; Connaughton et al., 2002). The relationship is such that larger fish, with more developed sonic muscle blocks tend to produce calls of higher source level and lower frequency, than smaller or less developed fish. However, this relationship becomes more complicated if multiple twitches of the swimbladder are used to produce calls from a train of pulses. Further work is therefore required to establish the source of Chorus V.

3.5.8 Ecological relevance

This study has revealed a diverse range of information regarding the spatial and temporal patterns of fish choruses around Lizard Island. From a spatial perspective, the high site fidelity displayed by fish choruses contributes to our understanding of population spatial dynamics, potentially revealing aggregation hotspots and dispersal patterns of soniferous fish, which currently are not well documented (Luczkovich et al., 2008). Fish that aggregate have an increased vulnerability to exploitation, which has been demonstrated in several large aggregating species, notably the Jewfish, *Epinephelus itajara* and the Nassau grouper, *Epinephelus striatus* (Sadovy & Eklund, 1999; Sadovy and Domeier, 2005) and black jewfish, *Protonibea diacanthus* (Semmens et al., 2010). In the Caribbean, this species has experienced dramatic population declines from

overfishing and has recently been placed on the endangered species list. Determining with passive acoustics where fish aggregations occur can help develop ecosystem models of fish populations, guide seasonal closure of key fish spawning areas, placement of future marine reserves and estimation of fish stocks, thereby ensuring the survival of exploited species (Luczkovich et al., 1999; 2008; Claydon, 2004; Holt, 2008; Mann and Grothues, 2009).

By identifying temporal patterns in fish choruses and determining their drivers we can greatly improve understanding of marine soundscapes. Understanding and quantifying periodicities of fish choruses over a wide range of temporal scales from hours through to years improves occurrence, abundance and distribution estimates of reef fish, and collectively the ecology of their corresponding ecosystems. Quantifying environmental periodicities also helps to improve monitoring methodology and has particular relevance for ecological monitoring and assessments, whose accuracy strongly depends on quantifying these rhythms. This in turn, benefits marine protection strategies by maximising locality and timing of management actions.

The repeating spatio-temporal patterns exhibited by several choruses highlights their potential as long-term monitoring reef indicators. Traditionally scarce due to the challenges of surveying highly complex systems for prolonged periods, long-term reef indicators are urgently required after two successive years of widespread coral bleaching, which has caused mass coral mortality throughout the GBR (Mumby, et al., 1999; Ainsworth et al., 2016; Hughes, et al 2017). However, the relatively short-term spatio-temporal patterns in choruses that were detected around the islands demonstrate that a single recording site alone cannot adequately be used to represent a complex reef soundscape and that long-term recordings across a range of sites are key to accounting for variations that can occur in the soundscape. This reinforces the necessity for establishing multiple on-going field sites. While these variations are significant, even in the short-term, coral reef soundscapes are highly complex acoustic environments, where hundreds of sound sources, many of biological origin, can be recorded over a short period from a single location. Identification of individual signals contributes significant knowledge to understanding species diversity within the soundscape, yet classification of sound sources is a challenging and time consuming task. Automated signal recognition and source identification show great promise, yet remain in developmental stages (Alonso et al., 2017).

3.6 Conclusion

The coral reefs surrounding Lizard Island in the GBR have a diverse soundscape that contains a plethora of bioacoustic phenomena, notably biological choruses produced by fish. Six fish choruses identified exhibited notable spatial and temporal patterns around Lizard Island from 2014 to 2016. Several choruses displayed high site fidelity, indicating that certain sites may represent important 'habitat hotspots' for fish species, such as fish spawning aggregations sites.

The choruses displayed a broad range of periodicities, from diel to annual. This information provides new insights into the ecology of vocalising fish species and the surrounding reef ecosystem. All choruses were affected by one or more environmental variables including temperature and moonlight, the latter of which had a significant influence on the timing and received levels.

Results from this work highlight the application of passive acoustic monitoring (PAM) for long-term monitoring of coral reefs. This is highly relevant following recent extensive global disturbance events, particularly coral bleaching.

Chapter 4

Lost in the noise? Anthropogenic activity around Lizard Island in the Great Barrier Reef

The low attenuation of low frequency (<100 Hz) sound in water causes the marine environment to be susceptible to large introductions of acoustic energy. Consequently, the contribution and subsequent impacts that anthropogenic noise may have in marine ecosystems, particularly in coral reefs, has gained substantial attention in the last decade. This study identified that vessels (commercial, recreational and research) are the key sources of anthropogenic noise in coral reef soundscapes around Lizard Island. Significant spatial differences in research vessel activity were present around Lizard Island, which led to several vessel traffic hotspots in areas of high activity. Daily activity of commercial vessels was similar throughout the year, but a notable rise in recreational vessel density occurred during the start of the austral wet season, which coincides with peak biophonic activity in the form of fish choruses. Noise from commercial vessels raised sound levels at lower frequencies at all field sites except the sheltered Lagoon site. The long-term noise contributions of research vessels were not clearly visible at field sites with lower research traffic, but were apparent at sites that had high levels of research boat activity. With commercial ship numbers and size continuing to increase, it is expected that vessel noise will be a growing contributor to coral reef soundscapes. Combined climate change related stressors, this is likely to be an important additional threat to coral ecosystems.

4.1 Introduction

Sound is an integral component of the marine environment and one of key transmitters of information (Cotter, 2008). The properties of water enable sound at certain frequencies and in certain environments to travel long distances, (e.g. McCauley et al. [2001] calculated around 1 km for several fish calls) resulting in acoustic connection between underwater habitats at greater ranges than the equivalent on land. Many marine organisms rely on underwater acoustics as one of their primary sensory modalities for navigating their habitat, foraging and reproduction (Mann and Lobel, 1997; Hawkins and Amorim, 2000; McCauley and Cato, 2000; Popper et al., 2003; Buscaino et al., 2011; Leis et al., 2011; van Opzeeland and Slabbekoorn, 2012). Underwater sound is capable of conveying information about both habitat location and environmental quality (Kingsford et al., 2002; Montgomery et al., 2006; Radford et al., 2010) and may play an important role in the settlement stages of reef fish and other marine larvae (Simpson et al., 2005; Montgomery et al., 2006).

Coral reef soundscapes exhibit characteristic and diverse biophonies, where the main sources of biological sounds are vocalising fish, cetaceans and soniferous invertebrates, notably the snapping shrimp (Kennedy et al., 2010; Kaplan et al., 2015; Nedelec et al., 2015; McWilliam et al., 2017). Wind, waves, precipitation, polar ice-breakup and subsea volcanoes and earthquakes are geophonic contributors. The third component of soundscapes is the anthropophony and refers to human-generated noise from vessels, fishing activity, seismic explorations and marine construction.

Over the last sixty years, substantial increases in acoustic energy generated from human activities have resulted in elevated ambient noise levels in many parts of the world oceans, particularly in localised areas near ports (McDonald et al., 2006). Consequently, the contribution and subsequent impacts that anthropogenic noise may have in marine ecosystems, particularly in coral reefs, has gained substantial attention in the last decade (Hawkins and Popper, 2016). This has resulted in its designation as a high research priority topic by the European Commission (Tasker et al., 2010) and listing as a threat in the Great Barrier Reef (GBR) 2050 Long-term Sustainability Plan (Australian Government and Queensland Government, 2015).

Considerable changes in soundscapes are likely to continue with the growth of global shipping. The associated increase in underwater noise represents a potential threat to marine environments and may have far-reaching effects and consequences, which are difficult to predict (Miller, 2008; Rountree et al., 2012). With the GBR and many reefs worldwide in a state of decline, there is a pressing requirement to investigate anthropogenic contributions to coral reefs to better understand the potential impacts before such expansion occurs (Hughes et al., 2017).

Short-term impacts may include:

- Habitat avoidance in killer whales (*Orcinus orca*) (Morton et al., 2002)

- Disorientation in beaked whales (family *Ziphiidae*) (Weilgart, 2007)
- Acoustic masking in marine mammals (Erbe et al., 2016c)
- Hearing loss and temporary threshold shift in grey and harbour seals *Halichoerus grypus*, *Phoca vitulina* (Jones et al., 2017), the fathead minnow, *Pimephales promelas* (Scholik, and Yan, 2002), brown meagre (*Sciena umbra*), Mediterranean damselfish (*Chromis chromis*) and red-mouthed goby (*Gobius cruentatus*) (Codarin et al., 2009)
- Noise-induced stress in fish (*Carassius auratus*) (Smith et al., 2004) and North Atlantic right whales (*Eubalaena glacialis*) (Rolland et al., 2012)
- Orientation in fish larvae (*Apogon doryssa*) (Holles et al., 2013)
- Habitat selection in bottlenose dolphins (genus *Tursiops*) (Allen et al., 2000)

Long-term impacts include:

- Increased susceptibility to predation in settlement stage larvae and juvenile reef fish (Simpson et al., 2016b)
- Reduced growth rates and egg viability in estuarine fish (*Cyprinodon variegatus* and *Fundulus similis*) (Banner and Hyatt, 1973)
- Decreased mate selection effectiveness in Lusitanian toadfish (*Halobatrachus didactylus*) (Vasconcelos et al., 2007)

However, extensive studies would need to be carried out to determine the proportion of species that may be affected by vessel noise due to the large range of hearing abilities in marine fauna, of which we have a limited understanding (Slabbekoorn et al., 2010; Hawkins and Popper, 2016).

Hearing abilities also need to be categorised in terms of sensitivity to acoustic pressure and particle motion, the other component of a sound wave. Throughout this chapter, the acoustic metric being studied is the sound pressure component of vessel noise. While not measured in this study, many marine organisms, particularly invertebrates and fish are sensitive to particle motion (Chapman and Hawkins, 1973; Chapman and Sand, 1974; Popper and Hawkins, 2018). Therefore, particle motion generated by vessels may have a significant impact on organisms that are sensitive to this kinetic energy, making this is a key area of research (Nedelec et al., 2016). Direct field-based measurements in open water are minimal mainly due to financial costs and limited availability of equipment. Hence, we have limited knowledge on what levels of particle motion organisms are exposed to and how these levels vary over different spatial and temporal scales. Therefore, to improve our understanding of particle motion, a number of experiments need to be conducted; including measuring hearing thresholds in fish and invertebrates, and long-term temporal measurements of particle motion around coral reefs (Horodysky et al., 2008).

Special consideration of the potential noise impacts should be taken into consideration in light of widespread and ongoing coral bleaching events across the GBR (Hughes et al., 2017). Much of

the GBR is currently in a critical state and its long-term future is uncertain following extensive damage from these disturbance events. The most recent five-yearly condition analysis of the GBR, released in August 2014, determined that its condition is poor and deteriorating, and that reductions in all stressors are required to improve its state (Hughes et al., 2015).

Apart from the noise generated by ships, the risk of other types of environmental pollution, such as large chemical spills or ship groundings, remains high and potential catastrophic risk in the event of (Marshall et al., 2002). Many of these ships, particularly bulk carriers and petroleum tankers, carry cargo that is considered a threat to marine ecosystems in the GBR. Anthropogenic noise from coastal development, particularly shipping ports, which require pile driving and dredging of the seabed, have been shown to produce significant levels of noise (Erbe, 2009; Bailey et al., 2010; Reine et al., 2014).

Recent scientific, public and political awareness in respect to the increase in coal mining and shipping along the GBR have raised concern regarding their potential effects on the reef (Hughes et al., 2005; Greenpeace Australia, 2012). Studies have discovered that water-borne pollutants can cause mortality and growth inhibition of tropical marine organisms including cetaceans, reef fish, coral and seagrass (Haynes et al., 2005; Berry et al., 2016).

4.2 Aim of study

The aim of this study is to determine the contribution of anthropogenic noise to the coral reef soundscape around Lizard Island and to address the following questions:

1. What are the key sources of anthropogenic noise and how do they change over space and time?
2. How do these inputs alter the soundscape and what are future contributions likely to be?

4.3 Methodology

4.3.1 Study area

Situated within the World Heritage listed GBR, Lizard Island is located 270 km north of Cairns, around 30 km off the coast (14°40.88'S, 145°27.82'E). Three other smaller islands: Palfrey, South Island and Bird Island are situated close to Lizard Island and together they constitute the Lizard Island Group (Fig. 4.1). The three smaller islands are bordered by coral reef and a fine belt of fringing reef encompasses much of the main island.

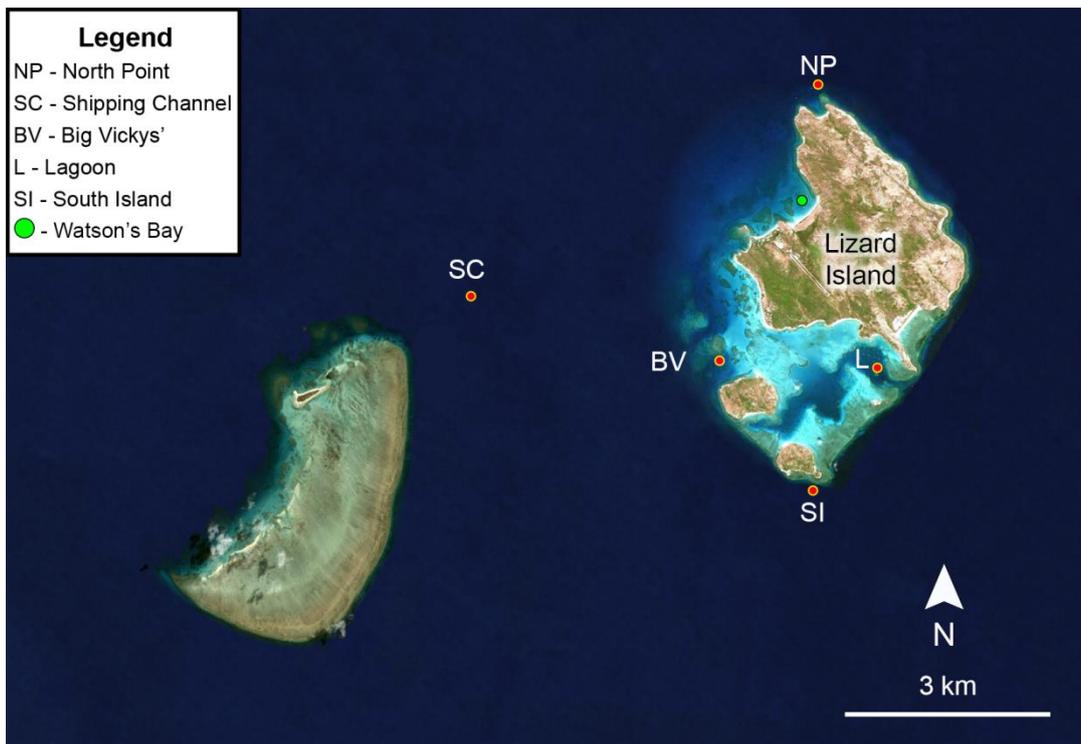


Figure 4.1 Locations of field sites around Lizard Island.

A more extensive area of reef surrounds the Blue Lagoon situated between Lizard and South Island. Water depths around the island rarely exceed 30 m and within the lagoon this drops to a maximum of 12 m. (Leon et al., 2013). Tidal range around Lizard is ± 3 m. Current speeds fluctuate around the group of islands, with the lagoon entrances and North Point promontory experiencing current speeds that can exceed 30 cm/s during tidal cycles (Frith et al., 1986).

From April to September, the island is subjected to south-easterly trade winds with maximum monthly wind speeds averaging 42 km/h for this period (Frith et al., 1986). In the last months of the year, winds decline greatly, averaging 28 km/h and become more directionally variable. November and December are generally the calmest months of the year and hence, the most popular time for recreational boating.

4.3.2 Data collection

Sequences of underwater sound recordings were collected around Lizard Island from five field sites between 2014 and 2016 (Fig. 4.1). Recordings were obtained using SoundTrap 202 (Ocean Instruments, New Zealand) digital sound recorders with a 48 ksps sample rate (manufacturer's specifications of a flat response within ± 3 dB between 20 Hz and 60 kHz) and an underwater sound recorder (USR) [developed by the Centre for Marine Science and Technology (CMST) at Curtin University and the Defence Science and Technology Organisation] with a calibrated omnidirectional, HTI 96-min hydrophone (HighTech Inc., MS, USA) programmed with a 18 ksps sample rate, was deployed at the Shipping Channel site. The USR was set to record for 180s every 900s, giving a duty cycle of 20%.

The USR was deployed using a research station vessel. The recorder was lowered to the seafloor by a rope pulley system, followed by a 100 m rope line with a 60 kg sacrificial dump weight. This was done to minimise extraneous noise and provide a contingency retrieval mechanism. An acoustic release and a series of sub-surface buoys were attached to the dump-weights to allow surface-based retrieval of the recorder.

Each device was piston-phone calibrated with a known level of 121 dB re 1 μ Pa at 250 Hz by the manufacturer, while the USR was calibrated with a white noise generator at -90 dB re 1 V^2 /Hz. Recorders' clocks were manually programmed to Australian Eastern Standard Time (AEST). For each successive deployment, a Garmin 60Csx GPS unit and a computer with internet connection were employed to ensure SoundTrap clock accuracy to within 1 s. Field recording sites were chosen to be representative of Lizard Island's various seascapes. Site locations were recorded with a Garmin 60Csx GPS, accurate to ± 3 m.

Sound recorders were secured to weighted mounts and diver-deployed to the seabed on sandy substrates, at a minimum distance of 3 m from coral reef. Devices were collected and redeployed on a 10-14 day cycle for downloading data and battery recharge. A second SoundTrap was deployed about 5 minutes prior to retrieval of the first SoundTrap to ensure adequate cross-over time. Spectrograms of the overlapping *.wav files were visually and audibly scrutinised to define an appropriate cross-over point in SoundTrap wav files, i.e., where diver and handling noise was diminished. To assist equipment relocation in turbid conditions, a sub-surface marker composed of two concrete breeze blocks and a rope attached to a sub-surface buoy were positioned about 5 m from each SoundTrap.

4.3.3 Audio analysis

Acoustic datasets were analysed using a combination of audio inspection of recordings and long-term spectrogram visual analysis. Calibrated power spectral density (PSD) averages were computed over 300 s windows and joined chronologically to create long-term spectrograms with time on the x-axis and frequency on the y-axis, with colour representing power. A Graphical User Interface (GUI) toolbox, CHaracterisation Of Recorded Underwater Sound (CHORUS; Gavrilov & Parsons 2014) was used to display and inspect the spectrograms in the MATLAB software environment (The Mathworks Inc., Boston, MA). CHORUS was designed to analyse long-term underwater sound recordings. The GUI allows the user to adjust the spectrogram from a single day to several months. Local sunrise and sunset times (when the upper edge of the sun's disk touches the horizon) were determined with a custom MATLAB routine, which utilises an algorithm developed from expressions by Dogget et al. (1978).

4.3.4 Anthropogenic sources

Ship, boat and aircraft noise underwater was identified by audio and visual inspection of spectrograms and comparison of the detected acoustic signatures with previous studies on this

subject (Buckingham et al., 2002; Hildebrand, 2009; MacGillivray et al., 2014; Merchant et al., 2014; Erbe et al., 2016a). Ships were defined as vessels large enough to log AIS data; whereas boats were defined as small personal and local research vessels that don't go far offshore and don't normally log AIS. The exact identity of aircraft was further confirmed by matching the aircraft flyover time with the arrival and departure times of the passenger planes used to access the research station and the Lizard Island Resort. Ship and boat activity was measured using the following procedures: vessel acoustic footprints counts, GPS tracking of research vessels, Automatic Identification System (AIS) data analysis and hotspot spatial analysis combined with heatmaps.

4.3.4.1 Vessel counts

Daily vessels counts using specific selection criteria (signal duration >180 s and sustained level > 100 dB re 1 μ Pa) were manually counted at each long-term field site through visual and audible inspection of recordings using the CHORUS GUI.

4.3.4.2 GPS and AIS tracking

From October to December 2015, Holux RCV-3000 GPS loggers (Holux Technology Inc.) were used to track movements of research boats around Lizard Island. Research boats consisted of; 1) up to twelve 5 m metal dinghies fitted with 30 hp 2 stroke engines; 2) two 6 m centre-console boats, each with a 90 hp motor; and; 3) a 6 m catamaran with twin 90 hp motors. GPS units were stored in a clear, waterproof plastic box and attached to each boat every morning. Units were positioned on-board to provide maximum satellite cover (i.e., an open sky view). Loggers were set to record a position at a minimum 10 s interval in order to capture fine-scale movement of the boat. Usage of all boats varied on a daily basis, though nearly all were active from October to December, which are the busiest months of the year for field research. GPS data were downloaded and batteries were recharged each night and redeployed the subsequent morning. The following parameters were extracted from the GPS track data:

Boat_ID	Date and Time	Latitude	Longitude	Speed (km/h)
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For all other vessels equipped with AIS receivers, AIS data recorded during periods of sound recordings were downloaded from the Australian Maritime Safety Authority (AMSA) website (<https://www.operations.amsa.gov.au>). Datasets contained the following information:

Craft_ID	Timestamp	Latitude	Longitude	Speed (knots)	Course	Vessel Type	Length (m)	Draught (m)
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4.3.4.3 Heatmap (analysis parameters)

Hotspots of boat activity (i.e., areas with high occurrence of vessel GPS points) were determined by running a Hot-spot Getis Ord analysis in arcMap 9.3 and creating a heatmap from Holux GPS point data. GPS point data were uploaded and processed in the open-source geographic information system (GIS) QuantumGIS (QGIS). GPS points that fell outside a pre-defined speed range (5-50 km/h) were filtered to exclude static boats and erroneous points. Point data were converted to a raster (GeoTIFF) using the Heatmap plugin, which employs Kernel Density Estimation to create a density raster from the point data.

The Heatmap plugin calculates the magnitude per unit area of point features using a kernel density function. The actual point density pixel-value is a measure of how many points from the source layer are contained within the specified radius around the pixel. To capture fine scale spatial patterns in small boat activity a radius of 50 layer units was used. For the AIS heatmaps, spread over a larger area and at a lower density, a coarser radius of 100 was selected. Layer units are a function of distance measured in degrees (using the WGS84 geodetic coordinate system).

A Quartic (biweight) Kernel with a boat speed weighting was used to highlight areas with increased boat activity. The subsequent heatmap was then projected onto a satellite image of Lizard Island. This method was repeated for generating heatmaps of AIS data recorded during the same periods that sound recordings were being made.

4.3.4.4 Field site boat activity

Boat density around the field sites was calculated using custom developed code in MATLAB and the QGIS spatial analysis toolbox. Individual research boat acoustic footprints were first analysed in order to identify overlapping boat GPS tracks and acoustic recordings. The range (m) and broadband received levels of selected research boats were matched in time (vessel track interpolated at time of broadband sound recording) and then plotted. Broadband measures were derived using 2 s power spectral averages and summing power above 20 Hz (the system roll-off). See Figure 4.2. Boat spectrograms and recordings from each field site were then analysed to determine the distance at which an approaching boat could be first detected above ambient noise levels. Due to the bathymetric differences between field sites, two detection distances (300 m and 1000 m) were chosen. Therefore, any research boats that came within 300 or 1000 m of each field site were identified and selected.

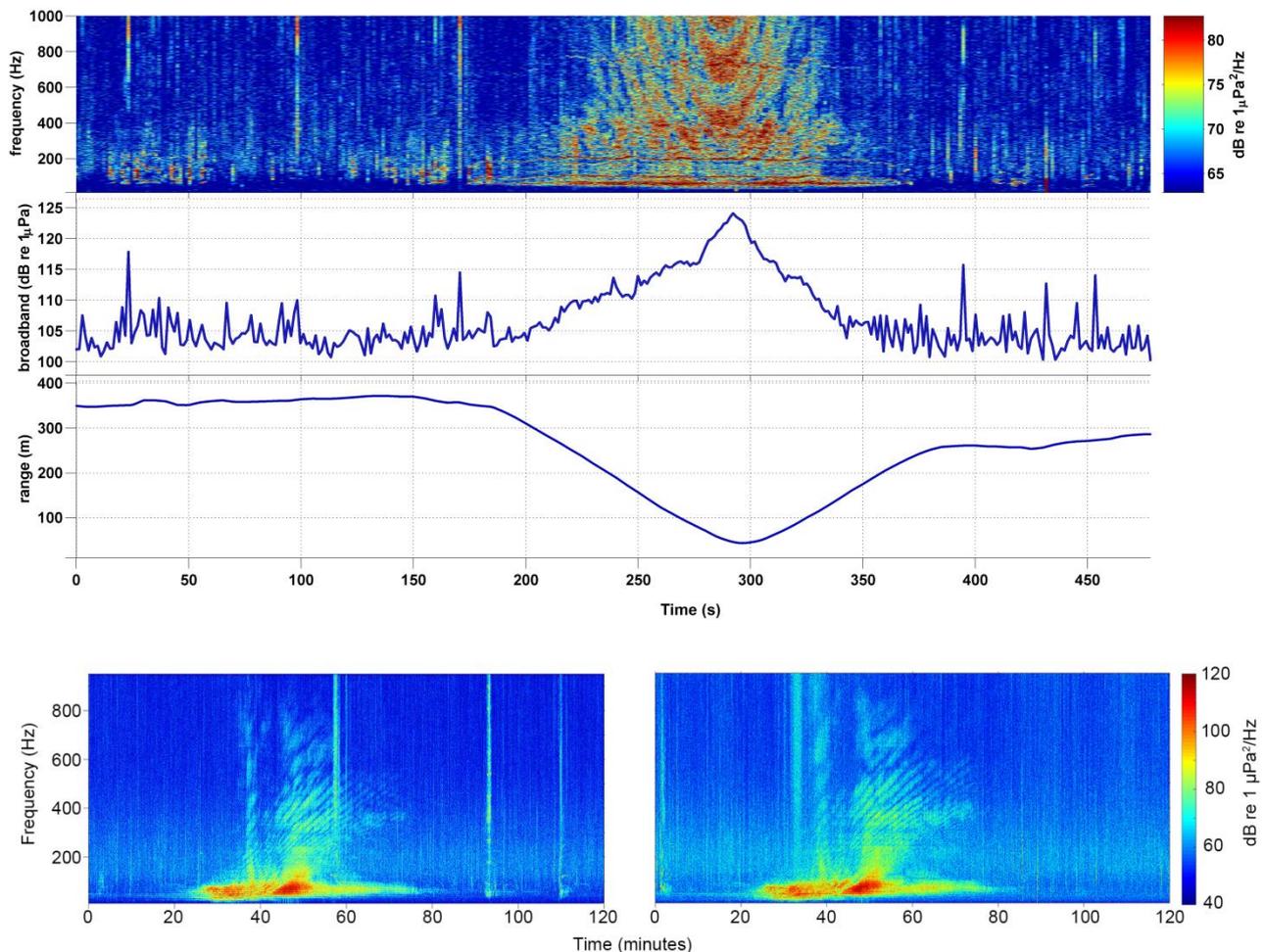


Figure 4.2 The range and broadband received levels of a research boat (top) and examples of two ship acoustic footprints (bottom).

4.3.4.5 Anthropogenic soundscape contributions

Thirty individual vessel passes (180-s window) were selected from audio recordings taken at the shipping channel field site. Sample wav files were combined and PSD percentiles and probability density were computed (see Merchant et al. [2013]; Erbe et al. [2016a] for more details on PSD percentiles with probability density). This procedure was then carried out for small research vessels, where the sampling duration was reduced to two seconds to reflect the acute (short) noise profile of the smaller vessels passing over the hydrophone. Vessel passes were recorded at the same depth and location to reduce variation.

Anthropogenic contributions to reef soundscapes were estimated by calculating PSD percentiles and probability density for five of the field sites with three months of continuous sound recordings. The median level PSD percentiles from the small and large vessel passes were selected and combined in a single plot for comparison.

4.3.4.6 Future shipping growth

Future predictions of shipping growth around the GBR were estimated using data from the GBR and Torres Strait Vessel Traffic Service (REEFVTS available at <https://www.amsa.gov.au>). Counts of individual vessels within the GBR area from 2006 to 2016 were used to calculate compound annual growth rate in shipping (Fig. 4.3). Decadal growth in vessel traffic was categorised into vessel types. The five most common vessel types were selected and average annual gross tonnage and numbers of vessels were calculated for each type. Total vessel growth until 2025 was estimated with 10 years of vessel count data (2006–2016) using linear regression ($r = 0.89$).

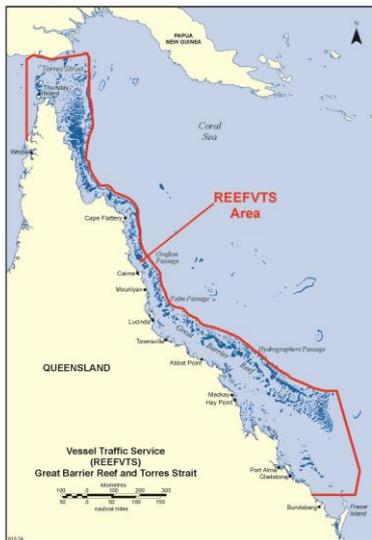


Figure 4.3 Defined REEFVTS survey area for monitoring vessel traffic along the GBR.

4.4 Results

4.4.1 Anthropogenic sources

Several anthropogenic sources were identified from audio recordings taken at field sites around Lizard Island, including small boats (Fig. 4.4 [A & D]), large vessels (Fig. 4.4 [B]) and light aircraft (Fig. 4.4 [C]). Research boats were recorded at all long-term field sites. Large vessels (>100 m length) were confined to the shipping channel west of Lizard Island. Acoustic footprints of large vessels were some of the most prominent soundscape features at the SC site, with received broadband levels of large boats exceeding 150 dB re 1 μ Pa. Aircraft noise from light aircraft (Cessna single and twin-prop models) used as the main aerial transportation mode to and from the island was also present in the reef soundscape.

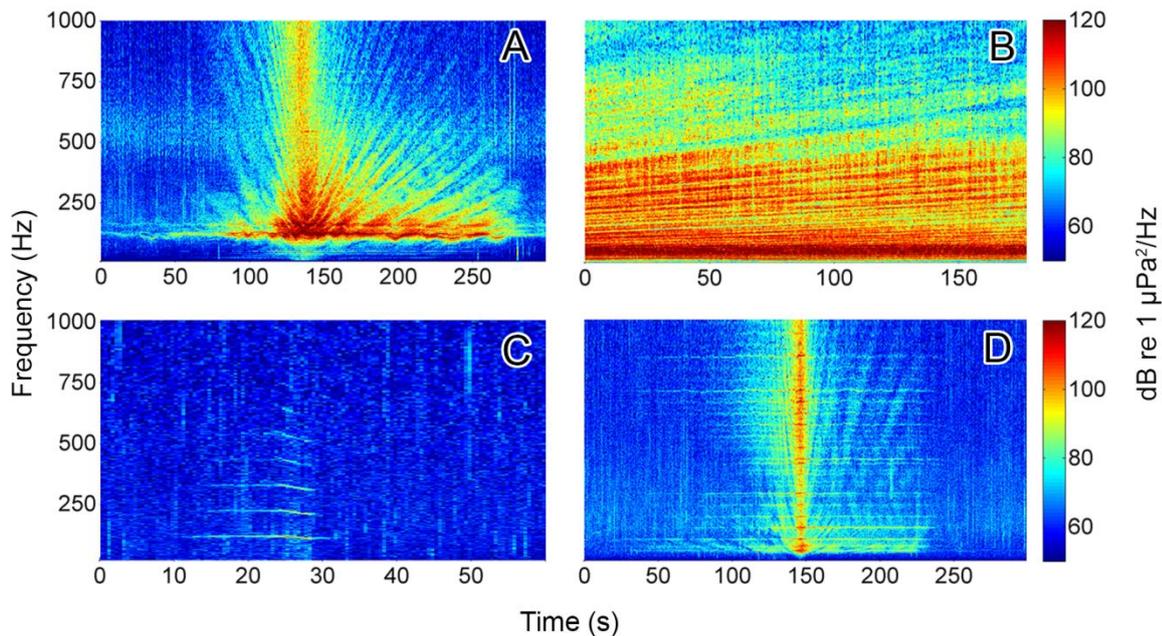


Figure 4.4 Spectrograms of anthropogenic sources in the coral reef soundscape around Lizard Island (1 s Hanning window, 50% overlap). (A) Small boat, (B) Large commercial vessel, (C) Light aircraft, (D) Research dinghy.

4.4.2 Vessel activity

Movements of large commercial vessels were predominantly confined to the shipping lane on the west side of Lizard Island, with very limited traffic on the east side of Lizard (Fig. 4.6). Recreational and private craft activity was significantly clustered around Watson's Bay, the main mooring location that provides access to the island's resort.

Spatial variation in research vessel traffic shifts considerably around the island, with statistically significant hot spots of activity concentrated around the research station mooring area and surrounding boat pathways used to navigate through the reef (Fig. 4.6). Research boat activity (for 300 and 1000 m search distance criteria) was highest at BV and lowest at SC (Table 4.1). LG was the second busiest area, where research vessels exhibited the highest average speed of all the sites after SC. NP and SI experienced much lower levels of research boat activity, due to their remote and exposed location. The opposite, windward side of the island experienced limited research and recreational boat activity and no large commercial vessel traffic, e.g. cargo ships or tankers.

4.4.2.1 Temporal variation

Research boat traffic, like most recreational vessel activity, was confined to daylight hours, unlike larger commercial vessels, which were active during a full 24-hour cycle. Annual peak vessel activity of AIS transmitting ships was in the 'tourist summer' months (October – December), accounting for 38 % of the annual vessel traffic. These patterns are observed in the AIS data heat-maps (Fig. 4.6), showing activity concentrated within the shipping lane. From October to December

2015, a clearly visible hotspot of small vessel activity was concentrated at the mooring area close to the Lizard Island Resort.

4.4.3 Boat noise: anthropogenic contribution to coral reef soundscapes

4.4.3.1 Shipping

With the exception of LG, noise profiles of large vessels were recorded at all long-term field sites across daily, weekly and monthly scales, even though the routes of most ships were confined to the shipping channel west of Lizard Island. Activity was highest at SC followed by BV, SI and then NP (Table 4.1). Noise generated by large vessels was predominantly concentrated at lower frequencies, below 100 Hz (Fig. 4.2). Ship generated noise forms strong peaks in energy below 100 Hz in the long-term PSD percentile plots and reflects the substantial contribution of large ship noise to soundscapes around the field site (Fig. 4.7). In contrast, LG had much lower PSD values at these lower frequencies (between 10 and 20 dB) compared to the other locations and it had much weaker peaks, which may reflect the limited contribution of ship noise to the site. Strong similarities between the frequencies of peaks in the long-term PSD percentiles and ship noise PSD median percentiles were apparent at NP, BV and, in particular, SI (Fig. 4.7). This provides further evidence that ships are a key low-frequency contributor to reef soundscapes around Lizard Island.

The contribution of small research boats can be seen at BV and LG, with the latter displaying similar peaks to the small boat median PSD percentile at approximately 95, 180, 285 and 1000 Hz. These peaks are mostly in the 1st percentiles, but extend down to the 5th percentile at LG, demonstrating that small boats have a short, but prominent presence at these sites. However, similar frequency peaks are not seen in the NP and SI plots, indicating that the research boats do not appear to sustain any notable long-term presence here.

Long-term PSD percentiles also displayed the contribution of several biological sources, including fish choruses and snapping shrimp snaps at several of the field sites. Fish choruses elevate the surrounding background noise levels between 500 and 800 Hz over 50% of the recording time at NP and SI, the latter to a lesser degree (Fig. 4.7). A suspected fish chorus peak can also be seen at 600 Hz at BV and LG. A peak between 2 and 3 kHz originating from snapping shrimp can be seen at BV (Fig. 4.7).

4.4.3.2 Aircraft

Compared to the vessel footprints, the acoustic footprint of aircraft was brief, usually lasting a maximum of 20 s when the aircraft's flight path was in close proximity to LG (Fig 4.5).



Figure 4.5 Aircraft flight paths for take-off and landing from Lizard Island. LG site (red dot).

Table 4.1 Summary statistics of large ship and small boat activity around Lizard Island field sites.

Ships							
Site	Count	Ships / day	Start	End			
NP	64	0.80	Sep 15	Dec 15			
SC	400*	1.86	Dec 14	Jul 15			
BV	109	1.36	Sep 15	Dec 15			
LG	0	0	Sep 15	Dec 15			
SI	62	0.86	Sep 15	Dec 15			

Boats							
Site	Count	Boats / day	Average speed (km/h)	Radius 1000 m			
				Count	Boats	Average speed (km/h)	
NP	1730	0.70	15.1 ± 9.1	5166	1.02	17.3 ± 9.6	
SC	26	0.11	41.7 ± 6.1	127	0.12	39.1 ± 7.9	
BV	3206	2.74	16.7 ± 8.9	41403	7.58	14.5 ± 8.6	
LG	3237	1.47	23 ± 7.9	15904	3.56	21.3 ± 8.5	
SI	205	0.23	16 ± 7.7	687	0.39	18.1 ± 8.3	

* Duty cycle (180 s every 900 s) † individual GPS points ^ ± standard deviation

Table 4.2 Summary statistics for Holux GPS boat and AIS vessel tracks.

Tracks	Start date	End date	Total count	Unique boat tracks	Average boat speeds (km/h)
Holux	Oct 15	Dec 15	98054	436	18 ± 7.1
AIS	Jan 15	Dec 15	1248	378	9.9 ± 4.8
AIS	Oct 15	Dec 15	470	159	8.5 ± 5.5
AIS	Dec 14	Jul 15	578	228	10.9 ± 4.0

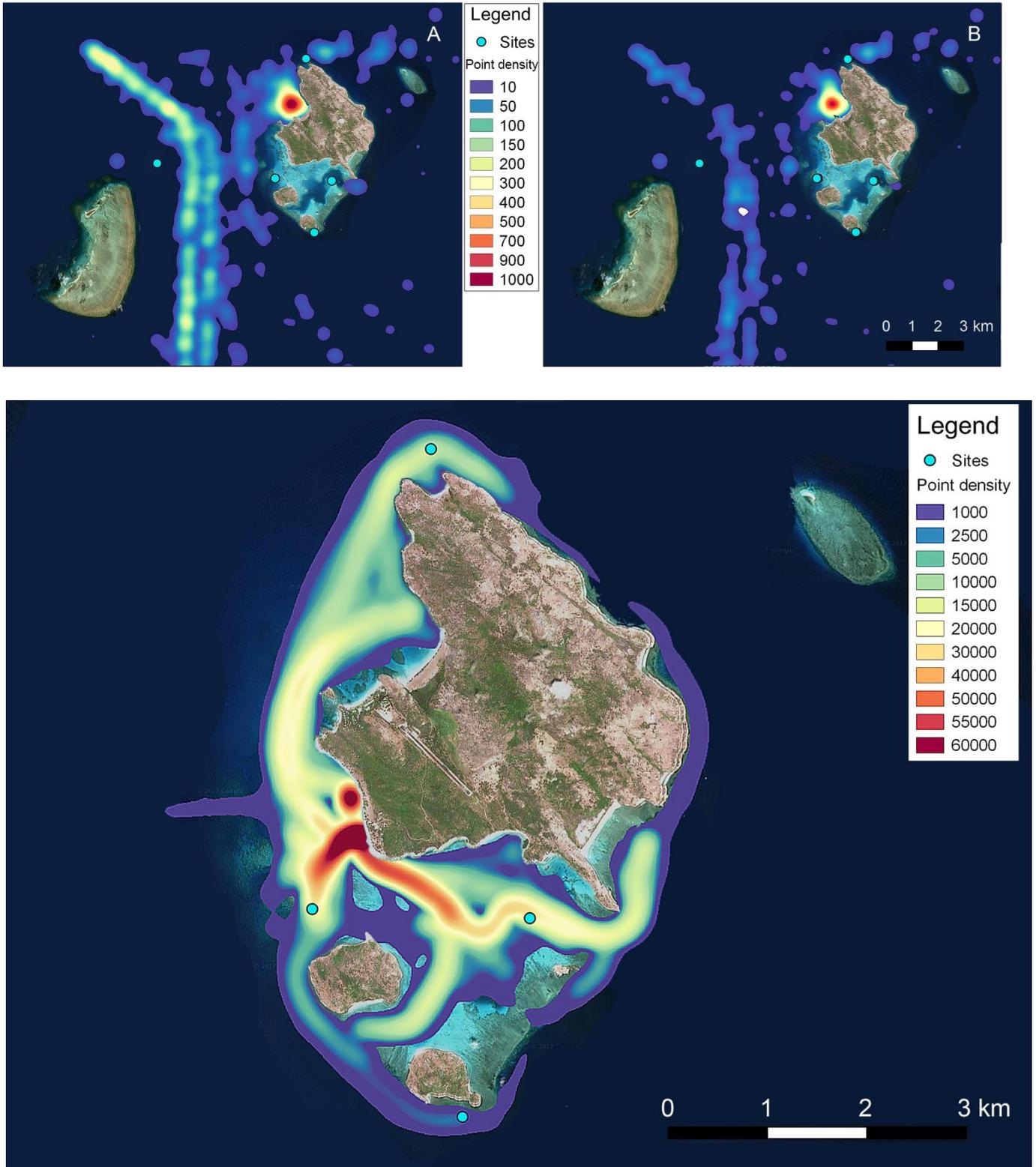


Figure 4.6 Point density heatmaps of AIS counts from December 2014 to July 2015 (A), October to December 2015 (B) and research boat GPS track counts around Lizard Island from October to December 2015 (C).

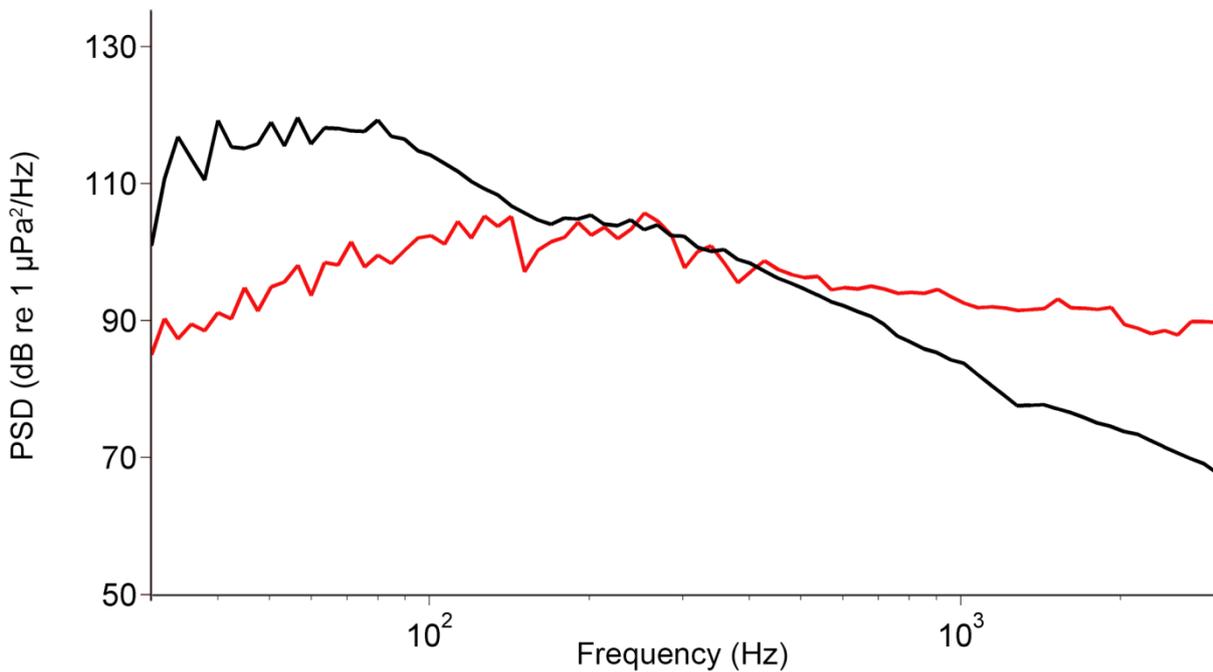
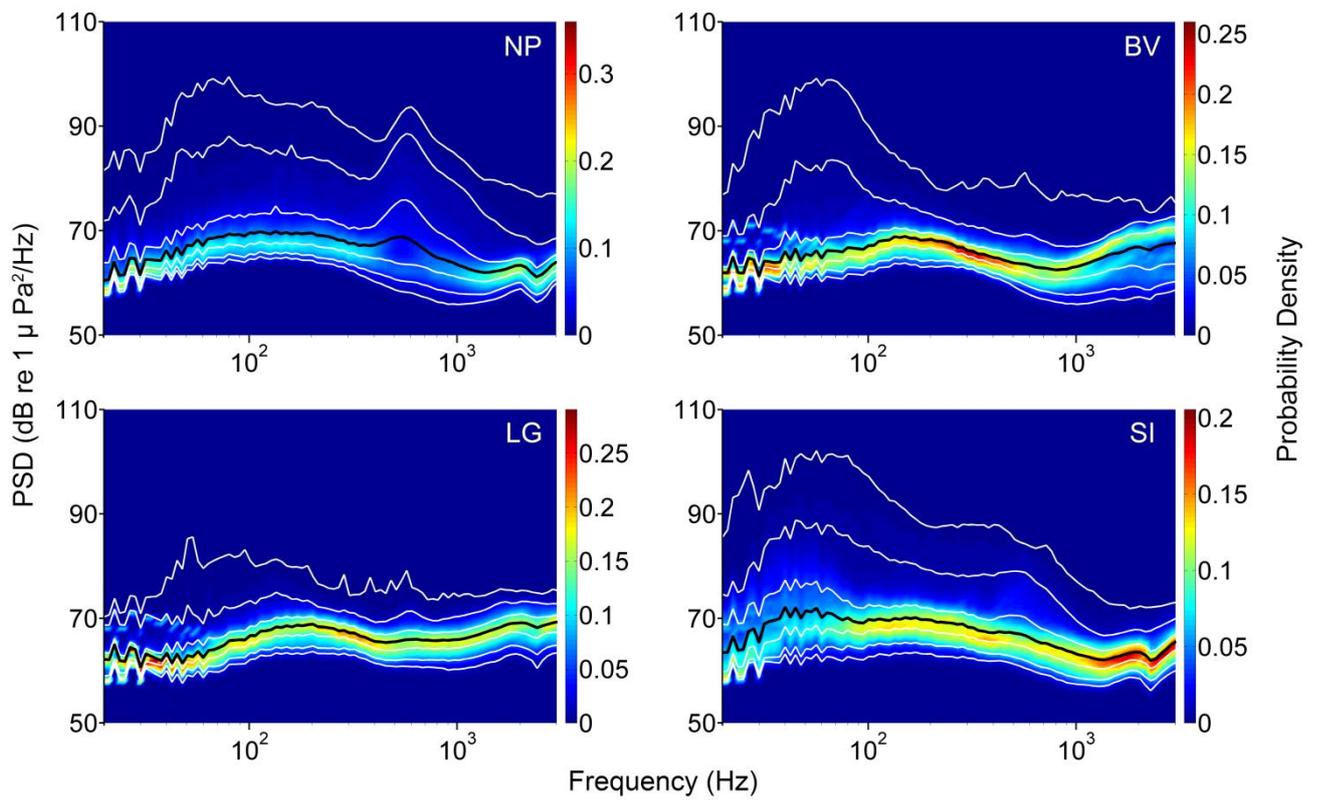


Figure 4.7 (Top) PSD percentiles (bottom up: 1, 5, 25, 75, 95 and 99th displayed as white lines; 50th shown as black lines with probability density of PSD levels shown in colour bands. Each plot was calculated from ≈ 3 months of continuous recordings at four sites around Lizard Island, Sep – Dec 2015. (Bottom) Median PSD percentiles of large ships (red line) and small boats (green line).

4.4.4 Anthropogenic masking events

Fish choruses appear to constitute a core part of the soundscape around Lizard Island yet, potential masking of these acoustic events by passing large vessels was observed on a number of occasions, for periods exceeding 1 hour (Fig. 4.8). This was observed more commonly for choruses with power focussed in the lower frequencies (e.g., Chorus VI) [see McWilliam et al., 2017 for fish chorus details]. On some occasions, over 20 large commercial vessels passed through the shipping lane on a single day. This number and shipping traffic in general is predicted to increase in the GBR (GBRMPA, 2013) (Fig. 4.9).

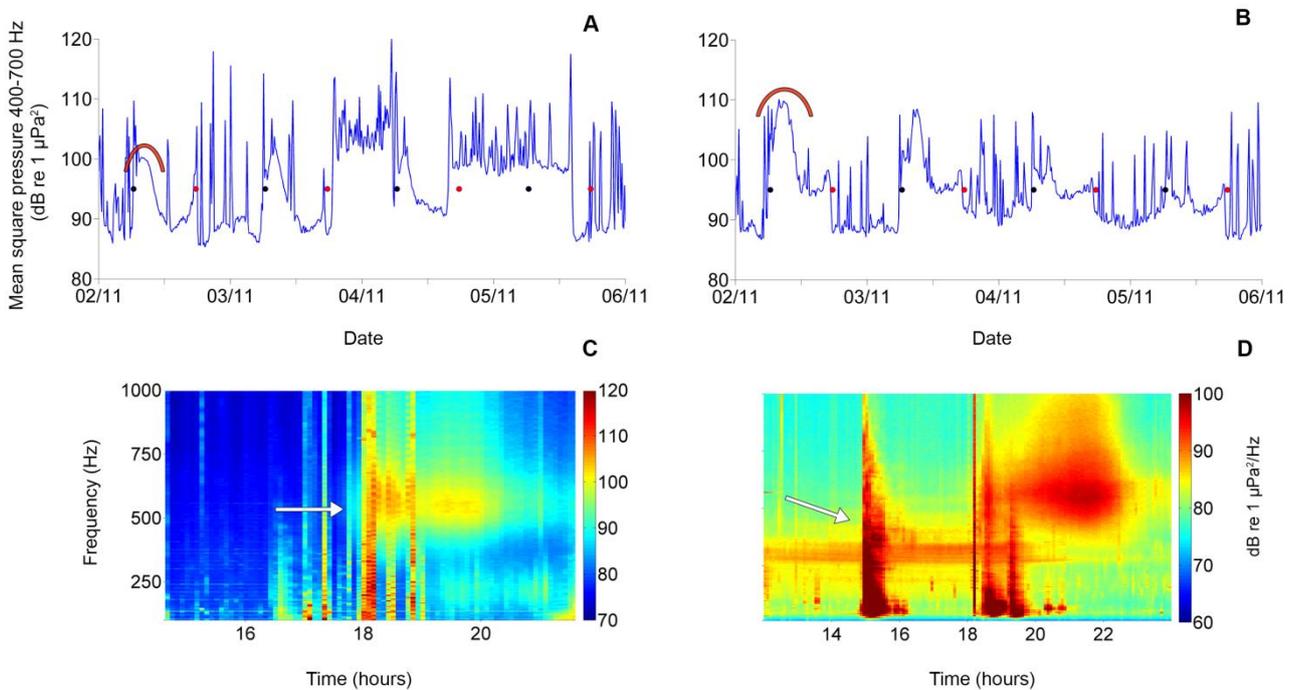


Figure 4.8 Examples of masking of Chorus I at different sites (A+B) and two different fish choruses (arrows) at North Point (C) and South Island (D), colours are PSD [dB re 1 $\mu\text{Pa}^2/\text{Hz}$]. Red crescents indicate a fish chorus. Sunset (black circle) and sunrise (red dot).

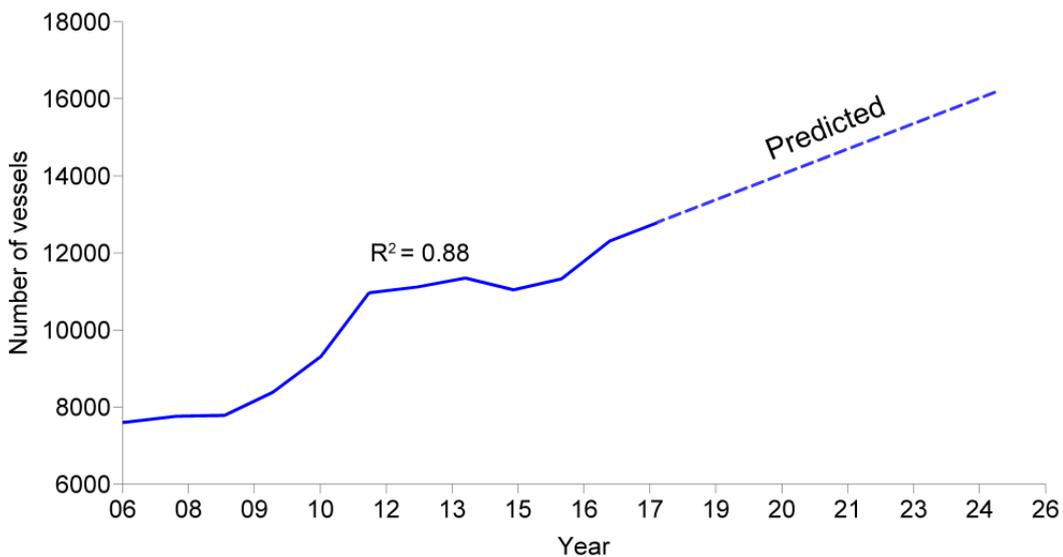
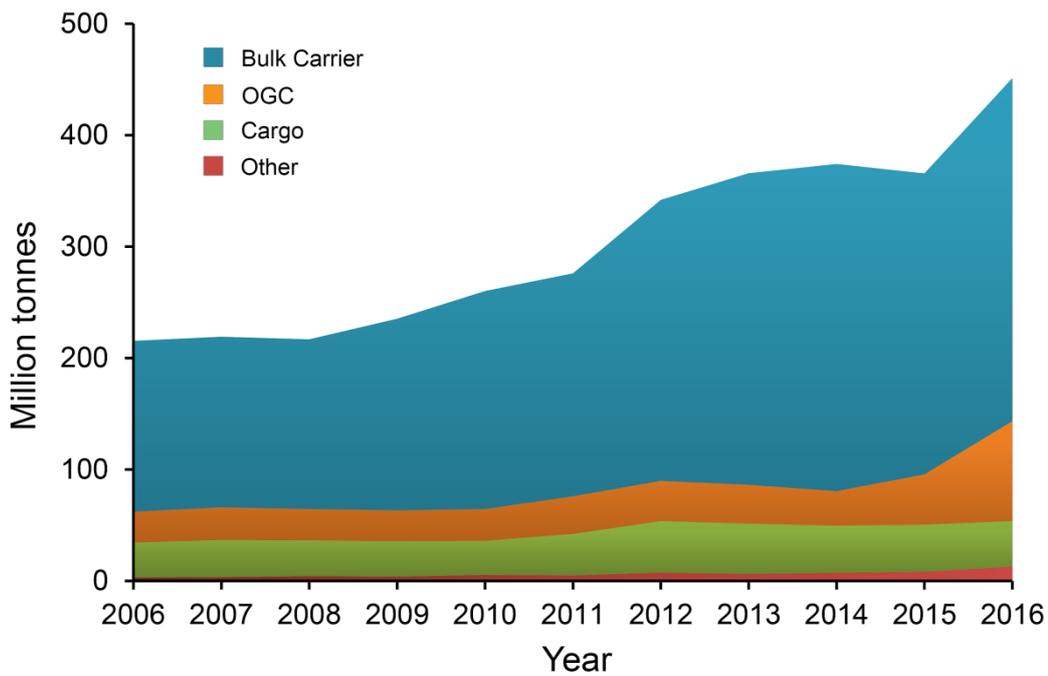


Figure 4.9 Expansion of GBR shipping activity over a 10-year period (top) and approximate predicted future growth (bottom). Shipping tonnages within the GBR, based on AIS data from 2006–2016 (downloaded from REEFVTS database). The categories are: a) cargo (container ships, livestock, car carriers, general cargo); b) bulk carriers (coal, grain, etc.); c) oil, gas or chemical (OGC); and d) other shipping (small commercial vessels, fishing, yacht, passenger, defence, research, etc.).

4.5 Discussion

4.5.1 Key sources of anthropogenic noise

Large commercial ships were the primary anthropogenic contributors to soundscapes around Lizard Island. Due to their combined level and duration (exceeding 1 h) passing ships featured prominently, particularly at field sites closest to the shipping lane on the west side of the island. In 2015, there was constant large vessel activity each month over the full 12-month period, reflecting their 'round-the-clock' anthropogenic presence. Despite having a shipping lane in close proximity, ship activity around Lizard Island can be considered to be relatively low compared to other areas of the Reef that are located closer to larger shipping ports. As a comparison, in 2014/15, commercial vessel stopping in port at Cape Flattery (30 km WSW of Lizard Island) totalled 40, which is less than 3% of Gladstone port calls (data obtained from www.portsaustralia.com.au). Apart from the distance from large shipping ports, the low vessel traffic can also be explained by more ships using a second shipping route, further inland to the west of Eagle Island.

4.5.1.1 Aircraft

An often overlooked source of anthropogenic noise in the marine environment is aircraft. Aircraft noise was routinely recorded at the LG site, which lies below the flight path for landing and take-off from the island's small airstrip. With a few exceptions, the effect of this acute contribution of power underwater on marine fauna remains largely unknown and in general has been limited to tanks with playback of sounds rather than the study of actual aircraft flyovers (Rucker, 1973; Mancini et al., 1988).

4.5.1.1 Research boats

Research boats were a notable anthropogenic contributor to reef soundscapes at sites with higher boat traffic, specifically at the LG and BV. Approaching boats in the lagoon were detected up to a 300 m range, showing that the radius of influence from boat noise is substantial, in relation to the size of the lagoon. One of the main drivers behind spatial variation in research vessel activity around Lizard is site accessibility. Sheltered sites, which are close to the station and easy to access, are preferred areas for researchers, particularly when conducting repetitive and prolonged field work that requires multiple boat trips each day. Sheltered sites also afford a level of protection during inclement weather periods. During these periods, remote and exposed sites are visited far less frequently. The designated mooring area at Watson's Bay (Fig. 4.1) strongly influences traffic patterns around Lizard Island for recreational and private vessels, as does the shipping lane for large commercial vessels, whose draught (>10 m) physically restricts the craft from other areas around Lizard Island.

The austral 'tourist summer' period is the busiest time for recreational and research boating activity due to the calm weather conditions and the increased biological activity of many marine organisms of research interest. In comparison with commercial vessels, the significant level of research boat activity during these months appears to be an acute rather than chronic contributor to the soundscape. This peak in anthropogenic activity also coincides with the main peak in biological activity, particularly spawning for hundreds, if not thousands of reef species (Harrison et al., 1984; Almany et al., 1997). Boat noise can adversely affect territorial behaviour of sonic fishes, such as nesting damselfish *Chromis chromis* (Picciulin et al., 2010) and territorial gobies *Gobius cruentatus* (Sebastianutto et al., 2011). Two studies have found evidence that the level of impact that boat noise has on fishes may vary depending on engine type. Decreased boldness and response to alarm cues was observed in juvenile damselfish exposed to 30 hp 2-stroke outboard motors, compared to minor responses when exposed to 30 hp 4-stroke outboard motors (McCormick et al., 2018). A significant increase in the heart rates of staghorn damselfish *Amblyglyphidodon curacao* embryos, was observed in the presence of boat noise, with 2-stroke powered boats having twice the effect on heart rates compared to 4-stroke powered boats (Jain-Schlaepfer et al., 2018). Consequently, the potential impact of small boats on marine biota should not be underestimated, particularly in areas of high levels of vessel traffic that lie very close to areas of coral reef (Simpson et al., 2016a). Determining the extent of impacts is an important but complex and challenging task and will require significant field-based research to accomplish.

4.5.2 Future contributions, vessel growth and ship noise

Over a 10-year period from 2006 to 2016, the number of vessels travelling within the GBR increased by over 43%. By 2026, this number is predicted to reach over 16,000 per year, double the number compared to 2006, based on a linear regression over the years 2006–2016. The average carrying capacity of vessels (gross tonnage) has also steadily increased over the years. Larger vessels typically have bigger propellers and engine size, which at higher speeds, are capable of generating much higher noise levels, but shorter periods of exposure (McKenna et al., 2012). While sound exposure from individual vessels at any one specific site might be reduced if vessels go faster, the cumulative noise emission in the oceans is going to increase.

The distinct fish choruses around Lizard Island appear to be a significant and integral part of the coral reef soundscape (McWilliam et al., 2017). With considerable vessel growth predicted, the instances of masking and prolonged boat noise contributing to the reef soundscape are likely to rise considerably. Biological activity is governed by natural rhythms and organisms have evolved to harmonise with these. Anthropogenic activity in the terrestrial and marine environment is ubiquitous and constant. How increased anthropogenic noise will affect coral reefs, particularly in the long-term remains uncertain as there are still large gaps in our knowledge regarding the potential impact of noise exposure in the marine environment (Hawkins and Popper, 2016).

However, a growing body of research has found preliminary evidence that boat noise can negatively impact marine fauna across a range of taxa, scales and severities.

4.5.3 Ecological implications and research significance

The continued growth of human activity in the marine environment has developed a pressing requirement to investigate potential impacts to coral reef ecosystems. An increase in human generated sound energy in the world's oceans may be causing damage to many marine ecosystems (Nowacek et al., 2007; Codarin et al., 2009). Masking of important acoustic cues resulting from human induced soundscape fragmentation could threaten community-scale life processes on both short and long-term time scales (Cato, 1992; Slabbekoorn and Halfwek, 2009; Slabbekoorn et al., 2010; Codarin et al., 2012; Parsons et al., 2012; Stanley et al., 2012). This is particularly poignant in light of industrial development along the GBR combined with the recent and ongoing bleaching that has caused severe mortality of many corals across the entire length of the reef (over 2300 km) (Hughes et al., 2017).

Passive acoustic monitoring (PAM) shows promise as a complementary method for long-term survey of coral reefs. Hotspots of boat activity determined with PAM have cross-disciplinary application, particularly for population disturbance studies as they are an important variable to consider in animal observational studies. For example, do resident fish living on coral reef, that are exposed to higher levels of boat traffic, have different behaviours and potential physiological abilities to individuals inhabiting reef in quiet, low-traffic areas?

The utility of soundscape characteristics and indicators such as Acoustic Complexity Indices (ACIs), Acoustic Richness (AR) (Depraetere et al., 2012; Farina et al., 2014; Sueur et al., 2014) has been proven in the terrestrial environment and is currently being explored in the marine environment, (McWilliam and Hawkins, 2013; Staaterman et al., 2014; Harris et al., 2016; Rice et al., 2017) including investigating differences in acoustic diversity in coral reef environments (Kaplan et al., 2015; Bertucci et al., 2016; Butler et al., 2016). Reefs in the GBR have been shown to emit prominent and distinct biophonic components (fish choruses, McWilliam et al., (2017) and these show potential for being developed into robust indicators of ecosystem health. However, the value and effectiveness of these long-term indicators are at risk of reduced efficacy with increased boat presence around the GBR. High levels of vessel noise may cause fragmentation and potentially long-term homogenisation of soundscapes, where many other sound sources are masked, making it unfeasible to distinguish soundscape contributors. This could in turn, potentially mask the acoustic health of the site. Fragmentation of coral reef soundscapes poses a real threat to the long-term efficacy of PAM as a tool for long-term ecosystem survey. Therefore, marine spatial planning should include potential impacts of noise (Jones et al., 2017). Currently, the Reef 2050 document does acknowledge this threat but no mitigation measures or protocols have yet been developed.

4.6 Conclusions

This study has identified that vessels (commercial, recreational and research) are the key sources of anthropogenic noise in coral reef soundscapes around Lizard Island. There were significant spatial differences in vessel activity around Lizard Island, which in areas of high activity, led to several vessel traffic hotspots. Activity of commercial vessels appeared to be fairly constant throughout the year, but a notable rise in recreational vessel density occurred at beginning of the austral wet season, which coincides with peak biophonic activity in the form of fish choruses. Noise from ships raised soundscape sound levels at lower frequencies at all field sites with the exception of the sheltered Lagoon site. Long-term noise contributions from research vessels were not clearly visible at field sites with lower research traffic, but were apparent at sites that had high levels of research boat activity. With commercial ship numbers and size continuing to increase, it is expected that vessel noise will be a growing contributor to coral reef soundscapes. The short and long-term impacts to reef ecosystem remains largely unknown, but combined with stressors from climate change, this is likely to be an important additional threat to coral ecosystems, which are already under an unprecedented level of stress. Future research should focus on investigating the potential effects of vessel noise on key reef species.

Chapter 5

Long-term changes and acute stressors in a coral reef soundscape

Monitoring soundscapes around Lizard Island over a three-year period and comparison of historical recordings revealed ecological information on long-term temporal and preliminary spatial patterns of several fish choruses, anthropogenic activity and two major disturbance events. Distinct seasonal patterns were observed in fish choruses, which exhibited a prominent presence at the start of the wet season and then a minimal presence across the dry season. Comparison of current soundscape recordings with ones collected in the early 1990s revealed long-term site fidelity, possibly on a decadal scale. Bioacoustics features, demonstrating a long-term presence provide strong evidence that soundscape can be developed into a powerful long-term coral reef monitoring tool, with fish choruses showing potential as an ecological indicator of coral reef condition. Lizard Island was exposed to a Category 4 cyclone in March 2015, which resulted in widespread damage to several areas of reef around the Island. The following year, large parts of the GBR experienced severe bleaching; including Lizard Island, resulting in substantial mortality of corals. Fish choruses were still present at sites that sustained significant cyclone damage, but a change in chorus energy attributes was observed. Sound recordings shortly after the start of the bleaching event did not reveal any discernible short-term changes to the soundscape. Recordings taken around Lizard Island in November and December of 2016 contained five of the six choruses recorded pre-bleaching, also similar to those measured in the previous two years, which implies at least some short-term resilience. However, the long-term impact of these destructive disturbance events and how soundscapes and their key constituents will be affected is yet to be determined. The potential influence of disturbance events on socio-economic activity was also detected in soundscapes, where in 2016, post-bleaching, a notable drop in low-frequency noise corresponded with a reduction in vessel activity in the same area.

5.1 Introduction

Coral reefs provide indispensable ecosystem services, to hundreds of millions of people, and a habitat for almost one third of the world's named marine fish species (McCallister, 1991; Moberg and Folke, 1999). Globally, coral reef ecosystems are in a state of decline, particularly the Great Barrier Reef (GBR), where in the last 30 years, nearly half of the coral has disappeared due to a combination of environmental stressors (Hoegh-Guldberg et al., 1999; Pandolfi et al., 2003; De'ath et al., 2012; Hughes et al., 2017). In the past two decades, prolonged high water temperatures, combined with several major storm events (category 4 or 5 cyclones), have been associated with widespread bleaching and significant coral mortality throughout the GBR, particularly in northern reefs in 2016 and then central areas in 2017 (Fig. 5.1).

Safeguarding the future of this iconic ecosystem requires effective environmental management to prevent further reef deterioration. One of the key determining factors of effective environmental action is the ability to access and utilise comprehensive datasets, which is where the significance of long-term monitoring data becomes apparent (Day, 2008). Identifying and investigating long-term patterns facilitates our understanding of how these complex systems respond to environmental stressors over different time scales and improves modelling outputs of how different processes and events affect the system (Magurran et al., 2010; Sutter et al., 2015). Cumulatively, these help develop clear and realistic management objectives and consequently, improve the efficacy of conservation management initiatives.

Passive acoustic monitoring (PAM) and assessment of the local soundscapes present a promising approach to long-term monitoring of coral reefs, due to relatively low deployment costs and the ability to capture simultaneous measurements of variables over a wide range of spatio-temporal scales (Lammers et al., 2008). However, a current lack of long-term coral reef soundscape studies has hindered progress, which has resulted in an underestimation of the potential application of soundscapes in coral reef conservation and research projects.

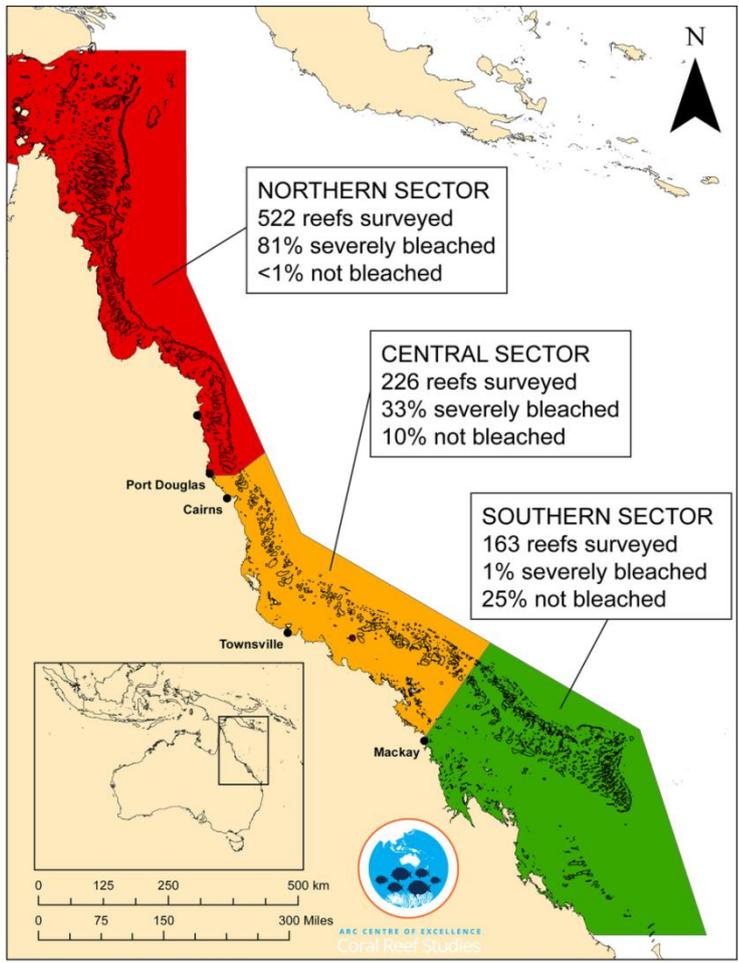


Figure 5.1 Map of the Great Barrier Reef showing results of aerial surveys for 911 reefs in 2016 (A) and results from aerial surveys in 2016 and 2017 (B). Credit: Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies / Tom Bridge and James Kerry (A) Terry Hughes (B).

This study investigates the application of soundscapes for long-term monitoring of coral reefs by consulting an acoustic dataset spanning a three-year period, along with historical soundscape recordings at the same sites taken over 25 years ago (McCauley, 2001).

In 2014, a number of prominent bioacoustic features, fish choruses, were identified around Lizard Island (McWilliam et al., 2017). Some of these closely matched choruses first described by McCauley (2001) (see Chapter 1 for more information). Between 2014 and 2016, the region of the GBR surrounding Lizard Island experienced two major disturbance events. A Category 4 cyclone (Nathan) passed directly over Lizard Island in March 2015 and at the beginning of the austral dry season of 2016/17, corals in the area, exhibited mass bleaching in response to environmental stressors. Widespread disturbances can have devastating effects on reef fish, thus these two occurrences in the GBR have provided a unique opportunity to investigate the potential impacts of large disturbance events on coral reefs, from a soundscape perspective (Wilson et al., 2006).

5.2 Aim of study

The aim of this study was to explore the long-term monitoring potential of coral reef soundscapes using Lizard Island as a case study, addressing the following questions:

- a) How do large disturbance events significantly alter coral reef soundscapes across short and medium time scales?
- b) Are the prominent fish choruses observed around Lizard Island affected after a large-scale disturbance event?

5.3 Methodology

5.3.1 Study area

Lizard Island (14°40.88'S, 145°27.82'E) is located approximately 30 km off the east coast of Australia, 270 km north of Cairns, inside the World Heritage listed GBR. Around this island lie three other smaller islands: Palfrey, South Island and Bird Island, which form the Lizard Island Group (Fig. 5.2). A thin band of fringing reef encircles much of the Island group. In the middle of Lizard and South Island, a large area of reef surrounds the Blue Lagoon, with water depths extending down to 12 m. The maximum tidal range at Lizard is ± 3 m. Current speeds fluctuate around the island chain, with entrances to the Blue Lagoon and areas around North Point experiencing current speeds in excess of 30 cm/s during tidal cycles (Frith et al., 1986).

During the austral dry season (April–September) the maximum monthly wind speeds average 42 km/h, where the island is exposed to south-easterly trade winds (Frith et al., 1986). Through the wet season, wind speeds drop, averaging 28 km/h and become more variable, where gusty north-westerly winds are interposed with calm weather in November and December.

5.3.2 Data collection

Underwater sound recordings were collected at established field sites around Lizard Island, from 2014 to 2016 (Fig. 5.1 and Table 5.1). Recordings were made using: 1) SoundTrap 202 (Ocean Instruments, New Zealand) digital sound recorders with a 48 ksps sample rate (manufacturer's specifications of a flat response within ± 3 dB between 20 Hz and 60 kHz) and; 2) an underwater sound recorder [USR] (developed by the Centre for Marine Science and Technology (CMST) at Curtin University and the Defence Science and Technology Organisation) with a calibrated omnidirectional, HTI 96-min hydrophone (HighTech Inc., MS, USA) with a 18 ksps sample rate.

Table 5.1 Details of acoustic recordings taken around Lizard Island.

Year	Site	Equipment	Sampling type	Dates	Total number of recording days	
2014	North Point	ST	C*	29/10 - 08/11	10	
		ST	16.67%	10/11 - 17/11	7	
		ST	C	18/11 - 30/11	12	
	Eagle Island	ST	C	31/10 - 8/11	8	
	South Island	ST	C	22/11 - 27/11	5	
	Big Vicky's	ST	C	28/11 - 30/11	2	
	Lagoon	ST	C	18/11 - 21/11	3	
	Turtle Beach	ST	C	02/11 - 06/11	4	
	South Bay	ST	C	21/11 - 24/11	3	
	Crystal Cove	ST	C	06/11 - 08/11	2	
	Coconut Beach	ST	C	29/10 - 01/11	3	
	Palfrey	ST	C	19/11 - 22/11	3	
	Shipping Channel	USR	20%	01/12 - 31/12	31	
2015	North Point	ST	C	07/03 - 16/03	9	
		ST	C	26/09 - 15/12	80	
	South Island	ST	C	30/09 - 15/12	76	
		ST	C	06/03 - 17/03	11	
	Big Vicky's	ST	C	27/09 - 16/12	80	
		ST	C	06/03 - 15/03	9	
	Lagoon	ST	C	26/09 - 13/12	78	
		ST	C	01/01 - 05/07	186	
2016	North Point	ST	C	07/04 - 07/05	30	
		ST	93%	12/11 - 27/11	15	
		ST	C	20/11 - 28/11	8	
		ST	C	27/11 - 03/12	6	
	South Island	ST	C	07/04 - 23/04	16	
		ST	C	29/11 - 03/12	4	
	Big Vicky's	ST	C	07/04 - 07/05	30	
		ST	C	26/11 - 04/12	8	
	Lagoon	ST	C	07/04 - 07/05	30	
		ST	C	26/11 - 04/12	8	
	Palfrey	ST	C	28/11 - 04/12	6	
	Grand total					783

*ST: SoundTrap (48 ksps sample rate)

**USR: Underwater Sound Recorder (18 ksps sample rate)

Each SoundTrap was piston-phone calibrated by the manufacturer with a known level of 121 dB re $1\mu\text{Pa}$ at 250 Hz, while the CMST USR was calibrated with a white noise generator at -90 dB re $1\text{V}^2/\text{Hz}$. Recorders' clocks were manually set to Australian Eastern Standard Time (AEST). For every subsequent deployment, a Garmin 60Csx GPS unit and a laptop with internet connection were employed to ensure recorder clock accuracy. Field sites were chosen to represent the variety

of seascapes found around Lizard Island. Site locations were recorded with a Garmin 60Csx GPS, accurate to ± 3 m.

SoundTraps were attached to weighted mounts and diver-deployed to the seabed on sand, at least 3 m from coral reef. To help relocate equipment in low visibility, a marker made out of two concrete breeze blocks and a rope attached to a sub-surface buoy were placed about 5 m from each recorder. SoundTraps were retrieved and redeployed every 10–14 days for data download and battery charge. To provide enough cross-over time between deployments, the subsequent SoundTrap was deployed for a period of about 5 minutes prior to collection of the one preceding it.

The USR was deployed off the side of one of Lizard Island's research vessels (Kirsty K). The logger was gently lowered to the seafloor by a rope pulley system, followed by a 100 m rope line with a 60 kg sacrificial dump weight in order to maximise the distance of the hydrophone from potential sources of extraneous noise. An acoustic release consisting of and sub-surface buoys was attached to the dump-weights for surface-based retrieval of the USR.

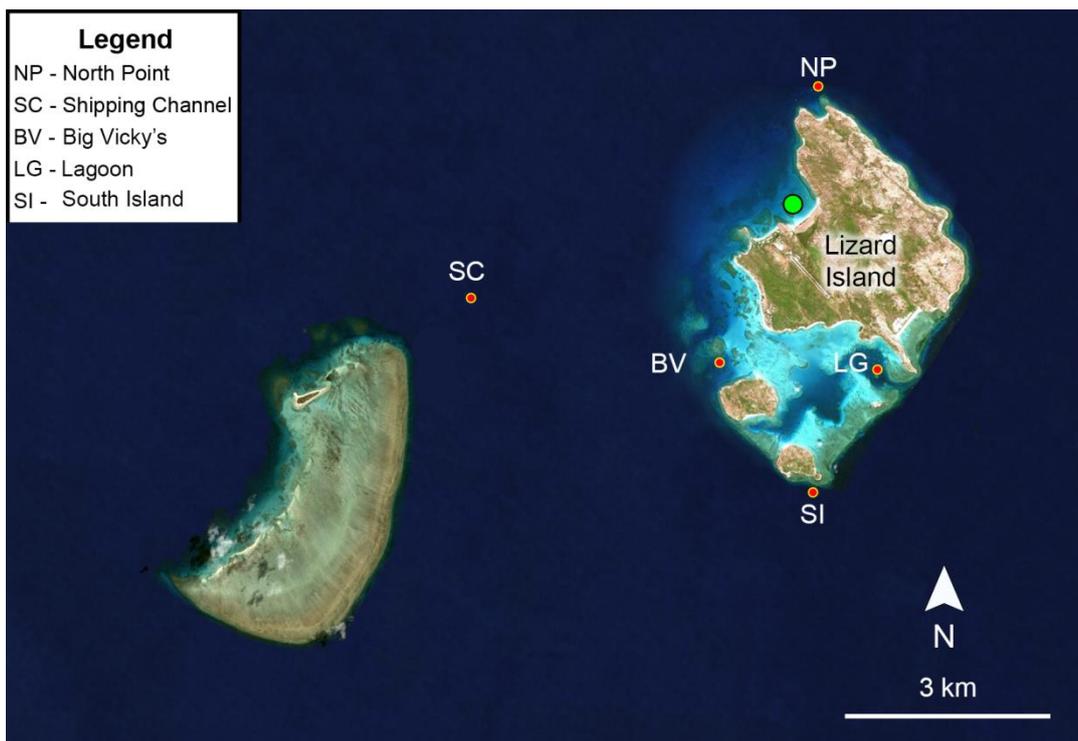


Figure 5.2 Location of field sites around Lizard Island (red dots) and Watson's Bay (green dot)

5.3.3 Audio analysis

Acoustic datasets collected from 2014 to 2016 were analysed using a mixture of long-term spectrogram visual analysis and audio inspection of recordings. Calibrated power spectral density (PSD) averages were calculated over 300 s windows and linked chronologically to create long-term spectrograms with time on the x-axis and frequency on the y-axis, with colour representing power. Spectrograms of the overlapping *.wav files were visually and audibly inspected to determine an appropriate cross-over point in SoundTrap *.wav files and to remove diver and handling noise. A Graphical User Interface (GUI) toolbox, CHaracterisation Of Recorded Underwater Sound (CHORUS; Gavrilov & Parsons, 2014) was used to display and inspect the spectrograms in the MATLAB software environment (The Mathworks Inc. Boston, MA). CHORUS was designed to analyse long-term underwater sound recordings. The GUI allows the user to adjust the spectrogram size from a single day to several months in length.

5.3.4 Long-term PSD percentiles

Biophonic, geophonic and anthropophonic contributions to reef soundscapes were examined at seasonal and annual scales by calculating PSD percentiles and probability density at sites with multi-year series of sound recordings (four in total). More details on PSD percentiles with probability density can be found in Merchant et al. (2013) and Erbe et al. (2016a).

5.3.5 Historical recording comparisons

Underwater sound recordings made by McCauley (2001) around the GBR between 1990 and 1993 were digitised from Sony HF-EF cassette tapes to *.wav files using a Sound Devices 722 2-Channel High-Resolution Portable Recorder (48 ksp/s sample rate, 24 bit). Field notes taken during the recording periods were used to identify relevant recordings sites around Lizard Island, which contained biological sounds (fish calls) of interest. Spectrograms of selected recordings were generated in MATLAB and then visually and audibly inspected to isolate fish calls. Maps of McCauley's recording sites and current field sites were created in the mapping software QGIS to display their location in relation to each other.

To improve display of fish calls, which had low-signal-to-noise in spectrograms, a high (250 Hz) and low pass (450 Hz) filter were applied to Chorus II. Ambon damselfish (*Pomacentrus amboinensis*) calls had background noise manually removed from the image using Adobe Photoshop (version CS6). Calibration levels could not be verified for tape recordings (in the process of being acquired), so a standardised sensitivity level of -150 dB re 1 μ Pa was used to improve visual comparison of spectrographic features. Acoustic power therefore, should not be considered as absolute values, but only as a reference point to identify spectrographic features of fish.

5.3.6 Influence of disturbance events on reef soundscapes

On the 20th of March 2015, Lizard Island was exposed to cyclone Nathan, which resulted in widespread damage to several areas of reef around the Island. South Island reef in particular, was heavily damaged, where benthic composition was significantly altered by the destruction of hard and soft corals, down to depths of 15 m (diver observation). Audio recordings were made before, during and after the cyclone passed over Lizard Island using a combination of SoundTraps and the USR, deployed in the shipping channel (SC). It should be noted that the SC site was the only recording site active during and immediately after the cyclone. Short-term influences of cyclone Nathan were investigated by consulting local environmental weather measurements (wind speeds rainfall and temperature) collected during the disturbance period (available at <http://data.aims.gov.au>). In March and April 2016, large parts of the GBR experienced severe bleaching; including around Lizard Island, resulting in substantial mortality of corals (Hughes et al., 2017). Acoustic recordings were collected around Lizard Island during this period (April–May) and from November/December, nine months after the first recorded coral bleaching. For nearly one month (28th February–24th March 2016) water temperatures around Lizard Island remained above 30°C (with the exception of three days, where the temperature dropped to 29.8°C). Prolonged elevations of water temperature, in combination with high UV levels were responsible for the most severe coral bleaching event ever recorded at Lizard Island (ARC, 2016). This resulted in widespread mortality of soft and hard corals (mostly *Acropora* spp.), particularly in the shallower areas.

The potential influence that disturbance events may have had on tourist and recreational boat activity around Lizard Island was investigated by exploring Automatic Identification System (AIS) data collected pre (November and December 2015) and post-cyclone (November and December 2016). Data are freely available from (<https://www.operations.amsa.gov.au>). AIS point data were uploaded and processed in the open-source geographic information system (GIS) QuantumGIS (QGIS). To capture recreational and tourist activity, AIS points that fell within a 2 km radius of Watson's Bay, the main mooring area for visiting vessels were selected using the QGIS spatial analysis toolbox (Fig. 5.2).

5.4 Results

5.4.1 Long-term spectrograms: acoustic features

Sound recordings made at field sites around Lizard Island revealed that reef soundscapes contained several notable acoustic features, including ship noise, snapping shrimp clicks and several different fish choruses and calls (Fig. 5.3) [Further details can be found in Chapters 2, 3 and 4]. Distinct seasonal patterns were observed at all field sites, where several fish choruses exhibit a prominent presence, at the start of the wet season, but then a minimal presence across

the dry season. This is particularly apparent in Chorus I (400–700 Hz) at North Point, (described in Chapter 2 and 3). Ship noise contributions appear to remain relatively consistent throughout the year, displaying a much lower level of seasonal variation by comparison, whereas small boats were common at the start of the wet season. For ships passing at a distance of 2–3 km, ship noise occupies frequencies from approximately 20 Hz to 500 Hz, but is most concentrated in frequencies below 100 Hz (see Chapter 4, Fig. 4.4). At closer distances (<2 km), ship noise contributions extend into the higher frequencies (500–1000 Hz). In comparison, a small boat passing overhead has a shorter, more broadband noise signature, beginning from around 50 Hz and extending upwards of 1 kHz, depending on the distance of the vessel.

Several similarities were observed between the choruses and individual fish calls that were recorded from 1990 to 1994 and recordings collected from 2014 to 2016. For example, historical and current field sites containing Chorus VI lie in close proximity to each other (<500 m) [Fig. 5.5]. Peak chorus activity occurred around midday (see Chapter 2 and 3), closely matching the peak time stated by McCauley (2001), where knocking calls 'reached a peak at 12:00 between Eagle Reef and Lizard Island'. Similar temporal patterns in historic recordings are also apparent in Chorus I and II, with peak activity occurring in the latter a few hours after sunset (\approx 20:00 hours) at Feather Reef, 300 km south of Lizard Island in 1993 (Fig. 7.7).

5.4.2 Disturbance events

5.4.2.1 Cyclone Nathan

Increased wind (exceeding 180 km/h) and rainfall during the build-up and passing of the cyclone were clearly visible in spectrograms, and raised broadband (50–2000 Hz) ambient noise levels by over 20 dB, particularly at the shallower, more exposed field sites, for several days (Fig. 5.8.) Sound recordings collected at South Island in November 2014 contained several fish choruses. In November 2015, eight months after the cyclone hit Lizard Island, fish choruses were once again recorded at South Island, despite widespread damage to the reef habitat. The most active fish chorus (Chorus I) is clearly present in the 2015 recordings, where chorus levels and timing at this particular location displayed similar patterns to those prior to the cyclone (Fig. 5.9).

5.4.2.2 Bleaching

Sound recordings taken close to the start of the bleaching event did not reveal any discernible changes to the soundscape. Recordings taken around Lizard Island in November and December of 2016 contained five of the six choruses recorded pre-bleaching, with Chorus I, displaying high chorus levels at North Point, similar to those measured in the previous two years (Fig 5.10).

5.4.2.3 Additional factors

A comparison of PSD percentiles of North Point in 2016 from previous years reveals a notable drop in low-frequency noise in the 99th and 95th percentile levels (Fig. 5.10). Comparison of AIS data from 2015 November and 2016 showed that there was a 41% decrease in vessel AIS positions in November. A decrease in non-commercial vessel traffic (AIS positions) could be related to decreases in tourists due to the actual infrastructural damage and perceived environmental damage caused by these major disturbance events.

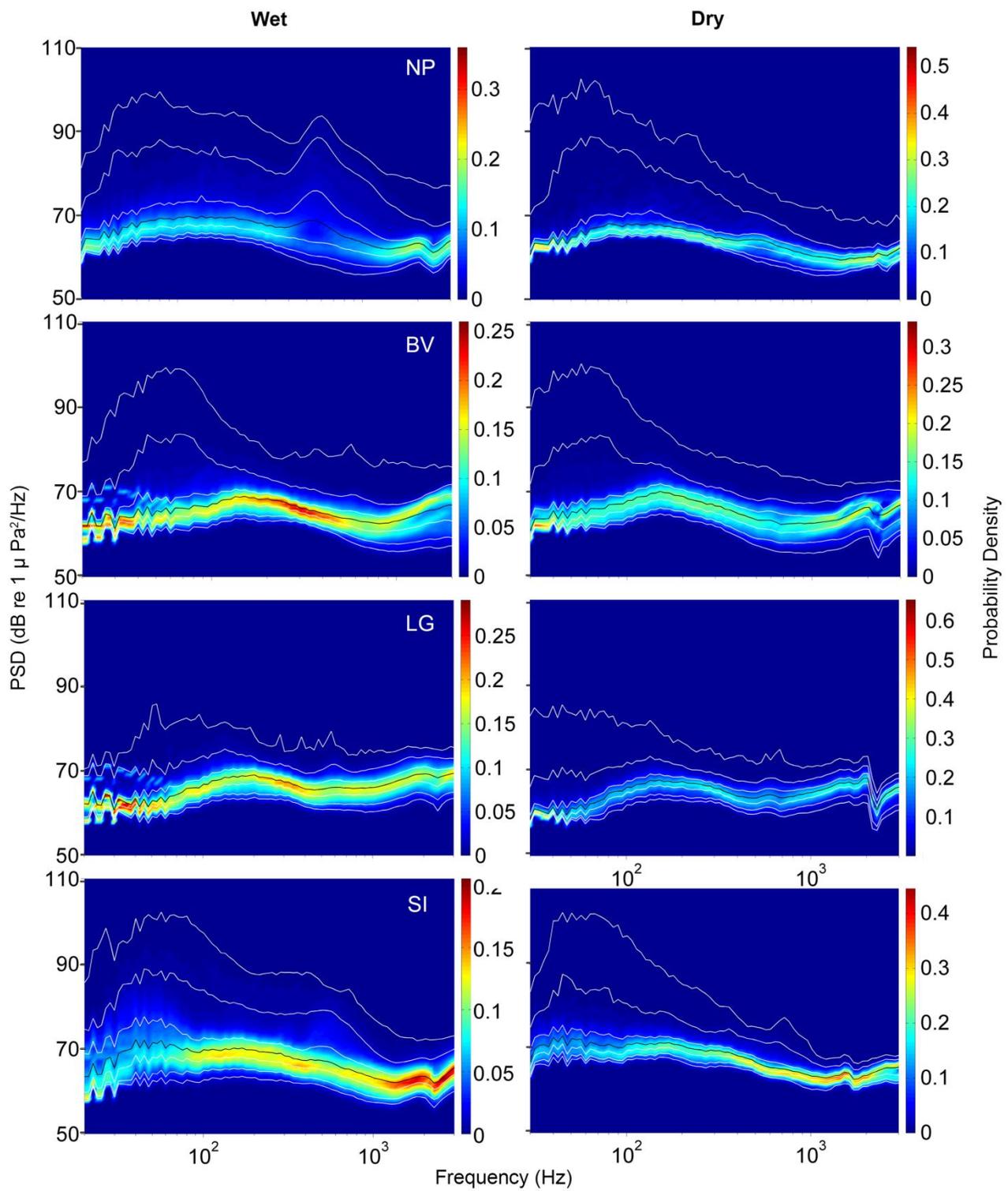


Figure 5.3 PSD Percentiles from four established field sites around Lizard Island, showing seasonal variation (wet vs. dry). NP: North Point, BV: Big Vicky's, LG: Lagoon, SI: South Island.

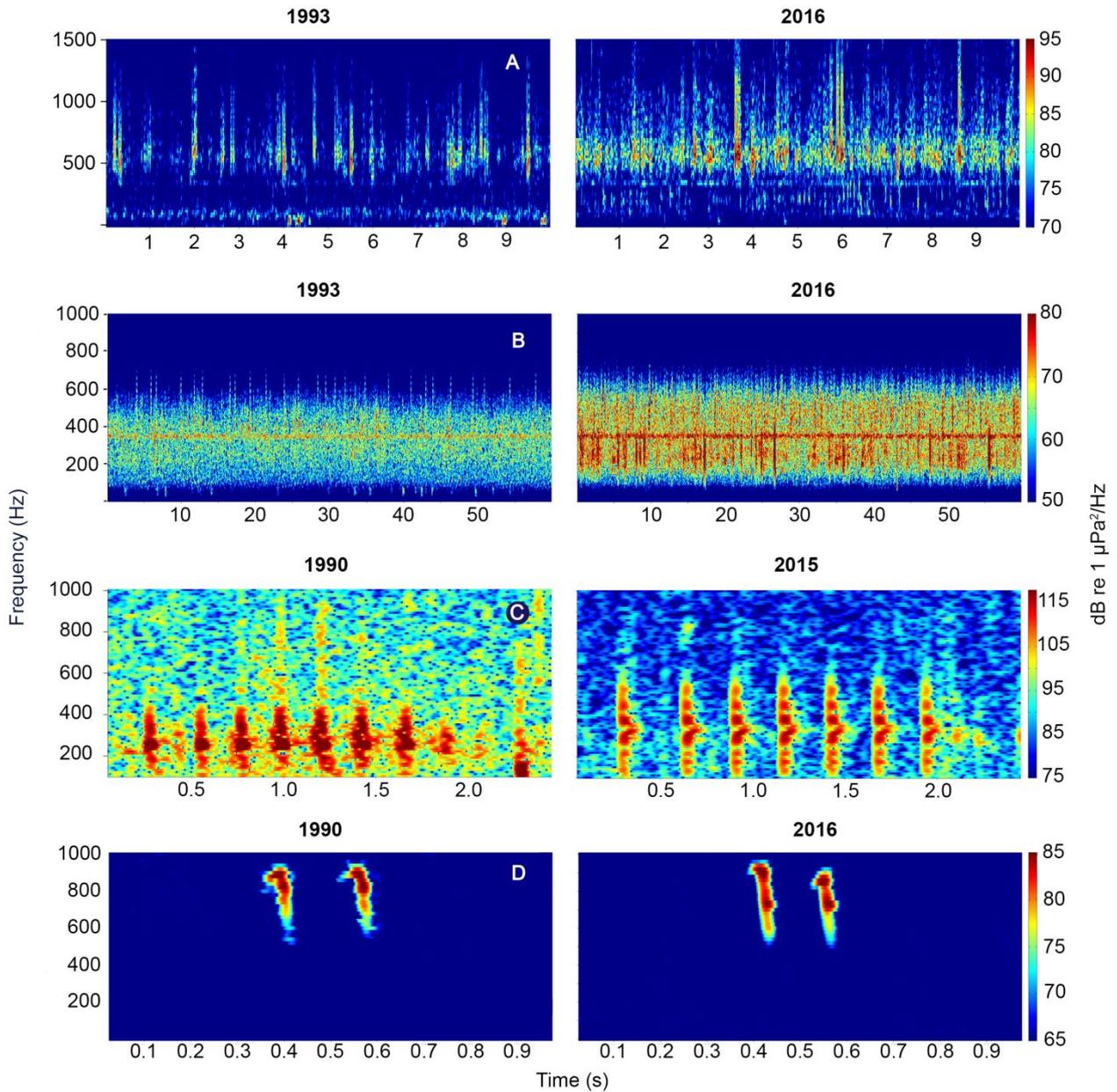


Figure 5.4 Spectrograms of fish choruses from recordings made in 1990's by McCauley (2001) and recordings made 2015 and 2016. Chorus I or 'popping chorus' (A); Chorus II (B); Chorus VI or 'knocking chorus' (C); Ambon damselfish, *Pomacentrus amboinensis* call (D). To highlight the chorus, the spectrograms in B were band-pass filtered (250 – 450 Hz). Manual removal of background noise was carried out in spectrograms (D).

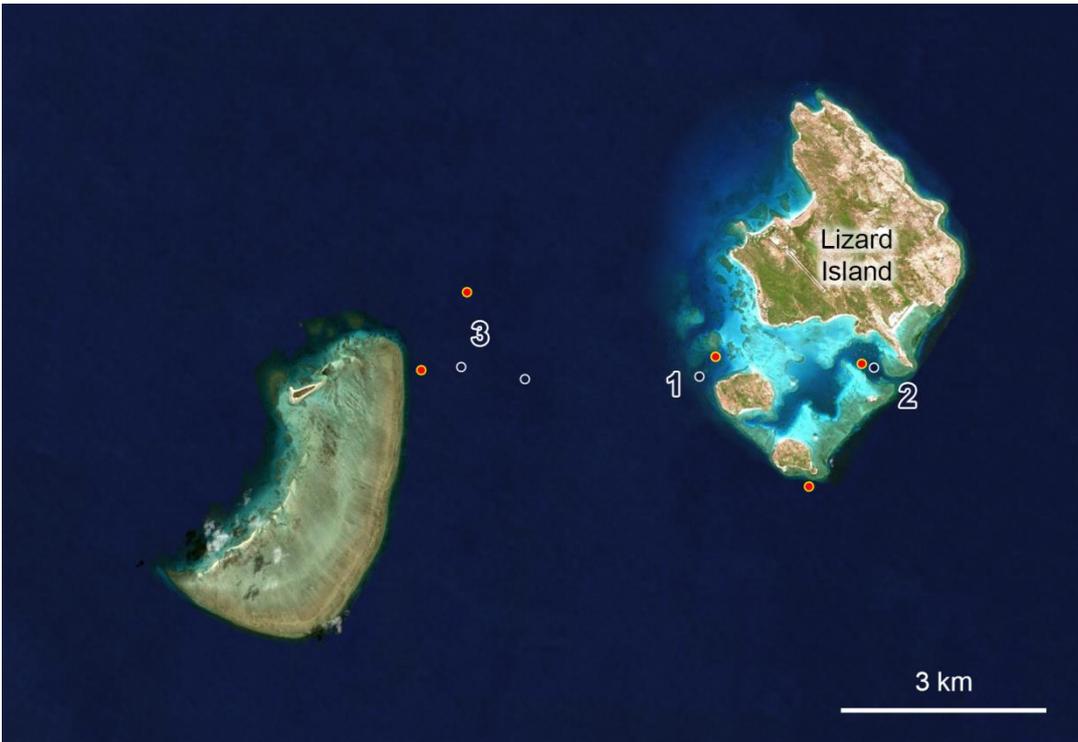


Figure 5.5 Locations of McCauley's 1990's recordings sites (black dots) around Lizard Island in relation to current field sites (red dots). (1+3) Chorus VI (2) *Pomacentrus amboinensis* calls [see Chapter 2].

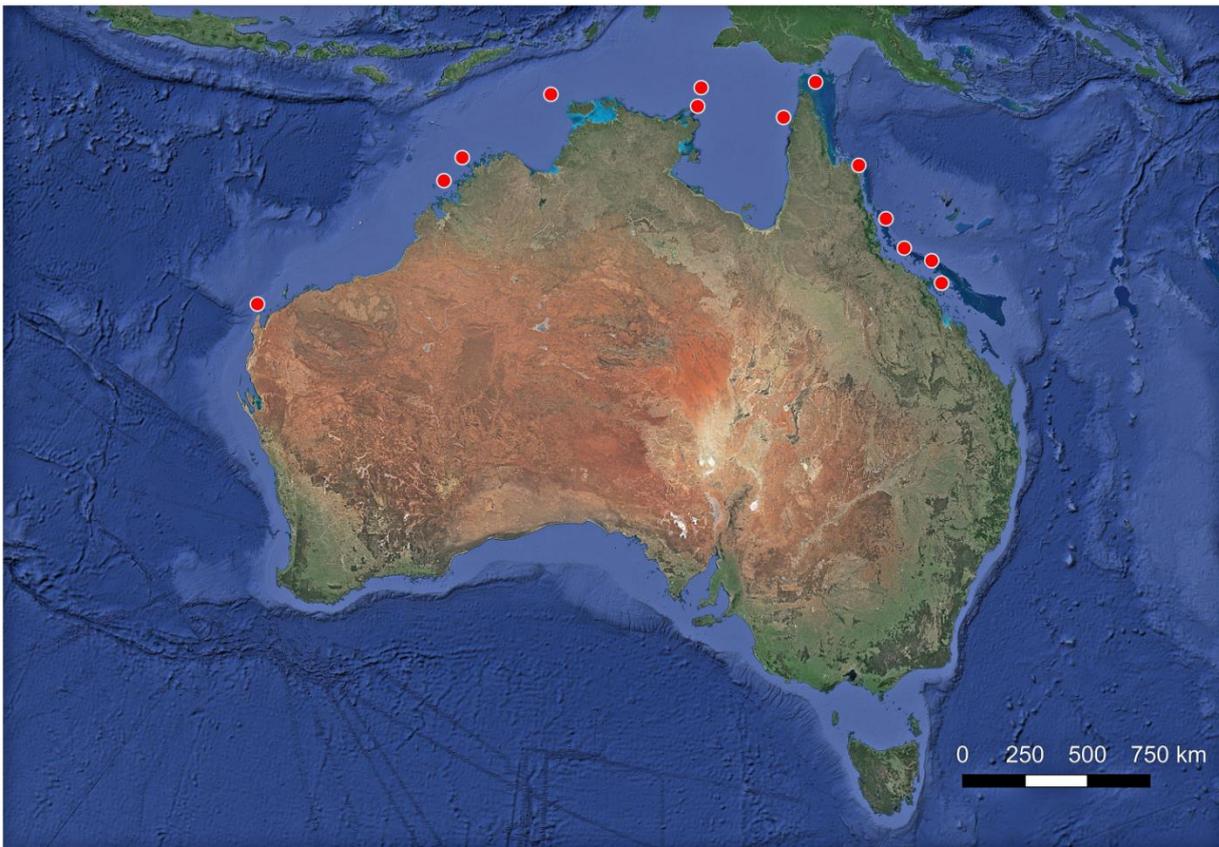


Figure 5.6 Location of sites at which Chorus I has been identified (red dots). All sampling was made within 20 km of reef systems or shoals. Adapted from McCauley (2001).

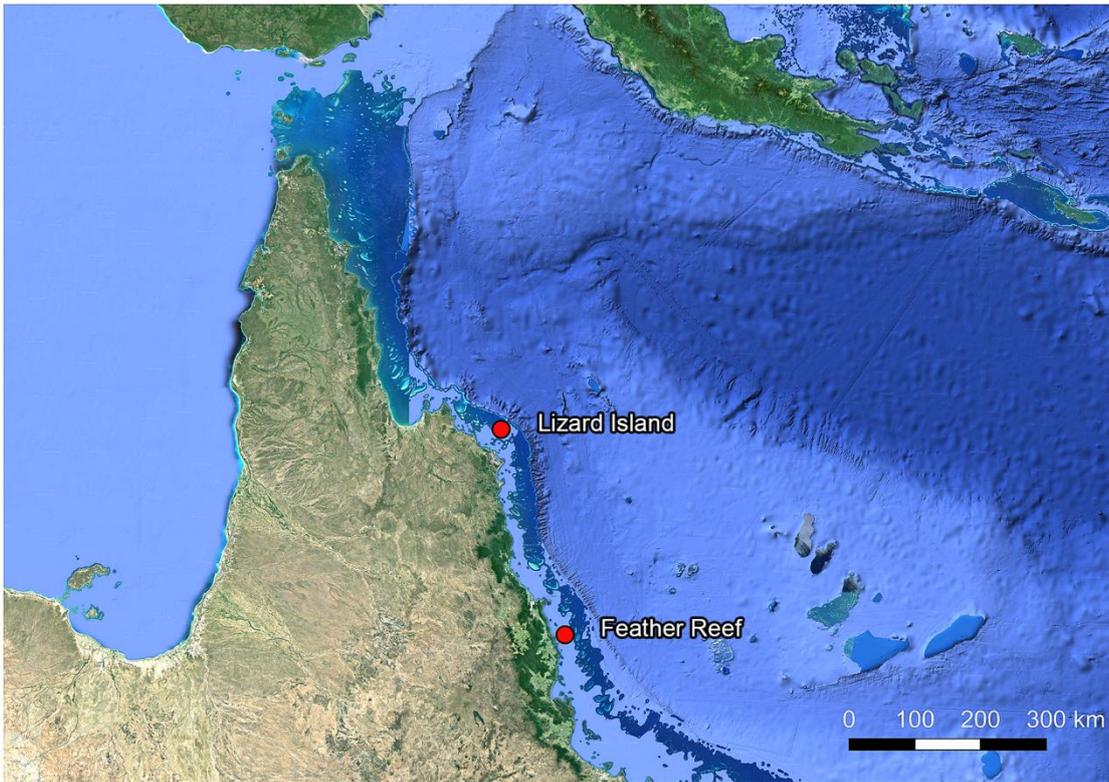


Figure 5.7 Locations of recording sites where Chorus I and Chorus II were recorded (1993 and 2014–16).

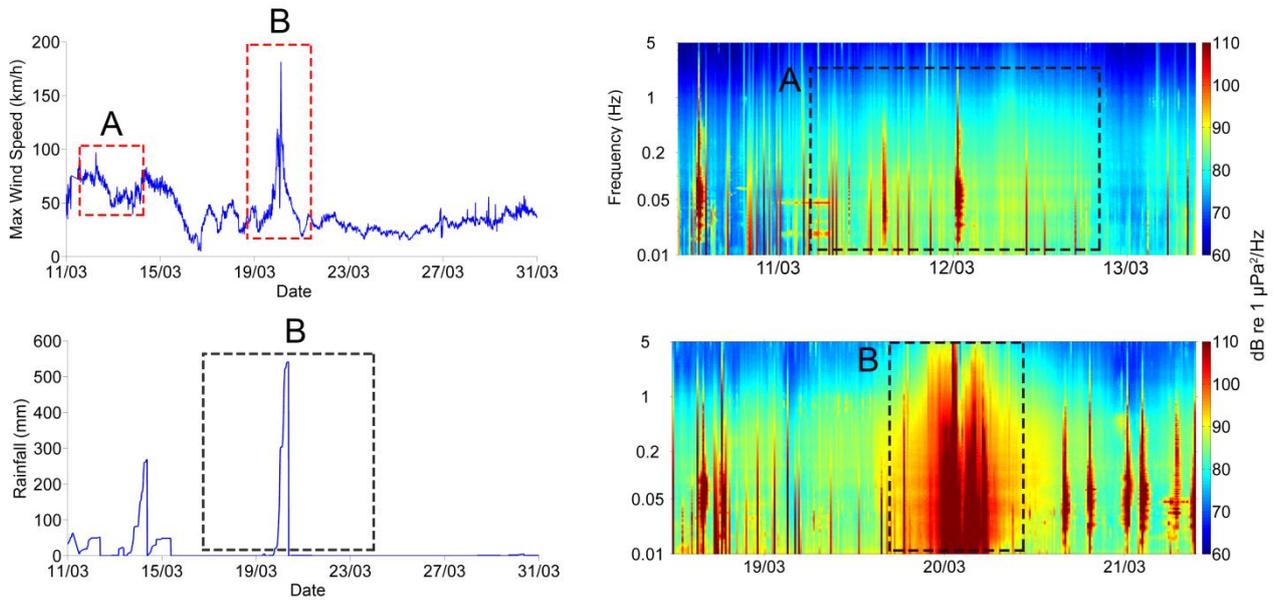


Figure 5.8 Spectrograms showing cyclone passing over Lizard Island in 2015, with corresponding wind speeds and rainfall measurements. (A) Build-up period to cyclone, (B) cyclone passing over Lizard Island. The SC site was used for both spectrograms.

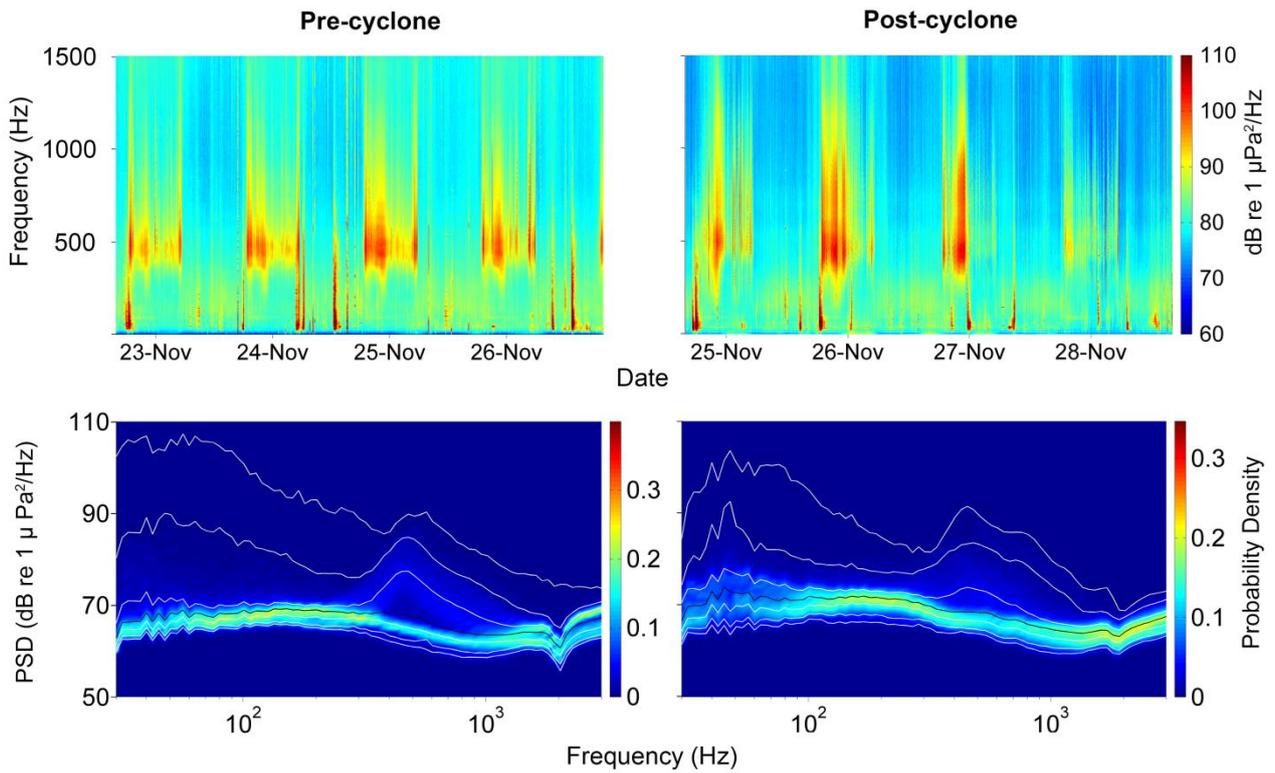


Figure 5.9 Spectrograms and PSD percentiles from South Island for four days at the end of November 2014 (pre cyclone) and November 2015 (post cyclone).

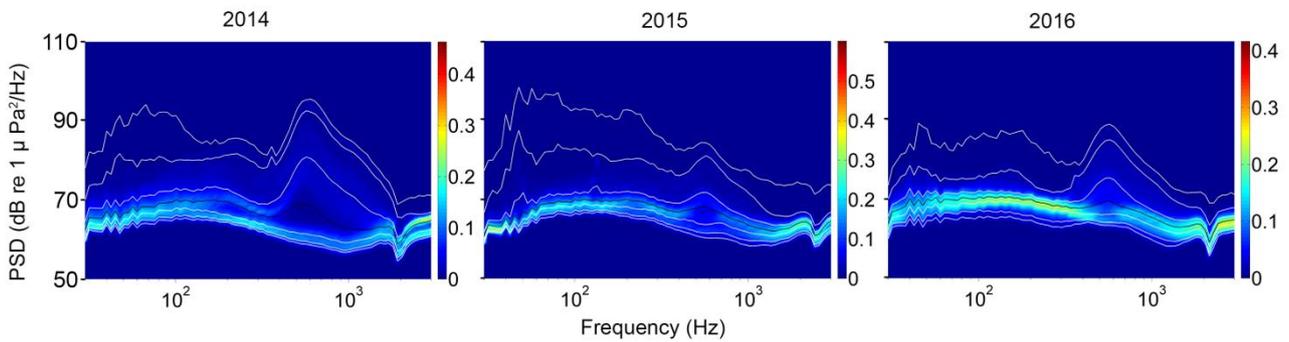


Figure 5.10 PSD percentiles from North Point field site made each year at the start of the wet season (November).

Table 5.2 Counts of AIS point positions within Watson's Bay, Lizard Island.

AIS points			
	Nov	Dec	% change
2015	1160	687	-41
2016	671	555	-17

5.5 Discussion

Monitoring soundscapes around Lizard Island over a three-year period and comparison of historical recordings has revealed ecological information on long-term temporal and preliminary spatial patterns of several fish choruses, anthropogenic activity and two major disturbance events.

5.5.1 Fish choruses - temporal and spatial patterns

Long-term site fidelity, possibly on a decadal scale, inferred from the presence of similar fish choruses around Lizard Island, is a powerful source of information for marine managers. For example, long-term site fidelity in several reef fish, particularly grouper whose spawning aggregations return to the same site over several decades, has allowed detailed monitoring for exploring fish population dynamics (Sadovy and Domeier, 2005; de Mitcheson et al., 2011; Schärer et al., 2012a). Comparison of current soundscape recordings with ones in the early 1990s reveals that some fish chorus are long-term features of reef soundscapes in certain areas. The period between data collection in this study (25 years) is a considerable period of time and provides direct evidence that PAM can be developed into a powerful long-term coral reef monitoring tool, preferably to be applied on a regular basis. Parsons et al. (2015) and McCauley and Cato (2016) have used this to monitor fish choruses in the Swan River and Perth Canyon regions of Western Australia, respectively, for over ten years.

5.5.2 Disturbance events

5.5.2.1 Cyclone

The apparent increase in the frequency and severity of tropical storms in the last few decades highlights the need to understand and establish the ecological consequences of major environmental disturbances (Emmanuel, 2005; Madin and Connolly, 2006). Significant changes to coral communities around Lizard Island and the northern GBR occurred after Cyclone Nathan and the 2016 bleaching. Cyclones are the primary cause of the reduction in hard coral cover on the GBR, bringing immediate changes to coral reefs through physical damage, causing displacement of reef communities (De'ath et al., 2012). However, Lasig (1983) discovered that cyclones passing over Lizard Island caused high juvenile mortality, but adults did not appear to be affected as severely. This may partly explain why fish choruses were still present in areas that sustained significant cyclone damage (e.g. South Island). A reduction in suitable habitat combined with decreased numbers of juvenile recruits, may in subsequent years, result in a smaller fish population and lower fish chorus levels compared to previous years.

Comparison of the upper PSD percentiles for pre and post-cyclone PSD plots at South Island suggest a larger more diffuse spread in the choruses' total energy post-cyclone, indicating that prior to the disturbance, when present, the chorus total energy was more concentrated. In the

summer wet season period of 2015, (post-cyclone) a second fish chorus (Chorus V) appears at South Island, which was not previously observed in the summer of 2014. Explanations for this pattern are uncertain due to the short recording period taken in 2014 (5 days).

5.5.2.2 Bleaching

Short-term effects of bleaching on coral reefs can include rapid reduction in live coral communities and algal overgrowth of corals, which in turn, can lead to a phase shift to seaweed dominated system (Mumby et al., 2007). During field trips to Lizard Island in 2016, mass bleaching of corals was highly visible in April/May and then widespread coral mortality in November/December. These observations are reflected in the 2016/17 aerial surveys carried out by the ARC Centre for Excellence for Coral Reef Studies. Increased frequency of severe disturbances can have devastating impacts on coral reefs and associated reef fish communities (Emmanuel, 2005, Wilson et al., 2006). A meta-analysis study on 17 independent coral reef studies discovered that 62% of fish species declined in abundance within three years of disturbance events that caused a 10% decline in coral cover (Wilson et al., 2006). However, fish choruses continued to be present in November 2016, displaying similar levels and spatio-temporal patterns observed in pre-bleaching years. The apparent lack of impact on soniferous fish populations compared to coral communities may be a time-lag response, as many of the reef choruses are suspected to be produced by planktivorous fish, who do not directly rely on corals as a food source, unlike corallivores, whose numbers have been shown rapidly decline post-bleaching (Chabanet, 2002; Graham et al., 2007). This pattern may change over time, during fish settlement stages of future fish populations and if food sources for planktivores become severely depleted (McCormick et al., 2010).

5.5.2.2 Additional factors

Disturbance events such as cyclones can remove extensive areas of coral reef structures. This can have a significant ecological impact on reef biodiversity, particularly reductions in coral cover, species richness and abundance of associated fish communities (Cheal et al., 2017). This extends to socio-economic impacts, which can be long-lasting and severe (Wilkinson et al., 1999). Long-term PAM allows temporal changes to the soundscape to be explored, which can reveal how biophonic, geophonic and anthropophonic activities may influence each other. For example, the press coverage following the bleaching and cyclone potentially reduced the appeal of luxury resorts, whose main attraction/selling feature is the surrounding coral reef. This may explain the drop in low frequency sound levels from boats in November 2016 at NP, situated close to the Island's resort. However, more in-depth work comparing long-term visiting tourist numbers and vessel calls to the island is required before this can be ascertained.

5.5.3 Fish chorus applications: ecological indicators

Fish choruses are an integral, long-standing component of coral reef soundscapes at Lizard, occurring in specific areas for at least a quarter of a century, and this implies that they are an important part of the reef ecosystem. Choruses are not just confined to reef around Lizard Island, but extend to other parts of the GBR and around the Australian coastline, revealing a long-standing and widespread spatio-temporal presence. Their presence currently remains an important, but untapped source of ecological knowledge for researchers and marine managing authorities around the GBR, which in the current climate should not be overlooked. Dale and Beyeler (2001) suggested a number of criteria which should be met by data sources that could potentially be used as ecological indicators to assess the condition of the environment and monitoring changes to conditions over time. Fish choruses have shown potential to meet two of these criteria, including:

1. be easily measured: Fish choruses can be measured with high-quality sound recorders, which are relatively inexpensive and straightforward to deploy over large areas.
2. be integrative, i.e., provide a measure of coverage of key gradients across ecological systems (depths, space, time and benthic types): As fish choruses have been shown to be related to habitat and exhibit significant temporal and spatial patterns, they are considered to provide a measure of environmental factors.

Therefore, based on the widespread presence of fish choruses around Australia (McCauley, 2001; McCauley, 2012; Parsons et al., 2012; McCauley and Cato, 2016; Parsons et al., 2016a, b) and the ability to simultaneously assess the influence of anthropogenic activity across extensive spatio-temporal scales, it is suggested that the diversity, distribution and density of fish choruses should be investigated as a potential ecological indicator of coral reef condition. Additionally, despite our limited understanding of the function of snapping shrimp snaps, spatial and temporal patterns of snapping shrimp noise should also be considered as a potential ecological reef indicator (Lillis et al., 2017). Yet, as the spatial and temporal coverage of passive acoustic datasets increases, advances in the development and application of automated signal processing will be required to process these large datasets. This will have to occur before we can fully determine if fish choruses and snapping shrimp noise can be used as ecological indicators.

Chapter 6

General discussion

6.1 Aim and objectives of thesis

The overall aim of this thesis was to explore the potential application of coral reef soundscapes for long-term ecological survey of coral reefs, using PAM as the principal measurement tool around Lizard Island. The aim was achieved by investigating several linked coral soundscape topics with the following objectives:

1. Categorise key biological reef sounds
2. Identify and explain temporal patterns of fish choruses
3. Investigate the contribution of anthropogenic (vessel) noise around a coral reef
4. Investigate how large disturbance events may influence coral soundscapes

6.2 Key biological reef sounds

Several distinct bioacoustic signals in the form of six predominant fish choruses were discovered at six study sites around Lizard Island, along with two additional fish choruses. Between them, the choruses occupied a broad frequency band, displaying energy from approximately 50 Hz to 2000 Hz, contributing significantly to the ambient noise levels. On some occasions, chorus levels extended above 2000 Hz, e.g. Chorus I and V.

Many other suspected biological sounds were captured during field recording at Lizard Island, including individual fish calls (described in Chapter 2), dolphins and unknown soniferous species, though their energetic contribution to the reef soundscape in comparison to fish choruses was minor.

Several of these biological sounds, particularly fish choruses and individual fish calls were heard repeatedly across multiple years. The field recordings of these sounds represent a permanent acoustic record of bioacoustic diversity around Lizard Island, which holds significant value from a long-term monitoring standpoint. For example, the ability to track the presence and absence of fish choruses over multiple years allows us to investigate potential long-term impacts, such as mass coral mortality on these sonic fish populations and factor in potential lag effects (Graham et al., 2007). Our understanding of bioacoustic diversity and the value of these records increases when identification of individual signals is performed. However, the time consuming nature of signal classification means call identification remains limited. Further progress in automated signal recognition is required and this is still in developmental stages (Alonso et al., 2017).

During peak activity, each chorus dominated its respective frequency band, indicating that this is an important time for vocalising fish. However, interspecific masking was apparent in several of the fish choruses. Chorus I, when reaching peak levels, usually around the new moon period, displayed a wider spectral content, extending down to lower frequencies and effectively masking Chorus II. Interspecific masking was also observed at the SI site between Chorus I and V, with the latter effectively dominating the 'active acoustic space' for the periods it was active. Acoustic niche partitioning has been an important area of research interest that has seen renewed attention in marine studies. A recent study by Ruppé et al. (2015) reported that nocturnal vocalising fish partitioned the active space by time and frequency to reduce call overlap, while soniferous fish active during the day showed less evidence of partitioning. Examples from Lizard Island show that nocturnal acoustic partitioning is not always apparent. Therefore, care should be taken when identifying key bioacoustic reef sounds, particularly when they have high levels compared to the background noise level as they may be masking other biological signals. This also reinforces the importance of taking long-term recordings because there is more likelihood of revealing other biological sounds. Additionally, acoustic interactions between interspecific soniferous species and how they may influence each other's calling behaviour is a relatively unexplored, but important area of research, which falls beyond the scope of this study.

Call received levels from each chorus were low compared with source levels of some Australian fish (McCauley, 2001, Parsons et al., 2012, 2013b, 2016a), but were also low compared to the chorus levels themselves, suggesting that overall, a large number of calls per minute were emitted. This in turn indicates that the choruses were produced by either a large number of individuals calling slowly, or smaller numbers of individuals that produce calls repetitively and in quick succession, for prolonged periods. The calling repetition rates observed for individual fish suggest that the former was the case here. The reported received levels also provide information for future studies at these sites. As source levels of individuals, and to an extent each species, are thought to be comparatively consistent (Connaughton et al., 2000; Parsons et al., 2012), the reported received levels of individual calls provide an indication of the caller range. When combined with the estimated calling rate and the chorus levels it is then possible to estimate the likelihood of any day-to-day change in chorus level as being a result of fewer fish, or greater range from the hydrophone (McCauley, 2001; Parsons, 2010). Targeted passive acoustic monitoring is often limited by the number of underwater recording systems that can be deployed, thus the ability to identify even relative changes in range can improve confidence in long-term monitoring of chorus levels by assisting in understanding whether these changes are the result of changing callers numbers or range.

6.3 Temporal patterns of fish choruses

The fish choruses detected in long-term recordings displayed temporal patterns that ranged from diel to annual, which provides new insights into the ecology of vocalising reef fish species and the surrounding ecosystem. The influences of environmental variables on fish chorus temporal changes were diverse and varied between choruses at the same site and the same chorus at different sites, potentially reflecting varying local environmental conditions. Moonlight levels in particular, showed a strong negative relationship with the vast majority of the fish choruses, indicating that, like findings in other studies, the lunar period holds an important behavioural function for many of the vocalising fish around Lizard Island (McCauley, 2012; Staaterman et al., 2014). Temperature, which has been shown to be a key driver of behavioural and physiological changes among tropical fish (Samoilys, 1997), displayed a strong and significant relationship in four of the fish choruses, where peak chorus level increased with higher water temperatures. Therefore, it may be possible to detect short and long-term community impacts caused by changes in sea temperatures from climatic anomalies (El Niño) that cause above average water temperatures.

The negative relationship of wind speed and peak chorus levels was an interesting finding (stronger winds resulting in lower chorus levels), where the correlation was strongest at NP for Choruses I-III and Chorus V at SI. Currents, particularly in shallow water areas around Lizard Island are predominantly wind-driven and this may affect the dispersal patterns of marine fauna like fish larvae and zooplankton, which provide food for soniferous planktivorous fish, (Lasig, 1983; Kingsford and Finn, 1997). Therefore, variation in shallow water fish choruses may be a result of wind-driven currents fluctuations.

Another difficulty associated with identifying potential drivers of fish choruses is that the fish producing them do not remain static. Movement in the water column can change frequency content of calls and a change in distance in relation to recording device alters the chorus sound level (McCauley, 2001). When fish alter their position in the water column, pressure exerted on the fishes body increases with depth. This can cause the swim bladder, the appendage which is used by many fish to produce sound to be compressed (Fassler et al., 2009). The change in size can alter the resonance frequency of the swim bladder and spectral content of the fish call, until the fish ascends to shallower water or alters the size of its swim bladder (McCauley, 2001). The spectral characteristics of the call are also associated with the coupled nature of the swimbladder and surrounding muscle, as well as the material around the swimbladder. Therefore, these factors need to be considered along with swimbladder size when studying the resonance frequency in relation to depth.

However, many of the choruses at Lizard Island appeared to display high site fidelity, which suggest that either: 1) The fish show a minimal dispersal pattern in an area, indicating a resident

fish species or 2) The fish follow a very similar daily migration pattern. Systems with multiple hydrophones (array) would improve passive tracking of fish choruses and may allow identification of migration patterns of soniferous fish or short-term movements of individual fish (McCauley, 2001; Parsons et al., 2009).

High site fidelity indicates that particular sites are important 'habitat hotspots' for fish species, such as fish spawning aggregations areas. Spawning sites are commonly used by multiple species, hence, identification and subsequent protection of an area used by one species may directly benefit other species. Protection of these areas may also serve as an effective precautionary approach in marine spatial planning. Therefore, this information would be of use to industry, government departments, research organisations and other marine researchers and highlights PAM's cross-disciplinary application and utility in long-term reef monitoring and management.

6.4 Contribution of anthropogenic (vessel) noise around a coral reef

Large commercial ships were the primary contributors of anthropogenic noise around Lizard Island. Investigations into the contribution of anthropogenic noise around coral reef revealed that their combined level and duration (exceeding 1 h) meant that passing ships featured prominently, particularly at field sites closest to the shipping lane on the west side of the island. Temporally, there was a low level of annual variation in large vessel activity during 2015, reflecting the 'round-the-clock' anthropogenic activity in the Great Barrier Reef. Research boats were a notable anthropogenic contributor to reef soundscapes at sites with higher boat traffic, specifically at the shallower sites, where research boat activity hotspots were identified.

6.4.1 Masking

Masking of several of the fish choruses by vessel noise specifically, commercial ships were observed at nearly all field sites. Vessel noise may have deleterious effects on marine life (see section 4.1), ranging from habitat avoidance (Morton et al., 2002) and disorientation (Weilgart, 2007), hearing loss, temporary threshold shift (Scholik, and Yan, 2002; Codarin et al., 2009; Jones et al., 2017) acoustic masking (Erbe et al., 2016) and noise-induced stress (Smith et al., 2004; Rolland et al., 2012). Long-term impacts may include increased susceptibility to predation (Simpson et al., 2016b), reduced growth rates and egg viability (Banner and Hyatt 1973) and decreased mate selection effectiveness (Bee and Swanson, 2007). However, extensive field-based studies would need to be carried out in order to determine the proportion of species that may be affected by vessel noise due to the large range of hearing abilities in marine fauna, of which we have a limited understanding (Slabbekoorn et al., 2010; Hawkins and Popper, 2016). This includes measuring sensitivity to particle motion as well as sound pressure because many marine organisms, particularly fish and invertebrates detect and are sensitive to particle motion (Nedelec et al., 2016; Popper and Hawkins, 2018). Direct field-based measurements of particle motion over

a broad range of spatio-temporal scales are required along with experiments that improve our understanding of particle motion thresholds in reef fish and invertebrates (Horodysky et al., 2008).

6.4.2 Vessel traffic around Lizard Island

Lizard Island reef is exposed to very limited vessel traffic compared to other areas of the GBR. For example commercial vessel calls to Cape Flattery (30 km WSW of Lizard Island) in 2014/15, amounted to 40, which is less than 3% of Gladstone Port calls (data obtained from www.portsaustralia.com.au). Another shipping route, further inland to the west of Lizard Island, is commonly used by ships and this route may explain the low vessel traffic levels around Lizard. Vessel traffic is growing and with that continued growth, increased human-induced soundscape fragmentation could threaten community-scale life processes on both short and long-term time scales (Cato, 1992; Slabbekoorn and Halfwek, 2009; Slabbekoorn et al., 2010; Codarin et al., 2012; Parsons et al., 2012; Stanley et al., 2012). Future marine spatial planning in the GBR should include investigating the potential impacts of noise (Jones et al., 2017). While the Reef 2050 document does acknowledge this threat, there have been no mitigation measures or protocols put in place to target this issue.

6.5 Disturbance events

The increasing frequency and severity of tropical storms and disturbances highlights the need to understand and establish the ecological consequences of major environmental disturbances (Emmanuel, 2005; Madin and Connolly, 2006). Lizard Island was exposed to a Category 4 cyclone in March 2015, resulting in widespread damage to several areas of reef around the Island where field sites were located. The following year, large parts of the GBR experienced severe bleaching, including around Lizard Island. This resulted in substantial mortality of corals, especially in shallow water areas.

6.5.1 Impacts

Fish choruses were still present at sites that sustained significant cyclone damage, but a change in chorus energy attributes and the presence of an additional chorus was observed. Sound recordings taken close to the start (1-2 weeks) of the bleaching event did not reveal any discernible short-term changes to the soundscape. Recordings taken around Lizard Island in the summer of 2016 contained five of the six choruses recorded pre-bleaching, with similar chorus levels to those measured in the previous two years which, implies at least some short-term resilience. However, the long-term impact of these destructive disturbance events and how soundscapes and their key constituents will be affected is yet to be determined. A meta-analysis study on coral reef studies discovered that 62% of fish species declined in abundance within three years of disturbance events that caused a 10% decline in coral cover (Wilson et al., 2006). Therefore, continued

monitoring of field sites is essential for determining any long-term changes in fish choruses. Long-term monitoring will also help improve our ecological understanding of these soniferous fish. Sound recordings collected from these sites can be considered as historical baselines and potentially provide valuable information for future studies.

Socio-economic impacts of disturbance events may also be detected in coral soundscapes. A drop in low frequency vessel noise in November 2016 at NP site, situated close to the Island's resort may be indicative of reduced tourist visits following the coral bleaching and associated global press coverage. For example, decreased tourist activity was observed after the 1998 bleaching event (Wilkinson et al., 1999). A substantial drop in AIS vessel logs at Watson's Bay during the two busiest months from 2015 to 2016 provides supporting evidence for a drop in recreational activity, but more in-depth investigations are required before any direct association can be established.

6.6 Future research and management implications

Compared to many recent studies on coral reef soundscapes, this research had a significant number of continuous sound recordings collected from long-term field sites. However, logistical (equipment failure) and temporal restrictions meant that it was not always possible to equally sample the same periods every year. This has limited the ability to confirm or sufficiently address certain questions, such as, 'Did Chorus V exist at the South Island site in 2014?' or to fully investigate annual variations in periodicities of fish choruses. The value of long-term datasets lies in the continuity of data collection. While their value is not always apparent at the time of collection, the ecological value of long-term data becomes strongly apparent especially after large changes in natural systems (Magurran et al., 2010). Future research should focus on maintaining long-term acoustic datasets, expanding spatio-temporal studies and developing automated signal processing techniques to analyse the large amounts of data that are generated with long-term datasets.

To achieve standardised and replicable analysis techniques, signal processing of sounds should be an automatic, unsupervised process (Stowell and Plumbley, 2014). However, this is a very challenging area of research due to the complex mix of intricate and overlapping sounds that contain a high level of intra and inter-specific variation (Sueur and Farina, 2015). Quantification of sound recordings with the use of mathematical indices has provided an alternative, less intensive and relatively standardised approach to analysing acoustic environments. Promising, albeit mixed results have been generated from a number of marine studies (Parks et al., 2014; Staaterman et al., 2014, 2017; Bertucci et al., 2016; Harris et al., 2016) indicating that using acoustic indices for analysing large acoustic datasets has potential (see Chapter 1 [1.4]). Research is still required to test the robustness of these indices under different environmental scenarios (Harris et al., 2016). At this stage, a single number is likely to be too analytically coarse for complex marine soundscapes, e.g. coral reefs (Sueur et al., 2014). A better understanding of the spatio-temporal acoustic patterns and the key contributors to coral reef soundscapes is required before the

effectiveness of acoustic indices for monitoring ecosystem dynamics can be ascertained (Parsons et al., 2016c).

There may be potential scope for citizen science to be used to process the large amounts of acoustic data generated by PAM, but collection and processing of bioacoustic data is currently more tailored to terrestrial analysis. This is due to the complexities of marine soundscapes and the relatively high costs of high quality calibrated recording equipment. Currently, processing requires a high degree of familiarity with the data, level of competency in coding and acoustic software and rigorous quality checks, which are skills that most of the general public do not possess. This means that we are still in the developmental stages of using citizen science in marine bioacoustics research (Kismala et al., 2016). Once more user-friendly interfaces for processing data has been established, there will be more of an opportunity to engage members of the public.

6.7 Conclusions

This study has investigated several linked coral reef soundscape topics, which have provided a strong body of evidence to support progressing the management application of coral reef soundscapes for long-term ecological survey. Monitoring of coral reef soundscapes enables the collection of quantifiable information on multiple coral reef species and processes, including disturbance events over appropriate spatio-temporal scales. This broad monitoring scope, particularly the ability to collect data during intense disturbance events that currently remains unfeasible for other survey methods, is an important asset to consider. In light of the extensive degradation of coral reefs, these findings are likely to be an important future resource for conservation management strategies. Fish choruses appear to be a widespread and enduring feature of coral reefs around the GBR, and this study implies that there may be at least some short-term resilience in certain soniferous fishes after a Category 4 cyclone and extensive coral bleaching. However, these destructive disturbance events have fundamentally altered reef ecosystems within the GBR and it is yet to be determined how soundscapes and their key constituents, e.g. fish choruses, will be impacted in the long-term. Therefore, sound recordings also represent a historical baseline and a potential valuable resource for further studies. Future work should concentrate on automating acoustic analysis and expanding soundscape monitoring across the GBR, with a focus on sampling areas that contain a range of live coral coverage.

There is still a window of opportunity to conserve these iconic ecosystems but time and sound are of the essence.

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Chapter 2



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Chapter 3

Dear Jamie McWilliam,

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Patterns of biophonic periodicity on coral reefs in the Great Barrier
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