Spatial and temporal characteristics of the underwater soundscape around the Motiti Protection Area: Ōtaiti/Astrolabe Reef and Motiti Island

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Abstract

Marine ecosystems around the world have been impacted by degradation and loss of biodiversity as a result of human impacts and climate change. The monitoring and management of ecologically significant areas is vital in understanding the effects of habitat degradation on marine ecosystems. Traditional monitoring methods are often expensive, time consuming, labour intensive and invasive. Soundscapes offer a unique opportunity for monitoring habitats in a way that is cost effective, minimally invasive and efficient. The aim of this study was to use passive acoustic monitoring to create a baseline data set using ambient sound data to investigate the spatial and temporal changes in ambient sound pressure levels, and to identify biotic, abiotic and anthropogenic sound sources which make up the marine soundscapes at the Motiti Island and Ōtaiti/Astrolabe Reef. Five diverse and ecologically significant sites in the Motiti Protection Area – at Ōtaiti/Astrolabe Reef and Motiti Island, in the Bay of Plenty, New Zealand were selected and monitored over the course of a year. This provided a wide variety of data to show the diel, lunar and seasonal patterns and trends in acoustic biological activity in order to represent the ecosystems accurately. The results showed that all sites showed strong diel patterns, with a sound pressure level increase of ~6-10dB during daylight hours compared to dark hours, and evident peaks during dawn and dusk hours as a result of biological choruses composed largely of sea urchins. There were also strong seasonal trends among the five sites, with Summer having the overall highest sound pressure level compared to Spring, Autumn and Winter, this also had an effect on the peaks in dusk choruses, which were also found to be highest during Summer. Lunar phases were also found to have an impact on the sound pressure levels of all five sites, with increased sound pressure levels during the new moon, compared to sound pressure levels during the full moon. This study created a baseline data set for a culturally, ecologically, and economically valuable area. Passive acoustic monitoring was found to be an incredibly useful tool in understand the ecosystems health and biological condition, and offers an alternative to traditional monitoring which is an effective, minimally invasive, and less labour intensive way of monitoring marine ecosystems.

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Chapter 1: Introduction

1.1 Soundscape Ecology

Soundscapes refer to the relationship between a natural environment, and the composition of the sound within it (Pijanowski et al. 2011a). It incorporates a wide range of acoustic contributions made up of biological, natural abiotic and anthropogenic sounds (Pijanowski et al. 2011b). These biological, natural abiotic and anthropogenic sounds vary spatially and temporally; for example, natural landscapes such as rainforests support a diverse array of sound produced by organisms, while habitats such as urban landscapes are largely filled with human activity produced sounds (Pijanowski et al. 2011a). The soundscape of a habitat is an intrinsic feature, which can influence other ecological processes such as mating, habitat selection and predation (Rossi et al. 2016). Therefore, characterising the soundscape of a habitat is a valuable indicator of ecologically important aspects, such as biodiversity, species interaction, and degree of human disturbance (Dumyahn and Pijanowski 2011, Pavan 2017, Mooney et al. 2020).

The soundscape of an ecosystem can represent the ecological status of a specific habitat. Healthy ecosystems contain a wide range of vocalising and sound producing species, which contribute to the unique soundscape of that specific habitat. This plays a vital role in ecosystem functioning (Lamont et al. 2022b). While many species rely on light and chemical cues as effective forms of receiving information from their environment on a small spatial scale, sound allows for significant information to be conveyed over far greater distances (Pieretti et al. 2017). Furthermore, marine soundscapes play a vital role in the life history of many marine species, ranging from mate selection to habitat selection. For example, many marine larvae species use sound as a tool for orientation and settlement cues, locating objects such as food, attracting potential mating partners and deterring predators in self-defence (Radford et al. 2010). Therefore, sound is a fundamental aspect of the lifecycle of many different marine species (Pieretti et al. 2017). As a result of this, habitat degradation causes drastic changes to the soundscape of habitats which reduces the dispersal of acoustic settlement cues to settlement-stage organisms (Gordon et al. 2018, Lamont et al. 2022b).

Variation of sound-producing species within a community structure in a habitat often results in recognisable patterns; generally, natural soundscapes created by organisms follow daily, monthly, seasonal, and lunar cycles (Harris and Radford 2014). These habitat-level differences in soundscapes can be viewed as signatures of unique ecosystems, and therefore have great potential in enriching our understanding of their trends, if they are monitored consistently over time (Pijanowski et al. 2011a). Consistent monitoring of soundscapes within marine ecosystems for changes in their characteristics may be able to provide an early indication of disturbances, therefore baseline metrics for soundscapes are a vital component of being able to recognise and interpret any changes within a soundscape as they relate to monitoring and managing MPAs (Dumyahn and Pijanowski 2011, Pavan 2017, Mooney et al. 2020).

The consistent monitoring of soundscapes over time allows these changes to be placed within the context of the pre-existing biological, geological and anthropogenic patterns (Wenz 1962, Fournet et al. 2018, Haver et al. 2019, Erbe et al. 2021); this then allows for detailed progress reports on habitat health, which can help distinguish between healthy and deteriorating ecosystems (Pijanowski et al. 2011a).

While acoustic monitoring has many positive aspects, there are also challenges posed by variability within the marine realm. The effectiveness of an acoustic sampling regime of a soundscape is largely influenced by the acoustic variability of a habitat throughout space and time (Mooney et al. 2020). Acoustic sources such as biotic and abiotic factors like vocalising species and wind/wave action can change drastically with within a habitat; through diel, lunar, and seasonal cycles, as well as factors such as temperature, salinity, and upwelling (Nedelec et al. 2015, Lillis and Mooney 2018). Not only does the acoustic variability frequently change between habitats, but it has also been shown to change within the same habitat; with significant variations taking place at hydrophone sites placed just metres apart (Kaplan et al. 2015). Furthermore, the activity of species which produces sound, whether that be directly through vocalising or indirectly as a by-product of feeding, affects their detectability through acoustic monitoring. Organisms can only be detected by hydrophones if they are acoustically active, and if they are not being masked by the acoustic signals of other species (Mooney et al. 2020). Most species produce sound at different intensities, so while the presence of key vocalising species that are easily identified can be indicators of a healthy ecosystem. There may also be keystone species that could be an indication of high biodiversity and a healthy ecosystem, yet their presence is not known due to them either not being a sound producing species or being drowned out by others (Mooney et al. 2020). When using acoustic monitoring it is vital to address the diversity of the habitats in question. It is important that both the differences within and amongst habitats are addressed, as well as the complex dynamics of biotic and abiotic influences in order to accurately represent the soundscape (Kaplan et al. 2015).

1.2 Physics of sound in the underwater marine environment

Sound is a longitudinal waveform, which travels through a medium such as air or water, as a result of vibrations of particles within the medium itself, created by released pressure waves (Rogers and Cox 1988). Sound has three variables which characterise it, frequency (f), wavelength (λ) and amplitude (intensity/energy level) (Nummela and Thewissen 2008). The frequency of sound equates to the amount of times an oscillation occurs within a specific period of time, usually number of cycles per second, and it is measured in Hertz (Hz). Wavelengths refer to the measurable distance between the crests of an acoustic wave, and sound amplitude refers to the magnitude as well as the direction of sounds energy and represents a time averaged measurement of sounds pressure and particle velocity, measured in Decibels (dB) (Urick 1983, Nummela and Thewissen 2008). Sound waves consist of alternating pressure deviations, which cause compression and refraction within localised areas (Urick 1983). The wavelength and frequency of sound are inversely related and come together to form sound velocity ($c = \lambda f$), sound velocity (c), refers to the velocity at which sound travels through a medium (Nummela and Thewissen 2008).

Sound is transmitted more effectively through water than air, travelling up to five times faster, this is due to the difference in densities between the two mediums, enabling low environmental attenuation and absorption rates in water, and therefore a long-range transmission of information (Rogers and Cox 1988). Generally, high frequencies are attenuated more rapidly and generally propagate a relatively short distance of a few kilometres (Nagelkerken et al. 2019), while low frequency sounds travel farther (>100 kilometres) because their energy is absorbed more slowly (Bass and Clark 2003). For example, a 500 Hz signal only suffers 1 dB of attenuation due to absorption in 100 km of propagation (Ainslie and McColm 1998). The simplest model for sound propagation underwater is spherical spreading, where sound intensity decreases as radial distance from the source increases in a boundless medium (Urick 1983).

However, sound propagation in shallow water is intrinsically different to deep water propagation, given that sound can only propagate over distances greater than the water depth by repeatedly interacting with the surface and seafloor (Rogers and Cox 1988, Bass and Clark 2003). Consequently, cylindrical spreading is a more accurate description of sound propagation in these environments. Both spherical and cylindrical spreading only approximate sound propagation in the underwater environment (Lurton 2002), and shallow waters also vary vastly in bathymetry, sediment composition, surface roughness, temperature, depth, and salinity, which can all influence the acoustic nature of an ecosystems (Bass and Clark 2003, Erbe et al. 2016a). Sound transmission remains one of the least understood aspects of the physics of sound in shallow waters due to the many details regarding the physical attributes of the environment and how much they vary site by site (Radford 2007).

1.3 Underwater Sound Sources

Underwater soundscapes change vastly through space and time. Technological advances over recent years have allowed for the aquisition of long-term recordings, which can encompass years' worth of data with minimal interference to marine life. These enhanced recording capabilities allow for a better understanding and characterisation of marine soundscapes and assist in identifying the sources of the individual sounds (Vieira et al. 2021).

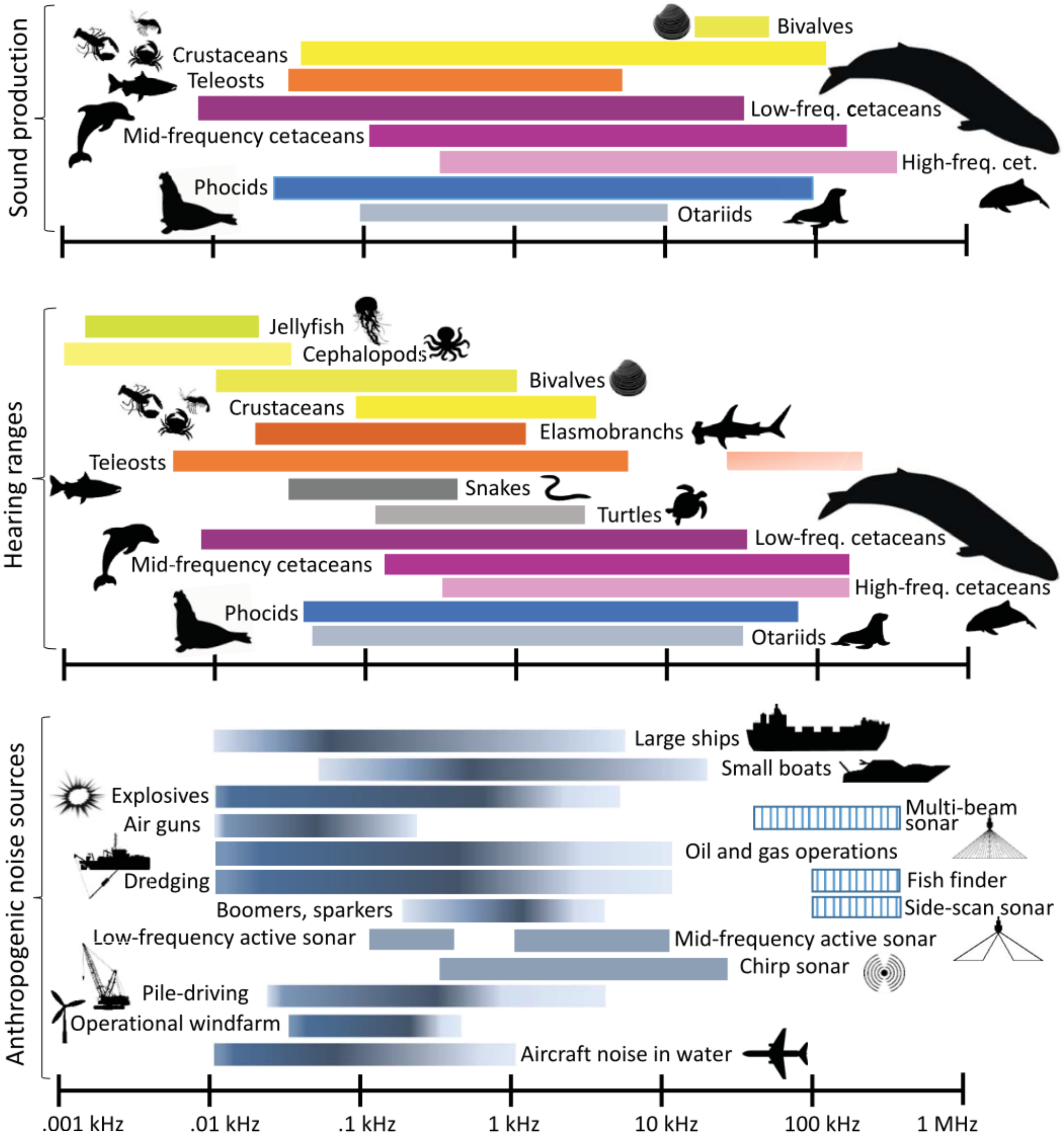


Figure 1. The approximate sound production and hearing ranges of various marine taxa, and frequency range of examples of common anthropogenic sound sources. Ranges represent the acoustic energy over the dominant frequency range of the sound source. Colour and shading represent the dominant energy band of each sound source, and the dashed lines represent sonars to depict the multifrequency nature of these sounds. Sourced from (Duarte et al. 2021).

1.3.1 Biotic

Many marine species have sensory systems that provide them with information on their surrounding environment, the most common sensory signals that marine species use are light, chemical and/or acoustic. Species are likely to use several different forms of sensory signals, as each possess its own unique communication properties. Sound is a very efficient sensory signal as it can provide information rapidly and in certain conditions over great distances (Popper et al. 2020). Four groups of marine animals are known to produce and contribute to biological sound sources; fish, urchins, crustaceans and marine mammals, ranging from 10 to >100,000Hz (Putland et al. 2017). Over 800 species of fish alone have been identified as vocal (La Manna et al. 2021). Fish typically produce sound for means of social cohesion, reproductive display, migration, and territorial defence (Putland et al. 2017, Popper et al. 2020). Sea urchins don't produce sound as a form of communication but rather a by-product of tasks such as feeding, their tests contribute to the magnification of the sound produced by feeding as they act as resonators, reaching between 800-2,800Hz (Radford et al. 2008a). Snapping shrimp create sound through opening and closing an oversized claw, which compresses trapped air, creating a snap that can range in frequency between 3,000 - 22,000 Hz; this behaviour is often produced to stun or kill its prey (Versluis et al. 2000). Marine mammals such as whales, dolphins and seals also produce a wide range of different vocalisations over a wide frequency range, which also contribute to the acoustic signatures of different marine ecosystems and habitats (Han et al. 2021).

Underwater choruses have been shown to be a vital component in assisting the larval of key reef species such as fish, crayfish, and crabs to find a suitable habitat (Tolimiere et al. 2002, Montgomery et al. 2006). In New Zealand, the first time this phenomenon was described was at Great Barrier Island by Tait (1962), after an observed increase in the 700 – 2000 Hz frequency band. Typically, evening dusk choruses begin at sunset and can continue for up to 5 hours, and dawn choruses typically begin just before sunrise (Radford 2007). Underwater dusk and dawn choruses have been shown to enhance the potential use of underwater sound as an orientation cue to many species, they convey information on the species inhabiting an ecosystem which can transmit further offshore for larvae species to identify and follow (Radford 2007). While many of the species that are responsible for the dusk and dawn choruses around the world are still unidentified, in New Zealand coastal water, the primary sources of sound that makes up the dusk and dawn choruses are sea urchins and snapping shrimp (Radford et al. 2008a).

1.3.2 Abiotic

Abiotic sound is classified as naturally occurring sound originating from the geophysical environment, such as wind, rain, earthquakes, and volcanic activity. Abiotic sound is among the more intense and highly variable yet regular components of a soundscape (Putland et al. 2017). Most commonly occurring abiotic sound sources include wave action and rain, which produces frequencies ranging from 100 Hz – 20 kHz, mostly impacting shallower coastal systems (Duarte et al. 2021). This occurs through the oscillation of air bubbles entrained at the surface of the water, when for example, whitecaps are formed by wind speeds greater than 5m/s, and the effect of the physical impact of the rain on the sea surface produces sound (Erbe et al. 2015).

Less frequent abiotic sound sources such as earthquakes and underwater volcanoes are shown to produce long impulses which produce frequencies ranging from 1 – 1,000 Hz, which can attenuate over thousands of kilometres (Duarte et al. 2021).

1.3.3 Anthropogenic

Human activities have altered the underwater soundscape within many marine environments, while also adding anthropogenic sound (Duarte et al. 2021). For example, degradation of diverse ecosystems such as kelp forests, coral reefs, sponge beds and sea grass beds has led to a reduced level of biodiversity and therefore less diverse biotic sounds (Butler et al. 2016, Gordon et al. 2018), and global warming contributes to changes in abiotic sound in polar areas through a decrease in ice cover (Duarte et al. 2021). Anthropogenic sound is the product of the operation of man-made creations such as cars, trains, airplanes, and industrial machinery (Farina 2013). While most human activities don’t intend to directly alter the soundscape of an environment, it is often a by-product. Seismic surveys, multibeam echosounders and side-scan sonars are all examples of deliberate human use of marine sound, while unintentional human produced sounds can include a wide range of activities from pile driving for offshore windfarms to recreational activities such as motorboats, and even traffic on bridges and fireworks (Duarte et al. 2021). Both intentional and unintentional anthropogenic sounds produced can vary in frequency, intensity and duration and therefore also vary in degree of impact and change to a soundscape. The anthropogenic component of the soundscape has become and is continuing to become more intrusive and dominant in many areas of the world, largely associated with growing urban development and globalised trade (Farina 2013).

1.4 Ecological Relevance of Sound

For many species, sound reception is an intrinsic component that allows organisms to relate and interact with their surrounding environment. Many species use sound and sound reception abilities to receive important signals and interact with their surrounding environment or other organisms (Pavan 2017). Individuals derive meaning from these acoustic signals, which vary widely, from mate attraction, courtship, navigation, foraging, agnostic displays, and territorial defence (Pavan 2017). For example, male toadfish guard their benthic nests and produce humming sounds to attract females (Thorson and Fine 2002), Atlantic cod use sound in order to assemble large aggregations to coordinate spawning events (Rowe and Hutchings 2006), and many marine mammals vocalise as a form of communication to aid in mating, rearing their young and group cohesion for social and feeding functions (Erbe et al. 2016b). Marine mammals produce mechanical sounds as well as vocalisations, for example the sound produced by the animal’s body on environmental substrates, like humpback whales breaching and tail-slapping the surface of the water, this can often convey information on size and body mass (Dunlop et al. 2008). Some species also use sound as a means of foraging and hunting for food, snapping shrimp produce a loud snap sound in order to stun their prey (Lillis and Mooney 2018), and odontocetes such as sperm whales and various species of dolphins use bio-sonar systems which produce sounds in order to echolocate to detect and hunt prey (Thomas et al. 2004). Species such as invertebrates and fishes are generally thought to largely perceive relatively low frequencies (<8 kHz), with some exceptions like herring, shad, cod etc., while species such as cetaceans can also detect higher frequencies (up to 200 kHz). Knowledge of a species' reception bandwidth is a critical determinant of their potential responses and vulnerability to different components of marine soundscapes, especially anthropogenic sound (Duarte et al. 2021). The diversity, composition, and density of biotic sound sources are a key component of soundscapes, they play an important role in understanding the health status and functionality of an ecosystem (Duarte et al. 2021). Many larval vertebrate and invertebrate species use soundscapes as a navigational cue to detect suitable settlement habitats (Montgomery et al. 2006).

1.4.1 Anthropogenic sound/noise

Prior to the industrial revolution, soundscapes within marine environments were, to a great degree, composed of sounds stemming from geological and biological sources, with very limited anthropogenic sound from human activities (Duarte et al. 2021). Since the industrial revolution, soundscapes have changed substantially due to anthropogenic sound, and it continues to be a growing concern as oceans become busier and noisier (Van Geel et al. 2022). It is vital to understand the contexts and relative contributions of all sound sources in order to provide an insight into how anthropogenic activities change and influence natural ocean soundscapes, and their effects on marine life as well as the overall health of the ocean (Duarte et al. 2021). While it has been a well-known issue in the terrestrial world of study, there is a growing understanding that anthropogenic sound also plays a critical, and arguably more detrimental role in the marine environment as a major pollutant of international concern (Putland et al. 2017). Anthropogenic sound has been found to cause effects at scales ranging from individual organisms to entire ecological communities, causing behavioural effects and in rarer cases, physical injury (Putland et al. 2017).

There are growing international concerns that underwater anthropogenic sounds can have significant impacts on marine species (Popper et al. 2020). Anthropogenic sound has not only been shown to have direct effects on marine species, but also has been shown to have indirect impacts on marine ecosystems as a whole; for example, behavioural reactions of fishes due to sound exposure can lead to displacement in wider areas, forcing predators such as marine mammals that rely on these species as a source of food to have to search farther for food (Gill et al. 2012). In addition to this, increased levels of anthropogenic sound within an ecosystem has been shown to change the behaviour of individual organisms and can lead to physiological damage to their hearing systems, altering their startle responses and attention distraction which can lead to individuals being overstimulated and distracted, making them more susceptible to predation (Peng et al. 2015).

Many marine organisms depend on the ability to take in and interpret acoustic information from their surrounding ecosystem for their survival (Peng et al. 2015). Acoustic interference is one of the main growing concerns for marine species affected by increased levels of anthropogenic sound. Acoustic interference or masking is referred to when the collective noise from many individual sources impedes an individual's ability to understand, recognise or detect sounds of interest and importance (Clark et al. 2009). It has been shown that acoustic masking due to increased levels of anthropogenic sound has a prevalent impact on species access to vital acoustic information which is essential for communication, navigation, and prey/predator detection (Clark et al. 2009). There are two kinds of masking, energetic, and informational. Energetic masking refers to when the signal of interest is overlapped by a sound of the same frequency and time, while informational masking refers to when a sound signal cannot be distinguished from the ambient soundscape (Clark et al. 2009, Putland et al. 2019). Both result in the sound signal not being perceived, recognised, or understood. For example, vessel sound is a chronic, lower level anthropogenic sound that could have disruptive masking effects on communication between fish (Stanley et al. 2017).

Due to global concerns about the effects of anthropogenic sound on marine ecosystems, there have been associated increases in the extent of research on the subject, attempts to develop regulations and guidelines to protect species from increased levels of anthropogenic sound, and ongoing research in an attempt to potentially mitigate the harmful level of anthropogenic sound being produced (Popper et al. 2020).

1.4.1.1 Shipping Sound

Many marine species produce and use sound in accordance with critical life functions; anthropogenic sound such as shipping and vessel sound can impede the ability of these species to communicate, find food sources and mating partners, or orient and interact with their surrounding environment. Individual vessels have been shown to contribute to overall ambient sound levels on variable spatial scales. Depending on their nature and use, ships are often equipped with underwater detection systems, such as sonars, which additionally increase underwater noise radiating acoustic impulses (Kozaczka and Grelowska 2004). Additionally, factors such as abundance, position, speed, and type of boat are all likely to influence the level of sound produced (Wilson et al. 2022). In ships such as container ships, the main source of sound generated comes from the ship’s auxiliary generator, which supplies uninterrupted electrical power from the bow of the ship to the stern. This radiates tonal components which largely contribute to the radiated sound power of the vessel, which is independent from the vessel's movement and speed (Kozaczka and Grelowska 2004).

Studies have shown that ambient sound levels in the marine environment have been rising since the 1960’s due to increases in shipping traffic and tonnage (Merchant et al. 2012b). Following current global trends, New Zealand is expected to have increased levels of vessel traffic by 70-75% over the next 20 years (Port of Tauranga 2022). Based off Maritime New Zealand Recreational Boating Monitor statistics, the amount of recreational vessel users in the country has increased from approximately 30% in 2014, to 55% in 2022 (MaritimeNZ 2022). In 2011, Auckland residents alone were found to have the highest recreational vessel ownership per capita in the world, estimated at 132,000, which is expected to increase to 183,000 by 2041 (Beca 2012).

1.5 Marine Protected Area Management in New Zealand

Marine Protected Areas (MPAs) are now globally recognised as a vital element of the approach to fisheries management and biodiversity conservation (Davies et al. 2018). The aim of MPAs is to be a contributing factor to a larger marine management system which is designed to "achieve an appropriate balance between protecting the marine environment and maximising commercial, recreational and cultural opportunities now and in the future" (Scott 2016). This is generally focused on areas deemed valuable to preserve, such as sites that serve as a typical example of important ecosystem features and values in their natural state (Scott 2016).

New Zealand is known as a pioneer in the marine conservation field, with the first MPA being proposed in 1965, known as the Goat Island Marine Reserve, adjacent to the Leigh Marine Laboratory, which was ultimately established in 1977 (Brake and Peart 2015). Despite the clear environmental, scientific, and economic benefits of marine protected areas, MPA planning is highly complex; and can take extended periods as they require careful consideration and analysis of data, as well as taking into consideration the cultural aspects and balancing conflicting and overlapping interests (Davies et al. 2018). The MPA policy provides a robust structure for implementing marine protected areas through planning forums, which state that sectors that will be affected by the establishment of a marine protected area, such as Tangata Whenua, commercial fisheries, and recreational users, should be represented where relevant (Davies et al. 2018).

Despite the overwhelming amount of scientific evidence that anthropogenic sound has negative effects on marine species, there are very few examples of legislation or spatial planning that focuses directly on the management of underwater anthropogenic sound (Scott 2004, McCarthy 2007, Erbe 2013, Daly 2015). In addition to this, domestic legislation focusing on underwater anthropogenic sound has been implemented in a handful of countries, however the legislation is generally aimed at managing the effects on marine mammals only, or specific activities such as seismic surveys (Compton et al. 2008, Daly 2015). In New Zealand, the effects of anthropogenic sound on soundscapes, and sound pollution are very minimally considered in New Zealand's protection standards (Pine et al. 2013). The primary piece of resource management legislation in New Zealand is the Resource Management Act 1991 (RMA), which governs the use of land and the Coastal Marine Area (CMA) (Nolan 2011). While the RMA provides regional councils across the country with various forms of legislative instruments, the ability for spatial planning and requires councils to manage the adverse effects of noise in terrestrial environments; regional councils are said to be taking a ‘minimalist approach’ to this same planning and management for underwater noise (Palmer 2013, Pine et al. 2013).

1.5.1 Motiti Protection Area

In 2018 the Environmental Court released a decision which found that the reef ecosystems off the coast of the Bay of Plenty and Motiti Island had outstanding natural attributes and high values which required greater protection. Consequently, on 24th April 2020 the Environmental Court released its final decision for the Bay of Plenty Regional Council to execute new rules within its Coastal Management Plant to protect this area and complete scientific monitoring to inform future marine management (Crawshaw 2022). The Court of Appeal determined the statutory relationship between the Resource Management Act 1991 (RMA) and the Fisheries Act 1996 (FA) in the protection and maintenance of biological diversity, which is primarily centred on indigenous biodiversity and acknowledges the significant marine landscape and cultural values in the area (Urlich 2020). It was stated that the implications of Motiti Island and Astrolabe Reef are wide-ranging and nuanced, and will become apparent with time, for example, cultural motives to protect the biodiversity within these systems could result in place-based fishing restrictions to prevent the decline of biodiverse kelp forests and proliferation of kina barrens as a result of overfishing of species that control sea urchin populations (Urlich 2020). Protection of the area came into effect in August 2021 (BOPRC 2022) (See Figure 3).

1.6 Passive Acoustic Monitoring

Monitoring marine ecosystems is one of the best tools in aiding the management and recovery of marine ecosystems. However, there are numerous challenges associated with biodiversity and habitat condition measurements. Assessing biodiversity in the field, even in easy access study sites is time-consuming, labour-intensive, expensive, generally invasive and highly susceptible to human bias and error (Merchant et al. 2015). Furthermore, more often than not, especially in marine studies, it requires trained specialists who must individually identify and count species within a predetermined study site by hand, this is a process that can take weeks or months to complete depending on the study site and duration of the study (Harris and Radford 2014). Additionally, there are unavoidable biases such as bias towards species which are larger and more visible, and human presence having an effect on attracting and deterring species to the area of study (Merchant et al. 2015).

However, although monitoring and measuring biodiversity over large spatial and temporal scales in marine ecosystems is challenging; continued global biodiversity loss requires data at these large scales to be able to make informed management and policy decisions in regards to marine and biodiversity protection and management (Harris and Radford 2014). Acoustic monitoring allows for detailed reports on biological, geological or anthropogenic sounds emanating from the monitored site and can give indications on habitat health over extended periods of time with minimal interference with the marine ecosystem (Harris and Radford 2014).

Autonomous passive acoustic monitoring, also known as PAM, is a form of remote monitoring which allows for non-invasive means of recording acoustic data (Mellinger et al. 2007, Thomas and Marques 2012). This monitoring technique allows for habitat health monitoring through a range of aspects such as biological presence which is necessary to characterise soundscapes, and anthropogenic influence such as vessels, sonar, or underwater explosives. Furthermore, PAM allows for continuous, long-term monitoring which provides data with various time scales such as diurnal reef chorusing and seasonal migratory patterns (Merchant et al. 2015). This provides a broad spectrum of all acoustic contributions to a specific ecosystem including biotic, abiotic, and anthropogenic sounds.

1.7 Aims and Significance of Thesis

The overall aim of this study was to use standardised equipment and analysis techniques to collect ambient underwater sound data and derive measurements to investigate spatial and temporal changes in ambient sound pressure levels and identify biological and anthropogenic sound sources contributing to the soundscape to support within and among site comparisons of the underwater soundscapes of Motiti Island and Ōtaiti/Astrolabe Reef in the Bay of Plenty. This will develop ‘baseline’ data sets on the local soundscapes and well as forming a better understanding of human presence and use in the area, while recording any early changes in human activities after the recent formation of the Motiti Marine Protection Area. It is hoped that this research will highlight future opportunities for integrating non-acoustic and acoustic variables in order to inform area specific management questions of interest.

The research is essential as with an ever-increasing population, identifying a baseline data set of soundscapes will help gain a better understanding for future management and mitigation methods. The field of sound pollution is a relatively young one, with many areas which still have knowledge gaps. This means that a large amount of groundwork data collection is required to develop a framework. This framework would be used in order to make conclusions on how the ecosystem function is affected over time to a variety of changing soundscapes; and how we can implement this knowledge in the establishment of future marine protected areas.

This research will focus on understanding the local soundscapes around Motiti Island and Astrolabe reef, in addition to this, the research will also focus on the impacts and effects of local anthropogenic sound coming from recreational and commercial vessels such as the container ships coming into the Tauranga Port.

Anthropogenic sound pollution is an issue that is not very widely understood, this research will provide vital information to understanding local soundscapes and the impacts that local marine fauna is exposed to with anthropogenic sounds coming from recreational and commercial vessels. This research is a vital component of understanding and implementing areas of marine conservation, such as marine reserves and marine protected areas. This is especially significant research in the Bay of Plenty due to the recent establishment of the Motiti Protection Area as it will create a base-line acoustic data set for future marine protected areas.

Chapter 2: Methods

2.1 Study Locations and Deployment Schedule

The five recording sites selected for acoustic monitoring during this study were positioned offshore, around Motiti Island and Astrolabe Reef in the Bay of Plenty, New Zealand (Figure 3, Table 1). The study sites ranged in depth (between 15-20 m), and habitat type (rocky reef and soft sediment) (Table 1). Sites 1 and 2 were located on the east and west sides of Motiti Island, Sites 3, 4 and 6 were located within the northern area of the Ōtaiti/Astrolabe Reef, Okarapu Reef and Te Papa/Brewis Shoal Motiti Protection Area (MPA1) (Figure 2 & 3, Table 1). The study sites were chosen as an area of significance due to cultural, ecological and economic significance, specifically in relation to the new Motiti Protection Area that was established in 2020 and came into effect in August 2021 (Figure 3). The sites were chosen using available data that reflected areas that are likely to be influenced by variable acoustic influence from sound producing species such as snapping shrimp and fish, and human activity such as vessel movement. Given the relatively localised acoustic propagation field around shallow water sites, it is understood that two to three recording locations is not sufficient to describe the soundscape conditions in the entire area. Therefore, locations were chosen where other information sources were available (including past information from diver surveys and other oceanographic sampling), and where acoustic signals of interest would likely be present (both biotic and/or anthropogenic).

2.1.1 Motiti Island

Motiti Island is located 12 km offshore from the Bay of Plenty coast (Briggs et al. 2006). The island has a number of both exposed and sheltered sandy bays and relatively shallow macroalgae rocky reefs that reach a depth of 25 m before hitting sand. Motiti Island was affected by the events of the MV Rena, as Astrolabe reef is located 7 km away from Motiti, oil from the spill, shipping containers and their contents all reached the shores of the island.

2.1.2 Ōtaiti/Astrolabe Reef

Ōtaiti/Astrolabe Reef is located 7 km North of Motiti Island (Figure 2), it is situated towards the southern end of a chain of reefs and islands lying offshore and parallel to New Zealand's northeast coast. It rises from a depth of 90 m, to a narrow peak which breaks the sea surface at mid-low tide (Ross et al. 2016). Astrolabe Reef is subject to greater wave action and currents than Motiti Island due to its exposed locations, and its deeper surrounding water. Astrolabe Reef has been of great significance in relation to monitoring since New Zealand's worst maritime environmental disaster occurred in 2011, when the MV Rena ran aground on the reef, resulting in 350 t of heavy fuel oil leaking into the surrounding sea, causing detrimental environmental impacts (Faaui et al. 2017).

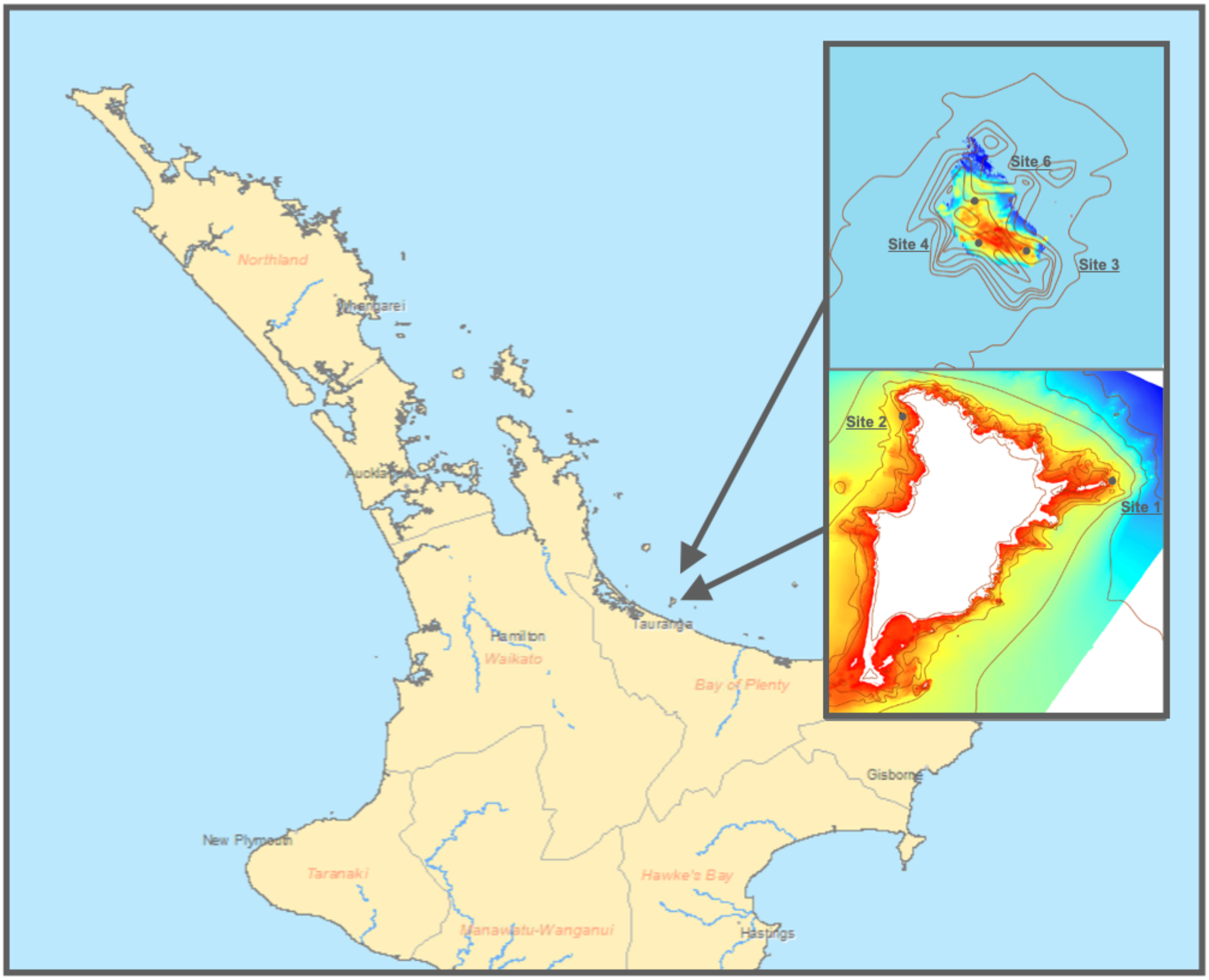
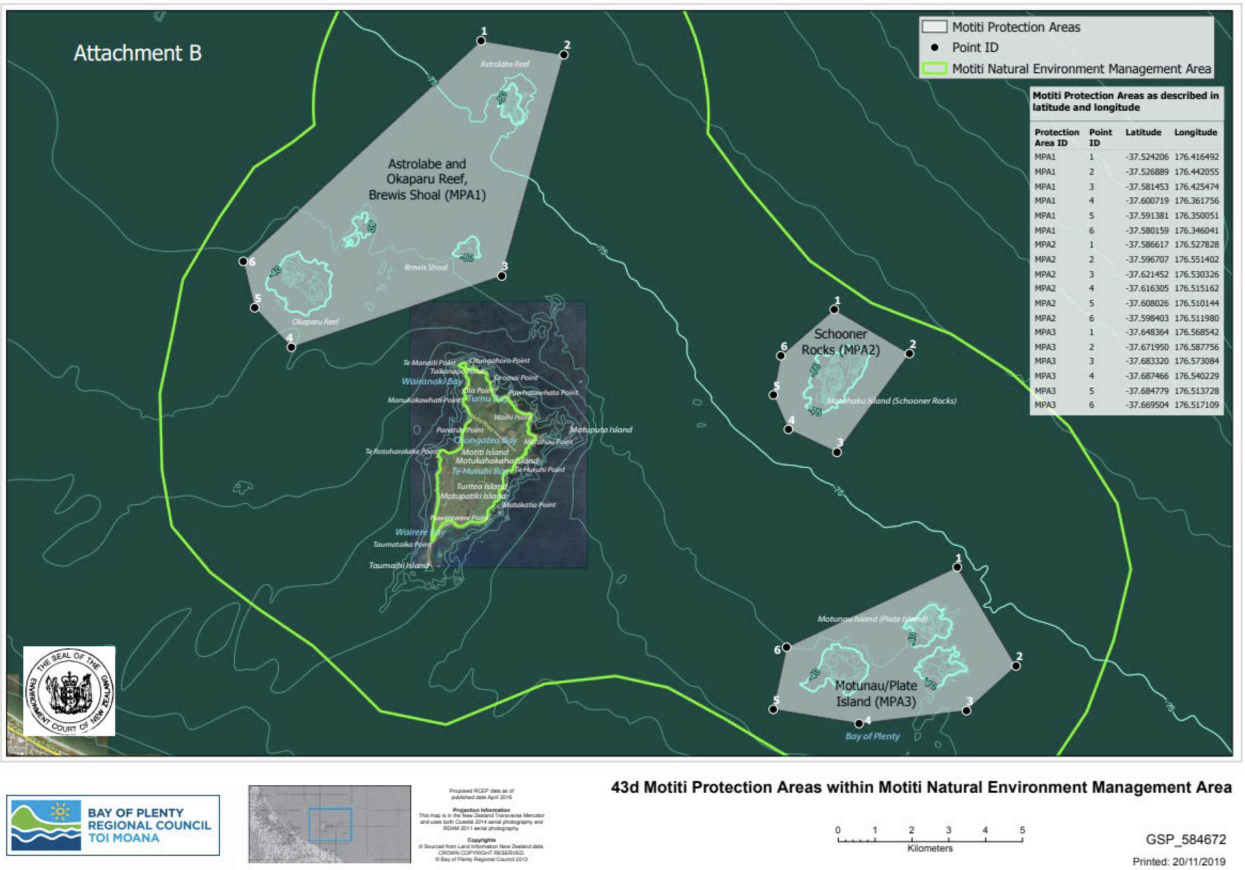


Figure 2. Locations of hydrophone sites in and around the Motiti Protection Area, Bay of Plenty, New Zealand. Maps not drawn to scale.



Motiti Protection Areas as described in latitude and longitude

Protection Area ID	Point ID	Latitude	Longitude
MPA1	1	-37.524206	176.416492
MPA1	2	-37.526889	176.442055
MPA1	3	-37.581453	176.425474
MPA1	4	-37.600719	176.361756
MPA1	5	-37.591381	176.350051
MPA1	6	-37.580159	176.346041
MPA2	1	-37.586617	176.527828
MPA2	2	-37.596707	176.551402
MPA2	3	-37.621452	176.530326
MPA2	4	-37.616305	176.515162
MPA2	5	-37.608026	176.510144
MPA2	6	-37.598403	176.511980
MPA3	1	-37.648364	176.568542
MPA3	2	-37.671950	176.587756
MPA3	3	-37.683320	176.573084
MPA3	4	-37.687466	176.540229
MPA3	5	-37.684779	176.513728
MPA3	6	-37.669504	176.517109

Proposed RCEP data as of published date April 2016

Projection Information
This map is in the New Zealand Transverse Mercator and uses both Coastal 2014 aerial photography and RDAM 2011 aerial photography.

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© Bay of Plenty Regional Council 2013

Figure 3. Location and area of the Motiti Protection Area, established in August 2020 (Bay of Plenty Regional Council, 2020).

Table 1. Habitat classification and location information of the five hydrophone sites in and around the Motiti Protection Area, Bay of Plenty, New Zealand.

Site	Identifier	Location	Number of deployments	Type of habitat	Latitude	Longitude	Water depth (m)
Site 1	MotitiPA01	Motiti Island	2	Shallow boulder/rocky reef	S 37.61806	E 176.45018	19
Site 2	MotitiPA02	Motiti Island	2	Shallow sand with adjacent shallow rocky reef	S 37.60644	E 176.41209	16.5
Site 3	MotitiPA03	Astrolabe Reef	2	Shallow macroalgae dominated boulder reef	S 37.54161	E 176.42896	20
Site 4	MotitiPA04	Astrolabe Reef	2	Shallow macroalgae dominated rocky reef	S 37.54089	E 176.42618	15
Site 6	MotitiPA06	Astrolabe Reef	2	Shallow macroalgae dominated rocky reef	S 37.53864	E 176.42586	18

2.2 Passive Acoustic Data Collection

Two, five to six month deployments took place during this study, resulting in data collected for each season for close to one year. Hydrophones were set to be deployed and record for approximately five months at a time, deployment and retrieval dates varied, however, due to complications with field operations during COVID-19 Pandemic Alert Level 3 & 4 mandatory “lockdowns”, and weather conditions. Deployment 1 took place from 03/05/21 – 10/11/21, and deployment 2 took place from 09/11/21 – 13/05/22. Seasons were defined using the New Zealand standard calendar, and sunrise and sunset times, and lunar phase cycle data were obtained from the Royal Astronomical Society of New Zealand (http://rasnz.org.nz/in-the-sky/sun-rise-and-set). The following austral seasons are used throughout the thesis in general, Winter 2021 (June - August), Spring 2021 (September – November), Summer 2021/2022 (December – February), and Autumn (March/April).

Table 2. Duration of acoustic recordings (days) at each site per season. Number of days vary due to the timing on ability to retrieve dur to COVID-19 restrictions (R), reaching memory capacity (M), or instrument malfunction (IM).

Site	Identifier	Location	Winter (June-Aug)	Spring (Sept-Nov)	Summer (Dec-Feb)	Autumn (Mar-April)	Total
Site 1	MotitiPA01	Motiti Island	88 (M)	42 (R)	90 (R)	20 (M)	240
Site 2	MotitiPA02	Motiti Island	92 (M)	43 (R)	90 (R)	48 (M)	273
Site 3	MotitiPA03	Astrolabe Reef	92 (M)	57 (R)	90 (R)	41 (M)	280
Site 4	MotitiPA04	Astrolabe Reef	0 (IM)	22 (IM)	90 (R)	42 (M)	154
Site 6	MotitiPA06	Astrolabe Reef	0 (IM)	22 (IM)	90 (R)	24 (M)	136

2.2.1 Instrumentation

All acoustic recordings in this study were made using SoundTrap ST 300 (Site 1 & 2 – Winter) and ST600 (all remainder) with a self-noise less than sea-state 0 at 100 Hz - 2 kHz and <36 dB re 1uPa above 2 kHz (Ocean Instruments, Auckland, New Zealand). All recording sites were continuously sampled at a rate of 48,000 Hz with a flat full-scale frequency response between 20 and 60 kHz (±3 dB), excluding Sites 1 and 2 during Deployment 1 at Motiti Island, which were duty cycled, and set to record 5 min every 15 min. Each instrument was calibrated by the manufacturer directly before the study and each had a unique end-to-end response sensitivity. Once retrieved, raw data files were decompressed and directly downloaded to a computer using the SoundTrap host software (Ocean Instruments, Auckland, New Zealand).

2.2.2 Mooring configuration

The acoustic recording hydrophones were deployed and retrieved by divers; fixed securely to a rigid and weighted steel stand (35 kg) located on the benthos of each site, with no surface or subsurface mooring lines or floats in order to eliminate any interfering sound. The hydrophone element was therefore approximately one metre from the seafloor in order to reduce flow noise across the hydrophone element which increases in the water column, and reduce noise created by sediment moving across the element when directly on the benthos (Stanley et al. 2021). Furthermore, the moorings were specifically designed in order to reduce any extraneous noise from the stands themselves at each site.

Figure 4. Photograph of mooring configuration with weighted stand and attached SoundTrap 600 in the laboratory.

2.3 Passive Acoustic Data Analysis

All acoustic data were analysed using custom written scripts in MATLAB software (version 2018a & 2021a) (MathWorks Inc., Natick, Massachusetts, USA) and statistical tests were run in SigmaPlot 13 by Systat Software (Build 13.0.0.83) and RStudio (version 1.1.456, R version 3.5.1; R Core Team 2020). The low frequency limit of the analysis was 20 Hz and SoundTraps have a built-in high pass filter set at 20 Hz to partially remove potential low frequency surface motion noise or vibration and flow noise. All times are standardised for local standard time at each site (daylight savings offset removed).

To quantify ambient sound levels at each recording site and variation with frequency and time scale broadband (20–24,000 Hz) Root-Mean-Squared (RMS), median (50th percentile) and 5th and 95th percentile sound pressure levels (BB SPLs) and power spectral densities (PSD) median (50th percentile) and 5th and 95th percentiles were calculated for all recordings. Power spectral densities were calculated using a Discrete Fourier transformation with a Hann window resulting in 1 Hz, 60 s resolution with 50% overlap, together representing the distribution of signal frequency components in a way that can be visually interpreted. To determine if season affected the broadband ambient sound recorded at each recording site, broadband RMS SPLs were averaged in 60-s (Stanley et al. 2021). Kruskal-Wallis statistical tests were subsequently used to test for differences. If such tests provided significant results, a Dunn's pairwise multiple comparison, with Bonferroni correction, was then used to isolate further differences. Non-parametric statistical methods were used to test for differences among seasons as the data had unequal variance among treatments and data had a non-normal distribution (Zar 1999).

Broadband SPLs were also averaged, in 5-minute bins, across each recording season, within each site, to produce an average diel trend plot for each site over each season. Sound pressure levels or band levels were also calculated in one third octave bands with a 60-s resolution for all recordings. Diel trends in select octave frequency bands, centred on 125, 251, 501, 630 and 1,250 Hz were plotted for three days around each moon phase for each recording site per location (Motiti Island and Astrolabe Reef) over all seasons to illustrate the variation among the selected frequency bands, to visualize the varying contributions of each and to demonstrate any periodicity within octave band levels. A three-day period was selected around each moon phase to illustrate daily patterns during intensity minimum and maximum, while identifying anomalies such as human activities, i.e., vessel passages. 72-h long-term spectral averages were also produced with a 5 s, 12 Hz resolution window with 50% overlap for the new and full moon phases at each site during each seasonal recording period to assist in illustrating and identifying peak daily patterns (specifically of intense acoustic biological or anthropogenic activity) for that season and day.

Spectral probability density (SPD) of the PSD was calculated using MATLAB modified scripts provided by Merchant (Pers. Comm.) for each site and seasonal recording period to assess instrument performance. The SPD can also further assist in characterising sound levels in the soundscape illustrating episodic vs. sustained changes in sound levels at particular frequencies, performance of various averaging metrics and the presence of outliers. The SPD can reveal multimodality, unwanted system noise and/or inadequate dynamic range of the system limiting adequate data collection (Merchant et al. 2013, Merchant et al. 2015).

2.3.1 Biotic and abiotic

It was not the intent of this study to manually identify and quantify all acoustic signals of biological, abiotic and anthropogenic origin. However, due to the methods of other analyses, presence and/or absence at each site during each seasonal sampling period for five commonly observed organisms was noted; sea urchin or kina (*Evechinus chloroticus*), Snapping Shrimp (*Synalpheus* sp.), Bigeye fish (*Pempheris adspersa*), two-spot demoiselle (*Chromis dispilus*), bluefin gurnard (*Chelidonichthys kumu*), and either the echolocation or whistle signals of cetaceans (various species).

Manual inspection during the verification and validation of the vessel detections required inspecting many hours per day in each seasonal recording period for each site. Every recording day was examined to some extent at all sites in all recording periods. Presence of biotic signals produced by the organisms above were recorded and subsequently summarized presence during each seasonal recording period. As every minute of each recording was not thoroughly inspected, lack of reported presence does not infer absence. The presence of cetacean signals, either whistles or echolocation clicks, at each site was examined by visually inspecting a long-term spectra average (LTSA) with a 24-hour time window, time averaging of 5 s and frequency bin size of 12 Hz for each day of the entire recording period for each site.

In addition to this, Earthquake data was retrieved from the GeoNet Project (http://quakesearch.geonet.org.nz/) in order to quantify the presence of earthquakes and compared to the acoustic recordings. Due to the high frequency of tectonic movement in New Zealand, and the hydrophones limited ability to pick up on smaller earthquakes, only earthquakes with a magnitude of four and above were included.

2.3.2 Anthropogenic

To better understand human use patterns in these areas, specifically vessel presence, all acoustic data collected at each site was run through a vessel detection algorithm (Triton Remora) to estimate the vessel presence at each site. Anthropogenic sound generally creates a substantial increase in the sound level within a soundscape, making them generally easy to identify through visual inspection of the spectrograms (Figure 5). However, each vessel detection was manually inspected; if visual inspection was still uncertain, aural analysis was used to confirm the presence or absence of a vessel.

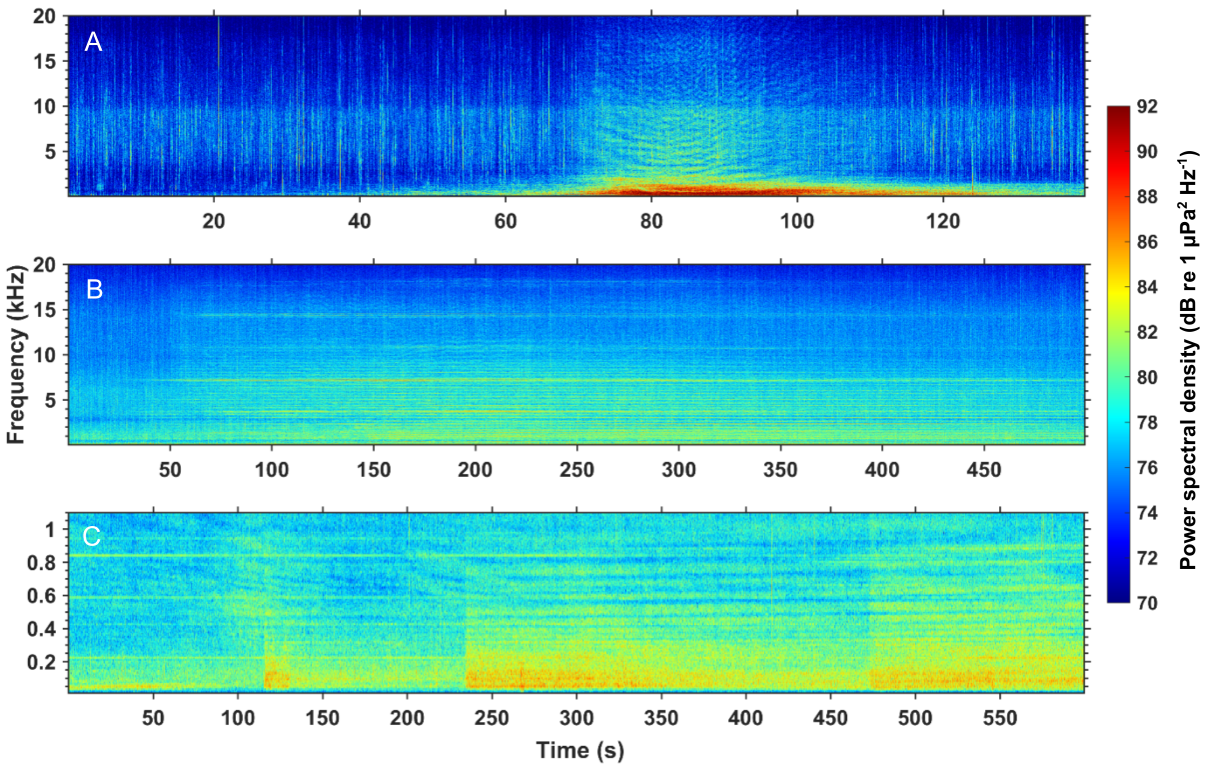


Figure 5. Spectrograms of three examples of the various types of vessel signals detected in the Motiti Protection Area and Motiti Island region. A. Small to medium sized pleasure craft transiting nearby the hydrophone, B. Large ship transiting at low speeds, C. Large ship transiting and manoeuvring at low speeds. All produced using FFT length = 6048 points, Hanning window and 80% overlap.

2.3.2.1 Triton vessel detector

All acoustic data was analysed through MATLAB software (version 2018a) (MathWorks Inc., MA, USA) using Triton Version 1.0 2021 09 21. Long-term spectra average (LTSA) files were produced for all available acoustic data for each recording site using raw .wav files using a time averaging of 5 s and a frequency bin size of 12 Hz. An LTSA is essentially a three-dimensional time-frequency energy plot or spectrogram where the power spectra plotted over time is averaged over a longer period than a typical spectrogram. The time averaging is the duration over which consecutive single-window spectra are averaged. The averaged spectra are then plotted chronologically with energy represented in colour preserving the temporal-spectral resolution of the acoustic data (Wiggins, Roch, Hildebrand 2021).

Using the created LTSA files for each site, the interactive detector was used to adjust parameters needed to meet requirement for best detecting vessels in various different locations. This step improved the performance of the detector rather than going straight into batch detection. The LTSAs were analysed in blocks of data (windows), where the PSD estimates are averaged in three frequency bands, set depending on the sampling parameters and types of vessels being detected. During the current study the following bands were set; low (30 – 100 Hz), medium (100 – 500 Hz) and high (500 – 3000 Hz). Start and end times of a detected vessel passage were then saved if the three averaged PSDs met the following conditions:

1. The amplitude of the signal is above a set time-dependant threshold, with the threshold computed using a histogram of the averaged PSD whereby it is divided into two equal regions, and the mode of each is taken as the lower and upper levels. The time-dependant threshold is then calculated as the mean of the lower and upper levels.
2. The ‘event’ duration above the threshold in the three bands (above) must be longer than a specified time, the close passage duration threshold. In addition, the duration in the higher band must be shorter than the medium band, to discard dolphin signals. Or the ‘event’ duration above the threshold in the lower and medium bands must be longer than a specified time, the distant passage duration threshold. In addition, the medium band must be shorter than the lower band to disregard click signals such as those produced by odontocetes.
3. Vessel ‘events’ are distinguished from weather events when averaged received levels in the lower band is above a specified percentage of the background noise window, the received level threshold.

To ensure ‘events’ on the edges of the analysis window (1 h) were detected, an overlapping sliding window (0.5 h) was applied.

When the most suitable parameters for the data (Table 3) were identified these settings were then used for batch detection for the entire duration of each site. Batch detection results were then verified within Triton and classified as either ‘vessel’ or ‘ambient’, false positives were corrected here to 0 %. Subsequent detection results were then outputted to a .csv format for further analysis. In the current study the parameters we set conservatively at the expense of having to classify a higher number of detections (false positives), however, this almost eliminated the error of false negatives. Parameters which were kept consistent among sites for greatest performance and consistency.

Table 3. Parameters used during batch detection with the Triton vessel detector.

Parameter	Value
Low Band (Hz)	30 – 100
Medium Band (Hz)	100 – 500
High Band (Hz)	500 – 1000
Close passage duration threshold (s)	8
Distant passage duration threshold (s)	10
Received level threshold (%)	0.003 %
Time between passages (s)	0.05
Buffer time (m)	3
Window size (h)	1
Overlapping window (h)	0.5

2.3.2.2 Testing Triton vessel detector

To understand the efficacy of the vessel detector, five days were taken at random for each site and visually and aurally inspected for vessel presence in Raven Pro 1.6 (1.6.3) (The Cornell School of Ornithology, NY, USA) whereby a training selection table file was created. This training file was overlaid on the LTSA along with the detector output from Triton and both sets of results compared. Sensitivity (Equation 1) and False Positive Rates (Equation 2) were then calculated for each of the sites (Yack et al. 2009). When a signal not originating from a vessel was detected, it was referred to as a false positive and when a signal originating from a vessel was not detected, but was present, it was referred to as a false negative.

$$Sensitivity = \frac{true\ positives}{(true\ positives + false\ negatives)} \qquad (Equation\ 1)$$

$$False\ Positive\ Rate = \frac{false\ positives}{(true\ positives + flase\ positives)} \qquad (Equation\ 2)$$

2.3.2.3 Vessel Metrics

Three metrics were calculated from the raw verified vessel detection data in order to better understand vessel presence at each recording site. Firstly, average daily vessel detections for each site, over the entire data collection period. Secondly, per day average of the vessel detections (AD) per site and seasonal recording period. Thirdly, the average number of hours per day (24 max) that had any vessel presence (AHD) per site and per seasonal recording period.

Kruskal-Wallis statistical tests were used to test for differences within and among sites, as well as among seasonal recording periods. If such tests provided significant results, a Dunn’s pairwise multiple comparison, with Bonferroni correction, was then used to isolate further differences. Non-parametric statistical methods were used to test for differences as the data had unequal variance among treatments and had a non-normal distribution (Zar 1999).

2.3.3.4 Implications of COVID-19 Pandemic

As this study was conducted over the course of a year, it is important to note that during this time there were intermittent periods of the Bay of Plenty region, and other regions being subject to Alert Level 3 & 4 Lockdowns (August – December 2021) and travel restrictions. During this time Alert Level restrictions meant that recreational boating and small charter businesses such as whale watching, and dive shops were likely to be greatly reduced. Because this study only included one year of data, the intermittent changes in Alert Levels and travel restrictions makes it very difficult to understand and tease apart changes in vessel activity levels due to these reasons and the Motiti Protection Area coming into effect in August of 2021.

Chapter 3: Results

3.1 Soundscape ‘Baselines’

3.1.1 Patterns in broadband sound pressure level

3.1.1.1 Site 1

At Site 1, median broadband (20 – 24,000 Hz) sound pressure levels (BB SPL) varied by as much 2.9 dB re 1 µPa among the recording seasons (118.4 – 121.3 dB re 1 µPa, Table 4 & 5). Seasonal fluctuations in BB SPL were statistically significant (Kruskal-Wallis $P < 0.001$, $H = 54139.6$, $DF = 3$), with the Winter recording period having the highest median BB SPL, followed by Summer and Spring, and with the lowest BB SPLs recorded in the Autumn (Table 4). The Winter recording period at Site 1 also had the highest 95th percentiles, with 95% of the data being on or below 125.8 dB re 1 µPa.

Diel patterns in broadband sound pressure level (BB SPL) varied among seasonal recording periods (Figure 6) both temporally and in amplitude. The Winter period tended to show a small increase in median BB SPL (~2 dB) around dawn and then again around dusk (~1.5 dB), following the temporal patterns in sunrise and sunset times (length of day). The Spring period also showed this temporal pattern; however, the amplitude of the rise was much greater, with a ~2.5 dB increase around dawn and ~10 dB rise after the dusk period. The peak in the evening also occurred later into the dark period than in the Winter recording period. Summer and Autumn recording periods differed from the two other recording periods in there was no distinct rise in median BB SPL around dawn. However, the peak after Dusk was of similar temporal patterning to the Spring, due to lengthening of daylight hours, and intermediate between Spring and Winter in terms of amplitude (~6 dB for both Summer and Autumn).

3.1.1.2 Site 2

At Site 2, the median BB SPL varied by 20.3 dB dB re 1 µPa among the four seasons (108.4 – 128.7 dB re 1 µPa, Table 4 & 5). The seasonal fluctuations in BB SPL were statistically significant (Kruskal-Wallis $P < 0.001$, $H = 33323.0$, $DF = 2$), with the Autumn recording period having the highest median BB SPL, followed by Summer, Spring, with the lowest being Winter (Table 4). The highest 95th percentiles at Site 2 were during the Autumn and Summer, with 95% of the data being on or below 108.9 dB re 1 µPa.

At Site 2, the diel patterns in median BB SPL varied among the four seasonal recording periods (Figure 6) both temporarily and in amplitude. The Winter recording period showed small crepuscular peaks in BB SPL, with a ~2.7 dB increase during the dawn hours, and a ~1 dB increase during dusk hours. Aside from the diel peaks, the Winter recording period also exhibited higher BB SPL during daylight hours compared to dark hours (1.5 dB on average). The Spring period showed a strong temporal pattern, with a ~2.6 dB peak in BB SPL during the dawn period and an ~11.2 dB increase after dusk, with minor bi-modal peak. The Summer period also followed the diel temporal pattern, and showed an increase of ~2.1 dB during the dawn period, and an increase of ~19 dB just after the dusk period. The Autumn recording period showed slight increase of ~1.7 dB during the dawn period, and a and a bimodal increase in BB SPL of ~5.8 just on dusk and ~8.6 dB peak approximately 2 hours later.

3.1.1.3 Site 3

At Site 3, the BB SPL varied by as much as 18.5 dB re 1 µPa among the recording seasons (110.4 – 128.9 dB re 1 µPa, Table 4 & 5). Seasonal fluctuations in BB SPL was statistically significant (Kruskal-Wallis P < 0.001, H = 131289, DF = 3), with the Summer recording period having the highest median BB SPL, followed by Autumn and Spring and with the lowest BB SPLs recorded in the Winter period (Table 4). The Summer recording period also has the highest 95th percentiles, with 95% of the data being on or below 114.6 dB, followed closely by Autumn with 114.1 dB.

The diel patterns in BB SPL varied temporarily and in amplitude among the four seasons (Figure 6). There was a marked difference in median BB SPL between the Autumn and Summer, and the Spring and Winter recording periods at Site 3, with all four seasonal recording periods showing strong temporal spikes in SPL around crepuscular periods. The Winter recording period had a ~6 dB increase during both the dawn and dusk periods. Spring had a 3.9 dB increase in BB SPL during the dawn period and a bimodal increase of 3.4 dB during the dusk period, and again by ~5.3 dB around one hour later. The Summer and Autumn recording periods exhibited a slight increase in BB SPL of ~1.7 and 0.8 dB re 1 µPa during the dawn hours, and a more pronounced ~8.5 dB and ~14.7 dB increase on and after the dusk hours. The dusk peak during the Autumn recording period showed an almost bimodal temporal pattern, with two rates of increase over the peak period (Figure 6).

3.1.1.4 Site 4

The BB SPL varied by 18.5 dB among the four seasons at Site 4 (109.6 – 128.1 dB re 1 µPa, Table 4). Seasonal fluctuations in BB SPL were found to be statistically significant (Kruskal-Wallis P < 0.001, H = 10009, DF = 2, Table 5), with the Spring recording period having the highest BB SPL, followed by Summer and lastly Autumn. The Spring recording period also had the highest 95th percentiles, with 95% of the data being over on or below 114.4 dB.

Diel patterns in broadband sound pressure level (BB SPL) varied temporally among the seasonal recording periods, however, excluding the crepuscular peaks, amplitude was fairly consistent, especially during daylight hours (Figure 6). The Spring recording period had a small increase (2.4 dB) in BB SPL of 2.4 dB at the beginning of the dawn period, following the dawn peak, BB SPL gradually declined during daylight hours (~2 dB reduction from pre-dawn to predusk) and was followed by a peak after the dusk period producing a 12.9 dB increase in BB SPL. Following the dusk peak BB SPL was ~ 2 dB higher than levels prior to the peak. Both the Summer and Autumn recording periods only exhibited a crepuscular peak during and shortly after the dusk period, with a sharp increase in SPL of 9.5 and 7 dB respectively. During the dusk peak, the Autumn period exhibited a bi-modal gradual peak, with a small increase (~3 dB) followed by a larger increase (~7 dB) around 1.5 hours later.

3.1.1.5 Site 6

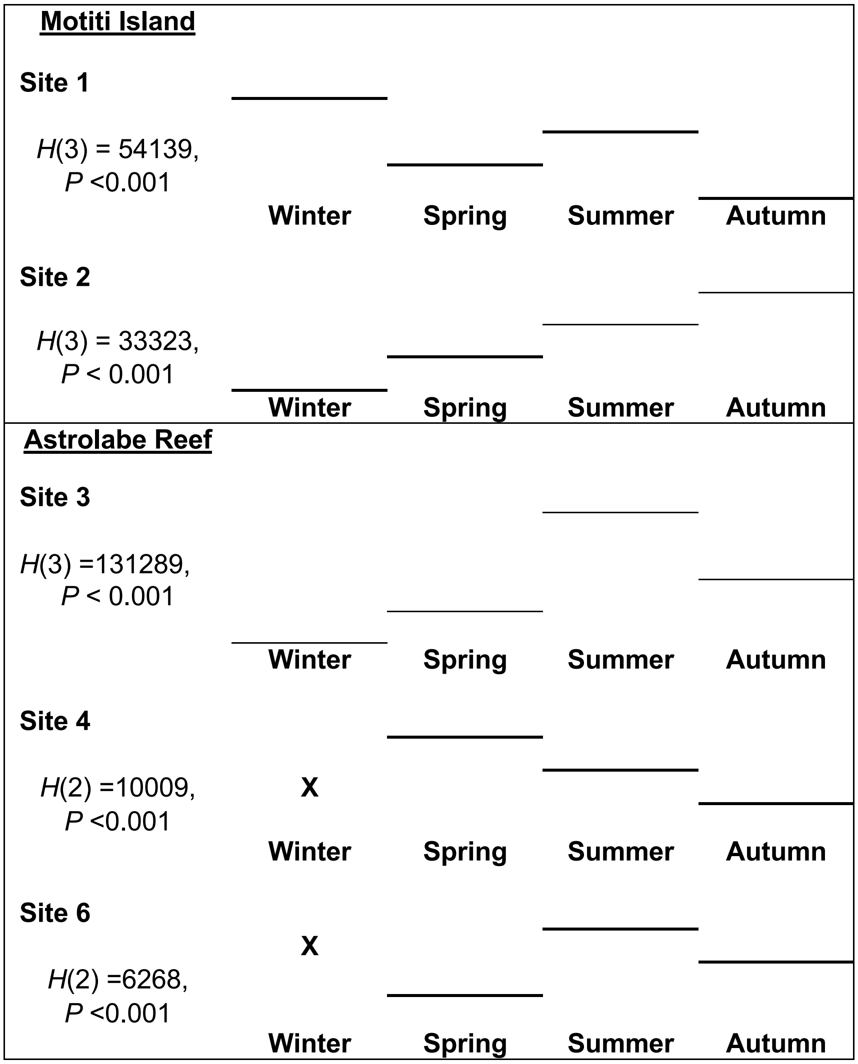
At Site 6, the BB SPL varied by 14.5 dB among the three recorded seasons (116.6 – 131.1 dB re 1 µPa, Table 4). Seasonal fluctuations in BB SPL were found to be statistically significant (Kruskal-Wallis $P < 0.001$, $H = 6268$, $DF = 2$, Table 5), with Summer having the highest median BB SPL, followed by Autumn and then Spring. Summer also had the highest 95th percentiles, with 95% of the data being on or below 116.5 dB.

Diel patterns in broadband sound pressure level (BB SPL) varied among seasonal recording periods both temporally and to a lesser extent amplitude, with Spring deviating from the other recording periods with a greater reduction in BB SPL during daylight hours (Figure 6). None of the seasonal recording periods showed strong increases in BB SPL during the dawn period, with Spring only exhibiting a ~1 dB rise during this time. However, the Spring period had a sharp peak in SPL of ~21.2 dB at the end of the dusk period. Similarly, Summer had an increase of 17 dB towards the end of the dusk period. Autumn had a gradual increase of 3.8 dB during the dusk period.

Table 4. Broadband (BB) sound pressure level (dB re 1 µPa) statistics, 20 – 24,000 Hz, using 60 s bins, for each recording site during each recording season. Motiti Island (Site 1 and Site 2) and Astrolabe Reef (Site 3, Site 4 and Site 6). NB. Red numbers signify highest BB median SPL within each *Recording site*. Bolded numbers signify the highest median BB SPL and italicized numbers signify highest Root Mean Squared (RMS) broadband SPL (per site) per sampling season.

Location	Motiti Island		Astrolabe Reef		
Site ID	Site 1	Site 2	Site 3	Site 4	Site 6
Winter: June – August					
BB Median	**121.3**	109.2	110.6	-	-
5th percentile	118.5	106.7	106.2		
95th percentile	125.8	113.1	122.6		
BB RMS	*122.8*	111.8	119.4		
Spring: September – November					
BB Median	**118.6**	109.6	114.1	116.2	117.4
5th percentile	117.0	107.7	107.3	114.4	115.7
95th percentile	123.4	119.6	123.1	125.1	127.4
BB RMS	120.2	119.8	120.1	119.9	*121.3*
Summer: December – February					
BB Median	**119.4**	109.9	117.1	115	119
5th percentile	117.7	108.9	114.6	112.1	116.1
95th percentile	124.7	123.2	126.4	126.2	128.7
BB RMS	121.7	121.6	122.0	121.1	*123.9*
Autumn: March – May					
BB Median	118.4	110.1	116.6	114.5	**118.5**
5th percentile	116.7	108.9	114.1	111.3	115.9
95th percentile	122.9	119.5	124.2	124.5	124.3
BB RMS	119.4	116.4	119.7	119.1	*120.5*

Table 5. Seasonal groupings according to similarity of broadband SPL with 60 s averaging. Lines on different levels indicate significant differences (P < 0.001, Dunn's test). X indicates no recordings.



Motiti Island

Site 1

H(3) = 54139,
P <0.001

Winter **Spring** **Summer** **Autumn**

Site 2

H(3) = 33323,
P < 0.001

Winter **Spring** **Summer** **Autumn**

Astrolabe Reef

Site 3

H(3) =131289,
P < 0.001

Winter **Spring** **Summer** **Autumn**

Site 4

H(2) =10009,
P <0.001

X

Winter **Spring** **Summer** **Autumn**

Site 6

X

H(2) =6268,
P <0.001

Winter **Spring** **Summer** **Autumn**

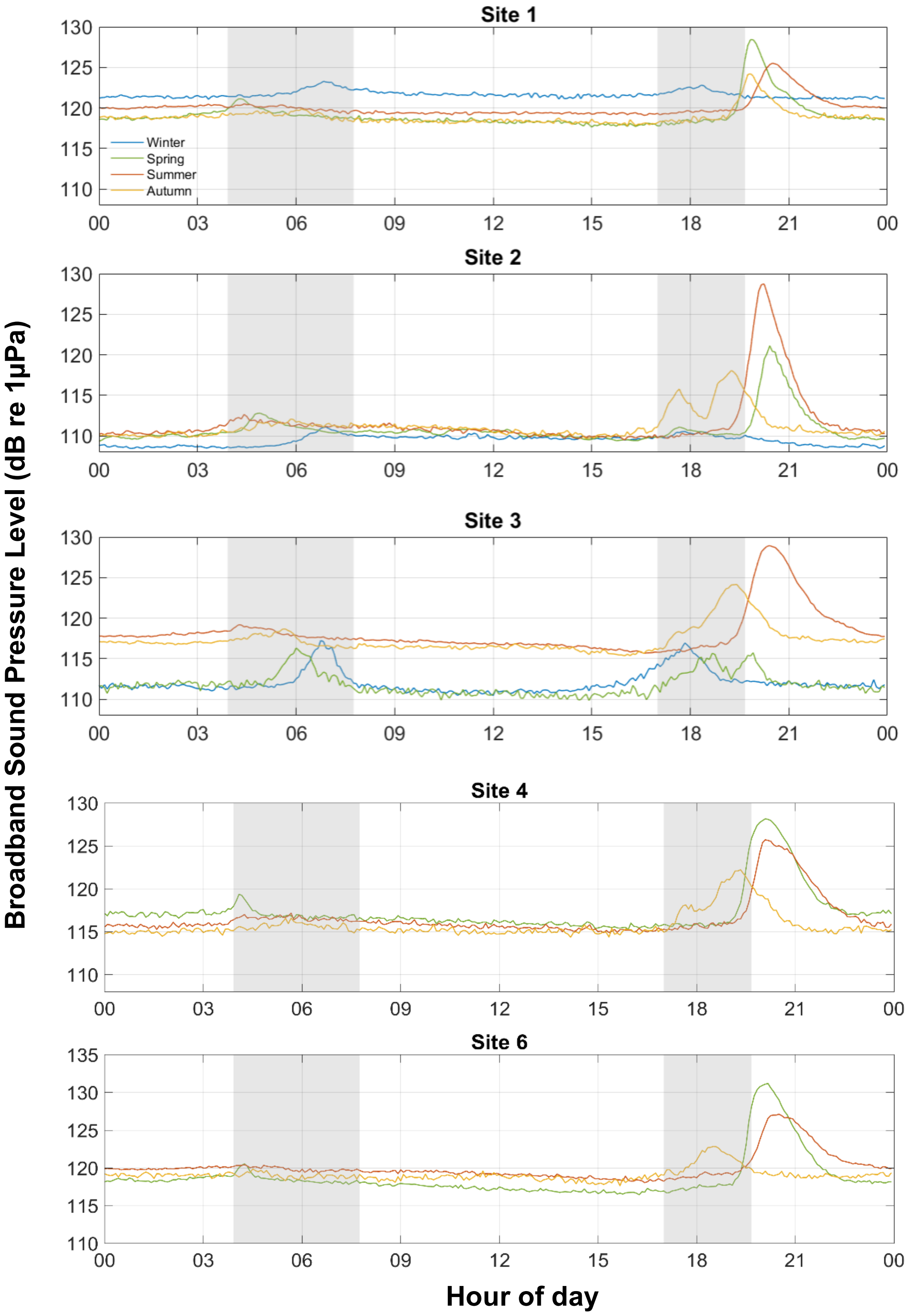


Figure 6. Diel time series plots showing the seasonal averages of broadband sound pressure levels at each site. Shaded grey bars indicate the seasonal ranges of dusk and dawn (± 1.5 hours around sunrise and sunset) times in local standard time. Motiti Island (Site 1 and Site 2) and Astrolabe Reef (Site 3, Site 4 and Site 6). Varying x-axis used to better illustrate fluctuations and all time of day are standardised for local standard time.

3.1.2 Spectral composition of the soundscape

3.1.2.1 Site 1

In relation to spectral composition, Site 1 was relatively complex due to the variety of biotic, abiotic and anthropogenic acoustic contributors (Figure 7a). Patterns in median sound pressure level were consistent across the sampling bandwidth and among seasonal recording periods with a general trend of high sound pressure levels (SPL) in the low frequencies (20 – 30 Hz), decreasing in the 40 – 70 Hz range, followed by a peak at cantered on 200 Hz, 1000, and then a broadband rise in the 4000 – 10,000 Hz range, followed by a sharp decline after 11,000 Hz. The PDS for this site was dominated by the acoustic signals of vessels, sea urchins and snaps produced by snapping shrimp. As the site was relatively shallow (19 m), there was also the presence of low frequency signal (20 – 300 Hz) associated with wind and waves acting on the water surface. Periods of high winds, at times, caused an increase in broadband SPL.

Site 1 had the highest median sound pressure levels in the 4000 – 6000 Hz frequency range frequency range, peaking at 4990 Hz at ~ 80 dB re 1 $\mu Pa^2/Hz^{-1}$ during the Winter recording period. Generally, the median power spectral density varied among seasonal recording periods, with the largest difference occurring in the low frequencies (20 – 40 Hz range). At 25 Hz, the Winter recording period was 12 dB re 1 $\mu Pa^2/Hz^{-1}$ higher than Spring, the lowest season. This pattern was also evident in the 95th percentiles, with the higher acoustic power of any frequencies at ~103 dB re 1 $\mu Pa^2/Hz^{-1}$, also occurring during the Winter recording period. There were two prominent peaks in median SPL and the 95th percentiles at 60 and again 103 Hz also during the Winter recording period that were of unknown origin but were consistent though the sampling period. The Spring recording period exhibited spectral peaks of increase acoustic power (~87 dB re 1 $\mu Pa^2/Hz^{-1}$) in the 95th percentiles in the mid-frequencies (800 – 1300 Hz) due to the presence of acoustic signals produced by the increased grazing activity of sea urchins during periods around dawn and dusk. Seasonal median SPL converged in the high frequencies (6000 – 10,000 Hz) with a difference among all seasons of 3 dB re 1 $\mu Pa^2/Hz^{-1}$.

The maximal spectral probability density (SPD) closely reflected the median in all seasons suggesting fairly low variation in intensity in the soundscape. However, during Autumn and to an extent the Winter period the SPD exhibited patterns of bi-modality with a lesser secondary ridge in the 80 – 100 Hz range, indicating some transient temporal component at this intensity in this frequency range (Figure A1 a-d; Appendix 1).

3.1.2.2 Site 2

At Site 2, the PSD was very consistent among seasonal recording periods, across the entire sampling bandwidth (Figure 7b). The highest median sound pressure levels occurred in the 80 – 300 Hz frequency range, peaking at ~ 79 dB re 1 $\mu Pa^2/Hz^{-1}$ at 128 Hz during the Autumn recording period, however, with less than 3 dB difference among the recording seasons. Median sound pressure levels dropped to ~68 dB re 1 μPa^2/Hz^{-1} in frequencies above 300 Hz and remained stable until around 7000 Hz whereby they dropped rapidly in frequencies above this. Multiple small harmonic spikes in the spectra from 40 – 1000 Hz were observed in the median and percentiles, increasing the spectral levels at irregular intervals by as much as 5 dB re 1 μPa^2/Hz^{-1} during all seasonal recording periods, although, were most pronounced during the Winter season. These spikes originated from the persistent, yet variable in frequency, low level sounds from the regular and frequency movements of island residents in small vessels launching and returning to the slipway (Figure 7b).

The percentiles were also fairly consistent among seasons and low and high frequencies; the 95th percentile was highest in the low frequencies (30 – 100 Hz) with less than 3 dB difference among recording seasons. In the mid frequencies, the 95th percentile diverged among seasons, with Summer exhibiting the highest spectral levels of ~78 – 88 dB re 1 μPa^2/Hz^{-1} across 700 – 3000 Hz. This dropped by up to 7, 10 and 17 dB re 1 μPa^2/Hz^{-1} in the Spring, Autumn and Winter recording seasons respectively.The maximal spectral probability density (SPD) closely reflected the median in all seasons suggesting fairly low variation in intensity in the soundscape (Figure A2 a-d; Appendix 1). The SPD also illustrates that the 40 – 1000 Hz spikes observed in the spectra were relatively persistent throughout the recording periods due to the relative lack of data points below the spikes.

3.1.2.3 Site 3

At Site 3, patterns in median sound pressure levels were fairly consistent across the sampling bandwidth and seasonal recording period, with a general trend of highest SPLs in the low frequencies (20 – 100Hz), gradually decreasing in the mid frequency range (100 – 3000 Hz), before rising again in the high frequencies (3000 – 10,000 Hz), then rapidly dropping off after 11,000 Hz. However, there were notable differences in acoustic power among these recording periods (difference of up to ~15 dB in the high frequencies) (Figure 7c). The PDS for this site was dominated by the acoustic signals of vessels, sea urchins and snaps produced by snapping shrimp. As the site was relatively shallow (20 m), there was also the presence of low frequency signal (20 - 300 Hz) associated with wind and waves acting on the water surface and on the surrounding reef (wave surge) and periods of noise from the movement of parts of the MV Rena wreckage on the reef. Periods of high winds, at times, caused an increase in broadband SPL.

Site 3 had the highest median SPL in the 300 – 1000 Hz frequency range, peaking at 79.2 dB re 1 μPa^2/Hz^{-1} at 35 and 76 Hz during the Summer recording period, however, there was less than 5 and 4 dB difference at 35 and 75 Hz respectively among recording seasons. Notably, the Summer and Winter recording had the highest 95th percentiles in the lower frequencies (20 – 800 Hz) with SPLs of approximately 94 dB re 1 μPa^2/Hz^{-1} at 24 Hz. Median sound pressure levels dropped to ~68 dB re 1 μPa^2/Hz^{-1} in frequencies above 300 Hz and remained stable until around 7000 Hz whereby rapidly dropping off in frequencies above this. However, there were substantial spectral peaks in acoustic power (up to 94 dB re 1 µPa^2/Hz^{-1} at 1188 Hz during the Summer) in the 95th percentiles in the 600 – 3000 Hz frequency range during all recording periods due to the presence of acoustic signals produced by the increased grazing activity of sea urchins during periods around dawn and dusk. The Summer and Autumn had the highest median PSD across the entire sampling spectra, compared to Winter and Spring recording seasons. Sound pressure levels were marginally greater during the Winter compared to the Spring recording period in the lower and mid frequencies (30 – 1000 Hz). This then reversed in the high frequencies (1000 – 24,000 Hz) with the greatest difference around 8000 Hz of approximately 6 dB re 1 µPa^2/Hz^{-1}.

The maximal spectral probability density (SPD) closely reflected the median in all four seasons suggesting fairly low variation in intensity in the soundscape at these frequencies. However, during the Spring recording period the SPD exhibited patterns of bi-modality in the high frequencies (2300 – 24,000 Hz range) indicating some transient temporal component at differing intensities in this frequency range (Figure A3 a-d; Appendix 1).

3.1.2.4 Site 4

At Site 4, patterns in median sound pressure levels were once again fairly consistent across the sampling bandwidth and seasonal recording period, with a general trend of highest SPLs in the low frequencies (30 – 100Hz), dropping in the mid frequency range (100 – 3000 Hz), before exhibiting a small rising again in the high frequencies (3000 – 10,000 Hz), followed by a rapid drop off after 11,000 Hz (Figure 7d). The PDS for this site was dominated by the acoustic signals of vessels, sea urchins and snaps produced by snapping shrimp. This site was also relatively shallow 15 m), therefore, at times there was also the presence of low frequency signal (20 - 300 Hz) associated with wind and waves acting on the water surface and on the surrounding reef (wave surge). Periods of high winds, at times, caused an increase in broadband SPL.

Generally, median power spectral density was fairly consistent among recording seasons, with the greatest difference occurring in the low and high frequencies (~5 dB re 1 µPa^2/Hz^{-1} at ~28 Hz & ~4 dB re 1 µPa^2/Hz^{-1} at ~14,000 Hz) with Spring being greater than both Summer and Autumn sample periods (Figure 7d). Differences were also minimal in the low frequencies (20 – 100 Hz), with Summer being 3.5 dB re 1 µPa^2/Hz^{-1} higher than both Autumn and Spring recording periods at 37 Hz. Seasonal median SPL converged in the mid frequencies (200 – 3000 Hz). Median SPLs where highest in the low frequencies for all recording periods, with Summer exhibiting the greatest of all seasons (20 – 200 Hz). This trend was also present in the 95th percentiles which peaked at ~ 102 dB re 1 µPa^2/Hz^{-1} at 22 Hz. Again, there were substantial peaks in SPL in the 95th percentiles during all recording seasons due to the presence of urchin signals, with the greatest levels (83 to 92 dB re 1 µPa^2/Hz^{-1} in the 600 – 1200 Hz range) occurring during the Spring.

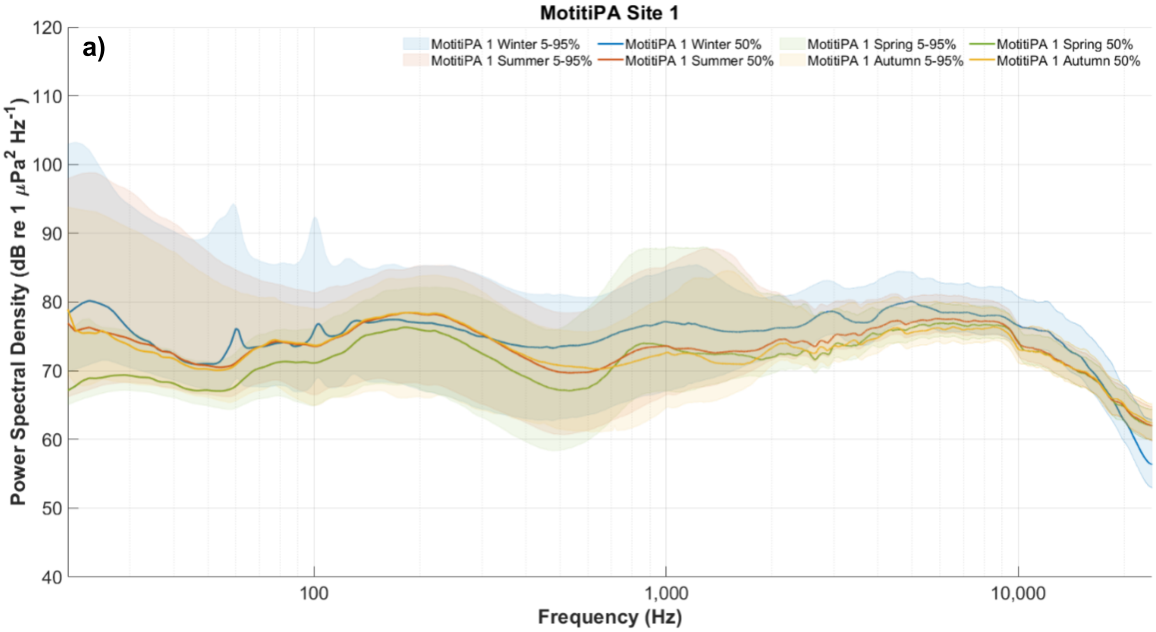
The maximal spectral probability density (SPD) closely reflected the median in all four seasons suggesting fairly low variation in intensity in the soundscape. The PDS also illustrated the presence of higher power, low-mid frequency broadband (20 – 900 Hz) outliers during all recording seasons, however, they were not common enough to heavily effect the median SPL (Figure A a-c; Appendix 1).

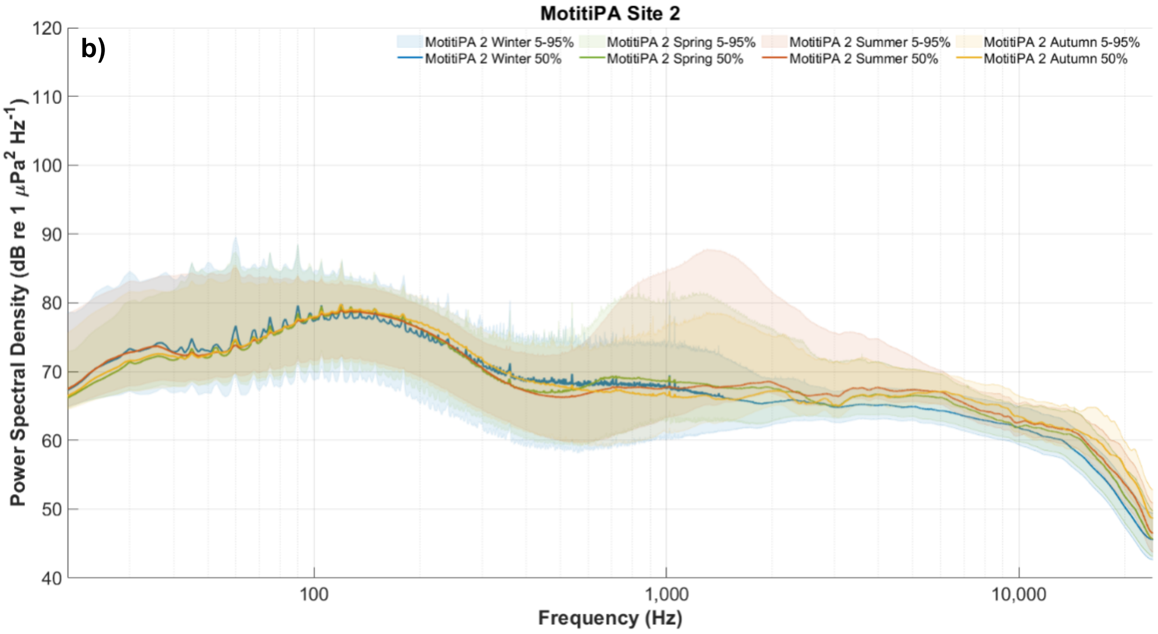
3.1.2.5 Site 6

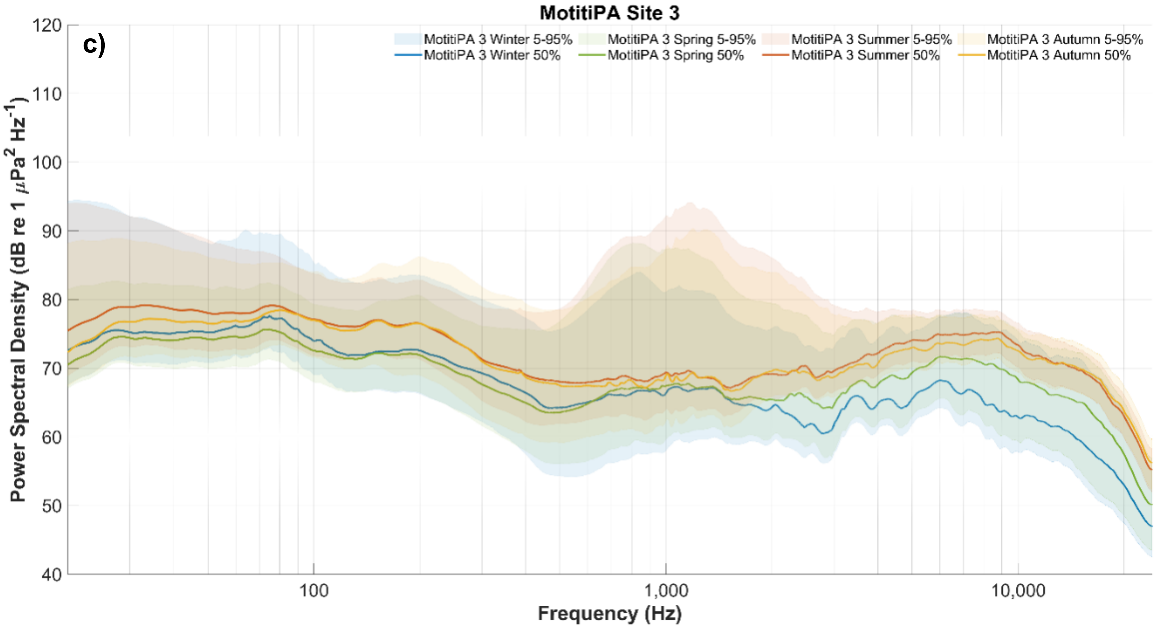
At Site 6, patterns in median sound pressure levels were consistent across the sampling bandwidth and seasonal recording period, with a general trend of highest SPLs in the low frequencies (30 – 200Hz), dropping in the mid frequency range (300 – 3000 Hz), before exhibiting a small rising in the high frequencies (3000 – 9,000 Hz), followed by a rapid drop off after 15,000 Hz (Figure 7e). The PDS for this site was dominated by the acoustic signals of vessels, sea urchins and snaps produced by snapping shrimp. This site was also relatively shallow 18 m), therefore, at times the presence of low frequency signal (20 - 300 Hz) associated with wind and waves acting on the water surface and on the surrounding reef (wave surge) was present. Periods of high winds, at times, caused an increase in broadband SPL.

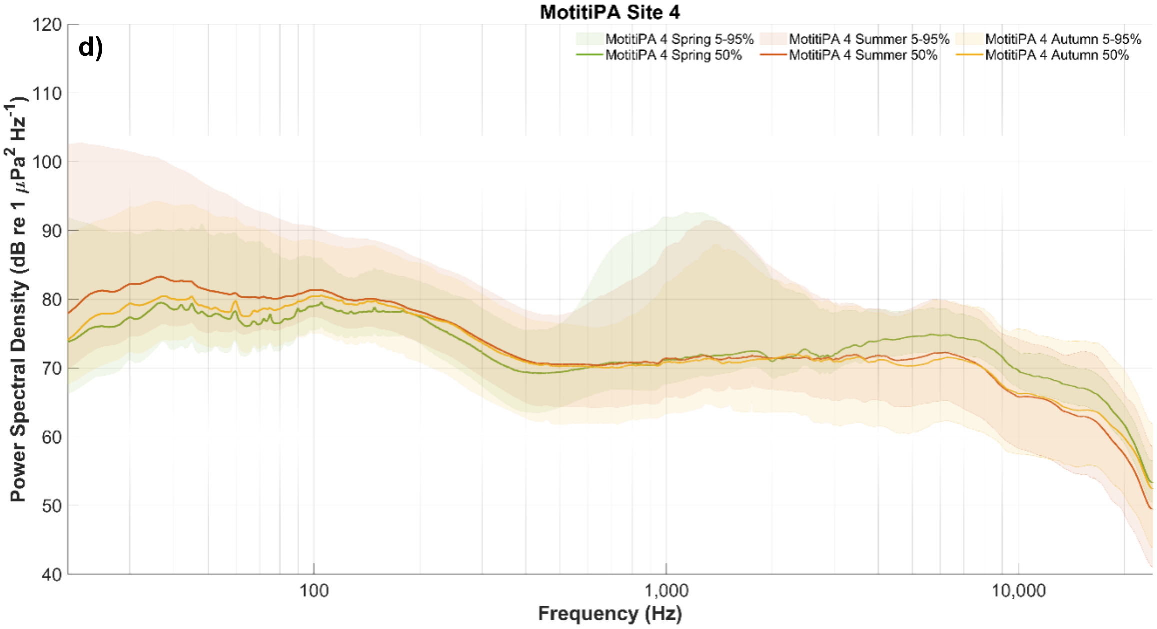
Generally, median power spectral density was fairly consistent among recording seasons, with the greatest difference occurring in the mid-high frequencies (≤ 6 dB re 1 $\mu Pa^2/Hz^{-1}$ at 500 – 3000 Hz) with Spring being greater than both Summer and Autumn sample periods (Figure 7e). Differences were also minimal in the low frequencies (20 – 100 Hz), with Summer being 4 dB re 1 $\mu Pa^2/Hz^{-1}$ higher than both Autumn and Spring recording periods at 30 Hz. Median SPLs where highest in the low frequencies for all recording periods, with Summer exhibiting the greatest of all seasons (20 – 200 Hz). This trend was also present in the 95th percentiles which peaked at ~ 108 dB re 1 $\mu Pa^2/Hz^{-1}$ at 25 Hz before steadily dropping. Again, there were substantial peaks in SPL in the 95th percentiles during all recording seasons due to the presence of urchin signals, with the greatest levels (96 dB re 1 $\mu Pa^2/Hz^{-1}$ at 1000 Hz) occurring during the Spring.

The maximal spectral probability density (SPD) closely reflected the median in all seasons suggesting fairly low variation in intensity in the soundscape. The PDS also illustrated the presence of higher power, low-mid frequency broadband (20 – 2000 Hz) outliers in the Autumn recording period, however, they were not common enough to heavily effect the median SPL (Figure A4 a-c; Appendix 1).


MotitiPA Site 1
a)
MotitiPA 1 Winter 5-95%
MotitiPA 1 Winter 50%
MotitiPA 1 Spring 5-95%
MotitiPA 1 Spring 50%
MotitiPA 1 Summer 5-95%
MotitiPA 1 Summer 50%
MotitiPA 1 Autumn 5-95%
MotitiPA 1 Autumn 50%
Power Spectral Density (dB re 1 μPa² Hz⁻¹)
120
110
100
90
80
70
60
50
40
100
1,000
10,000
Frequency (Hz)


MotitiPA Site 2
b)
MotitiPA 2 Winter 5-95%
MotitiPA 2 Spring 5-95%
MotitiPA 2 Summer 5-95%
MotitiPA 2 Autumn 5-95%
MotitiPA 2 Winter 50%
MotitiPA 2 Spring 50%
MotitiPA 2 Summer 50%
MotitiPA 2 Autumn 50%
Power Spectral Density (dB re 1 μPa² Hz⁻¹)
120
110
100
90
80
70
60
50
40
100
1,000
10,000
Frequency (Hz)


MotitiPA Site 3
c)
MotitiPA 3 Winter 5-95%
MotitiPA 3 Winter 50%
MotitiPA 3 Spring 5-95%
MotitiPA 3 Spring 50%
MotitiPA 3 Summer 5-95%
MotitiPA 3 Summer 50%
MotitiPA 3 Autumn 5-95%
MotitiPA 3 Autumn 50%
Power Spectral Density (dB re 1 $\mu Pa^2 Hz^{-1}$)
120
110
100
90
80
70
60
50
40
100
1,000
10,000
Frequency (Hz)


MotitiPA Site 4
d)
MotitiPA 4 Spring 5-95%
MotitiPA 4 Spring 50%
MotitiPA 4 Summer 5-95%
MotitiPA 4 Summer 50%
MotitiPA 4 Autumn 5-95%
MotitiPA 4 Autumn 50%
Power Spectral Density (dB re 1 $\mu Pa^2 Hz^{-1}$)
120
110
100
90
80
70
60
50
40
100
1,000
10,000
Frequency (Hz)

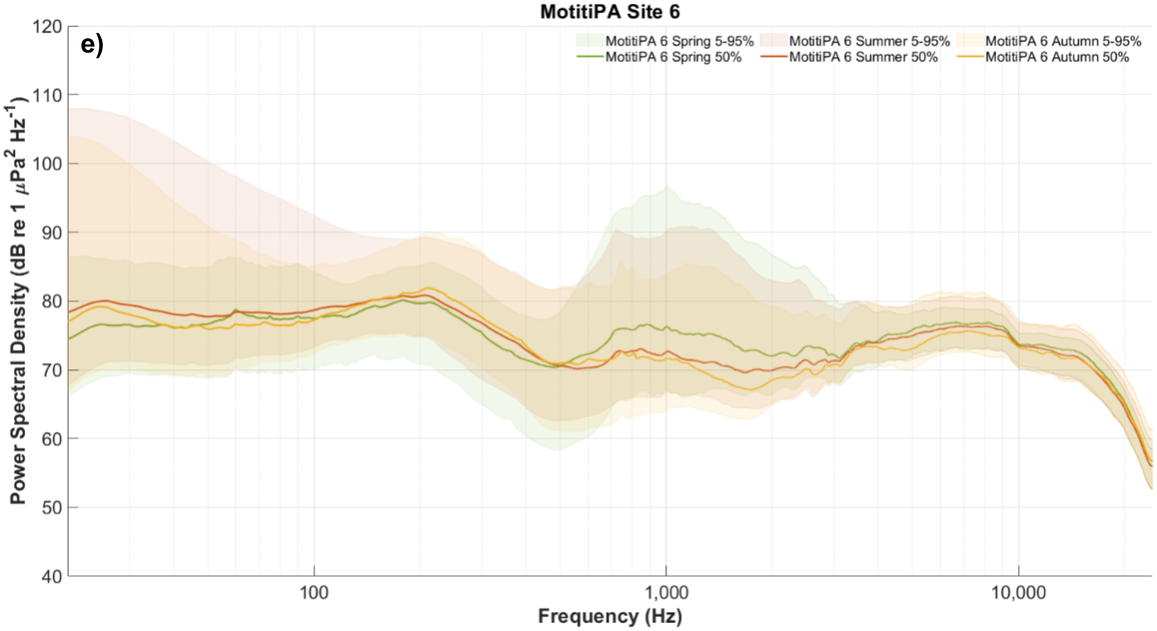


Figure 7. Seasonal power spectral density levels for each recording site, including median, 5th and 95th percentiles. Solid line represents seasonal median and shaded area represents percentiles (Discrete Fourier transformation length = 48,000, Hanning window and 50 % overlap). Motiti Island (Sites 1 & 2) and Astrolabe Reef (Sites 3, 4 & *6*). a) Site 1, b) Site 2, c) Site 3, d) Site 4, and e) Site 6.
NB. Data for Winter seasonal recording period excluded from Site 4 & Site 6 due to instrument malfunctions.

3.1.3 Patterns in 1/3 octave band levels

3.1.3.1 Site 1

At Site 1, all seasonal recording periods exhibited diel trends in sound pressure level (SPL) in all of the 1/3 octave bands selected for analysis (Figure 8, Figure A6; Appendix 1). There were crepuscular peaks in SPL around dusk and to a lesser extent dawn periods (±1.5 hours sunrise and sunset) in the bands centred on 501, 630 and 1259 Hz, which was most pronounced during the Spring, Summer and Autumn periods. These peaks lasted on average 2.8 hours in duration during the Winter and Autumn and 4.2 hours during the Spring and Summer recording periods. The band centred on 1259 Hz exhibited the greatest increase in SPL with an increase of 5 – 17 dB and 15 – 27 dB re 1 μPa around dawn and dusk respectively.

During the Winter recording period, the crepuscular peaks in SPL only occurred in bands centred on 1259 and to a lesser extent 630 Hz and were more similar in intensity between dawn and dusk when compared to the other seasonal recording periods. This was most pronounced during the new moon phase and resulted in an increase in SPL of on average 14 dB re 1 μPa in the 1259 Hz band. This peak lasted for around two hours with levels remaining elevated during light hours (between the times of dawn and dusk) and dropping again after the dusk peak. This was most pronounced during the new and three-quarter moon phases (~ 8 dB re 1 μPa) (Figure 8, panels a & c, Figure A6; Appendix 1). Bands centred on 251, 501 and 630 Hz also exhibited a rise and sustained increase in SPL (~8 – 12 dB re 1 μPa) for approximately 11 hours during the daylight hours but without the dramatic peak at dawn and dusk (Figure 8). These patterns were least evident during the first quarter moon phase (Figure 8, panel b, Figure A6; Appendix 1).

During the Spring recording period, the crepuscular peaks occurred in 1/3 octave bands centred on 501, 630 and 1259 Hz 1/3 octave bands. These peaks where at their greatest during the new and full moon phases (Figure 8, panels e & g) and resulted in a ~ 23 dB and 15.5 dB re 1μPa rise is SPL around dusk and dawn respectively in the 1259 Hz band, and ~11.5 dB and 15 dB re 1μPa in the 630 Hz band. During the first quarter moon phase the 1259 Hz band also exhibited a smaller peak in SPL just after midnight (Figure 8, panel f). All bands exhibited higher SPLs during daylight compared to dark hours during all four moon phases with gradual rise of ~6 – 10 dB re 1μPa throughout the day (Figure 8, panels e, f, g & h). During the mid-afternoon on November 12th and 30th during the first and third quarter moon phases the 501, 630 Hz and to a lesser extent 251 and 1259 Hz bands exhibited a transient rise in SPL (~7 dB) (Figure 8, panels f & h).

During the Summer period the crepuscular peaks were most pronounced in the 630 and 1258 Hz bands during the full moon phase (Figure 8, panel i). This recording period showed very similar diel trends to the Spring recording period, including timing and amplitude of the dawn and dusk peaks and sustained increase in SPL during the daylight hours and drop during dark hours. The Summer recording period exhibited small scale transient variations in in all 1/3 octave band SPLs during the daylight hours during all moon phases, this is due to short transits of recreational vessels close to the hydrophone.

Finally, the Autumn recording period again showed very similar trends in SPL to both the Spring and Summer recording periods, including sustained increase in SPL during the daylight hours and drop during dark hours. However, unlike the Spring and Summer periods crepuscular peaks were only present in the 1259 Hz band, with the remaining bands (125, 251, 630 Hz) only exhibiting the sustained rise in SPL during daylight hours. Similarly, to the spring recording period, there was a transient spike in the 630 and 1259 Hz bands of ~7 dB re 1µPa around midnight on March 19th during the full moon.

3.1.3.2 Site 2

At Site 2, all seasonal recording periods exhibited diel trends in sound pressure level (SPL) in all of the 1/3 octave bands selected for analysis (Figure 9, Figure A7; Appendix 1). In the bands centred on 501, 630 and 1259 Hz there were crepuscular peaks in SPL around dusk during the Spring, Summer and Autumn recording periods, and to a lesser extent, dawn periods during the Spring and Summer recording periods. Furthermore, these peaks were predominantly absent during the Winter recording period. These peaks lasted on average 2.1 hours in duration during the Autumn and 4 hours during the Spring and Summer recording periods. The band centred on 1259 Hz exhibited the greatest increase in SPL with 6 – 13 dB and 21 – 31 dB re 1 µPa around dawn and dusk respectively.

During the Winter recording period, the 1/3 octave band SPL showed less pronounced diel trends during all four moon phases than the other seasons. The bands centred on 251, 501, 630 and 1259 Hz were relatively stable, especially during the new and first quarter moons, while 125 Hz had transient peaks in SPL during the full and to some extent the three-quarter moon phases (Figure 9, panels c, & d, Figure A7; Appendix 1) due to the presence and slow speed transiting of large vessels. These peaks resulted in an increase of 2.5 – 15 dB re 1 µPa in SPL in the 125 Hz band for short periods (<1 hour). All frequency bands exhibited a rise and sustained increase in SPL (4.8 - 7.4 dB re 1 µPa) during daylight hours, this was most pronounced during the new, full, and three-quarter moon phases and quarter moon to a lesser extent.

During the Spring recording period, crepuscular peaks in SPL occurred in bands centred on 501, 630 and 1259 Hz, and to a lesser extent on the bands centred on 125 and 251 Hz (Figure 9, panels e, f, g, & h). These peaks were most prominent during the three-quarter moon phase (Figure 9, panel h), which resulted in an increase of ~28.4 dB and 27 dB re 1 µPa during dusk and dawn periods respectively. In addition to the dawn and dusk peaks, the 1/3 octave bands centred on 125, 251, 501 and 630 Hz also exhibited smaller peaks at and just after midnight during the new, full, and three-quarter moon phases (Figure #, panels e, g, & h), due to the presence of vessels. All frequency bands displayed a higher SPL with multiple small transient peaks during daylight hours, during all moon phases, with a significant peak around midday on November 20th during the full moon phase due to vessel activities in close proximity to the recording site.

In the Summer recording period, the crepuscular peaks were present during all four moon phases in the bands centred on 501, 630 and 1258 Hz, and only during the dusk period during new and first quarter moon phases in the bands centred on 125 and 251 Hz (Figure 9, panels i, j, k, & l). These peaks were similar in intensity throughout all four moon phases in 501, 630 and 1258 Hz bands, which resulted in an increase in SPL of on average 12, 19 and 31 dB re 1 µPa respectively during the dusk period, which were the highest for any site. All frequency bands presented a higher SPL during daylight compared to dark hours and exhibited small scale transient variations in all 1/3 octave band SPLs during the new and first quarter moon phases due to the presence of small and large vessel activities (Figure 9, panels i & j).

During the Autumn recording period, crepuscular peaks in SPL bands centred on 630 and 1258 Hz were most prominent around dusk during the new, first quarter and full moon phases, which resulted in an average increase in SPL of 28 dB, 26.5 dB and 26 dB re 1 µPa respectively during (Figure 9, panels m, n, & o). The bands centred on 125, 251 and 501 Hz were consistently higher during daytime compared to dark hours, with a rapid increase around dawn, remaining elevated (7 – 9 dB higher) during the day and rapidly dropping around dusk. Similar to the Spring recording period, 125, 251 and to a lesser extent 630 Hz bands also exhibited smaller peaks around midnight during all four moon phases. All frequency bands exhibited small scale transient variations in all 1/3 octave band SPLs during the daylight hours during the new, first quarter and full moon phases due to vessel activities and periods of heavy rain (Figure 9, panels m, n, & o).

3.1.3.3 Site 3

At Site 3, all seasonal recording periods exhibited strong crepuscular trends in SPL in all of the 1/3 octave bands selected for analysis (Figure 10, Figure A8; Appendix 1). There were significant peaks in SPL around dusk and to a lesser extent dawn periods in the bands centred on 501, 630 and 1259 Hz, which was most pronounced during the Spring, Summer and Autumn periods. These peaks lasted on average 2.8 hours in duration during the Winter and Autumn and 4.2 hours during the Spring and Summer recording periods. The band centred on 1259 Hz exhibited the greatest increase in SPL with an increase of 6 – 18 dB and 14 – 32 dB re 1 µPa around dawn and dusk respectively.

During the Winter recording period frequency bands 251, 501 and 630 Hz exhibited higher SPL (~4 – 9 dB re 1 µPa) during daylight hours when compared to dark hours, this was observed during all four moon phases. All frequency bands exhibited a divergence from usual diel patterns and small-scale transient variations in all 1/3 octave band SPLs from just after midday on July 17th for approximately 20 hours during the first quarter moon phase due to increased swell height and wind speeds and movement of the wreckage of the Rena (Figure 10, panel b).

During the Spring the crepuscular peaks where at their greatest during first quarter and third quarter phases, however, were strong through all phases (Figure 10, panels e, f, g, & h), and resulted in a 28 – 32 dB and 15 – 17 dB re 1µPa rise in SPL around dusk and dawn respectively in the 1259 Hz band. During the third quarter and to a lesser extent the new moon phases, the 501, 630 and 1259 Hz band also exhibited smaller peaks in SPL just after midnight (Figure 10, panel h). Excluding these peaks, 1/3 octave band levels were fairly consistent between daylight and dark hours in all moon phases. (Figure 10, panels e, f, g, & h). There were several transient peaks SPL in all frequency bands during new and full and third quarter moon phases due to vessel activities.

The large peaks in SPL in the 630, 1259 and to a lesser extent the 531 Hz 1/3 octave bands continued during the Summer recording period. The 1259 Hz band exhibited the largest peaks around dusk and to a lesser extent the dawn period during all four moon phases (Figure 10, panels i, j, k, & l), with the new moon phase being the most pronounced (~35 dB rise in SPL). The 630 Hz band exhibited these strong peaks during the new, first quarter and third quarter moon phases (Figure 10, panels i, j, & l), and the 501 Hz during the new and three-quarter moon phase which all lasted approximately two hours (Figure 10, panels i, & l). During the first-quarter moon phase, the band centred on 630 Hz had double or bimodal peaks during each dusk peak for three consecutive nights (Figure 10, panel j). Band levels were also fairly consistent between daylight and dark hours in all frequencies and during all moon phases, with occasional transient spikes due to the passage of vessels. However, on January 17th, during the full moon phase the lower frequency bands 125 and 251 Hz saw a general increase in SPL the early hours of the 18th due to an increase in wind speeds and swell height and movement of the wreckage of the MV Rena.

During the Autumn recording period, crepuscular peaks resulted in an average increase of 14 and 26 dB re 1 µPa in bands centred on 630 and 1259 Hz respectively. All frequency bands displayed a higher SPL during daylight hours, along with multiple transient peaks, with an approximate increase ranging from 10 – 20.6 dB re 1 µPa. First quarter and full moon phases exhibited the greatest difference between daytime and dark hours (average 21 dB re 1 µPa), again these periods were influenced by increased swell height and movement of the MV Rena wreckage, as well biological sources.

3.1.3.4 Site 4

At Site 4, all five 1/3 octave bands selected for analysis exhibited strong crepuscular trends in SPL during all seasonal recording periods and all moon phases (Figure 11, Figure A9; Appendix 1). There were substantial peaks in SPL around dusk and dawn periods in the bands centred on 630, 1259 Hz and to a lesser extent 501 Hz. The band centred on 1259 Hz exhibited the greatest increase in SPL of 5 – 13 dB and 18 – 26 dB re 1 µPa around dawn and dusk respectively. These peaks lasted on average 4 hours in duration during the Spring and Summer and 3.4 hours in the Autumn recording periods. All seasons saw transient spikes in SPL in all 1/3 octave bands due to vessel activities in the vicinity of the recording site.

During the Spring recording period, the crepuscular peaks were strong during all four moon phases in the band centred on 630, 1259 and to a lesser extent 501 Hz (Figure 11, panel a, b, c, & d), resulting in an approximate increase of 7.6, 23.3, and 24.2 dB re 1 µPa SPL in the 501, 630 and1259 Hz bands respectively. The band centred on 125 Hz showed a smaller peak after midnight on November 11th and 20th during the new and full moon phases due to large vessel activities (Figure 11, panels b & c). Band levels were fairly consistent between daylight and dark hours in all frequencies and during all moon phases, with occasional transient spikes in the lower frequency bands.

During the Summer recording period 1/3 octave bands centred on 630 and 1259 Hz exhibited in an average increase in SPL of 15 and 20 dB re 1 µPa respectively. There was a distinctive rise in SPL in bands centred on 125 and 251 Hz on January 17th lasting into the early hours of the 18th, during the full moon phase due to an increase in wind and swell and occasional sand and shell scour against the hydrophone element (Figure 11, panel g). Band levels were fairly consistent between daylight and dark hours in all frequencies and during all moon phases, with frequent transient spikes in the lower frequency bands during daylight hours.

During the Autumn recording period the crepuscular peaks in SPL in the 1258 Hz 1/3 octave band were strong during all four moon phases. All frequency bands displayed a higher SPL during daylight hours, with an approximate increase of 9 dB re 1 µPa, which was most pronounced in the 501 and 630 Hz 1/3 octave bands and exhibited an abrupt drop in SPL around the dusk period, during the full moon phase. Furthermore, during the first quarter moon phase, bands centred on 125 and 251 Hz were higher than usual, compared to the other frequencies, due to an increase in wind speeds (Figure 11, panel j).

3.1.3.5 Site 6

At Site 6, all five 1/3 octave bands selected for analysis exhibited strong crepuscular trends in SPL during all seasonal recording periods and during all moon phases (Figure 12, Figure A10; Appendix 1). There were substantial peaks in SPL around dusk and dawn periods in the bands centred on 630, 1259 Hz and to a lesser extent 501 Hz during the Spring and Summer, and just the 1259 Hz band in the Autumn recording period. The band centred on 1259 Hz exhibited the greatest increase in SPL of 4 – 17 dB and 12 – 28 dB re 1 µPa around dawn and dusk respectively. These peaks lasted on average 4.4 hours in duration during the Spring and Summer and 2.7 hours in the Autumn recording periods recording periods. All seasons saw transient spikes in SPL in all 1/3 octave bands due to vessel activities in the vicinity of the recording site.

At Site 6, during the Spring recording period, the crepuscular peaks were present in the 501, 630 and 1259 Hz, during all four moon phases. Bands centred on 125 and 251 Hz to a much lesser extent only exhibiting peaks during the new and full moon phase and only during the dusk period, often offset to after midnight due to vessel activity (Figure 12, panel a, b, c, & d). This resulted in an average increase of in SPL of 17, 23, and 25 dB re 1 µPa for the bands centred on 510, 630 and 1259 Hz respectively during the dusk peak. All frequency bands displayed a higher SPL during daylight hours, along with multiple small peaks throughout all four moon phases (Figure 12, panels a, b, c, & d).

Similarly, during the Summer recording period the crepuscular peaks were present during all four moon phases in the bands centred on 501, 630, and 1259 Hz, and the bands centred around 125 and 251 Hz to a lesser extent and only during the first and third quarter moon phases (Figure 12, panels e, f, g, & h). This resulted in an average increase of 9.2, 18, and 23.5 dB re 1 μPa of SPL for the bands centred on 510, 630 and 1259 Hz respectively. The band centred on 630 Hz had bimodal peaks during the dusk chorus periods, during the first and third-quarter moon phase (Figure 12, panel f). There was a distinctive rise in SPL in bands centred on 125 and 251 Hz on January 4th for six hours and again on the 17th lasting into the early hours of the 18th, during the full moon phase due to an increase in wind and swell and occasional sand and shell scour against the hydrophone element, this was also seen at Site 3 and 4. All frequency bands, excluding these peaks, were fairly consistent in SPL between daylight and dark hours in all moon phases, there were also small-scale transient variations in SPL in all band and moon phases due to vessel activities (Figure 12, panels e, g, & h).

During the Autumn recording period the crepuscular peaks in SPL were consistent around the dusk period in the 1258 Hz band during all four moon phases and only present during the dawn period in this band during the new and full moon phases. All frequency bands displayed an abrupt drop in SPL after the dusk peak and remining low during dark hours. Around the dawn period levels increased and gradually built during daylight hours during all moon phases, with an average increase of 12 dB re 1 μPa between the height of the dark vs light hours. Furthermore, all moon phases saw several transient spikes in SPL in all 1/3 octave bands due to vessel activities in the vicinity of the recording site. (Figure 12, panels i-l).

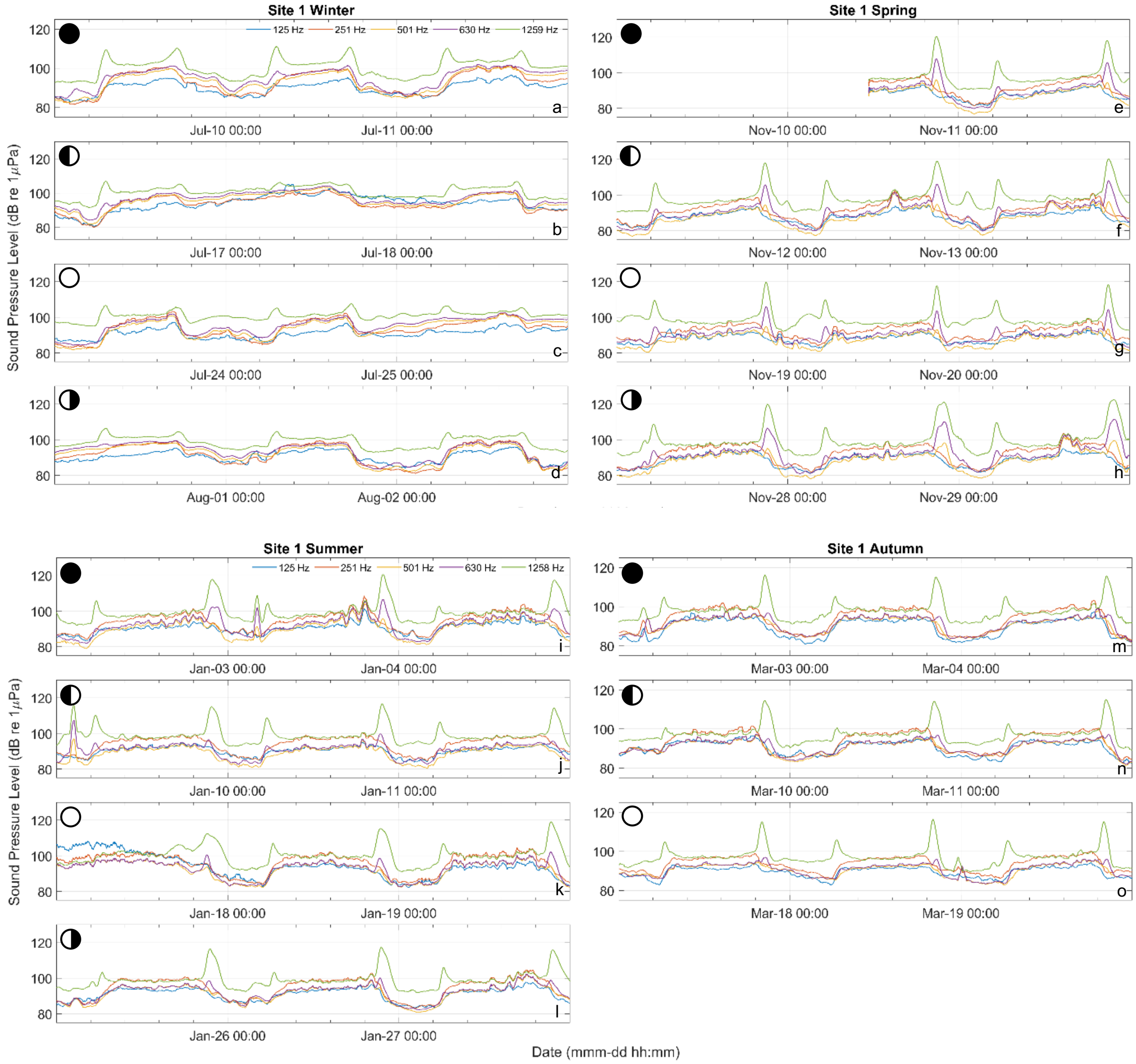


Figure 8. Sound pressure levels in one-third octave bands centred on 125, 251, 501, 630, and 1,250 Hz during three days over all moon phases during the Winter, Spring, Summer, and Autumn seasonal recording periods at Site 1. Open, right half open, closed, and left half open circles indicate new, first quarter, full and third quarter moons respectively.

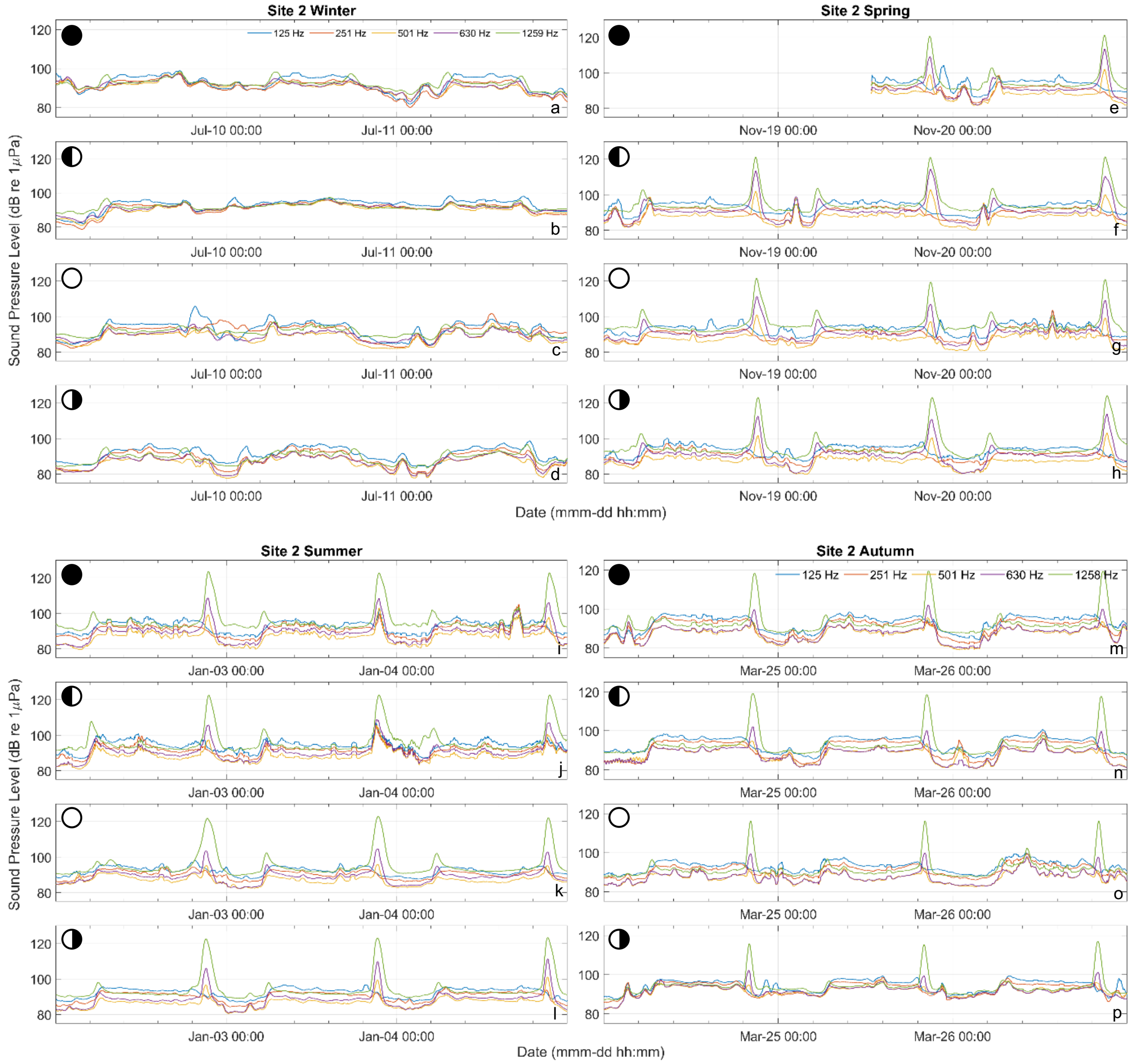


Figure 9. Sound pressure levels in one-third octave bands centred on 125, 251, 501, 630, and 1,250 Hz during three days over all moon phases during the Winter, Spring, Summer, and Autumn seasonal recording periods at Site 2. Open, right half open, closed, and left half open circles indicate new, first quarter, full and third quarter moons respectively.

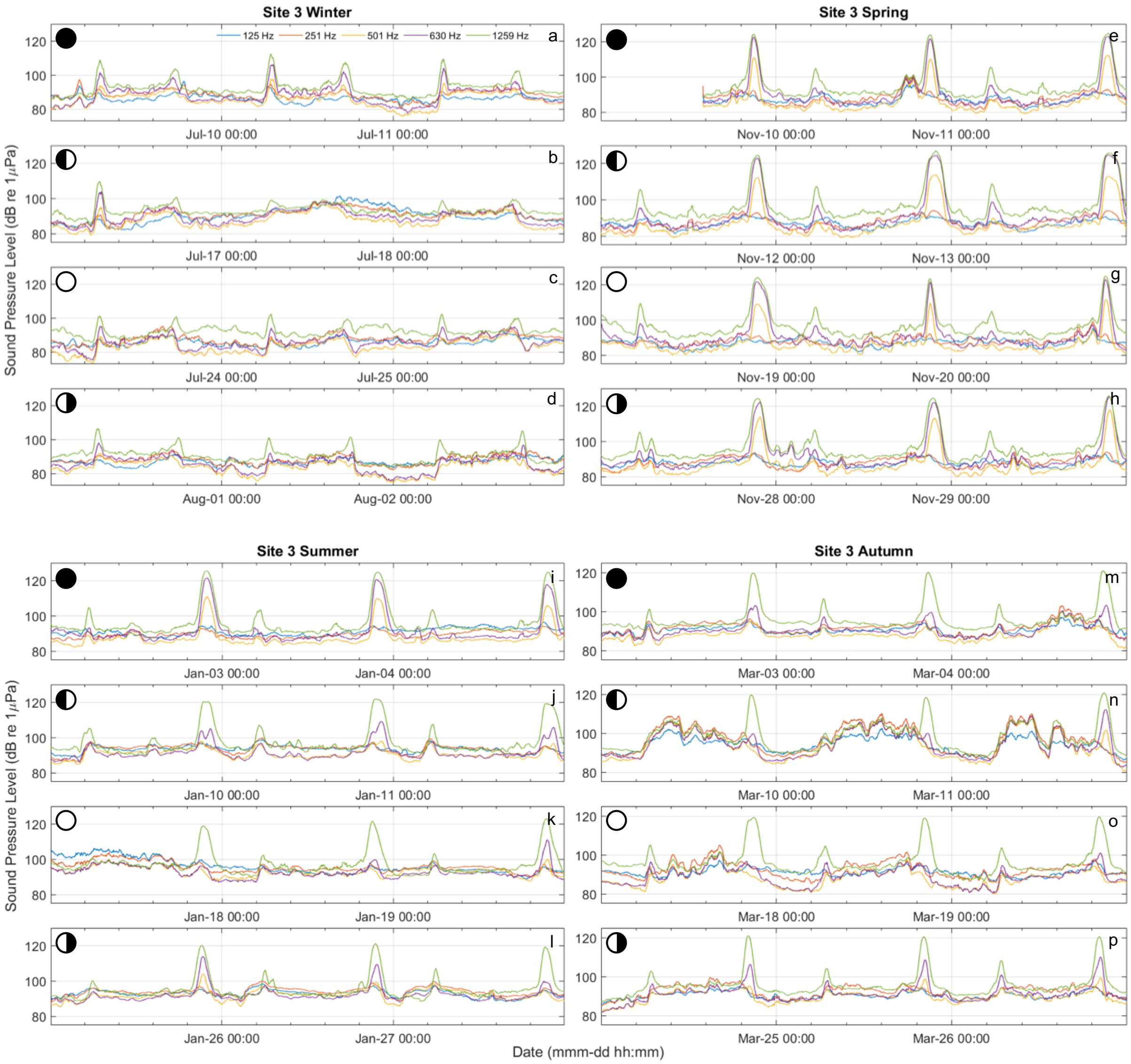


Figure *10*. Sound pressure levels in one-third octave bands centred on 125, 251, 501, 630, and 1,250 Hz during three days over all moon phases during the Winter, Spring, Summer, and Autumn seasonal recording periods at Site 3. Open, right half open, closed, and left half open circles indicate new, first quarter, full and third quarter moons respectively.

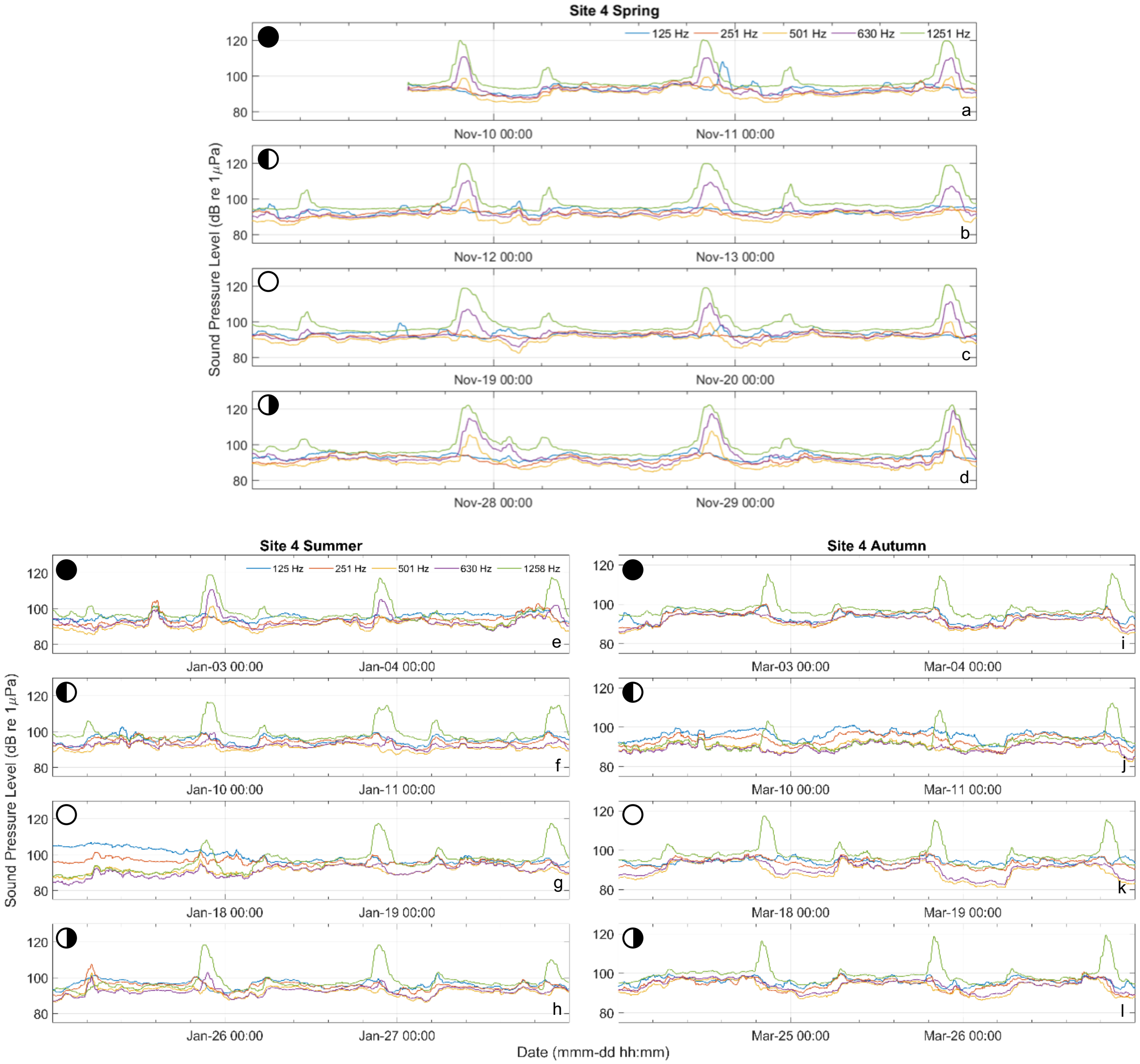


Figure 11. Sound pressure levels in one-third octave bands centred on 125, 251, 501, 630, and 1,250 Hz during three days over all moon phases during the Spring, Summer, and Autumn seasonal recording periods at Site 4. Open, right half open, closed, and left half open circles indicate new, first quarter, full and third quarter moons respectively.

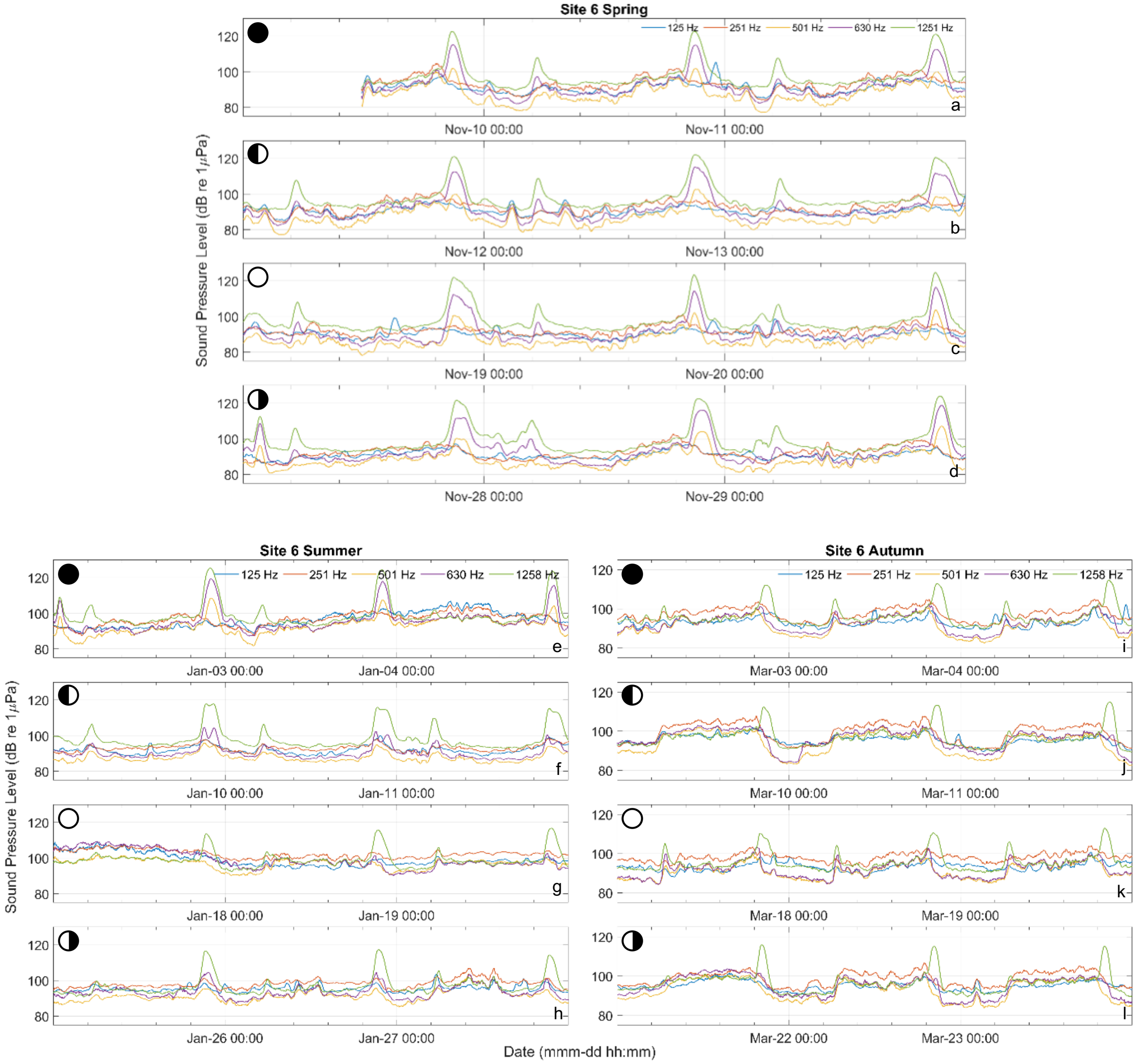


Figure *12*. Sound pressure levels in one-third octave bands centred on 125, 251, 501, 630, and 1,250 Hz during three days over all moon phases during the Spring, Summer, and Autumn seasonal recording periods at Site 6. Open, right half open, closed, and left half open circles indicate new, first quarter, full and third quarter moons respectively.

3.1.4 Inter-site comparisons

3.1.4.1 Broadband sound pressure levels

The median broadband (20 – 24,000 Hz) sound pressure levels (BB SPL) varied by as much as 12 dB between each site and season. On average, Site 1 had the highest BB SPL in three out of the four seasonal recording periods, Winter, Spring and Summer, with Site 6 having the highest SPLs during the Autumn recording period (Table 4 & 5). Site 2 had the lowest levels of BB SPL during all recording periods. Site 1 was the only site to have a significantly higher BB SPL in Winter, with an average of 121.3 dB, compared to the winter averages of 109.2 and 110.6 dB re 1 µPa at Sites 2 and 3 respectively (Table 4 & 5). All other sites, which included data for the Winter recording seasons, exhibited lowest SPL during this time.

Highest median BB SPLs were variable among sites and seasonal recording periods, with highest levels at each site occurring during unique seasons except for Sites 3 and 6 sharing the highest levels during the Summer recording period. Site 3 had the highest variability among recording seasons, with a 6.5 dB re 1 µPa between the highest (Summer) and lowest (Winter) seasons. Whereas Site 2 had the lowest variability among recording seasons, with only 0.9 dB re 1 µPa between the highest (Autumn) and lowest (Winter) seasons.

All sites followed similar patterns in diel median BB SPLs with crepuscular peaks occurring during dawn and/or dusk periods. Dusk peaks were observed at every recording site during all recording seasons; however, dawn peaks were generally only present during the Winter and Spring periods, with the exception of Site 3 which exhibited these peaks during all four seasons (Figure 6). Generally, the crepuscular peaks were largest in magnitude during the Spring and Summer recording periods, with the exception of Site 3 during the dawn period which saw Winter and Spring being larger than Summer and Autumn (Figure 6).

The timing of the crepuscular peaks in median BB SPL varied between sites and seasonal recording periods, with Spring and Summer generally occurring later into and following the dusk period compared to Autumn and Winter periods. At Sites 2, 3 and 4 during the Autumn and to a lesser extent Spring recording period, the dusk peaks in SPL exhibited bi-modality, with a small peak preceding a larger peak by ~1 – 2 hours (Figure 6).

3.1.4.2 Spectral composition

At all five recording sites there was a general trend of higher SPLs at low frequencies (<100Hz), and again at ~1000 Hz, decreasing into the higher frequencies >10,000 (Figure 7). The PSD showed that the most commonly occurring sounds were grouped together closely around the median, suggesting that for 50% of the time, the soundscape at all five sites remain relatively unchanged. The 5th and 95th percentiles showed more variation among the five sites, displaying the greatest differences in sound pressure levels in the lower frequency levels throughout all seasons, due to vessel presence and weather impacts causing wind and wave action. However, at all sites the 95th percentile displayed a peak in the spectra SPLs at the mid frequencies (700 – 1200 Hz) especially during the Spring and Summer recording periods due to biological chorusing (Figure 7). There was a constant, yet slightly variable rise in the spectra from 3000 – 11,000 Hz at all sites and all seasons to the pervasive acoustic activity of snapping shrimp. It is in these frequencies that the percentiles were closest to the median.

The 1/3 octave bands showed variation within and among all five sites throughout the four seasonal recording periods, and frequencies (Figure 8 – 12). Generally, the higher frequency bands (630 and 1259 Hz) displayed greater sound pressure levels at all sites, especially during the crepuscular periods due to biological chorusing, as well as generally producing higher sound pressure levels during the Summer and Spring recording periods. All frequencies generally displayed a strong diel pattern, with increased levels of sound pressure levels during daylight hours compared to the dark hours, with an approximate increase of ~6 to ~10 dB (Figures 8 – 11, Figures A6-24; Appendix 1). All sites also generally displayed differences in sound pressure levels during the four moon phases, with a higher sound pressure level occurring during the new moon phase compared to the full moon phase, specifically during the crepuscular peaks due to the biological choruses (Figures 8 – 11, Figures A6-24; Appendix 1).

3.2 Biologics

Manual inspection throughout the deployment period identified four different taxon groups (previously described and published) to be producing acoustic signals within the five sites (sea urchin, snapping shrimp, fish and marine mammals). Each of which occupied a different frequency range; however, all had some degree of frequency overlap especially in the case of the urchin and two-spot demoiselle.

There were also four acoustic signal types that were regularly observed (> 20 occurrences) in at least two of the five recording sites although were unable to be identified and could be produced many of the fishes and invertebrates inhabiting the region.

Table 6. Seasonal presence of identified sound producing organism at each recording site.

NB. lack of presence does not signify absence, as not every minute of each recording was inspected.

Site	**Site 1**				**Site 2**				**Site 3**				**Site 4**				**Site 6**			
Seasonal recording period	**W**	**Sp**	**Su**	**A**	**W**	**Sp**	**Su**	**A**	**W**	**Sp**	**Su**	**A**	**W**	**Sp**	**Su**	**A**	**W**	**Sp**	**Su**	**A**
Species																				
Sea urchin *Evechinus chloroticus*	P	P	P	P	P	P	P	P	P	P	P	P	n/a	P	P	P	n/a	P	P	P
Snapping shrimp *Synalpheus* Sp.	P	P	P	P	P	P	P	P	P	P	P	P	n/a	P	P	P	n/a	P	P	P
Bigeye *Pempheris adspersa*	P	P	P	P					P	P	P	P	n/a	P	P	P	n/a	P	P	P
Two-spot demoiselle *Chromis dispilus*		P								P	P	P	n/a	P	P	P	n/a	P	P	P
Blue-fin gurnard *Chelidonichthys kumu*		P				P	P						n/a				n/a			
Cetacean Spp.			P		P		P	P	P	P	P	P	n/a		P	P	n/a	P	P	P

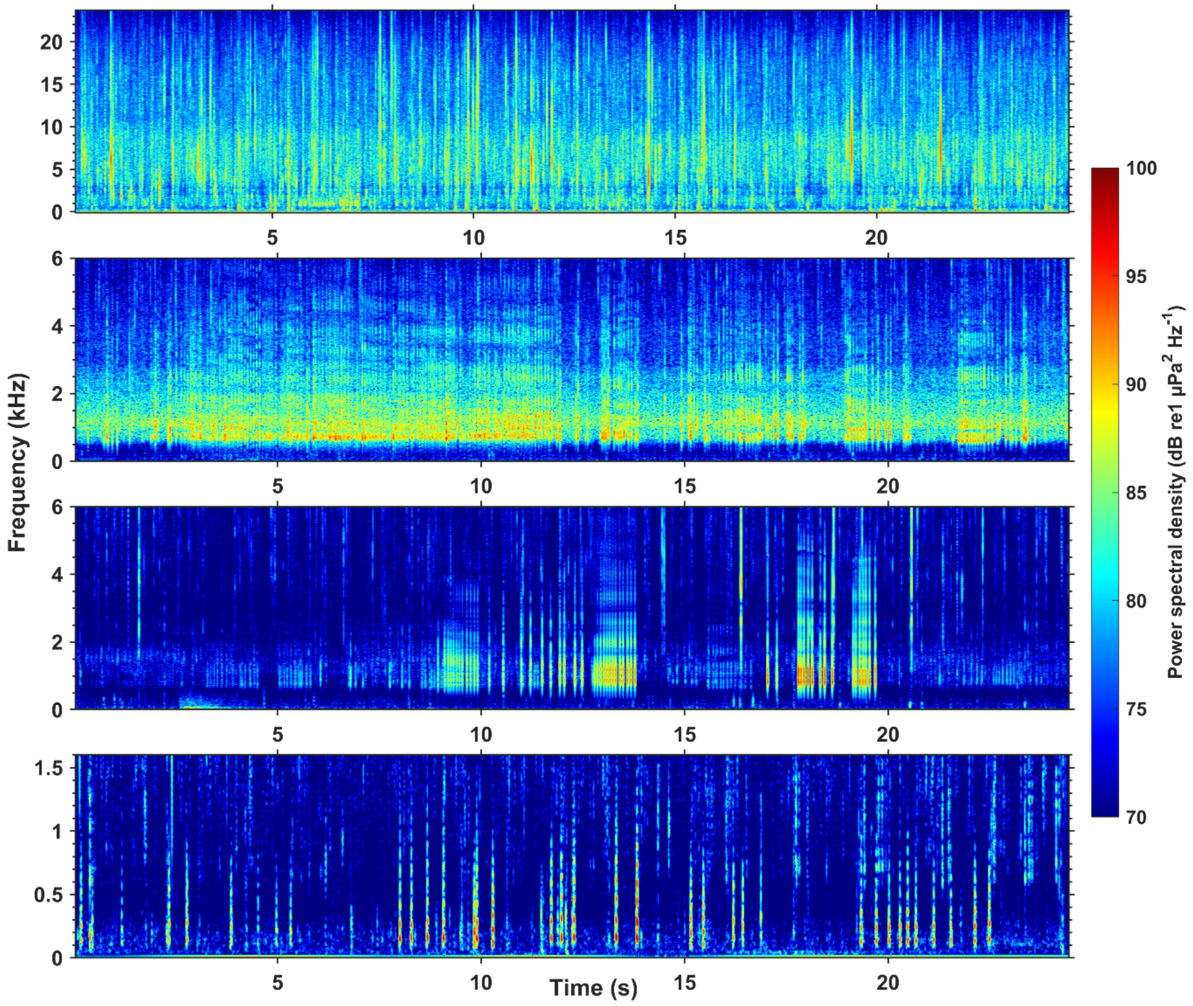


Figure 13. Spectrograms of the three of the three most common acoustic contributors to the underwater soundscape at the recording sites. a) Snapping shrimp, *Synalpheus* sp., "snaps", b) Sea urchin, *Evechinus chloroticus*, "scrape" chorus, c) single sea urchin "scrape", d) Bigeye, *Pempheris adspersa*, "pops". FFT length = 4048 points, Hanning window and 80% overlap.

3.2.1 Invertebrates

The "snaps" from snapping shrimp (*Synalpheus* sp.) occupied a frequency range of ~2,000Hz – 10,000 Hz with energy extending up to 24,000 Hz. The peak of the acoustic energy was in the 4,000 – 10, 00 Hz range (Figure A6-23; Appendix 1). These signals were consistently recorded at all five sites, during all seasonal recording periods with relatively little (< 2 dB) change in acoustic power (Table 6). Snapping shrimp signal was present throughout the diel period, however, would peak around dusk and dawn periods and often stay slightly elevated during the dark hours (Figure A6-23; Appendix 1).

The acoustic signals produced by the feeding rasp ("scrape") of the sea urchin (*Evechinus chloroticus*) occupied a frequency range of ~800 – 2,000 Hz with energy extending up to 3000 Hz. The peak of the acoustic energy was in the 900 – 1,500 Hz range, depending on the site (Figure 7 & A6 – 23; Appendix

1). These signals were also consistently recorded at all five sites, during all seasonal recording periods (Table 6), however, there were vast differences in the acoustic power of their frequency band among seasons (see sections above). The “scrapes” would generally peak around dusk and dawn periods whereby they would constitute a chorus, however, there was episodic activity during the daylight hours also. The least activity was during the dark hours.

3.2.2 Fishes

Manual inspection throughout the deployment period observed three identifiable fish species: Bigeye fish (*Pempheris adspersa*), two-spot demoiselle (*Chromis dispilus*), bluefin gurnard (*Chelidonichthys kumu*). There were also four additional regularly observed signals that could not be identified to species but due to their features were likely to have been produced by fishes.

The Bigeye “pop” consisted of short, repeated pulses. The signal occupied the 70 – 1200 Hz range, with a peak frequency of 225 ± 9 Hz and a single pulse duration of 0.9 ± 0.06 s (n = 20 used for parameter analysis). The signals from the bigeye were most abundant during dawn and dusk periods and would add to the urchin chorus, however, were also heard sporadically throughout light and dark hours. They were present at every site, during every seasonal recording period except for Site 2, which is not surprising due to the habitat type.

The two-spot demoiselle “click” consisted of short, repeated click trains, lasting longer than that of the bigeye. The signal occupied the 950 – 2000 Hz, with a peak frequency of 1150 ± 30 Hz (n = 20). Similarly, to the bigeye signals, two-spot “clicks” were most abundant during dawn and dusk periods, however, were also heard throughout the light hours but not on mass. They were present at every site, during every seasonal recording period except for Site 2.

The bluefin gurnard “grunt” was thought to be only observed at Sites 1 and 2, and only during the spring and summer recording periods. The signal consisted of short, repeated grunt pulses and occupied the 95 – 115 Hz frequency range, with a peak frequency of 104 ± 2 Hz (n = 17). Gurnard grunts tended to be sporadic through light and dark hours, and no discernible pattern could be detected, however, that could be due to the low sample size.

3.2.3 Marine mammals

Either the whistles or the echolocation clicks of odontocete cetaceans were observed at every site during the duration of the recording (Table 6). The frequency range of these two signals were fairly variable due to the various species, however, the whistles generally occupied the 3,000 – 15,000 Hz range and echolocation clicks >10,000 Hz (Figure 14).

The low frequency downsweep vocalisations of the assumed mysticete sei whale (*Balaenoptera borealis schlegeli*), based on vocal patterns, was also detected at Site 4 on November 10, 2022, and was present and vocalising within the listening range of the hydrophone for approximately 120 min. During this presence, the downsweeps occupied the 40 - 100 Hz frequency range, with the peak of the energy centred on 58 ± .3 Hz. The signals consisted of single down sweeps with a pulse duration of approximately 1.3 ± .4 s and repeated approximately every 10 – 25 s (n = 20 used for parameter analysis).

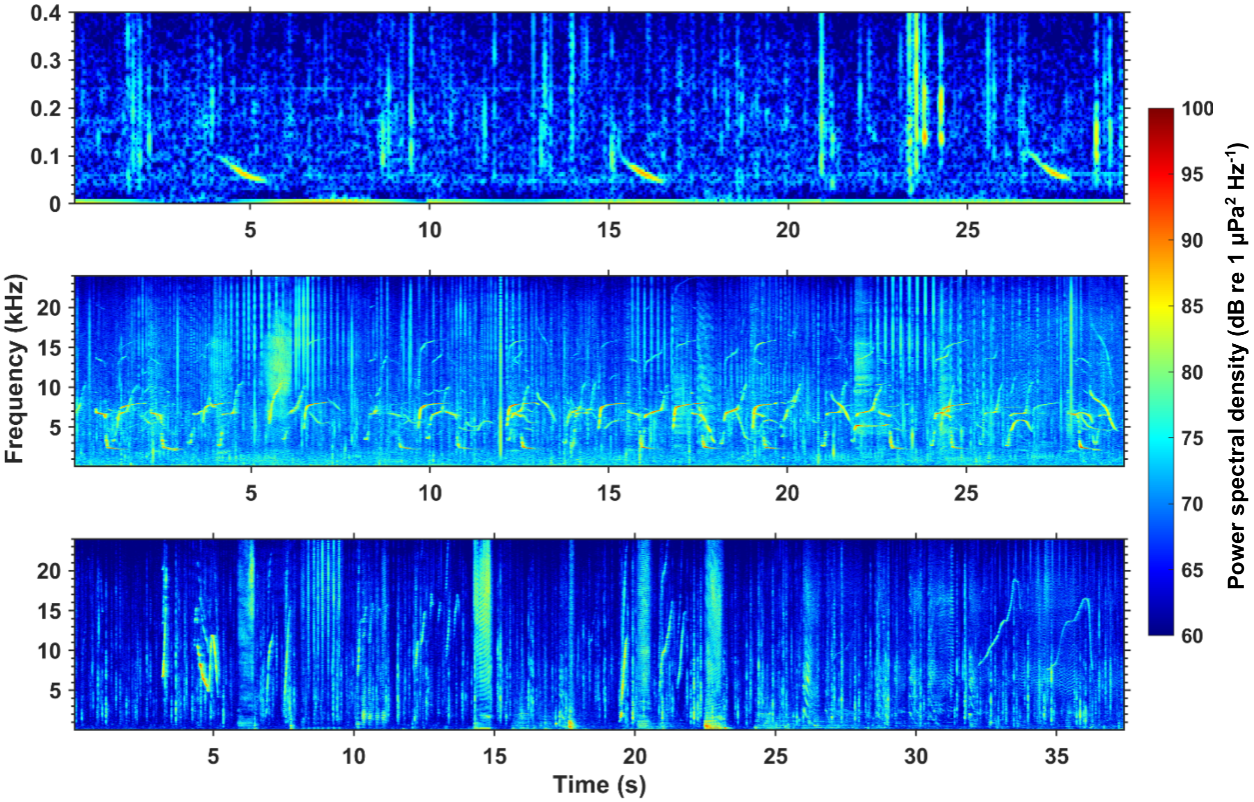


Figure 14. Spectrograms of three difference cetacean species observed in the Motiti Protection Area. a) Sei whale (*Balaenoptera borealis schlegeli*) down sweep, FFT length = 10048 points, Hanning window and 80 % overlap, b) Common dolphin (*Delphinus delphis*), FFT length = 6048 points, Hanning window and 80 % overlap, c) Bottlenose dolphin (*Tursiops truncates*), FFT length = 6048 points, Hanning window and 80 % overlap.

3.3 Abiotic

3.3.1 Earthquakes

Throughout the duration of the current study, 1,891 earthquakes occurred within the Bay of Plenty area. Due to New Zealand having a high frequency of tectonic movement and earthquakes, and due to the hydrophones limited ability detect the smaller earthquakes, only those with a magnitude greater than four were considered, of which there were 17 in total. Of the 17 earthquakes, seven were identified in the acoustic data, either manually or by the vessel detector (Figure 15). Those of which were not identified occurred during times of high-level low frequency sound due to other signals such as vessels or low frequency abiotic sounds.

Of the earthquakes that occurred during the recording period, the hydrophone of Site 3 detected one on the 2nd July 2021. This 4.2 magnitude earthquake occurred at 210 km depth occupied the 10 – 138 Hz frequency range with a peak frequency of 23.5 Hz and lasted approximately 40 s.

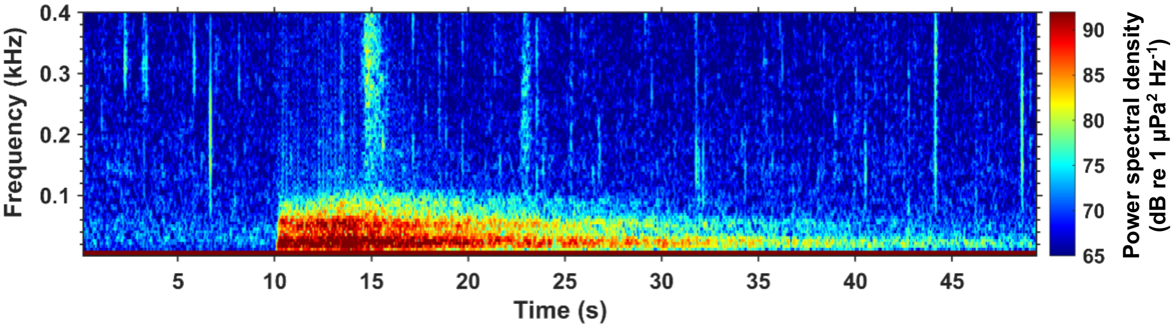


Figure 15. Spectrogram of 4.2 magnitude earthquake at 210 km depth off to the northeast of Astrolabe Reef (Site 3) (02-07-2021). FFT length = 10048 points, Hanning window and 80 % overlap.

3.4 Anthropogenics

3.4.1 Testing Triton vessel detector

Testing of the Triton vessel detector resulted in a sensitivity of 84% and greater, a false positive rate of less than 8% pre-verification and 0 % post-verification for all recording sites (Table 6).

Table 7. Efficacy of the Triton vessel detector at each of the five sampling sites reporting sensitivity and false positive rate. Note. False positive rate is corrected to 0% during manual verification.

Site	Location	Sensitivity	False positive rate pre-verification	False positive rate post-verification
Site 1	Motiti Island	93	.6%	0%
Site 2	Motiti Island	84	.8%	0%
Site 3	Astrolabe Reef	96	.8%	0%
Site 4	Astrolabe Reef	89	.6%	0%
Site 6	Astrolabe Reef	90	.7%	0%

3.4.2 Vessel presence

Three metrics were calculated from the raw verified vessel detection data in order to better understand vessel presence at each recording site. Firstly, average daily vessel detections for each site, over the entire data collection period; secondly, per day average of the vessel detections (AD) per site and seasonal recording period; and thirdly, the average number of hours per day (24 max) that had any vessel presence (AHD) per site and per seasonal recording period.

Daily vessel presence varied greatly among sites, with statistically significant differences among the average daily number of vessel detections per site over the entire data collection period (Figure #, Table 7) (Kruskal-Wallis Test; H = 351.6, P = <0.001, Dunn's Method; P = ≤ 0.001). On average, Site 2 had the greatest vessel presence with 17.3 detections per day, this was followed by Site 3 with 13.3 detections, then Site 4 and Site 6 (no significant difference, Dunn's Method; Q = 0.65, P = 1.0) with 9.9 and 11.8 detections respectively, and Site 1 having the lowest, with an average of 3.4 vessels detections per day.

The average number of daily vessel detections (AD) also varied among seasonal recording periods within sites, with Autumn being the most common period within a site to have the highest number of daily vessel detections. Although Winter at Site 2 showed the highest AD with 22, while also having the highest 95th percentile at 35 detections (Table 7).

Both Site 3 and Site 4 had the highest during the Autumn recording period with 15.5 and 11.4 average daily detections respectively. Spring saw Site 6 and Site 1 having the greatest number of detections, with 12.5 and 4.9 detections respectively. Interestingly, the Summer period was the most common for the lowest number of daily detections when comparing within a site, with Site 3, 4 and 6 all having the lowest occurrence during this recording period. For Sites 1 and 2, the lowest AD occurred in the Autumn recording period. These differences were all statistically significant (Kruskal-Wallis Test; $P = \leq 0.01$, Dunn's Method; $P = \leq 0.01$) except in the case of Site 3 which didn't exhibit any significant differences among seasonal recording periods, however, there was the general trend of highest in Autumn, followed by Spring and Winter and finally Summer (Table 7).

The average number of hours per day (AHD) that had vessel presence within them also varied among sites and within sites (Kruskal-Wallis Test; $P = < 0.001$, $H = 433$). Site 4 had the highest AHD during the Winter, Spring and Summer recording periods, but had the second lowest compared to other sites during the Autumn recording period. Site 4 also on average had the highest 5th and 95th percentiles, compared to the other four sites. Sites 3, 4 and 6 had relatively similar AHD. Site 3 had the highest average number of hours her day with vessel presence in Autumn at 9.4 hours of the day, and Sites 4 and 6 having the highest in the Spring with vessels present for 8.9 and 10.1 hours of the day respectively. Sites 3, 4 and 6 also had the lowest AHD during the Summer recording period, with vessels only present for 6.5, 6.9, and 7.5 hours of the day respectively. Site 1 had the lowest AHD, throughout all four seasonal recording periods, with the highest occurring in Spring with 3.5 hours. Site 1 also had the lowest 5th and 95th percentiles, ranging from 0-5.7.

Table 8. Metrics of daily number of vessel detections per site and season. NB. Bolded numbers signify seasonal recording period with the highest average number of vessel detections within each. Red numbers signify the recording site with the highest average number of vessel detections per seasonal recording period.

Location	Motiti Island		Astrolabe Reef		
Site ID	Site 1	Site 2	Site 3	Site 4	Site 6
Entire duration					
Average daily	3.4	17.3	13.3	9.9	11.8
Winter: June – August					
Average daily detection	3.3	**22**	13.9	-	-
5th	0	7.6	3	-	-
95th	12.4	35	34.5	-	-
Average number of hours per day with presence	1.8	14	8.5	-	-
5th	0	6	2.6	-	-
95th	5.7	19	18	-	-
Spring: September – November					
Average daily detection	**4.9**	17.5	11.9	11.1	**12.5**
5th	0	3.1	3.8	4	6.1
95th	13	33.6	21	19	19
Average number of hours per day with presence	3.5	11.6	8	8.9	10.1
5th	0	3	2	3	4
95th	8	18	13	15	14
Summer: December – February					
Average daily detection	3.8	14.2	11.4	8.9	9.4
5th	0	3.9	0.5	3	1.9
95th	12	25.6	29.7	17	18.6
Average number of hours per day with presence	2.8	10	6.5	6.9	7.5
5th	0	2.5	0.5	2	1.5
95th	9	17	17	12	13
Autumn: March – May					
Average daily detection	1.1	9.7	**15.5**	**11.4**	11.8
5th	0	5	0	3.1	4.5
95th	3.4	13.7	39	22.8	19.7
Average number of hours per day with presence	0.8	4.8	9.4	8.6	9.2
5th	0	0	0	3	4.3
95th	3	12.4	21	16	13.9

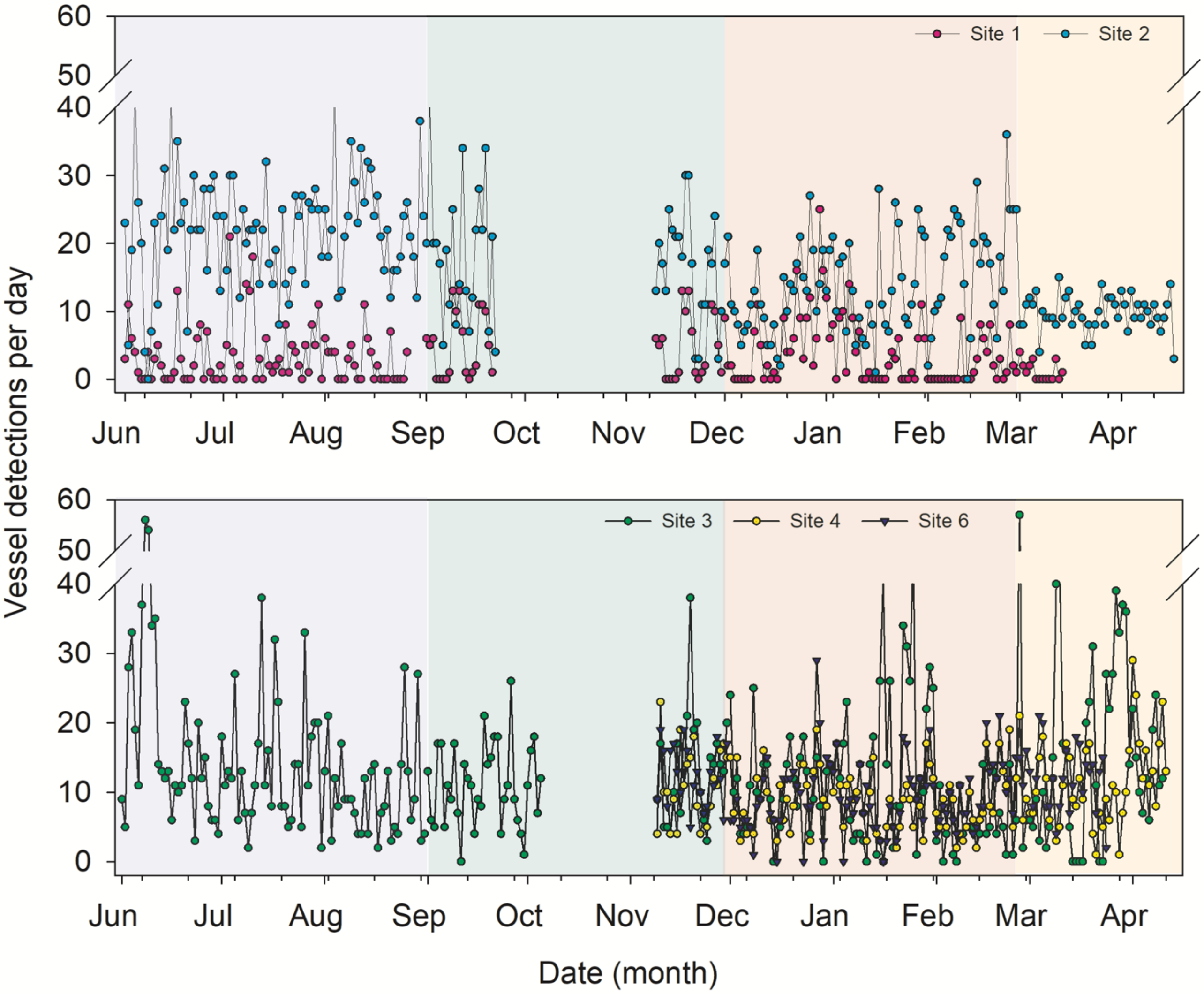


Figure 16. Time series of daily vessel detections for all sites and seasonal recording periods. A) Motiti Island; Site 1 and 2, b) Astrolabe Reef; Site 3, Site 4 and Site 6. Blue, green, red and orange shading highlights the Winter, Spring, Summer and Autumn seasonal recording periods respectively.

Chapter Four: Discussion

The current study focused on creating a baseline acoustic characterisation of the underwater soundscape of five ecologically varying sites at Motiti Island and Ōtaiti/Astrolabe reef providing information on acoustic drivers of diel and seasonal patterns in the soundscape including elements associated with anthropogenic presence. Generally, studies that focus on marine soundscapes focus on temporal trends and variation within one unique habitat, with these studies helping to better understand the biological and anthropogenic changes within an ecosystem (Stanley et al. 2021). However, over the last few years a great number of studies have been exploring the spatial as well as the temporal variation among multiple habitats (Staaterman et al. 2014, Putland et al. 2017, Stanley et al. 2021), to gain a better understanding of how soundscapes vary among various ecological and geographical types of habitats and ecosystems, this is the approach we have taken in the current study. When comparing various sites which are geographically, biologically, and physically different, a standardised approach to monitoring all sites is necessary. This can be difficult, due to the unique and distinct environmental features of each site, for example, depth, temperature, and substrate type. In this study, the most prominent example of this is the substrate type, ranging from rocky reefs to sand flat substrates, and depth, which among sites ranges closely from 15-20m. This needs to be taken into consideration when comparing sound pressure levels (SPL), especially at low frequencies among the five sites, as sound propagates differently depending on depth and substrate type. Regardless of these considerations, differences in propagation characteristics cannot account for many sources of variation in the soundscape parameters observed here.

The overall aim of this present study was to collect ambient underwater sound data from five sites at Motiti Island and Ōtaiti/Astrolabe Reef in the Bay of Plenty, in an attempt to derive measurements to investigate spatial and temporal changes in ambient sound pressure levels and identify the biological, abiotic, and anthropogenic sound sources that are contributing to the individual soundscapes at these locations. This research will help form a better understanding of the acoustic and biological diversity of these unique sites, and therefore hope to become a useful tool for future research opportunities to aid in the conservation and management of unique and irreplaceable New Zealand marine ecosystems.

This research is essential to building 'baseline' data sets on the local underwater soundscapes as well as forming a better understanding of human use, while recording any early changes in human activities after the recent formation of the Motiti Marine Protection Area. It is hoped that this research will highlight future opportunities for integrating non-acoustic and acoustic variables in order to inform area specific management questions of interest.

4.1 Discussion of results

All five sites were found to have vast differences in broadband sound pressure levels (20 – 24,000 Hz), spectral composition, one-third band levels, and levels of anthropogenic input through vessel presence. Each site had its own unique characteristics due to differences in biological diversity, propagation patterns due to the physical composition and climates of the sites, and human use patterns, which differed through diel and seasonal patterns. Unsurprisingly, there was less variation seen in the measured soundscape parameters at sites in the same location, for example, Site 3, 4 and 6, all within the general Ōtaiti/Astrolabe Reef area. Conversely, this is not the case in the sites at Motiti Island, as habitat type was more dissimilar between Site 1 and 2, than Site 1, 3, 4 and 6, with the latter all being macroalgae dominated rocky or boulder reefs.

Patterns in ambient sound pressure levels within shallow marine ecosystems are often due to biological sound sources. Many sound producing organisms are responsible for creating regular contributions to the soundscape, with daily, lunar, and seasonal patterns identified in both temperate and tropical ecosystems (Cato 1978, Radford et al. 2008b, Radford et al. 2010, Staaterman et al. 2014, Stanley et al. 2021). For example, in sub-tropical habitats of north-eastern New Zealand the crepuscular activity of urchins and certain fish species have been observed to cause an evident increase in ambient sound levels (Radford et al. 2008a, Radford et al. 2010, van Oosterom et al. 2016, Putland et al. 2017). These common phenomena are often known as dawn and dusk choruses. Furthermore, ambient sound levels of shallow reef habitats vary considerably over the lunar cycle, with often a greater intensity produced over the new moon and less intense during the full moon (Staaterman et al. 2014).

In the current study, biological sound sources gave soundscapes regular diurnal, lunar and seasonal patterns. As general rule, the median BB and 1/3 octave band SPLs exhibited considerably higher crepuscular peaks during the dusk compared to the dawn hours (e.g., 14.7 & 0.8 dB re 1 μPa BB SPL respectively at Site 3 during the Autumn), daylight compared to dark hours, and were the highest over the Summer and Spring recording periods compared to Winter at four of the five sites, which is commonly observed in temperate coastal habitats (Radford et al. 2008b, Haxel et al. 2013, Harris and Radford 2014, Putland et al. 2017). Putland et al, (2017) also found similar results, with the broadband root-mean squared sound pressure levels ranging from 90 -110 dB re 1 μPa between winter and summer months at all study sites, however, it must be noted that BB SPL (RMS) values are often higher than median BB SPL due to the nature of their calculation (Merchant et al. 2012a). The RMS level is strongly influenced by the highest sound levels in the sample and therefore should not be applied to sound recordings with intermittent high-amplitude events (Merchant et al. 2015). Furthermore, the dusk chorus consistently had considerably higher ambient sound pressure levels in the 600 – 1,200 Hz frequency range, compared to the dawn chorus. For example, patterns in the 1/3 octave band levels (Figure 8, Panels i-l) at Site 1 in the Summer recording period demonstrated an increase of 5 – 7 dB re 1 μPa and an increase of 15 – 27 dB re 1 μPa during dawn and dusk respectively. Here, this was largely due the increased acoustic activity of the sea urchin, *Evechinus chloroticus*, either directly from the habitat where the hydrophone was located, or due the acoustic signal of these organisms propagating from neighbouring habitats as in the case of Site 2, which has neighbouring rocky reef approximately 170 m away, known to have high densities of sea urchin.

Sea urchins were found to be one of the most dominant acoustic contributors in the soundscapes at all five sites, especially during the dusk choruses, throughout all seasons, consistent with previous studies in New Zealand and elsewhere (Castle and Kibblewhite 1975, Radford et al. 2008a, Radford et al. 2010, Putland et al. 2017). The acoustic signal produced by these organisms was present among all sites and all seasonal recording periods; however, they were most prominent during the Summer and Spring recording periods. Sound produced by sea urchins was found to be most significant during dusk and dawn periods, however, isolated signals from random individual sea urchins were also observed throughout the daylight hours. Along with fish vocalisations and small recreational vessels, these isolated urchin signals are also a cause of the increase of sound levels (2 – 3 dB re 1 µ Pa) during daylight hours. These isolated urchin signals were not regularly observed during the dark hours. The decline during the Autumn and Winter is likely due to either the area no longer supporting large numbers of sea urchins and/or the urchins present are not as active and are therefore not producing as much sound during the colder months (Putland et al. 2017). Analogous to their levels in sound production, sea urchins have been found to have substantial fluctuations in seasonal feeding activity, consumption rates of algae increase during Summer, indicating that there is a higher availability and quality of food during the warmer months (Larson et al. 1980, Rodgers and Shears 2016, Putland et al. 2017). Rodgers and Shears (2016) reported that kelp biomass and photosynthetic rates are reduced during the colder months in temperate reefs in New Zealand, indicating that there is less food available for grazers such as sea urchins during these periods.

Site 3 exhibited the highest crepuscular peaks, with the acoustic activity of urchins of raising the BB SPL by up to 14.7 dB re 1 µPa. Sites 2, 3 and 4 displayed bimodal peaks in BB SPL during the dusk hours, which varied among seasonal recording periods in timing but generally would see a small peak followed by a larger peak approximately 1 – 1.5 hour later. These were most pronounced during the Autumn recording period at Sties 2 and 4, and during the Spring recording period at Site 3. This bimodal trend is likely due to different groups of the same species or two different species producing sound at different times. Radford (2007) suggested that this could be due to different sized sea urchins producing two temporal peaks. Urchins are nocturnal animals, therefore, as larger sea urchins are less susceptible to being preyed on, smaller sea urchins may remain active during the day, while the larger urchins become more active during dusk, causing a second peak and the subsequent amalgamation of the bimodal peak. Until the 1960's, the most southern point, *Centrostephanus rodgersii*, the long spined sea urchin, was found was on islands in the eastern Bass Strait and north-eastern Tasmania in Australia, today, likely due to the transport of larvae in the East Australian current and warming waters due to the effects of climate change, this species has also become prominent on the eastern coast of New Zealand. (Ling et al. 2009, Ling et al. 2015, Byrne and Andrew 2020). This addition of the long spined sea urchin, specifically in high numbers, has been a recent occurrence in the Bay of Plenty (Pers. Comm. Crawshaw, 2022), and there are now observed to be areas of high density (> 2 per m^2) occurring at Astrolabe Reef (Pers. Comm. Stanley, 2021, 2022). The addition of this species could also be changing the acoustic signature of the urchin band, both temporally and in frequency, and may be the cause of high SPLs in this band during the seasons where the feeding is usually low in *E. chloroticus*. Little to no information is known in regards to the feeding and/or acoustic ecology of *C. rodgersii* in the Bay of Plenty, however, there are a number of studies underway investigating these factors to better understand this species and what it could mean for other species assemblages it shares habitat with. The distinctive acoustic signature from these grazing organisms (urchin species) has the potential to be used as a metric of feeding activity, or with some further work a proxy for species identification, population levels and size structure. Passive acoustic monitoring could become a valuable tool in the monitoring of sea urchin overgrazing and barren formation and distribution spread of new species to an area, like *C. rodgersii* along the east coast of New Zealand (Ling et al. 2009, Miller and Shears 2022).

Snapping shrimp, along with sea urchin, were also observed to be one of the most dominant and ubiquitous acoustic signallers. The snaps from snapping shrimp were also continuously present at all five recording sites and were found to be one of the main contributors to the ambient soundscape in the 2000 – 12,000 Hz frequency range at each. This is consistent with previous research which have also stated that snapping shrimp have been found to inhabit a wide range of habitats such as shallow sandy bays to rocky and coral reefs, in temperate and tropical waters (Au and Banks 1998, Radford et al. 2010). It is also suggested that there is a higher increase in snapping shrimp activity during the Summer period due to an increase in water temperature (Radford et al. 2008b, Bohnenstiehl et al. 2016, Buscaino et al. 2016), as they are poikilotherms, and they are therefore likely to be more active during periods with warmer water temperatures (Radford 2007). During the new and full moons during the Summer recording period there was significant weather events, with increased wind and swell. During this time at Site 6, there was a trend of increased SPL in the low frequency (20 – 700 Hz) and a reduction in SPL in the higher bands (1500 – 10,000 Hz) which includes the band dominated by the snaps of snapping shrimp. In contrast, there are previous studies which reported category 4 hurricanes in 2004 and 2017 in Charlotte Harbour, FL and Florida Keys, USA respectively, did not inhibit the night chorusing of spawning fish or the level of sound production by snapping shrimp. It is possible that the increased swell at Site 4 altered the acoustic behaviour of the usually ever-present snapping shrimp and other vocalisers and should be further investigated (Locascio and Mann 2005, Simmons et al. 2021).

While sea urchins and snapping shrimp make up the majority of the dusk choruses in New Zealand, previous studies have strongly suggested that fish vocalisations and choruses are also a common feature of New Zealand reefs (Ghazali 2011). During the current study, multiple unique fish vocalisations were common throughout all seasonal recording periods and to an extent occurred at every site, however, they largely did not constitute a traditionally defined chorus, whereby the sound from many individuals is continuously above ambient background levels for an extended period using an averaging time of 1 sec. Several unique signals, including those ones identifiable as being produced by bigeye, *Pempheris adspera*, two spot demoiselle, *Chromis dispilus,* and bluefin gurnard, *Chekidonichthys kumu*, were observed sporadically and often in isolation during both daylight and dark hours and seasonal sampling periods (Radford et al. 2015, Radford et al. 2016, Putland et al. 2017). Why fish vocalise is largely unknown, unlike the known acoustic biproduct of feeding and territorial defence in urchin and snapping shrimp respectively, however, the irregular vocalisations produced by the bluefin gurnard could be linked to previously reported behaviours (Radford et al. 2016).

Conversely, the single pops and pop trains produced by multiple bigeyes were found to contribute to the substantial increase in SPL (up to 30 dB) in the 501 Hz and 251 Hz 1/3 octave band during the dusk period in the Spring and Summer seasonal recording periods at Sites 3, 4 and 6, and to a much smaller extent the dawn period. Bigeyes are nocturnal, planktivorous reef fish, which are known feed in loose shoals. Vocalisations have been reported to be used as contact calls to maintain group cohesion during times when visual cues are absent (van Oosterom et al. 2016). Considering the timing and characteristics of the observed vocalisations it is possible that group cohesion is also the reason for this acoustic behaviour in the two-spot demoiselle. Furthermore, although the acoustic signals of the two-spot demoiselle and sea urchin were aurally distinguishable by the types of sounds they produced, and visually distinguishable when viewed in a spectrogram or LTSA, it was difficult to tease apart the contribution each during the dawn and dusk peaks in the 1/3 octave band centred on 1259 Hz. As both peak frequencies were in the 800 – 1100 Hz range, largely dependent on the urchin populations size distribution (Radford et al. 2008a). Site 2 returned the lowest overall BB, 1/3 octave band, and full spectrum SPLs, this is likely due to the site being located in a sandy bay with the closest reef being ~170 m away. Consequently, this site was likely to have less biodiversity when compared to rocky reef systems that support a wide variety of species. However, Site 2 had the greatest occurrence of vocalisations of the blue fin gurnard and was the only site to have vocalisations of this species identified during each recording season. This supports the findings of Radford (2007), who also found that sound emanating from different habitat types were significantly different, with reef habitats having a significantly higher ambient sound pressure level when compared to soft sediment habitats.

Previous studies have observed that during certain seasons several distinct types of fish choruses can be found present together, however, would largely hold their own aural or temporal niche within the soundscape. For example, in Greys Reef National Marine sanctuary, off the coast of Georgia, USA, four distinctive fish chorus were found to occupy the same time during the spring, whereby peaking around dusk. Although these shared a temporal component, they resided in different frequency space (Stanley et al. 2021). It was observed that choruses during dark hours were most often frequency partitioned, with some slight temporal off set in peak SPL. Conversely, vocalisations that occurred during light hours were often observed to overlap and would not usually constitute a ‘chorus’. This is also consistent with the findings of the current study, especially during light hours where there are several unidentified fish signals, however, many of which overlapped in frequency space. These observations support the theory for environmental constraints (dark vs. light) driving/facilitating the use of diverse acoustic strategies to avoid masking by another source or misinterpretation by the target receiver during these acoustically busy time periods, supporting the acoustic niche hypothesis (Krause 1993). Although, partitioning of the acoustic space in the marine environment, especially by fishes, is not well documented, frequency or temporal separation has been demonstrating in a wide variety of other groups such as insects, birds and mammals (Ruppe et al. 2015, Schmidt and Balakrishnan 2015, Desiderà et al. 2019, Hart et al. 2021). Unfortunately, not all acoustic signals were able to be identified to species, however, many were aurally and visually identifiable as fish vocalisations based on their characteristics and resemblance to other known signals produced by fishes. Fishes were contributors to the overall ambient marine soundscape and a contributor to the evening choruses among at all sites especially during the Spring and Summer recording period. However, generally, the vocalisations sharing the same acoustic space together with the sound production of other species such as sea urchins and snapping shrimp and were consequently difficult to separate (D’spain and Batchelor 2006). Ghazali (2011), concluded that the fish choruses occurred at the same time as those produced by snapping shrimp and sea urchins, and that the intensity of the sound produced by the snapping shrimp and sea urchins was considerably higher than those of the fish.

The light intensity during the various moon phases can vary greatly and have drastic effects on marine soundscapes. Many marine nocturnally active species will modify their activity and behaviour based on the changes in light intensity due to the lunar cycle (Radford 2007). Furthermore, the light intensity due to moon phases can affect species differently depending on whether they are a predator species, prey species, or both (Lang et al. 2006). An example of this is snapping shrimp, which are both a predator and prey species, snapping shrimp show a strong diel and lunar activity pattern, and have been reported to produce a significantly higher amount of snaps around the dawn periods during new moon compared to other times of the day and/or a full moon when there is a lower level of light intensity (Radford 2007). A good example of this is Sites 1, 3 and 6 during the Spring, Summer and Autumn recording periods. Here the snapping shrimp band was 3 - 5 dB re 1 μ Pa greater over the new moon period than the full moon period. This could be due to the snapping shrimp communicating more when the light levels are at the lowest in order to reduce the risk of predation, and/or a reduced risk of being detected by their prey (Radford 2007). Sea urchins are reported to be crepuscularly and nocturnally active organisms, with smaller cryptic sea urchins largely a prey species to some nocturnal, however mostly diurnal predator species (Hereu 2005). Therefore, it is likely that the decrease in ambient sound during a full moon phase is also in part due to smaller sea urchins remaining in crevices so they are less susceptible to visual predators (Radford et al. 2008a). Ghazali (2011), reported that fish vocalisations within New Zealand habitats form greater dusk choruses during the new moon phase, across all seasons. Similar to the snapping shrimp and sea urchins, many fish species have been found to vocalise significantly more during the new moon phase compared to the full moon phase, this is likely due to fish reducing the risk of predation during periods where there are elevated levels of light (Ghazali 2011). However, other studies also observed fish choruses to occur during the full moon, this however also coincided with spawning events (Luczkovich et al. 1999). This is likely due to enhanced food availability during full moon, as this would promote higher growth rates, and therefore reduce the risk of predation for early larval stages of fish species as a higher growth rate due to increased food intake implies lower exposure to predators (Hernández-León 2008). Male toadfish have been found to produce their characteristic whistle, in order to attract a mating partner, through a sonic muscle, which is attached to the fish's swim bladder, this muscle vibrates and creates a one to one relationship with the calls frequency. The call rate and to some extent frequency of toadfish vocalisation have been found to be largely seasonally dependant due to changes in water temperature and light availability (Butler et al. 2016). Butler (2016) observed that the gulf toadfish (*Opsanus beta)* produced a higher number of calls and had a greater contribution to the soundscape during the new moon, compared to the other moon phases during the spring and summer months in Florida Bay sea grass habitat.

A rather complex combination of abiotic sound sources contributes to marine soundscapes. Environmental variables such as depth, location, bottom level composition and the intensity of physical sound at the water's surface can alter the soundscape in varying degrees (McWilliam and Hawkins 2013). Weather, specifically wind and precipitation are considered to be key contributing abiotic factors to a soundscape, as wind speed and rainfall increase, the PSD generally also increases. Stanley et al. 2021 reported that in a number of US National Marine Sanctuaries BB SPL had moderate to no linear relationship with wind speed (m/s), however, when using the SPLs in the 63, 125, 251 and 501 Hz octave bands the relationship increased (Stanley et al. 2021). Weather is a significant factor in shallow marine environments as the sound from the surface is able to propagate through the water column and to the sea floor which can have significant effects on marine soundscapes (Piggott 1964, Urick 1983, Staaterman et al. 2014, Putland et al. 2017). A large majority of abiotic sound present in marine soundscapes are not periodic phenomena, high winds, wave action, and precipitation are weather dependant and therefore do not occur in a pattern form. Water movement through currents due to tidal cycles are more periodic, and often create 'self-noise' by moving past moorings (Urick 1983, Staaterman et al. 2014).

In the current study, changes in sound pressure levels throughout the four seasons were evidently related to weather conditions, however, the closest weather station with quantitative data was 24 km in land from the coast. There was intent to investigate the correlation between SPLs and wind speed, swell height and precipitation, however, the lack of auxiliary data sets containing accurate hourly data made it impossible and any inferences made would have been misleading. Therefore, only large-scale weather events could be tracked. Abiotic sound is a large contributor to soundscapes, specifically at Sites 3, 4 and 6, which are located on Astrolabe Reef. This is due to the topography of the reef and reaching the surface of the water at low tides, creating wave and swash action. A weather event during the Winter recording period and consistent periods of high wind speeds and swell in the vicinity of Astrolabe reef caused debris from the wreckage of the container ship Rena to move on the underlying rocky reef. This created a unique acoustic signature to any biotic, abiotic and/or anthropogenic previously encountered and also caused variation in the 1/3 octave band levels. To the authors knowledge at the time of writing, there is no previously published work on the acoustic signatures created by shipwrecks, either stationary or moving due to weather conditions and would be an interesting area for further development.

New Zealand is renowned for being very tectonically active due to the countries position on the boundary of the Australian and Pacific tectonic plates (Putland et al. 2017). There were 1,891 earthquakes within the Bay of Plenty region during the recording period, ranging from <2 – ≥7 in magnitude, and <15 – ≥200 km deep (http://quakesearch.geonet.org.nz/), however, only 17 were above a magnitude of ≥4. Of these 17, seven were able to be identified in the acoustic data. Earthquakes can be detected hundreds of kilometres away from the initial source and have been found to be able to raise the ambient sound pressure for short periods of time (Putland et al. 2017). However, due to earthquakes not being a consistent abiotic feature, they are not considered to be a dominant contributor to the soundscape (Putland et al. 2017). It is largely unknown if the sound from earthquakes has effects on marine organisms. Although, a study by Warren et al. (2021) suggested that since earthquakes can produce high intensity sounds similar to levels emitted by seismic surveying, and especially due to earthquakes often happening abruptly without warning, there is the possibility that there could have a behavioural effect on marine mammals and potentially causing communication masking (Warren et al. 2021).

Marine shipping represents a major source of low-frequency anthropogenic noise and is steadily increasing in many ocean regions (Hildebrand 2009). At frequencies of 300 Hz and below, the ambient noise level can be elevated by 15 – 20 dB when exposed to distant shipping (McKenna et al. 2012, McKenna et al. 2013). Vessel noise is a by-product from ship operations, largely propeller cavitation (Ross 1976). Scientists and policy makers are raising concerns over the effects of increased noise levels on marine organisms (Hatch et al. 2012, Stanley and Jeffs 2016, Halliday et al. 2017, Stanley et al. 2017). However, predicting the noise levels from shipping in a given area, and the specific conditions that may increase these levels, remains relatively unknown.

Tauranga harbour and the Ports of Tauranga are located approximately 21 kilometres from Motiti Island and Astrolabe Reef, on the west edge of the Bay of Plenty, the harbour is protected on its seaward side by Matakana Island, where shipping traffic can enter the harbour from the northern or southern tips of the island (Inglis et al. 2006). The port of Tauranga is New Zealand’s largest and fastest growing commercial port, handling 1/3 of all cargo and ~40% of New Zealand’s exports. It is also the only port in New Zealand that can accommodate the world’s largest container vessels (Port of Tauranga Limited 2022). Anthropogenic sound within a soundscape is generally not a periodic phenomenon, as the use of vessels can often be weather and seasonally dependent. However, due to the proximity of the sites to Tauranga Harbour and the Ports of Tauranga, at times there was a daily pattern in increased BB SPL and in the lower 1/3 octave bands due to the transiting of large commercial vessels. There were also several days where large contained Anthropogenic sound made up a generous portion of each of the site's soundscapes, all five recording sites displayed increased PDS levels in the 80-120 dB re 1 $\mu Pa^2/Hz^{-1}$ range due to vessel presence. Site 2 specifically, showed several sharp peaks below 1,000 Hz, which are likely due to variable, low-level sound from vessels moving in the vicinity of the hydrophone location. This is due to the residents of Motiti Island using this bay as an entry point to the island. Local vessel traffic, whether commercial or recreational affected each site differently. There was a wide range of vessels detected among the five sites, the majority of vessels detected were commercial vessels which includes various cargo ships such as container ships, logging ships and fishing vessels for imports and exports. In addition to this, tug vessels and pilot launches are also used in the Tauranga Harbour on a daily basis, as they guide large cargo vessels into the Port of Tauranga. At several sites there were the acoustic signatures of large stationary vessels for 2 – 3 days consecutively, with engines on and periodic use of bow thrusters and other machinery. This behaviour is likely due to vessel congestion and some arriving into harbour early and not having port space allocated at that time. It has been recently reported in the international media that due to congestion in global supply chains there have been record-breaking queues of container ships outsides the world's major ports such as Long Beach and Los Angeles in the US, and the Port of Shanghai (https://www.globaltimes.cn/page/202205/1267067.shtml, https://www.bbc.com/news/58926842). According to the Global times (Elane Inc.) congestion at the Port increased the average wait time of 28 hours at the end of April, to 71 hours in mid – May 2022.

4.2 Soundscapes potential for monitoring ecosystem health, conservation, and protection

Global domination of natural habitats by humans has resulted in a massive loss to biodiversity (Chapin et al. 2000, Rands et al. 2010). The total loss of species to this day is so significant, that some have concluded that earth is experiencing the 6th mass extinction event (Naggs 2017). With the loss of habitat degradation and biodiversity loss, ecosystems are losing their natural sounds, to the extent where natural sounds have previously been referred to as an endangered resource (Jensen and Thompson 2004, Pijanowski et al. 2011b). By understanding the importance and value of soundscapes, it is possible to educate people and have individuals change their behaviour towards this resource (Harmon 2003). Marine ecosystems provide earth with irreplaceable functions and services such as driving and modulating the earth's climate (Sydeman and Bograd 2009), as well as directly benefitting humanity by providing a food course, economic value and coastal protection (Selig et al. 2019). Information about local biodiversity is an essential part of being able to evaluate the ecological status of an ecosystem (Lin et al. 2021). Therefore, an efficient and cost-effective sensing system which is capable of monitoring the frequent changes and patterns in marine biodiversity is needed, this provides vital information on ecosystem changes, and allows for the diagnosis of potential risks due to environmental and anthropogenic stressors (Schmeller et al. 2017, Obura et al. 2019, Lin et al. 2021). Ecosystem monitoring can reveal the community structure of marine soundscapes, and provide vital information on spatiotemporal changes in biotic and abiotic sounds being produced within an ecosystem (Lin et al. 2021). Creating a baseline set of data for an ecosystem is vital in order to create a platform of data which helps with understanding what an ecosystem looks like, that can then be used to monitor and detect ecological changes and risks due to environmental and anthropogenic stressors.

Until relatively recently, consistent monitoring the soundscapes of marine ecosystems has been largely ignored, as it wasn't believed to directly benefit marine conservation and management (Miksis-Olds et al. 2018, Howe et al. 2019, Lin et al. 2021), and although still an emerging scientific topic, acoustic monitoring has advanced greatly over recent years with the number of scientific publications in the field increasing mostly throughout the previous 10 years (Lindseth and Lobel 2018). The ecological monitoring of marine habitats is key to understanding how the ecosystems function, as well as being able to measure the effect of conservation and restoration efforts. Currently, these monitoring efforts often rely visual census surveys, which come with limitations such as requirement of trained data collectors, logistical complexities, are often expensive and are typically poor at monitoring cryptic species within an ecosystem. Furthermore, visual census surveys are only able to capture a single snapshot of time rather than long term, continuous data (Mooney et al. 2020, Munger et al. 2022, Williams et al. 2022). Conservation monitoring is often limited by time, available resources and funding, making it challenging to sufficiently and accurately represent an ecosystem and its progress over time (Rilov et al. 2020). Automated passive acoustic monitoring has the potential to mitigate many of these limitations (Mooney et al. 2020, Lamont et al. 2022a). Relatively low-cost acoustic recording technology (hydrophones) is starting to become readily available, which is capable of continuous recording over a few months, or duty cycled for extended periods of time (Lamont et al. 2022a). Hydrophones are able to be deployed rapidly, and can be left to record autonomously, twenty-four hours a day, therefore only needing to be deployed and collected a few months later, compared to traditional survey techniques which require consistent physical surveys (Williams et al. 2022). Furthermore, unlike traditional methods of surveying marine ecosystems, acoustic monitoring is minimally invasive, discrete and less affected by human presence which can alter the presence and behaviour of species, as well as also still being able to survey under adverse meteorological conditions, when traditional methods of surveying are not possible, which provides a unique perspective (Pieretti et al. 2017).

This study was the first to examine the underwater soundscapes within and around the Motiti Protection Area at Ōtaiti/Astrolabe Reef and Motiti Island creating baseline acoustic data sets. This is a crucial first step in monitoring this newly created marine protected area, this baseline data needs to be continued in order to successfully show changes in the ecosystems at these sites as they recover from being openly fished and exploited.

4.3 Study limitations and potential improvements

Acoustic monitoring is a powerful tool in detecting, localising, and providing information about a soundscape, However, it does come with limitations, for example, when objects, phenomena and species in question don’t produce sound, either directly or as a by-product (Howe et al. 2019).

This study took place throughout 2021/2022, and was therefore impacted by nationwide lockdowns, travel restrictions, protocols, regulations, and limited available staff members due to COVID-19. This delayed the retrieval and subsequent turnaround of hydrophones, resulting in a period of time with no acoustic data. This fact coupled with gear malfunctioning resulted in no data being collected for the Winter recording period at Sites 4 and 6. The retrieval and deployment dates were also affected by weather, as the conditions have to meet certain criteria (winds consistently < 12 knots and < 1.2 m swell) for the safety of the staff and divers.

After country-wide lockdowns ended, the Bay of Plenty region as well as other regions such as Auckland were still subject to Alert Levels 3 and 4 restrictions, which resulted in water-based activities and businesses such as recreational boating, charter vessels and dive shops being greatly reduced during this time. Consequently, this would have also been reflected in the soundscape analysis, therefore, a longer study could have represented the anthropogenic influence on these soundscapes more accurately. Issues with the hydrophones themselves also had some limits on this study.

Time constraints and limitations due to COVID-19 prevented a more thorough study, specifically in order to gather enough acoustic data to accurately represent the seasonal fluctuations, therefore, gathering acoustic data over multiple years would represent the soundscapes of each site more accurately. Furthermore, there was no available weather data, as there is no weather station within the vicinity of the sites, the closest weather station was on the mainland in Tauranga, 23.6km away. Therefore, the correlation between wind speed and precipitation on the soundscapes at Motiti Island and Ōtaiti/Astrolabe Reef could not be explored, due to the lack of auxiliary data sets.

4.4 Future directions

Currently, we are in the best-timed situation to use the Motiti Protection Area as a test bed for how underwater soundscapes in several different habitats change through the lifecycle of protection. In the future it will be of great research importance to look back on these early years and examine the changes. It is hoped we can also learn more regarding human use and changes in human use patterns within the protection areas and in neighbouring areas where there is no protection, to investigate the potential impacts of activity displacement, and whether other nearby sites are being over utilised due to these recent changes.

Conducting acoustic research in a wide variety of habitats around the world over spatial and temporal scales is vital in understanding how soundscapes function, which aspects change due to habitat degradation and identifying what tool could be helpful in identifying the health and biodiversity of marine ecosystems. More studies like the current one, which examine soundscapes within marine protected areas, are crucial in creating ‘baseline’ data set exploring what a ‘protected’ ecosystem sounds like. This will aid in achieving the goal of marine resource management and enable temporal examination of habitats during the lifecycle of protection. Furthermore, these data sets are vital and currently time sensitive, if we want to be able to use them in aid of understanding of what effects climate change and warming oceans have on habitats, their inhabitants and their ambient soundscapes. For example, as mentioned in this study, the sea urchin species *Centrostephanus rodgersii*, has only over the past years migrated to New Zealand due to warming seas, and continues to expand down the east coast, it is vital to understand the change this has on existing soundscapes.

Furthermore, it is important for studies which look at the monitoring and management of marine ecosystems to look into the potential acoustic monitoring holds. (Daly 2015), found that when spoken to, only 38% of councils contacted regarding underwater sound protection, stated that they saw a need for specific underwater noise provisions. However, they also identified two issues with the implementation of those previsions, firstly there is a sever lack of expertise and education within New Zealand councils on the importance of underwater soundscapes, and secondly, there are limited resources, therefore councils are likely to target resources to where they are most effective (Daly 2015). As a result of this, soundscapes are likely to go unnoticed due to a lack of awareness and expertise, without sufficient information, advice, and support, councils will be unable to implement any provisions to monitor marine soundscapes. Acoustic monitoring can offer a unique perspective on the health and biological condition of marine soundscapes, and do so in an efficient, minimally invasive, and cost-effective way, however this method of monitoring cannot be implemented through government and councils if it is not recognised and well understood.

4.5 Concluding remarks

Soundscapes have the potential to be a very efficient and effective form of assessing an ecosystem’s health and biological condition. However, acoustic monitoring remains widely untested, especially in New Zealand and therefore lacks conviction. For this study, acoustic monitoring was found to be simple, labour efficient, and uninvasive means of monitoring a Marine Protection Area and its surrounds.

It provided accurate data on the soundscapes at the five sites at Motiti Island and Ōtaiti/ Astrolabe Reef and created a crucial baseline data set that can be used as the first step to the acoustic monitoring of the Motiti Protection Area. Passive acoustic monitoring has the potential to be a successful tool in monitoring marine ecosystems to draw conclusions on their health and biological condition. This study highlights the biotic, abiotic and anthropogenic contributors to the soundscapes at these sites and give an insight to how soundscapes can be used to accurately describe a marine ecosystem, It is hoped that this study will highlight the importance of marine soundscapes, and contribute to the introduction of acoustic monitoring and soundscapes into the world of marine conservation and management in New Zealand.

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