

Listening to nature

*Acoustic analysis for monitoring wildlife management and
protected areas*

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Abstract

Sampling methods able to capture information about various taxa, over broad time and spatial scales are essential to assess the successes of protected areas (PAs) and pest control programmes. Passive acoustic monitoring (PAM) coupled with acoustic indices and automated identification are promising tools for biodiversity monitoring. However, two technical bottlenecks are still important limitations for their wide use. Automatic identification commonly presents high false positive rates and there are no standardised protocols for the use of acoustic indices for monitoring. In this thesis I approach these gaps and test the use of PAM associated with automated identification and acoustic indices for monitoring PAs and conservation management. In chapters 2 and 3, instead of using acoustic indices as biodiversity indicators, I use them as filters that allow the identification of the acoustic region that differs most between sites. I define the acoustic regions as units of analysis bounded by a specific time period and frequency range adjusted to capture the main groups of biologically relevant acoustic events within a soundscape. By splitting indices data into acoustic regions, I facilitate statistical analysis of indices results and simplify the identification of sounds that are driving the indices results. In chapter 2 I test if acoustic indices are sensitive enough to measure significant differences in the soundscapes for the Serra do Cipó National Park, Brazil, and a surrounding farmland area. The soundscapes differ significantly for all the 12 indices tested during autumn from 05:30 – 09:00am and within the range of 0.988-3.609 kHz. Sonotype results show that the soundscape outside the park is strongly influenced by domestic animals (present in 63% of the sound files aurally analysed). In chapter 3 I propose and test a workflow for the monitoring of two sites within the Waitakere Ranges Regional Park, New Zealand, that have different pest mammal management levels. The analysis of variance and pairwise comparisons indicated the acoustic region encompassed within 21:00 to 23:59 and a range of 0.988-3.609 kHz in autumn as the one that differs most between sites. The sounds responsible for the main differences on indices measurements are emitted by the activity of invasive mammals in the site with no pest control. In chapter 4 I present and test the Assemblage of Focal Species Recognizers - AFSR, for decreasing false positives of automated acoustic identification for 5 seabird species from Burgess Island, New Zealand. I used MatlabHTK, a hidden Markov models interface for bioacoustics analyses, for illustrating AFSR technique by comparing two approaches, 1) a multispecies recognizer where all species are identified simultaneously, and 2) an assemblage of focal species recognizers (AFSR), where several recognizers that each prioritise a single focal species are then summarised into a single output, according to a set of rules designed to exclude unreliable segments. False positive rate improved for all the five species when using AFSR achieving a remarkable 0% false positives and 100% precision for three of five seabird species. Instead of attempting to withdraw useful information from every fragment in a sound recording, AFSR prioritises more trustworthy information from sections with better quality data. AFSR can be applied to automated species identification from multispecies PAM recordings worldwide. These results confirm that PAM sampling associated with automated identification and acoustic indices are able to represent condition and detect trends in acoustic communities, which are the main focus of monitoring programmes. PAM is able to provide information on acoustic community composition and dynamics, affording useful information for PAs management and conservation programmes.

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Chapter 1. Introduction

Drivers of biodiversity loss and need for management programmes and protected areas

Life on Earth is facing one of the most dramatic moments in the planet's history. The current extinction rates confirm that the Earth's sixth mass extinction is in progress (Barnosky et al. 2011). Nearly a quarter (22%) of mammals; one in eight (13,6%) birds; and one third (31%) of amphibians are currently threatened or have become extinct since 1500 A. D. (Vié, Hilton-Taylor & Stuart 2009). Given contemporary global biodiversity declines (Pimm & Brooks 2000; Myers & Knoll 2001), understanding the process of biodiversity loss and improving the efficiency and effectiveness of the tools used for species conservation are extremely important.

Among the main causes of extinctions is the introduction of alien species (Clavero & Garcia-Berthou 2005; Bellard, Cassey & Blackburn 2016). Invasive species often affect native animals by competing for resources or due to predation. These scenarios are commonly worse in island ecosystems, in which typically there are less resources available and native animal species are commonly naïve to mammalian predators that are frequently absent during their evolutionary history (Blackburn et al. 2004). Among island endemic extinctions since 1500 A.D., 86% are reportedly due to alien species (Bellard, Cassey & Blackburn 2016). Management programmes focusing on control of invasive species are crucial for native species conservation, especially for islands.

Another main driver of biodiversity loss is habitat degradation associated with land use (Sala et al. 2000; Brooks et al. 2002; Hoekstra et al. 2005). Habitat loss is the main source of biodiversity declines in the tropics, most of the extremely rich tropical forests are vanishing at accelerated rates (Laurance 2007). To optimize conservation efforts, Myers et al. (2000) distinguished hotspots for biodiversity conservation identifying that 1.4% of land surface is inhabited by 44% of the species of vascular plants and 35% of the species of vertebrates. At a global scale, the priority regions for conservation include tropical biomes with high species richness such as the Cerrado (Brazilian savannah), as well as groups of islands with high proportions of endemic species such as New Zealand. Françoso et al. (2015), indicate the urgent need for Protected Areas (PAs) in the fast-disappearing Cerrado biome to ensure the representativeness and persistence of its conspicuous biodiversity.

Protected areas (PAs) provide crucial habitat that prevents the extinction of many species (Le Saout et al. 2013). Studies suggest that, in spite of receiving scarce economic resources and often poor management, PAs are effectively contributing to biodiversity conservation (Gaston et al. 2008; Leverington et al. 2010). They are globally recognized as essential for conservation and are the focus of international agreements such as the Aichi Targets that define goals of protecting 17% of terrestrial and inland water ecosystems and 10% of marine and coastal ecosystems within PAs by 2020, established by the parties of the Convention on Biological Diversity (CBD 2010). Although undoubtedly important for conservation, robust information on the role of PAs in sustaining biodiversity is scarce.

Monitoring challenges

The main reason for the lack of robust information on the wildlife communities of PAs is the range of technical challenges in carrying out monitoring programmes (Nichols et al. 2011), which makes it difficult to implement decision-making processes for wildlife management. Monitoring protocols commonly aim to assess biodiversity and to be able to represent condition and detect trends (Lee, McGlone & Wright 2005). Sampling methods able to capture varied taxa information over broad time and spatial scales are essential to improve biodiversity monitoring (Schmeller et al. 2017). Monitoring protocols traditionally detect animals visually, aurally, or by their feeding, faeces and footprints. More invasive methods such as trapping and marking or tagging are also common. However, these methods are time consuming and expensive which makes them impractical for use in many PAs and management programmes. Monitoring initiatives in natural PAs and conservation programmes should be able to record the effects of changes in communities and ecosystems, giving additional and more comprehensive information for management and providing information to enhance societal awareness of the values of protected areas and biodiversity conservation programmes. A cost-effective and easy to implement sampling method for monitoring is crucial for assessing and sustaining the conservation outputs from alien species control programmes and PAs.

Potential of passive acoustic monitoring - PAM

Recent technological advances in the use of autonomous acoustic sensors have significantly improved the possibilities of using sound recording in monitoring programmes. It is now possible to implement systematic long-term sampling using programmable recording schedules (Sueur et al. 2012; Digby et

al. 2013). These autonomous recorders provide reduced observer bias and broader temporal and spatial sampling. They also have less impact on animal behaviour, since the presence of the researcher in the field is no longer required. Due to these advances, passive acoustic monitoring (PAM) now stands as a promising tool for biodiversity surveys, enabling its use in ecological, behavioural and conservation studies (Sueur & Farina 2015; Ribeiro, Sugai & Campos-Cerqueira 2017; Wrege et al. 2017). The number of studies using PAM has grown exponentially during the last decades, increasing from an average of 2.8 papers per year in the 1990s to 42.5 papers per year in the 2010s (Sugai et al. 2018). Recordings sampled by PAM are enduring and can therefore be retro-analysed using different or new analytical approaches. The two approaches with greatest potential of using PAM data for wildlife monitoring purposes are automated identification of calls and soundscape studies.

Acoustic automated identification techniques commonly focus on computerized identification of target calls. They can be used for detecting the presence of target species (Potamitis et al. 2014), to measure relative species abundance (Borker et al. 2014), to determine bird acoustic activity patterns (Cragg, Burger & Piatt 2015; Stowell, Benetos & Gill 2017), to study intraspecific song variants (Ranjard et al. 2015) and to improve animal distribution and occupancy models (Kalan et al. 2015; Campos-Cerqueira & Aide 2016; Campos-Cerqueira et al. 2017). These automated techniques use diverse software, statistical models and sound processing algorithms (Acevedo et al. 2009; Stowell, Gill & Clayton 2016; Katz, Hafner & Donovan 2016; Bas, Bas & Julien 2017; Ranjard et al. 2017; Ovaskainen, de Camargo & Somervuo 2018) to facilitate analysis of enormous sound file data sets generated by a PAM approach. These identification methods have been applied to numerous taxa, such as insects (Aide et al. 2013; Zilli et al. 2014), anurans (Xie et al. 2016; Deichmann et al. 2017), bats (Andreassen, Surlykke & Hallam 2014; Newson, Evans & Gillings 2015), canids (Rocha et al. 2015; Palacios et al. 2016), birds (Sanders & Mennill 2014), and elephants (Wrege et al. 2017). PAM associated with automated identification can be especially useful when species are nocturnal or cryptic, or when sites are remote and have only intermittent access, which makes these techniques suitable for the study of seabirds (Buxton & Jones 2012; Borker et al. 2014). However, high false positive rates seem to be a constant challenge when applying these identification methods (Borker et al. 2014; Zwart et al. 2014; Cragg, Burger & Piatt 2015; Newson, Evans & Gillings 2015; Rocha et al. 2015; Ranjard et al. 2017), which limits their application to wildlife monitoring surveys. Research on methods to decrease false positives are needed to enlarge the utility of automated identification techniques for wildlife monitoring.

Another analytical approach with great potential for using PAM data for monitoring is the study of soundscapes. Soundscape studies commonly focus on extracting biological information from PAM

recordings using acoustic indices. Rather than focusing on individual species identity, these studies commonly aim to represent overall activity patterns of the acoustic community (Sueur et al. 2008; Servick 2014; Gasc et al. 2015). They can be especially useful for ecosystems in which species identification is challenging due to high diversity (Duarte et al. 2015) and when monitoring aims to detect overall states, trends and changes in the acoustic community. Soundscape studies have initiated a new research area, first called soundscape ecology (Pijanowski et al. 2011) and more recently ecoacoustics (Sueur & Farina 2015). The conceptual framework of soundscape ecology builds on the acoustic niche hypothesis developed by Krause (1993) who described that in environments with high diversity of vocal animals, spectral and temporal overlap are reduced, avoiding signal masking. In this perspective, species compete for acoustic space in order to communicate. As a result, each species emits their acoustic signals using a specific temporal and frequency bandwidth, which optimizes acoustic signal transmission and reception (Krause & Farina 2016). The ensemble of each species acoustic communication within their specific bandwidths compound what Krause (2012) called “the animal orchestra”. The acoustic signals ensemble can be used as a representation of the acoustic footprint of a given environment, which can be measured and used for long term monitoring (Farina, Pieretti & Piccioli 2011). To detect and describe the soundscape, the use of acoustic indices is necessary.

Acoustic indices work as mathematical filters that extract information about how the acoustic energy is distributed across time and frequency in a sound file. Each index can be sensitive to a different acoustic feature, each providing information about different aspects of a sound file. There is a substantial number of acoustic indices described in the literature (Sueur 2018). Soundscapes have been studied using acoustic indices in different habitats worldwide. These include tropical savannah (*Cerrado*) (Machado, Aguiar & Jones 2017; Ferreira et al. 2018) and Atlantic forest (Duarte et al. 2015) both in Brazil, neotropical forest in French Guiana (Rodriguez et al. 2014), tropical forest in the Tanzanian coast (Sueur et al. 2008), subtropical woodland in Australia (Tucker et al. 2014; Towsey et al. 2014), temperate woodland in France (Depraetere et al. 2012), shrubland Mediterranean maqui in Italy (Farina & Pieretti 2014), and marine environments (Harris, Shears & Radford 2016; Buscaino et al. 2016). Studies have aimed to relate acoustic indices with biodiversity features such as habitat condition (Sueur et al. 2008; Fuller et al. 2015), vegetation structure (Farina & Pieretti 2014; Pieretti et al. 2015) and composition of the acoustic community (Tucker et al. 2014; Towsey et al. 2014; Phillips, Towsey & Roe 2018).

The soundscape is composed of three broad sound categories, namely i) biophony: the sounds emitted by animals, ii) geophony: the sounds created by geophysical processes (such as wind, rainfall,

earthquake, thunder, etc), and iii) anthrophony: the sounds generated by human activities (machinery, industries, cars, airplanes, etc). Indices such Acoustic Complexity Index (ACI) (Pieretti, Farina & Morri 2011) and Entropy Index (ENT, also called $H[t]$) (Sueur et al. 2014) are acknowledged to be sensitive to biophonies. The ENT was demonstrated to be linked to ecological condition (Fuller et al. 2015) and bird species richness (Gasc et al. 2015). The ACI was the best bird biodiversity indicator among 14 acoustic indices tested by Towsey et al. (2014) and positively correlated with avian vocalization (Fuller et al. 2015). These two indices (ACI and ENT) are often calculated in soundscape studies that use multiple indices (Tucker et al. 2014; Towsey et al. 2014; Fuller et al. 2015; Harris, Shears & Radford 2016; Ferreira et al. 2018). The ENT index is especially sensitive to the energy temporal dispersal in a sound file. It is expected that more species emitting sounds will result in a higher energy dispersal. The ACI is sensitive to the oscillation of amplitude in sound files. Anthrophony and geophony typically present more constant amplitudes values, while biophony commonly presents greater intensity oscillation (Farina, Pieretti & Piccioli 2011). Hence, these two indices are sensitive to different features of biophonies, being complementary to each other and suitable for acoustic ecological studies.

Technical challenges in using Ecoacoustics for biodiversity monitoring

Even though the potential of soundscape studies for monitoring is considerable, some remaining technical challenges are preventing their wide-ranging use. The first group of difficulties are related to sampling and storage of sound files. The lack of standardized sampling protocols for monitoring makes experimental design a complex task and may result in data comparability problems with existing data sets. Additionally, there are important obstacles related to handling the very large data sets generated by PAM studies, regardless of the analysis performed. The second group of difficulties are specific to the analysis performed, such as automated identification and acoustic indices calculations.

The commonly found high false positive rates are a main limitation when using automated identification analysis. High levels of false positives create unreliable data on animal presence and are therefore not useful for supporting management decision-making. Improving methods to decrease false positive rates is essential for using automatic identification for wildlife PAM recordings, especially in a multiple species context that typically presents a potential increase of false positives rates.

Other common obstacles when using acoustic indices are related to the analysis of extremely large data sets, the lack of standardized PAM sampling protocols (Sugai et al. 2018), the difficulties in visualizing acoustic indices calculations (Towsey, Truskinger & Roe 2015) and the technical problems in identifying which animals (or other sound sources) are generating different indices results (Machado, Aguiar & Jones 2017). Also, the acoustic indices' relationships with traditional biodiversity measures are contradictory in some soundscapes (Fuller et al. 2015; Mammides et al. 2017). Eldridge et al. (2018) report that acoustic indices are a good indicator of avian species richness in temperate, but not tropical, habitats. Therefore, straightforward interpretations of acoustic indices as simple biodiversity indicators should be taken cautiously. Instead, for monitoring, I advocate using a combination of acoustic indices, primarily as filters that help to identify which sounds are resulting in significant differences between sites and across time. Additionally, biodiversity monitoring commonly focuses on focal species that are expected to respond to the management that is being applied (Sugai et al. 2018). However, management outputs can emerge from unexpected taxa, and different temporal and spatial scales.

Ideally, biodiversity monitoring should be able to navigate across different spatial and time scales, being able to represent a broad picture of the acoustic community at the same time as providing information at a more precise scale about which animals are generating differences on acoustic indices results. Animal behaviour commonly changes across seasons (e.g., breeding season), which is the reason why traditional monitoring protocols are commonly season dependent. Therefore, acoustic monitoring should ideally be able to report on the more important groups of acoustic activity within a day (e.g., dawn and dusk chorus), and should also be sensitive to variations across seasons. A monitoring protocol should also be able to be applied in different management contexts and habitats worldwide, allowing soundscape comparisons and identification of acoustic patterns at a broader scale. The development of a workflow that can be applied in different habitat and management levels, that allows the navigation across different time and spatial scales, as well as allows the identification of sounds that generate small changes in the soundscape, will considerably increase the utility of acoustic indices analysis for biodiversity monitoring.

Research aims

The overarching aim of this project is to test the suitability of passive acoustic sampling techniques associated with different sound analyses for protected areas and conservation management programmes monitoring biodiversity. Here I test two analytical methods on information derived from

PAM recordings, the acoustic automated identification and acoustic indices. Additionally, in this thesis I also seek to develop improvements to analytical methods in order to increase their utility for real management situations, particularly in relation to multispecies automated identification, effectiveness of predator control and human land use impacts in and near protected areas.

Specifically, the studies were designed to address the questions:

- 1) Can passive acoustic sampling coupled with acoustic indices analysis assist in monitoring the biodiversity outcomes associated with different management levels?
- 2) Are current acoustic indices effective in identifying seasons and acoustic regions (frequency range and time period) of relevance for biodiversity monitoring interest?
- 3) Does visualization of acoustic indices measurements facilitate analyses of very large data sets and identification of the sounds that underlie biologically meaningful differences in indices results?
- 4) Are acoustic automated species identification techniques sensitive to changes in species composition and variation in relative temporal abundance?

Thesis Outline

This thesis contains three data chapters (2-4) that can be read as stand-alone research papers. The final chapter (5) is an overall discussion of the major questions based on findings presented in the previous chapters as well as points to future research. I have made an effort to give a continuous reading flow throughout the thesis. However, because all the data chapters share some similar types of data and approaches, there is some inevitable repetition of methods.

Chapter 2 uses passive acoustic recordings sampled in each season in the Cerrado Biome (savannah), at the Serra do Cipó National Park, Brazil, and in a surrounding area outside this protected area. Twelve acoustic indices are calculated and their measurements are separated into specific time periods and frequency ranges. Analysis of variance and pairwise comparisons are used to indicate the periods and frequency of monitoring interest. Long duration false colour spectrograms are used to facilitate the identification of acoustic events. Sonotype counts are provided to describe the main acoustic events in the soundscape. Cosine similarity heat maps are used to check for data

inconsistency. If the techniques used here are capable of measuring the significant changes in animal biodiversity during the four seasons, and inside and outside the protected area, then PAM associated with these acoustic analyses could provide useful, low-cost protocols for protected areas monitoring that could be used to detect long term changes in acoustic communities.

Chapter 3 proposes and tests a workflow for passive acoustic monitoring in two nearby protected forest sites that have different management levels for controlling introduced mammals. Here acoustic indices measurements are aggregated into acoustic regions defined by frequency range and time period, then statistical analysis are performed to identify which acoustic region differs most between sites. The identified acoustic region is the focus of a more detailed examination. First, acoustic events within this region are visually identified using long duration false colour spectrogram. Second, sound files with acoustic events are aurally and visually scanned using traditional spectrograms and the sound responsible for differences in indices results is described. Passive acoustic sampling was conducted at two sites within the Waitakere Ranges Regional Park, New Zealand, that have different management practices: Ark in the Park (high level pest mammal control) and Fairy Falls (low level pest control).

Chapter 4 presents a novel approach for decreasing false positives and increasing models' precision in multispecies contexts to expand the utility of automated identification techniques for wildlife surveys. The Assemblage of Focal Species Recognizers - AFSR, focusses on decreasing false positives by excluding unreliable soundfile segments that are prone to misidentification. I used MatlabHTK, a hidden Markov models interface for bioacoustics analyses, for illustrating AFSR technique by comparing two approaches, 1) a multispecies recognizer where all species are identified simultaneously, and 2) an assemblage of focal species recognizer (AFSR), where several recognizers that each prioritise a single focal species are then summarised into a single output, according to a set of rules designed to exclude unreliable segments. I applied these recognisers to PAM recordings from Pokohinu/Burgess Island, located ca. 90km northeast of Auckland's east coast, in Aotearoa/New Zealand. I compared the recognisers outputs with manual identification of calls of five Procellariiformes seabird species: *Pelecanoides urinatrix* (Kūaka, Common diving petrel), *Puffinus gavia* (Pakahā, Fluttering shearwater), *Pterodroma gouldi* (Ōi, Grey-faced petrel), *Puffinus assimilis* (Little shearwater), and *Pelagodroma marina* (Takahikare-moana, White-faced storm petrel).

Chapter 5 revisits the main questions of the studies in the thesis and considers the general utility of passive acoustic monitoring for biodiversity condition and trend assessments in protected natural areas. I conclude with recommendations for future research.

Chapter 2. Testing the use of acoustic indices and long-duration false-colour (LDfC) spectrograms for monitoring biodiversity at *Serra do Cipó* National Park, Brazil

ABSTRACT

Protected areas (PAs) are crucial for conserving habitat that buffers many species against extinction as well as providing essential ecosystem services. However, despite their overwhelming importance, PAs monitoring is a technical bottleneck that limits the implementation of decision-making processes for natural resource and wildlife management. Recent methodological advances make passive acoustic monitoring (PAM) and associated acoustic indices analysis an increasingly suitable method for PAs monitoring. These acoustic indices are mathematical filters that can provide standardised comparative information about the acoustic energy, which could be applied to compare acoustic communities. In this study I test if acoustic indices are sensitive to measure significant differences in the soundscape across the four seasons for a PA (the *Serra do Cipó* National Park, Brazil) and a surrounding farmland area. Statistical analyses on 12 acoustic indices results are used to identify which of 20 acoustic regions (defined by frequency range and time period) presents the biggest differences between these two sites. Three of the indices calculated are then used to build long-duration false-colour (LDfC) spectrograms for visual representation of the acoustic structure and facilitate the identification of acoustic events. The soundscape differed most in autumn within Panel 6 (representing 05:30 – 09:00am and a range of 0.988-3.609 kHz), which presents significant differences for all the 12 indices tested. The visual examination of 65 LDfC spectrograms resulted in the selection of 865 (from 1365) sound files within the range of Panel 6, which confirms the utility of daily LDfC spectrograms to facilitate the indication of acoustic events. Sonotypes analysis of the 865 files shows that the soundscape outside the park is strongly influenced by the human activity, with domestic animals rare in the park soundscape (1% of the sound files), while very common in the surrounding farmland environment (63% of the sound files). The main goal of monitoring programmes is to be capable of detecting differences in biodiversity trends across sites and time, which is here achieved via PAM and acoustic indices. This confirms the utility of the techniques used

here for PAs monitoring, especially in the face of anthropogenic transformations related to the different land uses that are a common threat to natural habitats in parks and reserves.

INTRODUCTION

Protected areas (PAs) such as national parks and reserves are crucial for sustaining indigenous biodiversity. They conserve habitat that buffers many species against extinction (Le Saout et al. 2013) as well as providing essential ecosystem services for humans such as the maintenance of air and water quality, agriculture pollination, places for outdoor activities, etc. (Watson et al. 2014). Their importance to conservation is such that the parties of the Convention on Biological Diversity adopted as one of the Aichi Biodiversity Targets (Aichi Targets) the protection of 17% for terrestrial and inland water ecosystems and 10% for marine and coastal ecosystems globally (CBD 2010). However, despite their overwhelming importance, robust information on the contribution of PAs to biodiversity conservation and their wildlife communities are rare.

One reason for the shortage of reliable information about how PAs contribute to biodiversity conservation is the difficulty of carrying out monitoring in protected areas. Monitoring programmes often aim to be sensitive enough for measuring trends in biodiversity, and to report on condition and change (Lee, McGlone & Wright 2005), which is very challenging to achieve with any sampling protocol given the complex hierarchical character of biodiversity. Ideally, monitoring should be broad enough to provide a comprehensive picture of the biodiversity and capable of providing information on different levels (populations, species, communities) and different temporal and spatial frames (Schmeller et al. 2017). Traditionally, monitoring of animal diversity is done by seeing and hearing animals or their tracks and signs such as scats or burrows, or by more invasive methods such as trapping. These are very expensive, time consuming, and require specialist training. Furthermore, these techniques can only be conducted during limited time periods so might not record rare species. Trapping also has implications for animal welfare and conservation efforts for populations that are often already at-risk or are high priorities for management.

Additionally, animal behaviour commonly changes across seasons (e.g., breeding season), which is a reason why monitoring protocols should also be able to report in a seasonal scale. Protected areas monitoring is a technical bottleneck, limiting implementation of decision-making processes for natural resource and wildlife management (Nichols et al. 2011). A cost-effective and efficient approach for routine biodiversity surveying is needed.

A newly developing option for monitoring of protected areas is the use of acoustic recordings, where automatic recordings are made of the natural soundscape and used to infer animal and therefore general biodiversity. Acoustic information is well-known to vary throughout the day, among seasons, and spatially. Passive acoustic sampling protocols can synthesize and represent diversity for a wide range of animal species in a non-invasive manner. Recordings can be made simultaneously in multiple sites in a robust sampling design, resulting in audio files that are relatively easy to be stored, shared and accessed by multiple researchers. However, there are important limitations on the amount of acoustic information that can be analysed by a researcher listening to the files.

Recent advances in acoustic analysis methods now make passive acoustic monitoring (PAM) an increasingly suitable method for PAs monitoring. A key innovation is the development of acoustic indices that extract specific features from the acoustic information. These acoustic indices are mathematical calculations that represent aspects of how the acoustic energy is distributed in time and frequency in a sound file. These features can be compared between recordings that vary across time and space. In this way, they can be used to provide standardised comparative information about the acoustic activity of animal communities that could be applied generally to compare the acoustic community of PAs and their surrounding areas. These standardised measurements can be used not only to detect differences in the more important groups of acoustic activity within a day (e.g., dawn and dusk chorus), but they can also be sensitive to soundscape variations across seasons and years.

Nowadays there is substantial literature on different acoustic indices (Sueur 2018). The Acoustic Complexity Index (ACI) (Pieretti, Farina & Morri 2011) was validated as a suitable metric for the study of avian vocalization and supposedly avian abundance in fragmented Australian forest landscapes, although it was not correlated with landscape parameters (Fuller et al. 2015). ACI was indicated as the best bird biodiversity indicator among 14 acoustic indices tested by Towsey et al. (2014). This index measures the oscillation of amplitude in a sound files and is sensitive to the typical amplitude transitions of biophony, the sounds produced by animals (birds, insects, amphibians, mammals, etc). The Acoustic Entropy index (ENT or just H) (Sueur et al. 2014) was selected among seven indices tested as the most promising for bird species richness from simulated bird assemblages (Gasc et al. 2015). ENT was indicated as one of the indices that best linked soundscape with landscape characteristics, ecological condition and bird richness (Fuller et al. 2015). ENT is especially sensitive to the energy dispersal across the frequency frames. It is expected that the more species of birds

singing, the higher this energy dispersal. Therefore, these two indices are sensitive to different aspects of biophony which makes them complementary to each other.

Acoustic indices have been applied to a broad range of habitats, such as temperate woodland in France (Depraetere et al. 2012), subtropical woodland in Australia (Tucker et al. 2014; Towsey et al. 2014), maqui shrubland in Mediterranean Italy (Farina & Pieretti 2014), tropical forest in Tanzanian (Sueur et al. 2008), neotropical forest in French Guiana (Rodriguez et al. 2014), and tropical savannah (Cerrado) in Brazil (Machado, Aguiar & Jones 2017; Ferreira et al. 2018). Acoustic indices are even applicable to marine environments (Harris, Shears & Radford 2016; Buscaino et al. 2016). Studies using acoustic indices commonly aim to extract biological information from data sampled by passive acoustic monitoring (PAM) to identify overall patterns of acoustic communities, irrespective of species identity (Sugai et al. 2018). This area of research is known as soundscape ecology (Pijanowski et al. 2011), or more recently ecoacoustics (Sueur & Farina 2015).

Despite their remarkable potential for ecoacoustics studies, the relationship between acoustic indices and traditional biodiversity measures can be contradictory (Fuller et al. 2015; Mammides et al. 2017). Eldridge et al. (2018) report that indices are a good indicator of avian species richness in temperate, but not tropical habitats. Therefore, interpretations of acoustic indices as straightforward biodiversity indicators should be taken with caution. Instead, I advocate that for monitoring purposes, it is best to use a combination of acoustic indices, and these should be used as filters that help to identify which sounds are resulting in significant differences between sites and across time, not as simple biodiversity indicators.

Each acoustic index is sensitive to different acoustic features, and they can be combined to generate a more holistic representation of the acoustic structure in a given soundscape. Towsey et al. (2014) developed the long-duration false-colour (LDFC) spectrograms where a single image represents three different indices using the RGB colour model (each index assigned to a different colour: red, green or blue). Any three indices can be represented in LDFC, however independent or not correlated indices will provide different acoustic filters, which will result in more informative images (Towsey et al. 2018). LDFC spectrograms have been shown to be a useful tool for visualization of acoustic events in large audio data sets (Towsey, Truskinger & Roe 2015) as well as allowing the easy identification of single acoustic events representing frog calls, bat echolocation calls and Tasmanian Lewin's Rail (*Lewinia pectoralis brachipus*) calls, enabling it to assist in studies involving single or multiple species (Towsey et al. 2018).

Given the broad range of acoustic information they can summarise, LDFC spectrograms could be used to monitor for subtle changes in soundscapes that may accompany changes in biodiversity resulting from human impacts or conservation focused management efforts. Here I test if acoustic indices and LDFC spectrograms are sensitive enough to measure significant differences in the soundscape across the four seasons of the year for a protected area (the *Serra do Cipó* National Park, Brazil) and the surrounding regions that are not subject to the same conservation management efforts. Detecting differences resulting from management is important to justify the ongoing existence of protected areas in Brazil. Statistical analysis on indices measurements are used to identify specific acoustic regions (defined by frequency range and time period) that present the biggest differences between these two soundscapes. Three of the indices calculated (ACI, ENT and EVN) are then used to build LDFC spectrograms for visual representation of the acoustic structure and facilitate the identification of acoustic events. Sonotype counts are provided to briefly describe the acoustic events in the soundscape. Here, instead of using indices as simple biodiversity indicators, I use them as filters that help to identify which sounds are driving the significant differences between sites and across time. If the techniques used here are capable of measuring the significant changes in animal activity inside and outside the protected area, then PAM associated with these acoustic analyses could provide useful, low-cost protocols for protected areas monitoring that could be used to detect long term changes in communities.

METHODS

2.3.1 Study site

The *Serra do Cipó* National Park, Brazil, is a protected area managed by the *Chico Mendes* Institute for Biodiversity Conservation - ICMBio, a federal agency of the Ministry of Environment, responsible for managing national natural protected areas in Brazil. Extending over 330 km², the park was created in September 1984, entirely in the *Minas Gerais* State. It supports several species of flora and fauna on the Brazilian Threatened Species List (do Nascimento & Campos 2011; Martinelli & Moraes 2013) and IUCN Red List, including birds such as the Vinaceous-breasted amazon (*Amazona vinacea*) and Sharp-tailed tyrant (*Culicivora caudacuta*), the Cunha's Brazilian Lizard (*Placosoma cipoense*), and the plant *Vellozia gigantea*. The *Serra do Cipó* National Park has a great diversity of ecosystems, including two biodiversity hotspot biomes: *Cerrado* (savannah) and Atlantic Forest (Myers et al. 2000). The park is located in the *Espinhaço* Mountain Range, recognized by UNESCO as a Biosphere Reserve.

Outside the park's western perimeter (where this study was performed), the land is mostly non-intensive farmland primarily producing cattle and dairy. It is common for small farms also to produce chicken meat, eggs and varied vegetables. Occasionally neighbours come into the national park for animal grazing. Although illegal, this issue is not considered a cause of main concern to park management when compared to human induced forest fires that often consume large areas. The fire regime, management and ecology of fire in ecosystems in the park have been the focus of research in the past years (Figueira et al. 2016; Alvarado et al. 2017). Within the last decade, farmlands have been increasingly landscaped into urban areas. It is expected that these landscape transformations will increase the anthropic pressures upon natural ecosystems in the region, although this recent phenomenon has not yet been investigated.

This study was performed within the *Cerrado* (savannah) Biome, on the Western limits of the *Serra do Cipó* National Park. The *Cerrado* Biome presents a great diversity of habitat types, varying from forests to fields. I did not include the field habitats (dirty field, *cerrado* field, and rocky grasslands), or locations greater than 900 meters above sea level, or urban areas in this study. Within the remaining areas, I randomly selected four locations inside the park and four locations outside the perimeter for the installation of eight automatic acoustic sensors (one in each selected location) (Figure 1).

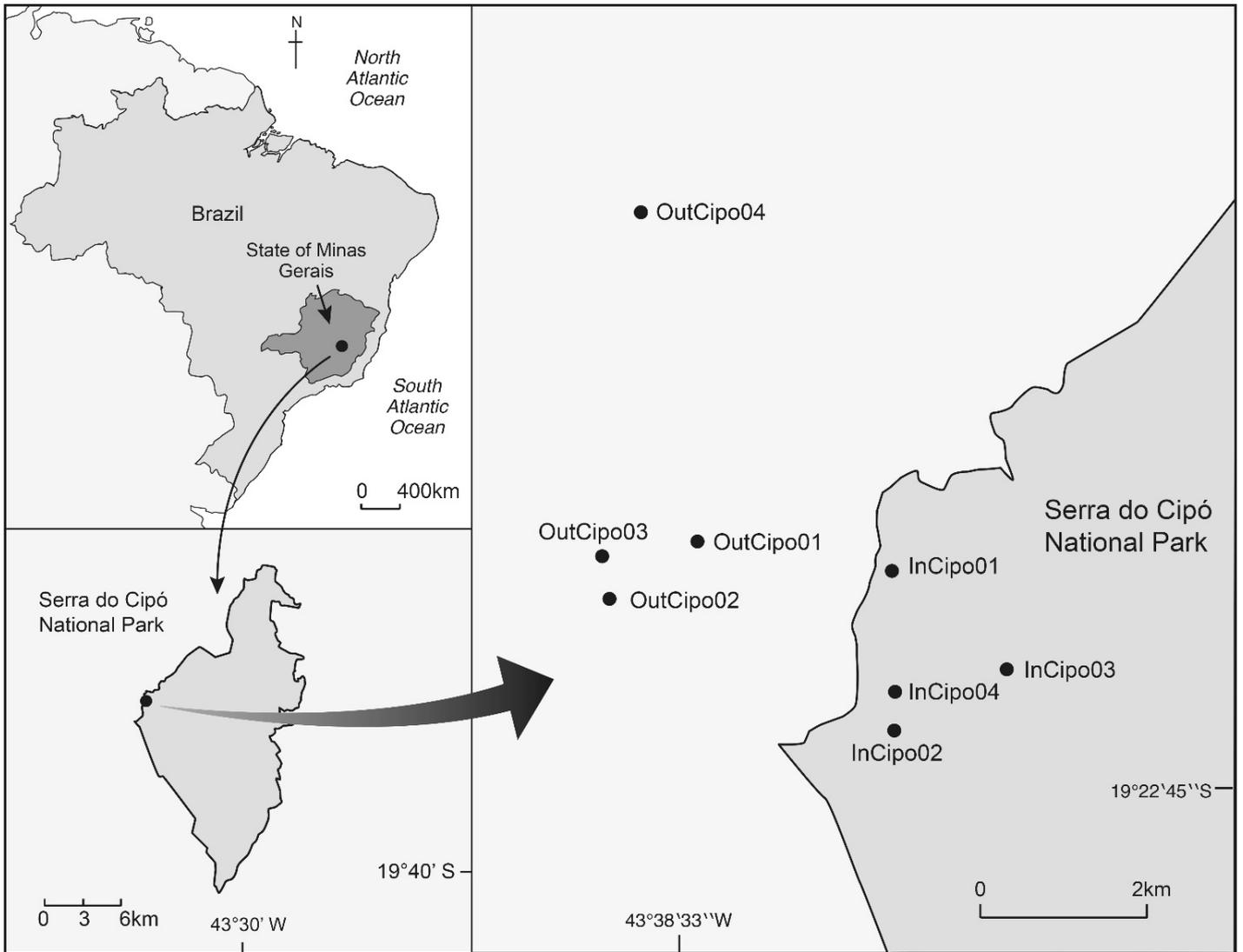


Figure 1: Serra do Cipó region. Location of eight recorders in the *Serra do Cipó* region (four recorders inside the protected area and four outside).

Habitat loss is the main source of biodiversity declines in the tropics, since most of the extremely rich tropical forests are vanishing at accelerated rates (Laurance 2007). Much like other tropical biomes, the main threat faced by the fast-disappearing Cerrado is habitat degradation (Françoso et al. 2015). In this local context, establishing the National Park prevented the transformation of all the Cerrado habitat in the *Serra do Cipó* region. Vegetation type and other habitat variables are expected to differ inside and outside the park as a result of different land uses. The aim of this study is to test if the acoustic approach is suitable for detecting acoustic differences between sites with these two land uses, and therefore, capable of monitoring these soundscape differences. Thus, habitat characteristics were not measured. In order to dilute the effect of possible differences in habitat, four locations were sampled in each site within and outside the Park.

2.3.2 Recording schedule and settings

The acoustic sensors were programmed to perform 1 minute of recording every 10 minutes (one minute of recording, followed by 9 minutes break), resulting in 144 one-minute sound files per location, per day of sampling. Temporal sampling schemes were previously assessed by Pieretti et al. (2015), who found this scheme provided reliable data on acoustic diversity of the community in the Serra do Cipó region, for both dry and wet seasons. This 1/10 minutes recording schedule has also been used successfully in other studies (Aide et al. 2013; Ospina et al. 2013; Alvarez-Berrios et al. 2016; Campos-Cerqueira & Aide 2016; Campos-Cerqueira et al. 2017; Aide et al. 2017; Campos-Cerqueira & Aide 2017).

The passive acoustic recordings were performed for 10 consecutive days approximately in the middle of each season. The recordings were sampled using autonomous acoustic sensors SongMeter Digital Field Recorders (SM2) (Wildlife Acoustics, Inc., Massachusetts), at a sampling rate of 44,100Hz, set at 32 bits; from 9-18th May 2016; 8-17th August 2016; 31st October to 9th November 2016; and 2-11th February 2017. Recorders were fixed on trees approximately 1.5m above the ground.

2.3.3 Acoustic Indices Calculation

For calculation of acoustic indices, all one-minute files were mixed down to mono and down-sampled to 22,050 Hz. Indices were calculated for each one of the 256 frequency bins (each with a bandwidth of ≈ 43 Hz). Calculations for the indices were performed according to Towsey et al. (2014; 2017; 2018). I calculated 12 indices, including the three (ACI, ENT, EVN) used for the generation of LDFC spectrograms as performed by Towsey (2017).

The Acoustic Complexity Index (ACI) measures the amplitude oscillation in each frequency bin (Pieretti, Farina & Morri 2011). It is calculated from an amplitude spectrogram following the approach of Towsey et al (2018). It is commonly used as a measure of the biophony, being one of the most used acoustic indices among ecologists (Duarte et al. 2015; Fuller et al. 2015; Harris, Shears & Radford 2016). The Temporal Entropy index (ENT) measures the energy dispersal over the frames of each frequency bin. It was first derived from the Shannon index aiming to measure the evenness of different sound categories (Sueur et al. 2008; Sueur et al. 2014). Here the converted version of the index is used to provide the “energy concentration”, as calculated by Towsey et al (2018). Event Count (EVN) counts the number of events in each frequency bin per minute (Towsey 2017).

The Acoustic Cover (CVR) calculates the fraction of cells in each frequency bin of the noise-reduced spectrogram which surpasses 2 dB (Towsey et al. 2014). Power minus Noise (PMN) measures the maximum decibel value in each frequency bin of the noise-reduced decibel spectrogram (Towsey 2017). Spectral Peak Tracks (SPT) computes the spectral peaks (local maxima) identified in each spectrum, as calculated by Towsey et al (2018). Background Noise (BGN) extracts the decibel value of background noise in each frequency bin calculated as the modal decibel value in each frequency bin of the decibel spectrogram, following Towsey et al (2018).

I also calculated five Ridges Indices, which are derived from the noise-reduced decibel spectrogram according to Towsey et al. (2017). Four indices were calculated corresponding to the four directions of the ride slope and one is a combination of three of them. The Ridge Horizontal (RHZ) corresponds to the horizontal dimension of the ride slope. Ridge Vertical (RVT) corresponds to the vertical dimension of the ride slope. Ridge Positive having an upward slope (RPS) corresponds to the ridge positive having an upward slope. Ridge Negative having downward slope (RNG) corresponds to the ridge negative having a downward slope. Lastly, the Ridge 3 Dimensions (R3D) equals the maximum of RHZ, RPS, and RNG. Further details about acoustic indices calculations are described by Towsey et al. (2014; 2017; 2018).

2.3.4 Indices visualization using Long Duration False colour spectrograms

Long duration false colour (LDFC) spectrograms were generated for each day of recording for each of the eight locations where recorders were installed. All LDFC spectrograms used in this research are representations of ACI, ENT and EVN indices. These three indices are sensitive to different aspects of the sound signal, being complementary to each other. The LDFC spectrograms were generated as described by Towsey et al. (2014).

2.3.5 Analysis of Variance and Pairwise comparisons

In order to test for differences inside and outside the park in a more precise and informative scale, the indices values for each day were divided into 20 panels. Each panel corresponds to an acoustic region defined by a specific frequency range and period of the day. The frequency ranges (four in total) and the periods of the day (five) were defined according to the most common acoustic events as revealed by the LDFC spectrograms. The four frequency ranges defined were: 0 kHz to 0.988 kHz; 0.988 kHz to 3.609 kHz; 3.609 kHz to 7.906 kHz; and 7.906 kHz to 11 kHz. The five time periods defined were:

00:00 to 5:29 am; 5:30 to 9:00am; 9:01am to 5:29pm; 5:30pm to 8:59pm; and 9:00pm to 23:59pm.

Figure 2 shows an example of how 20 panels were identified from the LDFC spectrogram output.

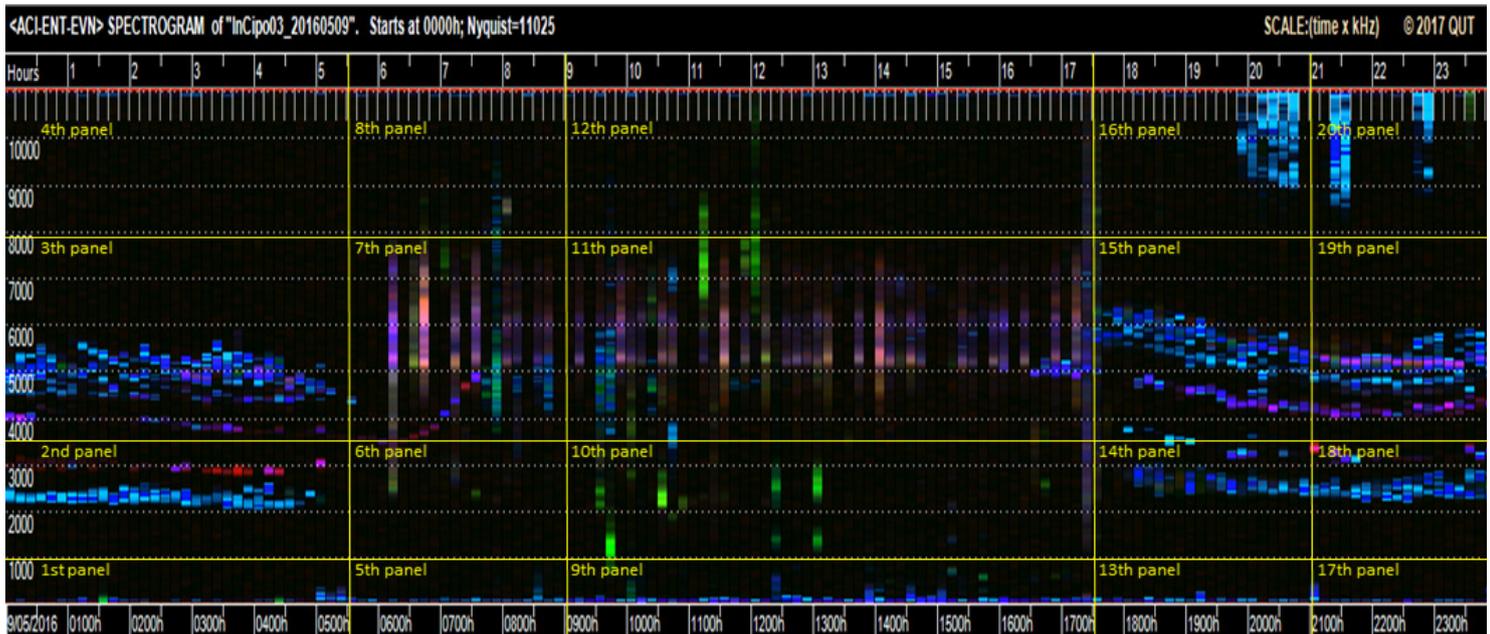


Figure 2: Illustration of frequency range and time used to define each of the 20 panels. The Long Duration False Colour (LDFC) Spectrogram presented here was created from audio files recorded inside the Serra do Cipó National Park (site: InCipo03) on 5th May 2016. This LDFCS was selected as an example of common acoustic events recorded at this region. The y axis represents the frequency varying from 0 to 11 kHz, while the x axis represents time (24 hours in total). The yellow lines show the time and frequency chosen as the bounds that define each different panel.

Since the data sets were vast (more than 10 million different values calculated per each index), any statistically significant differences could be the result of type I errors. To mitigate this, aggregation of data sets using average and summation of index values were tested. Aggregation by the summation of index values within each panel per day was selected as the most appropriate unit for subsequent analysis as it resulted in wider confidence intervals, as well as a better relation of residual fits. The Shapiro-Wilk test confirmed the normality assumptions for most of the panels tested, while quantile-quantile and residual fits plots show a normal data distribution for all the panels (appendix A – ENT index models are taken as example)

Before fitting the models, the interval that captured 98% of the values for each index was defined. The 1% lowest values falling below the lower limit as well as the 1% falling above the maximum were truncated to the interval defined. The values were then scaled 0 to 1 interval. This normalization was important to reduce the outlier effects and to facilitate comparisons among different indices, similarly to what was performed by Towsey et al. (2014) to adjust the samples into the interval within each index typically takes values.

In order to test for significant effects due to interactions as well as differences between sites and the seasons, I performed Analysis of Variance (ANOVA) and then Pairwise comparisons (T test). P values were adjusted using Bonferroni corrections to address the multi-comparison issue. The models for each index were fitted independently. The index value (log transformed) was defined as the outcome variable, while the explanatory variables were season (autumn, spring, summer, winter) and site (location inside or outside the park). The size of the effects were calculated from the Pairwise comparison and back transformed to ratios.

2.3.6 Describing the differences

To describe the main differences in the types of sounds (sonotypes) between inside and outside the protected area, I aurally and visually scanned the sound files of the season and panel in which the significant differences on indices' values achieved higher proportions. This process was performed in two steps. First, each of the LDFC spectrograms corresponding to the identified season was visually checked to identify acoustic events on the specific panel. Second, the sound files corresponding to each acoustic event identified on the LDFC spectrograms were then aurally and visually scanned. This second step was performed using traditional spectrograms generated by the Audacity software. The sonotypes used here were: birds, insects, frogs, mammals, domestic animals (rooster, chicken, turkey, guinea fowl, cow, horse, donkey or dog), human voice, geophony (rain, stream or wind) and anthrophony (road sound, airplane, engine or other). The presence or absence of each sonotype was assigned to each one-minute sound file analysed. The sonotypes used here cannot be compared to morphospecies as performed by other research (Aide et al. 2017; Ferreira et al. 2018). The sonotypes here are broader groups used only to provide an overall description of the soundscape and its examination was performed specifically within the panel (specific time and frequency ranges) that presented the biggest differences between the recording sites.

2.3.7 Cosine similarity heatmap

To allow the visualisation of missing data and identify atypical patterns, I created cosine similarity heatmaps. These figures were generated from the matrix of averaged cosine similarity between pairs of days for ACI, ENT and EVN indices. Cosine similarity has been used as a similarity measure for research in a wide range of disciplines due to their utility for representing big data sets in a single picture area (Murray, Renals & Carletta 2005; Muflikhah & Baharudin 2009; Van Dongen & Enright 2012; Sejal et al. 2016).

RESULTS

There were significant differences in the acoustic indices values inside and outside the park. The soundscape differed most in autumn - the highest number of significantly different indices values occurred in Panel 6, representing 05:30 – 09:00am and a range of 0.988-3.609 kHz. The soundscape differed least in Panel 15-winter, achieving the most non-significantly different indices values (representing 17:30-20:59pm, and 3.609-7.906 kHz).

Among all the results with a significant difference in the acoustic indices, the panel that appeared most frequently at the top with the biggest ratios for each one of the indices was Panel 6 (followed by Panel 5). Autumn was the season that more frequently appeared at the top, indicating greatest dissimilarity between field sites. The panel that appeared more frequently at the second position was again Panel 6 (followed by Panel 5 again), and also during autumn. The panel that appeared most at the third position was Panel 7, with summer the season that more frequently appeared at the third biggest ratio among all indices.

Investigating soundscape similarities between the park and non-park areas, panel 15 was the most frequent. The 19th panel was the second most frequent among non-significant results. Spring and winter are the seasons with less marked differences between inside and outside the National Park. .

Figure 3 shows the number of times each panel appears within the top 10% highest ratios among all the significant differences between field sites. Appendix B presents the P values and ratios for all the 960 single pairwise comparisons (20 panels times 12 indices times four seasons).

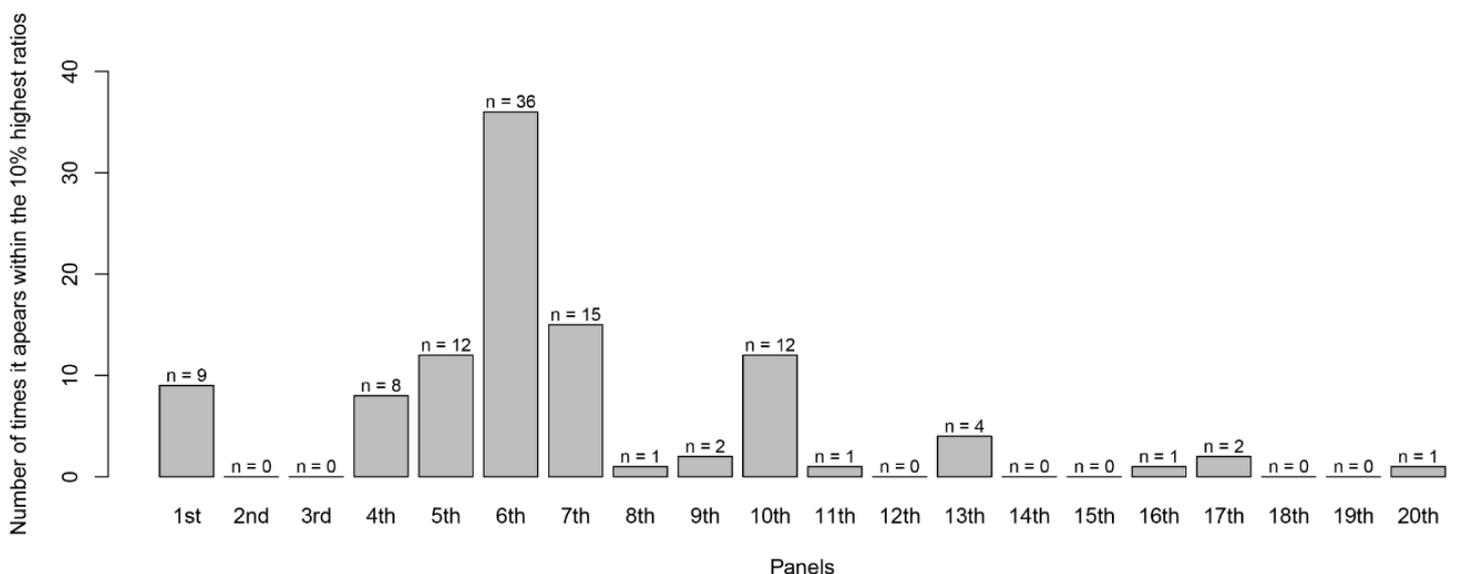


Figure 3: Panels which differed most between inside and outside of the National Park. Pairwise comparisons were

performed within each of the 20 panels and four seasons. The number of times each panel appears in the top 10% highest ratios for each index was counted and the summation among all the indices is presented in the histogram. It is important to note that for each index, a given panel can be counted up to four times (one per season). Again, panel six differs most between field sites. Only the comparisons with significant results were included in this analysis. The complete results for all the 960 pairwise comparisons performed are presented in Appendix B.

Figure 4 illustrates the opposite patterns presented by panel 6 in autumn (differed most between sites) and panel 15 in winter (more similar between sites) for three indices results (ACI, ENT, EVN), while table 1 presents the pairwise comparisons results for the same panels for all calculated indices.

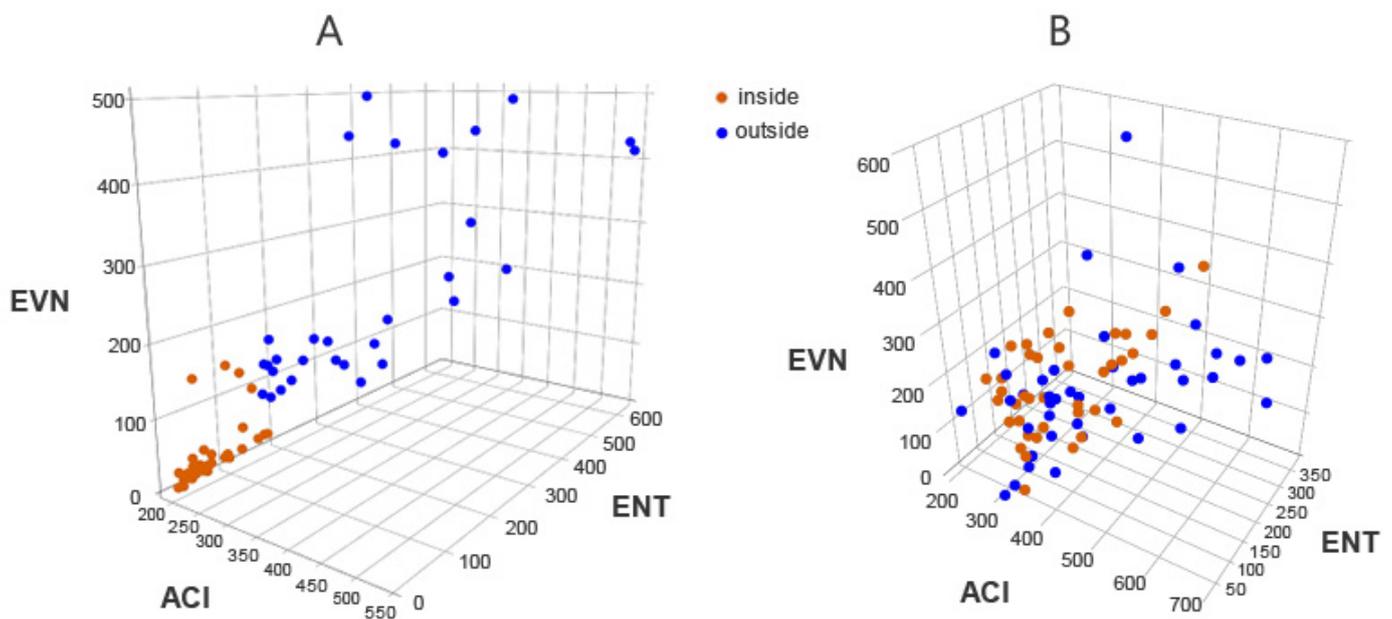


Figure 4: ACI, ENT and EVN values for panel 6 in autumn and panel 15 in winter. Summation of Acoustic Complexity Index , Acoustic Entropy Index and Event Count Index values within the 6th panel (A) for each one of the days recording during autumn (on the left), when index values differed most; and within 15th panel (B) for each one of the days recording during winter (on the right), when index values were more similar. The orange dots represent data sampled inside the Serra do Cipó National park, while blue dots represent data recorded in non-park sites.

Table 1: Pairwise comparisons for the 6th panel in autumn and for the 15th panel in winter for all the acoustic indices calculated

| 6th Panel autumn season | | | 15th Panel winter season | | |
|----------------------------|------------|---------|-----------------------------|----------|---------|
| Index | P value | Ratio | Index | P value | Ratio |
| ACI | 3.34E-06 * | -1.4120 | ACI | 0.1257 | --- |
| ENT | 3.17E-28 * | -5.8150 | ENT | 0.0298 * | -1.2447 |
| EVN | 1.64E-26 * | -5.9400 | EVN | 0.0920 | --- |
| CVR | 3.84E-26 * | -5.1396 | CVR | 0.2733 | --- |
| PMN | 3.72E-29 * | -4.8435 | PMN | 0.4264 | --- |
| R3D | 1.91E-28 * | -2.6518 | R3D | 0.4619 | --- |
| RHZ | 4.54E-28 * | -2.0768 | RHZ | 0.3860 | --- |
| RNG | 4.47E-29 * | -2.6607 | RNG | 0.9911 | --- |
| RPS | 2.40E-28 * | -2.6219 | RPS | 0.9873 | --- |
| RVT | 1.48E-26 * | -2.9691 | RVT | 0.1894 | --- |
| SPT | 1.10E-26 * | -3.8510 | SPT | 0.7126 | --- |
| BGN | 5.93E-06 * | 2.1922 | BGN | 0.9609 | --- |

Results of Pairwise comparisons between recordings from inside the park and outside for the 6th panel during autumn and for 15th panel during winter for all the acoustic index calculated. The ratio is presented only for significant results. * indicates significant results.

All the indices presented significant differences for the 6th panel during autumn. The only index that presented significant results for the 15th panel during winter was ENT (ratio -1.2447). However, the ratio presented by the same index for the 6th panel during autumn was considerably higher (ratio - 5.8150, meaning that the ENT measurements were 5.8 times higher outside the park than inside).

Figures 5, 6 and 7 presents the daily average of the ACI, ENT and EVN measurements for each panel in all the four seasons, respectively. These figures show that the indices behave differently on the 6th panel, presenting the biggest differences between sites, especially during autumn. The complete results for all the indices and panels are presented in the appendix B.

Acoustic Complexity Index (ACI) within each Panel

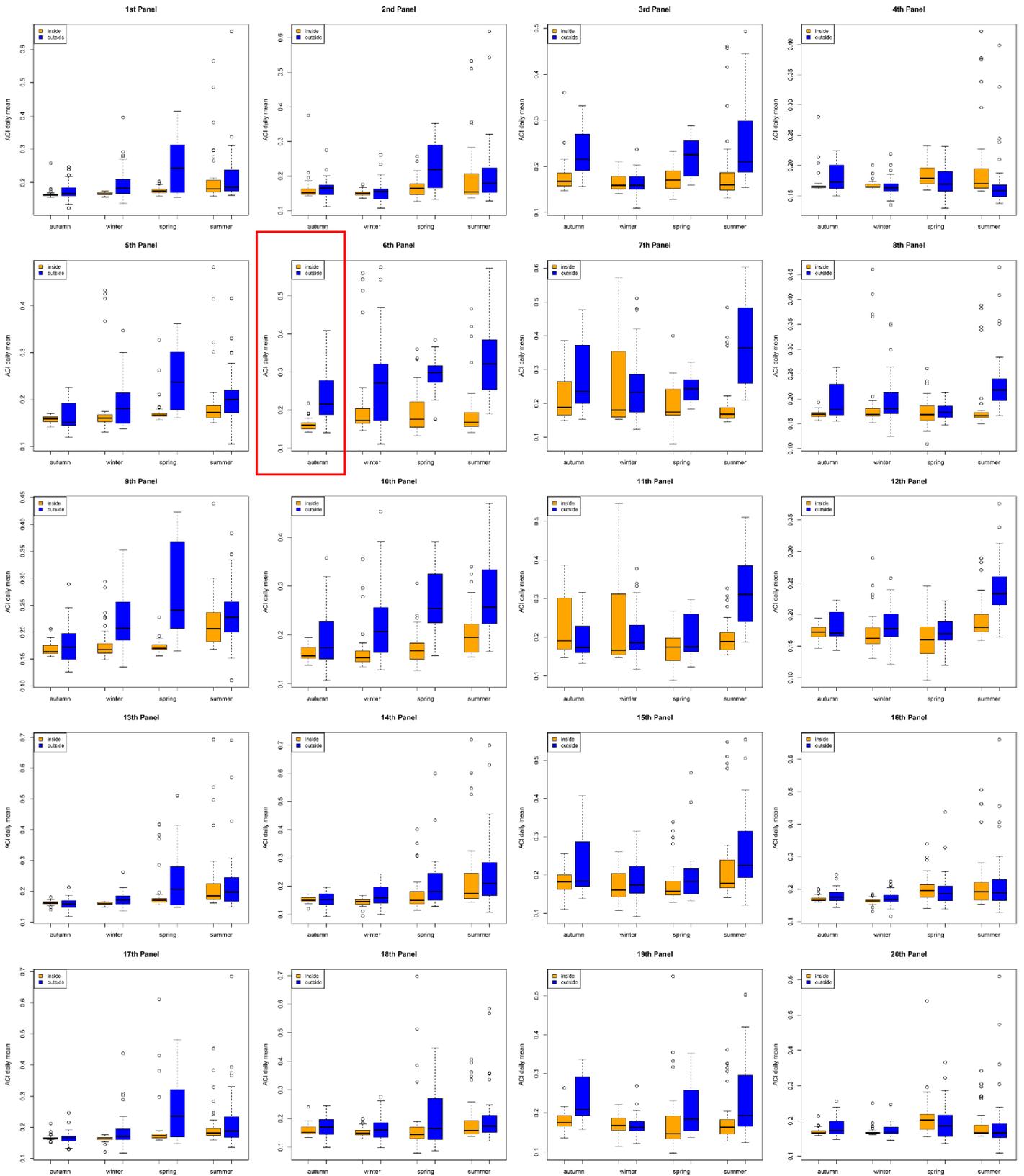


Figure 5: Acoustic Complexity Index within each Panel and season. The values were averaged within each panel per day of recording in each of the eight locations. The red rectangle indicated panel 6 in autumn, which differed most between inside and outside the park when considering all the 12 indices.

Temporal Entropy (ENT) within each Panel

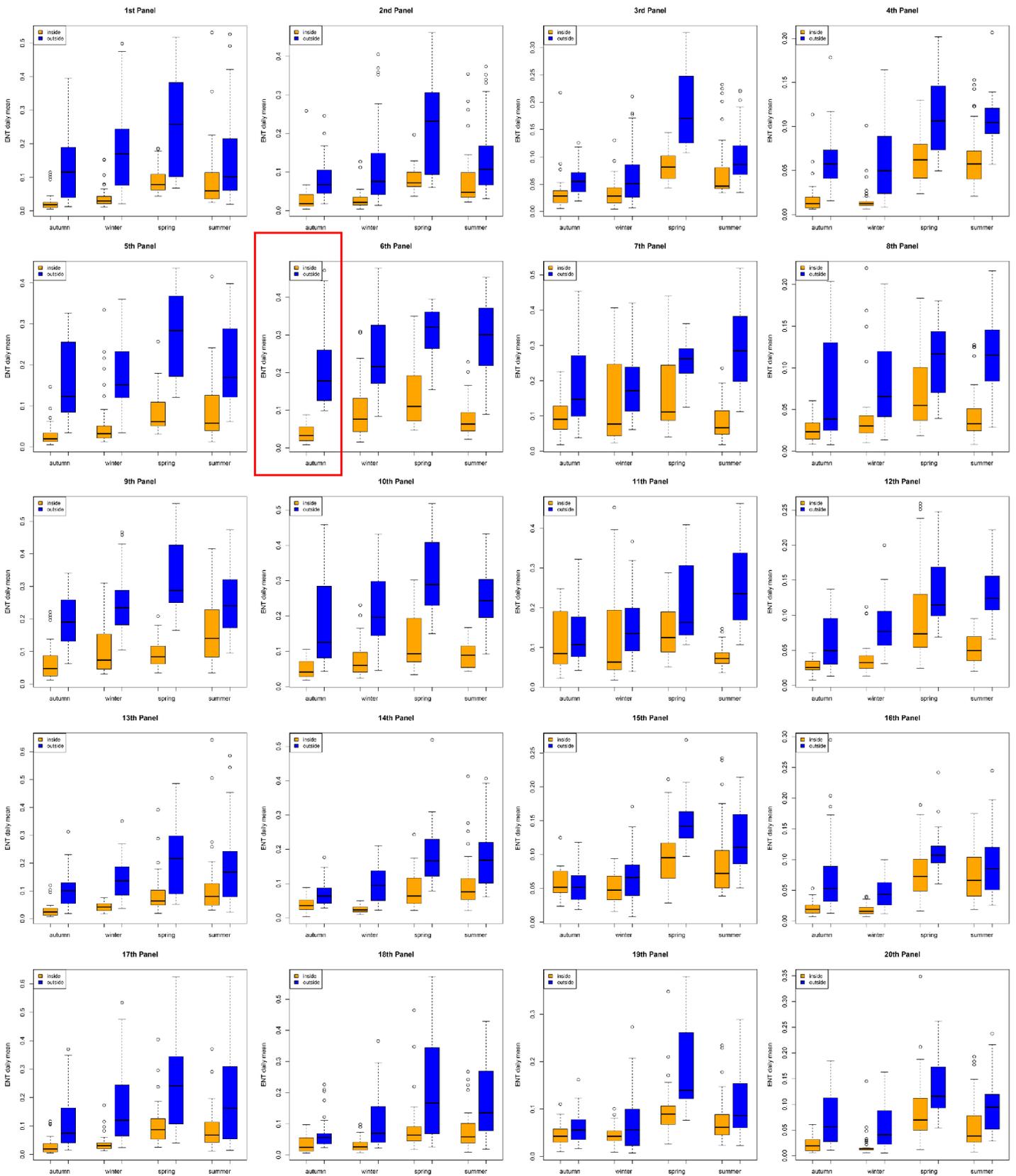


Figure 6: Temporal Entropy Index within each Panel and season. The values were averaged within each panel per day of recording in each of the eight locations. The red rectangle indicated panel 6 in autumn, which differed most between inside and outside the park when considering all the 12 indices.

Event Count (EVN) within each Panel

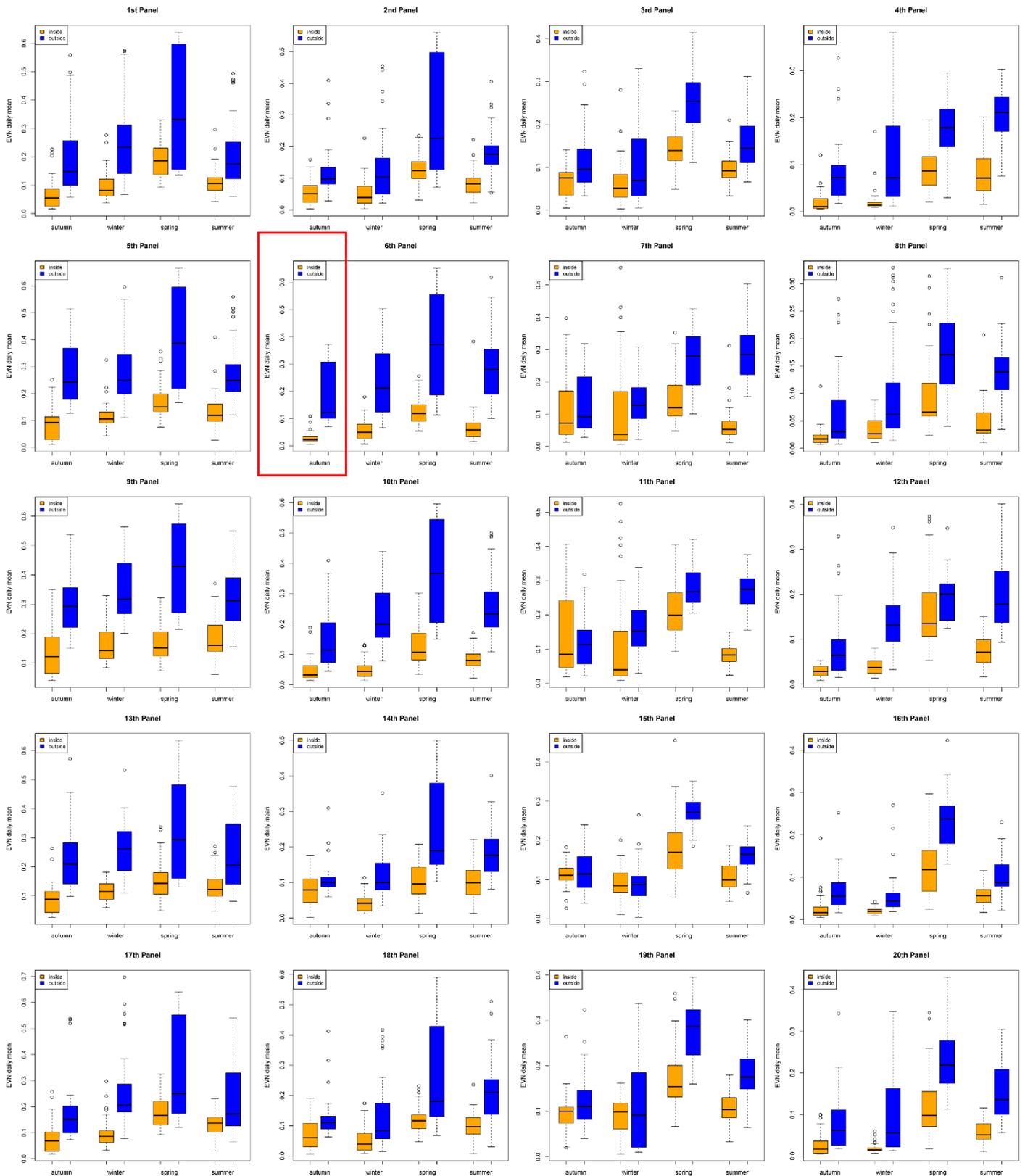


Figure 7: Event Count Index within each Panel and season. The values were averaged within each panel per day of recording in each of the eight locations. The red rectangle indicated panel 6 in autumn, which differed most between inside and outside the park when considering all the 12 indices.

2.4.1 Describing the differences: acoustic events on 6th panel in autumn

Each one of the 65 LDFC spectrograms from the autumn recordings were visually scanned to identify acoustic events in the time period and frequency range related to the 6th panel. From 1365 files (735 from inside and 630 from outside) recorded from 5:30 to 9:00 am during autumn, 865 files (322 from inside and 543 from outside) were identified as having acoustic events on the 6th panel. Each one of these 865 identified files were aurally and visually scanned in order to assign the presence or absence of each of the target sonotypes. Figure 8 illustrates the identification of acoustic events through LDFC spectrograms including representations of the highlighted acoustic events on traditional grey-scale spectrogram.

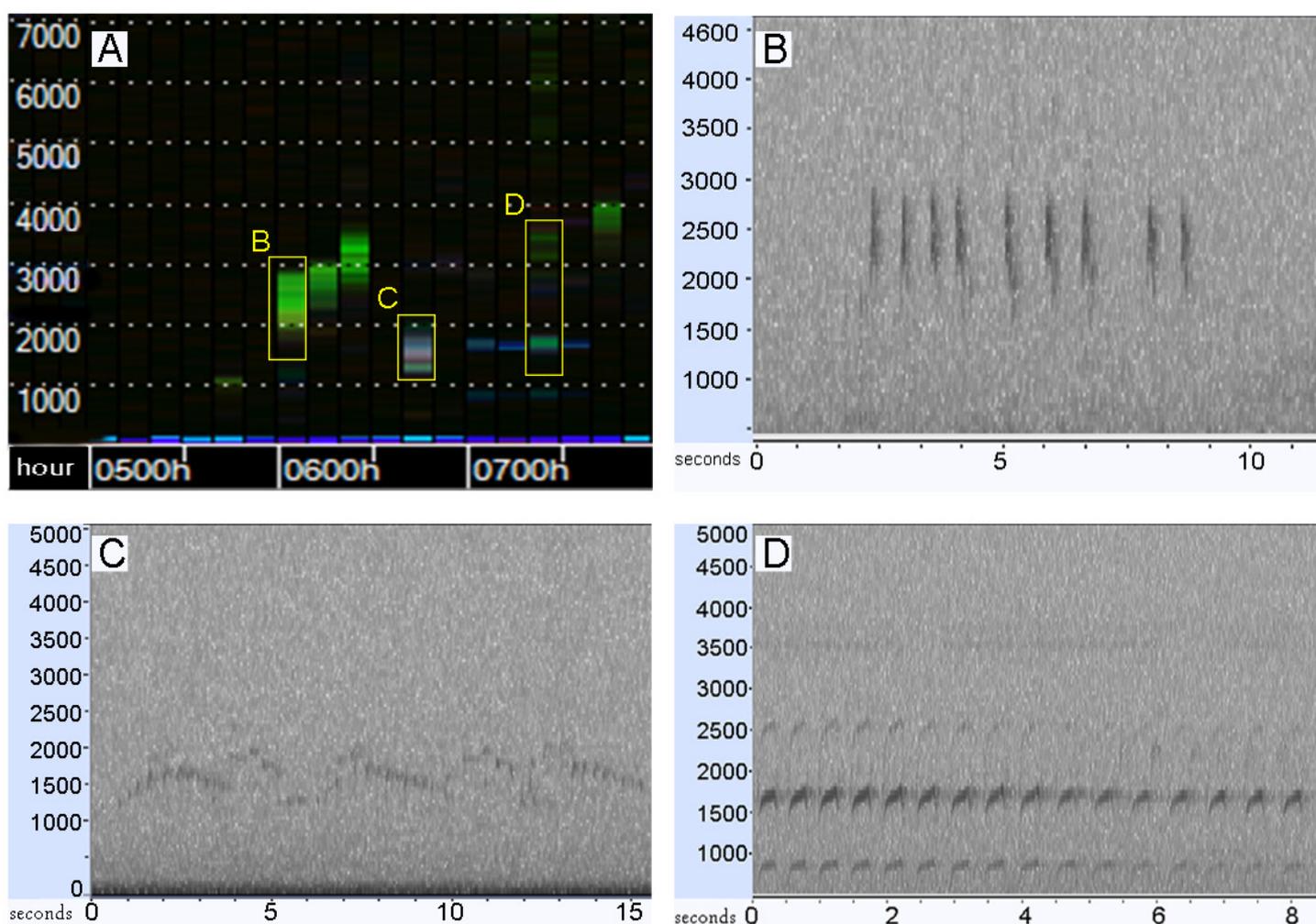


Figure 8: Example of acoustic events' visualization on LDFC spectrograms. (A) Three-hour sample (05:00 to 8:00) from a 24-hour LDFC spectrogram, with yellow rectangles indicating examples of acoustic events. (B) Twelve-second portion of standard grey-scale spectrogram extracted from the sound file with the acoustic event (assigned to the bird sonotype) indicated by letter B in A. (C) Fifteen-second portion of standard grey-scale spectrogram extracted from the sound file with the acoustic event indicated (assigned to the bird sonotype) indicated by letter C in A. (D) Eight-second portion of standard grey-scale spectrogram extracted from the sound file with the acoustic event indicated (assigned to the bird sonotype) indicated by letter D in A. The y axis represent the frequency in Hertz while the x axis represent time in seconds (B, C and D) and hours (A).

The major differences in the sonotypes identified inside and outside the protected area are clearly related to domestic animals (p-value < 2.2e-16), and anthrophony (p-value < 2.2e-16) (Figure 9). Domestic animal calls were identified in only 4 files from inside the park compared to 344 files from outside. Of the 344 files with domestic animals recorded outside the park, 128 files had more than one species of domestic animal. Sounds related to anthrophony were identified in 17 files recorded inside the park (approximately 5 %), compared to 281 files outside. The most common types of anthrophony outside the park are sounds from the road (231 files), engines (57) and airplanes (32). Inside the park, 16 of the 17 files also recorded airplane sounds.

The human voice was not identified in the files from inside the park, but was present in 52 files from outside (approximately 10% of the files) (p-value = 2.406e-08). Birds were recorded on 218 files from inside the park and 472 files recorded outside (p-value = 1.874e-11), while insects were recorded on 176 files from inside and 207 files from outside (p-value = 3.124e-06). Sounds associated with the frog sonotype were scarce both inside and outside, however significant differences were detected as indicated by the chi-square test (p-value = 0.03616).

The percentage of files with more than one of either bird, insect and/or frog sonotypes appear in the same file is similar inside (31 %, 101 files) and outside (34%,183 files). There was no record of any native mammal species' calls in any of the listened and visually scanned files.

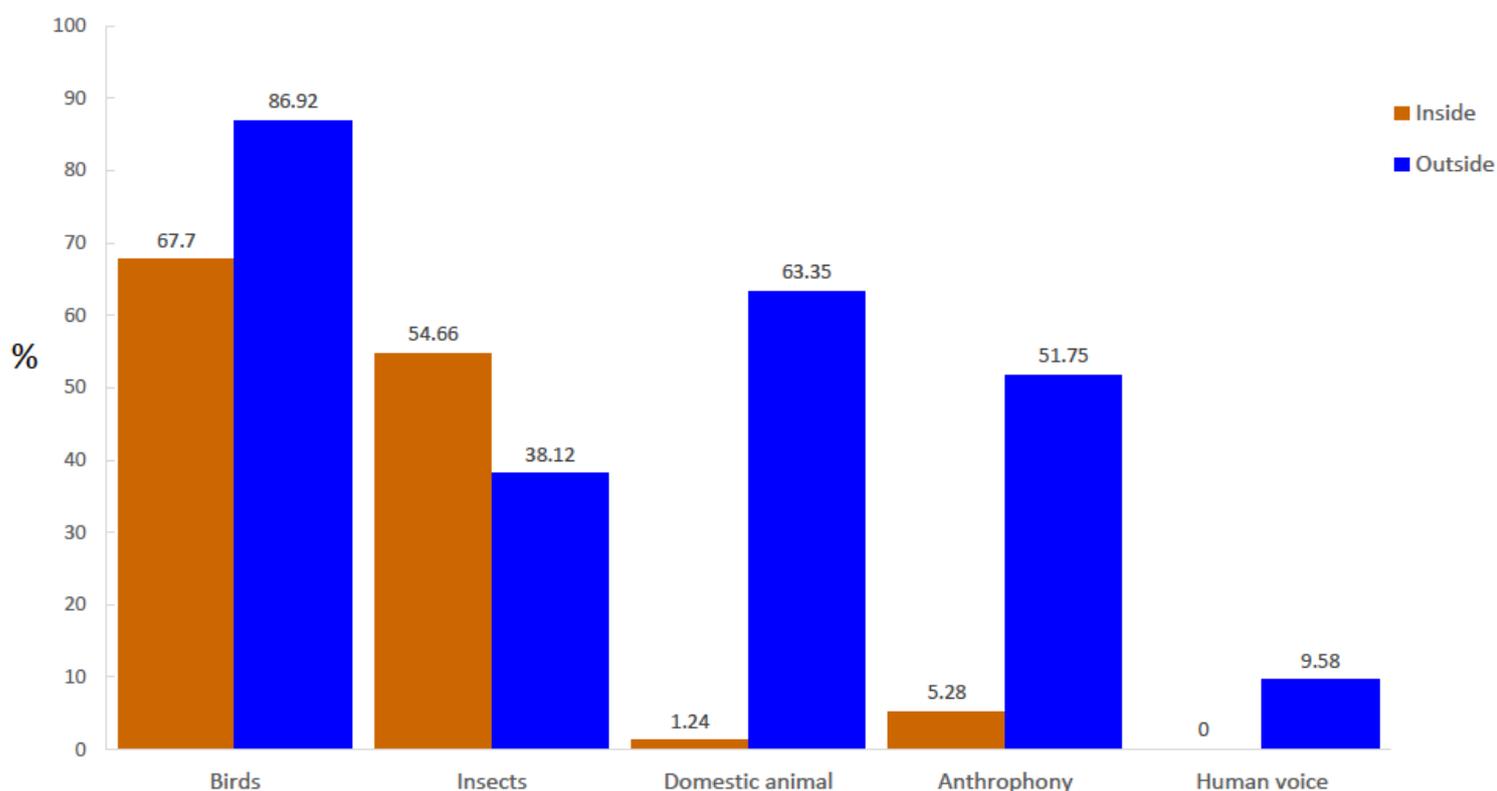


Figure 9: Sonotypes recorded inside and outside the park within panel 6 in autumn. The proportions are given in percentage of presence of each sonotype within the sound files with acoustic events identified inside (total of 322 files with acoustic events) and outside the park (543 files).

Eleven of the 865 sound files selected (approximately 1.3%) had none of the sonotypes described earlier. In all these 11 files, sounds of birds or insects were identified immediately above the 6th panel frequency range. The LDFC spectrograms in which these 11 sound files were represented received a second and more detailed visual examination and the absence of visual signals of acoustic events on the 6th panel was confirmed.

2.4.2 Cosine similarity heatmap: checking overall recording similarity

The heatmaps generated for ACI, ENT and EVN from the averaged cosine similarity among days were used for checking overall recording similarity. It allowed me to identify, and then remove from further analysis, one day, outside our planned recording schedule, in which a malfunctioning acoustic sensor made extra recordings (12th February 2017, by recorder OutCipo01). Besides recording when it should not, the device did not follow the usual schedule, generating less recordings than the other sampling days. The smaller number of recordings have produced differences on the cosine similarity and generated a visible footprint on the cosine similarity (Figures 10). The heatmaps generated for ENT and EVN showing a similar visible footprint are presented in the appendix C.

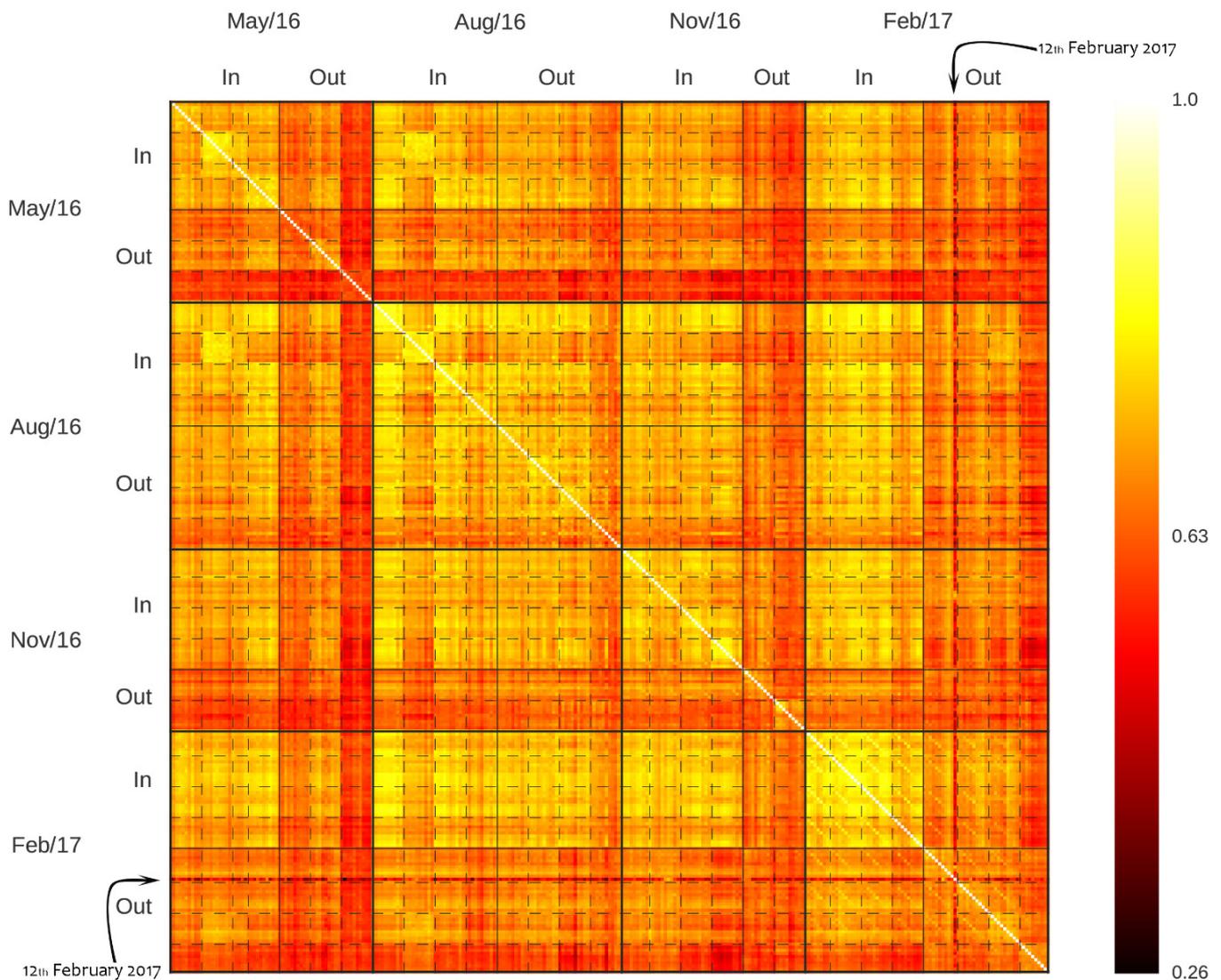


Figure 10: ACI cosine similarity heatmap. The averaged cosine similarity between days for ACI index. The continuous lines separates treatments (inside/outside), while the segmented lines separate the different recorders. The arrow indicates the day which is different from the others (12th February 2017, recorder OutCipo01) from all sites in all seasons.

2.4.3 Missing recordings

The analysis presented here uses data from 282 recording-days, performed in eight different locations (four inside the park plus four outside – see Fig 1) during four sampling rounds (one in each season). These recordings resulted in a total of 40832 one-minute files, with 9403 files recorded in autumn, 11586 files in winter, 8545 in spring and 11298 in summer. The differences in the number of files per season is due to a few recorders occasionally malfunctioning. The recorder identified as InCipo 01 worked for only nine days (one day missing) in spring and eight days (two days missing) in summer. The recorder at the location InCipo 02 worked for only five days in autumn (5 missing days). The recorder OutCipo02 did not work during autumn and spring sampling rounds (10 days missing in each season). The spring malfunction was due to destruction of the microphone by a big animal. This

also occurred for the microphones of the recorder OutCipo03 during the spring sampling round (10 days missing).

DISCUSSION

Combining several acoustic indices allowed detection of significant differences in soundscapes between the inside and outside of the National Park protected area. The significant differences between the inside and outside of the park in panel 6 during autumn, found for all the indices, was not found for the other panels. This finding enables us to give special focus to the times and sound frequencies represented by panel 6 (05:30 – 09:00am and a range of 0.988-3.609 kHz) when monitoring the soundscape on the Serra do Cipó National Park. This panel is likely to represent the “acoustic region” in which I can detect significant changes resulting from any increased human activity associated with reducing the conservation management status of this protected area.

The aggregation of acoustic indices data into 20 panels allowed me not only to identify which panel differs most between sites, but also to determine the shortlist of the amount of files to be visually scanned on LDFC spectrograms. This downsized the 40,832 sound files used in this research to only 1,365 ($\approx 3.3\%$) sound files for scanning using LDFC spectrograms.

The comparative study confirmed that daily LDFC spectrograms can be used as a tool to facilitate the indication of acoustic events in the soundscape, consistent with the findings of Towsey et al. (2018). The visual examination of 65 LDFC spectrograms resulted in the selection of 865 (from 1365) sound files with acoustic events within the range of Panel 6. The 865 sound files aurally and visually scanned on traditional spectrograms correspond to approximately 2% of the total amount of sound files used in this research. Only 11 of 865 ($\approx 1.3\%$) sound files aurally and visually scanned had none of the sonotypes detected. The incorrect selection of these 11 files was due to the presence of visual signals of acoustic events immediately above the 6th panel frequency range that was initially misinterpreted as being inside the 6th panel range.

A major benefit of using LDFC spectrograms is that they can represent acoustic activity in any timeframe, including daily, over a given month or season (Towsey et al. 2014). These averaged LDFC spectrograms can provide a broader overview of the soundscape which can be especially useful for detecting trends using long term monitoring. However, it is important to stress that the longer the time represented in a LDFC spectrogram, the lower its power to provide visual indication of a single

acoustic event. Studies focusing on target species or specific vocalizations will probably be better represented by daily, or even shorter, LDFC spectrograms than from wider time windows.

The cosine similarity heatmaps were also found to be a useful visualization tool. They made possible the identification of a day (12th February 2017, recorder OutCipo01) with an unusual number of recordings, allowing us to subsequently exclude it from the analysis (Figure 10). When dealing with mammoth data sets it is important to visualize some aspect of the entire data set in order to check for data inconsistency. However, cosine similarity heatmaps are a summarization of similarities within a massive amount of data, so they do not show enough detail to allow any ecological inferences.

The sonotypes analysis provides a useful complement to the indices results, and both show higher acoustic activity outside the park within the 6th panel during autumn. The results show that the soundscape outside the park is strongly influenced by the human activity. Domestic animals and anthrophony rare in the park soundscape, while very common outside of it in the farmland environment. The analysis presented here only considered presence/absence of a sonotype, and did not consider the dominance of each sonotype by counting the number of times it appears or time length of each sonotype in a given sound file, similar to the analysis performed by Ferreira et al. (2018). The anthropic influence on the soundscape can be even more dramatic if the sonotype dominance is considered.

The dawn chorus is typically the period that covers most birds' acoustic activity. This corresponds with Panels 5, 6, 7, and 8 covering 5:30 to 9am. Accordingly, the bird sonotype was the most frequent both inside and outside the park during this time within panel 6. As well as panel 6, studies aiming to focus specifically on the bird community should also give special attention to the 7th panel, since its frequency range (3.609 kHz to 7.906 kHz) covers most bird calls. Further research is necessary to determine if the bird activity within the 7th panel is also higher outside the park, as shown for panel 6.

ACI and ENT measurements indicate a higher biophony activity outside the national park, which was confirmed by the sonotype count for panel 6 in autumn. EVN also highlights the greater number of acoustic events in the park surroundings. There are many possible explanations for these findings that can be further explored. For example, animals that mostly live within the park may nonetheless leave the park to visit surrounding farms to obtain additional food. Thus, biophony outside the park could be a sum of the acoustic activity of both permanent residents and visitors. Another possibility is that the compositions of the acoustic communities inside and outside the park are drastically different,

which would indicate an important difference among these habitats that could not be attributed simply to different levels of human use. In contrast, the sonotype count indicates more acoustic activity for insects inside the park. Aide et al. (2017) have found that the richness of insect acoustic morphospecies drives the acoustic space use, which is positively related to species richness in tropical forests. Thus, abundant insect sonotypes at Serra do Cipó could indicate generally high species richness compared to the surrounding farmland.

The BGN is the only index to achieve higher measurements inside than outside the park, indicating that there is more background noise inside the park than outside within the 6th panel in autumn (see the column ratios in table 1). It is important to mention that this index is sensitive to acoustic events that last for longer durations in a sound file, ie. those that create a sound that is approximately continuous throughout the sound file. In many cases, BGN commonly detects insect stridulation, and this may well be the case at Serra do Cipo. The sonotype count points in the same direction, suggesting greater presence of insects inside the park than outside.

This research focuses on developing a broader picture of the soundscape, instead of determining specific species or group of species sound profiles. For this reason, the examination of sonotypes is performed only within the season and panel that presented the biggest differences between sites to describe the sound sources responsible to the differences found by the indices analysis. Further research can be done to describe the sonotypes and morphospecies composition and expand it to other seasons and panels. This will provide a better understanding of the measures used and their links with local biodiversity composition and abundance.

Although I advocate here that acoustic indices and their visualization are a useful tool for PAs monitoring, their use as a surrogate for quick biodiversity assessment should be taken cautiously. Indices provide useful ecological information in different environments worldwide (Depraetere et al. 2012; Towsey, Parsons & Sueur 2014; Duarte et al. 2015; Fuller et al. 2015; Machado, Aguiar & Jones 2017; Sueur 2018), but it is not clear yet the relation of each acoustic index with true animal species richness (Eldridge et al. 2018), diversity, and abundance. It is also not clear how these indices will respond to acoustic communities composed by native species and domestic animals, as is commonly found in areas surrounding protected areas. However, this is not an over-riding limitation for the use of acoustic indices in protected areas monitoring. The varied sensitivity of each index to a different aspect of the acoustic energy means they can be used as complementary filters that enable the identification of the main difference between seasons and sites, as performed here. I do advocate that PAM monitoring associated with acoustic indices analysis should be implemented in protected

areas since they have shown to be cost-effective when compared to other traditional surveys methods (Ribeiro, Sugai & Campos-Cerqueira 2017; Wrege et al. 2017) and are capable of providing information on different levels (populations, species, communities) and different time and space frames. This study shows that acoustic indices are sensitive to domestic animal activity and anthrophony, and therefore, to the different land uses in a protected area and its surrounding farmlands. The main goal of monitoring programmes is to be capable of detecting biodiversity trends differences across sites and time (Lee, McGlone & Wright 2005), which is achieved via PAM and acoustic indices.

The findings presented here show that the acoustic indices are sensitive enough to measure the changes on soundscape differences between the park and its surroundings. It confirms that PAM associated with acoustic indices analysis are potential tools for long term monitoring in Serra do Cipó region, as well as contributing to the establishment of a baseline for park monitoring at this location. Because these techniques are able to provide summary results across seasonal scales, they are potentially able to provide measurements on a long term scale. This can be important for detecting trends, optimising park management and for promoting societal awareness about the importance of protected areas, especially in the face of human changes that are a common threat to parks and reserves (Françoso et al. 2015).

Further research on PAM should include longer sampling periods for a more precise characterization of the acoustic soundscape across years. Additionally they should cover periodic phenomenon such as El Niño, La Niña and other occurrences that play an important role on the ecology of savannah biomes, such as fire. Future research should also associate the soundscape approach with automated identification of endangered and iconic species to contribute to a broader application of passive acoustic approach in protected areas monitoring.

Chapter 3. Passive Acoustic Monitoring in a New Zealand forest: Comparative analyses of soundscapes from two sites with different pest management levels

ABSTRACT

One quarter of all terrestrial native bird species have become extinct after human arrival in New Zealand, which is commonly associated with a pervasive silence in many natural environments due to the decrease in native bird song. Passive acoustic techniques are a potential tool for environmental monitoring, especially for testing whether control of mammals can reverse the ‘silent forest’ effect. In this study I propose and test a workflow for the acoustic monitoring of two sites within the Waitakere Ranges Regional Park, New Zealand, that have different management practices: Ark in the Park (high level pest mammal control) and Fairy Falls (low level pest control). Measurements of acoustic indices extracted from two seasons of passive acoustic recordings are split into 20 acoustic regions and compared to identify which better responds to the management applied. I define the acoustic regions as units of analysis bounded by a specific time period and frequency range adjusted to capture the main groups of biologically relevant acoustic events within a soundscape. The acoustic events within the acoustic region that differs most between sites are identified using false-colour spectrograms (Towsey et al. 2014) and the sounds described after visual and aural analysis of sound files via traditional spectrograms. Analysis of variance and pairwise comparisons indicated the acoustic region “*Mid-high frequency/Night*”, (representing 21:00 to 23:59 and a range of 0.988-3.609 kHz) in autumn as the one that differs most between sites. The sounds responsible for the main differences on indices measurements are emitted by the activity of invasive mammals in the site with no pest control. Chew cards confirmed the different mammal abundance levels resulting from the major differences in pest management for the two areas. By splitting acoustic indices data into acoustic regions, I facilitate statistical analysis of indices results and simplify the identification of sounds that are driving the indices results. The workflow used in this research was capable of detecting the main differences between two soundscapes. It allowed identification of the main season, frequency range and time in which soundscape differences could be detected; as well as the sound source that caused differences in the indices results from sites with different pest management levels. These results support this workflow’s utility for monitoring conservation management actions.

INTRODUCTION

Introduced predators are among the most important threats to biodiversity on islands around the world (Clavero & García-Berthou 2005). In particular, species that have evolved in the absence of predators commonly do not exhibit antipredator behaviour, which makes them an easy target for introduced animals (Blackburn et al. 2004). The New Zealand avifauna is a good example of this problem. The introduction of the brushtail possum (*Trichosurus vulpecula*), rodents (*Rattus exulans*, *R. rattus*, *R. norvegicus*, *Mus musculus*) and mustelids (*Mustela nivalis*, *M. furo*, *M. ermine*) has resulted in extinctions and population declines for many native bird species. One quarter of all terrestrial native bird species have become extinct after human arrival in New Zealand around seven hundred years ago. These introduced predators are considered responsible for around 26.6 million losses of native birds, chicks and eggs every year (Russell et al. 2015) and are commonly associated with a pervasive silence in many New Zealand natural environments due the decrease in native bird song (Mudge 2002).

To address this problem, there has been significant and growing commitment to reducing or eradicating pest mammals. Introduced mammals have been eradicated from over a hundred New Zealand offshore islands (Towns, West & Broome 2012), and currently there are hundreds of programmes operated by community volunteers as well as by governmental agencies that aim to control mammal populations (Russell et al. 2015). The New Zealand government has also launched a national campaign, Predator Free 2050, an ambitious plan with the goal of eradicating possums, rats and stoats by the year of 2050 that may cost around ND\$9 billion (Russell et al. 2015). To access the success of these pest control programmes and their ecological outcomes, environmental monitoring initiatives are required to provide information about a broad range of native and introduced animals. Cost-effective monitoring will also be crucial for detecting mammal re-incursions into areas that they have already been eradicated from if the benefits are to be sustained.

Passive acoustic techniques are a potential tool for environmental monitoring (Sugai et al. 2018), especially for testing whether control of mammals can reverse the ‘silent forest’ effect. These represent a cost effective sampling protocol (Ribeiro, Sugai & Campos-Cerqueira 2017; Wrege et al. 2017) that enables recording different animal groups simultaneously over long time frames (Depraetere et al. 2012; Sueur et al. 2012). Acoustic sensors can be deployed and collected by volunteers, which can facilitate their use by a large number of New Zealand conservation initiatives that already are community based. This makes acoustic sampling suitable for monitoring in a wide range of environmental contexts. Once the recordings are obtained, they can be used for a range of

possible analyses. Automated identification analyses are commonly aimed towards population studies, targeting species that are the focus of conservation programmes. These identification algorithms have been applied to the study of varied taxa such as primates (Kalan et al. 2015), elephants (Wrege et al. 2017) and birds (Sanders & Mennill 2014; Stowell, Benetos & Gill 2017). In contrast, studies of the entire acoustic community and how it varies in space and time is commonly called soundscape ecology or ecoacoustics. These have been performed worldwide, in countries such as Australia (Fuller et al. 2015), France (Depraetere et al. 2012), Tanzania (Sueur et al. 2008), Brazil (Ferreira et al. 2018), among others. However, despite the applicability to a New Zealand pest control context, to my knowledge, there are as yet no published studies about New Zealand forest soundscapes.

Soundscape studies frequently aim to relate acoustic indices measurements calculated from passive acoustic recordings to other environmental characteristics such as vegetation structure (Farina & Pieretti 2014), habitat condition (Sueur et al. 2008), or composition of the acoustic community (Phillips, Towsey & Roe 2018). Acoustic indices can be defined as mathematical filters that describe how the acoustic energy is distributed across frequency and time in a sound file. Each index measures the distribution of energy within a sound file in a different way. Towsey et al. (2014) present an interesting explanation about the calculation of 14 different acoustic indices in a paper that also examines the relationship between the soundscape and ecological conditions in Australian forest fragments. Nowadays, there is considerable literature on varied acoustic indices (Sueur 2018).

The Acoustic Complexity Index (ACI) (Pieretti, Farina & Morri 2011) and Temporal Entropy (ENT) (Sueur et al. 2014) are sensitive to the composition of the acoustic community. The ACI measures the amplitude oscillation in each frequency bin. Anthrophony (human generated sound, e.g. airplanes and cars) and geophony (sounds generated by natural abiotic phenomenon such as wind and rain) typically present more constant intensity values, while biophony commonly present greater variability in intensity modulation (Farina, Pieretti & Piccioli 2011). The ACI measures the amplitude oscillation in each frequency bin, which makes it sensitive to biophony. The ENT (also called $H[f]$) is sensitive to the temporal dispersal of the energy in a sound file. It is expected that the more species emitting sounds, the bigger the energy dispersal recorded; this is the reason why ENT is considered sensitive to species richness. In this way, ACI and ENT are sensitive to different aspects of biophony, which makes them complementary to each other and places them among the most important acoustic indices for ecological studies. Due to these characteristics, calculations of ACI and ENT are often performed in research that apply several indices to the study of soundscape (Tucker et al. 2014; Towsey et al. 2014; Fuller et al. 2015; Harris, Shears & Radford 2016; Ferreira et al. 2018).

Although the soundscape approach has huge potential for ecological studies, some remaining technical challenges limit wider use. Acoustic indices are able to provide measurements that can be used to represent a soundscape as well as to compare soundscapes, e.g. over seasons (Chapter 2). However, visualising and understanding the enormous amount of data generated by acoustic indices make the interpretation of results very difficult. It can also be challenging to identify which animals are causing the differences in the index results between two soundscapes or across different seasons. These problems are particularly challenging when dealing with the vast data sets generated by passive acoustic monitoring (PAM).

As an attempt to manage these difficulties, I have developed a step-by-step workflow that determines which acoustic regions should be used to perform independent comparisons between the indices results generated from multiple soundscape recordings. The acoustic indices are used for filtering the acoustic information in the soundscape. I define the acoustic regions as units of analysis bounded by a specific time period and frequency range. These acoustic regions can be adjusted to capture the main groups of biologically relevant acoustic events within a soundscape. Good examples of relevant acoustic events with bounded frequency and time frames are the bird dawn chorus (mostly encompassed within mid frequencies and during the first hours of daylight) and bats' acoustic activities (commonly nocturnal and in high frequencies). By splitting soundscape data into these acoustic regions, I can facilitate statistical analysis of indices results, as well as simplify identification of sounds that are driving the indices results.

In this study, the proposed workflow is tested with passive acoustic recordings made in two nearby forest sites that have very different management of introduced mammals. If this analytical approach is able to facilitate the identification of which season, the frequency range and time period that varies most between sites, as well as facilitating identification of the sounds responsible for the main differences between soundscapes, the workflow could be very useful for monitoring New Zealand natural areas under pest management programmes.

METHODS

3.3.1 Study sites

The Waitakere Ranges is a regional park managed by the Auckland Council and located within the Auckland region, New Zealand. Comprising 160 km², the park is habitat for many native flora and

fauna, such as the iconic kauri tree (*Agathis australis*) that can live over 1500 years (Ahmed & Ogden 1987), the long-tailed bat (*Chalinolobus tuberculatus*), one of New Zealand's few native land-based mammals, and the kaka (*Nestor meridionalis*), among others.

Research was conducted at two sites within the Waitakere Ranges Regional Park that have different management practices: Ark in the Park (high level pest mammal control) and Fairy Falls (low level pest control). The Ark in the Park is a volunteer-based conservation initiative. It is a collaborative project between the community group Forest and Bird and Auckland Council, supported by Te Kawerau a Maki, the tangata whenua (people of the land) of the Waitakere region. Since 2002, the project has implemented a grid of mustelid traps and bait stations containing the second-generation anticoagulant brodifacoum. Due to its intensive pest control actions, the Ark in the Park area is considered to have high level pest management when compared with the surrounding areas outside the project's borders.

Fairy Falls is approximately 3 km away from Ark in the Park, and is also within the Waitakere Ranges park boundaries. Just like Ark in the Park, Fairy Falls is a natural area well visited by the public for recreation. However, this area does not receive pest control actions (at least during the period when this research was performed), and is considered unmanaged from the perspective of invasive mammals.

At both sites, a random-systematic sampling design was chosen in order to guarantee independent sound sampling as well as to allow comparisons between sites. A square (200m x 200m) was predefined as the systematic sampling grid. The location of the south-eastern corner of each square was randomly chosen, and from that the other three corners were defined. Each of the square's corners received one acoustic sensor during the sampling period. Figure 11 shows the location of each acoustic sensor in the two sites.

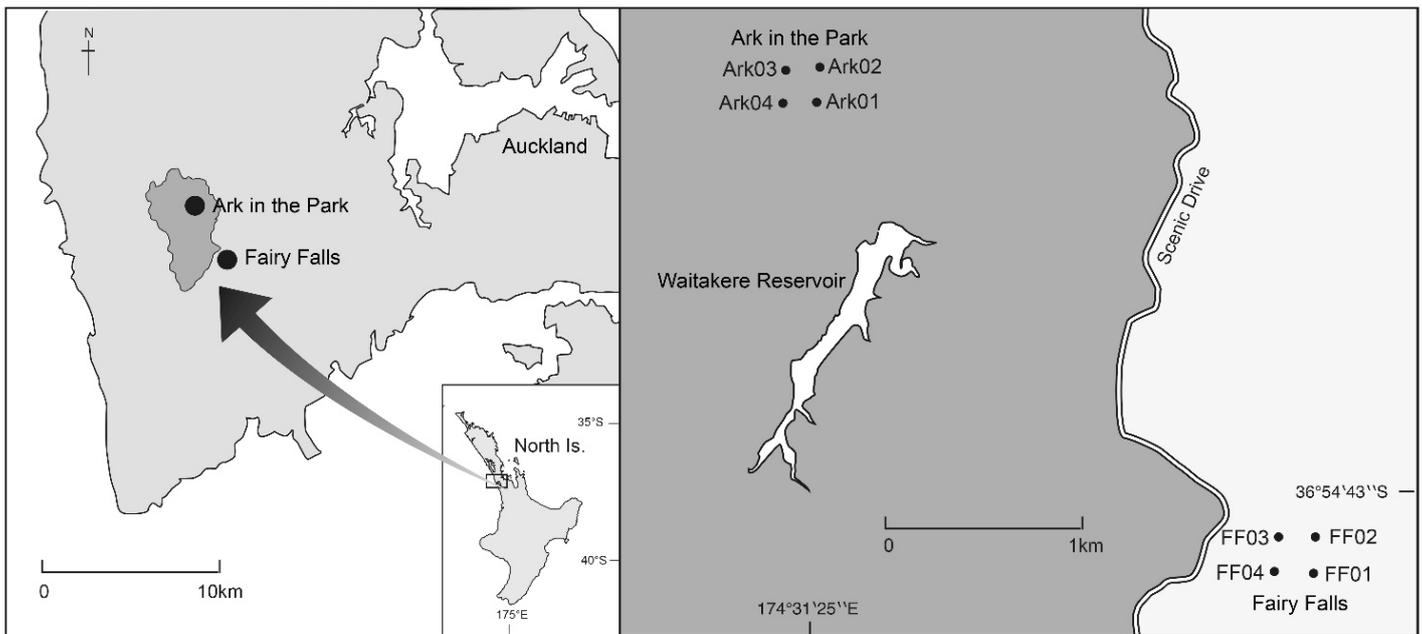


Figure 11: Waitakere Ranges region. Location of acoustic sensors in Ark in the Park and Fairy Falls sites.

3.3.2 Recordings settings

The recordings were performed for ten consecutive days during late spring (9th to 18th December 2016) and late autumn (11th to 20th June 2017) using two types of acoustic sensors: Song Meters SM3 and SM4 (Wildlife Acoustics), with two of each model at each site, at a sampling rate of 48000 Hz, set at 32 bits. Acoustic sensors were fixed on trees 1.5m above the ground.

The acoustic sensors were programmed to perform 1 minute of recording every 10 minutes, resulting in 144 one-minute sound files per location, per day of sampling. Temporal sampling scheme of 1/10 minutes recording schedule has been used successfully in previous studies (Aide et al. 2013; Ospina et al. 2013; Pieretti et al. 2015; Alvarez-Berrios et al. 2016; Campos-Cerqueira & Aide 2016; Campos-Cerqueira et al. 2017; Aide et al. 2017; Campos-Cerqueira & Aide 2017).

3.3.3 Acoustic Indices Calculation

To facilitate the calculation of acoustic indices, the sound files were down-sampled to 22,050 Hz and mixed down to mono. Indices were calculated for each frequency bin of ≈ 43 Hz, totalling 256 bins, according to Towsey et al. (2014; 2017; 2018). The Acoustic Complexity Index (ACI) and the Temporal Entropy (ENT) are among the more established acoustic indices and are known to be related to biophony, while the Event Count Index (EVN) has shown to be complementary to these two for the elaboration of the Long Duration False Colour spectrograms (Towsey 2017). Another nine indices were used to check for consistency between acoustic indices measurements and, although their

measurements were used for analysis of variance and pairwise comparisons, they were not explored in detail (Table 2).

Table 2: Acoustic Indices compared for sound recordings from nearby pest-controlled and unmanaged forest sites

| Index Name | Description |
|---|---|
| Acoustic Complexity Index (ACI) | Measures the amplitude oscillation in each frequency bin (Pieretti, Nadia, Farina & Morri 2011) . It is calculated from an amplitude spectrogram following Towsey et al (2018). |
| Temporal Entropy (ENT) | Measures the energy dispersal over the frames of each frequency bin. It was first derived from the Shannon index aiming to measure the evenness of different sound categories (Sueur et al. 2008; 2014). Here the converted version of the index is used to provide the “energy concentration”, as calculated by Towsey et al (2018). |
| Event Count (EVN) | Counts the number of events in each frequency bin per minute (Towsey 2017). |
| Acoustic Cover (CVR) | The fraction of cells in each frequency bin of the noise-reduced spectrogram which surpasses 2 dB (Towsey et al. 2014). |
| Power minus Noise (PMN) | Computes the maximum decibel value in each frequency bin of the noise-reduced decibel spectrogram (Towsey 2017). |
| Spectral Peak Tracks (SPT) | The spectral peaks (local maxima) identified in each spectrum, as calculate by Towsey et al (2018). |
| Background Noise (BGN) | The decibel value of background noise in each frequency bin calculated as the modal decibel value in each frequency bin of the decibel spectrogram, as in Towsey et al (2018). |
| Ridge Horizontal (RHZ) | Corresponding to the horizontal dimension of the ride slope. The Ridges Indices are derived from the noise-reduced decibel spectrogram (Towsey 2017). |
| Ridge Vertical (RVT) | Ridge Vertical (RVT) Corresponding to the vertical dimension of the ride slope. The Ridges Indices are derived from the noise-reduced decibel spectrogram (Towsey 2017). |
| Ridge Positive having an upward slope (RPS) | Corresponding to the ridge positive having an upward slope. The Ridges Indices are derived from the noise-reduced decibel spectrogram (Towsey 2017). |
| Ridge Negative having downward slope (RNG) | Corresponding to the ridge negative having an downward slope. The Ridges Indices are derived from the noise-reduced decibel spectrogram (Towsey 2017). |
| Ridge 3 Dimensions (R3D) | This index equals the maximum of RHZ, RPS, and RNG (Towsey 2017). |

3.3.4 Long Duration False Colour spectrograms

Long Duration False Colour (LDFC) spectrograms were produced for each day of recording generated by each acoustic sensor at each of the two field sites. These are a visual representation of three different indices measurements using colour coding whereby the ACI is red, ENT is green and EVN is blue (Towsey, Truskinger & Roe 2015). These three indices are sensitive to different aspects

of the sound signal (Table 2), making them complementary to each other and thus providing coverage of a range of soundscape elements. The LDFC spectrograms were generated as described by Towsey et al. (2014). In total 160 LDFD spectrograms were generated, each containing indices results from 144 sound files.

3.3.5 Acoustic Regions

Since the data sets were vast (more than 5 million different values calculated for each index), any statistically significant differences could be the result of type I errors. To mitigate this and to facilitate exploration of the results, the data sets were aggregated into acoustic regions. A visual examination of the 160 LDFC spectrogram has shown that the frequency and time boundaries used to establish each panel in Chapter 2 were able to capture the most important acoustic events in the Waitakere’s soundscape. Therefore, the same frequency ranges and five time periods were selected, resulting in 20 independent acoustic regions (Table 3). These acoustic regions were defined with the aim of representing the main groups of sound events happening within a day in an acoustic community.

Table 3. Acoustic Regions: frequency and time ranges boundaries

| Frequency ranges | Time periods | | | | |
|---|---|--|--|---|--|
| | 00:00 to 5:29 | 5:30 to 9:00 | 9:01 to 17:29 | 17:30 to 20:59 | 21:00 to 23:59 |
| 0 to \approx 0.988 kHz (bins 0 to 22) | <i>Low frequency/ Predawn</i> (Panel 1) | <i>Low frequency/ Dawn</i> (Panel 5) | <i>Low frequency/ Day</i> (Panel 9) | <i>Low frequency/ Dusk</i> (Panel 13) | <i>Low frequency/ Night</i> (Panel 17) |
| \approx 0.988 to \approx 3.609 kHz (bins 23 to 83) | <i>Mid-low frequency/ Predawn</i> (Panel 2) | <i>Mid-low frequency/ Dawn</i> (Panel 6) | <i>Mid-low frequency/ Day</i> (Panel 10) | <i>Mid-low frequency/ Dusk</i> (Panel 14) | <i>Mid-low frequency/ Night</i> (Panel 18) |
| \approx 3.609 to \approx 7.906 kHz (bins 84 to 183) | <i>Mid-high frequency/ Predawn</i> (Panel 3) | <i>Mid-high frequency/ Dawn</i> (Panel 7) | <i>Mid-high frequency/ Day</i> (Panel 11) | <i>Mid-high frequency/ Dusk</i> (Panel 15) | <i>Mid-high frequency/ Night</i> (Panel 19) |
| \approx 7.906 to \approx 11 kHz (bins 184 to 255) | <i>High frequency/ Predawn</i> (Panel 4) | <i>High frequency/ Dawn</i> (Panel 8) | <i>High frequency/ Day</i> (Panel 12) | <i>High frequency/ Dusk</i> (Panel 16) | <i>High frequency/ Night</i> (Panel 20) |

Frequency and time boundaries used to establish each acoustic region. Within parentheses the corresponding panel in chapter 2.

3.3.6 Comparing acoustic regions between sites

Statistical analyses were performed to identify whether any of the above described acoustic regions differed between the two treatment sites for each of the twelve indices. Before fitting the models, the

interval that captured 98% of the values for each index was defined. The 1% lowest values falling below the lower limit as well as the 1% falling above the maximum were truncated to the interval defined. To reduce the outlier effects and to facilitate comparisons among different indices, the data were normalized by scaling the values from a 0 to 1 (see Towsey et al. (2014)). Indices values were then aggregated by the summation within each acoustic region, day and location (each acoustic sensor represents one of the eight locations), resulting in 160 single aggregated observations per acoustic region. Aggregation by the summation of index values within each panel per day was selected as the most appropriate unit for subsequent analysis as it resulted in wider confidence intervals, as well as a better relationship of residual fits.

To test for significant effects due to interactions as well as differences between sites and the seasons, I performed Analysis of Variance (ANOVA) and then pairwise comparisons (T tests). The models for each index were fitted independently. The index value (log transformed) was defined as the outcome variable, while the explanatory variables were season (autumn, spring) and site (high pest management level at Ark in the Park, or unmanaged at Fairy Falls). The size of the effects were calculated from the pairwise comparison and back transformed to ratios. The Shapiro-Wilk test confirmed the normality assumptions for most of the panels tested, while quantile-quantile and residual fits plots show data are normally distributed in all the panels (appendix D – ENT index models are taken as example).

3.3.7 Describing events on the Acoustic Region of interest

To describe the sound sources that generate the main differences on indices results between the two sites, the acoustic events within the acoustic region of interest were scanned through two steps. First, each LDFC spectrograms corresponding to the identified season was visually checked to identify acoustic events. Second, the sound files corresponding to each acoustic event identified on the LDFC spectrograms were then aurally and visually scanned. This second step was performed using traditional spectrograms generated by the software AUDACITY®.

3.3.8 The overall workflow

Figure 12 illustrates the overall methods workflow used in this research.

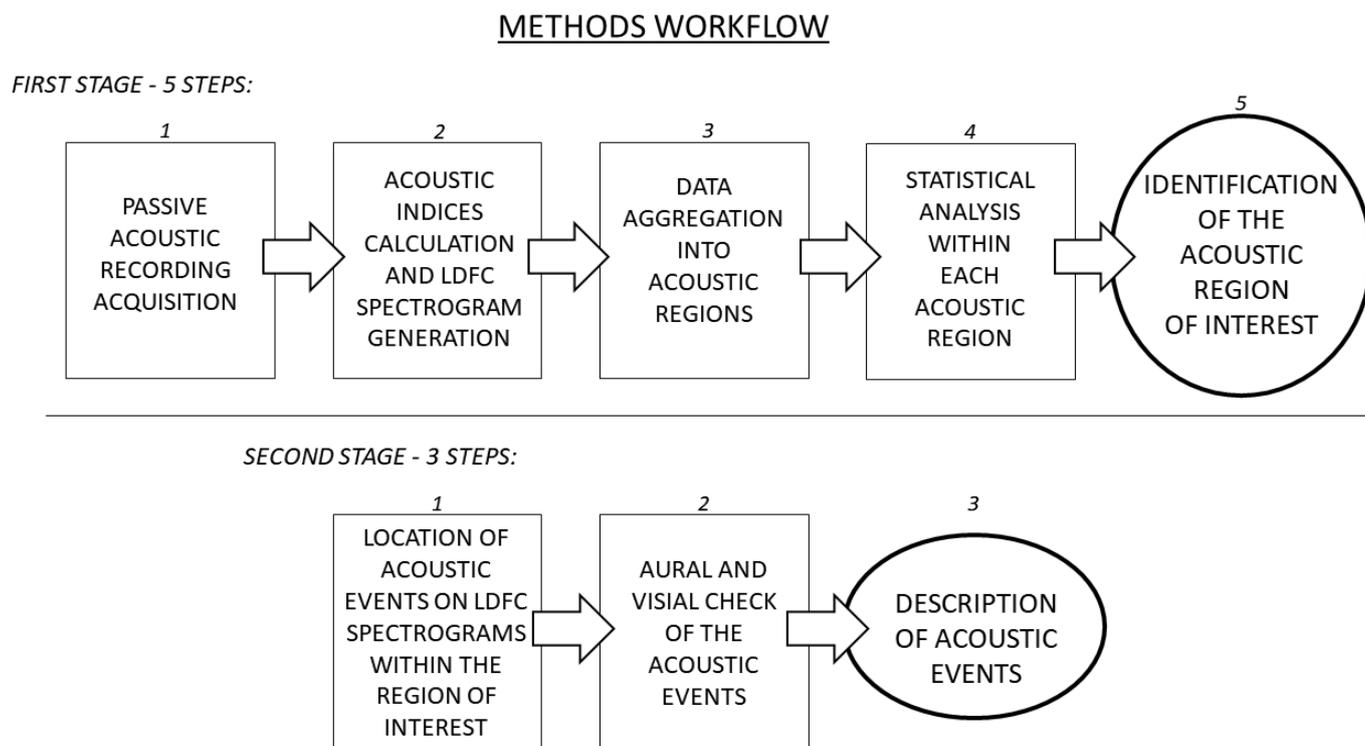


Figure 12: Overall methods workflow used in chapter 3.

3.3.9 Chew cards

To assess invasive mammal presence, chew cards were deployed and replaced after 5 days, resulting in 32 cards in total (8 per site in each season). Cards were fixed to the same tree as the sound recorders (at 30cm and 1.5m above the ground, respectively). Chew cards are a piece of polypropylene (90 x 180 x 3 mm) with internal flutes filled with an attractant (pasta) (Figure 16). The cards were bent into a right-angled position and mounted on tree trunks, similarly to Sweetapple & Nugent (2011). The cards are widely used in New Zealand to record the tooth impressions of animals that interact with it, allowing the identification and abundance estimation of invasive mammalian pests present in an area. The sampling effort used in this study was enough to allow overall comparisons between sites in order to ensure sites were under different pest management levels, but not enough to provide precise mammal abundances for each site.

RESULTS

There were significant differences in the acoustic indices values generated for the high pest mammal management site (Ark in the Park) compared to the no pest mammal management site (Fairy Falls). See appendix E for a full list of statistical comparisons of the soundscapes at Ark in the Park and Fairy Falls for all 12 indices, across all 20 acoustic regions.

The soundscape differed most between the high and no pest management sites in autumn - the highest number of significantly different indices values occurred in the acoustic region “*Mid-high frequency/ Night*”, representing 21:00 to 23:59 and a range of 0.988-3.609 kHz (Figure 13). This acoustic region had significant results for 11 of the 12 indices, and presented the highest ratios for all the acoustic regions for 8 of these indices. Table 4 presents the pairwise comparisons for the acoustic region of interest in autumn for all the acoustic indices calculated. However, this acoustic region did not differ during Spring, with no significant differences for 10 of the 12 indices (Figure 14; appendix E).

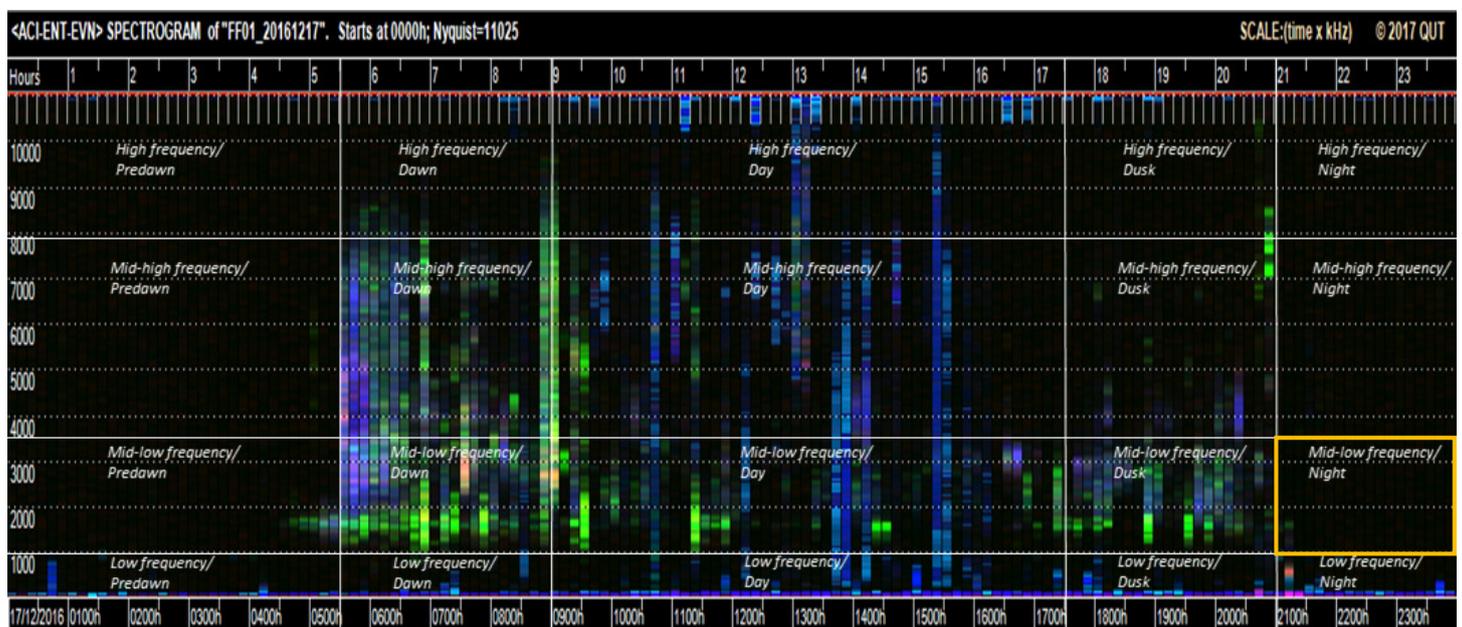


Figure 13: Long Duration False Colour (LDFC) Spectrogram illustrating the main acoustic activity within a day on Waitakere region’s soundscape, the boundaries of each acoustic region and highlighting the identified acoustic region of interest. The Long Duration False Colour (LDFC) Spectrogram presented here was created from audio files recorded inside the no pest mammal control site, Fairy Falls (location FF01), on 17th December 2016. The white lines across the false colour spectrograms show the time and frequency boundaries of each acoustic region. The orange rectangle indicates the acoustic region of interest that was indicated by statistical analysis. In this LDFC spectrogram the Acoustic Complexity Index (ACI) receives the red colour, Temporal Entropy (ENT) green and Event Count (EVN) blue.

Table 4: Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management within the acoustic region of interest

Mid-high frequency/ Night - autumn season

| Index | P value | Ratio |
|---|----------|-----------|
| Temporal Entropy (ENT) | 1.29E-05 | -3.0995 |
| Event Count (EVN) | 0.0010 | -2.6693 * |
| Acoustic Cover (CVR) | 0.0012 | -2.2922 * |
| Power minus Noise (PMN) | 0.0001 | -2.2478 * |
| Acoustic Complexity Index (ACI) | 0.0001 | -1.9106 * |
| Spectral Peak Tracks (SPT) | 0.0025 | -1.8081 |
| Ridge Vertical (RVT) | 0.0003 | -1.7498 * |
| Ridge Positive having an upward slope (RPS) | 0.0010 | -1.5398 * |
| Ridge Negative having downward slope (RNG) | 0.0010 | -1.5397 * |
| Ridge 3 Dimensions (R3D) | 0.0010 | -1.5307 * |
| Ridge Horizontal (RHZ) | 0.0030 | -1.3083 |
| Background Noise (BGN) | 0.5355 | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairly Falls). The * symbol indicates a ratio that was the biggest among all the acoustic regions for a specific index. The Background Noise (BGN) was the only index with no significant results for this acoustic region.

All indices results for the Mid-high frequency/ Night acoustic region

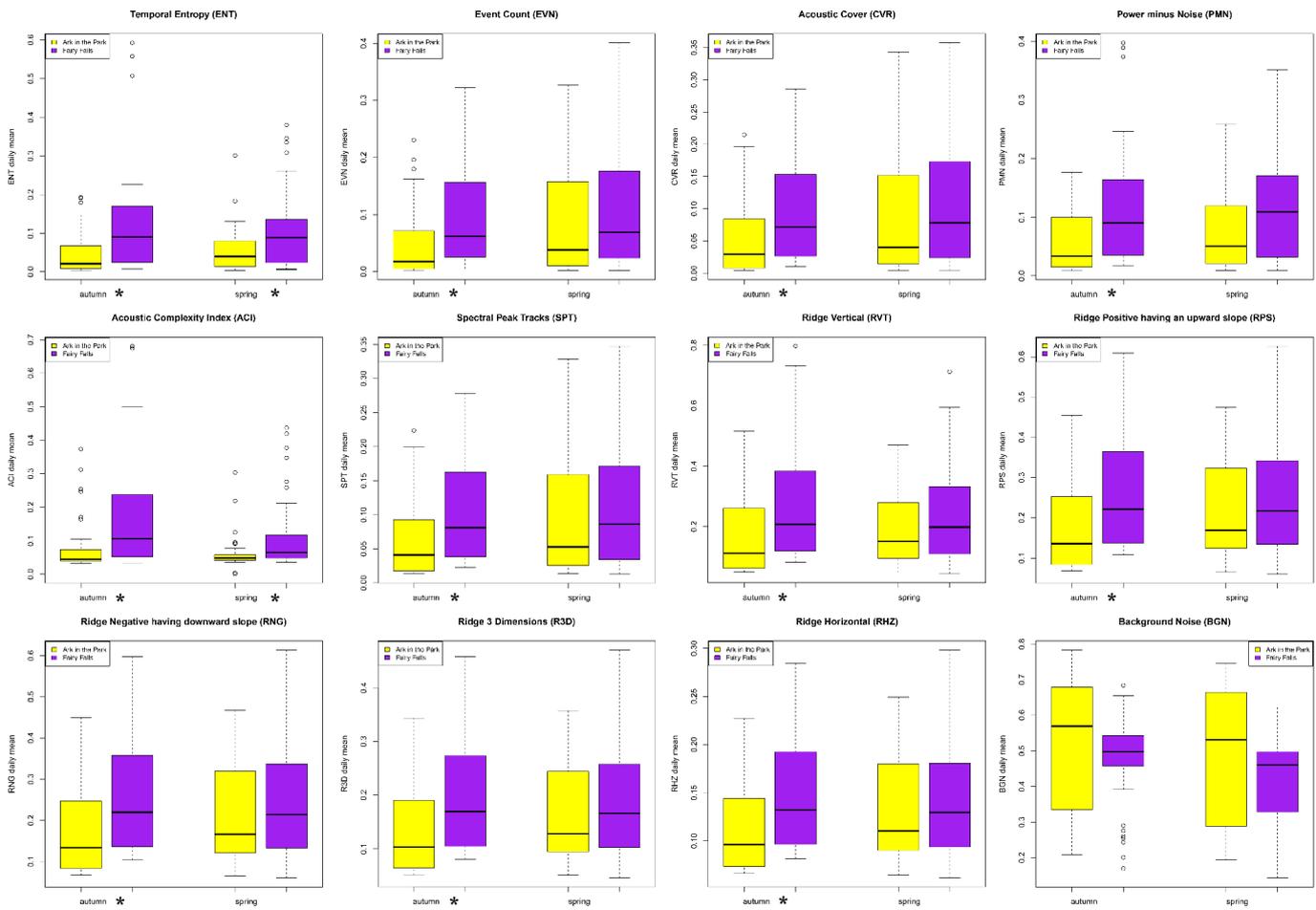


Figure 14: Histograms for each index for the Mid-high frequency/ Night” region for autumn and spring. * symbol indicates that the season presented significant soundscape differences between Ark in the Park and Fairy Falls for a given index.

The soundscape at the two field sites differed least in these 10 acoustic regions: *Mid-high frequency/ Dawn* in autumn, *Mid-low frequency/ Dawn* in autumn, *Low frequency/ Dawn* in autumn and spring, *Mid-high frequency/ Day* in autumn, *Mid-low frequency/ Day* in autumn, *Low frequency/ Day* in autumn and spring, *Mid-low frequency/ Dusk* in spring and *Low frequency/ Dusk* in spring. These regions were not significantly different for the two sites for all twelve indices tested (p values all > 0.05 ; appendix E).

Each one of the 80 LDFC spectrograms for the autumn recordings were visually scanned to identify acoustic events on the time period and frequency range related to the “*Mid-high frequency/ Night*” region (as per chapter 2). Rainy days were excluded from this analysis as the noise makes it difficult to locate acoustic events on LDFC spectrograms, as well as masking the acoustic signal, preventing

the aural and visual scan of sound files on traditional spectrograms. The “*Mid-high frequency/ Night*” acoustic region is typically quiet in the Waitakere region (Figure 13). After excluding files that were representing rain, only twenty sound files with acoustic events were selected. These files were distributed across 7 different days and three locations in the no pest mammal control site (Fairy Falls). The only Fairy Falls sound recorder for which no file was selected was FF03 (Figure 11). No sound files with these traits were selected from the high pest mammal control site (Ark in the Park).

The visual and aural scan of these files revealed an unusual sound consistently present in all of these files. Upon first consideration, it is similar to the representation of rain sound in a traditional spectrogram, although it has a bigger contrast around 2 kHz than is typical for rain (Figure 15). However, the aural analysis shows a very distinctive sound that could not be mistaken by rain or any other geophony. It was finally identified to be the sound of a mammal moving around the location in which the sound sensors were fixed, and interacting with the chew cards (biting and chewing).

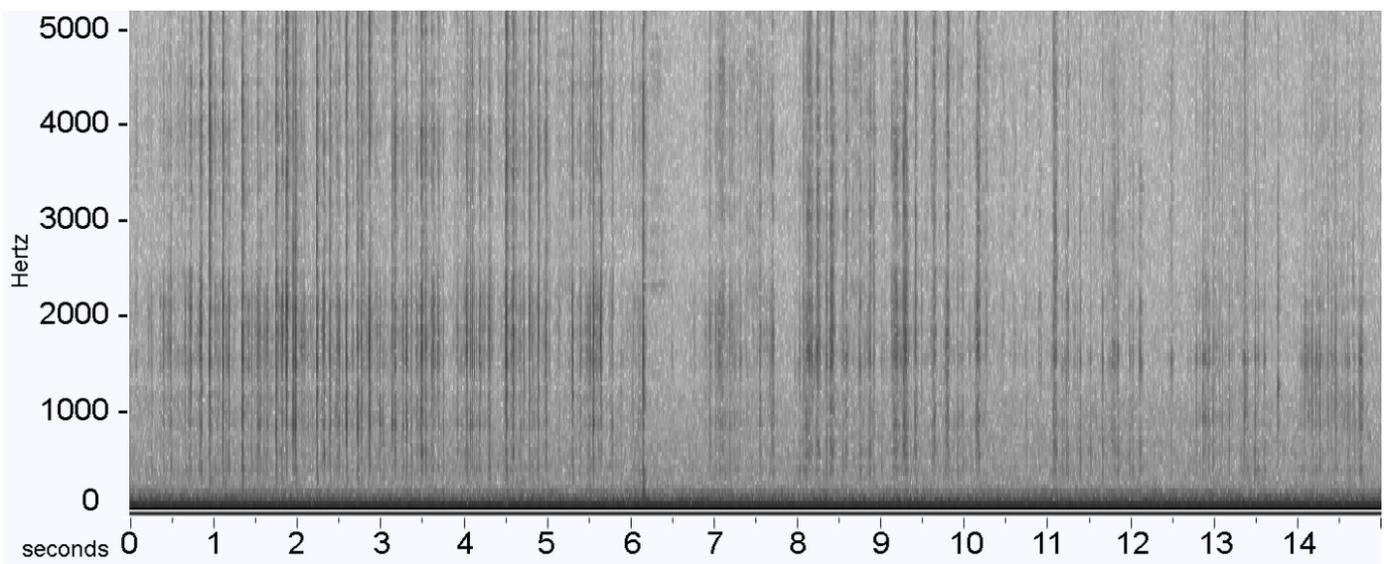


Figure 15: Traditional spectrogram of the mammal activity registered. Spectrogram of a 15 seconds section of one sound file in which the mammal activity was recorded. This sound file was sampled on 17th June 2017, in the FF04 location (see figure 11). It was interpreted as the sound of a mammal interaction with a chew card.

3.4.1 Chew cards

The chew cards indicated radically different mammal abundances at the high mammal control (Ark in the Park) and no mammal control sites (Fairy Falls) in both seasons sampled. All the eight cards sampled in autumn in Fairy Falls had rat chew marks, six had possum marks and five had mouse marks (Table 6). In the spring season, all the eight cards had possum marks, five had rat marks and two cards presented mouse marks (Table 5). A Fisher’s exact test indicates that the presence of mammals’ marks on chew cards was significantly different between the two sites in both seasons for

rats and possums. The marks of mice were significantly different between sites in autumn but not in spring (P value = 0.4667).

Figure 16 shows pictures of the chew cards used in the autumn sampling at Fairy Falls. The appendix F presents pictures cards used in Ark in the Park in autumn (with no mammal marks) as well as the cards used in spring in both sites.

Table 5: Mammals' marks identified in the chew cards during spring season in both sites

| Site | Recorder Location | season | card | Card side | Possum | Rat | Mouse | Other |
|-----------------|-------------------|--------|------|-----------|--------|-----|-------|-------|
| Ark in the Park | ARK01 | spring | 1st | A | - | - | - | - |
| Ark in the Park | ARK01 | spring | 1st | B | - | - | - | - |
| Ark in the Park | ARK01 | spring | 2nd | A | - | - | - | - |
| Ark in the Park | ARK01 | spring | 2nd | B | - | - | - | - |
| Ark in the Park | ARK02 | spring | 1st | A | - | - | - | - |
| Ark in the Park | ARK02 | spring | 1st | B | - | - | - | - |
| Ark in the Park | ARK02 | spring | 2nd | A | - | - | - | - |
| Ark in the Park | ARK02 | spring | 2nd | B | - | - | - | - |
| Ark in the Park | ARK03 | spring | 1st | A | - | - | - | - |
| Ark in the Park | ARK03 | spring | 1st | B | - | - | - | - |
| Ark in the Park | ARK03 | spring | 2nd | A | - | - | - | - |
| Ark in the Park | ARK03 | spring | 2nd | B | - | - | - | - |
| Ark in the Park | ARK04 | spring | 1st | A | - | - | - | - |
| Ark in the Park | ARK04 | spring | 1st | B | - | - | - | - |
| Ark in the Park | ARK04 | spring | 2nd | A | - | - | - | - |
| Ark in the Park | ARK04 | spring | 2nd | B | - | - | - | - |
| Fairy Falls | FF01 | spring | 1st | A | yes | yes | - | - |
| Fairy Falls | FF01 | spring | 1st | B | yes | yes | - | - |
| Fairy Falls | FF01 | spring | 2nd | A | yes | - | - | - |
| Fairy Falls | FF01 | spring | 2nd | B | yes | - | - | - |
| Fairy Falls | FF02 | spring | 1st | A | yes | - | - | - |
| Fairy Falls | FF02 | spring | 1st | B | yes | - | - | - |
| Fairy Falls | FF02 | spring | 2nd | A | yes | yes | - | - |
| Fairy Falls | FF02 | spring | 2nd | B | yes | yes | yes | - |
| Fairy Falls | FF03 | spring | 1st | A | yes | - | - | - |
| Fairy Falls | FF03 | spring | 1st | B | yes | - | - | - |
| Fairy Falls | FF03 | spring | 2nd | A | yes | yes | - | - |
| Fairy Falls | FF03 | spring | 2nd | B | yes | yes | - | - |
| Fairy Falls | FF04 | spring | 1st | A | - | yes | - | - |
| Fairy Falls | FF04 | spring | 1st | B | yes | yes | - | - |
| Fairy Falls | FF04 | spring | 2nd | A | yes | yes | - | - |
| Fairy Falls | FF04 | spring | 2nd | B | yes | yes | yes | - |

The word "yes" indicates the identification of the animals' marks in the respective card side.

Table 6: Mammals' marks identified in the chew cards during autumn season in both sites

| Site | Recorder Location | season | card | Card side | Possum | Rat | Mouse | Other |
|-----------------|-------------------|--------|------|-----------|--------|-----|-------|-------|
| Ark in the Park | ARK01 | autumn | 1st | A | - | - | - | - |
| Ark in the Park | ARK01 | autumn | 1st | B | - | - | - | - |
| Ark in the Park | ARK01 | autumn | 2nd | A | - | - | - | yes |
| Ark in the Park | ARK01 | autumn | 2nd | B | - | - | - | yes |
| Ark in the Park | ARK02 | autumn | 1st | A | - | - | - | - |
| Ark in the Park | ARK02 | autumn | 1st | B | - | - | - | - |
| Ark in the Park | ARK02 | autumn | 2nd | A | - | - | - | - |
| Ark in the Park | ARK02 | autumn | 2nd | B | - | - | - | - |
| Ark in the Park | ARK03 | autumn | 1st | A | - | - | - | - |
| Ark in the Park | ARK03 | autumn | 1st | B | - | - | - | - |
| Ark in the Park | ARK03 | autumn | 2nd | A | - | - | - | - |
| Ark in the Park | ARK03 | autumn | 2nd | B | - | - | - | - |
| Ark in the Park | ARK04 | autumn | 1st | A | - | - | - | - |
| Ark in the Park | ARK04 | autumn | 1st | B | - | - | - | - |
| Ark in the Park | ARK04 | autumn | 2nd | A | - | - | - | - |
| Ark in the Park | ARK04 | autumn | 2nd | B | - | - | - | - |
| Fairy Falls | FF01 | autumn | 1st | A | yes | yes | - | - |
| Fairy Falls | FF01 | autumn | 1st | B | yes | yes | - | - |
| Fairy Falls | FF01 | autumn | 2nd | A | yes | yes | yes | - |
| Fairy Falls | FF01 | autumn | 2nd | B | yes | yes | yes | - |
| Fairy Falls | FF02 | autumn | 1st | A | yes | yes | - | - |
| Fairy Falls | FF02 | autumn | 1st | B | yes | yes | yes | - |
| Fairy Falls | FF02 | autumn | 2nd | A | yes | yes | - | - |
| Fairy Falls | FF02 | autumn | 2nd | B | yes | yes | - | - |
| Fairy Falls | FF03 | autumn | 1st | A | - | yes | - | - |
| Fairy Falls | FF03 | autumn | 1st | B | - | yes | yes | - |
| Fairy Falls | FF03 | autumn | 2nd | A | - | yes | - | - |
| Fairy Falls | FF03 | autumn | 2nd | B | - | yes | yes | - |
| Fairy Falls | FF04 | autumn | 1st | A | yes | yes | - | - |
| Fairy Falls | FF04 | autumn | 1st | B | yes | yes | - | - |
| Fairy Falls | FF04 | autumn | 2nd | A | yes | yes | - | - |
| Fairy Falls | FF04 | autumn | 2nd | B | yes | yes | yes | - |

The word "yes" indicates the identification of the animals' marks in the respective card side. The only marks in chew cards installed in the Ark in the Park site were not properly identified and may have been made by a bird or insect (see letters I and J in the first figures of appendix F).

Chew Cards sampled during autumn season in Fairy Falls

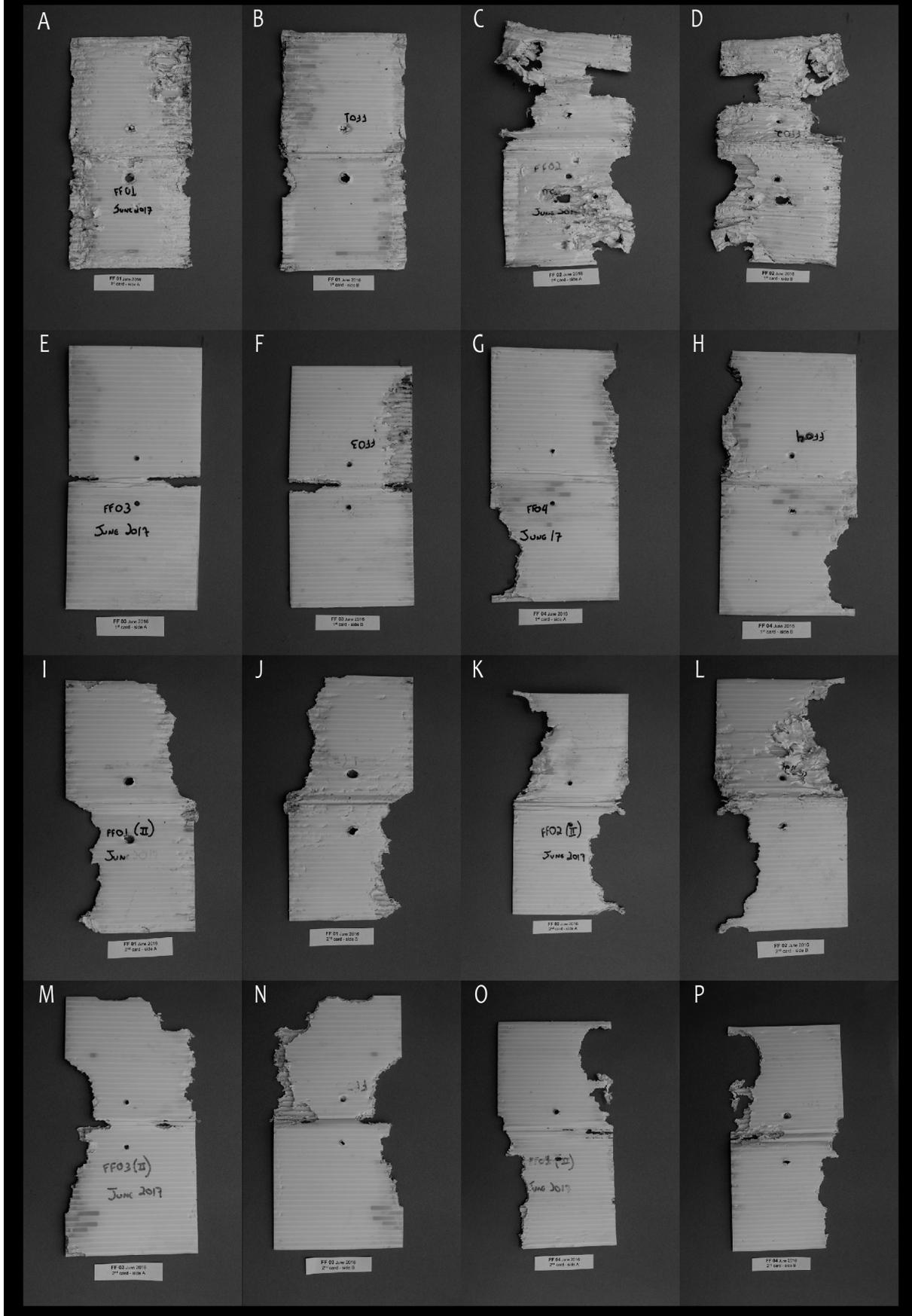


Figure 16: Chew Cards sampled during autumn season in Fairy Falls. First side of the first card fixed in the location FF01 during autumn 2017 (A); second side of the first card fixed in the location

FF01 during autumn 2017 (B); first side of the first card fixed in the location FF02 during autumn 2017 (C); second side of the first card fixed in the location FF02 during autumn 2017 (D); first side of the first card fixed in the location FF03 during autumn 2017 (E); second side of the first card fixed in the location FF03 during autumn 2017 (F); first side of the first card fixed in the location FF04 during autumn 2017 (G); second side of the first card fixed in the location FF04 during autumn 2017 (H); first side of the second card fixed in the location FF01 during autumn 2017 (I); second side of the second card fixed in the location FF01 during autumn 2017 (J); first side of the second card fixed in the location FF02 during autumn 2017 (K); second side of the second card fixed in the location FF02 during autumn 2017 (L); first side of the second card fixed in the location FF03 during autumn 2017 (M); second side of the second card fixed in the location FF03 during autumn 2017 (N); first side of the second card fixed in the location FF04 during autumn 2017 (O); second side of the second card fixed in the location FF04 during autumn 2017 (P).

DISCUSSION

The workflow used in this research was capable of detecting the main differences between two soundscapes. It has allowed identification of the main season, frequency range and time of day in which sound differed most; as well as the sound source that caused differences in the indices results from sites with different pest management levels.

The separation of indices measurements into acoustic regions that were then statistically analyzed independently has allowed us to perform efficient and targeted visual and aural scans of all the sound files with acoustic events within the acoustic region of interest. Without this prior categorization and selection, it would have been virtually impossible to scan all the sound files with acoustic events in all the acoustic regions and in both seasons.

It is important to mention that the use of other approaches that focus on acoustic regions that traditionally present more acoustic activity, such as those that encompass dawn and dusk choruses (Venier et al. 2012; Holmes, McIlwrick & Venier 2014), would not have allowed the identification of the “Mid-high frequency/ Night” as an acoustic region of interest in our data. This region does not have intensive acoustic activity in the Waitakere’s soundscape, so it would probably have been left aside in studies that focus only on acoustic regions with intense activity. This would have ignored a highly informative aspect of the soundscape.

The acoustic regions as identified and used here seem to have ecological meaning. Their frequency (kHz) and time boundaries were able to capture the most important groups of acoustic events in the soundscape. The statistical analyses have confirmed there were different patterns of variation across the different acoustic regions. Some regions presented significant differences between Ark in the Park and Fairy Falls for several indices, while other regions have not presented significant results for any indices.

Similar to the results of Towsey et al. (2018), the LDFC spectrogram facilitated the task of locating acoustic events within a large data set. The visual analysis of the LDFC spectrogram has avoided the visual and aural analysis through traditional spectrogram of every single 1440 one-minute sound files that correspond to the samplings made in autumn from 21h:00min to 23h:59min. Instead, less than 40 sound files were identified as having acoustic events of interest. After the exclusion of those that were caused by rain, 20 files remained as the ones that have been responsible for the biggest differences found on indices results, and thus worthy of more intensive visual and aural analysis.

The chew cards results confirmed that the study design was successful in selecting sites with two different levels of pest management. The decision of using chew cards was taken to confirm the presence of pests in Fairy Falls. Cards were fixed only in the locations in which the acoustic sensors were installed. Due to the small sampling effort made (32 cards in total: eight cards in each site in each season), it would be inaccurate to estimate mammals abundances in Fairy Falls or to ensure they are absent from Ark in the Park. However, from these results it is possible to confirm that the abundance profile of mammals differs between these two sites.

The identification of invasive mammal species as being the main source of differences on indices measurements between the two sites was unexpected. I expected that the greatest difference in the soundscape would be for an acoustic region capturing bird song, since increased bird abundances is a major desirable outcome for pest mammal management (Towns, West & Broome 2012; Jones et al. 2016). In fact, there are significant differences between sites during spring for the acoustic regions that capture the bird dawn chorus (Mid-high frequency/ Dawn, and Mid-low frequency/ Dawn - appendix G).

However, it does make sense that these invasive mammals do have an important direct impact on the soundscape due to their abundance and activity, resulting from a major difference in levels of pest management between the two areas. This result reinforces the importance of pest control and enlarges the range of impacts these species have on New Zealand environments, adding the direct impacts on the soundscapes to this list. It is expected that this direct impact in the soundscape will be easier to detect within acoustic regions with fewer acoustic events, such as “Mid-high frequency/ Night”.

The identification of the specific sound that is causing the main differences between the soundscape of these two areas makes the task of identifying the same sound in future studies easier. This sound profile can now be used for building automatic identification models that can help to search for it in

the same areas in the future, as well in other sites. This approach will be especially valuable for restoration projects that perform some level of pest control and require low-cost monitoring.

From a monitoring perspective, the results indicate that the “Mid-high frequency/ Night” acoustic region in autumn can be used for future soundscape monitoring. This region has shown to present significant indices differences between areas with different levels of pests’ abundance. It places this acoustic region as focus of monitoring interest for restoration projects that perform invasive mammals’ control, since it seems to change in terms of indices results when these pests are present.

It is also important to mention that the same “Mid-high frequency/ Night” acoustic region have presented different results over spring, during which only 2 of 12 indices have shown significant differences between sites. These pronounced differences in results makes this acoustic region also important for seasonal comparisons. Further research encompassing a longer time frame would be interesting to understand how each acoustic region changes in the long term, both within and between sites. It would be also interesting to test if passive acoustic sampling with no chew cards associated will indicate the “Mid-high frequency/ Night” in autumn as the acoustic region that differs most between sites.

Also, it is important to mention that in this research the acoustic indices have been used as mathematical filters that helped to identify the more important acoustic region for monitoring purposes, as well as to build Long Duration False Colour spectrogram for soundscape visualization and acoustic events identification. In this study, acoustic indices have shown to be effective. However, they were not here used as a surrogate for biodiversity. The use of acoustic indices as a biodiversity surrogate or as habitat condition indicator should be taken with caution, especially in environments known to be inhabited by invasive animal species. Invasive animal species will also contribute to the biophony as the same time that commonly have impacts on local biodiversity, which has shown to be the case of pest mammals in New Zealand. Additionally, removal of pests may increase bird abundance but result in very little change in predator-avoidance behaviour in the short term. This is a possible reason why an increase of acoustic activity may have not been detected after pest eradication.

The sound space is as a resource many animal species compete for in order to communicate (Endler 1993), and current soundscapes can be seen as a result of evolutionary processes. Through these, the different species may compete for the different frequency ranges and time periods for expressing their acoustic behavior. It is possible that some species have been excluded by competition and have

developed new adaptations regarding their acoustic activities, etc. In that perspective, more intense acoustic activity seems to be missing from the Waitakere's soundscape when looking for the acoustic regions that encompass predawn and night times (see figure 13). One possible explanation for this observation is that native species that used to exhibit acoustic behaviour within these acoustic regions are now extinct in the region.

To confirm that hypothesis, future research comparing the Ark in the Park soundscape with other New Zealand forest areas under pest management that are currently inhabited by kiwi birds (*Apteryx spp.*) and kākāpō (*Strigops habroptilus*) are necessary. The local extinction of these nocturnal birds on Waitakere can be cause of the quietness of the acoustic regions that encompass predawn and night times. Unfortunately, it is a much harder task to understand what role that moa species (*Megalapteryx didinus*, *Anomalopteryx didiformis*, *Pachyornis spp.*, *Emeus crassus*, *Euryapteryx curtus*, *Dinornis spp.*) had in the New Zealand soundscapes due to their extinction after human arrival in New Zealand.

Another possible explanation for the low acoustic activity during predawn and night times is that birds in New Zealand's main islands exhibit marked predator-avoidance behavior, such as not calling in times predators are more active. Antipredator behaviors have shown to be rapidly learned by birds (Maloney & McLean 1995; Griffin, Blumstein & Evans 2000). However, this does not explain the quietness of these acoustic regions when comparing to the same time periods in other habitats (chapter 2, figure 2).

These results support this workflow's utility for monitoring purposes. Future research about its utility for monitoring other habitats and management actions will confirm how broad this monitoring protocol can be applied.

Chapter 4. Assemblage of Focal Species Recognizers - AFSR: A technique for decreasing false positive rates of automatic identification of calls in a multiple species context

ABSTRACT

Passive acoustic monitoring (PAM) coupled with automated species identification is a promising tool for species monitoring and conservation worldwide. However, high false positive rates are still an important limitation and a crucial factor for acceptance of these techniques in wildlife surveys. Here I present the Assemblage of Focal Species Recognizers - AFSR, a novel approach for decreasing false positives and increasing models' precision in multispecies contexts. AFSR focusses on decreasing false positives by excluding unreliable sound file segments that are prone to misidentification. I used MatlabHTK, a hidden Markov models interface for bioacoustics analyses, for illustrating AFSR technique by comparing two approaches, 1) a multispecies recognizer where all species are identified simultaneously, and 2) an assemblage of focal species recognizers (AFSR), where several recognizers that each prioritise a single focal species are then summarised into a single output, according to a set of rules designed to exclude unreliable segments. Both approaches (the multispecies recognizer and AFSR) used the same sound files training dataset, but different processing workflow. I applied these recognisers to PAM recordings from a remote island colony with five seabird species and compared their outputs with manual species identifications. False positive rates and precision improved for all the five species when using AFSR achieving a remarkable 0% false positive rate and 100% precision for three of five seabird species, and < 6% false positive rates, and >90% precision for the other two species. AFSR' output was also used to generate daily calling activity patterns for each species. Instead of attempting to withdraw useful information from every fragment in a sound recording, AFSR prioritises more trustworthy information from sections with better quality data. AFSR can be applied to automated species identification from multispecies PAM recordings worldwide.

INTRODUCTION

Recent technical advances in sound-recording technologies and analyses have considerably enlarged the potential application of bioacoustics in conservation studies. Acoustic automated identification has been applied to numerous taxa including insects (Aide. et al. 2013; Zilli et al. 2014), anurans (Xie et al. 2016; Deichmann et al. 2017), bats (Andreassen, Surlykke & Hallam 2014; Newson, Evans & Gillings 2015), canids (Rocha et al. 2015; Palacios et al. 2016), birds (Sanders & Mennill 2014; Ranjard et al. 2015; Stowell, Benetos & Gill 2017; Ranjard et al. 2017), marine mammals (Putland et al. 2018) and elephants (Wrege et al. 2017). These automated techniques facilitate analysis of thousands of hours of sound files generated by a passive acoustic monitoring (PAM) approach, which could not realistically be done manually by a researcher. The integration of PAM recording with automated identification is a considerable advance that can be applied in biodiversity assessments in diverse environmental conditions and ecosystems. It can be particularly useful when species are rare, nocturnal or cryptic, or when sites are remote and have only intermittent access, e.g. seabird breeding colonies on offshore islands, which are a major conservation focus internationally (Mulder et al. 2011).

Although these methods show great potential for wildlife monitoring, limitations and uncertainties remain that discourage incorporation of these analyses into management programmes. Several researchers have identified high false positive rates (Zwart et al. 2014; Borker et al. 2014; Cragg, Burger & Piatt 2015; Rocha et al. 2015; Newson, Evans & Gillings 2015; Ranjard et al. 2017). These are typically associated with recordings involving multiple species (Jennings, Parsons & Pocock 2008), different environmental sound background (Cragg, Burger & Piatt 2015), recording quality and overlapping calls (Buxton & Jones 2012). Attempts to improve detection rates can also lead to more false positive identifications (Borker et al. 2014; Andreassen, Surlykke & Hallam 2014). Given that passive acoustic monitoring is often the only method used to monitor species and populations, a low false positive rate is crucial.

Automated identification studies commonly focus on increasing detection rates in order to maximise the number of identified target calls in a sound file. However, in PAM, the amount of sound being recorded can easily reach terabytes of data. Potamitis et al. (2014), for example, rejected 90–95% of their recordings because they did not meet their target specifications in the signal pre-processing stage. It is probably impossible to extract useful information from every single sound segment when monitoring long term. Instead, I advocate focus should be given to extracting more precise and

trustworthy information from the segments with the highest probabilities of providing a true indication of species presence. In other words, automated identification models should prioritise low false positive rates instead of high detection rates and accuracy. Otherwise, even with adequate similarity and accuracy, a high false positive rate renders automated identification useless in a PAM context. Techniques for decreasing false positives are especially important in circumstances known to generate higher false positive rates, such as studies involving multiple species, which is a common situation in natural environments.

Another important factor for the utility of automatic recognizers is “precision”, the probability that a positive indication of presence is actually correct, or a true positive. Low false positive rates can be achieved by decreasing detection rates, but decreasing detection rates can also result in decreased true positives. When the rates of true positives and false positives are similar, even if both are low, any indication of a species presence would have similar chances of being correct or incorrect, so any technique that decreases false positives must also be reliable in terms of precision.

Here I present the Assemblage of Focal Species Recognizers - AFSR, a technique for decreasing false positive rates of automated identification models for acoustic recordings made in a multiple species context. It uses MatlabHTK, a hidden Markov models interface for bioacoustics analyses (Ranjard et al. 2017). AFSR prioritises the extraction of information from more trustworthy sections of the recordings that can provide better quality data. It is a novel approach for increasing the precision of acoustic recognizers, increasing the applicability of automated identification techniques for wildlife surveys.

MATERIALS AND METHODS

4.3.1 Study site and species

Pokohinu/Burgess Island (35° 54' S, 175° 07' E) is part of the Mokohinau archipelago, located ca. 90km northeast of Auckland's east coast, in Aotearoa/New Zealand (Figure 17). The island became pest free after the eradication of the kiore or pacific rat (*Rattus exulans*) in 1990, and has since seen an increase in bird fauna (Ismar et al. 2014). I focus on the development of an automatic identification model for the calls of five Procellariiformes seabird species: *Pelecanoides urinatrix* (Kūaka, Common diving petrel), *Puffinus gavia* (Pakahā, Fluttering shearwater), *Pterodroma gouldi* (Ōi, Grey-faced

petrel), *Puffinus assimilis* (Little shearwater), and *Pelagodroma marina* (Takahikare-moana, White-faced storm petrel). These species are known to have breeding colonies at Burgess Island, although they do not co-occur at all locations on the island (Ismar et al. 2014).

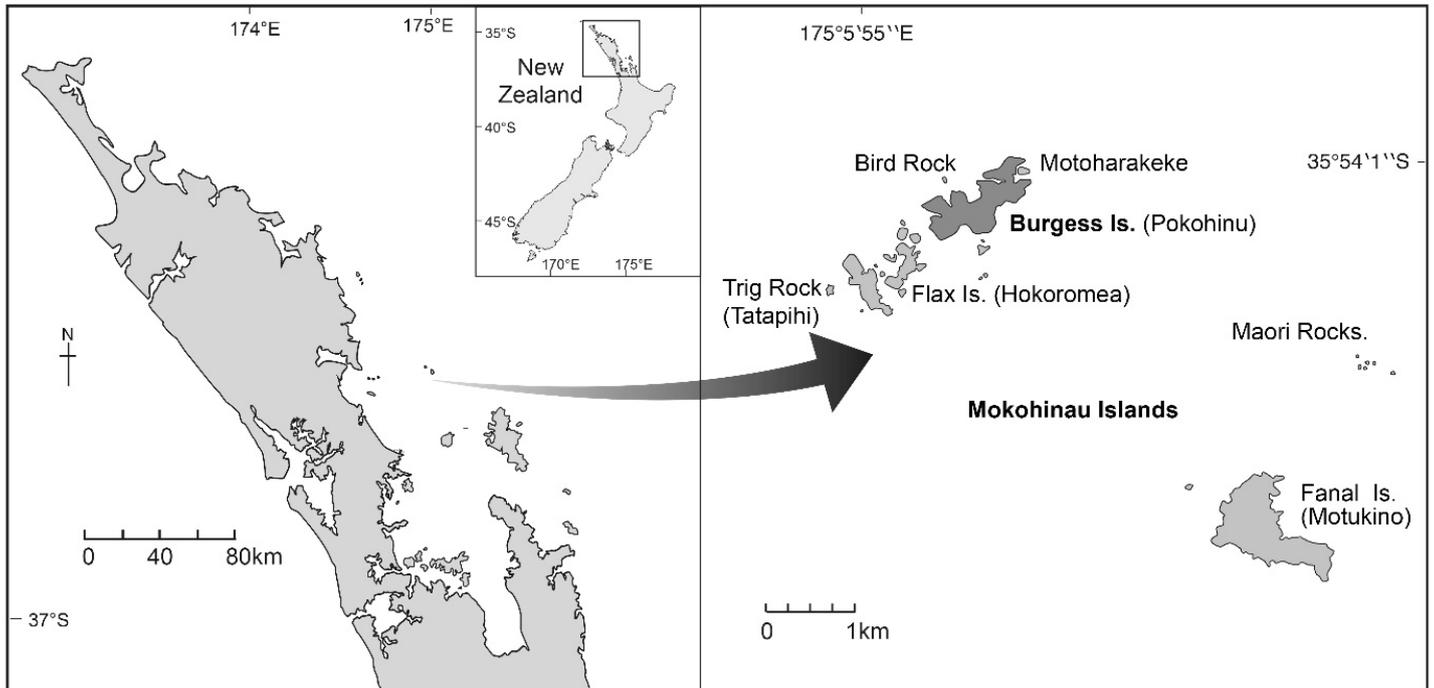


Figure 17: Pokohinu/Burgess Island, in the Mokohinau archipelago, Aotearoa/New Zealand.

4.3.2 Acoustic Recordings

I used active recordings made by researchers in the field, and PAM recordings made without researchers' presence using a pre-programmable acoustic sensor. The PAM recordings were made from 25th - 30th of September 2014, on Burgess Island (35.9057S, 175.1140E) using a sound recorder Song Meter SM2 (Wildlife Acoustics); at the sampling frequency of 44.1kHz; 32 bit resolution; from 6pm to 6am; totalling 60h of recordings. The active recordings were performed by seabird experts to obtain good examples of the birds' typical calls, with confident species identification. Active recordings of Grey-faced petrels were made from April to late May 2015 at Bethells Beach, New Zealand, using a 722 Digital Audio Recorder (Sound Devices, LLC) with a Sennheiser highly directional microphone (model K6 ME 66; Wennebostel, Wedemark, Germany). Active recordings of the other four species were made on Burgess Island in September 2014 using a FR-2 Field Recorder (Foster Electric Co., Ltd.) with an Audio Technica shotgun microphone (model AT835b) housed in a Rycote wind-kit. All files were converted to 44.1kHz and 32 bit format.

4.3.3 Building the training sound files

I built a data set of training sound files (total 179 MB) of good examples of the different species calls and their environmental background sound from sections of both the active and PAM recordings. From the active recordings, I selected and annotated calls that could be identified to species by seabird experts, and had good sound quality. I used these selected calls to create a preliminary species recogniser (see appendix G), that I then ran over the PAM recordings to fast track finding more examples of calls. All these calls extracted from the active and PAM recordings were combined into a single set of training sound files, which were then used for both our Multispecies Recogniser and our AFSR (assemblage of focal species recognizers). Even though the Multispecies Recogniser and AFSR were built from the same sound files, these files were associated with different sets of annotation text files in each approach and were processed through different workflows. An overall modelling workflow diagram is shown in the figure 18.

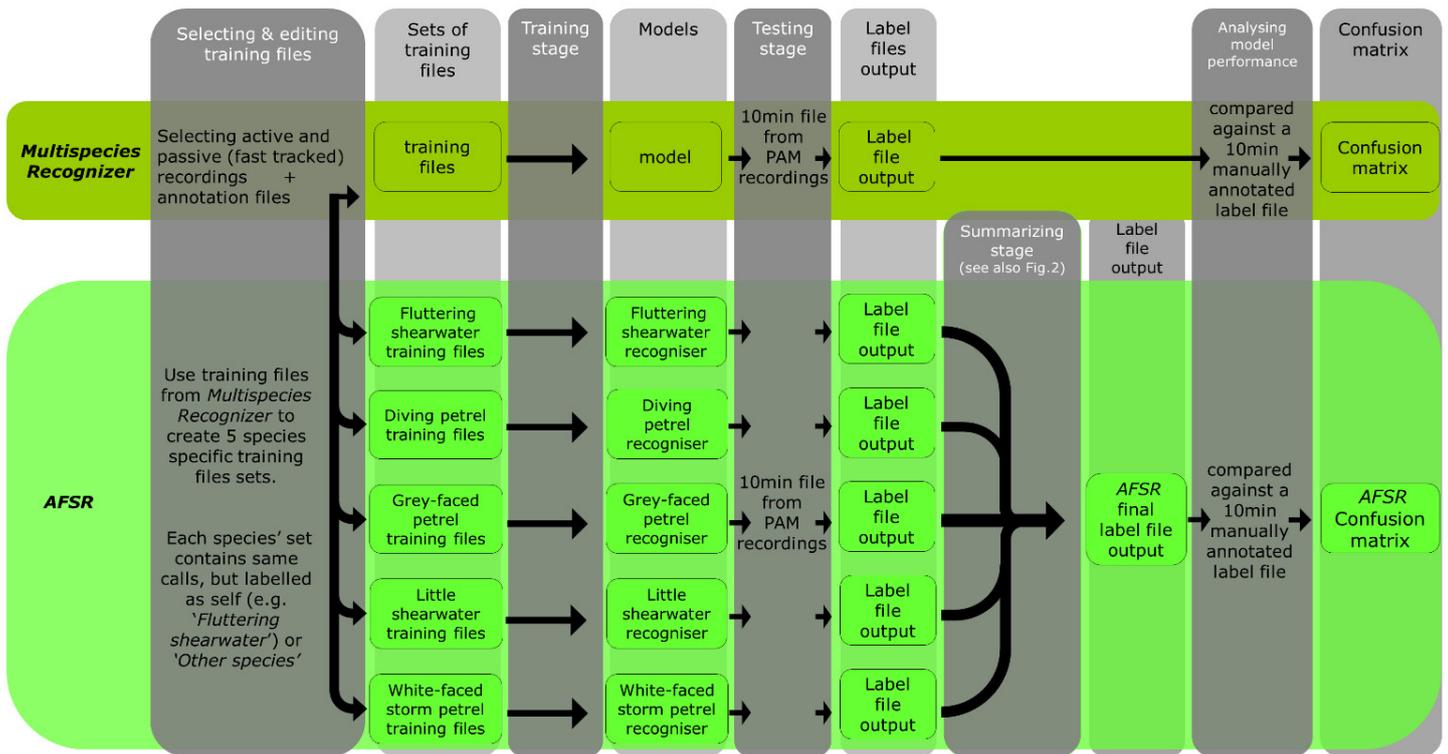


Figure 18: Modelling Workflow diagram. Each modelling approach is represented in horizontal lines. The workflow within each approach runs from left to right (columns) and the workflow from one modelling approach to the next runs from top to bottom.

1) Multispecies Recognizer

Annotation files (“label” format) were manually created using the software AUDACITY®. These annotation files assigned a category name to each sound within the data set of training sound files described above. The categories used in the Multispecies Recogniser were: *Background*; *Diving Petrel*; *Grey-faced Petrel*; *Little Shearwater*; *Fluttering Shearwater*; and *White-faced Storm Petrel*. The ‘*Background*’ category was assigned to sound fragments where there were no existing petrel calls. This recognizer followed the same processing workflow as described by Ranjard et al. (2017).

2) Assemblage of Focal Species Recognizers - AFSR

Five independent species-specific recognisers were built using exactly the same data set of sound files data set previously described. In each case the sound files were associated with different annotation text files. For example, in the Little shearwater independent recogniser, all of this species’ calls were assigned in the annotation files as ‘*Little Shearwater*’, while all the other four species’ calls were assigned as ‘*Other Species*’. This framework was applied to all the five independent recognisers, one for each of our five seabird species. According to Potamitis et al. (2014), a detection model needs to differentiate a target call from all non-target sounds, including other species’ calls and background sounds. In our system the category ‘*Other Species*’ was used in each one of the independent recognisers to help discriminate the target call from other species’ calls.

In this way, I obtained five species-specific outputs, which I then compared to detect and remove unreliable sections of the recordings prone to misidentification. I did this by creating a script named “AFSR_summarizing” (link provided in the appendix H) that applies a set of rules to summarize the independent outputs into one final annotation text file. Whenever the five recognisers disagreed about the species identification of any segment of the sound recording, the section was then labelled as ‘*Unidentified*’. Only the recording segments that showed consistent species identifications by all five independent recognisers were considered a valid indicator of species presence. The data accessibility information containing the for “AFSR_summarizing” script and the link for the MatlabHTK package are presented on the appendix H).

This processing approach, which consists of using a single sound file data set, to create and run independent recognizers and then summarize their results into a single output following a specific set of rules, I named AFSR (Assemblage of Focal Species Recognizers).

An illustration of the summarizing process is presented in the figure 19. The summarization of the five annotation text files (label format) into one follows seven rules:

1. When the five independent species-specific recognisers indicate the same category, the indicated category should be used. For example, if all five indicate “*Background*”, then “*Background*” should be used in the summarized annotation output. If all five indicate “*Other Species*”, then “*Other Species*” should be used in the summarized annotation output.
2. The “*Background*” category should be used in the summarized annotation output if it appears in at least one of the independent species-specific recognisers’ outputs. There are only two exceptions: i) when “*Background*” appears at the same time as “*Noise*”, the category “*Noise*” should be used in the summarized annotation output, or ii) if among the five recognisers annotation outputs there are four different categories indicated, the category “*Other Species*” should be used in the summarized annotation output (even when one of the four categories indicated is “*Background*”).
3. The “*Noise*” category should be used every time it appears in one of the independent species specific recognisers.
4. If two categories are indicated and one of the categories is one of the target species and the other is “*Other Species*”, use the target species category. For example, if one recogniser indicates “*Grey-faced Petrel*” and all the other four recognisers indicate “*Other Species*”, “*Grey-faced Petrel*” should be used in the summarized annotation output.
5. If three categories are indicated, the category “*Other Species*” should be used in the summarized annotation output. For example, if two of the categories indicated are target species and the other is “*Other Species*”, “*Other Species*” should be used in the summarized annotation output. The exception is when three categories are indicated and one of them is “*Background*”, then “*Background*” should be used in the summarized annotation output.
6. If four categories are indicated, “*Other Species*” should be used in the summarized annotation output.
7. After the summarizing process is completed, all fragments indicated as “*Other Species*” in the summarized annotation output should be replaced by “*Unidentified*”.

P.S. The “*Noise*” category included sounds typically produced when something touches the microphone during the sound sampling. The “*Noise*” category was not present in the models outputs, reason why it is not mentioned further.

Summarizing Independent Recognizers: *Assemblage of Focal Species Recognizers - AFSR*

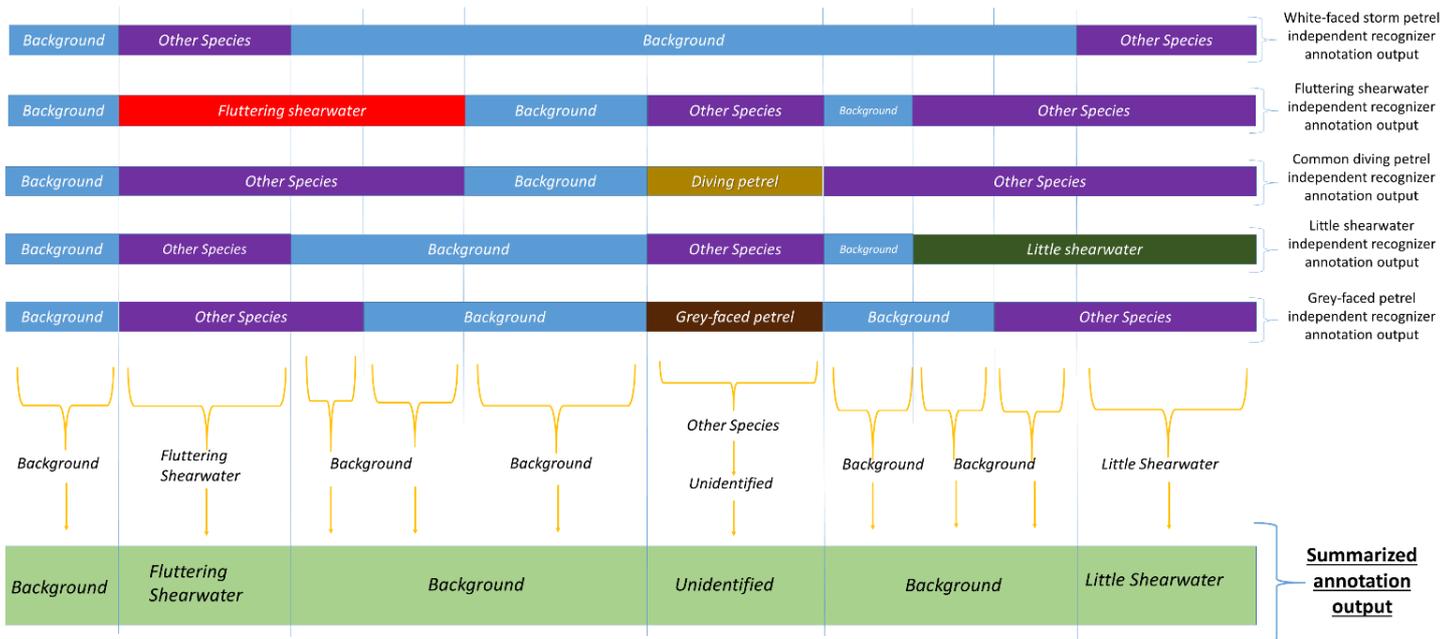


Figure 19: Illustration of the summarizing process. In this example of how AFSR converts category labels on a sound file fragment for five independent focal species recognisers into one summarized annotation based on specific rules, each of the upper horizontal lines represent one independent focal species recogniser's annotation output and the lowest horizontal line represents the final summarized annotation output.

4.3.4 MatlabHTK overview

The analyses were performed using the package MatlabHTK (Ranjard et al. 2017). MatlabHTK processes the outputs of the Hidden Markov Toolkit (HTK; (Young et al. 2006)), which was first designed for human speech analysis. In HTK, sound signal is typically represented as a sequence of parameter vectors, e.g. cepstrum coefficients, calculated for consecutive overlapping analysis windows. Hidden Markov Models (HMMs) statistically represent transitions between these windows. Therefore, HMMs are flexible and capable of dealing with variation of a given signal such as differing intensity, variations within species repertoire, diverse sound background, etc. MatlabHTK allows users to easily build and runs HTK acoustic models and to process the results.

Data analysis is typically performed in two stages; first, the HMM probabilities are estimated from training data (annotation text files + “.wav” sound files) and, second, recognition is performed on the

data (sound files only). The recognition stage outputs annotation files that indicate which categories have been identified throughout the data sound files. A detailed description about the training and the recognition stages is presented by Ranjard et al. (2017). The signal processing and statistical analyses were performed through an Octave environment (Eaton et al. 2014).

4.3.5 Analysing the Recognizers

To assess the utility of the two modelling approaches, I created a 10 minute sound file containing calls of all the five species as well as background, which were extracted from Burgess Island PAM recordings. The seabird experts in our team listened to the 10 minute file to manually assign the correct species to every bird call in the sound file. Species identifications were verified by different team members, based on their extensive experience and knowledge of wild seabird calls. Additionally to the bird species, ‘*Background*’ was also used as a category assigned to background sound.

I then ran the Multispecies Recognizer and the AFSR over this 10 min file and compared their outputs with the manual identification made by researchers. A 0.4 second time window was selected because this was the minimum length of any bird call in the training sound files (for a White-faced storm petrel call). To compare the two annotations, a similarity measure was defined: for each time window and for the two files, vectors indicating the percentage of the window’s duration assigned to each category were constructed. Then, the percentage similarity score “S” was defined as one minus the average Euclidean distance between vectors over all time windows (Ranjard et al. 2017). Let w be the window size in seconds, c the number of categories, d_1^x the duration in seconds of category x in the annotation file 1. Then, if the total number of windows is n , the similarity score between annotation file 1 and 2 is

$$S = 1 - \frac{\sum_1^n \sqrt{(\sum_{x=1}^c (d_1^x - d_2^x)^2) 2w}}{n}$$

I generated a confusion matrix tables (“.csv” format) to compare the manually annotated file with the automatically annotated files (outputs) generated by the Multispecies Recognizer and AFSR. All the similarity scores and confusion matrices were calculated using the same 0.4 second time window. Precision scores for each target species were calculated from the confusion matrix values as follows:

$$P = \frac{\text{true positives}}{(\text{true positives} + \text{false positives})}$$

In a final step, to benchmark the biological relevance of the AFSR, I ran it over the five nights of PAM recordings and used the output to generate activity pattern data showing the time periods in which our five target species were actively calling at their shared colony on Burgess Island.

RESULTS

1) Multispecies Recognizer

This recognizer achieved an overall similarity of 82% when compared with the 10 minute manually annotated file. The false positive rates for four of the petrel species were lower than 10% (Little shearwater 5%; White-faced storm petrel 2%, Fluttering shearwater 1%, Common diving petrel 9%). However, the Grey-faced petrel had a higher false positive rate (10%). The precision was higher than 90% for three species: Little shearwater (93%), Fluttering shearwater (99%) and White-faced storm petrel (98%). However, the probabilities of false positives were > 10% for the Common diving petrel and Grey-faced petrel (precision was 88% for both species) (Table 7). The confusion matrix comparing the manual identification with the Multispecies Recognizer output is presented in the appendix I.

2) Assemblage of Focal Species Recognizers - AFSR

The overall similarity score achieved by AFSR was lower than the Multispecies Recognizer (74% vs. 82%) but it considerably reduced the rates of false positives and increased precision scores for all five species (Table 7). For White-Faced storm petrels, Fluttering shearwaters and Little shearwaters, the false positive rate achieved was 0% - all the indications of presence for these three species were correctly assigned. The false positive rates were also much lower for Common diving petrels (1%) and Grey-faced petrels (5%). For all species, precision values were >90%, with a remarkable 100% for Little shearwaters, Fluttering shearwaters, and White-faced storm petrels. The confusion matrix comparing the manual identification with the AFSR output is presented in table 8. A Scatter plot of true positive rates versus false positive rates achieved by the Multispecies Recognizer and AFSR for each species is presented in the appendix J.

Table 7: Total false positive rate and Precision per species achieved by Multispecies Recognizer and AFRS

| Species | Multispecies Recognizer | | AFRS | |
|--------------------------|---------------------------|-------------|---------------------------|-------------|
| | Total false positive rate | Precision | Total false positive rate | Precision |
| Common diving petrel | <u>0.09</u> | <i>0.88</i> | <u>0.01</u> | <i>0.97</i> |
| Grey-faced petrel | <u>0.1</u> | <i>0.88</i> | <u>0.05</u> | <i>0.92</i> |
| Little shearwater | <u>0.05</u> | <i>0.93</i> | <u>0</u> | <i>1</i> |
| Fluttering shearwater | <u>0.01</u> | <i>0.99</i> | <u>0</u> | <i>1</i> |
| White-faced storm petrel | <u>0.02</u> | <i>0.98</i> | <u>0</u> | <i>1</i> |

Total false positive rates (underlined) and precision (*italic*) for each species were calculated from the values generated by confusion matrices for each model and are presented here in a scale from 0 to 1, being 1 equals to 100%.

Table 8: Confusion Matrix comparing manual species identification Versus AFRS summarized output for a 10 minute long sound file

| Manually Annotated | AFRS | | | | | | | |
|--------------------------|--------------|-------------|----------------------|--------------------|--------------------|-----------------------|--------------------------|---------------------------|
| | Unidentified | Background | Common diving petrel | Grey-faced petrel | Little shearwater | Fluttering shearwater | White-faced storm petrel | Total false positive rate |
| Background | <i>0.08</i> | <i>0.75</i> | <i>0.04</i> | <i>0.01</i> | <i>0.03</i> | <i>0.01</i> | <i>0.08</i> | <u><i>0.17</i></u> |
| Common diving petrel | <i>0.33</i> | <i>0.29</i> | <u><i>0.37</i></u> | <i>0</i> | <i>0</i> | <i>0.01</i> | <i>0</i> | <u><i>0.01</i></u> |
| Grey-faced petrel | <i>0.19</i> | <i>0.21</i> | <i>0.04</i> | <u><i>0.55</i></u> | <i>0</i> | <i>0.01</i> | <i>0</i> | <u><i>0.05</i></u> |
| Little shearwater | <i>0.26</i> | <i>0.37</i> | <i>0</i> | <i>0</i> | <u><i>0.37</i></u> | <i>0</i> | <i>0</i> | <u><i>0</i></u> |
| Fluttering shearwater | <i>0.22</i> | <i>0.22</i> | <i>0</i> | <i>0</i> | <i>0</i> | <u><i>0.56</i></u> | <i>0</i> | <u><i>0</i></u> |
| White-faced storm petrel | <i>0.25</i> | <i>0.2</i> | <i>0</i> | <i>0</i> | <i>0</i> | <i>0</i> | <u><i>0.55</i></u> | <u><i>0</i></u> |

The proportion of the time in which each category indicated at the manually annotated text file is assigned to each one of the categories at the AFRS's output text file is presented in a scale from 0 to 1 (being 1 equals to 100%) as follows: cells with *values in italic*: negative indications of presence; underlined values: true positive indication of presence, values with no special formatting: false positive indication of presence; *values underlined and italic*: total false positive rate for each one of the categories (sum of the cells with no special formatting in each line).

AFSR results provided comprehensive daily activity patterns for individual species and the colony. Grey-faced petrels are the first species to vocalize at the colony after dusk (from ~19:20 hrs), shortly followed by Common diving petrels, Fluttering shearwaters, and White-faced storm petrels (all vocalizing from around ~19:30 hrs; Figure 20). The White-faced storm petrels are the first to depart before dawn around 04:20 hrs, followed by Grey-faced petrels and Fluttering shearwaters (about 5:00 hrs), then Common diving petrels (around 5:10 hrs). The low acoustic activity of Little shearwaters prevented a specific daily activity pattern from being produced.

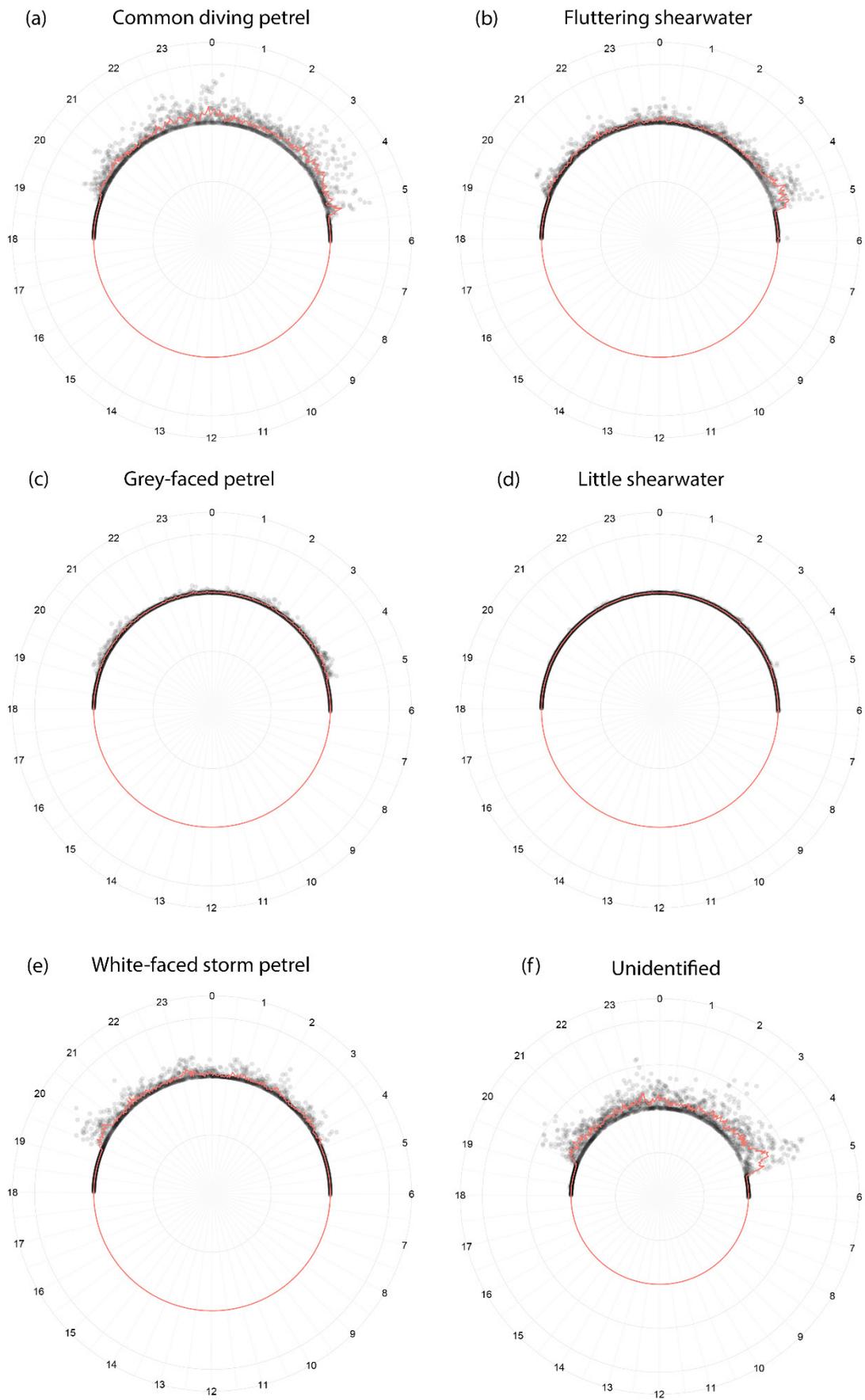


Figure 20: Daily pattern of acoustic activity identified by AFSR for the five seabird species. Common diving petrel [a]; Fluttering shearwater [b]; Grey-faced petrel [c]; Little

shearwater [d]; White-faced storm petrel [e]; and the category Unidentified [f]; all identified from PAM recordings made for 5 consecutive days. Each circle is one indication of presence using 2 minute long analysis windows. The line represents the average.

Figure 21 shows the average percentage of identification from 18:00 to 6:00 hrs for all categories combined (the five seabird species, as well as the *Unidentified* category). For the colony, the first peak of activity happens after the sunset when the birds arrive, from 19:20 to 20:30 hrs. The activity then declines but is persistent at some level through the night, with exception to the period between 23:00 and 00:00 hrs in which a moderate peak of activity occurs. The calling activity rises to the most intense level from 3:30 to 5:00 hrs, which occurs during the birds' departure. After 5:00 hrs the activity reduces, and remains low until more birds arrive following the sunset. The overall acoustic activity pattern presented at figure 21 is similar to the daily patten for calls assign to the *Unidentified* category (Figure 20- F).

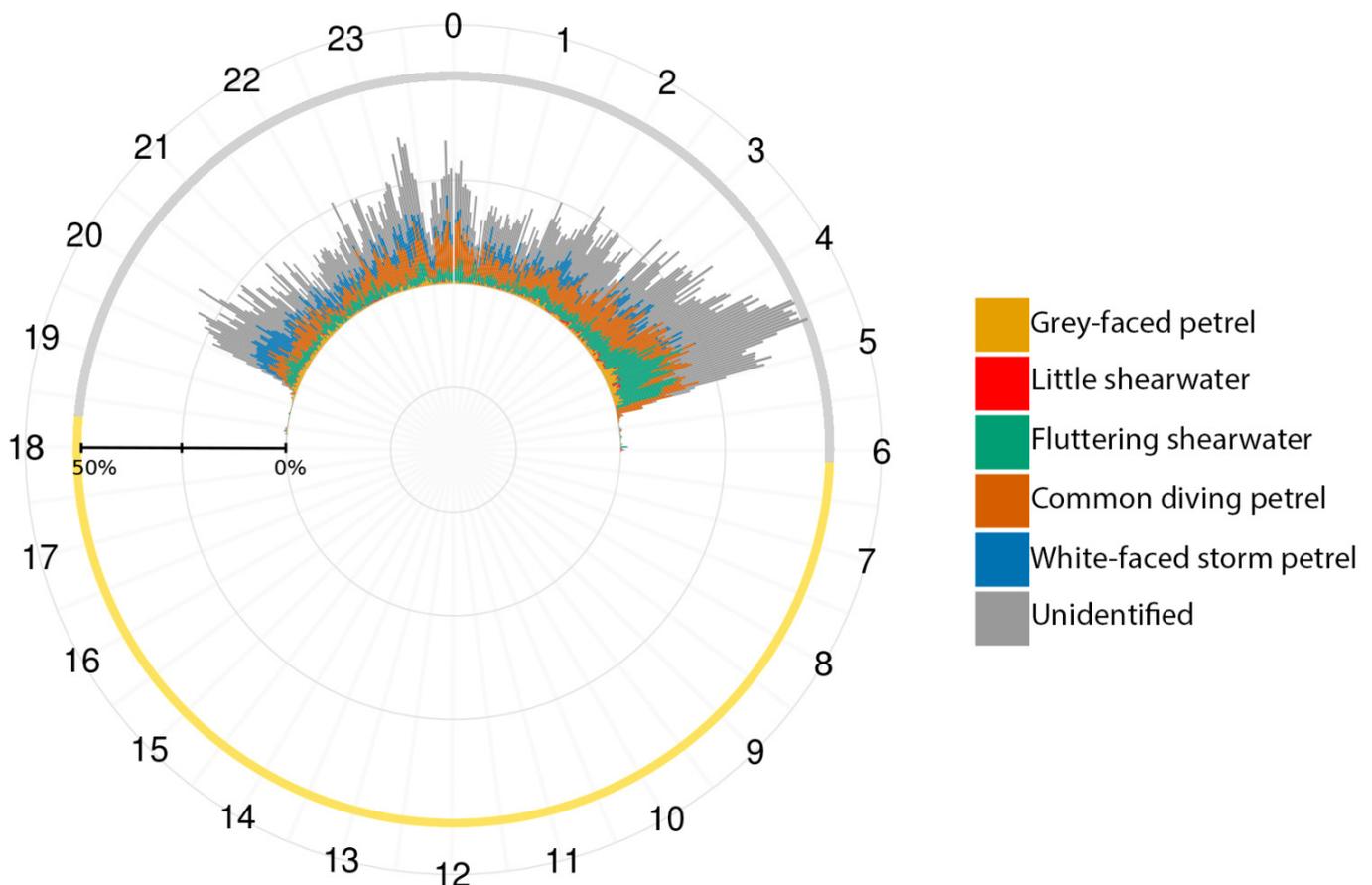


Figure 21: Colony mean daily acoustic activity for five seabird species, as well as sounds categorised as Unidentified by Assemblage of Focal Species Recognizers approach.

DISCUSSION

AFSR successfully decreased false positive rates and increased precision for all five target species in this comparative study of seabirds on an offshore island in New Zealand. Passive acoustic monitoring (PAM) recordings made in the natural settings can register complex soundscapes containing sound passages susceptible to generating misidentification. These sound passages can be a result of different individuals calling at the same time, call variations among individuals, different sound background, non-target species, among other reasons. When using the MatlabHTK interface (Ranjard et al. 2017), for every segment of sound in a testing file, only the category which best matches with the sound segment is indicated in the annotation output. The use of MatlabHTK combined with AFSR helps to significantly reduce false positives. The false positive and precision improvements achieved by AFSR are a result of the identification of the problematic sound fragments and their assignment to a new category (“*Unidentified*”), avoiding potentially incorrect indications of presence.

In order to prioritize reduced false positives and increased precision I accepted an overall decrease in similarity. As a consequence, I assumed I would have an increased level of false negatives. However, a relatively high false negative rate is not necessarily a problem for PAM. The three main sources of sound in a soundscape are biophony (sound produced by biological organisms); geophony (non-biological sound); and anthropony (human-induced noise) (Gage, Napoletano & Cooper 2001). While geophony and anthropony are irrelevant for biodiversity monitoring, a portion of the biophony present in passive acoustic recordings is also not useful due to calls overlapping, signal masking, and other phenomena, which can produce poor quality sound segments. In general, when applying automatic identification to PAM recordings I should target sound segments with reliable and relevant information and leave poor quality remaining passages out of the analyses.

The use of AFSR is especially appropriate for multispecies monitoring at roosting and breeding colonies where the acoustic activity can be very intensive in some hours of the night, but absent at other times. This intense acoustic activity produces overlapping calls which makes their correct identification very difficult for conventional recognizer approaches and increases the chances of misidentification.

The biological relevancy of AFSR results is supported by the successful indication of presence of all the five species’ calls in our PAM recordings from Burgess Island. The activity patterns generated from the indications of presence confirm direct observations of these seabirds at natural colonies. The

first and last peaks of activity (Figure 20) match the general pattern for petrels, with increased vocal activity just after sunset when birds arrive at the colony and before sunrise when they depart (Warham 1990; Landers, Bannock & Hauber 2011). The first Grey-faced petrels' calls recorded from around one hour after sunset, agrees with Ross and Brunton's (2002) data on arrival time at the colonies. The overall vocal activity pattern found for Common diving petrels is consistent with that reported by Ranjard et al. (2017). To our knowledge, there is no information about the daily activity pattern of the other studied species that I can use to compare to our automatically generated activity patterns. The low calling activity detected for Little shearwaters may be a consequence of a relatively smaller population size in comparison to the other four species at our fieldsite. Further studies are necessary to confirm this hypothesis.

It is important to highlight that the activity pattern of calls assigned to the *Unidentified* category (Figure 20 [f]) follows the overall acoustic activity pattern (Figure 21). This confirms our assumption that when more birds are calling, there is a higher chance of recording overlapping calls, and hence more misidentifications and false positives. These coincident patterns show our AFSR approach was effective in categorising calls that are problematic to identify and thus they were assigned to the *Unidentified* category. In this way, it reduces the false positives. Nevertheless, all the seabird species were detected by AFSR in this study, emphasising the success of this approach and its utility for multispecies monitoring.

Numerous islands in New Zealand have become pest free environments as a consequence of the elimination of invasive mammals which reduce or eliminate native bird's populations (Howald et al. 2007). Following pest eradication, many seabird re-establish breeding colonies on islands (Bellingham et al. 2010). PAM associated with the AFSR model used in this paper can be an important tool for detecting and monitoring the process of the re-establishment of seabird breeding colonies in New Zealand islands and South Pacific region. However, the methods described here are likely to have broader applicability to any situation where multiple species with acoustic activity are being monitored to determine occupancy.

The use of AFSR also allows the addition of more species into a multiple species analysis. The same set of rules used for summarizing the annotations from the five independent models can be extended depending on the number of focal taxa. It makes AFSR suitable for being applied to multiple species from different animal communities and diverse ecosystems monitored by a passive acoustic monitoring approach around the world.

Chapter 5. Synthesis

This thesis explored the application of passive acoustic sampling for biodiversity monitoring in three situations: i) effects of general park management and human activities in a protected natural area in Brazil (Chapter 2); ii) contrasting management for predator control (Chapter 3), and iii) seabird colonisation assessment following island restoration (Chapter 4), both in New Zealand. Overall, the results presented support the use of passive acoustic sampling, supplemented with automated identification analysis and acoustic indices calculations for biodiversity monitoring in protected natural areas and conservation management programmes.

In addition to confirming the utility of acoustic techniques for monitoring, the analytical methods presented here provide improvements that increase the effectiveness of acoustic techniques for monitoring real management situations. This has been shown particularly in relation to human land use impacts in protected areas, effectiveness of predator control management programmes, and surveying of multispecies sea bird colonies on, all of which address major conservation issues worldwide such as invasive species and habitat loss.

In the following, I review the research results (Chapters 2 – 4) in relation to the primary questions presented at the first chapter.

1) Can passive acoustic sampling coupled with acoustic indices analysis assist in monitoring the biodiversity outcomes associated with different management levels?

Passive acoustic monitoring associated with acoustic indices has shown to be able to detect biodiversity outcomes related to different management levels. In chapters 2 and 3, twelve acoustic indices (ACI, ENT, EVN, CVR, PMN, SPT, BGN, RHZ, RVT, RPS, RNG and R3D) were applied over PAM recordings (see indices description in Table 2, chapter 3). In chapter 2, these techniques have been able to detect soundscape differences related to the different land use inside the protected area and outside of it. The soundscape outside the park is strongly influenced by human activity - domestic animals and anthrophony are rare in the park

soundscape, but very common outside it in the farmland environment (Figure 9, chapter 2). Chapter 3 shows that these techniques are able to detect soundscape differences associated with two different levels of pest management (Table 4, chapter 3). The differences in indices results between sites was found to be due to the activity of invasive mammals in the area with no pest control (Figures 15 and 16, chapter 3). In both chapters, the differences between sites were first detected by statistical analysis of indices measurements, and then examined in more detail. These results support the utility of acoustic indices for detecting and monitoring biodiversity outcomes associated with different management levels.

2) Are acoustic indices effective in identifying seasons and acoustic regions (frequency range and time period) of relevance for biodiversity monitoring interest?

The use of acoustic indices was found to be effective to identify the acoustic regions of relevance for monitoring. In chapter 2, the panel 6 (05:30 to 09 am and a range of 0.988-3.609 kHz) in autumn was indicated as the region in which the acoustic indices have differed most between inside and outside the park (Figures 5, 6 and 7). This panel presented the highest number of significant differences between indices results, as well as appeared more times at the top with the biggest ratio for each one of the twelve indices calculated (which means the differences between indices measurements from the two sites were bigger in this panel – see Table 1). In chapter 3, the acoustic region “*Mid-high frequency/ Night*” (21:00 to 23:59 and a range of 0.988-3.609 kHz) also in autumn was the one that differed most between sites (Figure 13). This acoustic region had significant results for 11 of the 12 indices, and presented the highest ratios for 8 of these indices (Table 4). These acoustic regions are the ones that had the more marked responses to the management applied in each case, differing most between sites.

The identification of these priority frequency ranges and time periods now allows more targeted analyses of the acoustic data, and optimisation of future research at those sites. From my research, each of these two acoustic regions are now considered as being of biodiversity monitoring interest in each site, since they have shown to better represent the differences in acoustic activity related to different management levels in each habitat. For example, panel 6 in autumn can be used for detecting and monitoring the transformation of natural habitats into rural and urban areas, which is a result of increasing anthropic pressure upon natural

ecosystems and source of main environmental concerns in the region. It can also be used for monitoring a possible increment in the activity of domestic animals inside the Serra do Cipó national park due to the proximity of the farming activities. In New Zealand forests, the “*Mid-high frequency/Night*” acoustic region can be used for monitoring the success of pest control management and for detecting mammal re-incursions into areas from which they had previously been eradicated.

3) Does visualization of acoustic indices measurements facilitate analyses of very large data sets and identification of the sounds that underlie biologically meaningful differences in indices results?

The use of long duration false colour (LDFC) spectrograms was found to facilitate the process of navigating very large data sets and identifying acoustic events of interest.

Each LDFC spectrograms (examples: Figures 2 and 13) used in chapters 2 and 3 illustrate one day of recordings, resulting in the representation of three indices results for 144 one-minute soundfile each (sampling scheme of 1/10 minutes recording). These are a colour coded representation of indices measurements whereby the ACI is red, ENT is green and EVN is blue (Towsey, Truskinger & Roe 2015). These three indices are sensitive to different aspects of the sound signal (Table 2 – chapter 3), making them complementary to each other and thus providing coverage of a range of soundscape elements (Towsey 2017). The LDFC spectrograms were generated as described by Towsey et al. (2014). In total 442 LDFD spectrograms were generated (282 for chapter 2 and 160 for chapter 3). Each single figure is a visual representation of 110,592 independent indices measurements (one measurement for each of the 256 frequency bins per minute -144 minutes recorded per day- for each of the 3 different indices).

In chapter 2, the examination of 65 LDFC spectrograms resulted in the selection of 865 (from 1365) sound files with acoustic events within the range of Panel 6. Only 11 of 865 ($\approx 1.3\%$) sound files aurally and visually scanned had none of the sonotypes detected. The use of a visual examination of 65 LDFC spectrograms has avoided a detailed aural and visual analysis of at least 500 sound files with no acoustic events detected. In chapter 3, the visual analysis

of 80 LDFC spectrogram has avoided the aural and visual analysis of over 1400 sound files. From 1440 sound files that correspond to the samplings made in autumn from 21h:00min to 23h:59min, only 40 (3%) of them were selected as having significant acoustic events. These results confirm the utility of LDFC spectrograms for large data sets analysis and identification of acoustic events of interest, consistent with the findings of Towsey et al. (2018).

It is important to note that LDFC spectrograms can also be generated with other time scales, for example monthly or yearly (Towsey et al. 2014). In my study, daily spectrograms are used because they facilitated distinguishing files with acoustic events from the 140 files recorded by each acoustic sensor per day.

My study also found that the use of cosine similarity heat maps was useful for detecting data inconsistency in a large data set. Cosine similarity has been used for the visual representation of similarities within big data sets in a wide range of disciplines (Murray, Renals & Carletta 2005; Muflikhah & Baharudin 2009; Van Dongen & Enright 2012; Sejal et al. 2016). It was used here to identify one day with missing data, which was then excluded from the analysis. However, no useful ecological information could be extracted from the figure at the scale used here, in which one figure represents the average similarity existing within the entire data set of 10,432,512 measurements for a single index (figure 10- Chapter 2). Cosine similarity heat maps were only used in chapter 2 because it has the largest data set of all the data chapters, since PAM recordings were performed over four seasons, compared with only two seasons in chapter 3. Chapter 4 analyses did not involve acoustic indices calculations and had the smaller data set among data chapters.

4) Are acoustic automatic species identification techniques sensitive to changes in species composition and variation in relative temporal abundance?

The results presented in chapter 4 investigating sea bird re-colonization of a recent predator-free island showed that acoustic automated species identification techniques are sensitive to changes in species composition and variation in relative temporal abundance. The assemblage of focal species recognizer (AFSR) proposed here was able to decrease false positive rates and improve precision for five sea bird species studied, achieving remarkable 0% false

positives and 100% precision for three species (White-Faced storm petrel, Fluttering shearwater and Little shearwater), and < 6% false positive rates, and >90% precision for the other two species (Common diving petrel and Grey-faced petrel).

The AFSR outputs were also used to generate daily calling activity patterns for each species, illustrating relative acoustic temporal abundance among species. The activity patterns generated from the indications of presence confirm direct observations of these seabirds at natural colonies. The first and last peaks of activity (Figure 20) match the general pattern for petrels, with increased vocal activity just after sunset when birds arrive at the colony and before sunrise when they depart (Warham 1990; Landers, Bannock & Hauber 2011). The first Grey-faced petrels' calls recorded from around one hour after sunset, agrees with Ross and Brunton's (2002) data on arrival time at the colonies. The overall vocal activity pattern found for Common diving petrels is consistent with that reported by Ranjard et al. (2017). To our knowledge, there is no information about the daily activity pattern of the other species studied. These results highlight that passive acoustic monitoring on remote islands for important conservation species is an efficient and effective method for analysing species presence, and able to provide some activity and behavioural data.

Methodological advances

The analytical advances presented in this thesis overcome several of the existing technical challenges in automated identification as well as the use of acoustic indices for monitoring purposes. When using automated identification, high false positive rates are a constant challenge (Borker et al. 2014; Zwart et al. 2014; Cragg, Burger & Piatt 2015; Newson, Evans & Gillings 2015; Rocha et al. 2015; Ranjard et al. 2017). This limits the use of acoustic automated identification for wildlife monitoring. Instead of aiming to extract useful information from every single sound segment, AFSR prioritises the extraction of information from more trustworthy sections of the recordings that can provide better quality data. In this way, AFSR is capable of increasing the precision and decreasing false positive rates of acoustic recognizers, increasing the applicability of automated identification techniques for wildlife surveys.

Studies describing soundscapes based on acoustic indices measurements generally attempt to relate indices measurements to specific biodiversity features such habitat condition (Sueur et al. 2008;

Fuller et al. 2015), vegetation structure (Farina & Pieretti 2014; Pieretti et al. 2015) and the composition of the acoustic community (Tucker et al. 2014; Towsey et al. 2014; Phillips, Towsey & Roe 2018). However, currently no studies are seeking to use acoustic indices to aid the identification of the acoustic regions of monitoring interest. This thesis contributes to addressing this gap, providing a workflow that has shown to be effective in different habitats and different land use realities and management contexts. Here, instead of trying to describe the biodiversity features to which each acoustic index is associated, I instead use these indices measurements as mathematical filters to compare soundscapes and identify the acoustic regions that vary most between sites. This was done irrespective of the biodiversity feature to which each index was associated. The description of the sounds that are causing differences within indices results is a further step that involves aural and visual scanning of files that have been indicated to have acoustic events, following a visual analysis of long duration false colour spectrogram. This analytical approach has contributed towards avoiding the use of acoustic indices as biodiversity surrogates, which has already shown to be problematic in some soundscapes (Fuller et al. 2015; Mammides et al. 2017; Eldridge et al. 2018). It also avoids biased analysis of animal groups that are assumed to respond to management actions (for example birds on Chapter 3). I do acknowledge that monitoring specific animal groups can be crucial for conservation programmes focusing iconic and endangered species, for monitoring reintroduction success, population studies, etc. However, monitoring protocols with no predefined target taxa are important for revealing unpredicted outcomes that can result from management actions, such as the monitoring workflow performed in chapters 2 and 3 (Figure 12).

Additional findings

Results presented in chapters 2 and 3 show that environments with higher human impacts have higher overall acoustic energy. This pattern was detected by the majority of the acoustic indices (Tables 1 and 4; and Figures 4, 5, 6, 7 and 14). As ecologists, we frequently assume that higher acoustic energy (more sound) is invariably associated with improved biodiversity status. However, this may not be always the case, and especially not when dealing with invasive animal species and domestic animals that are common in rural environments.

My results also indicate that maximum acoustic discrimination between management outcomes often occurs when overall acoustic activity is low. For example, in the Serra do Cipó region (Brazilian data, chapter 2) and Waitakere regions (New Zealand, chapter 3) autumn was found to be the most

important season for monitoring. This was the season with overall lower acoustic activity. One possible explanation for this is that when the communities achieve their lowest acoustic activity, a small increment of activity in one site can be more readily detected due to contrast in indices results. Further research involving other habitats will show if this is a consistent pattern.

An interesting discovery was the unexpectedly low acoustic activity in the mammal-controlled Ark in the Park site (chapter 3) during predawn and night periods (Figure 13). It is generally predicted that acoustic signallers in a community will partition acoustic regions (e.g frequencies and time) to increase communication efficacy (Krause 1993). This seems to occur in my Brazilian study site (Figure 2), but not my New Zealand site (Figure 22). This low acoustic activity in the New Zealand site may reflect the loss of avifauna in Ark in the Park that are known to be nocturnal such as kiwi (*Apteryx sp.*) and kākāpō (*Strigops habroptilus*). Further research comparing the predawn and night soundscapes in different New Zealand forests with the presence of kiwis and kākāpō will answer if the nocturnal silence of Ark in the park is a consequence of these local extinctions.

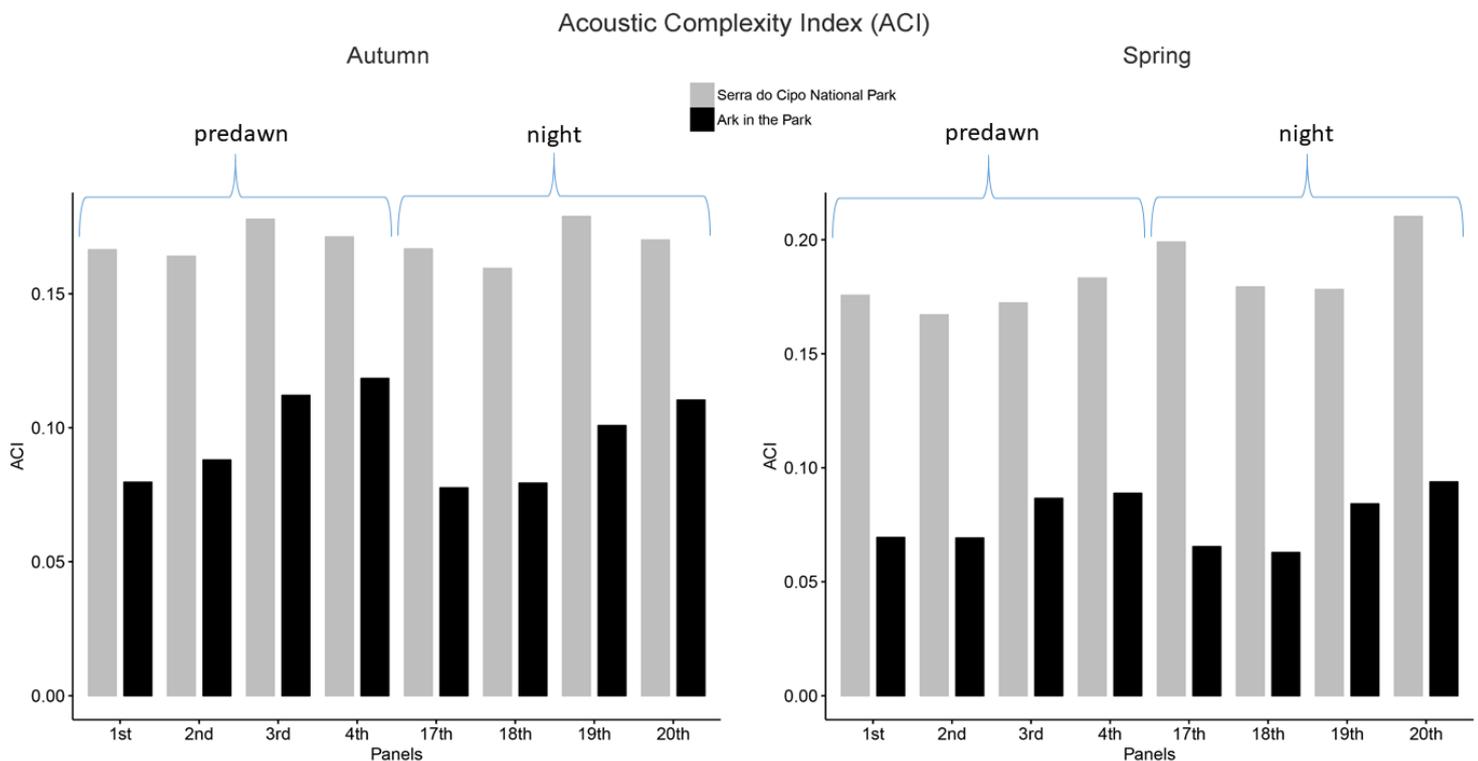


Figure 22: ACI results in spring and autumn for all the acoustic regions encompassed within predawn and night times in Ark in the Park and in Serra do Cipó national park illustrating the relatively low acoustic activity at the New Zealand site

Using PAM and standardized analyses to avoid human bias

Acoustic analyses often involve human bias. Human observers are known to be an important source of biases in traditional avian point count monitoring (Simons et al. 2009). This bias is hard to control because it is related to the way humans hear. When people make an intentional effort to listen to sounds, we notice sounds we were unaware of prior to paying attention. Sounds emitted by vehicles, constructions sites, machines, neighbours, children playing or crying faraway, water drops from a shower or a sink, and a wide variety of other sounds may be within our acoustic reach, but generally ignored. This happens because humans learn to filter acoustic information to extract the sounds that are more familiar or important (Schafer 1993). As a result, each person has singular hearing abilities, which reflects inevitable bias in acoustic analyses. Standardized sampling protocols, statistical analyses and observer training may contribute for decreasing the observer bias, but will add costs and limit a broad applicability of standardized methods, since observer training focus in specific acoustic communities and their typical sounds. Accurate and objective analyses of acoustic information require methods that combat human acoustic biases.

One of the main advantages of using PAM sampling and automated analyses to interpret complex soundscapes is the possibility of a more efficient data processing workflow and reduced impact of human biases on collecting and assessing biophony data. Acoustic sensors record air pressure variations in a given sampling rate, irrespective of observer intention or experience. For example, in my study, the acoustic sensors record sounds, and then indices extract standardised measurements from sound files recorded in both the Brazilian Cerrado and in the New Zealand Waitakere forest in the same way. All three data chapters show how these standardised sound sampling and indices or automated recognizer techniques can then be used to filter the soundscape into target and non-target sounds, in an objective manner. For example, statistical analysis have indicated acoustic regions of monitoring interest in Chapters 2 and 3, and the automated recognizer presented in chapter 4 was highly effective at identifying seabird species. However, as my studies show, there are still considerable challenges in filtering the biophony emitted by domestic or invasive species from the biophony of native species. This difficult task is impossible when using the currently available indices. Nevertheless, acoustic indices have shown to be helpful tools for understanding the acoustic energy patterns in a soundscape and their use as filters help to eliminate the observer bias and allow the replicable study of varied acoustic communities worldwide. The more complementary indices are used, the larger our capacity to identifying these patterns.

Additionally, acoustic monitoring commonly focuses on focal species (Sugai et al. 2018) that are expected to respond to the management that is being applied. However, management outputs can emerge from unexpected or non-focal taxa, and from different temporal and spatial scales. To address that, instead of looking for the regions in which birds typically present more intense acoustic activity, I have first identified the acoustic region that differs most between sites and only then the sounds that generated the differences on indices measurements were described. This approach has allowed me to find the unpredicted results that indices values were highly responsive to the acoustic activity of invasive (Waitakere region, New Zealand) or domestic animals (Serra do Cipó region, Brazil). These results were different to my predictions that management practices would result in higher indices values, due to an increase in birdsong (chapters 2 and 3), and highlights the importance of monitoring protocols that are irrespective to species identity. Also, it is practically impossible to identify all the acoustically active species when working in highly diverse biomes (Duarte et al. 2015). Taking birds as an example, countries like Colombia, Peru, Brazil, Ecuador and Indonesia are inhabited by more than 1,500 species each and the species richness can reach over 700 species in some locations (Newton 2003). Using acoustic indices as filters can help to avoid a biased predefinition of focal species to monitor, aid to study highly diverse soundscapes and assist the identification of the acoustic regions that clearly reflect the outcome of management irrespective to taxa identity.

It is also noteworthy that the general responses of acoustic indices to different taxa remains largely unknown (Gasc et al. 2013; Lellouch et al. 2014). Moreover, there is little consensus whether acoustic indices relationships with other biodiversity features are generalizable (Machado, Aguiar & Jones 2017; Browning et al. 2017). This suggests that using acoustic indices as a surrogate for biodiversity should be approached with caution. However, for monitoring purposes acoustic indices can be used as filters that help to identify what sounds are resulting in different indices measurements between sites and across time.

Limitations

This research focussed on testing and improving PAM analysis for protected areas and management monitoring. In chapters 2 and 3 I show that this approach is effective for detecting existing soundscape differences. However, ecological generalizations cannot be made based on these results. In order to study the overall patterns and trends of soundscapes inside and outside protected areas, a different sampling design including different parks is necessary. Similarly, to study the overall states and trends

of soundscapes in areas with different levels of pest management requires sampling in several sites with high and low levels of management.

The AFSR was found to be effective in decreasing false positive rates of acoustic automated identification. The AFSR is tested here with 5 species. At the current stage, it is unlikely that AFSR will work satisfactorily with hundreds of species. Countries like Colombia, Peru, Brazil, Ecuador and Indonesia are inhabited by more than 1,500 bird species each and the species richness can reach over 700 species in some locations (Newton 2003). Duarte et al. (2015) argues that it is practically impossible to identify all the acoustically active species when working in highly diverse biomes. Because of the existing technical bottleneck of using automated identification analysis in acoustic communities with hundreds of species, the soundscape approach is highly recommended for the study of extremely diverse habitats.

In this study, analyses approaches were tested at the same time as they were created. As consequence, I cannot provide a detailed assessment of the time taken for each analysis method. For a detailed time assessment, the workflow used in chapters 2 and 3 will need to be tested over a different PAM data set. However, it is important to highlight that the number of files with acoustic events within the acoustic region of interest varies among datasets, which makes it difficult to offer a conclusive pre-set time assessment. Similarly, the time required for building the recognizers for each species will vary with the species' vocabulary, the recordings availability and the modelling approach. Building recognizers for each species is a necessary previous step for the use of AFSR (appendix G). Therefore, even if a better time assessment for the analyses presented here can be provided, these will not be definitive since it will vary with the study.

The storage and analysis of the large amount of files generated by the acoustic approach is an important technical limitation for the use of PAM. In this study, I used an allocated memory in a virtual machine hosted at the University of Auckland as well as external hard drives as data storage options. Cloud storage options currently seems to be a cost-effective solution that brings the additional advantage of facilitated data sharing. Long term protected areas or conservation programs acoustic monitoring will need to account for this important technical obstacle.

Future research

The application of the assemblage of focal species recognizer (AFSR) presented in chapter 4 over recordings made in other New Zealand from offshore islands can now be tested by environmental agencies and conservation groups to understand the reproductive dynamics and relative abundances of these five sea bird species in the region. Also, the AFSR modelling approach can be adapted to and performed in other acoustic communities of monitoring interest, which will confirm its applicability to different habitat and focal species.

Future research will help to understand how soundscapes vary across different habitats. Comparisons between sites and across time in different habitat will also confirm if the acoustic regions defined in this thesis are able to capture the main acoustic activity in other acoustic communities associated with protected natural areas. Testing alternative acoustic regions frequency and time definitions could also confirm the ecological meaning of the current acoustic regions or improve their boundaries.

Additionally, it would be interesting to explore acoustic regions beyond the one that differed most between Ark in the Park and Fairy Falls. The pairwise comparisons indicate significant differences in the acoustic regions related to bird down chorus during spring (Mid-high frequency/ Dawn, and Mid-low frequency/ Dawn - appendix E). Aural and visual analysis of the sound files regarding these acoustic regions can help to understand if the pest control management is contributing to the recovery of bird populations in Ark in the Park.

Conclusion

Passive acoustic sampling has multiple benefits for biodiversity assessments. The technique can record broad temporal and spatial scales, reduce observer bias, have less impact on animal behaviour, allow different acoustic analysis, long-term files storage (Depraetere et al. 2012; Sueur et al. 2012; Sugai et al. 2018) and have a better cost-benefit relation when compared to traditional surveys (Ribeiro, Sugai & Campos-Cerqueira 2017; Wrege et al. 2017). These features encourage the use of sound sampling in ecological, behavioural and conservation studies (Sueur & Farina 2015; Ribeiro, Sugai & Campos-Cerqueira 2017; Wrege et al. 2017). PAM sampling is also able to capture varied

taxa information over broad time and spatial scales, which is essential to improve biodiversity monitoring (Schmeller et al. 2017).

This thesis confirms that PAM sampling associated with automated identification and acoustic indices are able to represent condition and detect trends in acoustic communities, which are the main focus of monitoring programmes (Lee, McGlone & Wright 2005). PAM is able to provide information on acoustic community composition and dynamics, affording useful information for protected areas managements and conservation programmes.

Besides confirming the efficacy of acoustic techniques for biodiversity monitoring, this thesis provides two main contributions to the research field.

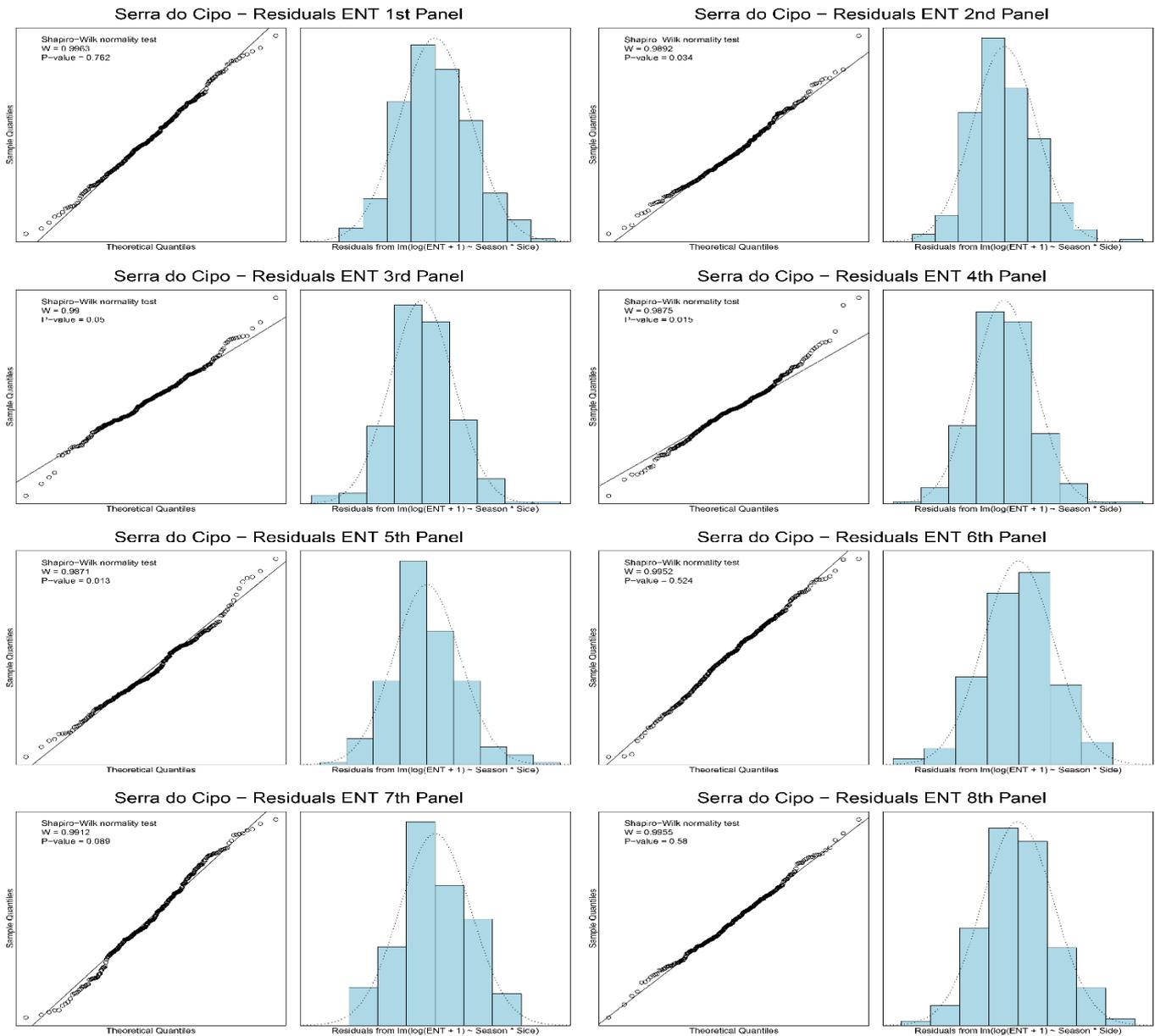
First, when using acoustic indices analysis, it identifies a workflow scheme that includes independent statistical analysis within each one of the acoustic regions here defined (chapters 2 and 3). This allows the identification of the main differences between soundscapes from two sites, enabling the identification of the acoustic regions of higher monitoring interest. Here acoustic indices are used as mathematical filters allowing the identification of acoustic regions of monitoring interest instead of as biodiversity indicator. The same analytical workflow can also be used for comparing a single site across time. Therefore, this approach is potentially suitable for monitoring different habitats worldwide, irrespective to the acoustic community and management regimes.

Second, the assemblage of focal species recognizer (AFSR) proposed in chapter 4 has shown to increase the utility of automated identification techniques by decreasing false positive rates and improving precision. This way, AFSR is able to provide more trustworthy indications of a species presence, which enlarges the utility of PAM associated with automated identification for wildlife monitoring worldwide. Both analysis, automated identification of focal species and soundscape analysis using acoustic indices, can be performed over the same PAM recordings which expands the utility of acoustic techniques for biodiversity monitoring.

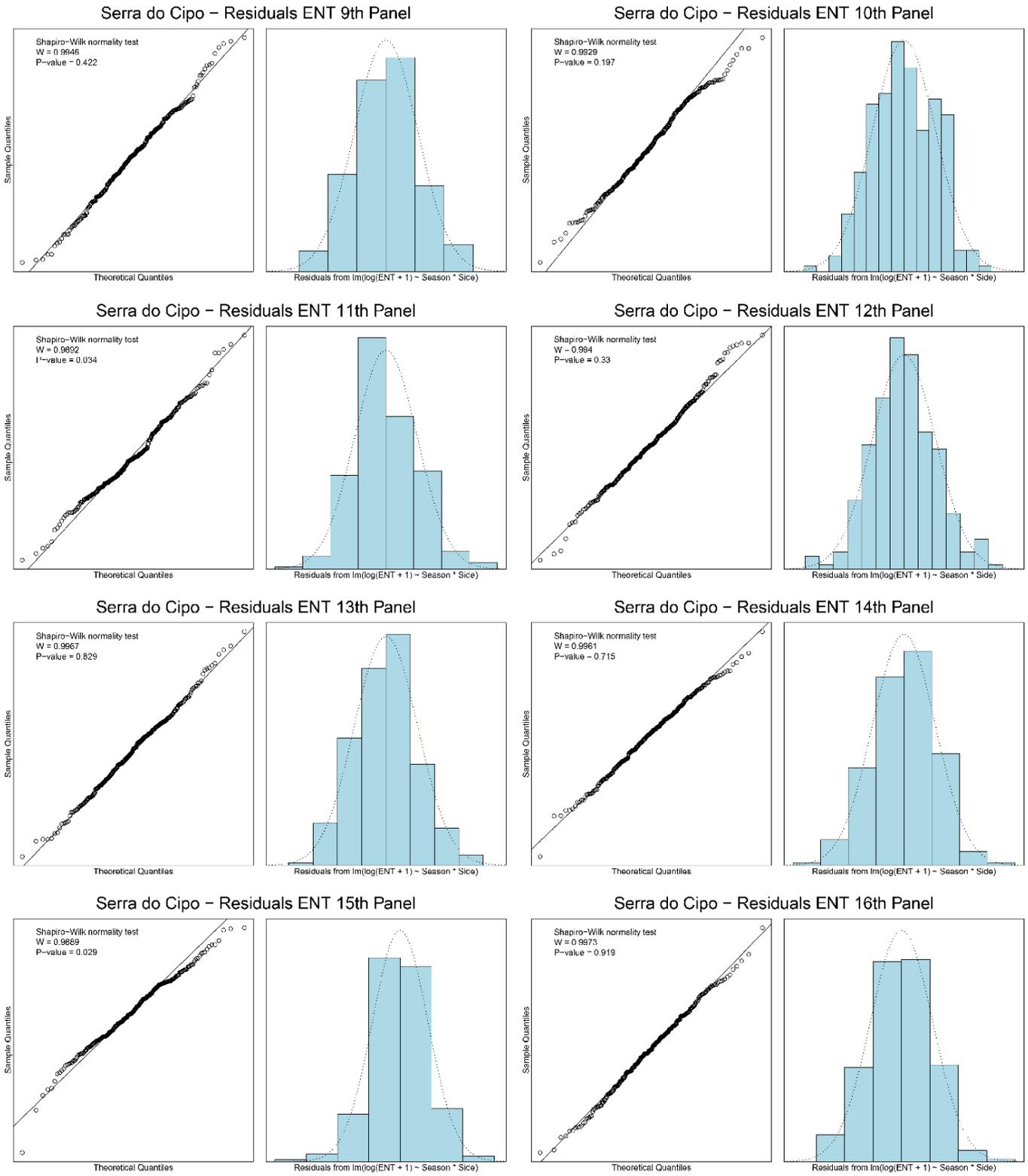
I advocate that PAM should be adopted by biodiversity monitoring initiatives more widely, not only due to its capacity of providing information about the acoustic community through varied acoustic analysis, but also due to its easy implementation, which makes it suitable as a complementary sampling protocol that can be added to new and ongoing monitoring programmes.

Appendices

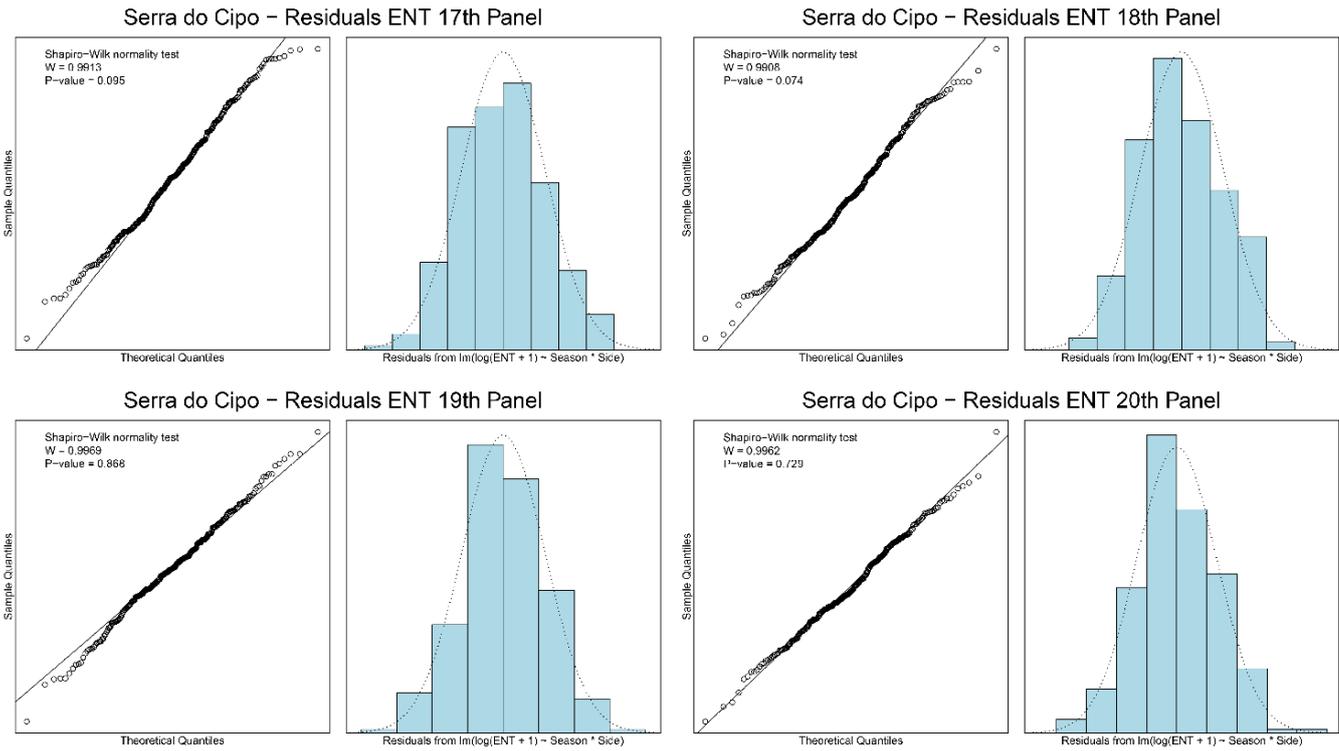
Appendix A. Shapiro-Wilk test and residual fits plots for chapter 2



Quantile-quantile and residual fits plots, along with the Shapiro-Wilk test for panels from 1 to 8. ENT index is taken here as an example.



Quantile-quantile and residual fits plots, along with the Shapiro-Wilk test for panels from 9 to 16. ENT index is taken here as an example.



Quantile-quantile and residual fits plots, along with the Shapiro-Wilk test for panels from 17 to 20. ENT index is taken here as an example.

Appendix B. Pairwise comparisons for panel in Chapter 2

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 1

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1875 | 274 | 4.8E-15 * | -4.7388 | -6.8430 | -3.2817 |
| ENT | winter | 0.1685 | 274 | 4.9E-15 * | -4.0466 | -5.6299 | -2.9085 |
| PMN | autumn | 0.1390 | 274 | 4.2E-16 * | -3.3299 | -4.3724 | -2.5359 |
| CVR | autumn | 0.1342 | 274 | 3.5E-16 * | -3.2068 | -4.1716 | -2.4652 |
| EVN | autumn | 0.1342 | 274 | 4.1E-16 * | -3.1965 | -4.1581 | -2.4573 |
| SPT | autumn | 0.1347 | 274 | 2.7E-15 * | -3.0926 | -4.0267 | -2.3752 |
| SPT | winter | 0.1210 | 274 | 7.6E-16 * | -2.8217 | -3.5771 | -2.2259 |
| POW | autumn | 0.1173 | 274 | 1.4E-16 * | -2.8116 | -3.5384 | -2.2341 |
| PMN | winter | 0.1249 | 274 | 7.9E-15 * | -2.7933 | -3.5680 | -2.1868 |
| CVR | winter | 0.1206 | 274 | 1.1E-12 * | -2.4602 | -3.1162 | -1.9423 |
| ENT | spring | 0.2072 | 274 | 2E-05 * | -2.4580 | -3.6895 | -1.6375 |
| EVN | winter | 0.1206 | 274 | 2.1E-12 * | -2.4296 | -3.0774 | -1.9182 |
| POW | winter | 0.1054 | 274 | 7.3E-14 * | -2.2973 | -2.8246 | -1.8685 |
| RVT | autumn | 0.0862 | 274 | 5E-18 * | -2.2271 | -2.6369 | -1.8809 |
| RPS | autumn | 0.0661 | 274 | 1.5E-21 * | -1.9863 | -2.2609 | -1.7451 |
| PMN | spring | 0.1536 | 274 | 2.2E-05 * | -1.9425 | -2.6249 | -1.4375 |
| RVT | winter | 0.0775 | 274 | 2E-15 * | -1.9212 | -2.2361 | -1.6506 |
| R3D | autumn | 0.0600 | 274 | 7.3E-23 * | -1.9108 | -2.1492 | -1.6988 |
| RNG | autumn | 0.0610 | 274 | 3.9E-21 * | -1.8712 | -2.1089 | -1.6602 |
| BGN | winter | 0.0770 | 274 | 9.6E-14 * | -1.8294 | -2.1273 | -1.5732 |
| RHZ | autumn | 0.0592 | 274 | 3.1E-19 * | -1.7732 | -1.9914 | -1.5790 |
| EVN | spring | 0.1483 | 274 | 0.00033 * | -1.7151 | -2.2937 | -1.2825 |
| EVN | summer | 0.1222 | 274 | 2E-05 * | -1.6983 | -2.1578 | -1.3367 |
| CVR | summer | 0.1222 | 274 | 3.1E-05 * | -1.6788 | -2.1330 | -1.3213 |
| CVR | spring | 0.1483 | 274 | 0.00058 * | -1.6754 | -2.2407 | -1.2528 |
| SPT | summer | 0.1226 | 274 | 4.3E-05 * | -1.6646 | -2.1168 | -1.3090 |
| RHZ | winter | 0.0532 | 274 | 1.2E-18 * | -1.6564 | -1.8384 | -1.4924 |
| BGN | summer | 0.0780 | 274 | 1.2E-09 * | -1.6341 | -1.9039 | -1.4025 |
| PMN | summer | 0.1265 | 274 | 0.00014 * | -1.6285 | -2.0868 | -1.2708 |
| RPS | winter | 0.0594 | 274 | 1.4E-14 * | -1.6213 | -1.8213 | -1.4432 |
| ENT | summer | 0.1707 | 274 | 0.0053 * | -1.6157 | -2.2576 | -1.1563 |
| POW | spring | 0.1297 | 274 | 0.00027 * | -1.6133 | -2.0801 | -1.2512 |
| R3D | winter | 0.0539 | 274 | 1.1E-16 * | -1.6111 | -1.7907 | -1.4495 |
| POW | summer | 0.1068 | 274 | 2.5E-05 * | -1.5805 | -1.9486 | -1.2820 |
| RNG | winter | 0.0548 | 274 | 1.4E-14 * | -1.5626 | -1.7400 | -1.4034 |
| SPT | spring | 0.1489 | 274 | 0.00726 * | -1.4958 | -2.0025 | -1.1173 |
| RVT | spring | 0.0953 | 274 | 0.00013 * | -1.4466 | -1.7436 | -1.2002 |
| ACI | spring | 0.0558 | 274 | 4.9E-08 * | -1.3680 | -1.5262 | -1.2262 |
| RVT | summer | 0.0785 | 274 | 0.00022 * | -1.3421 | -1.5652 | -1.1508 |
| RHZ | summer | 0.0539 | 274 | 1.6E-07 * | -1.3365 | -1.4855 | -1.2026 |
| BGN | spring | 0.0947 | 274 | 0.00448 * | -1.3117 | -1.5791 | -1.0896 |
| R3D | summer | 0.0546 | 274 | 2.1E-06 * | -1.3035 | -1.4508 | -1.1711 |
| RPS | summer | 0.0601 | 274 | 2E-05 * | -1.2979 | -1.4602 | -1.1536 |
| RNG | summer | 0.0556 | 274 | 1.2E-05 * | -1.2812 | -1.4286 | -1.1490 |
| RHZ | spring | 0.0654 | 274 | 0.00075 * | -1.2499 | -1.4210 | -1.0995 |
| R3D | spring | 0.0663 | 274 | 0.00301 * | -1.2196 | -1.3889 | -1.0710 |
| RPS | spring | 0.0730 | 274 | 0.03458 * | -1.1677 | -1.3474 | -1.0120 |
| RNG | spring | 0.0675 | 274 | 0.02409 * | -1.1654 | -1.3301 | -1.0210 |
| ACI | winter | 0.0454 | 274 | 0.00129 * | -1.1591 | -1.2670 | -1.0604 |
| BGN | autumn | 0.0856 | 274 | 0.00043 * | 1.3570 | 1.1473 | 1.6050 |
| ACI | summer | 0.0460 | 274 | 0.7976 | - | - | - |
| ACI | autumn | 0.0505 | 274 | 0.4067 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 2

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | winter | 0.1564 | 274 | 6.5E-15 * | -3.6362 | -4.9406 | -2.6763 |
| ENT | autumn | 0.1740 | 274 | 1.5E-10 * | -3.1859 | -4.4808 | -2.2652 |
| EVN | winter | 0.1536 | 274 | 1.5E-10 * | -2.7823 | -3.7595 | -2.0591 |
| PMN | winter | 0.1135 | 274 | 2.6E-14 * | -2.4932 | -3.1146 | -1.9958 |
| EVN | autumn | 0.1709 | 274 | 2.1E-07 * | -2.4837 | -3.4718 | -1.7768 |
| CVR | winter | 0.1275 | 274 | 8.5E-11 * | -2.3664 | -3.0382 | -1.8432 |
| ENT | spring | 0.1924 | 274 | 1.1E-05 * | -2.3655 | -3.4487 | -1.6225 |
| PMN | autumn | 0.1263 | 274 | 5.3E-10 * | -2.2560 | -2.8899 | -1.7612 |
| EVN | summer | 0.1556 | 274 | 5E-07 * | -2.2287 | -3.0234 | -1.6429 |
| CVR | autumn | 0.1419 | 274 | 7.2E-08 * | -2.1935 | -2.8967 | -1.6611 |
| BGN | winter | 0.1376 | 274 | 7.7E-08 * | -2.1389 | -2.8012 | -1.6332 |
| POW | winter | 0.1009 | 274 | 2.7E-11 * | -2.0162 | -2.4573 | -1.6542 |
| SPT | winter | 0.0984 | 274 | 6.8E-11 * | -1.9520 | -2.3674 | -1.6095 |
| POW | autumn | 0.1123 | 274 | 8.3E-09 * | -1.9504 | -2.4307 | -1.5650 |
| PMN | spring | 0.1396 | 274 | 3.5E-06 * | -1.9375 | -2.5475 | -1.4736 |
| ENT | summer | 0.1584 | 274 | 4E-05 * | -1.9370 | -2.6424 | -1.4199 |
| EVN | spring | 0.1889 | 274 | 0.00057 * | -1.9316 | -2.7970 | -1.3339 |
| CVR | summer | 0.1292 | 274 | 1.5E-06 * | -1.8870 | -2.4306 | -1.4650 |
| SPT | autumn | 0.1095 | 274 | 6.6E-08 * | -1.8375 | -2.2776 | -1.4825 |
| PMN | summer | 0.1150 | 274 | 2.9E-07 * | -1.8309 | -2.2939 | -1.4614 |
| CVR | spring | 0.1568 | 274 | 0.00062 * | -1.7218 | -2.3413 | -1.2662 |
| RVT | autumn | 0.0842 | 274 | 3.6E-09 * | -1.6718 | -1.9718 | -1.4174 |
| POW | summer | 0.1023 | 274 | 1.2E-06 * | -1.6618 | -2.0306 | -1.3599 |
| POW | spring | 0.1242 | 274 | 0.0001 * | -1.6312 | -2.0806 | -1.2788 |
| SPT | summer | 0.0997 | 274 | 3.5E-06 * | -1.6037 | -1.9499 | -1.3190 |
| RVT | winter | 0.0757 | 274 | 2.6E-09 * | -1.5941 | -1.8491 | -1.3743 |
| BGN | spring | 0.1693 | 274 | 0.0065 * | -1.5909 | -2.2168 | -1.1417 |
| SPT | spring | 0.1211 | 274 | 0.0004 * | -1.5433 | -1.9567 | -1.2173 |
| RNG | autumn | 0.0652 | 274 | 3.5E-09 * | -1.4888 | -1.6917 | -1.3102 |
| RPS | autumn | 0.0656 | 274 | 1.2E-08 * | -1.4714 | -1.6734 | -1.2938 |
| R3D | autumn | 0.0674 | 274 | 2.7E-08 * | -1.4703 | -1.6778 | -1.2885 |
| RVT | spring | 0.0931 | 274 | 6E-05 * | -1.4616 | -1.7543 | -1.2178 |
| BGN | summer | 0.1394 | 274 | 0.01101 * | -1.4290 | -1.8780 | -1.0873 |
| RVT | summer | 0.0767 | 274 | 3.3E-05 * | -1.3823 | -1.6065 | -1.1894 |
| RHZ | autumn | 0.0520 | 274 | 3.2E-09 * | -1.3749 | -1.5224 | -1.2416 |
| RNG | winter | 0.0586 | 274 | 2E-06 * | -1.3289 | -1.4906 | -1.1847 |
| RPS | winter | 0.0590 | 274 | 5.4E-06 * | -1.3146 | -1.4757 | -1.1711 |
| R3D | summer | 0.0613 | 274 | 1.3E-05 * | -1.3128 | -1.4804 | -1.1641 |
| ACI | spring | 0.0676 | 274 | 9E-05 * | -1.3083 | -1.4937 | -1.1460 |
| R3D | winter | 0.0605 | 274 | 2.1E-05 * | -1.2993 | -1.4629 | -1.1539 |
| RHZ | winter | 0.0467 | 274 | 8.2E-08 * | -1.2938 | -1.4179 | -1.1805 |
| RNG | summer | 0.0594 | 274 | 2.5E-05 * | -1.2900 | -1.4491 | -1.1483 |
| RPS | summer | 0.0598 | 274 | 3.4E-05 * | -1.2862 | -1.4460 | -1.1441 |
| RHZ | summer | 0.0473 | 274 | 3.5E-06 * | -1.2514 | -1.3731 | -1.1405 |
| RHZ | spring | 0.0575 | 274 | 0.00655 * | -1.1706 | -1.3102 | -1.0458 |
| BGN | autumn | 0.1531 | 274 | 5.8E-06 * | 2.0300 | 1.5036 | 2.7407 |
| ACI | autumn | 0.0612 | 274 | 0.9640 | - | - | - |
| ACI | winter | 0.0550 | 274 | 0.6314 | - | - | - |
| RNG | spring | 0.0721 | 274 | 0.3557 | - | - | - |
| RPS | spring | 0.0725 | 274 | 0.3386 | - | - | - |
| R3D | spring | 0.0744 | 274 | 0.2376 | - | - | - |
| ACI | summer | 0.0557 | 274 | 0.1997 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 3

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1609 | 274 | 8.4E-07 * | -2.2505 | -3.0847 | -1.6419 |
| ENT | autumn | 0.1455 | 274 | 1.3E-05 * | -1.9065 | -2.5357 | -1.4333 |
| CVR | autumn | 0.1430 | 274 | 1.3E-05 * | -1.8856 | -2.4958 | -1.4246 |
| PMN | spring | 0.1302 | 274 | 3.1E-06 * | -1.8588 | -2.3994 | -1.4400 |
| ENT | winter | 0.1308 | 274 | 5.8E-06 * | -1.8310 | -2.3660 | -1.4169 |
| EVN | autumn | 0.1677 | 274 | 0.00045 * | -1.8136 | -2.5193 | -1.3056 |
| EVN | spring | 0.1854 | 274 | 0.00161 * | -1.8051 | -2.5960 | -1.2552 |
| PMN | autumn | 0.1178 | 274 | 1.1E-06 * | -1.8010 | -2.2689 | -1.4297 |
| POW | autumn | 0.1136 | 274 | 1.1E-06 * | -1.7615 | -2.2009 | -1.4098 |
| SPT | autumn | 0.1120 | 274 | 2E-06 * | -1.7224 | -2.1453 | -1.3829 |
| CVR | spring | 0.1581 | 274 | 0.00102 * | -1.6909 | -2.3053 | -1.2403 |
| RVT | autumn | 0.0885 | 274 | 1.4E-08 * | -1.6775 | -1.9951 | -1.4104 |
| EVN | summer | 0.1527 | 274 | 0.00243 * | -1.5957 | -2.1523 | -1.1830 |
| BGN | winter | 0.1271 | 274 | 0.0003 * | -1.5934 | -2.0439 | -1.2421 |
| POW | spring | 0.1256 | 274 | 0.00029 * | -1.5859 | -2.0286 | -1.2399 |
| RPS | autumn | 0.0785 | 274 | 2.5E-08 * | -1.5691 | -1.8300 | -1.3453 |
| R3D | autumn | 0.0798 | 274 | 7E-08 * | -1.5558 | -1.8190 | -1.3306 |
| RNG | autumn | 0.0786 | 274 | 5E-08 * | -1.5539 | -1.8127 | -1.3320 |
| SPT | spring | 0.1238 | 274 | 0.00059 * | -1.5379 | -1.9603 | -1.2066 |
| PMN | winter | 0.1059 | 274 | 0.0002 * | -1.4909 | -1.8347 | -1.2114 |
| ENT | summer | 0.1325 | 274 | 0.00394 * | -1.4700 | -1.9060 | -1.1338 |
| CVR | summer | 0.1302 | 274 | 0.00392 * | -1.4607 | -1.8855 | -1.1316 |
| PMN | summer | 0.1073 | 274 | 0.00086 * | -1.4353 | -1.7711 | -1.1631 |
| EVN | winter | 0.1507 | 274 | 0.02195 * | -1.4152 | -1.9016 | -1.0533 |
| BGN | spring | 0.1563 | 274 | 0.02973 * | -1.4070 | -1.9112 | -1.0358 |
| CVR | winter | 0.1286 | 274 | 0.00929 * | -1.4005 | -1.8018 | -1.0885 |
| RHZ | autumn | 0.0602 | 274 | 6.1E-08 * | -1.3981 | -1.5730 | -1.2425 |
| RVT | spring | 0.0978 | 274 | 0.00079 * | -1.3935 | -1.6879 | -1.1504 |
| SPT | winter | 0.1007 | 274 | 0.00124 * | -1.3888 | -1.6918 | -1.1401 |
| POW | winter | 0.1021 | 274 | 0.00147 * | -1.3883 | -1.6959 | -1.1364 |
| SPT | summer | 0.1020 | 274 | 0.00159 * | -1.3844 | -1.6907 | -1.1336 |
| POW | summer | 0.1035 | 274 | 0.00251 * | -1.3711 | -1.6792 | -1.1194 |
| RVT | summer | 0.0806 | 274 | 0.00111 * | -1.3041 | -1.5271 | -1.1136 |
| RVT | winter | 0.0795 | 274 | 0.00098 * | -1.3034 | -1.5232 | -1.1153 |
| ACI | autumn | 0.0557 | 274 | 1E-05 * | -1.2842 | -1.4323 | -1.1515 |
| ACI | spring | 0.0615 | 274 | 0.0001 * | -1.2748 | -1.4382 | -1.1300 |
| ACI | summer | 0.0507 | 274 | 3.7E-06 * | -1.2704 | -1.4030 | -1.1503 |
| RPS | summer | 0.0715 | 274 | 0.00639 * | -1.2170 | -1.4000 | -1.0580 |
| R3D | summer | 0.0726 | 274 | 0.00752 * | -1.2160 | -1.4019 | -1.0547 |
| RPS | winter | 0.0705 | 274 | 0.00808 * | -1.2071 | -1.3860 | -1.0512 |
| RNG | winter | 0.0706 | 274 | 0.00888 * | -1.2046 | -1.3835 | -1.0489 |
| RPS | spring | 0.0868 | 274 | 0.03326 * | -1.2040 | -1.4272 | -1.0157 |
| RNG | spring | 0.0869 | 274 | 0.03532 * | -1.2018 | -1.4249 | -1.0136 |
| RNG | summer | 0.0716 | 274 | 0.01121 * | -1.2005 | -1.3813 | -1.0434 |
| RHZ | spring | 0.0665 | 274 | 0.0088 * | -1.1918 | -1.3577 | -1.0462 |
| RHZ | summer | 0.0548 | 274 | 0.00362 * | -1.1744 | -1.3075 | -1.0549 |
| R3D | winter | 0.0717 | 274 | 0.0495 * | -1.1519 | -1.3257 | -1.0009 |
| RHZ | winter | 0.0541 | 274 | 0.02266 * | -1.1319 | -1.2585 | -1.0181 |
| BGN | autumn | 0.1414 | 274 | 1.8E-08 * | 2.2717 | 1.7219 | 2.9970 |
| ACI | winter | 0.0500 | 274 | 0.8664 | - | - | - |
| BGN | summer | 0.1287 | 274 | 0.1548 | - | - | - |
| R3D | spring | 0.0882 | 274 | 0.0513 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 4

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | winter | 0.1524 | 274 | 1.5E-19 * | -4.4356 | -5.9794 | -3.2904 |
| EVN | autumn | 0.1696 | 274 | 3.1E-16 * | -4.3721 | -6.0955 | -3.1359 |
| CVR | autumn | 0.1477 | 274 | 2.7E-17 * | -3.8096 | -5.0891 | -2.8518 |
| ENT | autumn | 0.1392 | 274 | 4.5E-18 * | -3.6513 | -4.7968 | -2.7794 |
| CVR | winter | 0.1328 | 274 | 8E-18 * | -3.4032 | -4.4148 | -2.6234 |
| ENT | winter | 0.1251 | 274 | 7.5E-18 * | -3.1746 | -4.0568 | -2.4842 |
| PMN | autumn | 0.1202 | 274 | 5.3E-19 * | -3.1726 | -4.0158 | -2.5065 |
| EVN | summer | 0.1544 | 274 | 8.3E-12 * | -3.0114 | -4.0754 | -2.2252 |
| POW | autumn | 0.1166 | 274 | 1.2E-16 * | -2.8039 | -3.5238 | -2.2311 |
| PMN | winter | 0.1081 | 274 | 1.4E-17 * | -2.6859 | -3.3195 | -2.1732 |
| SPT | autumn | 0.1151 | 274 | 1.6E-15 * | -2.6490 | -3.3194 | -2.1140 |
| SPT | winter | 0.1034 | 274 | 2.3E-17 * | -2.5574 | -3.1323 | -2.0881 |
| POW | winter | 0.1048 | 274 | 2.4E-16 * | -2.4987 | -3.0684 | -2.0348 |
| CVR | summer | 0.1345 | 274 | 7.8E-11 * | -2.4860 | -3.2360 | -1.9099 |
| SPT | summer | 0.1048 | 274 | 5.3E-12 * | -2.1299 | -2.6155 | -1.7344 |
| EVN | spring | 0.1874 | 274 | 0.00013 * | -2.0672 | -2.9848 | -1.4317 |
| POW | summer | 0.1062 | 274 | 8.4E-11 * | -2.0491 | -2.5231 | -1.6642 |
| BGN | summer | 0.0955 | 274 | 3.2E-12 * | -2.0073 | -2.4205 | -1.6647 |
| PMN | summer | 0.1095 | 274 | 1.3E-09 * | -1.9898 | -2.4661 | -1.6055 |
| RVT | autumn | 0.0841 | 274 | 1.2E-14 * | -1.9865 | -2.3426 | -1.6845 |
| RNG | autumn | 0.0774 | 274 | 4E-15 * | -1.9053 | -2.2175 | -1.6370 |
| ENT | summer | 0.1267 | 274 | 1.3E-06 * | -1.8732 | -2.4014 | -1.4611 |
| RPS | autumn | 0.0745 | 274 | 5.3E-15 * | -1.8539 | -2.1454 | -1.6020 |
| R3D | autumn | 0.0720 | 274 | 5.3E-15 * | -1.8164 | -2.0919 | -1.5773 |
| CVR | spring | 0.1633 | 274 | 0.00036 * | -1.8050 | -2.4859 | -1.3106 |
| ENT | spring | 0.1539 | 274 | 0.00017 * | -1.7985 | -2.4317 | -1.3302 |
| RVT | winter | 0.0756 | 274 | 6.2E-12 * | -1.7223 | -1.9974 | -1.4851 |
| PMN | spring | 0.1329 | 274 | 0.00013 * | -1.6764 | -2.1754 | -1.2919 |
| RNG | winter | 0.0696 | 274 | 1.7E-11 * | -1.6306 | -1.8689 | -1.4227 |
| SPT | spring | 0.1272 | 274 | 0.00016 * | -1.6283 | -2.0895 | -1.2689 |
| RPS | winter | 0.0670 | 274 | 1.1E-11 * | -1.6090 | -1.8347 | -1.4111 |
| POW | spring | 0.1289 | 274 | 0.00031 * | -1.6014 | -2.0616 | -1.2439 |
| R3D | winter | 0.0647 | 274 | 1.1E-11 * | -1.5838 | -1.7980 | -1.3951 |
| BGN | winter | 0.0943 | 274 | 2.2E-06 * | -1.5776 | -1.8978 | -1.3115 |
| RHZ | autumn | 0.0552 | 274 | 7.3E-14 * | -1.5455 | -1.7220 | -1.3871 |
| R3D | summer | 0.0656 | 274 | 2.6E-10 * | -1.5381 | -1.7491 | -1.3526 |
| RNG | summer | 0.0705 | 274 | 3.6E-09 * | -1.5375 | -1.7653 | -1.3391 |
| RPS | summer | 0.0678 | 274 | 1.6E-09 * | -1.5278 | -1.7451 | -1.3376 |
| RVT | summer | 0.0766 | 274 | 1.6E-07 * | -1.5094 | -1.7539 | -1.2990 |
| RHZ | summer | 0.0502 | 274 | 2.3E-14 * | -1.4994 | -1.6545 | -1.3588 |
| RHZ | winter | 0.0496 | 274 | 3.3E-13 * | -1.4618 | -1.6110 | -1.3264 |
| BGN | spring | 0.1159 | 274 | 0.01314 * | -1.3356 | -1.6764 | -1.0641 |
| RVT | spring | 0.0930 | 274 | 0.00234 * | -1.3307 | -1.5967 | -1.1090 |
| RNG | spring | 0.0856 | 274 | 0.00664 * | -1.2638 | -1.4946 | -1.0686 |
| RPS | spring | 0.0824 | 274 | 0.00583 * | -1.2572 | -1.4775 | -1.0698 |
| R3D | spring | 0.0796 | 274 | 0.00518 * | -1.2516 | -1.4630 | -1.0707 |
| RHZ | spring | 0.0610 | 274 | 0.00029 * | -1.2509 | -1.4097 | -1.1099 |
| ACI | summer | 0.0349 | 274 | 0.00038 * | 1.1340 | 1.0590 | 1.2143 |
| BGN | autumn | 0.1049 | 274 | 1.9E-15 * | 2.4231 | 1.9728 | 2.9761 |
| ACI | winter | 0.0345 | 274 | 0.6716 | - | - | - |
| ACI | autumn | 0.0384 | 274 | 0.2489 | - | - | - |
| ACI | spring | 0.0424 | 274 | 0.1843 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 5

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1572 | 274 | 6.9E-24 * | -5.7276 | -7.7948 | -4.2086 |
| SPT | autumn | 0.1222 | 274 | 1.6E-25 * | -4.1197 | -5.2351 | -3.2420 |
| PMN | autumn | 0.1173 | 274 | 1.3E-25 * | -3.9039 | -4.9133 | -3.1018 |
| EVN | autumn | 0.1203 | 274 | 1.4E-23 * | -3.7566 | -4.7552 | -2.9678 |
| ENT | winter | 0.1413 | 274 | 3.1E-18 * | -3.7512 | -4.9483 | -2.8438 |
| CVR | autumn | 0.1195 | 274 | 1.7E-23 * | -3.7125 | -4.6919 | -2.9376 |
| ENT | spring | 0.1738 | 274 | 9.2E-12 * | -3.4502 | -4.8505 | -2.4542 |
| POW | autumn | 0.1039 | 274 | 8.4E-25 * | -3.2610 | -3.9980 | -2.6600 |
| SPT | winter | 0.1099 | 274 | 1.4E-17 * | -2.7313 | -3.3875 | -2.2021 |
| PMN | winter | 0.1055 | 274 | 4.9E-18 * | -2.6642 | -3.2759 | -2.1667 |
| RVT | autumn | 0.0807 | 274 | 9.3E-27 * | -2.6207 | -3.0695 | -2.2375 |
| PMN | spring | 0.1297 | 274 | 3.7E-12 * | -2.5684 | -3.3118 | -1.9918 |
| ENT | summer | 0.1432 | 274 | 7.3E-10 * | -2.4941 | -3.3019 | -1.8839 |
| CVR | winter | 0.1074 | 274 | 9.9E-15 * | -2.4095 | -2.9738 | -1.9523 |
| RPS | autumn | 0.0653 | 274 | 7.3E-32 * | -2.4011 | -2.7291 | -2.1125 |
| SPT | summer | 0.1113 | 274 | 3E-13 * | -2.3492 | -2.9218 | -1.8887 |
| EVN | winter | 0.1081 | 274 | 8.5E-14 * | -2.3399 | -2.8920 | -1.8932 |
| POW | winter | 0.0934 | 274 | 2.6E-16 * | -2.2601 | -2.7143 | -1.8820 |
| CVR | spring | 0.1320 | 274 | 3E-09 * | -2.2484 | -2.9125 | -1.7357 |
| R3D | autumn | 0.0602 | 274 | 5.9E-32 * | -2.2442 | -2.5251 | -1.9945 |
| RHZ | autumn | 0.0572 | 274 | 2.8E-34 * | -2.2375 | -2.5028 | -2.0004 |
| EVN | spring | 0.1329 | 274 | 5E-09 * | -2.2318 | -2.8961 | -1.7199 |
| RNG | autumn | 0.0606 | 274 | 6.5E-30 * | -2.1803 | -2.4555 | -1.9360 |
| PMN | summer | 0.1068 | 274 | 8.5E-12 * | -2.1440 | -2.6434 | -1.7390 |
| EVN | summer | 0.1095 | 274 | 1.3E-10 * | -2.0784 | -2.5759 | -1.6770 |
| POW | spring | 0.1149 | 274 | 9.4E-10 * | -2.0719 | -2.5953 | -1.6541 |
| CVR | summer | 0.1088 | 274 | 1.7E-10 * | -2.0586 | -2.5477 | -1.6634 |
| SPT | spring | 0.1351 | 274 | 2.3E-07 * | -2.0482 | -2.6692 | -1.5716 |
| POW | summer | 0.0946 | 274 | 2.9E-11 * | -1.9277 | -2.3207 | -1.6014 |
| RVT | winter | 0.0725 | 274 | 1.3E-15 * | -1.8505 | -2.1330 | -1.6054 |
| BGN | winter | 0.0651 | 274 | 1.4E-16 * | -1.7756 | -2.0174 | -1.5628 |
| RVT | summer | 0.0734 | 274 | 4.8E-12 * | -1.7005 | -1.9637 | -1.4725 |
| RHZ | summer | 0.0520 | 274 | 1.1E-20 * | -1.6943 | -1.8763 | -1.5300 |
| RVT | spring | 0.0892 | 274 | 2.3E-08 * | -1.6703 | -1.9893 | -1.4025 |
| RPS | summer | 0.0595 | 274 | 1.8E-15 * | -1.6522 | -1.8565 | -1.4704 |
| RHZ | winter | 0.0514 | 274 | 6.3E-19 * | -1.6356 | -1.8089 | -1.4789 |
| RPS | winter | 0.0587 | 274 | 4.9E-15 * | -1.6276 | -1.8261 | -1.4507 |
| BGN | summer | 0.0660 | 274 | 2.1E-12 * | -1.6253 | -1.8498 | -1.4282 |
| R3D | summer | 0.0548 | 274 | 2.4E-16 * | -1.6138 | -1.7967 | -1.4495 |
| R3D | winter | 0.0541 | 274 | 1.6E-15 * | -1.5806 | -1.7573 | -1.4216 |
| RNG | summer | 0.0552 | 274 | 2.1E-14 * | -1.5623 | -1.7409 | -1.4021 |
| RNG | winter | 0.0545 | 274 | 1.1E-13 * | -1.5318 | -1.7045 | -1.3766 |
| BGN | spring | 0.0801 | 274 | 7.6E-07 * | -1.5003 | -1.7554 | -1.2823 |
| RHZ | spring | 0.0632 | 274 | 3.9E-08 * | -1.4297 | -1.6182 | -1.2632 |
| R3D | spring | 0.0665 | 274 | 7.2E-07 * | -1.4014 | -1.5965 | -1.2301 |
| RPS | spring | 0.0722 | 274 | 2.7E-05 * | -1.3608 | -1.5677 | -1.1812 |
| ACI | spring | 0.0621 | 274 | 2.4E-06 * | -1.3488 | -1.5235 | -1.1942 |
| RNG | spring | 0.0670 | 274 | 1.5E-05 * | -1.3432 | -1.5318 | -1.1778 |
| BGN | autumn | 0.0725 | 274 | 0.00012 * | 1.3274 | 1.1517 | 1.5301 |
| ACI | autumn | 0.0562 | 274 | 0.5581 | - | - | - |
| ACI | winter | 0.0505 | 274 | 0.2683 | - | - | - |
| ACI | summer | 0.0512 | 274 | 0.0856 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 6

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | autumn | 0.1501 | 274 | 1.6E-26 * | -5.9400 | -7.9711 | -4.4265 |
| ENT | autumn | 0.1423 | 274 | 3.2E-28 * | -5.8150 | -7.6857 | -4.3996 |
| CVR | autumn | 0.1391 | 274 | 3.8E-26 * | -5.1396 | -6.7508 | -3.9129 |
| PMN | autumn | 0.1248 | 274 | 3.7E-29 * | -4.8435 | -6.1861 | -3.7923 |
| EVN | summer | 0.1366 | 274 | 4.7E-25 * | -4.7768 | -6.2435 | -3.6547 |
| EVN | winter | 0.1349 | 274 | 4.1E-24 * | -4.5084 | -5.8724 | -3.4612 |
| POW | autumn | 0.1159 | 274 | 5.2E-27 * | -4.0259 | -5.0523 | -3.2080 |
| ENT | summer | 0.1296 | 274 | 1.7E-22 * | -3.9921 | -5.1463 | -3.0968 |
| CVR | summer | 0.1267 | 274 | 6.2E-23 * | -3.9343 | -5.0430 | -3.0693 |
| CVR | winter | 0.1250 | 274 | 3.9E-23 * | -3.8944 | -4.9760 | -3.0480 |
| SPT | autumn | 0.1131 | 274 | 1.1E-26 * | -3.8510 | -4.8064 | -3.0855 |
| PMN | summer | 0.1137 | 274 | 6.9E-25 * | -3.6519 | -4.5632 | -2.9227 |
| POW | winter | 0.1041 | 274 | 1.2E-24 * | -3.2535 | -3.9902 | -2.6529 |
| SPT | summer | 0.1030 | 274 | 5E-25 * | -3.2467 | -3.9726 | -2.6535 |
| BGN | winter | 0.1527 | 274 | 2.7E-13 * | -3.2357 | -4.3648 | -2.3987 |
| POW | summer | 0.1055 | 274 | 1.7E-23 * | -3.1845 | -3.9160 | -2.5897 |
| SPT | winter | 0.1016 | 274 | 8.3E-25 * | -3.1763 | -3.8764 | -2.6027 |
| PMN | winter | 0.1122 | 274 | 5E-21 * | -3.1522 | -3.9275 | -2.5300 |
| RVT | autumn | 0.0916 | 274 | 1.5E-26 * | -2.9691 | -3.5527 | -2.4814 |
| ENT | winter | 0.1279 | 274 | 7E-15 * | -2.8702 | -3.6879 | -2.2338 |
| EVN | spring | 0.1659 | 274 | 8.4E-09 * | -2.6811 | -3.7111 | -1.9369 |
| RNG | autumn | 0.0776 | 274 | 4.5E-29 * | -2.6607 | -3.0976 | -2.2854 |
| R3D | autumn | 0.0784 | 274 | 1.9E-28 * | -2.6518 | -3.0924 | -2.2739 |
| RPS | autumn | 0.0777 | 274 | 2.4E-28 * | -2.6219 | -3.0533 | -2.2516 |
| ENT | spring | 0.1573 | 274 | 1E-08 * | -2.5311 | -3.4452 | -1.8596 |
| RVT | summer | 0.0834 | 274 | 5.4E-23 * | -2.4670 | -2.9048 | -2.0952 |
| RVT | winter | 0.0823 | 274 | 2.6E-23 * | -2.4574 | -2.8874 | -2.0914 |
| CVR | spring | 0.1538 | 274 | 8.4E-08 * | -2.3326 | -3.1532 | -1.7256 |
| PMN | spring | 0.1380 | 274 | 6.5E-09 * | -2.2862 | -2.9962 | -1.7445 |
| R3D | summer | 0.0714 | 274 | 3.6E-25 * | -2.2704 | -2.6115 | -1.9739 |
| RPS | summer | 0.0707 | 274 | 8.8E-25 * | -2.2345 | -2.5669 | -1.9452 |
| RNG | summer | 0.0706 | 274 | 1.2E-24 * | -2.2247 | -2.5550 | -1.9371 |
| R3D | winter | 0.0705 | 274 | 2.9E-23 * | -2.1585 | -2.4783 | -1.8800 |
| RNG | winter | 0.0697 | 274 | 3.3E-23 * | -2.1373 | -2.4503 | -1.8644 |
| RPS | winter | 0.0698 | 274 | 1.5E-22 * | -2.1115 | -2.4212 | -1.8414 |
| POW | spring | 0.1281 | 274 | 1.9E-08 * | -2.1001 | -2.6994 | -1.6339 |
| RHZ | autumn | 0.0593 | 274 | 4.5E-28 * | -2.0768 | -2.3328 | -1.8490 |
| BGN | summer | 0.1547 | 274 | 5E-06 * | -2.0553 | -2.7833 | -1.5177 |
| SPT | spring | 0.1250 | 274 | 2.2E-08 * | -2.0547 | -2.6251 | -1.6083 |
| BGN | spring | 0.1878 | 274 | 0.00021 * | -2.0251 | -2.9264 | -1.4014 |
| RHZ | summer | 0.0540 | 274 | 5.6E-28 * | -1.9425 | -2.1593 | -1.7475 |
| RHZ | winter | 0.0533 | 274 | 1.1E-26 * | -1.8876 | -2.0954 | -1.7004 |
| RVT | spring | 0.1012 | 274 | 3.6E-09 * | -1.8536 | -2.2602 | -1.5201 |
| ACI | summer | 0.0662 | 274 | 1.6E-14 * | -1.7119 | -1.9490 | -1.5036 |
| ACI | spring | 0.0804 | 274 | 1.4E-06 * | -1.4868 | -1.7404 | -1.2701 |
| R3D | spring | 0.0867 | 274 | 7E-05 * | -1.4192 | -1.6821 | -1.1974 |
| RPS | spring | 0.0859 | 274 | 6.7E-05 * | -1.4158 | -1.6754 | -1.1965 |
| RNG | spring | 0.0857 | 274 | 7.3E-05 * | -1.4124 | -1.6709 | -1.1939 |
| ACI | autumn | 0.0727 | 274 | 3.3E-06 * | -1.4120 | -1.6283 | -1.2245 |
| RHZ | spring | 0.0655 | 274 | 7E-07 * | -1.3951 | -1.5863 | -1.2269 |
| ACI | winter | 0.0653 | 274 | 0.00043 * | -1.2623 | -1.4347 | -1.1105 |
| BGN | autumn | 0.1699 | 274 | 5.9E-06 * | 2.1922 | 1.5712 | 3.0586 |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 7

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | summer | 0.1710 | 274 | 3.4E-19 * | -5.2218 | -7.3015 | -3.7344 |
| ENT | summer | 0.1427 | 274 | 7.2E-19 * | -3.9124 | -5.1751 | -2.9578 |
| CVR | summer | 0.1542 | 274 | 1.2E-16 * | -3.9101 | -5.2899 | -2.8902 |
| PMN | summer | 0.1362 | 274 | 3.5E-18 * | -3.5677 | -4.6595 | -2.7317 |
| SPT | summer | 0.1300 | 274 | 1.6E-16 * | -3.1388 | -4.0497 | -2.4328 |
| POW | summer | 0.1298 | 274 | 1.5E-16 * | -3.1362 | -4.0450 | -2.4316 |
| BGN | winter | 0.1662 | 274 | 8.9E-10 * | -2.8729 | -3.9789 | -2.0743 |
| RVT | summer | 0.1035 | 274 | 3E-17 * | -2.5481 | -3.1212 | -2.0802 |
| BGN | summer | 0.1683 | 274 | 2.3E-07 * | -2.4444 | -3.3999 | -1.7574 |
| EVN | winter | 0.1688 | 274 | 1.8E-06 * | -2.2811 | -3.1759 | -1.6385 |
| RPS | summer | 0.0872 | 274 | 7.1E-18 * | -2.2390 | -2.6564 | -1.8871 |
| RNG | summer | 0.0866 | 274 | 7.9E-18 * | -2.2236 | -2.6351 | -1.8764 |
| R3D | summer | 0.0865 | 274 | 1.1E-17 * | -2.2112 | -2.6197 | -1.8663 |
| CVR | winter | 0.1522 | 274 | 1.6E-06 * | -2.1107 | -2.8444 | -1.5662 |
| ENT | autumn | 0.1567 | 274 | 2.3E-05 * | -1.9654 | -2.6722 | -1.4455 |
| ACI | summer | 0.0770 | 274 | 2.8E-15 * | -1.9062 | -2.2167 | -1.6391 |
| ENT | spring | 0.1733 | 274 | 0.00029 * | -1.8898 | -2.6539 | -1.3456 |
| EVN | spring | 0.2077 | 274 | 0.00254 * | -1.8824 | -2.8280 | -1.2530 |
| POW | winter | 0.1282 | 274 | 2.5E-06 * | -1.8520 | -2.3808 | -1.4406 |
| SPT | winter | 0.1283 | 274 | 7.5E-06 * | -1.7970 | -2.3109 | -1.3974 |
| RHZ | summer | 0.0652 | 274 | 4.6E-17 * | -1.7953 | -2.0401 | -1.5799 |
| PMN | winter | 0.1345 | 274 | 2.9E-05 * | -1.7711 | -2.3052 | -1.3608 |
| BGN | spring | 0.2044 | 274 | 0.00771 * | -1.7309 | -2.5837 | -1.1596 |
| ENT | winter | 0.1409 | 274 | 0.00013 * | -1.7300 | -2.2801 | -1.3126 |
| RVT | winter | 0.1022 | 274 | 1.7E-06 * | -1.6486 | -2.0141 | -1.3494 |
| CVR | spring | 0.1872 | 274 | 0.0103 * | -1.6220 | -2.3411 | -1.1238 |
| PMN | spring | 0.1654 | 274 | 0.00431 * | -1.6098 | -2.2261 | -1.1641 |
| PMN | autumn | 0.1496 | 274 | 0.00255 * | -1.5771 | -2.1145 | -1.1762 |
| RNG | winter | 0.0855 | 274 | 5.8E-07 * | -1.5489 | -1.8315 | -1.3099 |
| RVT | spring | 0.1257 | 274 | 0.00072 * | -1.5372 | -1.9665 | -1.2016 |
| POW | spring | 0.1576 | 274 | 0.00683 * | -1.5367 | -2.0930 | -1.1283 |
| RPS | winter | 0.0861 | 274 | 1.1E-06 * | -1.5349 | -1.8170 | -1.2965 |
| R3D | winter | 0.0854 | 274 | 1.1E-06 * | -1.5298 | -1.8085 | -1.2940 |
| SPT | spring | 0.1578 | 274 | 0.00962 * | -1.5091 | -2.0562 | -1.1076 |
| RVT | autumn | 0.1137 | 274 | 0.00183 * | -1.4302 | -1.7872 | -1.1446 |
| RNG | autumn | 0.0951 | 274 | 0.00031 * | -1.4153 | -1.7055 | -1.1746 |
| RPS | autumn | 0.0958 | 274 | 0.00043 * | -1.4072 | -1.6979 | -1.1663 |
| POW | autumn | 0.1426 | 274 | 0.02327 * | -1.3846 | -1.8310 | -1.0470 |
| R3D | autumn | 0.0950 | 274 | 0.00122 * | -1.3641 | -1.6434 | -1.1323 |
| SPT | autumn | 0.1428 | 274 | 0.03616 * | -1.3507 | -1.7869 | -1.0210 |
| RHZ | winter | 0.0644 | 274 | 1.1E-05 * | -1.3342 | -1.5136 | -1.1761 |
| RNG | spring | 0.1052 | 274 | 0.01214 * | -1.3041 | -1.6027 | -1.0612 |
| RPS | spring | 0.1059 | 274 | 0.01452 * | -1.2976 | -1.5969 | -1.0543 |
| ACI | spring | 0.0935 | 274 | 0.00722 * | -1.2879 | -1.5469 | -1.0723 |
| R3D | spring | 0.1050 | 274 | 0.02146 * | -1.2750 | -1.5664 | -1.0378 |
| ACI | autumn | 0.0846 | 274 | 0.01418 * | -1.2321 | -1.4543 | -1.0439 |
| RHZ | autumn | 0.0716 | 274 | 0.00435 * | -1.2287 | -1.4139 | -1.0678 |
| RHZ | spring | 0.0792 | 274 | 0.02418 * | -1.1966 | -1.3974 | -1.0246 |
| BGN | autumn | 0.1849 | 274 | 1.3E-07 * | 2.7257 | 1.8971 | 3.9162 |
| ACI | winter | 0.0760 | 274 | 0.9970 | - | - | - |
| EVN | autumn | 0.1879 | 274 | 0.1055 | - | - | - |
| CVR | autumn | 0.1694 | 274 | 0.0551 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 8

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | summer | 0.1516 | 274 | 4.7E-14 * | -3.3411 | -4.4975 | -2.4821 |
| ENT | summer | 0.1405 | 274 | 6.5E-14 * | -3.0374 | -4.0003 | -2.3063 |
| CVR | summer | 0.1354 | 274 | 1.2E-10 * | -2.4738 | -3.2255 | -1.8973 |
| EVN | winter | 0.1497 | 274 | 1.6E-08 * | -2.3920 | -3.2076 | -1.7838 |
| PMN | summer | 0.1155 | 274 | 9.9E-13 * | -2.3739 | -2.9772 | -1.8929 |
| EVN | autumn | 0.1666 | 274 | 5E-07 * | -2.3578 | -3.2681 | -1.7011 |
| ENT | autumn | 0.1543 | 274 | 2.7E-07 * | -2.2576 | -3.0549 | -1.6684 |
| CVR | winter | 0.1336 | 274 | 7.8E-09 * | -2.2174 | -2.8813 | -1.7065 |
| CVR | autumn | 0.1487 | 274 | 9E-07 * | -2.1114 | -2.8258 | -1.5777 |
| ENT | winter | 0.1387 | 274 | 3.9E-07 * | -2.0564 | -2.6987 | -1.5670 |
| PMN | autumn | 0.1269 | 274 | 6.1E-08 * | -2.0277 | -2.6002 | -1.5812 |
| SPT | summer | 0.1075 | 274 | 2.6E-10 * | -2.0258 | -2.5010 | -1.6408 |
| PMN | winter | 0.1140 | 274 | 2.7E-09 * | -2.0169 | -2.5221 | -1.6129 |
| POW | summer | 0.1073 | 274 | 5.5E-10 * | -1.9946 | -2.4614 | -1.6163 |
| SPT | winter | 0.1061 | 274 | 1.9E-09 * | -1.9343 | -2.3816 | -1.5710 |
| POW | winter | 0.1059 | 274 | 2.3E-09 * | -1.9252 | -2.3693 | -1.5643 |
| POW | autumn | 0.1178 | 274 | 3.5E-07 * | -1.8502 | -2.3309 | -1.4686 |
| EVN | spring | 0.1841 | 274 | 0.00111 * | -1.8345 | -2.6317 | -1.2788 |
| SPT | autumn | 0.1181 | 274 | 4.5E-06 * | -1.7383 | -2.1910 | -1.3791 |
| ENT | spring | 0.1706 | 274 | 0.00204 * | -1.7011 | -2.3764 | -1.2177 |
| RVT | summer | 0.0808 | 274 | 8.7E-10 * | -1.6712 | -1.9581 | -1.4264 |
| BGN | winter | 0.1040 | 274 | 1.6E-06 * | -1.6664 | -2.0431 | -1.3592 |
| RVT | autumn | 0.0888 | 274 | 2.4E-07 * | -1.6002 | -1.9043 | -1.3446 |
| RNG | summer | 0.0709 | 274 | 5.9E-10 * | -1.5771 | -1.8124 | -1.3724 |
| CVR | spring | 0.1644 | 274 | 0.00597 * | -1.5769 | -2.1763 | -1.1426 |
| RVT | winter | 0.0798 | 274 | 5.5E-08 * | -1.5618 | -1.8261 | -1.3357 |
| RPS | summer | 0.0685 | 274 | 1.3E-09 * | -1.5381 | -1.7592 | -1.3447 |
| R3D | summer | 0.0659 | 274 | 9.9E-10 * | -1.5178 | -1.7271 | -1.3339 |
| RNG | autumn | 0.0779 | 274 | 2.3E-07 * | -1.5117 | -1.7611 | -1.2976 |
| RNG | winter | 0.0700 | 274 | 2.5E-08 * | -1.4944 | -1.7143 | -1.3028 |
| PMN | spring | 0.1403 | 274 | 0.00477 * | -1.4905 | -1.9622 | -1.1323 |
| RPS | autumn | 0.0753 | 274 | 2.5E-07 * | -1.4896 | -1.7264 | -1.2853 |
| RPS | winter | 0.0676 | 274 | 2.6E-08 * | -1.4737 | -1.6827 | -1.2907 |
| POW | spring | 0.1303 | 274 | 0.00322 * | -1.4729 | -1.9013 | -1.1410 |
| SPT | spring | 0.1306 | 274 | 0.00377 * | -1.4644 | -1.8914 | -1.1338 |
| R3D | winter | 0.0651 | 274 | 5.3E-08 * | -1.4394 | -1.6352 | -1.2671 |
| R3D | autumn | 0.0724 | 274 | 9.3E-07 * | -1.4383 | -1.6576 | -1.2480 |
| RVT | spring | 0.0981 | 274 | 0.00096 * | -1.3874 | -1.6816 | -1.1446 |
| RHZ | summer | 0.0503 | 274 | 8.1E-09 * | -1.3488 | -1.4884 | -1.2222 |
| RHZ | winter | 0.0496 | 274 | 5.4E-08 * | -1.3199 | -1.4547 | -1.1975 |
| RHZ | autumn | 0.0552 | 274 | 1.4E-05 * | -1.2768 | -1.4227 | -1.1459 |
| RNG | spring | 0.0861 | 274 | 0.00654 * | -1.2662 | -1.4990 | -1.0695 |
| BGN | summer | 0.1053 | 274 | 0.02683 * | -1.2642 | -1.5541 | -1.0284 |
| RPS | spring | 0.0832 | 274 | 0.00673 * | -1.2551 | -1.4774 | -1.0662 |
| ACI | summer | 0.0456 | 274 | 1.5E-06 * | -1.2513 | -1.3683 | -1.1444 |
| R3D | spring | 0.0800 | 274 | 0.01047 * | -1.2291 | -1.4378 | -1.0507 |
| RHZ | spring | 0.0610 | 274 | 0.00784 * | -1.1776 | -1.3272 | -1.0448 |
| ACI | autumn | 0.0501 | 274 | 0.02692 * | -1.1178 | -1.2331 | -1.0133 |
| BGN | autumn | 0.1157 | 274 | 1.1E-16 * | 2.7858 | 2.2206 | 3.4948 |
| ACI | spring | 0.0553 | 274 | 0.7331 | - | - | - |
| ACI | winter | 0.0450 | 274 | 0.5242 | - | - | - |
| BGN | spring | 0.1279 | 274 | 0.1038 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 9

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1524 | 274 | 4.5E-16 * | -3.7364 | -5.0372 | -2.7716 |
| ENT | autumn | 0.1379 | 274 | 6.4E-18 * | -3.5818 | -4.6931 | -2.7336 |
| PMN | autumn | 0.1038 | 274 | 1.6E-19 * | -2.7547 | -3.3763 | -2.2476 |
| PMN | spring | 0.1147 | 274 | 1.4E-16 * | -2.7492 | -3.4426 | -2.1955 |
| ENT | winter | 0.1239 | 274 | 2.3E-14 * | -2.7163 | -3.4631 | -2.1306 |
| SPT | autumn | 0.1024 | 274 | 6.1E-19 * | -2.6686 | -3.2620 | -2.1832 |
| CVR | autumn | 0.0983 | 274 | 4E-19 * | -2.5785 | -3.1261 | -2.1269 |
| EVN | autumn | 0.0973 | 274 | 9.6E-19 * | -2.5258 | -3.0566 | -2.0871 |
| EVN | spring | 0.1076 | 274 | 2.1E-15 * | -2.4747 | -3.0557 | -2.0042 |
| CVR | spring | 0.1086 | 274 | 2.3E-14 * | -2.4003 | -2.9697 | -1.9401 |
| POW | autumn | 0.0870 | 274 | 2.8E-20 * | -2.3869 | -2.8307 | -2.0128 |
| PMN | winter | 0.0933 | 274 | 1.1E-16 * | -2.2828 | -2.7408 | -1.9013 |
| SPT | winter | 0.0921 | 274 | 2.5E-15 * | -2.1658 | -2.5941 | -1.8083 |
| EVN | winter | 0.0875 | 274 | 3E-16 * | -2.1421 | -2.5427 | -1.8046 |
| POW | spring | 0.0962 | 274 | 7.9E-14 * | -2.1327 | -2.5750 | -1.7663 |
| CVR | winter | 0.0883 | 274 | 1E-15 * | -2.1233 | -2.5245 | -1.7859 |
| SPT | spring | 0.1132 | 274 | 3.5E-10 * | -2.0908 | -2.6103 | -1.6746 |
| RVT | autumn | 0.0657 | 274 | 8.5E-23 * | -2.0304 | -2.3096 | -1.7849 |
| POW | winter | 0.0782 | 274 | 2.2E-16 * | -1.9824 | -2.3107 | -1.7007 |
| ENT | summer | 0.1255 | 274 | 2.6E-06 * | -1.8263 | -2.3358 | -1.4280 |
| EVN | summer | 0.0886 | 274 | 2.1E-10 * | -1.7953 | -2.1358 | -1.5090 |
| RPS | autumn | 0.0503 | 274 | 2.1E-25 * | -1.7878 | -1.9731 | -1.6200 |
| RHZ | autumn | 0.0501 | 274 | 7.7E-25 * | -1.7695 | -1.9522 | -1.6038 |
| SPT | summer | 0.0933 | 274 | 4.6E-09 * | -1.7590 | -2.1118 | -1.4651 |
| R3D | autumn | 0.0474 | 274 | 2.3E-25 * | -1.7282 | -1.8965 | -1.5748 |
| CVR | summer | 0.0895 | 274 | 4.9E-09 * | -1.7172 | -2.0463 | -1.4410 |
| PMN | summer | 0.0945 | 274 | 3E-08 * | -1.7145 | -2.0634 | -1.4245 |
| RVT | winter | 0.0591 | 274 | 5E-17 * | -1.6982 | -1.9067 | -1.5125 |
| RVT | spring | 0.0727 | 274 | 3.5E-12 * | -1.6977 | -1.9576 | -1.4723 |
| RNG | autumn | 0.0467 | 274 | 3.2E-24 * | -1.6875 | -1.8494 | -1.5399 |
| POW | summer | 0.0792 | 274 | 6.6E-09 * | -1.6069 | -1.8767 | -1.3758 |
| ACI | spring | 0.0535 | 274 | 4.2E-14 * | -1.5318 | -1.7012 | -1.3794 |
| BGN | winter | 0.0518 | 274 | 8.8E-15 * | -1.5296 | -1.6930 | -1.3820 |
| RHZ | winter | 0.0451 | 274 | 2.1E-18 * | -1.5280 | -1.6691 | -1.3988 |
| R3D | winter | 0.0426 | 274 | 2.8E-17 * | -1.4704 | -1.5985 | -1.3526 |
| RPS | winter | 0.0452 | 274 | 1.2E-15 * | -1.4688 | -1.6049 | -1.3442 |
| BGN | summer | 0.0525 | 274 | 1.1E-11 * | -1.4514 | -1.6085 | -1.3096 |
| BGN | spring | 0.0637 | 274 | 2.1E-08 * | -1.4440 | -1.6360 | -1.2746 |
| RHZ | summer | 0.0456 | 274 | 6.7E-14 * | -1.4344 | -1.5686 | -1.3116 |
| RNG | winter | 0.0420 | 274 | 5E-15 * | -1.4165 | -1.5380 | -1.3046 |
| RHZ | spring | 0.0554 | 274 | 3.4E-09 * | -1.4029 | -1.5639 | -1.2585 |
| RVT | summer | 0.0599 | 274 | 4.7E-08 * | -1.3998 | -1.5740 | -1.2448 |
| R3D | spring | 0.0524 | 274 | 1.6E-09 * | -1.3875 | -1.5376 | -1.2520 |
| R3D | summer | 0.0432 | 274 | 3.8E-12 * | -1.3685 | -1.4894 | -1.2575 |
| RPS | summer | 0.0458 | 274 | 1.2E-10 * | -1.3593 | -1.4870 | -1.2426 |
| RNG | summer | 0.0425 | 274 | 1.2E-10 * | -1.3296 | -1.4452 | -1.2232 |
| RPS | spring | 0.0556 | 274 | 9E-07 * | -1.3226 | -1.4749 | -1.1860 |
| RNG | spring | 0.0516 | 274 | 1.5E-07 * | -1.3209 | -1.4616 | -1.1937 |
| ACI | winter | 0.0435 | 274 | 8.2E-05 * | -1.1900 | -1.2959 | -1.0928 |
| BGN | autumn | 0.0576 | 274 | 7.7E-06 * | 1.3006 | 1.1617 | 1.4561 |
| ACI | autumn | 0.0484 | 274 | 0.3406 | - | - | - |
| ACI | summer | 0.0441 | 274 | 0.1875 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 10

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | winter | 0.1167 | 274 | 1.6E-31 * | -4.7274 | -5.9424 | -3.7608 |
| CVR | winter | 0.1049 | 274 | 7.8E-30 * | -3.8444 | -4.7223 | -3.1297 |
| EVN | autumn | 0.1299 | 274 | 4.4E-17 * | -3.2102 | -4.1406 | -2.4888 |
| PMN | winter | 0.0976 | 274 | 9.3E-27 * | -3.2074 | -3.8833 | -2.6492 |
| ENT | autumn | 0.1281 | 274 | 4.1E-17 * | -3.1641 | -4.0669 | -2.4616 |
| EVN | summer | 0.1182 | 274 | 3.5E-19 * | -3.1320 | -3.9488 | -2.4842 |
| ENT | winter | 0.1151 | 274 | 5.2E-20 * | -3.1316 | -3.9241 | -2.4991 |
| SPT | winter | 0.0873 | 274 | 1.2E-30 * | -3.1269 | -3.7102 | -2.6353 |
| POW | winter | 0.0880 | 274 | 4.7E-29 * | -3.0311 | -3.6014 | -2.5512 |
| ENT | summer | 0.1166 | 274 | 4E-18 * | -2.9643 | -3.7255 | -2.3587 |
| CVR | autumn | 0.1168 | 274 | 8.1E-17 * | -2.8257 | -3.5524 | -2.2476 |
| EVN | spring | 0.1435 | 274 | 5E-12 * | -2.8202 | -3.7365 | -2.1286 |
| ENT | spring | 0.1416 | 274 | 2.8E-12 * | -2.8171 | -3.7180 | -2.1345 |
| PMN | autumn | 0.1086 | 274 | 2.2E-18 * | -2.7748 | -3.4326 | -2.2430 |
| PMN | summer | 0.0988 | 274 | 4.2E-18 * | -2.5107 | -3.0474 | -2.0686 |
| POW | autumn | 0.0979 | 274 | 2.6E-18 * | -2.5036 | -3.0330 | -2.0667 |
| CVR | summer | 0.1063 | 274 | 1.8E-15 * | -2.4547 | -3.0233 | -1.9929 |
| SPT | autumn | 0.0971 | 274 | 2.3E-17 * | -2.4138 | -2.9199 | -1.9955 |
| PMN | spring | 0.1200 | 274 | 1.3E-11 * | -2.3346 | -2.9536 | -1.8453 |
| CVR | spring | 0.1291 | 274 | 5.4E-10 * | -2.2951 | -2.9558 | -1.7821 |
| RVT | winter | 0.0660 | 274 | 1.7E-26 * | -2.1881 | -2.4900 | -1.9228 |
| SPT | summer | 0.0884 | 274 | 2.9E-16 * | -2.1598 | -2.5684 | -1.8161 |
| RVT | autumn | 0.0734 | 274 | 2.6E-21 * | -2.1330 | -2.4629 | -1.8472 |
| POW | summer | 0.0891 | 274 | 6.1E-15 * | -2.0883 | -2.4867 | -1.7536 |
| POW | spring | 0.1082 | 274 | 6.2E-10 * | -2.0011 | -2.4737 | -1.6188 |
| SPT | spring | 0.1073 | 274 | 1.2E-09 * | -1.9672 | -2.4278 | -1.5940 |
| RNG | winter | 0.0571 | 274 | 3.3E-25 * | -1.9278 | -2.1562 | -1.7237 |
| R3D | autumn | 0.0629 | 274 | 2E-21 * | -1.9188 | -2.1707 | -1.6961 |
| RNG | autumn | 0.0636 | 274 | 6.9E-21 * | -1.9110 | -2.1646 | -1.6872 |
| RPS | winter | 0.0573 | 274 | 1.5E-24 * | -1.9102 | -2.1372 | -1.7072 |
| R3D | winter | 0.0566 | 274 | 5.7E-25 * | -1.9081 | -2.1318 | -1.7079 |
| RPS | autumn | 0.0638 | 274 | 1.7E-20 * | -1.9007 | -2.1537 | -1.6774 |
| BGN | winter | 0.1106 | 274 | 9.7E-08 * | -1.8330 | -2.2767 | -1.4758 |
| RHZ | winter | 0.0444 | 274 | 1.6E-28 * | -1.7378 | -1.8957 | -1.5931 |
| RVT | spring | 0.0811 | 274 | 6.1E-11 * | -1.7376 | -2.0370 | -1.4822 |
| BGN | spring | 0.1360 | 274 | 0.00017 * | -1.6794 | -2.1926 | -1.2864 |
| RVT | summer | 0.0668 | 274 | 3.1E-13 * | -1.6691 | -1.9026 | -1.4642 |
| RHZ | autumn | 0.0494 | 274 | 1.2E-20 * | -1.6475 | -1.8148 | -1.4956 |
| R3D | summer | 0.0573 | 274 | 3.2E-13 * | -1.5512 | -1.7356 | -1.3864 |
| ACI | spring | 0.0640 | 274 | 6.2E-11 * | -1.5464 | -1.7531 | -1.3640 |
| RPS | summer | 0.0580 | 274 | 2.4E-12 * | -1.5315 | -1.7160 | -1.3668 |
| RNG | summer | 0.0579 | 274 | 3.3E-12 * | -1.5248 | -1.7079 | -1.3613 |
| RHZ | summer | 0.0449 | 274 | 4.7E-16 * | -1.4744 | -1.6101 | -1.3501 |
| BGN | summer | 0.1120 | 274 | 0.00133 * | -1.4383 | -1.7915 | -1.1547 |
| ACI | summer | 0.0527 | 274 | 2.8E-08 * | -1.3521 | -1.4993 | -1.2193 |
| RHZ | spring | 0.0546 | 274 | 2.4E-06 * | -1.3007 | -1.4475 | -1.1688 |
| ACI | winter | 0.0520 | 274 | 9.1E-06 * | -1.2654 | -1.4013 | -1.1427 |
| R3D | spring | 0.0696 | 274 | 0.00094 * | -1.2620 | -1.4464 | -1.1011 |
| RNG | spring | 0.0703 | 274 | 0.00119 * | -1.2586 | -1.4445 | -1.0967 |
| RPS | spring | 0.0705 | 274 | 0.00136 * | -1.2562 | -1.4423 | -1.0942 |
| ACI | autumn | 0.0579 | 274 | 0.02521 * | -1.1392 | -1.2761 | -1.0170 |
| BGN | autumn | 0.1231 | 274 | 1.7E-08 * | 2.0451 | 1.6068 | 2.6029 |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 11

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | summer | 0.1532 | 274 | 3E-14 * | -3.4199 | -4.6179 | -2.5327 |
| ENT | summer | 0.1287 | 274 | 3.9E-17 * | -3.1855 | -4.0998 | -2.4751 |
| PMN | summer | 0.1198 | 274 | 8.8E-15 * | -2.6745 | -3.3826 | -2.1146 |
| CVR | summer | 0.1324 | 274 | 4.6E-12 * | -2.6068 | -3.3788 | -2.0111 |
| EVN | winter | 0.1512 | 274 | 1.9E-09 * | -2.5615 | -3.4454 | -1.9044 |
| BGN | winter | 0.1222 | 274 | 4.1E-11 * | -2.3176 | -2.9449 | -1.8239 |
| CVR | winter | 0.1307 | 274 | 7.5E-10 * | -2.3017 | -2.9735 | -1.7817 |
| SPT | summer | 0.1131 | 274 | 5.1E-12 * | -2.2627 | -2.8241 | -1.8130 |
| POW | summer | 0.1098 | 274 | 9.3E-12 * | -2.1866 | -2.7118 | -1.7632 |
| SPT | winter | 0.1116 | 274 | 4.4E-09 * | -1.9674 | -2.4484 | -1.5808 |
| POW | winter | 0.1084 | 274 | 3.8E-09 * | -1.9354 | -2.3935 | -1.5649 |
| PMN | winter | 0.1183 | 274 | 7.8E-07 * | -1.8190 | -2.2937 | -1.4426 |
| RVT | summer | 0.0817 | 274 | 5.7E-12 * | -1.8019 | -2.1151 | -1.5352 |
| ENT | winter | 0.1271 | 274 | 6.2E-05 * | -1.6773 | -2.1516 | -1.3075 |
| RPS | summer | 0.0706 | 274 | 1.6E-11 * | -1.6432 | -1.8869 | -1.4310 |
| R3D | summer | 0.0692 | 274 | 9.2E-12 * | -1.6374 | -1.8753 | -1.4297 |
| RNG | summer | 0.0699 | 274 | 1.7E-11 * | -1.6336 | -1.8734 | -1.4244 |
| RVT | winter | 0.0807 | 274 | 2.6E-08 * | -1.5881 | -1.8602 | -1.3558 |
| BGN | summer | 0.1238 | 274 | 0.00037 * | -1.5621 | -1.9911 | -1.2255 |
| ACI | summer | 0.0677 | 274 | 2.3E-10 * | -1.5620 | -1.7838 | -1.3678 |
| RPS | winter | 0.0696 | 274 | 1.2E-09 * | -1.5503 | -1.7770 | -1.3524 |
| RNG | winter | 0.0690 | 274 | 9.6E-10 * | -1.5483 | -1.7725 | -1.3525 |
| ENT | spring | 0.1563 | 274 | 0.00578 * | -1.5447 | -2.0984 | -1.1371 |
| R3D | winter | 0.0683 | 274 | 1.1E-09 * | -1.5386 | -1.7590 | -1.3458 |
| RHZ | summer | 0.0550 | 274 | 5E-12 * | -1.4874 | -1.6566 | -1.3355 |
| RHZ | winter | 0.0542 | 274 | 1.3E-09 * | -1.4057 | -1.5633 | -1.2639 |
| RVT | spring | 0.0992 | 274 | 0.03196 * | -1.2386 | -1.5046 | -1.0196 |
| ACI | spring | 0.0822 | 274 | 0.01141 * | -1.2330 | -1.4487 | -1.0495 |
| RNG | autumn | 0.0768 | 274 | 0.01402 * | -1.2090 | -1.4053 | -1.0401 |
| RPS | autumn | 0.0775 | 274 | 0.01798 * | -1.2026 | -1.3998 | -1.0331 |
| R3D | autumn | 0.0760 | 274 | 0.01761 * | -1.1991 | -1.3917 | -1.0331 |
| RHZ | autumn | 0.0604 | 274 | 0.01454 * | -1.1600 | -1.3057 | -1.0306 |
| BGN | autumn | 0.1360 | 274 | 1.7E-07 * | 2.0753 | 1.5897 | 2.7092 |
| RHZ | spring | 0.0667 | 274 | 0.8736 | - | - | - |
| R3D | spring | 0.0840 | 274 | 0.8733 | - | - | - |
| EVN | autumn | 0.1683 | 274 | 0.8469 | - | - | - |
| RPS | spring | 0.0857 | 274 | 0.5683 | - | - | - |
| RNG | spring | 0.0849 | 274 | 0.5268 | - | - | - |
| CVR | autumn | 0.1454 | 274 | 0.3883 | - | - | - |
| PMN | autumn | 0.1316 | 274 | 0.3232 | - | - | - |
| SPT | autumn | 0.1242 | 274 | 0.2972 | - | - | - |
| ACI | winter | 0.0669 | 274 | 0.2895 | - | - | - |
| SPT | spring | 0.1373 | 274 | 0.2839 | - | - | - |
| BGN | spring | 0.1503 | 274 | 0.2770 | - | - | - |
| CVR | spring | 0.1607 | 274 | 0.2676 | - | - | - |
| POW | spring | 0.1333 | 274 | 0.2064 | - | - | - |
| POW | autumn | 0.1206 | 274 | 0.2058 | - | - | - |
| ENT | autumn | 0.1414 | 274 | 0.1308 | - | - | - |
| RVT | autumn | 0.0898 | 274 | 0.1168 | - | - | - |
| PMN | spring | 0.1455 | 274 | 0.1042 | - | - | - |
| EVN | spring | 0.1860 | 274 | 0.1005 | - | - | - |
| ACI | autumn | 0.0744 | 274 | 0.0516 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 12

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | winter | 0.1197 | 274 | 1.8E-23 * | -3.7236 | -4.7086 | -2.9446 |
| CVR | winter | 0.1039 | 274 | 1.5E-23 * | -3.1363 | -3.8448 | -2.5584 |
| EVN | summer | 0.1213 | 274 | 1.6E-15 * | -2.7919 | -3.5413 | -2.2011 |
| ENT | summer | 0.1033 | 274 | 5.7E-18 * | -2.6056 | -3.1903 | -2.1280 |
| SPT | winter | 0.0842 | 274 | 7.6E-24 * | -2.5433 | -2.9996 | -2.1564 |
| POW | winter | 0.0836 | 274 | 4.3E-23 * | -2.4795 | -2.9209 | -2.1048 |
| PMN | winter | 0.0872 | 274 | 4.1E-21 * | -2.4462 | -2.9020 | -2.0620 |
| ENT | winter | 0.1020 | 274 | 5.3E-15 * | -2.3278 | -2.8427 | -1.9061 |
| EVN | autumn | 0.1332 | 274 | 1.3E-09 * | -2.3117 | -3.0015 | -1.7804 |
| CVR | summer | 0.1053 | 274 | 3.1E-12 * | -2.1569 | -2.6512 | -1.7548 |
| CVR | autumn | 0.1156 | 274 | 2.2E-10 * | -2.1439 | -2.6892 | -1.7092 |
| PMN | summer | 0.0883 | 274 | 9.8E-16 * | -2.1248 | -2.5263 | -1.7871 |
| BGN | winter | 0.0944 | 274 | 4.1E-12 * | -1.9833 | -2.3863 | -1.6484 |
| POW | autumn | 0.0930 | 274 | 1.3E-11 * | -1.9296 | -2.3154 | -1.6080 |
| ENT | autumn | 0.1135 | 274 | 4.2E-08 * | -1.8963 | -2.3685 | -1.5182 |
| PMN | autumn | 0.0970 | 274 | 3.9E-10 * | -1.8775 | -2.2706 | -1.5524 |
| SPT | autumn | 0.0937 | 274 | 1.4E-10 * | -1.8691 | -2.2458 | -1.5556 |
| RVT | winter | 0.0580 | 274 | 1.1E-22 * | -1.8635 | -2.0877 | -1.6634 |
| RNG | winter | 0.0548 | 274 | 1E-23 * | -1.8323 | -2.0401 | -1.6458 |
| SPT | summer | 0.0853 | 274 | 1.3E-11 * | -1.8282 | -2.1608 | -1.5468 |
| RPS | winter | 0.0533 | 274 | 9.1E-24 * | -1.8045 | -2.0034 | -1.6253 |
| POW | summer | 0.0847 | 274 | 4.2E-11 * | -1.7900 | -2.1131 | -1.5162 |
| R3D | winter | 0.0515 | 274 | 2.2E-23 * | -1.7581 | -1.9449 | -1.5892 |
| RVT | autumn | 0.0645 | 274 | 6.3E-14 * | -1.6658 | -1.8903 | -1.4680 |
| RNG | autumn | 0.0610 | 274 | 9.1E-14 * | -1.6143 | -1.8192 | -1.4325 |
| RPS | autumn | 0.0594 | 274 | 1.1E-13 * | -1.5910 | -1.7873 | -1.4162 |
| RHZ | winter | 0.0419 | 274 | 6.9E-22 * | -1.5529 | -1.6859 | -1.4303 |
| R3D | autumn | 0.0573 | 274 | 3.3E-13 * | -1.5510 | -1.7355 | -1.3861 |
| RVT | summer | 0.0587 | 274 | 3.1E-11 * | -1.5016 | -1.6847 | -1.3383 |
| ENT | spring | 0.1254 | 274 | 0.00396 * | -1.4398 | -1.8410 | -1.1260 |
| RNG | summer | 0.0555 | 274 | 1.4E-09 * | -1.4162 | -1.5790 | -1.2702 |
| RPS | summer | 0.0540 | 274 | 2.8E-09 * | -1.3940 | -1.5497 | -1.2539 |
| RHZ | autumn | 0.0467 | 274 | 1.6E-11 * | -1.3887 | -1.5217 | -1.2674 |
| R3D | summer | 0.0522 | 274 | 4.4E-09 * | -1.3725 | -1.5204 | -1.2390 |
| RHZ | summer | 0.0425 | 274 | 9.9E-08 * | -1.2618 | -1.3713 | -1.1610 |
| ACI | summer | 0.0359 | 274 | 5.9E-09 * | -1.2404 | -1.3307 | -1.1562 |
| ACI | spring | 0.0435 | 274 | 0.02358 * | -1.1042 | -1.2025 | -1.0139 |
| ACI | winter | 0.0354 | 274 | 0.0358 * | -1.0775 | -1.1549 | -1.0053 |
| BGN | autumn | 0.1050 | 274 | 1E-11 * | 2.1087 | 1.7165 | 2.5905 |
| R3D | spring | 0.0634 | 274 | 0.7842 | - | - | - |
| RHZ | spring | 0.0516 | 274 | 0.6938 | - | - | - |
| RPS | spring | 0.0656 | 274 | 0.5317 | - | - | - |
| RNG | spring | 0.0674 | 274 | 0.5194 | - | - | - |
| BGN | summer | 0.0956 | 274 | 0.4775 | - | - | - |
| SPT | spring | 0.1035 | 274 | 0.3881 | - | - | - |
| ACI | autumn | 0.0394 | 274 | 0.3814 | - | - | - |
| CVR | spring | 0.1278 | 274 | 0.2884 | - | - | - |
| POW | spring | 0.1028 | 274 | 0.2877 | - | - | - |
| BGN | spring | 0.1161 | 274 | 0.1584 | - | - | - |
| PMN | spring | 0.1072 | 274 | 0.1367 | - | - | - |
| EVN | spring | 0.1473 | 274 | 0.0933 | - | - | - |
| RVT | spring | 0.0713 | 274 | 0.0545 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 13

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1645 | 274 | 1.8E-13 * | -3.5791 | -4.9410 | -2.5926 |
| SPT | autumn | 0.1252 | 274 | 2.8E-18 * | -3.2312 | -4.1296 | -2.5282 |
| ENT | winter | 0.1479 | 274 | 1E-12 * | -3.0227 | -4.0389 | -2.2622 |
| PMN | autumn | 0.1198 | 274 | 3.2E-16 * | -2.8356 | -3.5864 | -2.2420 |
| CVR | autumn | 0.1140 | 274 | 5.4E-17 * | -2.7737 | -3.4678 | -2.2184 |
| EVN | autumn | 0.1113 | 274 | 6.7E-17 * | -2.7008 | -3.3595 | -2.1712 |
| SPT | winter | 0.1125 | 274 | 4.7E-16 * | -2.6437 | -3.2958 | -2.1206 |
| POW | autumn | 0.1013 | 274 | 6E-18 * | -2.5548 | -3.1157 | -2.0949 |
| ENT | spring | 0.1819 | 274 | 5.9E-06 * | -2.3178 | -3.3104 | -1.6228 |
| PMN | winter | 0.1077 | 274 | 2E-13 * | -2.2997 | -2.8402 | -1.8621 |
| EVN | winter | 0.1001 | 274 | 1.2E-13 * | -2.1844 | -2.6578 | -1.7954 |
| RVT | autumn | 0.0799 | 274 | 3.5E-19 * | -2.1639 | -2.5309 | -1.8502 |
| CVR | winter | 0.1024 | 274 | 1.6E-12 * | -2.1357 | -2.6105 | -1.7473 |
| POW | winter | 0.0910 | 274 | 6.1E-14 * | -2.0555 | -2.4568 | -1.7197 |
| EVN | spring | 0.1231 | 274 | 1.5E-08 * | -2.0498 | -2.6090 | -1.6104 |
| PMN | spring | 0.1325 | 274 | 2.4E-07 * | -2.0186 | -2.6171 | -1.5570 |
| RPS | autumn | 0.0640 | 274 | 1.1E-22 * | -1.9891 | -2.2550 | -1.7545 |
| CVR | spring | 0.1260 | 274 | 2.9E-07 * | -1.9402 | -2.4835 | -1.5157 |
| RVT | winter | 0.0718 | 274 | 1.1E-17 * | -1.9341 | -2.2265 | -1.6801 |
| RHZ | autumn | 0.0607 | 274 | 4.7E-22 * | -1.8971 | -2.1369 | -1.6843 |
| R3D | autumn | 0.0585 | 274 | 1.8E-22 * | -1.8668 | -2.0935 | -1.6645 |
| RNG | autumn | 0.0586 | 274 | 2.2E-21 * | -1.8335 | -2.0567 | -1.6345 |
| POW | spring | 0.1119 | 274 | 3.2E-07 * | -1.7978 | -2.2389 | -1.4437 |
| BGN | winter | 0.0654 | 274 | 1.1E-16 * | -1.7847 | -2.0290 | -1.5699 |
| RPS | winter | 0.0575 | 274 | 7.2E-20 * | -1.7649 | -1.9756 | -1.5767 |
| SPT | spring | 0.1384 | 274 | 9.9E-05 * | -1.7275 | -2.2656 | -1.3172 |
| RHZ | winter | 0.0546 | 274 | 3.9E-20 * | -1.7217 | -1.9160 | -1.5471 |
| SPT | summer | 0.1140 | 274 | 3.1E-06 * | -1.7210 | -2.1517 | -1.3765 |
| R3D | winter | 0.0526 | 274 | 9.7E-20 * | -1.6769 | -1.8589 | -1.5128 |
| RNG | winter | 0.0527 | 274 | 6.2E-19 * | -1.6564 | -1.8366 | -1.4939 |
| EVN | summer | 0.1014 | 274 | 1.5E-06 * | -1.6456 | -2.0073 | -1.3490 |
| PMN | summer | 0.1091 | 274 | 8.6E-06 * | -1.6404 | -2.0316 | -1.3246 |
| CVR | summer | 0.1038 | 274 | 5.6E-06 * | -1.6168 | -1.9814 | -1.3193 |
| ENT | summer | 0.1498 | 274 | 0.00207 * | -1.5933 | -2.1370 | -1.1879 |
| RVT | spring | 0.0884 | 274 | 3.1E-07 * | -1.5902 | -1.8908 | -1.3373 |
| POW | summer | 0.0922 | 274 | 1.7E-06 * | -1.5702 | -1.8812 | -1.3106 |
| BGN | summer | 0.0663 | 274 | 1.5E-10 * | -1.5557 | -1.7716 | -1.3661 |
| RHZ | summer | 0.0553 | 274 | 1.6E-10 * | -1.4441 | -1.6093 | -1.2958 |
| RVT | summer | 0.0728 | 274 | 2.8E-06 * | -1.4162 | -1.6333 | -1.2279 |
| BGN | spring | 0.0805 | 274 | 0.0001 * | -1.3730 | -1.6076 | -1.1726 |
| RPS | summer | 0.0583 | 274 | 2.1E-07 * | -1.3641 | -1.5292 | -1.2168 |
| R3D | summer | 0.0533 | 274 | 2.3E-08 * | -1.3590 | -1.5085 | -1.2243 |
| R3D | spring | 0.0647 | 274 | 4.9E-06 * | -1.3520 | -1.5346 | -1.1910 |
| RHZ | spring | 0.0671 | 274 | 2.1E-05 * | -1.3374 | -1.5254 | -1.1726 |
| RNG | summer | 0.0534 | 274 | 2.9E-07 * | -1.3240 | -1.4700 | -1.1925 |
| RPS | spring | 0.0708 | 274 | 0.00015 * | -1.3132 | -1.5086 | -1.1431 |
| RNG | spring | 0.0648 | 274 | 6.9E-05 * | -1.2994 | -1.4754 | -1.1445 |
| ACI | spring | 0.0637 | 274 | 0.00409 * | -1.2024 | -1.3623 | -1.0614 |
| BGN | autumn | 0.0728 | 274 | 2.2E-05 * | 1.3697 | 1.1875 | 1.5799 |
| ACI | summer | 0.0524 | 274 | 0.9427 | - | - | - |
| ACI | autumn | 0.0576 | 274 | 0.6009 | - | - | - |
| ACI | winter | 0.0518 | 274 | 0.1660 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 14

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | winter | 0.1283 | 274 | 8.2E-20 * | -3.5410 | -4.5531 | -2.7538 |
| EVN | winter | 0.1335 | 274 | 2.5E-14 * | -2.9297 | -3.8060 | -2.2552 |
| PMN | winter | 0.0957 | 274 | 5.8E-20 * | -2.5800 | -3.1123 | -2.1388 |
| CVR | winter | 0.1105 | 274 | 1.3E-15 * | -2.5565 | -3.1745 | -2.0588 |
| ENT | spring | 0.1578 | 274 | 8.3E-09 * | -2.5552 | -3.4812 | -1.8755 |
| EVN | spring | 0.1642 | 274 | 2.9E-07 * | -2.3711 | -3.2714 | -1.7186 |
| POW | winter | 0.0855 | 274 | 2.7E-17 * | -2.1688 | -2.5645 | -1.8341 |
| SPT | winter | 0.0835 | 274 | 7.4E-18 * | -2.1629 | -2.5478 | -1.8362 |
| PMN | spring | 0.1177 | 274 | 6.6E-10 * | -2.1249 | -2.6763 | -1.6871 |
| CVR | spring | 0.1359 | 274 | 5.5E-07 * | -2.0077 | -2.6203 | -1.5384 |
| EVN | summer | 0.1353 | 274 | 6.2E-07 * | -1.9948 | -2.6004 | -1.5303 |
| ENT | autumn | 0.1427 | 274 | 3E-06 * | -1.9757 | -2.6134 | -1.4935 |
| ENT | summer | 0.1300 | 274 | 3.5E-07 * | -1.9718 | -2.5438 | -1.5284 |
| EVN | autumn | 0.1486 | 274 | 3.3E-05 * | -1.8717 | -2.5043 | -1.3989 |
| POW | spring | 0.1052 | 274 | 3.8E-08 * | -1.8134 | -2.2286 | -1.4756 |
| PMN | summer | 0.0969 | 274 | 4.9E-09 * | -1.7967 | -2.1727 | -1.4858 |
| RVT | winter | 0.0689 | 274 | 9E-15 * | -1.7596 | -2.0139 | -1.5375 |
| SPT | spring | 0.1028 | 274 | 1.7E-07 * | -1.7363 | -2.1237 | -1.4196 |
| CVR | summer | 0.1119 | 274 | 1.7E-06 * | -1.7279 | -2.1517 | -1.3876 |
| PMN | autumn | 0.1065 | 274 | 1.4E-06 * | -1.6905 | -2.0828 | -1.3721 |
| CVR | autumn | 0.1229 | 274 | 3.1E-05 * | -1.6831 | -2.1416 | -1.3228 |
| BGN | winter | 0.1426 | 274 | 0.00036 * | -1.6746 | -2.2144 | -1.2664 |
| SPT | summer | 0.0846 | 274 | 2.7E-08 * | -1.6233 | -1.9162 | -1.3752 |
| POW | summer | 0.0866 | 274 | 5.7E-08 * | -1.6218 | -1.9219 | -1.3686 |
| RNG | winter | 0.0576 | 274 | 5E-15 * | -1.6123 | -1.8049 | -1.4402 |
| RVT | spring | 0.0847 | 274 | 4.9E-08 * | -1.6088 | -1.8993 | -1.3627 |
| RPS | winter | 0.0573 | 274 | 2.2E-14 * | -1.5885 | -1.7773 | -1.4197 |
| R3D | winter | 0.0602 | 274 | 7.5E-13 * | -1.5729 | -1.7698 | -1.3979 |
| POW | autumn | 0.0951 | 274 | 7.9E-06 * | -1.5424 | -1.8586 | -1.2800 |
| SPT | autumn | 0.0930 | 274 | 2E-05 * | -1.4970 | -1.7962 | -1.2476 |
| BGN | summer | 0.1444 | 274 | 0.00749 * | -1.4757 | -1.9585 | -1.1119 |
| RVT | summer | 0.0698 | 274 | 1.6E-07 * | -1.4551 | -1.6682 | -1.2691 |
| BGN | spring | 0.1753 | 274 | 0.03603 * | -1.4469 | -2.0403 | -1.0261 |
| RHZ | winter | 0.0440 | 274 | 3.8E-15 * | -1.4428 | -1.5727 | -1.3237 |
| RVT | autumn | 0.0766 | 274 | 6E-06 * | -1.4244 | -1.6552 | -1.2258 |
| R3D | summer | 0.0610 | 274 | 5.7E-08 * | -1.4053 | -1.5836 | -1.2470 |
| RNG | summer | 0.0583 | 274 | 4.6E-08 * | -1.3882 | -1.5564 | -1.2382 |
| RPS | summer | 0.0581 | 274 | 5.9E-08 * | -1.3824 | -1.5490 | -1.2337 |
| RNG | autumn | 0.0641 | 274 | 4.6E-06 * | -1.3493 | -1.5298 | -1.1900 |
| RHZ | summer | 0.0446 | 274 | 6.7E-10 * | -1.3300 | -1.4514 | -1.2188 |
| R3D | autumn | 0.0670 | 274 | 2.9E-05 * | -1.3295 | -1.5160 | -1.1660 |
| RPS | autumn | 0.0638 | 274 | 1.2E-05 * | -1.3294 | -1.5064 | -1.1732 |
| RHZ | autumn | 0.0489 | 274 | 3.7E-06 * | -1.2601 | -1.3870 | -1.1449 |
| RHZ | spring | 0.0541 | 274 | 3E-05 * | -1.2581 | -1.3989 | -1.1316 |
| R3D | spring | 0.0740 | 274 | 0.00653 * | -1.2249 | -1.4161 | -1.0595 |
| ACI | spring | 0.0793 | 274 | 0.01148 * | -1.2235 | -1.4292 | -1.0475 |
| RPS | spring | 0.0705 | 274 | 0.00754 * | -1.2090 | -1.3881 | -1.0530 |
| RNG | spring | 0.0708 | 274 | 0.00822 * | -1.2075 | -1.3873 | -1.0510 |
| ACI | winter | 0.0644 | 274 | 0.03332 * | -1.1478 | -1.3024 | -1.0116 |
| BGN | autumn | 0.1586 | 274 | 5.2E-05 * | 1.9200 | 1.4070 | 2.6202 |
| ACI | autumn | 0.0717 | 274 | 0.8781 | - | - | - |
| ACI | summer | 0.0653 | 274 | 0.1718 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 15

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1232 | 274 | 9E-05 * | -1.6318 | -2.0776 | -1.2817 |
| EVN | spring | 0.1276 | 274 | 0.00018 * | -1.6233 | -2.0844 | -1.2642 |
| CVR | spring | 0.1117 | 274 | 4E-05 * | -1.5951 | -1.9856 | -1.2813 |
| PMN | spring | 0.0977 | 274 | 5.4E-06 * | -1.5731 | -1.9050 | -1.2990 |
| EVN | summer | 0.1051 | 274 | 3.4E-05 * | -1.5566 | -1.9126 | -1.2669 |
| POW | spring | 0.0908 | 274 | 8.2E-06 * | -1.5111 | -1.8055 | -1.2648 |
| ENT | summer | 0.1015 | 274 | 0.00013 * | -1.4832 | -1.8096 | -1.2156 |
| PMN | summer | 0.0804 | 274 | 3E-05 * | -1.4067 | -1.6469 | -1.2015 |
| SPT | spring | 0.0889 | 274 | 0.00019 * | -1.4006 | -1.6672 | -1.1766 |
| CVR | summer | 0.0920 | 274 | 0.00054 * | -1.3800 | -1.6528 | -1.1522 |
| RVT | spring | 0.0769 | 274 | 6.7E-05 * | -1.3650 | -1.5869 | -1.1741 |
| POW | summer | 0.0748 | 274 | 0.00023 * | -1.3224 | -1.5312 | -1.1421 |
| SPT | summer | 0.0732 | 274 | 0.00037 * | -1.3025 | -1.5035 | -1.1284 |
| RVT | summer | 0.0633 | 274 | 4E-05 * | -1.3024 | -1.4745 | -1.1504 |
| R3D | summer | 0.0561 | 274 | 7.8E-05 * | -1.2525 | -1.3982 | -1.1220 |
| ENT | winter | 0.1002 | 274 | 0.02977 * | -1.2446 | -1.5147 | -1.0227 |
| RPS | summer | 0.0549 | 274 | 9.2E-05 * | -1.2434 | -1.3845 | -1.1166 |
| RNG | summer | 0.0548 | 274 | 0.00015 * | -1.2345 | -1.3746 | -1.1087 |
| RPS | spring | 0.0666 | 274 | 0.00361 * | -1.2159 | -1.3855 | -1.0671 |
| R3D | spring | 0.0682 | 274 | 0.00517 * | -1.2119 | -1.3851 | -1.0603 |
| RNG | spring | 0.0666 | 274 | 0.00503 * | -1.2071 | -1.3754 | -1.0595 |
| ACI | autumn | 0.0703 | 274 | 0.01341 * | -1.1912 | -1.3672 | -1.0379 |
| ACI | summer | 0.0640 | 274 | 0.00853 * | -1.1848 | -1.3432 | -1.0451 |
| RHZ | spring | 0.0509 | 274 | 0.00146 * | -1.1779 | -1.3015 | -1.0660 |
| RVT | autumn | 0.0695 | 274 | 0.02533 * | -1.1693 | -1.3400 | -1.0203 |
| RHZ | summer | 0.0419 | 274 | 0.00025 * | -1.1681 | -1.2682 | -1.0760 |
| RHZ | autumn | 0.0461 | 274 | 0.04281 * | -1.0983 | -1.2020 | -1.0035 |
| BGN | autumn | 0.1174 | 274 | 1.1E-10 * | 2.1980 | 1.7461 | 2.7670 |
| RNG | winter | 0.0541 | 274 | 0.9911 | - | - | - |
| RPS | winter | 0.0541 | 274 | 0.9873 | - | - | - |
| BGN | winter | 0.1056 | 274 | 0.9609 | - | - | - |
| POW | winter | 0.0738 | 274 | 0.9144 | - | - | - |
| PMN | autumn | 0.0884 | 274 | 0.7430 | - | - | - |
| SPT | winter | 0.0723 | 274 | 0.7126 | - | - | - |
| EVN | autumn | 0.1154 | 274 | 0.5574 | - | - | - |
| R3D | winter | 0.0554 | 274 | 0.4619 | - | - | - |
| PMN | winter | 0.0794 | 274 | 0.4264 | - | - | - |
| CVR | autumn | 0.1011 | 274 | 0.4150 | - | - | - |
| RHZ | winter | 0.0414 | 274 | 0.3860 | - | - | - |
| ENT | autumn | 0.1115 | 274 | 0.2959 | - | - | - |
| CVR | winter | 0.0909 | 274 | 0.2733 | - | - | - |
| POW | autumn | 0.0821 | 274 | 0.2374 | - | - | - |
| SPT | autumn | 0.0804 | 274 | 0.2240 | - | - | - |
| RVT | winter | 0.0625 | 274 | 0.1894 | - | - | - |
| BGN | summer | 0.1069 | 274 | 0.1891 | - | - | - |
| ACI | spring | 0.0777 | 274 | 0.1759 | - | - | - |
| RPS | autumn | 0.0602 | 274 | 0.1333 | - | - | - |
| BGN | spring | 0.1298 | 274 | 0.1330 | - | - | - |
| ACI | winter | 0.0632 | 274 | 0.1257 | - | - | - |
| RNG | autumn | 0.0602 | 274 | 0.1186 | - | - | - |
| EVN | winter | 0.1037 | 274 | 0.0920 | - | - | - |
| R3D | autumn | 0.0617 | 274 | 0.0629 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 16

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | autumn | 0.1421 | 274 | 1.4E-12 * | -2.8734 | -3.7960 | -2.1750 |
| CVR | autumn | 0.1240 | 274 | 1.8E-15 * | -2.8480 | -3.6314 | -2.2337 |
| ENT | autumn | 0.1376 | 274 | 1.5E-12 * | -2.7772 | -3.6372 | -2.1206 |
| PMN | autumn | 0.1070 | 274 | 1.7E-17 * | -2.6533 | -3.2727 | -2.1512 |
| EVN | winter | 0.1277 | 274 | 5.1E-11 * | -2.3956 | -3.0768 | -1.8653 |
| ENT | winter | 0.1237 | 274 | 1.8E-11 * | -2.3803 | -3.0333 | -1.8679 |
| POW | autumn | 0.0975 | 274 | 4.9E-16 * | -2.3206 | -2.8093 | -1.9169 |
| EVN | spring | 0.1570 | 274 | 6.4E-07 * | -2.2274 | -3.0302 | -1.6373 |
| SPT | autumn | 0.0961 | 274 | 1.4E-14 * | -2.1860 | -2.6392 | -1.8107 |
| CVR | winter | 0.1114 | 274 | 7.5E-11 * | -2.1275 | -2.6467 | -1.7101 |
| PMN | winter | 0.0962 | 274 | 3.4E-11 * | -1.9436 | -2.3469 | -1.6096 |
| CVR | spring | 0.1370 | 274 | 2.4E-06 * | -1.9342 | -2.5302 | -1.4786 |
| POW | winter | 0.0876 | 274 | 2.1E-10 * | -1.7828 | -2.1168 | -1.5014 |
| SPT | winter | 0.0864 | 274 | 1.4E-10 * | -1.7796 | -2.1079 | -1.5024 |
| EVN | summer | 0.1293 | 274 | 2.4E-05 * | -1.7442 | -2.2475 | -1.3536 |
| RVT | autumn | 0.0756 | 274 | 3.5E-12 * | -1.7341 | -2.0111 | -1.4953 |
| RNG | autumn | 0.0685 | 274 | 1.3E-13 * | -1.7059 | -1.9509 | -1.4916 |
| POW | spring | 0.1078 | 274 | 1.5E-06 * | -1.7002 | -2.1001 | -1.3764 |
| SPT | spring | 0.1062 | 274 | 1.7E-06 * | -1.6818 | -2.0711 | -1.3656 |
| PMN | spring | 0.1183 | 274 | 2.1E-05 * | -1.6681 | -2.1035 | -1.3229 |
| RPS | autumn | 0.0665 | 274 | 3E-13 * | -1.6660 | -1.8981 | -1.4623 |
| ENT | spring | 0.1521 | 274 | 0.00111 * | -1.6508 | -2.2243 | -1.2252 |
| R3D | autumn | 0.0650 | 274 | 3.3E-13 * | -1.6444 | -1.8677 | -1.4478 |
| CVR | summer | 0.1129 | 274 | 0.00017 * | -1.5370 | -1.9176 | -1.2320 |
| RVT | spring | 0.0836 | 274 | 9.2E-06 * | -1.4590 | -1.7187 | -1.2385 |
| RVT | winter | 0.0680 | 274 | 1.2E-07 * | -1.4470 | -1.6531 | -1.2666 |
| RHZ | autumn | 0.0485 | 274 | 4.7E-12 * | -1.4199 | -1.5614 | -1.2913 |
| RNG | spring | 0.0757 | 274 | 2.2E-05 * | -1.3865 | -1.6082 | -1.1953 |
| RPS | spring | 0.0735 | 274 | 1.7E-05 * | -1.3796 | -1.5936 | -1.1944 |
| SPT | summer | 0.0875 | 274 | 0.0003 * | -1.3781 | -1.6360 | -1.1609 |
| RNG | winter | 0.0615 | 274 | 3.8E-07 * | -1.3777 | -1.5543 | -1.2212 |
| POW | summer | 0.0888 | 274 | 0.00041 * | -1.3741 | -1.6353 | -1.1547 |
| R3D | spring | 0.0718 | 274 | 2E-05 * | -1.3662 | -1.5727 | -1.1869 |
| RPS | winter | 0.0598 | 274 | 5.1E-07 * | -1.3603 | -1.5295 | -1.2099 |
| R3D | winter | 0.0584 | 274 | 1.4E-06 * | -1.3333 | -1.4949 | -1.1891 |
| PMN | summer | 0.0975 | 274 | 0.005 * | -1.3176 | -1.5949 | -1.0885 |
| RHZ | spring | 0.0536 | 274 | 1.2E-06 * | -1.3049 | -1.4494 | -1.1749 |
| RHZ | winter | 0.0436 | 274 | 6.5E-07 * | -1.2484 | -1.3597 | -1.1463 |
| RVT | summer | 0.0688 | 274 | 0.01022 * | -1.1949 | -1.3675 | -1.0440 |
| RNG | summer | 0.0623 | 274 | 0.00947 * | -1.1769 | -1.3299 | -1.0416 |
| RPS | summer | 0.0606 | 274 | 0.01025 * | -1.1695 | -1.3170 | -1.0386 |
| R3D | summer | 0.0591 | 274 | 0.00882 * | -1.1688 | -1.3125 | -1.0409 |
| RHZ | summer | 0.0441 | 274 | 0.00279 * | -1.1424 | -1.2456 | -1.0477 |
| BGN | autumn | 0.0991 | 274 | 1.6E-20 * | 2.7148 | 2.2354 | 3.2970 |
| ACI | spring | 0.0574 | 274 | 0.8391 | - | - | - |
| ACI | summer | 0.0473 | 274 | 0.7585 | - | - | - |
| BGN | spring | 0.1096 | 274 | 0.4509 | - | - | - |
| ACI | winter | 0.0467 | 274 | 0.3050 | - | - | - |
| ACI | autumn | 0.0519 | 274 | 0.2974 | - | - | - |
| BGN | winter | 0.0891 | 274 | 0.2091 | - | - | - |
| ENT | summer | 0.1253 | 274 | 0.1046 | - | - | - |
| BGN | summer | 0.0903 | 274 | 0.0923 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 17

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | winter | 0.1701 | 274 | 7.6E-14 * | -3.8243 | -5.3379 | -2.7398 |
| ENT | autumn | 0.1893 | 274 | 9.4E-11 * | -3.5816 | -5.1906 | -2.4713 |
| SPT | winter | 0.1220 | 274 | 2.3E-18 * | -3.1476 | -3.9977 | -2.4783 |
| SPT | autumn | 0.1357 | 274 | 1.8E-13 * | -2.8625 | -3.7348 | -2.1939 |
| PMN | winter | 0.1239 | 274 | 9.4E-15 * | -2.7617 | -3.5207 | -2.1663 |
| PMN | autumn | 0.1378 | 274 | 2.5E-12 * | -2.7484 | -3.6010 | -2.0977 |
| CVR | autumn | 0.1312 | 274 | 6.1E-13 * | -2.6959 | -3.4865 | -2.0846 |
| EVN | autumn | 0.1278 | 274 | 1.1E-12 * | -2.5971 | -3.3366 | -2.0215 |
| CVR | winter | 0.1179 | 274 | 1.3E-13 * | -2.5102 | -3.1629 | -1.9922 |
| EVN | winter | 0.1149 | 274 | 4.7E-14 * | -2.4943 | -3.1243 | -1.9914 |
| POW | autumn | 0.1154 | 274 | 2.2E-13 * | -2.4356 | -3.0536 | -1.9427 |
| POW | winter | 0.1037 | 274 | 1.8E-14 * | -2.3160 | -2.8379 | -1.8901 |
| ENT | spring | 0.2093 | 274 | 9.7E-05 * | -2.2888 | -3.4494 | -1.5187 |
| RVT | autumn | 0.0852 | 274 | 9.4E-15 * | -2.0105 | -2.3757 | -1.7014 |
| RVT | winter | 0.0765 | 274 | 3.9E-16 * | -1.9417 | -2.2560 | -1.6712 |
| PMN | spring | 0.1524 | 274 | 3E-05 * | -1.9101 | -2.5749 | -1.4170 |
| RPS | autumn | 0.0652 | 274 | 8.8E-19 * | -1.8622 | -2.1163 | -1.6387 |
| ENT | summer | 0.1724 | 274 | 0.00044 * | -1.8465 | -2.5886 | -1.3171 |
| BGN | winter | 0.0705 | 273 | 7.6E-16 * | -1.8302 | -2.1014 | -1.5940 |
| R3D | autumn | 0.0596 | 274 | 1E-19 * | -1.7958 | -2.0182 | -1.5978 |
| RNG | autumn | 0.0598 | 274 | 2.9E-18 * | -1.7501 | -1.9675 | -1.5566 |
| RHZ | autumn | 0.0616 | 274 | 3.5E-17 * | -1.7432 | -1.9671 | -1.5448 |
| EVN | spring | 0.1413 | 274 | 0.00013 * | -1.7308 | -2.2831 | -1.3121 |
| SPT | summer | 0.1236 | 274 | 1.3E-05 * | -1.7298 | -2.2039 | -1.3577 |
| PMN | summer | 0.1255 | 274 | 1.9E-05 * | -1.7258 | -2.2072 | -1.3495 |
| RHZ | winter | 0.0554 | 274 | 3.4E-19 * | -1.7079 | -1.9038 | -1.5321 |
| CVR | spring | 0.1450 | 274 | 0.00034 * | -1.6929 | -2.2495 | -1.2740 |
| BGN | summer | 0.0714 | 273 | 7.5E-12 * | -1.6676 | -1.9182 | -1.4498 |
| RPS | winter | 0.0586 | 274 | 6.2E-16 * | -1.6559 | -1.8576 | -1.4761 |
| R3D | winter | 0.0535 | 274 | 2.9E-17 * | -1.6229 | -1.8024 | -1.4612 |
| POW | spring | 0.1275 | 274 | 0.00019 * | -1.6198 | -2.0798 | -1.2616 |
| CVR | summer | 0.1195 | 274 | 9.2E-05 * | -1.6066 | -2.0304 | -1.2712 |
| EVN | summer | 0.1164 | 274 | 0.00011 * | -1.5808 | -1.9858 | -1.2583 |
| RNG | winter | 0.0537 | 274 | 1.8E-15 * | -1.5741 | -1.7488 | -1.4168 |
| POW | summer | 0.1050 | 274 | 4.3E-05 * | -1.5475 | -1.9013 | -1.2596 |
| SPT | spring | 0.1500 | 274 | 0.00686 * | -1.5049 | -2.0193 | -1.1215 |
| RVT | spring | 0.0941 | 274 | 0.00048 * | -1.3945 | -1.6770 | -1.1595 |
| RVT | summer | 0.0775 | 274 | 0.00014 * | -1.3498 | -1.5714 | -1.1595 |
| RHZ | summer | 0.0561 | 274 | 2.1E-07 * | -1.3482 | -1.5049 | -1.2077 |
| R3D | summer | 0.0542 | 274 | 1.8E-05 * | -1.2674 | -1.4096 | -1.1396 |
| ACI | spring | 0.0649 | 274 | 0.00034 * | -1.2655 | -1.4372 | -1.1142 |
| RPS | summer | 0.0594 | 274 | 9.7E-05 * | -1.2648 | -1.4210 | -1.1258 |
| BGN | spring | 0.0867 | 273 | 0.00749 * | -1.2632 | -1.4972 | -1.0657 |
| RNG | summer | 0.0544 | 274 | 0.0001 * | -1.2395 | -1.3789 | -1.1141 |
| RHZ | spring | 0.0681 | 274 | 0.00261 * | -1.2300 | -1.4058 | -1.0762 |
| R3D | spring | 0.0659 | 274 | 0.00553 * | -1.2022 | -1.3679 | -1.0566 |
| RNG | spring | 0.0661 | 274 | 0.03075 * | -1.1542 | -1.3138 | -1.0141 |
| ACI | winter | 0.0528 | 274 | 0.02197 * | -1.1294 | -1.2525 | -1.0183 |
| BGN | autumn | 0.0790 | 273 | 1E-05 * | 1.4261 | 1.2216 | 1.6649 |
| ACI | autumn | 0.0588 | 274 | 0.8852 | - | - | - |
| ACI | summer | 0.0535 | 274 | 0.3712 | - | - | - |
| RPS | spring | 0.0721 | 274 | 0.0571 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 18

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | winter | 0.1664 | 274 | 1.3E-10 * | -3.0403 | -4.2126 | -2.1942 |
| EVN | winter | 0.1507 | 274 | 9.1E-09 * | -2.4441 | -3.2840 | -1.8191 |
| PMN | winter | 0.1198 | 274 | 4.9E-11 * | -2.2710 | -2.8719 | -1.7959 |
| ENT | autumn | 0.1851 | 274 | 2E-05 * | -2.2317 | -3.2080 | -1.5525 |
| CVR | winter | 0.1286 | 274 | 5.3E-09 * | -2.1716 | -2.7944 | -1.6877 |
| ENT | summer | 0.1686 | 274 | 7.9E-06 * | -2.1555 | -2.9994 | -1.5490 |
| EVN | autumn | 0.1677 | 274 | 7.1E-06 * | -2.1545 | -2.9928 | -1.5510 |
| ENT | spring | 0.2047 | 274 | 0.00027 * | -2.1272 | -3.1770 | -1.4243 |
| EVN | summer | 0.1527 | 274 | 1.9E-06 * | -2.1043 | -2.8384 | -1.5601 |
| BGN | winter | 0.1359 | 273 | 2.3E-07 * | -2.0568 | -2.6845 | -1.5759 |
| POW | winter | 0.1034 | 274 | 9.8E-10 * | -1.9248 | -2.3572 | -1.5717 |
| PMN | summer | 0.1213 | 274 | 1.8E-07 * | -1.9143 | -2.4282 | -1.5091 |
| EVN | spring | 0.1854 | 274 | 0.00066 * | -1.8945 | -2.7244 | -1.3174 |
| CVR | summer | 0.1303 | 274 | 2.5E-06 * | -1.8713 | -2.4158 | -1.4494 |
| SPT | winter | 0.0987 | 274 | 1.8E-09 * | -1.8496 | -2.2445 | -1.5242 |
| PMN | spring | 0.1473 | 274 | 4.3E-05 * | -1.8449 | -2.4624 | -1.3822 |
| CVR | autumn | 0.1431 | 274 | 2.8E-05 * | -1.8397 | -2.4355 | -1.3897 |
| PMN | autumn | 0.1333 | 274 | 1.4E-05 * | -1.8020 | -2.3399 | -1.3877 |
| CVR | spring | 0.1582 | 274 | 0.00082 * | -1.7081 | -2.3291 | -1.2526 |
| POW | summer | 0.1047 | 274 | 1.7E-06 * | -1.6695 | -2.0499 | -1.3596 |
| SPT | summer | 0.1000 | 274 | 9.9E-07 * | -1.6499 | -2.0072 | -1.3562 |
| POW | autumn | 0.1150 | 274 | 2E-05 * | -1.6467 | -2.0632 | -1.3143 |
| SPT | autumn | 0.1098 | 274 | 1.6E-05 * | -1.6207 | -2.0101 | -1.3068 |
| BGN | summer | 0.1377 | 273 | 0.00074 * | -1.5998 | -2.0952 | -1.2214 |
| POW | spring | 0.1272 | 274 | 0.00033 * | -1.5880 | -2.0374 | -1.2377 |
| RVT | winter | 0.0781 | 274 | 1.6E-08 * | -1.5762 | -1.8371 | -1.3524 |
| SPT | spring | 0.1214 | 274 | 0.00059 * | -1.5251 | -1.9349 | -1.2021 |
| RVT | autumn | 0.0869 | 274 | 2E-06 * | -1.5248 | -1.8081 | -1.2859 |
| RNG | autumn | 0.0688 | 274 | 1.4E-06 * | -1.4041 | -1.6069 | -1.2269 |
| R3D | autumn | 0.0720 | 274 | 5.8E-06 * | -1.3955 | -1.6071 | -1.2117 |
| RVT | summer | 0.0792 | 274 | 3.9E-05 * | -1.3926 | -1.6263 | -1.1924 |
| RPS | autumn | 0.0696 | 274 | 5.6E-06 * | -1.3802 | -1.5819 | -1.2042 |
| RVT | spring | 0.0961 | 274 | 0.00181 * | -1.3537 | -1.6343 | -1.1213 |
| RNG | winter | 0.0619 | 274 | 4.7E-06 * | -1.3350 | -1.5072 | -1.1826 |
| RPS | winter | 0.0625 | 274 | 1.6E-05 * | -1.3163 | -1.4880 | -1.1645 |
| RHZ | autumn | 0.0549 | 274 | 1.6E-06 * | -1.3092 | -1.4578 | -1.1757 |
| R3D | winter | 0.0648 | 274 | 0.00012 * | -1.2872 | -1.4613 | -1.1338 |
| R3D | summer | 0.0656 | 274 | 0.00025 * | -1.2753 | -1.4503 | -1.1215 |
| RHZ | winter | 0.0493 | 274 | 1.9E-06 * | -1.2713 | -1.4002 | -1.1542 |
| RHZ | summer | 0.0500 | 274 | 4.3E-06 * | -1.2639 | -1.3939 | -1.1460 |
| RNG | summer | 0.0627 | 274 | 0.00024 * | -1.2629 | -1.4280 | -1.1170 |
| RPS | summer | 0.0634 | 274 | 0.00042 * | -1.2539 | -1.4196 | -1.1074 |
| RHZ | spring | 0.0606 | 274 | 0.03569 * | -1.1366 | -1.2800 | -1.0092 |
| BGN | autumn | 0.1522 | 273 | 2.9E-05 * | 1.9103 | 1.4175 | 2.5744 |
| RNG | spring | 0.0761 | 274 | 0.7207 | - | - | - |
| RPS | spring | 0.0769 | 274 | 0.6768 | - | - | - |
| R3D | spring | 0.0796 | 274 | 0.5654 | - | - | - |
| ACI | winter | 0.0663 | 274 | 0.4053 | - | - | - |
| ACI | summer | 0.0672 | 274 | 0.3555 | - | - | - |
| ACI | autumn | 0.0738 | 274 | 0.3308 | - | - | - |
| ACI | spring | 0.0816 | 274 | 0.1107 | - | - | - |
| BGN | spring | 0.1671 | 273 | 0.0542 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 19

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1630 | 274 | 0.00023 * | -1.8360 | -2.5272 | -1.3339 |
| EVN | spring | 0.1661 | 274 | 0.00127 * | -1.7172 | -2.3779 | -1.2401 |
| PMN | spring | 0.1251 | 274 | 5E-05 * | -1.6746 | -2.1400 | -1.3105 |
| CVR | spring | 0.1416 | 274 | 0.00061 * | -1.6342 | -2.1571 | -1.2381 |
| EVN | summer | 0.1368 | 274 | 0.00065 * | -1.6030 | -2.0959 | -1.2260 |
| POW | spring | 0.1138 | 274 | 0.00029 * | -1.5179 | -1.8971 | -1.2145 |
| SPT | spring | 0.1125 | 274 | 0.00037 * | -1.4999 | -1.8698 | -1.2031 |
| CVR | summer | 0.1167 | 274 | 0.00068 * | -1.4930 | -1.8766 | -1.1878 |
| PMN | summer | 0.1030 | 274 | 0.00024 * | -1.4677 | -1.7962 | -1.1993 |
| ENT | summer | 0.1343 | 274 | 0.01237 * | -1.4022 | -1.8243 | -1.0778 |
| POW | summer | 0.0937 | 274 | 0.00044 * | -1.3956 | -1.6769 | -1.1614 |
| SPT | summer | 0.0926 | 274 | 0.00067 * | -1.3753 | -1.6492 | -1.1469 |
| CVR | autumn | 0.1281 | 274 | 0.02181 * | -1.3439 | -1.7276 | -1.0454 |
| RVT | summer | 0.0718 | 274 | 9.4E-05 * | -1.3291 | -1.5300 | -1.1547 |
| RVT | autumn | 0.0789 | 274 | 0.0004 * | -1.3268 | -1.5485 | -1.1368 |
| POW | autumn | 0.1029 | 274 | 0.0067 * | -1.3247 | -1.6207 | -1.0827 |
| RVT | spring | 0.0872 | 274 | 0.00195 * | -1.3134 | -1.5581 | -1.1071 |
| SPT | autumn | 0.1018 | 274 | 0.00924 * | -1.3057 | -1.5940 | -1.0696 |
| PMN | autumn | 0.1132 | 274 | 0.01913 * | -1.3057 | -1.6300 | -1.0460 |
| ACI | autumn | 0.0645 | 274 | 7.1E-05 * | -1.2974 | -1.4724 | -1.1433 |
| R3D | autumn | 0.0689 | 274 | 0.00129 * | -1.2509 | -1.4316 | -1.0929 |
| RNG | autumn | 0.0681 | 274 | 0.0018 * | -1.2395 | -1.4164 | -1.0846 |
| RPS | autumn | 0.0677 | 274 | 0.00178 * | -1.2383 | -1.4141 | -1.0843 |
| R3D | summer | 0.0627 | 274 | 0.00111 * | -1.2296 | -1.3903 | -1.0874 |
| ACI | summer | 0.0588 | 274 | 0.00056 * | -1.2277 | -1.3776 | -1.0942 |
| RPS | summer | 0.0617 | 274 | 0.00126 * | -1.2226 | -1.3796 | -1.0834 |
| RHZ | autumn | 0.0552 | 274 | 0.00059 * | -1.2114 | -1.3498 | -1.0872 |
| ACI | spring | 0.0713 | 274 | 0.00787 * | -1.2105 | -1.3921 | -1.0525 |
| RNG | summer | 0.0620 | 274 | 0.00243 * | -1.2089 | -1.3651 | -1.0706 |
| RHZ | summer | 0.0502 | 274 | 0.00097 * | -1.1825 | -1.3049 | -1.0716 |
| RHZ | spring | 0.0610 | 274 | 0.02124 * | -1.1518 | -1.2981 | -1.0220 |
| BGN | autumn | 0.1236 | 273 | 1.4E-10 * | 2.2806 | 1.7898 | 2.9061 |
| RHZ | winter | 0.0496 | 274 | 0.9937 | - | - | - |
| ACI | winter | 0.0580 | 274 | 0.9595 | - | - | - |
| CVR | winter | 0.1152 | 274 | 0.9140 | - | - | - |
| R3D | winter | 0.0619 | 274 | 0.6838 | - | - | - |
| RNG | winter | 0.0612 | 274 | 0.5945 | - | - | - |
| RPS | winter | 0.0609 | 274 | 0.5434 | - | - | - |
| SPT | winter | 0.0915 | 274 | 0.4345 | - | - | - |
| POW | winter | 0.0925 | 274 | 0.3303 | - | - | - |
| PMN | winter | 0.1017 | 274 | 0.2405 | - | - | - |
| EVN | winter | 0.1350 | 274 | 0.2340 | - | - | - |
| RVT | winter | 0.0709 | 274 | 0.1311 | - | - | - |
| ENT | autumn | 0.1475 | 274 | 0.1279 | - | - | - |
| BGN | winter | 0.1104 | 273 | 0.1164 | - | - | - |
| BGN | spring | 0.1358 | 273 | 0.1024 | - | - | - |
| EVN | autumn | 0.1502 | 274 | 0.0981 | - | - | - |
| R3D | spring | 0.0761 | 274 | 0.0935 | - | - | - |
| RNG | spring | 0.0753 | 274 | 0.0714 | - | - | - |
| ENT | winter | 0.1325 | 274 | 0.0691 | - | - | - |
| BGN | summer | 0.1118 | 273 | 0.0643 | - | - | - |
| RPS | spring | 0.0749 | 274 | 0.0555 | - | - | - |

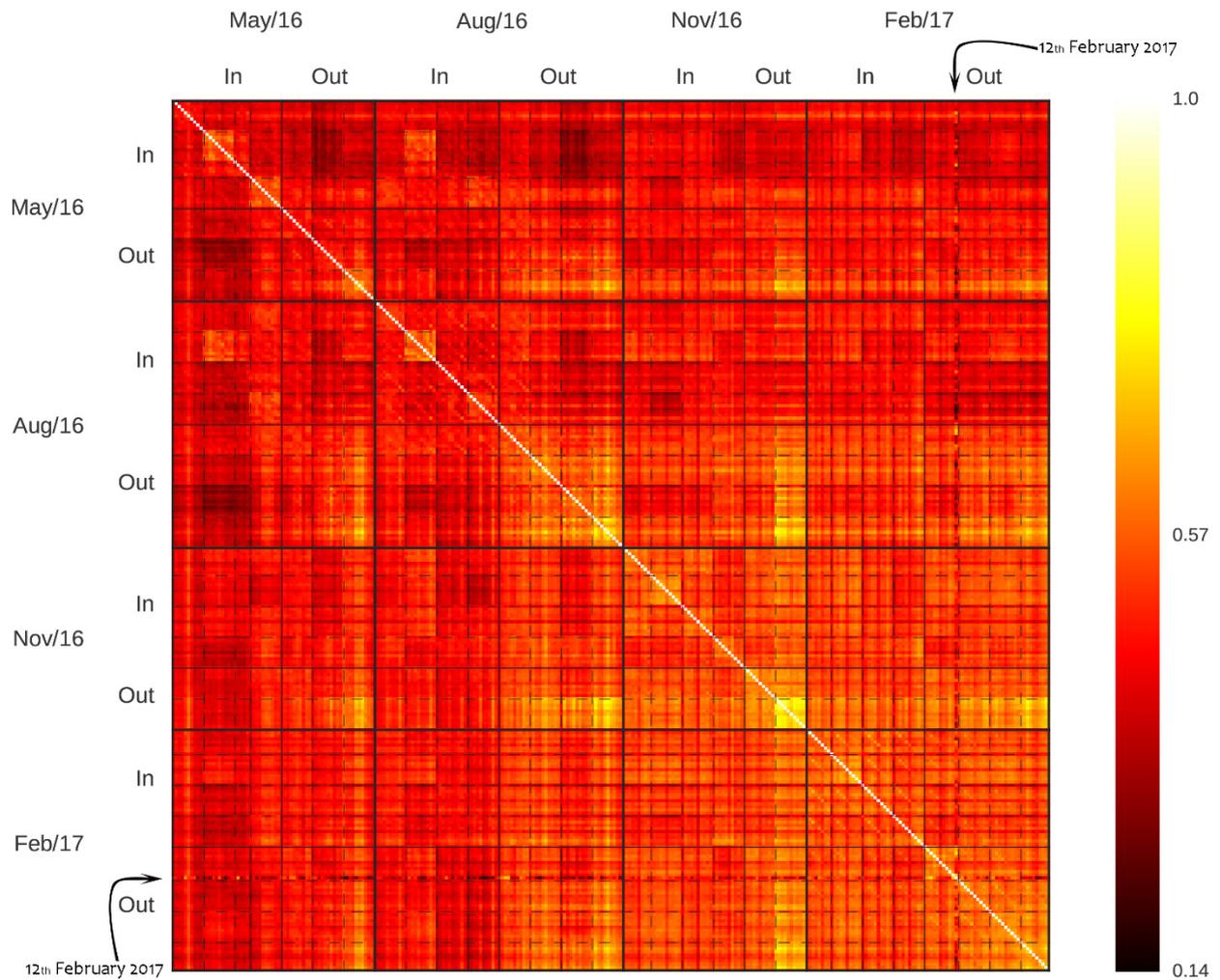
The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for the Serra do Cipó National Park and outside of it for Panel 20

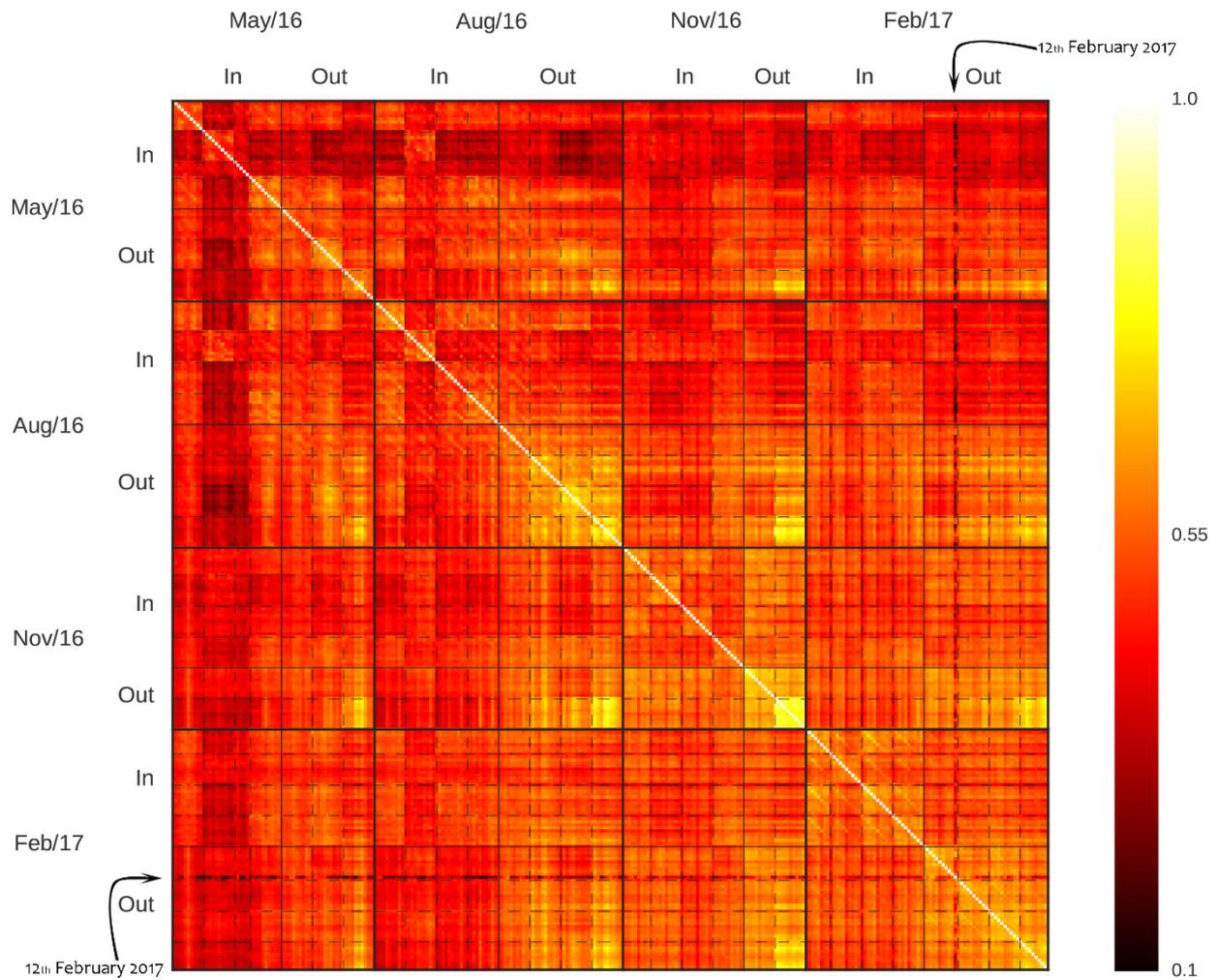
| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| EVN | winter | 0.1615 | 274 | 1E-12 * | -3.3438 | -4.5886 | -2.4367 |
| EVN | autumn | 0.1797 | 274 | 1.5E-10 * | -3.3070 | -4.7028 | -2.3254 |
| CVR | autumn | 0.1520 | 274 | 1.1E-12 * | -3.1103 | -4.1900 | -2.3089 |
| EVN | summer | 0.1636 | 274 | 6.7E-10 * | -2.8488 | -3.9256 | -2.0674 |
| PMN | autumn | 0.1311 | 274 | 4.6E-14 * | -2.8379 | -3.6690 | -2.1950 |
| ENT | autumn | 0.1680 | 274 | 2.7E-09 * | -2.8112 | -3.9072 | -2.0226 |
| CVR | winter | 0.1366 | 274 | 6E-13 * | -2.8101 | -3.6730 | -2.1499 |
| ENT | winter | 0.1510 | 274 | 1.3E-10 * | -2.7435 | -3.6881 | -2.0409 |
| POW | autumn | 0.1206 | 274 | 2.5E-13 * | -2.5304 | -3.2051 | -1.9976 |
| CVR | summer | 0.1384 | 274 | 9.5E-10 * | -2.4048 | -3.1542 | -1.8334 |
| SPT | autumn | 0.1186 | 274 | 3.7E-12 * | -2.3683 | -2.9878 | -1.8772 |
| PMN | winter | 0.1178 | 274 | 3.6E-12 * | -2.3559 | -2.9677 | -1.8703 |
| SPT | winter | 0.1066 | 274 | 4.2E-13 * | -2.2517 | -2.7747 | -1.8273 |
| POW | winter | 0.1084 | 274 | 1.8E-12 * | -2.2271 | -2.7543 | -1.8009 |
| EVN | spring | 0.1986 | 274 | 0.00019 * | -2.1201 | -3.1290 | -1.4365 |
| SPT | summer | 0.1079 | 274 | 1.3E-09 * | -1.9697 | -2.4338 | -1.5941 |
| PMN | summer | 0.1193 | 274 | 3.6E-08 * | -1.9674 | -2.4858 | -1.5572 |
| POW | summer | 0.1098 | 274 | 8.7E-09 * | -1.9196 | -2.3806 | -1.5479 |
| ENT | summer | 0.1529 | 274 | 3E-05 * | -1.9149 | -2.5842 | -1.4190 |
| RVT | autumn | 0.0892 | 274 | 3.6E-12 * | -1.9131 | -2.2784 | -1.6063 |
| CVR | spring | 0.1680 | 274 | 0.00023 * | -1.8712 | -2.6012 | -1.3461 |
| RNG | autumn | 0.0823 | 274 | 7.5E-13 * | -1.8581 | -2.1834 | -1.5813 |
| RPS | autumn | 0.0794 | 274 | 1.2E-12 * | -1.8065 | -2.1105 | -1.5462 |
| R3D | autumn | 0.0768 | 274 | 6.6E-13 * | -1.7855 | -2.0756 | -1.5360 |
| ENT | spring | 0.1857 | 274 | 0.003 * | -1.7436 | -2.5090 | -1.2117 |
| PMN | spring | 0.1449 | 274 | 0.00038 * | -1.6847 | -2.2378 | -1.2683 |
| SPT | spring | 0.1311 | 274 | 9.2E-05 * | -1.6826 | -2.1754 | -1.3014 |
| RVT | winter | 0.0801 | 274 | 8.5E-10 * | -1.6646 | -1.9477 | -1.4226 |
| POW | spring | 0.1333 | 274 | 0.00025 * | -1.6409 | -2.1309 | -1.2636 |
| RNG | winter | 0.0740 | 274 | 1.6E-09 * | -1.5869 | -1.8345 | -1.3727 |
| BGN | summer | 0.0967 | 273 | 6E-06 * | -1.5633 | -1.8897 | -1.2933 |
| RPS | winter | 0.0713 | 274 | 1.6E-09 * | -1.5619 | -1.7962 | -1.3581 |
| R3D | winter | 0.0690 | 274 | 2.7E-09 * | -1.5289 | -1.7503 | -1.3354 |
| RHZ | autumn | 0.0585 | 274 | 5.2E-12 * | -1.5252 | -1.7104 | -1.3600 |
| RVT | summer | 0.0812 | 274 | 4.6E-06 * | -1.4615 | -1.7136 | -1.2465 |
| BGN | winter | 0.0955 | 273 | 0.0001 * | -1.4567 | -1.7565 | -1.2080 |
| RNG | summer | 0.0749 | 274 | 3.2E-06 * | -1.4278 | -1.6537 | -1.2328 |
| R3D | summer | 0.0699 | 274 | 7.6E-07 * | -1.4248 | -1.6341 | -1.2423 |
| RPS | summer | 0.0723 | 274 | 2E-06 * | -1.4210 | -1.6372 | -1.2333 |
| RHZ | winter | 0.0526 | 274 | 3.8E-10 * | -1.4073 | -1.5600 | -1.2695 |
| RHZ | summer | 0.0532 | 274 | 6.9E-09 * | -1.3750 | -1.5263 | -1.2388 |
| BGN | spring | 0.1175 | 273 | 0.01009 * | -1.3557 | -1.7067 | -1.0769 |
| RVT | spring | 0.0986 | 274 | 0.00472 * | -1.3242 | -1.6064 | -1.0916 |
| RNG | spring | 0.0910 | 274 | 0.00961 * | -1.2678 | -1.5153 | -1.0607 |
| RHZ | spring | 0.0646 | 274 | 0.00041 * | -1.2604 | -1.4306 | -1.1104 |
| RPS | spring | 0.0877 | 274 | 0.0089 * | -1.2600 | -1.4964 | -1.0610 |
| R3D | spring | 0.0849 | 274 | 0.00937 * | -1.2488 | -1.4749 | -1.0573 |
| BGN | autumn | 0.1070 | 273 | 1.3E-16 * | 2.5734 | 2.0866 | 3.1738 |
| ACI | winter | 0.0452 | 274 | 0.7354 | - | - | - |
| ACI | summer | 0.0458 | 274 | 0.4172 | - | - | - |
| ACI | spring | 0.0556 | 274 | 0.4106 | - | - | - |
| ACI | autumn | 0.0503 | 274 | 0.1297 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher outside the park. The * symbol indicates p values <0.05.

Appendix C. ENT and EVN cosine similarity heatmaps

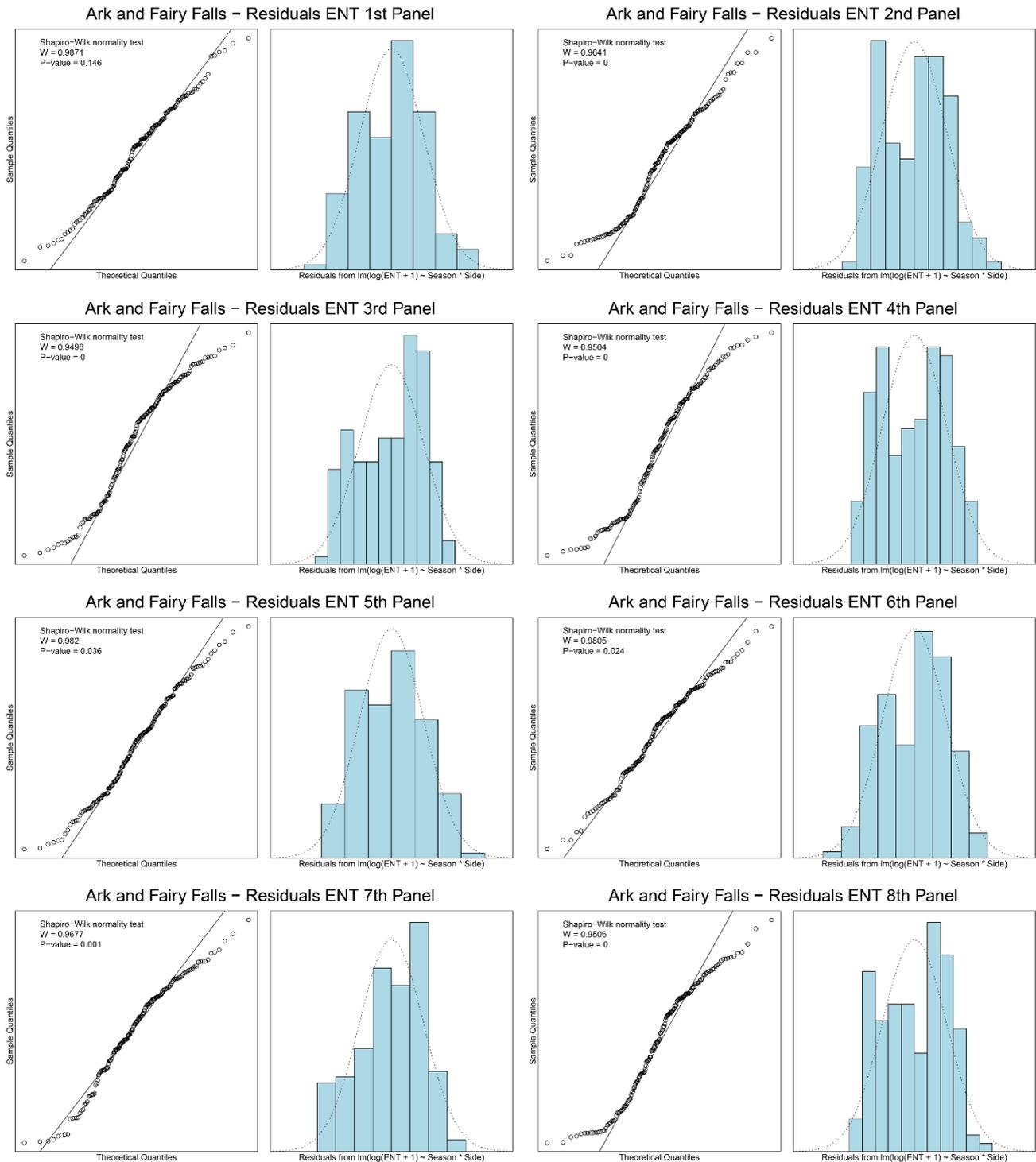


ENT cosine similarity heatmap. The averaged cosine similarity between days for ENT index. The continuous lines separates treatments (inside/outside), while the segmented lines separate the different recorders. The arrow indicates the day which is different from the others (12th February 2017, recorder OutCipo01) from all sites in all seasons.



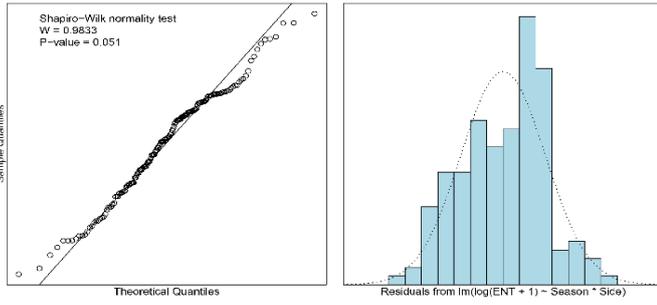
EVN cosine similarity heatmap. The averaged cosine similarity between days for EVN index. The continuous lines separates treatments (inside/outside), while the segmented lines separate the different recorders. The arrow indicates the day which is different from the others (12th February 2017, recorder OutCipo01) from all sites in all seasons.

Appendix D. Shapiro-Wilk test and residual fits plots for chapter 3

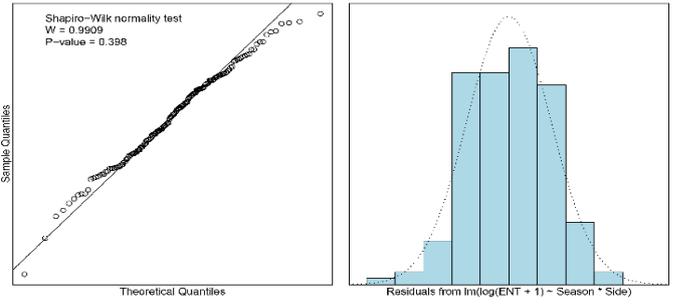


Quantile-quantile and residual fits plots, along with the Shapiro-Wilk test for panels from 1 to 8. ENT index is taken here as an example.

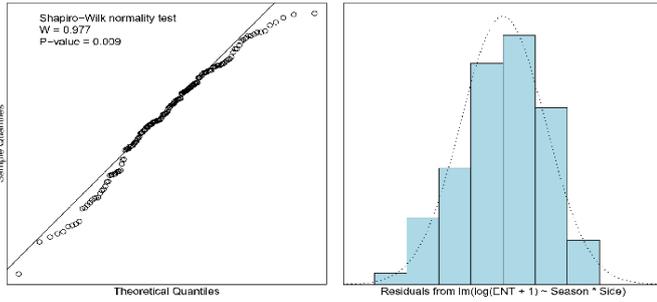
Ark and Fairy Falls – Residuals ENT 9th Panel



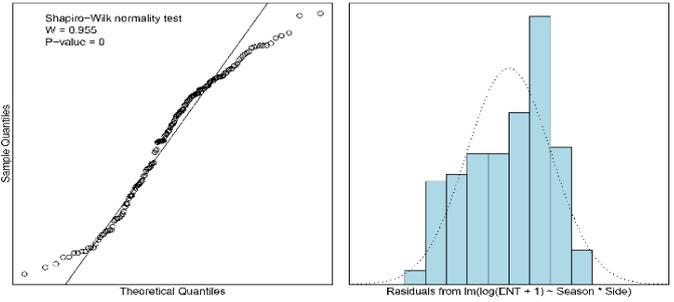
Ark and Fairy Falls – Residuals ENT 10th Panel



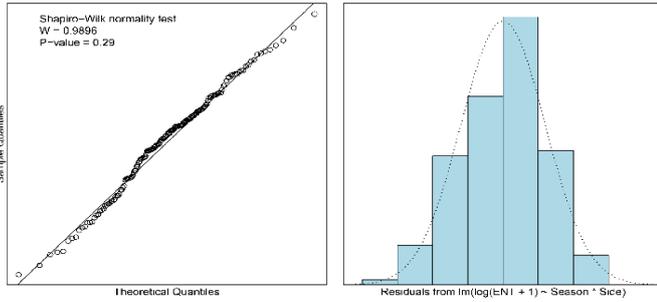
Ark and Fairy Falls – Residuals ENT 11th Panel



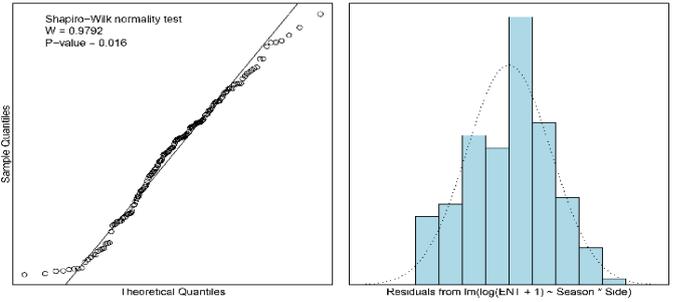
Ark and Fairy Falls – Residuals ENT 12th Panel



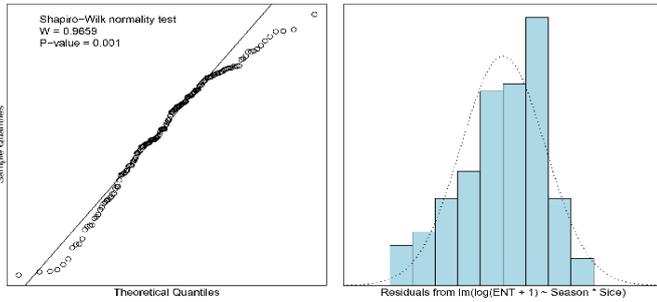
Ark and Fairy Falls – Residuals ENT 13th Panel



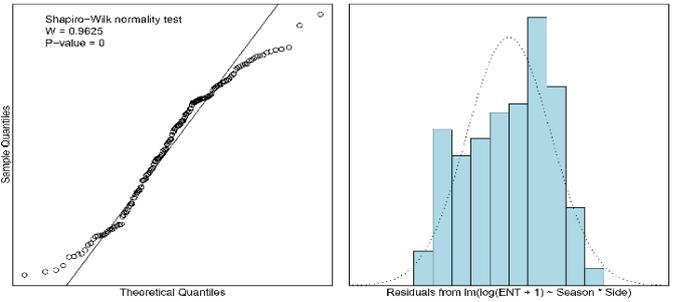
Ark and Fairy Falls – Residuals ENT 14th Panel



Ark and Fairy Falls – Residuals ENT 15th Panel

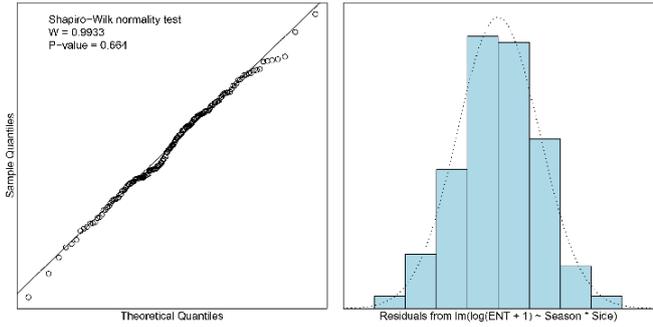


Ark and Fairy Falls – Residuals ENT 16th Panel

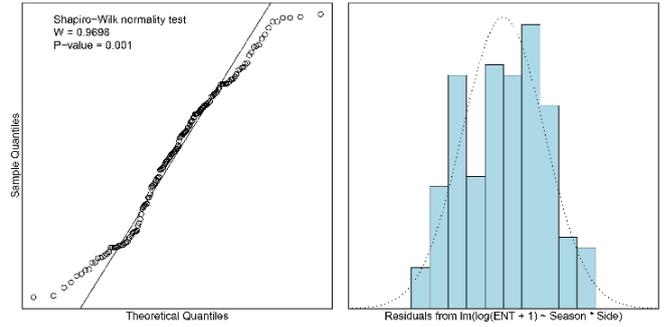


Quantile-quantile and residual fits plots, along with the Shapiro-Wilk test for panels from 9 to 16. ENT index is taken here as an example.

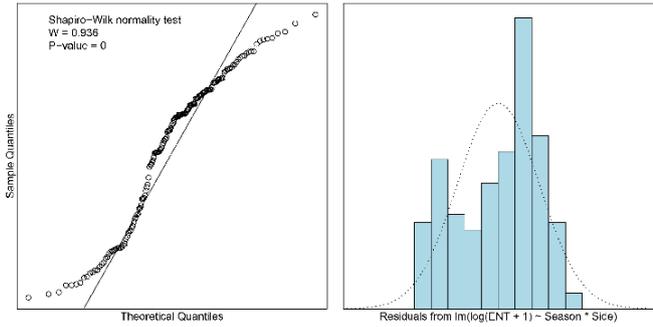
Ark and Fairy Falls – Residuals ENT 17th Panel



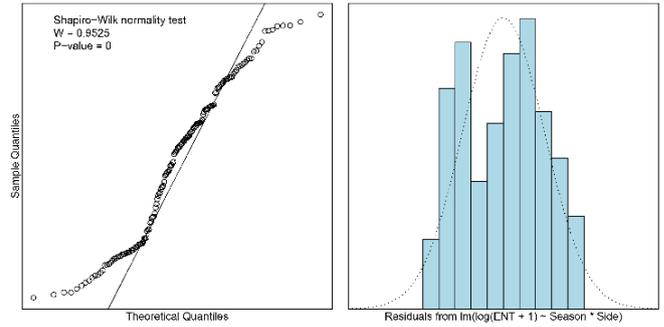
Ark and Fairy Falls – Residuals ENT 18th Panel



Ark and Fairy Falls – Residuals ENT 19th Panel



Ark and Fairy Falls – Residuals ENT 20th Panel



Quantile-quantile and residual fits plots, along with the Shapiro-Wilk test for panels from 17 to 20. ENT index is taken here as an example.

Appendix E. Pairwise comparisons for each acoustic region in Chapter 3

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region High frequency/ Predawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1660 | 156 | 4.9E-08 * | -2.5918 | -3.5883 | -1.8720 |
| SPT | autumn | 0.1515 | 156 | 5.1E-05 * | -1.8795 | -2.5293 | -1.3967 |
| ENT | spring | 0.1660 | 156 | 0.00021 * | -1.8767 | -2.5983 | -1.3555 |
| SPT | spring | 0.1515 | 156 | 0.00253 * | -1.5921 | -2.1424 | -1.1831 |
| PMN | autumn | 0.1185 | 156 | 0.0014 * | -1.4704 | -1.8549 | -1.1656 |
| PMN | spring | 0.1185 | 156 | 0.01096 * | -1.3569 | -1.7117 | -1.0756 |
| RVT | autumn | 0.0997 | 156 | 0.0028 * | -1.3535 | -1.6455 | -1.1133 |
| RHZ | autumn | 0.0730 | 156 | 0.00013 * | -1.3316 | -1.5365 | -1.1539 |
| ACI | autumn | 0.0824 | 156 | 0.00194 * | -1.2965 | -1.5236 | -1.1032 |
| POW | autumn | 0.1132 | 156 | 0.03983 * | -1.2646 | -1.5788 | -1.0129 |
| RHZ | spring | 0.0730 | 156 | 0.00262 * | -1.2503 | -1.4428 | -1.0835 |
| ACI | spring | 0.0824 | 156 | 0.02365 * | -1.2071 | -1.4186 | -1.0272 |
| RPS | autumn | 0.0882 | 156 | 0.0396 * | -1.2008 | -1.4274 | -1.0102 |
| BGN | autumn | 0.0388 | 156 | 0.00847 * | 1.1089 | 1.0278 | 1.1965 |
| BGN | spring | 0.0388 | 156 | 0.0009 * | 1.1402 | 1.0568 | 1.2303 |
| EVN | spring | 0.1404 | 156 | 0.42422 | - | - | - |
| EVN | autumn | 0.1404 | 156 | 0.33090 | - | - | - |
| RNG | spring | 0.0806 | 156 | 0.31248 | - | - | - |
| R3D | spring | 0.0813 | 156 | 0.19119 | - | - | - |
| RPS | spring | 0.0882 | 156 | 0.18968 | - | - | - |
| CVR | spring | 0.1290 | 156 | 0.16206 | - | - | - |
| RNG | autumn | 0.0806 | 156 | 0.11635 | - | - | - |
| POW | spring | 0.1132 | 156 | 0.10531 | - | - | - |
| CVR | autumn | 0.1290 | 156 | 0.09168 | - | - | - |
| RVT | spring | 0.0997 | 156 | 0.08633 | - | - | - |
| R3D | autumn | 0.0813 | 156 | 0.06425 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-high frequency/ Predawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2496 | 156 | 1E-05 * | -3.1229 | -5.0940 | -1.9145 |
| EVN | autumn | 0.2824 | 156 | 0.00121 * | -2.5379 | -4.4145 | -1.4591 |
| ENT | spring | 0.2496 | 156 | 0.00259 * | -2.1480 | -3.5038 | -1.3168 |
| CVR | autumn | 0.2427 | 156 | 0.00196 * | -2.1478 | -3.4559 | -1.3348 |
| PMN | autumn | 0.2058 | 156 | 0.00036 * | -2.1192 | -3.1720 | -1.4158 |
| POW | autumn | 0.1900 | 156 | 0.00336 * | -1.7612 | -2.5560 | -1.2136 |
| SPT | autumn | 0.1855 | 156 | 0.00496 * | -1.6968 | -2.4409 | -1.1795 |
| ACI | autumn | 0.1434 | 156 | 0.00043 * | -1.6755 | -2.2193 | -1.2650 |
| RVT | autumn | 0.1499 | 156 | 0.00082 * | -1.6677 | -2.2372 | -1.2432 |
| PMN | spring | 0.2058 | 156 | 0.03553 * | -1.5471 | -2.3158 | -1.0336 |
| ACI | spring | 0.1434 | 156 | 0.00389 * | -1.5225 | -2.0166 | -1.1494 |
| RNG | autumn | 0.1262 | 156 | 0.00135 * | -1.5100 | -1.9337 | -1.1791 |
| RPS | autumn | 0.1265 | 156 | 0.00147 * | -1.5063 | -1.9304 | -1.1755 |
| R3D | autumn | 0.1253 | 156 | 0.00144 * | -1.5017 | -1.9199 | -1.1747 |
| RHZ | autumn | 0.0876 | 156 | 0.00392 * | -1.2924 | -1.5345 | -1.0885 |
| BGN | autumn | 0.0853 | 156 | 0.74222 | - | - | - |
| RHZ | spring | 0.0876 | 156 | 0.29488 | - | - | - |
| SPT | spring | 0.1855 | 156 | 0.23040 | - | - | - |
| BGN | spring | 0.0853 | 156 | 0.19980 | - | - | - |
| POW | spring | 0.1900 | 156 | 0.18692 | - | - | - |
| R3D | spring | 0.1253 | 156 | 0.17615 | - | - | - |
| RNG | spring | 0.1262 | 156 | 0.17534 | - | - | - |
| RPS | spring | 0.1265 | 156 | 0.17481 | - | - | - |
| CVR | spring | 0.2427 | 156 | 0.15435 | - | - | - |
| EVN | spring | 0.2824 | 156 | 0.10425 | - | - | - |
| RVT | spring | 0.1499 | 156 | 0.09708 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-low frequency/ Predawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2851 | 156 | 0.00075 * | -2.6645 | -4.6588 | -1.5239 |
| EVN | autumn | 0.3188 | 156 | 0.00489 * | -2.4848 | -4.6417 | -1.3302 |
| CVR | autumn | 0.2721 | 156 | 0.00994 * | -2.0345 | -3.4683 | -1.1934 |
| PMN | autumn | 0.2328 | 156 | 0.0034 * | -1.9990 | -3.1549 | -1.2666 |
| POW | autumn | 0.2119 | 156 | 0.0158 * | -1.6771 | -2.5405 | -1.1071 |
| SPT | autumn | 0.2075 | 156 | 0.01994 * | -1.6289 | -2.4461 | -1.0846 |
| ACI | autumn | 0.1565 | 156 | 0.00273 * | -1.6106 | -2.1889 | -1.1851 |
| RVT | autumn | 0.1663 | 156 | 0.00789 * | -1.5646 | -2.1675 | -1.1294 |
| ACI | spring | 0.1565 | 156 | 0.01066 * | -1.4986 | -2.0366 | -1.1027 |
| RNG | autumn | 0.1398 | 156 | 0.01528 * | -1.4090 | -1.8532 | -1.0713 |
| RPS | autumn | 0.1400 | 156 | 0.01602 * | -1.4063 | -1.8504 | -1.0688 |
| R3D | autumn | 0.1392 | 156 | 0.01591 * | -1.4041 | -1.8446 | -1.0687 |
| RHZ | autumn | 0.0968 | 156 | 0.02821 * | -1.2390 | -1.4978 | -1.0250 |
| BGN | spring | 0.1394 | 156 | 0.97638 | - | - | - |
| RHZ | spring | 0.0968 | 156 | 0.57955 | - | - | - |
| R3D | spring | 0.1392 | 156 | 0.53651 | - | - | - |
| RPS | spring | 0.1400 | 156 | 0.52652 | - | - | - |
| RNG | spring | 0.1398 | 156 | 0.52598 | - | - | - |
| SPT | spring | 0.2075 | 156 | 0.44129 | - | - | - |
| POW | spring | 0.2119 | 156 | 0.43981 | - | - | - |
| BGN | autumn | 0.1394 | 156 | 0.34765 | - | - | - |
| CVR | spring | 0.2721 | 156 | 0.34491 | - | - | - |
| RVT | spring | 0.1663 | 156 | 0.27905 | - | - | - |
| PMN | spring | 0.2328 | 156 | 0.21852 | - | - | - |
| EVN | spring | 0.3188 | 156 | 0.18414 | - | - | - |
| ENT | spring | 0.2851 | 156 | 0.05980 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Low frequency/ Predawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2850 | 156 | 0.01627 * | -1.9980 | -3.4927 | -1.1430 |
| ENT | spring | 0.2850 | 156 | 0.04649 * | -1.7715 | -3.0968 | -1.0134 |
| ACI | spring | 0.1351 | 156 | 0.01347 * | -1.4017 | -1.8267 | -1.0756 |
| ACI | autumn | 0.1351 | 156 | 0.01483 * | -1.3950 | -1.8179 | -1.0705 |
| BGN | autumn | 0.2551 | 156 | 0.87892 | - | - | - |
| BGN | spring | 0.2551 | 156 | 0.81817 | - | - | - |
| RNG | spring | 0.1260 | 156 | 0.57050 | - | - | - |
| RPS | spring | 0.1218 | 156 | 0.56813 | - | - | - |
| POW | spring | 0.1978 | 156 | 0.56676 | - | - | - |
| R3D | spring | 0.1157 | 156 | 0.56187 | - | - | - |
| RHZ | spring | 0.0823 | 156 | 0.54103 | - | - | - |
| CVR | spring | 0.2541 | 156 | 0.54008 | - | - | - |
| EVN | spring | 0.3143 | 156 | 0.53549 | - | - | - |
| SPT | spring | 0.1844 | 156 | 0.52181 | - | - | - |
| RVT | spring | 0.1518 | 156 | 0.38266 | - | - | - |
| EVN | autumn | 0.3143 | 156 | 0.33136 | - | - | - |
| POW | autumn | 0.1978 | 156 | 0.30958 | - | - | - |
| CVR | autumn | 0.2541 | 156 | 0.29475 | - | - | - |
| RPS | autumn | 0.1218 | 156 | 0.27854 | - | - | - |
| R3D | autumn | 0.1157 | 156 | 0.27765 | - | - | - |
| RNG | autumn | 0.1260 | 156 | 0.26799 | - | - | - |
| RHZ | autumn | 0.0823 | 156 | 0.25183 | - | - | - |
| SPT | autumn | 0.1844 | 156 | 0.24137 | - | - | - |
| PMN | spring | 0.2269 | 156 | 0.21814 | - | - | - |
| RVT | autumn | 0.1518 | 156 | 0.19778 | - | - | - |
| PMN | autumn | 0.2269 | 156 | 0.11053 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region High frequency/ Dawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1553 | 156 | 4.1E-05 * | -1.9259 | -2.6113 | -1.4204 |
| SPT | autumn | 0.1476 | 156 | 0.00011 * | -1.7979 | -2.4010 | -1.3463 |
| ENT | spring | 0.1553 | 156 | 0.00193 * | -1.6321 | -2.2129 | -1.2038 |
| PMN | autumn | 0.1089 | 156 | 0.00087 * | -1.4473 | -1.7915 | -1.1692 |
| SPT | spring | 0.1476 | 156 | 0.01672 * | -1.4290 | -1.9083 | -1.0701 |
| CVR | autumn | 0.1154 | 156 | 0.00545 * | -1.3845 | -1.7359 | -1.1042 |
| POW | autumn | 0.1036 | 156 | 0.00341 * | -1.3608 | -1.6672 | -1.1108 |
| RHZ | autumn | 0.0689 | 156 | 7.8E-05 * | -1.3225 | -1.5136 | -1.1555 |
| RVT | autumn | 0.0907 | 156 | 0.00254 * | -1.3210 | -1.5782 | -1.1058 |
| EVN | autumn | 0.1216 | 156 | 0.0313 * | -1.3024 | -1.6530 | -1.0262 |
| PMN | spring | 0.1089 | 156 | 0.02873 * | -1.2716 | -1.5741 | -1.0273 |
| RPS | autumn | 0.0789 | 156 | 0.01231 * | -1.2212 | -1.4255 | -1.0462 |
| R3D | autumn | 0.0714 | 156 | 0.00692 * | -1.2159 | -1.3987 | -1.0571 |
| RVT | spring | 0.0907 | 156 | 0.04374 * | -1.2026 | -1.4366 | -1.0067 |
| ACI | spring | 0.0732 | 156 | 0.01404 * | -1.1993 | -1.3842 | -1.0391 |
| RHZ | spring | 0.0689 | 156 | 0.00935 * | -1.1987 | -1.3720 | -1.0473 |
| RNG | autumn | 0.0711 | 156 | 0.02006 * | -1.1819 | -1.3587 | -1.0281 |
| BGN | autumn | 0.0368 | 156 | 0.01534 * | 1.0944 | 1.0182 | 1.1762 |
| BGN | spring | 0.0368 | 156 | 0.00273 * | 1.1185 | 1.0407 | 1.2022 |
| EVN | spring | 0.1216 | 156 | 0.39719 | - | - | - |
| ACI | autumn | 0.0732 | 156 | 0.22633 | - | - | - |
| CVR | spring | 0.1154 | 156 | 0.19010 | - | - | - |
| POW | spring | 0.1036 | 156 | 0.13315 | - | - | - |
| RNG | spring | 0.0711 | 156 | 0.11590 | - | - | - |
| R3D | spring | 0.0714 | 156 | 0.08968 | - | - | - |
| RPS | spring | 0.0789 | 156 | 0.06870 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-high frequency/ Dawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1978 | 156 | 6.7E-06 * | -2.5140 | -3.7048 | -1.7059 |
| PMN | spring | 0.1833 | 156 | 0.00015 * | -2.0404 | -2.9222 | -1.4247 |
| ACI | spring | 0.1368 | 156 | 7.1E-06 * | -1.8884 | -2.4690 | -1.4443 |
| EVN | spring | 0.2211 | 156 | 0.00661 * | -1.8379 | -2.8349 | -1.1916 |
| CVR | spring | 0.2097 | 156 | 0.00806 * | -1.7556 | -2.6479 | -1.1640 |
| POW | spring | 0.1768 | 156 | 0.005 * | -1.6543 | -2.3392 | -1.1699 |
| SPT | spring | 0.1726 | 156 | 0.0046 * | -1.6427 | -2.3040 | -1.1711 |
| RVT | spring | 0.1410 | 156 | 0.00247 * | -1.5433 | -2.0345 | -1.1706 |
| R3D | spring | 0.1227 | 156 | 0.00078 * | -1.5231 | -1.9373 | -1.1974 |
| RPS | spring | 0.1231 | 156 | 0.00112 * | -1.5048 | -1.9153 | -1.1823 |
| RNG | spring | 0.1230 | 156 | 0.00121 * | -1.5000 | -1.9089 | -1.1787 |
| RHZ | spring | 0.0915 | 156 | 0.00052 * | -1.3834 | -1.6552 | -1.1563 |
| POW | autumn | 0.1768 | 156 | 0.98372 | - | - | - |
| RHZ | autumn | 0.0915 | 156 | 0.87784 | - | - | - |
| SPT | autumn | 0.1726 | 156 | 0.87588 | - | - | - |
| CVR | autumn | 0.2097 | 156 | 0.82009 | - | - | - |
| PMN | autumn | 0.1833 | 156 | 0.80610 | - | - | - |
| ACI | autumn | 0.1368 | 156 | 0.74676 | - | - | - |
| RPS | autumn | 0.1231 | 156 | 0.65828 | - | - | - |
| R3D | autumn | 0.1227 | 156 | 0.65270 | - | - | - |
| ENT | autumn | 0.1978 | 156 | 0.63634 | - | - | - |
| RNG | autumn | 0.1230 | 156 | 0.63315 | - | - | - |
| RVT | autumn | 0.1410 | 156 | 0.52054 | - | - | - |
| BGN | autumn | 0.0838 | 156 | 0.44566 | - | - | - |
| EVN | autumn | 0.2211 | 156 | 0.40537 | - | - | - |
| BGN | spring | 0.0838 | 156 | 0.19236 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-low frequency/ Dawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1948 | 156 | 0.00631 * | -1.7151 | -2.5126 | -1.1707 |
| EVN | spring | 0.2119 | 156 | 0.03019 * | -1.5896 | -2.4078 | -1.0494 |
| PMN | spring | 0.1844 | 156 | 0.01397 * | -1.5817 | -2.2704 | -1.1019 |
| CVR | spring | 0.2081 | 156 | 0.04714 * | -1.5165 | -2.2804 | -1.0085 |
| ACI | spring | 0.1500 | 156 | 0.0115 * | -1.4677 | -1.9694 | -1.0938 |
| POW | spring | 0.1785 | 156 | 0.04745 * | -1.4286 | -2.0270 | -1.0068 |
| RVT | spring | 0.1449 | 156 | 0.04536 * | -1.3396 | -1.7798 | -1.0084 |
| R3D | spring | 0.1222 | 156 | 0.04294 * | -1.2833 | -1.6307 | -1.0099 |
| RNG | spring | 0.1224 | 156 | 0.04676 * | -1.2782 | -1.6249 | -1.0054 |
| RPS | spring | 0.1228 | 156 | 0.04841 * | -1.2768 | -1.6243 | -1.0036 |
| PMN | autumn | 0.1844 | 156 | 0.99567 | - | - | - |
| POW | autumn | 0.1785 | 156 | 0.91144 | - | - | - |
| RHZ | autumn | 0.0914 | 156 | 0.89989 | - | - | - |
| ACI | autumn | 0.1500 | 156 | 0.87993 | - | - | - |
| R3D | autumn | 0.1222 | 156 | 0.87788 | - | - | - |
| CVR | autumn | 0.2081 | 156 | 0.86997 | - | - | - |
| RNG | autumn | 0.1224 | 156 | 0.86722 | - | - | - |
| RPS | autumn | 0.1228 | 156 | 0.86009 | - | - | - |
| EVN | autumn | 0.2119 | 156 | 0.81942 | - | - | - |
| SPT | autumn | 0.1746 | 156 | 0.81235 | - | - | - |
| ENT | autumn | 0.1948 | 156 | 0.79908 | - | - | - |
| RVT | autumn | 0.1449 | 156 | 0.71627 | - | - | - |
| BGN | spring | 0.1357 | 156 | 0.69655 | - | - | - |
| BGN | autumn | 0.1357 | 156 | 0.65791 | - | - | - |
| RHZ | spring | 0.0914 | 156 | 0.05980 | - | - | - |
| SPT | spring | 0.1746 | 156 | 0.05305 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Low frequency/ Dawn

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|---------|-------|---------------------------|---------------------------|
| RVT | autumn | 0.1540 | 156 | 0.96654 | - | - | - |
| EVN | autumn | 0.2961 | 156 | 0.95020 | - | - | - |
| PMN | autumn | 0.2295 | 156 | 0.94715 | - | - | - |
| ACI | autumn | 0.1457 | 156 | 0.94508 | - | - | - |
| CVR | autumn | 0.2550 | 156 | 0.92148 | - | - | - |
| POW | autumn | 0.2037 | 156 | 0.90426 | - | - | - |
| RHZ | spring | 0.0881 | 156 | 0.86973 | - | - | - |
| ENT | autumn | 0.2783 | 156 | 0.84572 | - | - | - |
| SPT | spring | 0.1940 | 156 | 0.82145 | - | - | - |
| RNG | autumn | 0.1299 | 156 | 0.81410 | - | - | - |
| RPS | autumn | 0.1260 | 156 | 0.81386 | - | - | - |
| BGN | autumn | 0.2461 | 156 | 0.78768 | - | - | - |
| SPT | autumn | 0.1940 | 156 | 0.77937 | - | - | - |
| R3D | autumn | 0.1202 | 156 | 0.77918 | - | - | - |
| POW | spring | 0.2037 | 156 | 0.76966 | - | - | - |
| R3D | spring | 0.1202 | 156 | 0.73814 | - | - | - |
| RHZ | autumn | 0.0881 | 156 | 0.73783 | - | - | - |
| RPS | spring | 0.1260 | 156 | 0.73479 | - | - | - |
| RNG | spring | 0.1299 | 156 | 0.72295 | - | - | - |
| CVR | spring | 0.2550 | 156 | 0.65784 | - | - | - |
| RVT | spring | 0.1540 | 156 | 0.60612 | - | - | - |
| BGN | spring | 0.2461 | 156 | 0.55677 | - | - | - |
| PMN | spring | 0.2295 | 156 | 0.52613 | - | - | - |
| EVN | spring | 0.2961 | 156 | 0.52454 | - | - | - |
| ACI | spring | 0.1457 | 156 | 0.32560 | - | - | - |
| ENT | spring | 0.2783 | 156 | 0.22494 | - | - | - |

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Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region High frequency/ Day

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1169 | 156 | 0.00014 * | -1.5771 | -1.9832 | -1.2541 |
| SPT | autumn | 0.1298 | 156 | 0.00093 * | -1.5500 | -1.9991 | -1.2018 |
| PMN | autumn | 0.0902 | 156 | 0.0051 * | -1.2919 | -1.5416 | -1.0827 |
| ENT | spring | 0.1169 | 156 | 0.03667 * | -1.2794 | -1.6090 | -1.0174 |
| CVR | autumn | 0.0963 | 156 | 0.01537 * | -1.2662 | -1.5292 | -1.0484 |
| RHZ | autumn | 0.0631 | 156 | 0.00036 * | -1.2586 | -1.4242 | -1.1122 |
| POW | autumn | 0.0899 | 156 | 0.01309 * | -1.2531 | -1.4946 | -1.0507 |
| RVT | autumn | 0.0817 | 156 | 0.01435 * | -1.2241 | -1.4366 | -1.0430 |
| R3D | autumn | 0.0632 | 156 | 0.01737 * | -1.1641 | -1.3177 | -1.0285 |
| BGN | autumn | 0.0339 | 156 | 0.03456 * | 1.0748 | 1.0058 | 1.1486 |
| BGN | spring | 0.0339 | 156 | 0.00063 * | 1.1254 | 1.0531 | 1.2026 |
| RNG | spring | 0.0647 | 156 | 0.68043 | - | - | - |
| RPS | spring | 0.0718 | 156 | 0.61204 | - | - | - |
| R3D | spring | 0.0632 | 156 | 0.53877 | - | - | - |
| RVT | spring | 0.0817 | 156 | 0.51489 | - | - | - |
| EVN | spring | 0.1002 | 156 | 0.47885 | - | - | - |
| POW | spring | 0.0899 | 156 | 0.46075 | - | - | - |
| CVR | spring | 0.0963 | 156 | 0.38347 | - | - | - |
| ACI | spring | 0.0581 | 156 | 0.27831 | - | - | - |
| SPT | spring | 0.1298 | 156 | 0.25518 | - | - | - |
| RHZ | spring | 0.0631 | 156 | 0.23381 | - | - | - |
| PMN | spring | 0.0902 | 156 | 0.21053 | - | - | - |
| RNG | autumn | 0.0647 | 156 | 0.08475 | - | - | - |
| ACI | autumn | 0.0581 | 156 | 0.08082 | - | - | - |
| RPS | autumn | 0.0718 | 156 | 0.05685 | - | - | - |
| EVN | autumn | 0.1002 | 156 | 0.05310 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-high frequency/ Day

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1675 | 156 | 1E-04 * | -1.9524 | -2.7113 | -1.4060 |
| PMN | spring | 0.1641 | 156 | 0.00346 * | -1.6277 | -2.2449 | -1.1801 |
| ACI | spring | 0.1136 | 156 | 0.00179 * | -1.4349 | -1.7929 | -1.1484 |
| BGN | spring | 0.0752 | 156 | 0.04971 * | 1.1603 | 1.0013 | 1.3445 |
| BGN | autumn | 0.0752 | 156 | 0.59068 | - | - | - |
| EVN | autumn | 0.2275 | 156 | 0.48581 | - | - | - |
| PMN | autumn | 0.1641 | 156 | 0.44978 | - | - | - |
| SPT | autumn | 0.1706 | 156 | 0.44753 | - | - | - |
| RHZ | autumn | 0.0828 | 156 | 0.41736 | - | - | - |
| ENT | autumn | 0.1675 | 156 | 0.41332 | - | - | - |
| POW | autumn | 0.1725 | 156 | 0.34306 | - | - | - |
| CVR | autumn | 0.2092 | 156 | 0.31649 | - | - | - |
| RPS | autumn | 0.1127 | 156 | 0.22237 | - | - | - |
| R3D | autumn | 0.1121 | 156 | 0.21656 | - | - | - |
| RNG | autumn | 0.1128 | 156 | 0.21134 | - | - | - |
| ACI | autumn | 0.1136 | 156 | 0.13726 | - | - | - |
| RVT | autumn | 0.1261 | 156 | 0.12646 | - | - | - |
| RVT | spring | 0.1261 | 156 | 0.09148 | - | - | - |
| RNG | spring | 0.1128 | 156 | 0.08723 | - | - | - |
| RPS | spring | 0.1127 | 156 | 0.08067 | - | - | - |
| R3D | spring | 0.1121 | 156 | 0.07771 | - | - | - |
| RHZ | spring | 0.0828 | 156 | 0.07307 | - | - | - |
| POW | spring | 0.1725 | 156 | 0.07239 | - | - | - |
| CVR | spring | 0.2092 | 156 | 0.07155 | - | - | - |
| EVN | spring | 0.2275 | 156 | 0.06828 | - | - | - |
| SPT | spring | 0.1706 | 156 | 0.06572 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-low frequency/ Day

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|----------|---------|---------------------------|---------------------------|
| ENT | spring | 0.1486 | 156 | 0.0358 * | -1.3698 | -1.8330 | -1.0237 |
| EVN | autumn | 0.2146 | 156 | 0.96334 | - | - | - |
| SPT | autumn | 0.1744 | 156 | 0.87633 | - | - | - |
| PMN | autumn | 0.1582 | 156 | 0.83991 | - | - | - |
| RHZ | autumn | 0.0861 | 156 | 0.83384 | - | - | - |
| CVR | autumn | 0.2063 | 156 | 0.81154 | - | - | - |
| POW | autumn | 0.1744 | 156 | 0.79116 | - | - | - |
| ENT | autumn | 0.1486 | 156 | 0.72230 | - | - | - |
| R3D | autumn | 0.1135 | 156 | 0.60624 | - | - | - |
| RPS | autumn | 0.1140 | 156 | 0.59993 | - | - | - |
| RNG | autumn | 0.1138 | 156 | 0.59959 | - | - | - |
| BGN | autumn | 0.1119 | 156 | 0.57080 | - | - | - |
| RHZ | spring | 0.0861 | 156 | 0.52464 | - | - | - |
| RPS | spring | 0.1140 | 156 | 0.46684 | - | - | - |
| RNG | spring | 0.1138 | 156 | 0.45755 | - | - | - |
| R3D | spring | 0.1135 | 156 | 0.45639 | - | - | - |
| RVT | spring | 0.1276 | 156 | 0.40180 | - | - | - |
| RVT | autumn | 0.1276 | 156 | 0.40115 | - | - | - |
| ACI | autumn | 0.1139 | 156 | 0.38468 | - | - | - |
| POW | spring | 0.1744 | 156 | 0.29456 | - | - | - |
| SPT | spring | 0.1744 | 156 | 0.29299 | - | - | - |
| CVR | spring | 0.2063 | 156 | 0.27064 | - | - | - |
| EVN | spring | 0.2146 | 156 | 0.26297 | - | - | - |
| BGN | spring | 0.1119 | 156 | 0.24555 | - | - | - |
| PMN | spring | 0.1582 | 156 | 0.10842 | - | - | - |
| ACI | spring | 0.1139 | 156 | 0.07630 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Low frequency/ Day

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|---------|-------|---------------------------|---------------------------|
| POW | spring | 0.2041 | 156 | 0.98471 | - | - | - |
| SPT | spring | 0.1994 | 156 | 0.98141 | - | - | - |
| ENT | autumn | 0.2291 | 156 | 0.94876 | - | - | - |
| RHZ | autumn | 0.0891 | 156 | 0.93207 | - | - | - |
| RVT | spring | 0.1410 | 156 | 0.89673 | - | - | - |
| PMN | autumn | 0.2141 | 156 | 0.89323 | - | - | - |
| SPT | autumn | 0.1994 | 156 | 0.88399 | - | - | - |
| CVR | spring | 0.2517 | 156 | 0.86443 | - | - | - |
| EVN | autumn | 0.2829 | 156 | 0.85784 | - | - | - |
| R3D | autumn | 0.1168 | 156 | 0.84629 | - | - | - |
| RPS | autumn | 0.1222 | 156 | 0.83181 | - | - | - |
| RNG | autumn | 0.1256 | 156 | 0.83103 | - | - | - |
| POW | autumn | 0.2041 | 156 | 0.82931 | - | - | - |
| EVN | spring | 0.2829 | 156 | 0.81075 | - | - | - |
| CVR | autumn | 0.2517 | 156 | 0.79349 | - | - | - |
| PMN | spring | 0.2141 | 156 | 0.75817 | - | - | - |
| BGN | autumn | 0.1915 | 156 | 0.68864 | - | - | - |
| RPS | spring | 0.1222 | 156 | 0.68667 | - | - | - |
| RNG | spring | 0.1256 | 156 | 0.68314 | - | - | - |
| R3D | spring | 0.1168 | 156 | 0.67185 | - | - | - |
| RVT | autumn | 0.1410 | 156 | 0.63674 | - | - | - |
| RHZ | spring | 0.0891 | 156 | 0.51334 | - | - | - |
| ENT | spring | 0.2291 | 156 | 0.46352 | - | - | - |
| ACI | spring | 0.1054 | 156 | 0.33030 | - | - | - |
| ACI | autumn | 0.1054 | 156 | 0.28325 | - | - | - |
| BGN | spring | 0.1915 | 156 | 0.19567 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region High frequency/ Dusk

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1355 | 156 | 8.4E-09 * | -2.2827 | -2.9773 | -1.7502 |
| SPT | autumn | 0.1362 | 156 | 0.00012 * | -1.7117 | -2.2355 | -1.3107 |
| PMN | autumn | 0.0977 | 156 | 5.8E-05 * | -1.4974 | -1.8134 | -1.2364 |
| ENT | spring | 0.1355 | 156 | 0.01876 * | -1.3797 | -1.7995 | -1.0579 |
| RVT | autumn | 0.0847 | 156 | 0.00057 * | -1.3474 | -1.5908 | -1.1413 |
| CVR | autumn | 0.1051 | 156 | 0.00651 * | -1.3365 | -1.6423 | -1.0876 |
| POW | autumn | 0.0947 | 156 | 0.00289 * | -1.3321 | -1.6039 | -1.1064 |
| SPT | spring | 0.1362 | 156 | 0.03864 * | -1.3285 | -1.7350 | -1.0173 |
| RHZ | autumn | 0.0630 | 156 | 3.6E-05 * | -1.3073 | -1.4792 | -1.1555 |
| ACI | autumn | 0.0805 | 156 | 0.00179 * | -1.2916 | -1.5124 | -1.1030 |
| EVN | autumn | 0.1111 | 156 | 0.03585 * | -1.2652 | -1.5731 | -1.0176 |
| RPS | autumn | 0.0733 | 156 | 0.00597 * | -1.2267 | -1.4162 | -1.0625 |
| R3D | autumn | 0.0657 | 156 | 0.00371 * | -1.2135 | -1.3802 | -1.0669 |
| RHZ | spring | 0.0630 | 156 | 0.0073 * | -1.1868 | -1.3428 | -1.0490 |
| RNG | autumn | 0.0663 | 156 | 0.0123 * | -1.1828 | -1.3469 | -1.0387 |
| BGN | autumn | 0.0323 | 156 | 0.02276 * | 1.0772 | 1.0111 | 1.1477 |
| BGN | spring | 0.0323 | 156 | 0.00336 * | 1.1011 | 1.0335 | 1.1732 |
| ACI | spring | 0.0805 | 156 | 0.85869 | - | - | - |
| RNG | spring | 0.0663 | 156 | 0.26679 | - | - | - |
| RPS | spring | 0.0733 | 156 | 0.22963 | - | - | - |
| EVN | spring | 0.1111 | 156 | 0.20219 | - | - | - |
| R3D | spring | 0.0657 | 156 | 0.16673 | - | - | - |
| RVT | spring | 0.0847 | 156 | 0.16441 | - | - | - |
| POW | spring | 0.0947 | 156 | 0.13229 | - | - | - |
| CVR | spring | 0.1051 | 156 | 0.12590 | - | - | - |
| PMN | spring | 0.0977 | 156 | 0.05584 | - | - | - |

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Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-high frequency/ Dusk

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2042 | 156 | 1.6E-07 * | -3.0675 | -4.5768 | -2.0559 |
| EVN | autumn | 0.2462 | 156 | 0.00022 * | -2.5385 | -4.1131 | -1.5666 |
| PMN | autumn | 0.1785 | 156 | 3.9E-05 * | -2.1303 | -3.0224 | -1.5015 |
| CVR | autumn | 0.2185 | 156 | 0.0008 * | -2.1115 | -3.2403 | -1.3760 |
| ACI | autumn | 0.1420 | 156 | 2.9E-05 * | -1.8440 | -2.4356 | -1.3961 |
| ENT | spring | 0.2042 | 156 | 0.00477 * | -1.7941 | -2.6769 | -1.2024 |
| POW | autumn | 0.1755 | 156 | 0.00132 * | -1.7752 | -2.5038 | -1.2586 |
| SPT | autumn | 0.1734 | 156 | 0.00268 * | -1.6972 | -2.3840 | -1.2082 |
| RVT | autumn | 0.1347 | 156 | 0.00017 * | -1.6805 | -2.1884 | -1.2905 |
| PMN | spring | 0.1785 | 156 | 0.01706 * | -1.5377 | -2.1817 | -1.0839 |
| RPS | autumn | 0.1159 | 156 | 0.00067 * | -1.4951 | -1.8765 | -1.1913 |
| RNG | autumn | 0.1157 | 156 | 0.00067 * | -1.4942 | -1.8744 | -1.1911 |
| R3D | autumn | 0.1148 | 156 | 0.00072 * | -1.4861 | -1.8612 | -1.1866 |
| ACI | spring | 0.1420 | 156 | 0.00909 * | -1.4550 | -1.9217 | -1.1016 |
| RHZ | autumn | 0.0845 | 156 | 0.00361 * | -1.2837 | -1.5150 | -1.0878 |
| BGN | autumn | 0.0759 | 156 | 0.67408 | - | - | - |
| BGN | spring | 0.0759 | 156 | 0.14886 | - | - | - |
| CVR | spring | 0.2185 | 156 | 0.12391 | - | - | - |
| POW | spring | 0.1755 | 156 | 0.10730 | - | - | - |
| SPT | spring | 0.1734 | 156 | 0.10614 | - | - | - |
| RVT | spring | 0.1347 | 156 | 0.09107 | - | - | - |
| EVN | spring | 0.2462 | 156 | 0.08683 | - | - | - |
| RNG | spring | 0.1157 | 156 | 0.06462 | - | - | - |
| RHZ | spring | 0.0845 | 156 | 0.06082 | - | - | - |
| RPS | spring | 0.1159 | 156 | 0.05920 | - | - | - |
| R3D | spring | 0.1148 | 156 | 0.05605 | - | - | - |

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Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-low frequency/ Dusk

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2106 | 156 | 2E-06 * | -2.8292 | -4.2752 | -1.8723 |
| EVN | autumn | 0.2544 | 156 | 0.00054 * | -2.4571 | -4.0454 | -1.4924 |
| PMN | autumn | 0.1896 | 156 | 0.00024 * | -2.0416 | -2.9604 | -1.4081 |
| CVR | autumn | 0.2296 | 156 | 0.00312 * | -1.9924 | -3.1247 | -1.2704 |
| ACI | autumn | 0.1504 | 156 | 7.9E-05 * | -1.8395 | -2.4700 | -1.3700 |
| POW | autumn | 0.1865 | 156 | 0.00464 * | -1.7084 | -2.4621 | -1.1854 |
| SPT | autumn | 0.1848 | 156 | 0.00724 * | -1.6534 | -2.3751 | -1.1511 |
| RVT | autumn | 0.1445 | 156 | 0.0012 * | -1.6108 | -2.1380 | -1.2136 |
| RNG | autumn | 0.1231 | 156 | 0.00404 * | -1.4320 | -1.8226 | -1.1251 |
| RPS | autumn | 0.1235 | 156 | 0.00432 * | -1.4300 | -1.8215 | -1.1226 |
| R3D | autumn | 0.1226 | 156 | 0.00422 * | -1.4277 | -1.8155 | -1.1227 |
| RHZ | autumn | 0.0897 | 156 | 0.01142 * | -1.2583 | -1.5002 | -1.0553 |
| RHZ | spring | 0.0897 | 156 | 0.58752 | - | - | - |
| BGN | spring | 0.1262 | 156 | 0.58566 | - | - | - |
| RPS | spring | 0.1235 | 156 | 0.50537 | - | - | - |
| R3D | spring | 0.1226 | 156 | 0.50195 | - | - | - |
| RNG | spring | 0.1231 | 156 | 0.49326 | - | - | - |
| SPT | spring | 0.1848 | 156 | 0.49187 | - | - | - |
| POW | spring | 0.1865 | 156 | 0.46588 | - | - | - |
| CVR | spring | 0.2296 | 156 | 0.46113 | - | - | - |
| RVT | spring | 0.1445 | 156 | 0.42843 | - | - | - |
| EVN | spring | 0.2544 | 156 | 0.39176 | - | - | - |
| BGN | autumn | 0.1262 | 156 | 0.37763 | - | - | - |
| PMN | spring | 0.1896 | 156 | 0.31551 | - | - | - |
| ENT | spring | 0.2106 | 156 | 0.19950 | - | - | - |
| ACI | spring | 0.1504 | 156 | 0.16625 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Low frequency/ Dusk

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2511 | 156 | 0.00497 * | -2.0451 | -3.3452 | -1.2503 |
| ACI | autumn | 0.1420 | 156 | 0.00733 * | -1.4709 | -1.9429 | -1.1135 |
| BGN | autumn | 0.2188 | 156 | 0.95838 | - | - | - |
| CVR | spring | 0.2481 | 156 | 0.95587 | - | - | - |
| RVT | spring | 0.1501 | 156 | 0.95258 | - | - | - |
| EVN | spring | 0.2860 | 156 | 0.91623 | - | - | - |
| POW | spring | 0.1990 | 156 | 0.88617 | - | - | - |
| SPT | spring | 0.1918 | 156 | 0.86211 | - | - | - |
| RNG | spring | 0.1268 | 156 | 0.78812 | - | - | - |
| RPS | spring | 0.1230 | 156 | 0.78695 | - | - | - |
| PMN | spring | 0.2179 | 156 | 0.77888 | - | - | - |
| R3D | spring | 0.1174 | 156 | 0.77334 | - | - | - |
| RHZ | spring | 0.0876 | 156 | 0.68555 | - | - | - |
| BGN | spring | 0.2188 | 156 | 0.38472 | - | - | - |
| CVR | autumn | 0.2481 | 156 | 0.37234 | - | - | - |
| POW | autumn | 0.1990 | 156 | 0.37010 | - | - | - |
| ACI | spring | 0.1420 | 156 | 0.35213 | - | - | - |
| EVN | autumn | 0.2860 | 156 | 0.35194 | - | - | - |
| ENT | spring | 0.2511 | 156 | 0.32895 | - | - | - |
| R3D | autumn | 0.1174 | 156 | 0.32509 | - | - | - |
| SPT | autumn | 0.1918 | 156 | 0.32441 | - | - | - |
| RPS | autumn | 0.1230 | 156 | 0.32412 | - | - | - |
| RHZ | autumn | 0.0876 | 156 | 0.31531 | - | - | - |
| RNG | autumn | 0.1268 | 156 | 0.29444 | - | - | - |
| RVT | autumn | 0.1501 | 156 | 0.18691 | - | - | - |
| PMN | autumn | 0.2179 | 156 | 0.08814 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region High frequency/ Night

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.1495 | 156 | 8.6E-08 * | -2.3171 | -3.1062 | -1.7285 |
| ENT | spring | 0.1495 | 156 | 6.9E-07 * | -2.1678 | -2.9061 | -1.6171 |
| SPT | autumn | 0.1375 | 156 | 1.8E-05 * | -1.8365 | -2.4046 | -1.4027 |
| SPT | spring | 0.1375 | 156 | 3E-05 * | -1.8059 | -2.3645 | -1.3793 |
| PMN | spring | 0.1032 | 156 | 2.4E-05 * | -1.5676 | -1.9191 | -1.2804 |
| PMN | autumn | 0.1032 | 156 | 6.5E-05 * | -1.5277 | -1.8704 | -1.2479 |
| CVR | spring | 0.1046 | 156 | 0.00218 * | -1.3855 | -1.7009 | -1.1286 |
| RVT | autumn | 0.0874 | 156 | 0.00038 * | -1.3737 | -1.6303 | -1.1574 |
| ACI | autumn | 0.0818 | 156 | 0.00015 * | -1.3733 | -1.6121 | -1.1699 |
| POW | spring | 0.0962 | 156 | 0.00166 * | -1.3607 | -1.6431 | -1.1268 |
| CVR | autumn | 0.1046 | 156 | 0.00454 * | -1.3516 | -1.6593 | -1.1010 |
| POW | autumn | 0.0962 | 156 | 0.00247 * | -1.3446 | -1.6237 | -1.1134 |
| RHZ | autumn | 0.0658 | 156 | 3.1E-05 * | -1.3264 | -1.5091 | -1.1659 |
| RHZ | spring | 0.0658 | 156 | 5.7E-05 * | -1.3133 | -1.4942 | -1.1543 |
| ACI | spring | 0.0818 | 156 | 0.00328 * | -1.2766 | -1.4986 | -1.0875 |
| RVT | spring | 0.0874 | 156 | 0.00805 * | -1.2644 | -1.5007 | -1.0654 |
| EVN | autumn | 0.1104 | 156 | 0.0388 * | -1.2587 | -1.5628 | -1.0138 |
| EVN | spring | 0.1104 | 156 | 0.0459 * | -1.2488 | -1.5505 | -1.0058 |
| RPS | autumn | 0.0758 | 156 | 0.00663 * | -1.2320 | -1.4294 | -1.0619 |
| R3D | autumn | 0.0684 | 156 | 0.00717 * | -1.2049 | -1.3777 | -1.0537 |
| RPS | spring | 0.0758 | 156 | 0.02191 * | -1.1919 | -1.3828 | -1.0273 |
| R3D | spring | 0.0684 | 156 | 0.01747 * | -1.1786 | -1.3477 | -1.0307 |
| RNG | autumn | 0.0682 | 156 | 0.018 * | -1.1771 | -1.3455 | -1.0298 |
| RNG | spring | 0.0682 | 156 | 0.04374 * | -1.1487 | -1.3130 | -1.0050 |
| BGN | autumn | 0.0353 | 156 | 0.00413 * | 1.1083 | 1.0342 | 1.1877 |
| BGN | spring | 0.0353 | 156 | 0.00117 * | 1.1239 | 1.0487 | 1.2044 |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-high frequency/ Night

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2510 | 156 | 1.3E-05 * | -3.0996 | -5.0696 | -1.8951 |
| EVN | autumn | 0.2950 | 156 | 0.00109 * | -2.6694 | -4.7587 | -1.4974 |
| CVR | autumn | 0.2528 | 156 | 0.00127 * | -2.2922 | -3.7621 | -1.3966 |
| PMN | autumn | 0.2113 | 156 | 0.00018 * | -2.2478 | -3.4011 | -1.4856 |
| ACI | autumn | 0.1688 | 156 | 0.00018 * | -1.9106 | -2.6601 | -1.3723 |
| POW | autumn | 0.1970 | 156 | 0.00157 * | -1.8848 | -2.7729 | -1.2812 |
| ENT | spring | 0.2510 | 156 | 0.01531 * | -1.8506 | -3.0268 | -1.1315 |
| SPT | autumn | 0.1931 | 156 | 0.00255 * | -1.8081 | -2.6401 | -1.2383 |
| RVT | autumn | 0.1526 | 156 | 0.00034 * | -1.7498 | -2.3599 | -1.2975 |
| ACI | spring | 0.1688 | 156 | 0.00168 * | -1.7160 | -2.3891 | -1.2325 |
| RPS | autumn | 0.1297 | 156 | 0.00109 * | -1.5398 | -1.9855 | -1.1942 |
| RNG | autumn | 0.1289 | 156 | 0.00102 * | -1.5397 | -1.9824 | -1.1959 |
| R3D | autumn | 0.1280 | 156 | 0.0011 * | -1.5307 | -1.9672 | -1.1911 |
| RHZ | autumn | 0.0892 | 156 | 0.00301 * | -1.3083 | -1.5582 | -1.0986 |
| BGN | autumn | 0.0842 | 156 | 0.53552 | - | - | - |
| RHZ | spring | 0.0892 | 156 | 0.29569 | - | - | - |
| SPT | spring | 0.1931 | 156 | 0.25438 | - | - | - |
| POW | spring | 0.1970 | 156 | 0.23793 | - | - | - |
| R3D | spring | 0.1280 | 156 | 0.22877 | - | - | - |
| RPS | spring | 0.1297 | 156 | 0.22800 | - | - | - |
| CVR | spring | 0.2528 | 156 | 0.22763 | - | - | - |
| RNG | spring | 0.1289 | 156 | 0.22000 | - | - | - |
| EVN | spring | 0.2950 | 156 | 0.21493 | - | - | - |
| BGN | spring | 0.0842 | 156 | 0.20893 | - | - | - |
| RVT | spring | 0.1526 | 156 | 0.19105 | - | - | - |
| PMN | spring | 0.2113 | 156 | 0.07676 | - | - | - |

The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Mid-low frequency/ Night

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2757 | 156 | 0.00014 * | -2.9407 | -5.0486 | -1.7129 |
| EVN | autumn | 0.3144 | 156 | 0.00303 * | -2.5777 | -4.7734 | -1.3920 |
| PMN | autumn | 0.2300 | 156 | 0.00066 * | -2.2237 | -3.4906 | -1.4167 |
| CVR | autumn | 0.2703 | 156 | 0.00437 * | -2.1855 | -3.7125 | -1.2866 |
| ACI | autumn | 0.1706 | 156 | 0.00031 * | -1.8754 | -2.6199 | -1.3425 |
| POW | autumn | 0.2118 | 156 | 0.00425 * | -1.8488 | -2.8001 | -1.2207 |
| SPT | autumn | 0.2081 | 156 | 0.00584 * | -1.7893 | -2.6906 | -1.1899 |
| RVT | autumn | 0.1653 | 156 | 0.00159 * | -1.7011 | -2.3519 | -1.2304 |
| ACI | spring | 0.1706 | 156 | 0.0065 * | -1.6008 | -2.2363 | -1.1459 |
| RNG | autumn | 0.1387 | 156 | 0.0037 * | -1.5048 | -1.9748 | -1.1467 |
| RPS | autumn | 0.1390 | 156 | 0.00396 * | -1.5019 | -1.9724 | -1.1436 |
| R3D | autumn | 0.1381 | 156 | 0.00384 * | -1.4999 | -1.9663 | -1.1442 |
| RHZ | autumn | 0.0965 | 156 | 0.00776 * | -1.2973 | -1.5674 | -1.0737 |
| BGN | spring | 0.1365 | 156 | 0.97111 | - | - | - |
| BGN | autumn | 0.1365 | 156 | 0.59252 | - | - | - |
| R3D | spring | 0.1381 | 156 | 0.58436 | - | - | - |
| RPS | spring | 0.1390 | 156 | 0.58351 | - | - | - |
| RNG | spring | 0.1387 | 156 | 0.57691 | - | - | - |
| RHZ | spring | 0.0965 | 156 | 0.54264 | - | - | - |
| CVR | spring | 0.2703 | 156 | 0.54168 | - | - | - |
| POW | spring | 0.2118 | 156 | 0.53455 | - | - | - |
| SPT | spring | 0.2081 | 156 | 0.50101 | - | - | - |
| RVT | spring | 0.1653 | 156 | 0.44076 | - | - | - |
| EVN | spring | 0.3144 | 156 | 0.43648 | - | - | - |
| PMN | spring | 0.2300 | 156 | 0.26907 | - | - | - |
| ENT | spring | 0.2757 | 156 | 0.07777 | - | - | - |

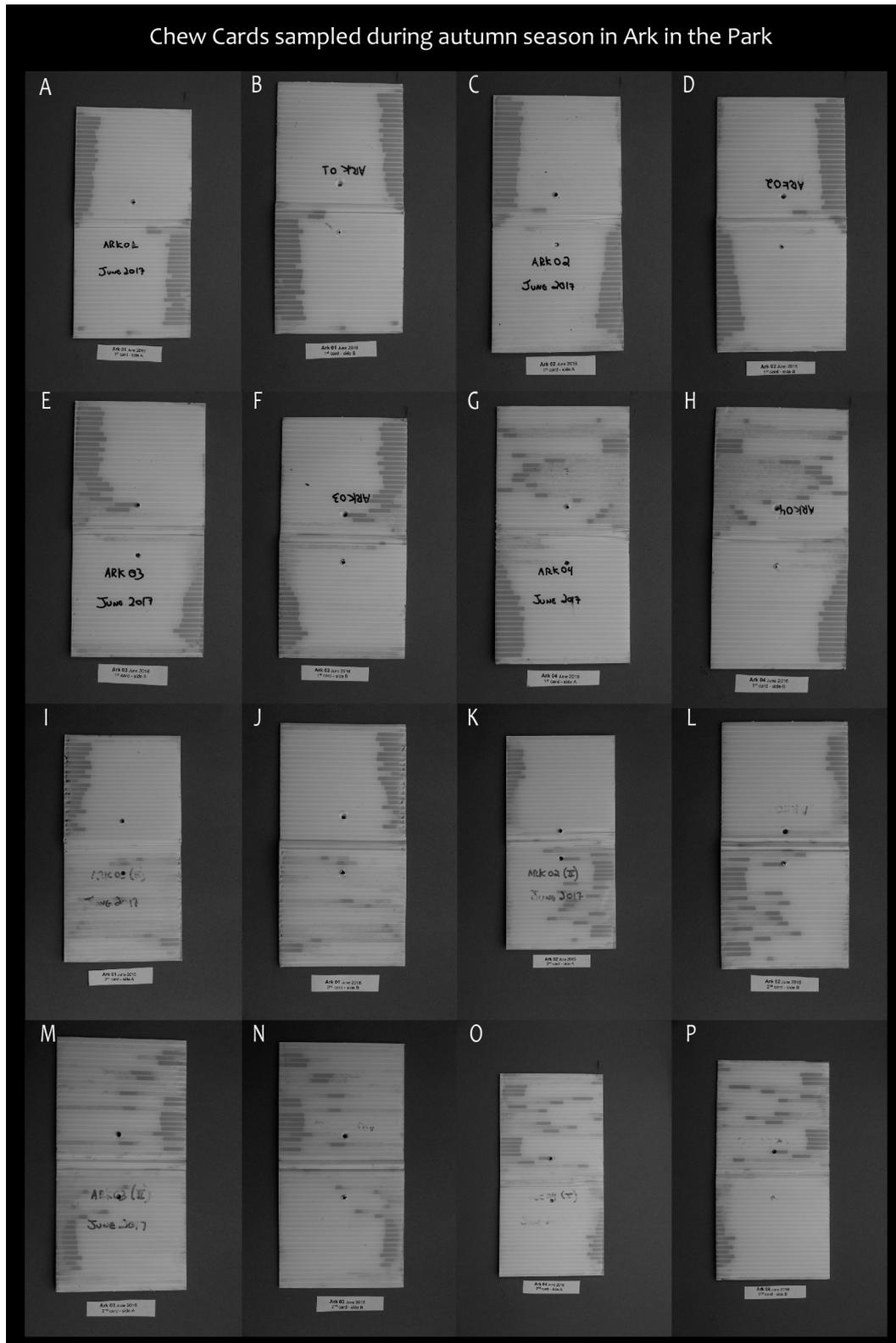
The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Pairwise comparisons of acoustic indices measurements for sites with high versus no pest mammal management for the acoustic region Low frequency/ Night

| Index | Season | Standard Error | Degrees of Freedom | p.value | Ratio | lower Confidence Interval | upper Confidence Interval |
|-------|--------|----------------|--------------------|-----------|---------|---------------------------|---------------------------|
| ENT | autumn | 0.2869 | 156 | 0.00532 * | -2.2503 | -3.9487 | -1.2824 |
| PMN | autumn | 0.2309 | 156 | 0.042 * | -1.6054 | -2.5241 | -1.0211 |
| ACI | autumn | 0.1485 | 156 | 0.00413 * | -1.5410 | -2.0618 | -1.1518 |
| ACI | spring | 0.1485 | 156 | 0.02909 * | -1.3870 | -1.8558 | -1.0367 |
| BGN | autumn | 0.2444 | 156 | 0.81969 | - | - | - |
| BGN | spring | 0.2444 | 156 | 0.74889 | - | - | - |
| RNG | spring | 0.1287 | 156 | 0.71296 | - | - | - |
| RPS | spring | 0.1246 | 156 | 0.69228 | - | - | - |
| RHZ | spring | 0.0857 | 156 | 0.67560 | - | - | - |
| R3D | spring | 0.1186 | 156 | 0.66372 | - | - | - |
| POW | spring | 0.2009 | 156 | 0.63437 | - | - | - |
| CVR | spring | 0.2551 | 156 | 0.61222 | - | - | - |
| SPT | spring | 0.1907 | 156 | 0.57987 | - | - | - |
| RVT | spring | 0.1550 | 156 | 0.57567 | - | - | - |
| EVN | spring | 0.3101 | 156 | 0.55549 | - | - | - |
| PMN | spring | 0.2309 | 156 | 0.34595 | - | - | - |
| EVN | autumn | 0.3101 | 156 | 0.27514 | - | - | - |
| RPS | autumn | 0.1246 | 156 | 0.20560 | - | - | - |
| CVR | autumn | 0.2551 | 156 | 0.20534 | - | - | - |
| R3D | autumn | 0.1186 | 156 | 0.20196 | - | - | - |
| RHZ | autumn | 0.0857 | 156 | 0.19691 | - | - | - |
| POW | autumn | 0.2009 | 156 | 0.19645 | - | - | - |
| RNG | autumn | 0.1287 | 156 | 0.19195 | - | - | - |
| ENT | spring | 0.2869 | 156 | 0.16398 | - | - | - |
| SPT | autumn | 0.1907 | 156 | 0.15665 | - | - | - |
| RVT | autumn | 0.1550 | 156 | 0.12036 | - | - | - |

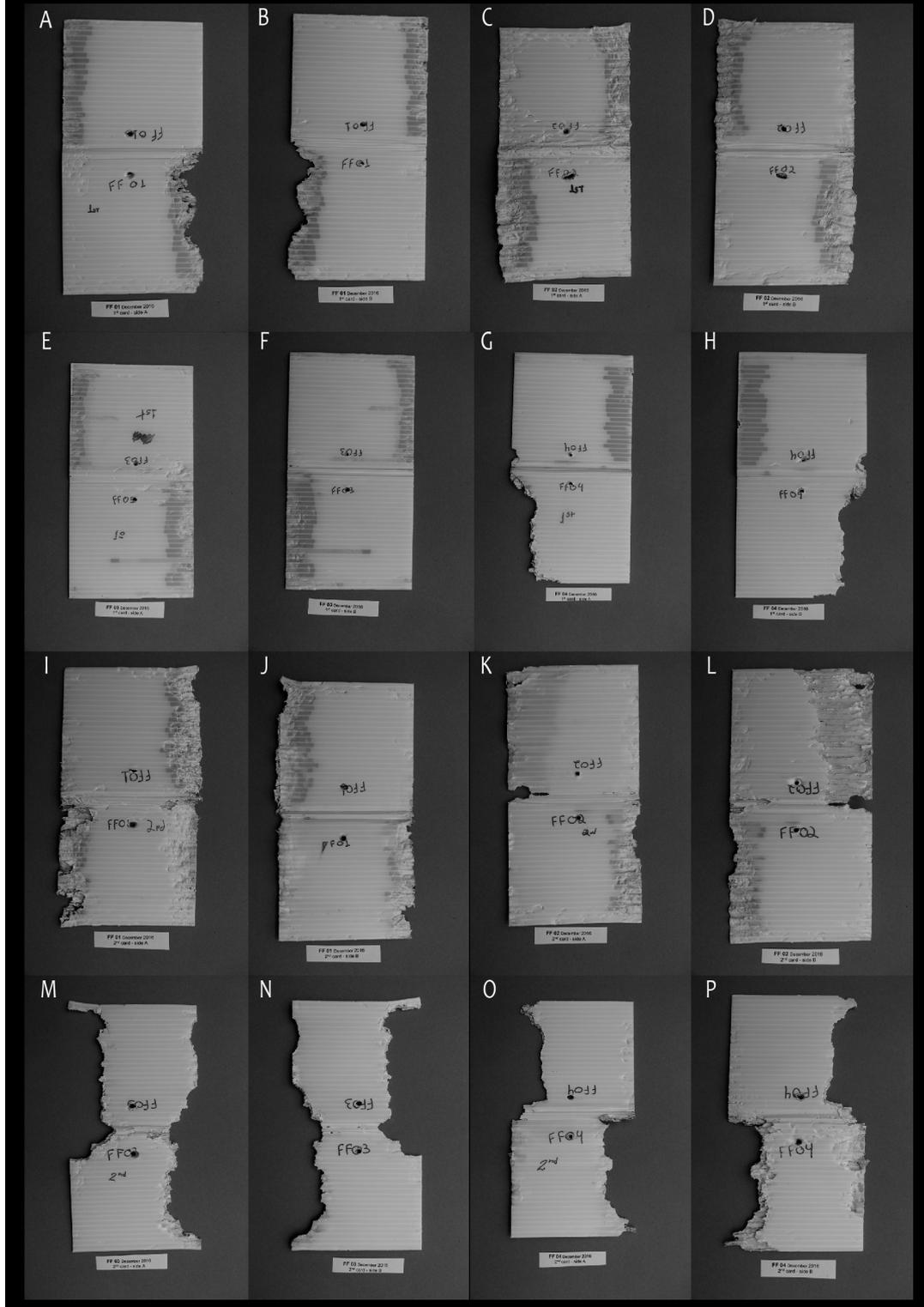
The negative signal on Ratio column indicates the direction of the effect, meaning that indices results were higher in the no pest mammal management site (Fairy Falls). The * symbol indicates p values <0.05.

Appendix F. Chew cards pictures



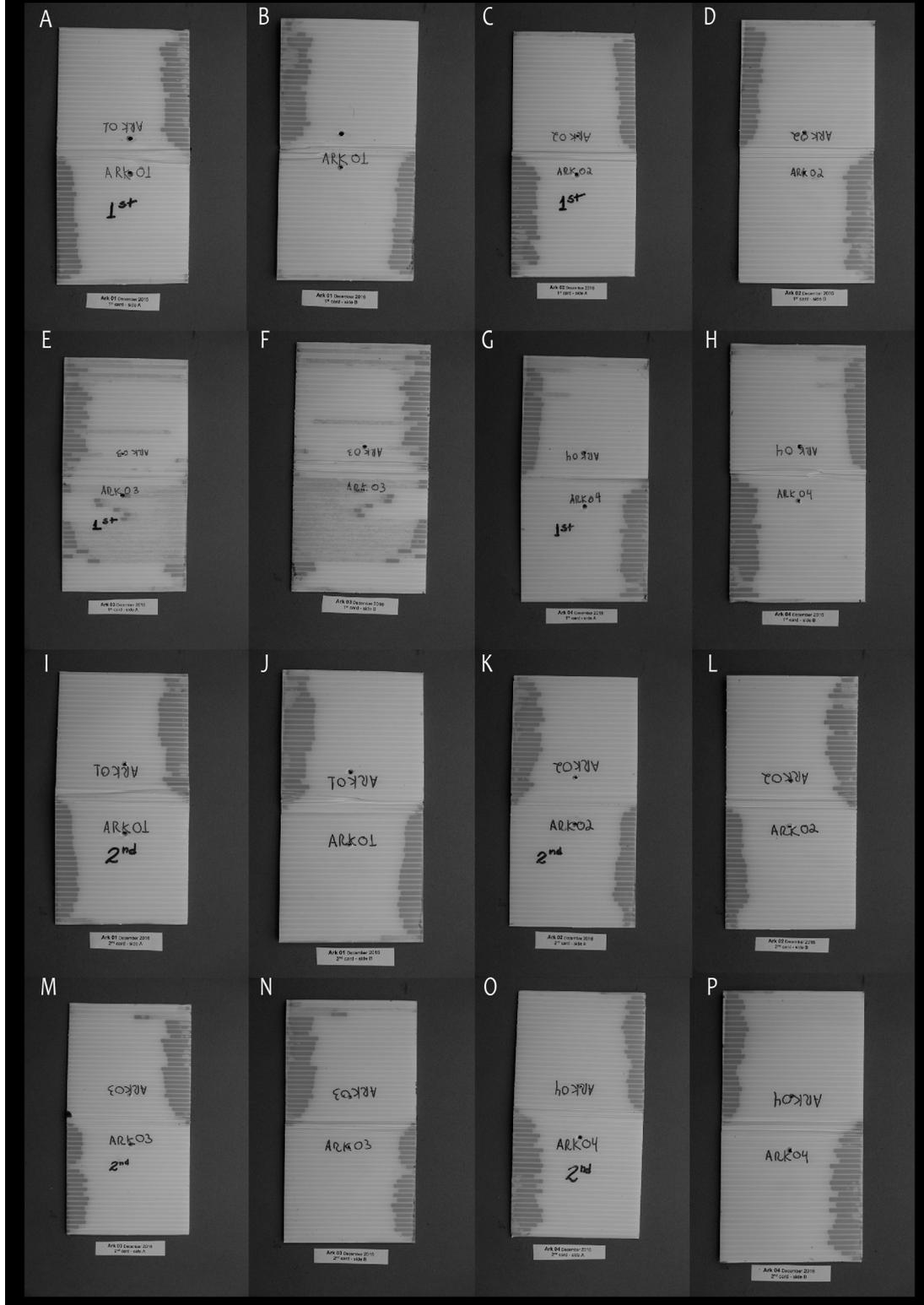
Chew Cards sampled during autumn season in Ark in the Park. First side of the first card fixed in the location ARK01 during autumn 2017 (A); second side of the first card fixed in the location ARK01 during autumn 2017 (B); first side of the first card fixed in the location ARK02 during autumn 2017 (C); second side of the first card fixed in the location ARK02 during autumn 2017 (D); first side of the first card fixed in the location ARK03 during autumn 2017 (E); second side of the first card fixed in the location ARK03 during autumn 2017 (F); first side of the first card fixed in the location ARK04 during autumn 2017 (G); second side of the first card fixed in the location ARK04 during autumn 2017 (H); first side of the second card fixed in the location ARK01 during autumn 2017 (I); second side of the second card fixed in the location ARK01 during autumn 2017 (J); first side of the second card fixed in the location ARK02 during autumn 2017 (K); second side of the second card fixed in the location ARK02 during autumn 2017 (L); first side of the second card fixed in the location ARK03 during autumn 2017 (M); second side of the second card fixed in the location ARK03 during autumn 2017 (N); first side of the second card fixed in the location ARK04 during autumn 2017 (O); second side of the second card fixed in the location ARK04 during autumn 2017 (P).

Chew Cards sampled during spring season in Fairy Falls



Chew Cards sampled during spring season in Fairy Falls. First side of the first card fixed in the location FF01 during spring 2017 (A); second side of the first card fixed in the location FF01 during spring 2017 (B); first side of the first card fixed in the location FF02 during spring 2017 (C); second side of the first card fixed in the location FF02 during spring 2017 (D); first side of the first card fixed in the location FF03 during spring 2017 (E); second side of the first card fixed in the location FF03 during spring 2017 (F); first side of the first card fixed in the location FF04 during spring 2017 (G); second side of the first card fixed in the location FF04 during spring 2017 (H); first side of the second card fixed in the location FF01 during spring 2017 (I); second side of the second card fixed in the location FF01 during spring 2017 (J); first side of the second card fixed in the location FF02 during spring 2017 (K); second side of the second card fixed in the location FF02 during spring 2017 (L); first side of the second card fixed in the location FF03 during spring 2017 (M); second side of the second card fixed in the location FF03 during spring 2017 (N); first side of the second card fixed in the location FF04 during spring 2017 (O); second side of the second card fixed in the location FF04 during spring 2017 (P).

Chew Cards sampled during spring season in Ark in the Park



Chew Cards sampled during spring season in Ark in the Park. First side of the first card fixed in the location ARK01 during spring 2017 (A); second side of the first card fixed in the location ARK01 during spring 2017 (B); first side of the first card fixed in the location ARK02 during spring 2017 (C); second side of the first card fixed in the location ARK02 during spring 2017 (D); first side of the first card fixed in the location ARK03 during spring 2017 (E); second side of the first card fixed in the location ARK03 during spring 2017 (F); first side of the first card fixed in the location ARK04 during spring 2017 (G); second side of the first card fixed in the location ARK04 during spring 2017 (H); first side of the second card fixed in the location ARK04 during spring 2017 (I); second side of the second card fixed in the location ARK01 during spring 2017 (J); first side of the second card fixed in the location ARK02 during spring 2017 (K); second side of the second card fixed in the location ARK02 during spring 2017 (L); first side of the second card fixed in the location ARK03 during spring 2017 (M); second side of the second card fixed in the location ARK03 during spring 2017 (N); first side of the second card fixed in the location ARK04 during spring 2017 (O); second side of the second card fixed in the location ARK04 during spring 2017 (P).

Appendix G. Preliminary Recognizers

General Modelling approach

I created a sequence of four recognizers, each with a training and testing stage. These four recognizers were divided in two groups, preliminary recognizers and optimised recognizers. The preliminary recognizers are not described in the main text and are only presented here in the supporting information. The preliminary recognizers, a) *Initial Recognizer* and b) *Edited Recognizer*, were built from training files extracted from active recordings. They were tested against a 2.5 minute long sound file containing a subset of the training calls.

The optimised recognizers, c) *Multispecies Recognizer* and d) *AFSR*, received additional training calls extracted from passive acoustic recordings (as described in the paper). The process for selecting these was fast-tracked by running the b) *Edited Recognizer* over these PAM recordings as this provided an initial identification that could then be confirmed by a seabird expert. The optimised recognizers were tested more rigorously against a 10 minute long sound file created from fragments of the PAM recordings.

The two preliminary recognizers were crucial for the construction of the sound file training data set (total 179 MB) used in the paper. Since the a) *Initial Recognizer* and b) *Edited Recognizer* are not described in the paper, a short description of these two recognizers is given in this Appendix.

Description of the Preliminary Recognizers

a) *Initial Recognizer*

Manually annotated label files were created for all sound files initially selected from the active recordings previously described. The inclusion of these files into the set of training files was performed until the recognizers were able to identify calls from all the five petrels, generating a single recognizer containing all the species. This initial selection of sound files and manual creation of the annotation text files generated 189 MB of training files.

b) *Edited Recognizer*

Poor quality training files used for a) *Initial Recognizer* were identified by visual and aural inspection of spectrograms and excluded to build the training files set of the *Edited Recognizer*. Moreover, additional good quality files were identified from the active recordings and added. The minimal interval between two calls or different sound categories was here defined as 0.1 second. It means that two consecutive calls from the same species would be separately annotated if the interval between them was longer than or equal to 0.1 second. This avoided inclusion of unnecessary background sound within sound fragments used to create the recogniser statistical profile for each category during the training stage. After the edits, file exclusions, and additions, the resulting *Edited Recognizer* had 109 MB of training sound files.

The Edited Recognizer was then ran over the PAM recordings to fast track finding more examples of calls. All these calls extracted from the active and PAM recordings were combined into a single set of training sound files, which were then used for both our multispecies recogniser and our AFSR (assemblage of focal species recognizers).

Preliminary Recognizers' Results

When compared with the 2.5 minute manually annotated file the a) *Initial Recognizer* achieved 63% similarity, while the b) *Edited Recognizer* achieved 69%. The *Initial Recognizer's* results for Fluttering shearwater, Common diving petrel, and Grey-faced petrel were considered poor due to the high false positives (43%, 50%, and 94%) and low precision (57%, 50%, and 6%, respectively) achieved. Overall the *Edited Recognizer* was only slightly more accurate than the *Initial Recognizer*, showing lower false positive rates and higher precision for Grey-faced petrel, Fluttering shearwater and White-faced storm petrel (Table 1). However, there was an increase in the false positive rate (from 4% in the *Initial recognizer* to 17%) for Little shearwater, and extremely poor results for for Common diving petrel, with no true positive indication of presence (false positive rate of 100%).

The preliminary recognizers did not achieve a high performance and represent only a previous step for building the optimised recognizers, c) *Multispecies Recognizer* and d) *AFSR*.

Total false positive rate and Precision per species achieved by each of the four recognizers tested

| Species | a) Initial Recognizer | | b) Edited Recognizer | | c) Multispecies Recognizer | | d) AFSR | |
|--------------------------|---------------------------|-------------|---------------------------|-------------|----------------------------|-------------|---------------------------|-------------|
| | Total false positive rate | Precision | Total false positive rate | Precision | Total false positive rate | Precision | Total false positive rate | Precision |
| Common diving petrel | <u>0.5</u> | <i>0.5</i> | <u>1</u> | <i>0</i> | <u>0.09</u> | <i>0.88</i> | <u>0.01</u> | <i>0.97</i> |
| Grey-faced petrel | <u>0.94</u> | <i>0.06</i> | <u>0.06</u> | <i>0.94</i> | <u>0.1</u> | <i>0.88</i> | <u>0.05</u> | <i>0.92</i> |
| Little shearwater | <u>0.04</u> | <i>0.96</i> | <u>0.17</u> | <i>0.83</i> | <u>0.05</u> | <i>0.93</i> | <u>0</u> | <i>1</i> |
| Fluttering shearwater | <u>0.43</u> | <i>0.57</i> | <u>0.04</u> | <i>0.96</i> | <u>0.01</u> | <i>0.99</i> | <u>0</u> | <i>1</i> |
| White-faced storm petrel | <u>0.04</u> | <i>0.96</i> | <u>0</u> | <i>1</i> | <u>0.02</u> | <i>0.98</i> | <u>0</u> | <i>1</i> |

Total false positive rates (underlined) and precision (*italic*) for each species were calculated from the values generated by confusion matrices for each recognizer and are presented here in a scale from 0 to 1, being 1 equals to 100%.

Appendix H. Data Accessibility

The MatlabHTK package can be downloaded from:

<https://github.com/LouisRankard/matlabHTK>. The use of MatlabHTK requires the beforehand installation of Octave (Eaton et al., 2014) and HTK (HTK, Young et al., 2016).

The AFSR_summarizing script can be downloaded from:

<https://github.com/klee8/AFSR>.

Data deposited in the Dryad Repository: <http://dx.doi.org/10.5061/dryad.6kv00>

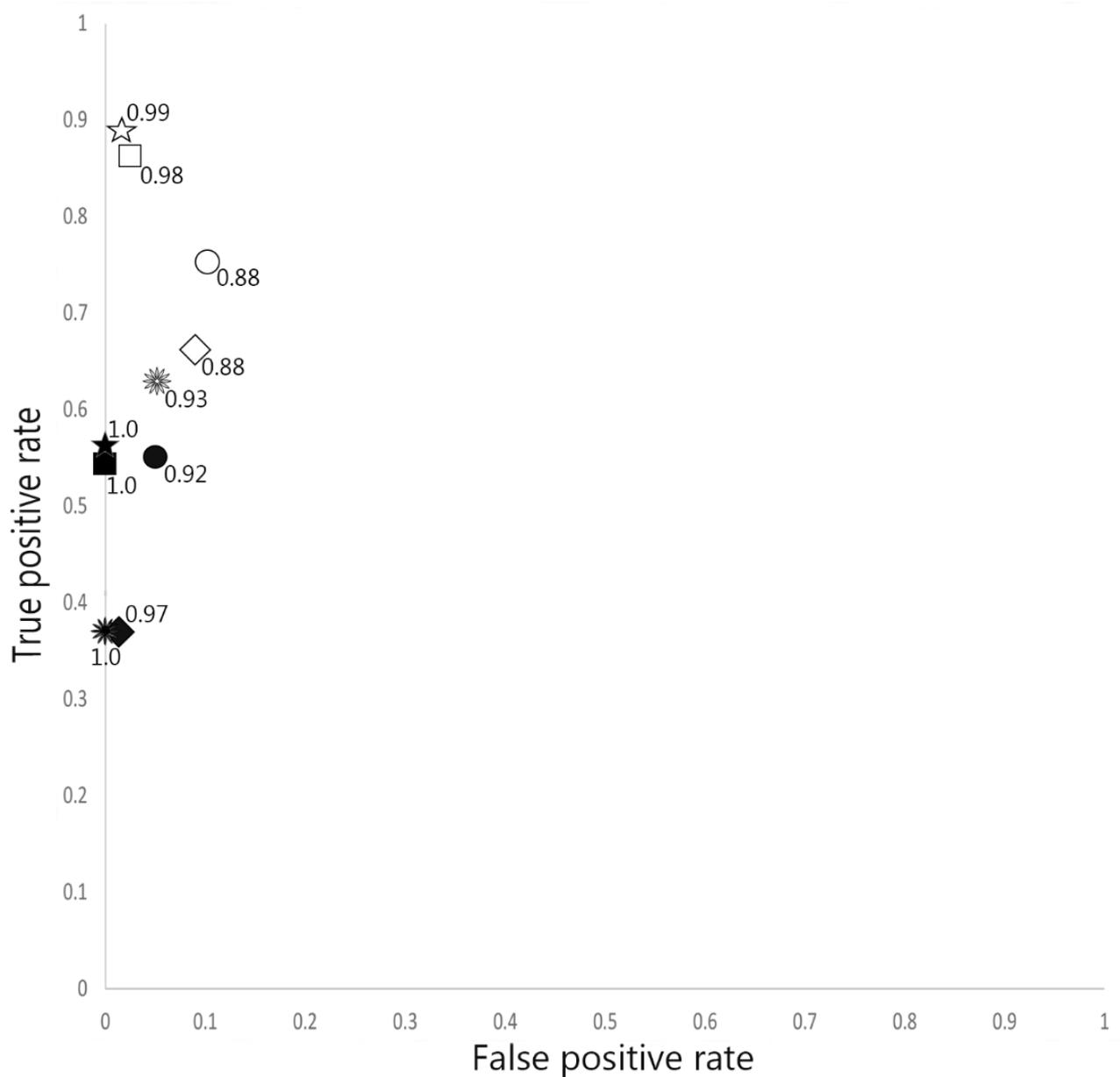
Appendix I. Confusion Matrix comparing manual identification versus the Multispecies Recognizer

Confusion Matrix comparing manual species identification *Versus* the Multispecies Recognizer output for a 10 minute long sound file

| Manually Annotated | Multispecies Recognizer | | | | | | |
|--------------------------|-------------------------|----------------------|--------------------|--------------------|-----------------------|--------------------------|---------------------------|
| | Background | Common diving petrel | Grey-faced petrel | Little shearwater | Fluttering shearwater | White-faced storm petrel | Total false positive rate |
| Background | <i>0.72</i> | 0.09 | 0.02 | 0.04 | 0.03 | 0.1 | <u><i>0.28</i></u> |
| Common diving petrel | <i>0.25</i> | <u><i>0.66</i></u> | 0.02 | 0 | 0.06 | 0.01 | <u><i>0.09</i></u> |
| Grey-faced petrel | <i>0.15</i> | 0.05 | <u><i>0.75</i></u> | 0.01 | 0.04 | 0 | <u><i>0.1</i></u> |
| Little shearwater | <i>0.32</i> | 0 | 0 | <u><i>0.63</i></u> | 0.05 | 0 | <u><i>0.05</i></u> |
| Fluttering shearwater | <i>0.1</i> | 0.01 | 0 | 0 | <u><i>0.89</i></u> | 0 | <u><i>0.01</i></u> |
| White-faced storm petrel | <i>0.12</i> | 0 | 0 | 0 | 0.02 | <u><i>0.86</i></u> | <u><i>0.02</i></u> |

The proportion of the time in which each category indicated at the manually annotated text file is assigned to each one of the categories at the Multispecies Recognizer's output text file is presented in a scale from 0 to 1 (being 1 equals to 100%) as follows: cells with *values in italic*: negative indications of presence; underlined values: true positive indication of presence, values with no special formatting: false positive indication of presence; values underlined and italic: total false positive rate for each one of the categories (sum of the cells with no special formatting in each line).

Appendix J. Scatter plot of true positive rates versus false positive rates



Scatter plot of true positive rates versus false positive rates achieved by the Multispecies Recognizer and AFSR for each seabird species. Precision values for automatic species recognizer results for five seabird species from PAM recordings of a natural seabird colony. Diamond = Common diving petrel, circle = Grey-faced petrel, asterisk = Little shearwater, star = Fluttering shearwater, and square = White-faced storm petrel). White symbols are results of Multispecies Recognizer. Black symbols are results of the Assemblage of Focal Species Recognizers.

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