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Acoustic region workflow for efficient comparison of soundscapes under different invasive mammals' management regimes

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ABSTRACT

One quarter of all terrestrial native bird species have become extinct since human arrival in New Zealand, leading to 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 the control of mammals can reverse the 'silent forest' effect. Here we compare soundscapes from two nearby sites within the Waitakere Ranges Regional Park, New Zealand, that have contrasting predator control levels: one with high-level pest mammal control, and the other with low-level pest control. Measurements of twelve acoustic indices extracted from two seasons of passive acoustic recordings are split into 20 acoustic regions to identify which regions best discriminate between the two management regimes. We define the acoustic regions as units of analysis bounded by a specific time period and frequency range chosen to capture the main groups of biologically relevant acoustic events within a soundscape. Analysis of variance and pairwise comparisons indicated the acoustic region bounded from 9 pm to 11:59 pm and a range of 0.988–3.609 kHz in autumn presented the greatest differences between sites. The sounds responsible for these acoustic differences were generated by invasive mammals in the site with no pest control. Results also supports spring season as the most important for bird monitoring in New Zealand. Acoustic indices analysis did not detect a reversal of the "silence forest" effect in the site with high-level predator control.

1. Introduction

Introduced predators are among the most important threats to biodiversity on islands around the world (Clavero and García-Berthou, 2005). In particular, locally endemic 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 since human arrival in New Zealand approximately seven hundred years ago. These introduced predators are considered responsible for 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 to the decrease in native bird song (Mudge, 2002). The pervasive silence associated to the decline of bird populations is commonly referred as 'silent forest' effect and is reported for other Pacific islands such as Hawai'i (Pérez, 2021) and Guam (Rogers, 2011). 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

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offshore islands (Towns et al., 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). Many of these community groups adopt names that include the words Birdsong, Song, or Songbird, indicating that restoration of the soundscape is a primary aspiration. 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 2050 that may cost around NZ$9 billion (Russell et al., 2015). To assess 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.

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. Passive acoustic monitoring is a cost effective sampling protocol (Ribeiro et al., 2017; Wrege et al., 2017) that enables different animal groups to be monitored simultaneously over long time frames (Depraetere et al., 2012; Sueur et al., 2012). Acoustic sensors can be deployed and collected by volunteers, enabling their use in community-based conservation initiatives. This makes acoustic sampling suitable for monitoring in a wide range of environmental contexts.

Once recordings are obtained, they can be used for a range of possible analyses. Automated classification analyses are commonly aimed towards monitoring populations of individual species. These classification 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 and Mennill, 2014; Stowell et al., 2017). In contrast, study of the entire acoustic community and how it varies in space and time is commonly called soundscape ecology or ecoacoustics. Such soundscape studies have been performed worldwide, in countries including Australia (Fuller et al., 2015), France (Depraetere et al., 2012), Tanzania (Sueur et al., 2008), Brazil (Ferreira et al., 2018).

Soundscape studies frequently aim to relate acoustic indices calculated from passive acoustic recordings to other environmental characteristics such as vegetation structure (Farina and Pieretti, 2014), habitat condition (Sueur et al., 2008), or composition of the acoustic community (Phillips et al., 2018). Acoustic indices are signal processing tools 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. (2014a) explain the calculation of 14 different acoustic indices and use them to examine the relationship between the soundscape and ecological conditions in forest fragments. Many recent studies employ multiple acoustic indices in parallel to exploit their complementary strengths (Campos et al., 2021; Gan et al., 2020; Indraswari et al., 2020; Phillips et al., 2018).

The Acoustic Complexity Index (ACI) (Pieretti et al., 2011) and Temporal Entropy (ENT, also called H) (Sueur et al., 2014) are among the most widely-used acoustic indices for soundscape studies (Ferreira et al., 2018; Fuller et al., 2015; Harris et al., 2016; Towsey et al., 2014b; Tucker et al., 2014). Anthrophony (human generated sound, e.g. airplanes and cars) and geophony (sounds generated by natural abiotic phenomena such as wind and rain) typically present more constant intensity values, while biophony commonly presents greater variability in intensity modulation. The ACI measures the amplitude oscillation in each frequency bin, being primarily sensitive to biophony (Pieretti et al., 2011). The ENT measures the temporal dispersal of the energy in a sound file. The temporal distribution of energy is typically larger when sounds are emitted from more species, so the ENT is considered sensitive to species richness. ACI and ENT when associated with an index sensitive to the number of acoustic events such the Event Count Index (EVN) (Towsey, 2017) can provide a comprehensive illustration of a given soundscape (Towsey et al., 2018).

Acoustic indices measurements can be used to represent a soundscape as well as to compare soundscapes. However, it is a considerable challenge to visualize and draw inferences on the enormous amounts of data generated by acoustic indices. Where soundscape differences are identified, it is natural to ask which species or sound sources drive these differences; but the manual workload involved in screening thousands of sound-files or training automatic classification tools is prohibitive.

To address these difficulties, we have developed a step-by-step workflow to facilitate efficient analysis and inference from huge soundscape datasets. We simplify the search for soundscape differences by partitioning the sound spectrum into a set of acoustic regions, which are times of day and frequency ranges defined to capture the main groups of biologically relevant acoustic events within a soundscape. Examples of relevant bioacoustic events with bounded frequency and time frames are the bird dawn chorus, which is mostly encompassed within the mid-frequency range and during the first hours of daylight; and the acoustic activities of bats, which are commonly nocturnal and occupy the high-frequency range. Focusing analysis on individual acoustic regions helps to ensure that there is biological relevance in any soundscape differences detected, and reduces the swamping effect whereby valid soundscape discriminators are lost in the mass of highly variable data (Campos et al., 2021). Having identified which acoustic regions are of primary interest for soundscape discrimination, we use visualisation tools to pinpoint a small, targeted set of sound files for manual review to identify the driving sound sources.

In this study, the proposed workflow is tested with passive acoustic recordings made in two nearby forest sites in New Zealand with different levels of management for introduced mammals. We aim to assess the season, frequency range, and time period that best discriminates the soundscapes of the two sites, as well as identify which species or sounds are responsible for the main differences detected. The workflow is intended as a template for large-scale bioacoustics studies to assess the outcomes of conservation management programmes and their impacts on the soundscape.

2. Methods

2.1. Study sites

The Waitakere Ranges (37°S, 174.5°E) is a regional park located in the Auckland region, New Zealand. Comprising 160 km^2, the park is habitat for many endemic sonic fauna, such as the long-tailed bat (*Chalinolobus tuberculatus*), one of New Zealand’s few native land-based mammals; the kōkako wattlebird (*Callaeas wilsoni*); and the kākā forest parrot (*Nestor meridionalis*).

Research was conducted in 2016 and 2017 at two sites within the Waitakere Ranges Regional Park which had experienced different management regimes with respect to pest mammal control. The first site was the community project known as Ark in the Park, with a high level of pest mammal control since 2002. The second site was Fairy Falls, located about 3 km away and unmanaged for pest mammals.

The systematic sampling grid at each site comprised four acoustic sensors arranged as a square of size 200 m × 200 m, with the location of the south-eastern corner chosen at random within the site. Fig. 1 shows the location of each acoustic sensor in the two sites.

2.2. Passive acoustic recording acquisition

Recordings were collected for ten consecutive days during late austral 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). Two SM3 and two SM4 were deployed at each site, at a sampling rate of 48 kHz, set at 32-bits resolution. Acoustic sensors were fixed on trees 1.5 m above the ground.

The acoustic sensors were programmed to perform 1 min of recording every 10 min, resulting in 144 one-minute sound files per location, per day of sampling. The temporal sampling schedule of 1/10 min follows that used in previous studies (Aide et al., 2013; Aide et al., 2017; Alvarez-Berríos et al., 2016; Campos et al., 2021; Campos-

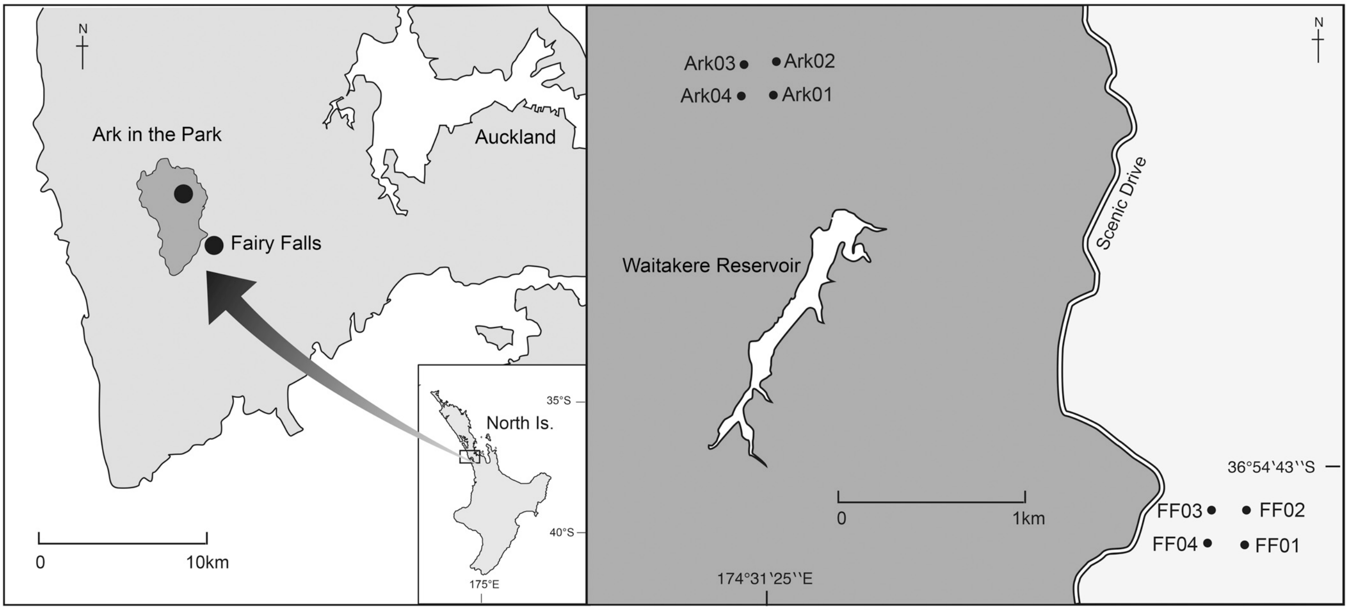

Fig. 1. Location of acoustic sensors in Ark in the Park and Fairy Falls sites, Auckland, New Zealand.

Cerqueira and Aide, 2016; Campos-Cerqueira and Aide, 2017; Ospina et al., 2013; Pieretti et al., 2015).

2.3. *Workflow*

Fig. 2 presents the methodological workflow used in this research. The first stage results in the identification of the principal acoustic region and has five steps. The second stage results in the description of acoustic events responsible for the main differences detected between the two sites and has three steps.

2.4. *Acoustic index calculations*

To facilitate the calculation of acoustic indices, the sound files were down-sampled to 22.05 kHz and mixed down to mono. Within each one-minute file, acoustic indices were calculated for each frequency bin of 43 Hz, totalling 256 bins, according to Towsey (2017) and Towsey et al. (2014b, 2018). We calculated values of 12 different acoustic indices (Table 1) for each frequency bin and each sound file using the Ecoacoustics Audio Analysis Software version 17.12.000.13 (Towsey et al., 2018), which is open source and written in C#.

2.5. *Long Duration False Colour spectrograms*

Long Duration False Colour (LDFC) spectrograms (Towsey, 2017) were produced for each day of recording at each location of the two field sites. The LDFC spectrograms provide a visual representation of three different index measurements using colour coding, enabling researchers to identify when notable sound events occurred on the basis of a quick visual scan. Here, we depict the ACI in red, the ENT in green, and the EVN in blue (Towsey et al., 2015). These three indices are sensitive to different aspects of the sound signal (Table 1), making them

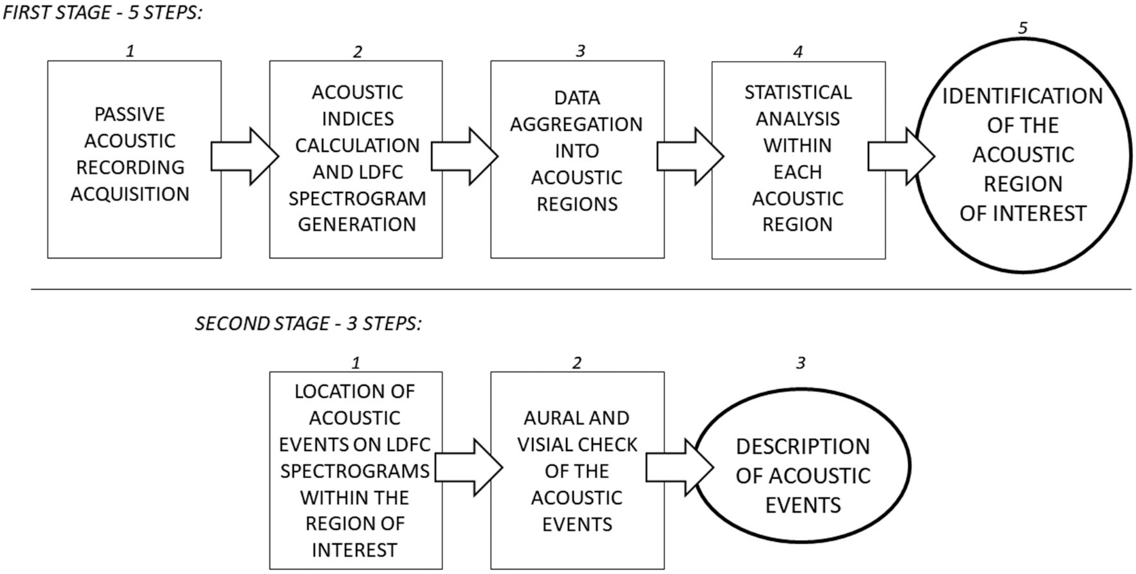

Fig. 2. Illustrates the methodological workflow for the application of acoustic regions. In the second step of the first stage and in the first step of the second stage, "LDFC Spectrograms" stands for Long Duration False Colour Spectrogram.

Table 1
Acoustic Indices used for comparing 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 et al., 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 surpass 2 dB (Towsey et al., 2014b).
Power minus Noise (PMN)	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 calculated 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)	Corresponds to the horizontal dimension of the ridge slope. The Ridges Indices, RHZ, RVT, RPS, and RNG, are derived from the noise-reduced decibel spectrogram (Towsey, 2017).
Ridge Vertical (RVT)	Corresponds to the vertical dimension of the ridge 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.
Ridge 3 Dimensions (R3D)	This index equals the maximum of RHZ, RPS, and RNG (Towsey, 2017).

The range for all the indices' values was from 0 to 1.

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. (2014b). In total 160 LDFC spectrograms were generated, each containing index results from 144 sound files.

2.6. *Acoustic regions*

Using a combination of contextual knowledge and visual examination of the 160 LDFC spectrograms, we established 20 acoustic regions defined by four frequency ranges (Table 2) and five time periods (Table 3). These regions were designed to capture the most important acoustic events happening within a day in the Waitakere soundscape.

2.7. *Statistical analysis within each acoustic region*

Statistical analyses were performed to identify whether each of the acoustic regions differed between the two treatment sites, for each of the twelve indices. Before fitting the models, we normalised the data following (Towsey et al., 2014b) to reduce outlier effects and allow comparisons between different indices. First, the interval that captured 98% of the values was defined for each index. The values falling below and above the lower or the upper boundaries were truncated to the corresponding boundary values. The data were then rescaled to the interval from 0 to 1. To facilitate interpretation of the vast data set, which comprised over 5 million records for each index, and to reduce effects of autocorrelation between index calculations extracted from abutting frequency bins and times, we summed index values within each acoustic region per day. Accordingly, for each of the 12 indices, we compiled the data into one summary value per day for each recording station, for each of the 20 acoustic regions.

Table 2
Frequency ranges used to establish the 20 acoustic regions.

Frequency range	Name of the frequency range
7.906 to 11 kHz (bins 184–255)	High frequency
3.609 to 7.906 kHz (bins 84–183)	Mid-high frequency
0.988 to 3.609 kHz (bins 23–83)	Mid-low frequency
0 to 0.988 kHz (bins 0–22)	Low frequency

The name of the acoustic region is given by the combination of the frequency range name and the name of the time period (example: *Mid-low frequency/Night*).

Table 3
Time boundaries used to establish the 20 acoustic regions.

Time period	Name of the Time period
0:00 to 5:29 am	Predawn
0:00 to 5:29 am	Dawn
0:00 to 5:29 am	Day
5:30 pm to 8:59 pm	Dusk
9 pm to 11:59 pm	Night

Times reported in New Zealand Standard Time (NZST). The name of the acoustic region is given by the combination of the frequency range (Table 2) name and the name of the time period (example: *Mid-low frequency/Night*).

The models were fitted separately for each index and each acoustic region. To test for soundscape differences between sites and seasons, we fitted Analysis of Variance (ANOVA) models and then inspected all pairwise comparisons using *t*-tests, adjusted for multiple comparisons using the Bonferroni correction. The log-transformed index value was the outcome variable, while the explanatory variables comprised the interaction between season (autumn, spring) and site (high pest management level at Ark in the Park, or unmanaged at Fairy Falls). The effect sizes were calculated from the pairwise comparisons and were back-transformed to ratios, which can be interpreted as the ratio of median indices at the two sites for the corresponding acoustic region and season. We present these as the ratio of the higher to the lower result, marked with a negative sign if the higher result is in the unmanaged Fairy Falls site. Normality assumptions were checked using quantile-quantile and residual plots and were found to be adequate (Appendix S1 – ENT index models are provided as example).

2.8. *Describing events in specific acoustic regions*

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

2.9. *Chew cards*

To assess invasive mammal presence as a possible driver of soundscape differences between the two sites, chew cards were deployed and replaced after 5 days, resulting in 32 cards in total (8 per site in each season). Cards were fixed 30 cm above the ground to the same tree as the sound recorders, which were 1.5 m above the ground. Chew cards consist of a 90 × 180 × 3 mm piece of polypropylene with internal flutes filled with an attractant (pasta) (Fig. 4). The cards were bent into a right-angled position and mounted on tree trunks, as per Sweetapple & Nugent (2011). The cards are widely used in New Zealand to record the tooth impressions of introduced animals, enabling identification of invasive mammal pests present in an area, together with an index of prevalence.

3. Results

Comparisons between the acoustic index values generated from the high pest mammal management site (Ark in the Park) and the non-management site (Fairy Falls) revealed a large number of significant differences after adjusting for multiple comparisons. Appendix S2 gives 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.

3.1. *Principal acoustic region*

For each index, we inspected the acoustic region and season that presented the largest effect sizes (ratios) of the significant pairwise differences. The soundscape differed most between two sites in the acoustic region "*Mid-low frequency/ Night*" in autumn, representing 9 pm to 11:59 pm and a range of 0.988–3.609 kHz (Fig. 3). This acoustic region had significant results for 11 of the 12 indices and presented the highest ratios among all acoustic regions for 8 of these indices. It was therefore selected as the principal acoustic region for further analysis. Table 4 presents the pairwise comparisons for this acoustic region 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 (Appendix S2).

Each of the 80 LDFC spectrograms for the autumn recordings was visually scanned to identify acoustic events in the time period and frequency range related to the principal acoustic region, "*Mid-low frequency/ Night*". Three rainy days were excluded from this part of the analysis as the noise of rain makes it difficult to locate acoustic events on LDFC spectrograms, as well as masking the acoustic signal to impede aural and visual scanning of sound files on traditional spectrograms. These three rainy days corresponded to 30% of the data, totaling 432 files removed from the visual scan for acoustic events (216 from each site). The "*Mid-low frequency/ Night*" acoustic region is typically quiet in the Waitakere region (Fig. 3). Only 20 sound files with acoustic events were selected. These files were distributed across seven 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 (Fig. 1). No sound files with these traits were selected from the high pest mammal control site (Ark in the Park).

Table 4
Pairwise comparisons of acoustic index measurements for sites with high versus no pest mammal management within the principal acoustic region (*Mid-low frequency/Night* – autumn season).

Index	*P* value	Ratio
Temporal Entropy (ENT)	1.29E-05	−3.01
Event Count (EVN)	0	−2.67*
Acoustic Cover (CVR)	0	−2.29*
Power minus Noise (PMN)	0	−2.25*
Acoustic Complexity Index (ACI)	0	−1.91*
Spectral Peak Tracks (SPT)	0	−1.81
Ridge Vertical (RVT)	0	−1.75*
Ridge Positive having an upward slope (RPS)	0	−1.54*
Ridge Negative having downward slope (RNG)	0	−1.54*
Ridge 3 Dimensions (R3D)	0	−1.53*
Ridge Horizontal (RHZ)	0	−1.31
Background Noise (BGN)	0.53	–

Negative signs in the Ratio column indicate the direction of the effect, specifying that index results were higher in the no pest mammal management site (Fairy Falls); and the * symbol indicates a ratio that was the largest among all acoustic regions for a specific index.

The visual and aural scan of these files revealed an unusual sound consistently present in each of the files. Upon first consideration, this sound appeared similar to the visual representation of rain in a traditional spectrogram, although it had greater amplitude around 2 kHz than is typical for rain (Appendix S3). However, the aural analysis revealed a very distinctive sound that could not be mistaken for 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). The chew cards indicated radically different levels of mammal activity at the high mammal control (Ark in the Park) and no mammal control (Fairy Falls) sites 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. In the spring season, all eight cards had possum marks, five had rat marks and two cards presented mouse marks. In Ark in the Park, all eight cards were empty in spring, and seven of the eight

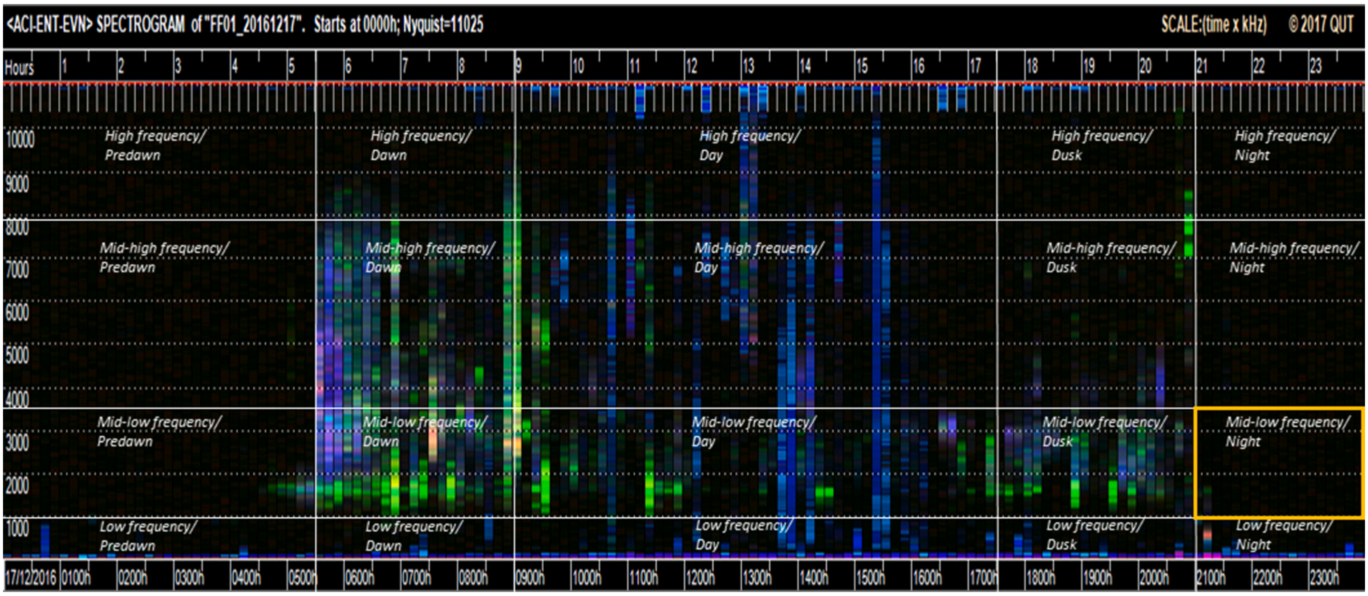

Fig. 3. Long Duration False Colour Spectrogram generated from audio files recorded in the no pest mammal control site, Fairy Falls (location FF01), on 17th December 2016 (spring season). The y- axis presents the frequency in Hz, while the x-axis the time of the day. White lines show the time and frequency boundaries of each acoustic region. The orange rectangle indicates the principal acoustic region, which presents the greatest differences between sites. In this LDFC spectrogram, indices are colour coded to RGB channels (ACI – red; ENT-green; EV- blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

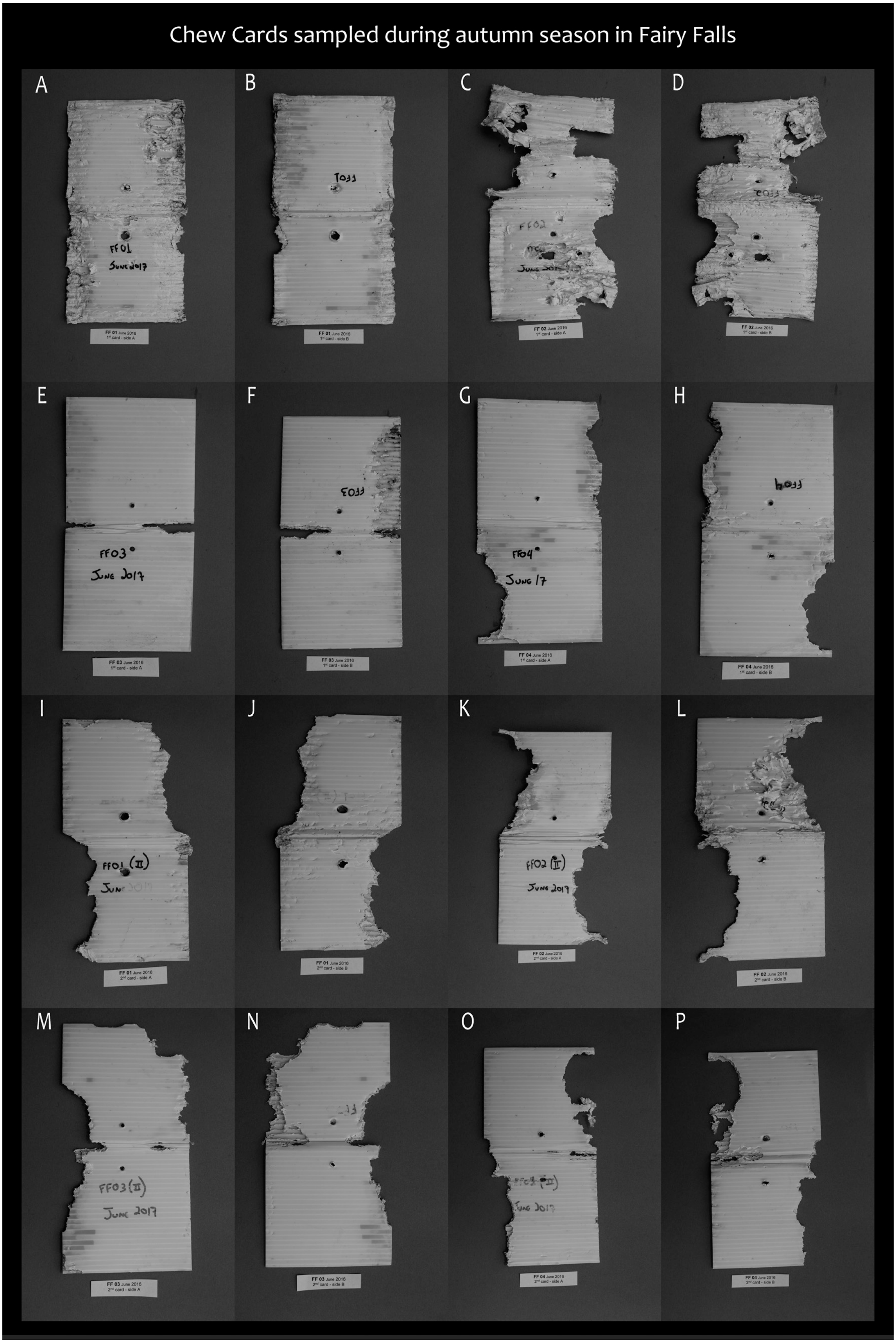

Fig. 4. Chew Cards sampled during the autumn season in Fairy Falls. Each card is shown in two adjacent pictures displaying the front and reverse side. Panels A to H show the cards placed for the first 5 sampling days in locations FF01, FF02, FF03, and FF04 respectively. Panels I to P show the cards placed for the following 5 sampling days in the corresponding locations.

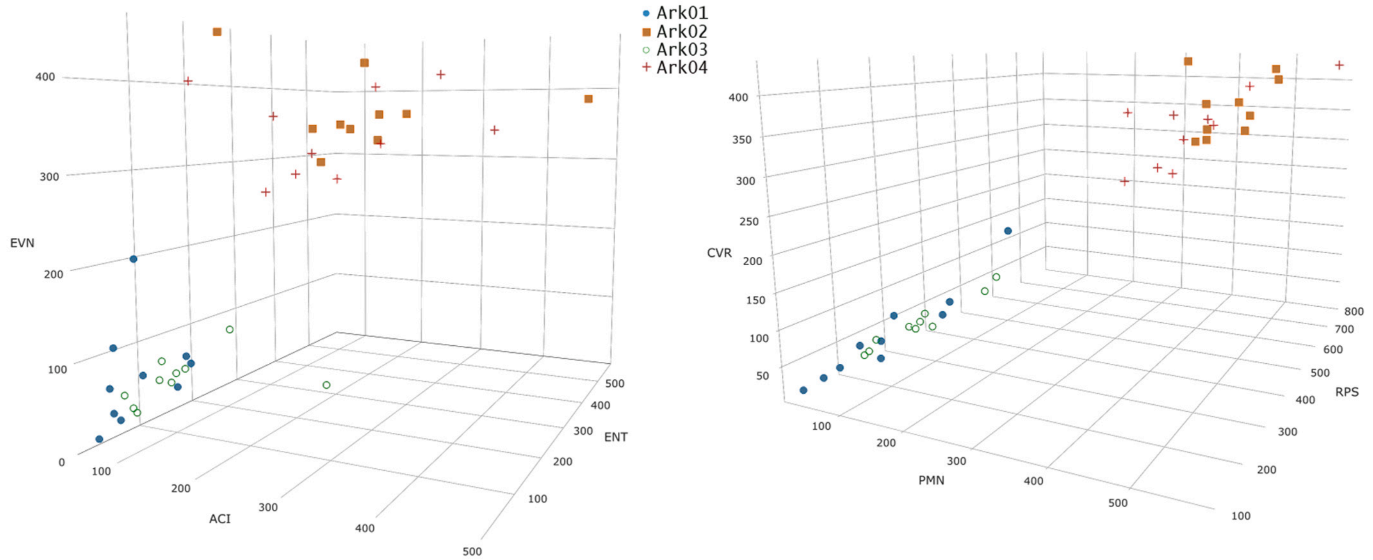

Fig. 5. Measurements of 6 indices for acoustic region "*Mid-low frequency/ Dawn*" in each of the four locations in Ark in the Park during spring. The graphic on the left presents ACI, ENT and EVN measurements, while the one on the right represents measurements of PMN, RPS and CVR.

cards were empty in autumn; marks on the remaining card could not be identified but were presumed to be either bird or insect. A Fisher's exact test indicated that the presence of mammals' marks on chew cards was significantly different between the two sites in both seasons for rats (*P* value = 0 in autumn; and *P* value = 0.03 in spring) and possums (*P* value = 0 in autumn; and *P* value = 0 in spring). The marks of mice were significantly different between sites in autumn (*P* value = 0.03) but not in spring (*P* value = 0.47). Appendix S4 presents pictures of all cards used in autumn and spring in both sites, as well as tables containing the summary of the cards results.

3.2. *Bird dawn chorus*

The two acoustic regions that best capture the bird dawn chorus activity presented significant differences between sites in spring (Table 5) but no significant differences were detected in autumn. "*Mid-low frequency/ Dawn*" presented significant differences for 11 of 12 indices, while "*Mid-high frequency/ Dawn*" presented significant results for nine of 12 indices tested, both in spring. The effect size coefficient indicated a higher acoustic activity in the non-managed area.

The indices measurements in the managed site show that two locations (Ark01 and Ark03) present a very low activity within these two acoustic regions in spring. Fig. 5 shows a clear separation between these two locations with low activity and the other two locations in Ark in the Park within the acoustic region "*Mid-low frequency/ Dawn*". When excluding the two locations with low activity from the pairwise analysis, most of significant differences between sites disappear for the region "*Mid-low frequency/ Dawn*". Only BGN presents differences between the non-managed and the highly-managed sites for this acoustic region, with higher activity measured at Fairy Falls (non-managed) (Table 5). For "*Mid-high frequency/ Dawn*", nine of 12 indices presented significant differences between sites. The effect size coefficient indicates a higher activity in the managed site, with exception to the BGN index.

4. Discussion

The identification of invasive mammal species as being the main source of differences in acoustic indices between the two sites was unexpected. We anticipated that the greatest difference in the soundscape would correspond to an acoustic region capturing bird song, since increased bird abundance is a primary objective of pest mammal management regimes (Jones et al., 2016; Towns et al., 2012). However, it is probable that invasive mammals should have an important direct impact on the soundscape due to their abundance and activity. This result reinforces the importance of pest control and enlarges the range of impacts these species have on New Zealand environments, adding direct impacts

Table 5
Pairwise comparisons of sites with high versus no pest mammal management within acoustic regions that capture bird dawn chorus (*Mid-low frequency/Dawn* and *Mid-high frequency/Dawn* in spring season).

Index	*Mid-low frequency/ dawn*		*Mid-high frequency/ dawn*		*Mid-low frequency/dawn* (excluding two locations with low activity)		*Mid-high frequency/dawn* (excluding two locations with low activity)	
	P value	Ratio	*P* value	Ratio	*P* value	Ratio	*P* value	Ratio
Temporal Entropy (ENT)	0	−2.51	0	−1.71	0.13	–	0.05	–
Power minus Noise (PMN)	0	−2.04	0.01	−1.58	0.84	–	0	1.06
Acoustic Complexity Index (ACI)	0	−1.88	0.01	−1.46	0.08	–	0.96	–
Event Count (EVN)	0	−1.83	0.03	−1.58	0.18	–	0.04	1.04
Acoustic Cover (CVR)	0	−1.75	0.04	−1.51	0.13	–	0.01	1.06
Spectral Peak Tracks (SPT)	0	−1.64	0.05	–	0.14	–	0.01	1.05
Ridge Vertical (RVT)	0	−1.54	0.04	−1.33	0.42	–	0.085	–
Ridge 3 Dimensions (R3D)	0	−1.52	0.04	–1.28	0.45	–	0.02	1.05
Ridge Positive having an upward slope (RPS)	0	−1.50	0.04	−1.27	0.35	–	0.02	1.06
Ridge Negative having downward slope (RNG)	0	−1.50	0.04	−1.27	0.34	–	0.02	1.06
Ridge Horizontal (RHZ)	0	−1.38	0.05	–	0.31	–	0.01	1.03
Background Noise (BGN)	0.19	–	0.69	–	0.01	−1.06	0	−1.09

Negative signs in the Ratio (effect size coefficient) column indicate index results higher in the non-managed site (Fairy Falls).

on the soundscape to this list. It is expected that this direct impact on the soundscape will be easier to detect within acoustic regions with fewer acoustic events, such as "*Mid-low frequency/ Night*".

From our data, it is not possible to distinguish the sounds of mammals moving around from the sounds of their interactions with the chew cards because these two are present in the same sound files. Therefore, PAM recordings not associated with chew cards are necessary to confirm the direct impacts of introduced mammals on the soundscape. It is possible that the presence of the chew cards drove "*Mid-low frequency/ Night*" as the principal acoustic region by attracting invasive mammals and inducing their noisy interaction, which may have resulted in a biased selection of the principal acoustic region. Nonetheless, it is notable that the "*Mid-low frequency/ Night*" acoustic region presented different results in spring, during which only 2 of 12 indices exhibited significant differences between sites (Appendix S2). PAM samplings were associated with chew cards in all sites and both seasons studied.

Interestingly, alternative approaches that focus on acoustic regions that traditionally present high acoustic activity, such as those that encompass dawn and dusk choruses (Holmes et al., 2014; Venier et al., 2012), would not have allowed the identification of the "*Mid-low frequency/ Night*" region as being the principal discriminative region between the two sites in our data. This region does not have intense acoustic activity in the Waitakere soundscape, so there was no a priori reason to consider it to be an informative aspect of the soundscape.

The acoustic activity within the regions that capture the bird dawn chorus present significant differences in spring but not in autumn (Table 4, Appendix S2). It highlights the importance of "*Mid-low frequency/ Dawn*" and "*Mid-high frequency/ Dawn*" in spring for long-term bird monitoring, while the same acoustic regions in autumn season seem to be irrelevant for monitoring purposes.

The clear separation between two locations with low acoustic activity and two with high activity shown in the Fig. 5 indicates that birds exhibit preferences for specific spots within the Ark in the Park site. For a better understanding of how birds use the park area, future research with an increased spatial sampling effort is needed.

A volunteer bird monitoring ran by the Ark in the Park project in both sites (point count in three locations in each site) indicates a higher number of individuals across all species in the managed site (Appendix S5). It points to the same direction of the significant differences found in acoustic region "*Mid-high frequency/ Dawn*" after excluding the two locations with low activity. The higher number of birds detected by the volunteer monitoring suggests that the pest control resulted in an increase of overall bird abundance in Ark in the Park when compared with the Fairy Falls site. However, the ratios found for "*Mid-high frequency/ Dawn*" in spring after excluding the two locations with low activity indicates that the magnitude of the differences in the acoustic activity are subtle, varying from 1.06 (for PMN index) to 1.05 for (for ACI index) (Table 4). When all four locations from Ark in the Park are included into the ANOVA, the ratios found for most of indices in "*Mid-low frequency/ Dawn*" and "*Mid-high frequency/ Dawn*" in spring indicates a higher acoustic activity in the non-managed site (Table 3).

Overall, we can state that pest management did not result in important indices differences between sites within acoustic regions that typically encompass bird activity. The significant differences found in spring within the two acoustic regions that encompass bird dawn chorus most probable are a result of an overall increase in bird activity due to breeding season than a response to predator control. The results point to a higher activity in the non-managed site when considering all the four locations in Ark in the Park in the ANOVA and to a higher activity in the managed site when excluding the two locations with low activity from the analysis. The anticipated increase in the acoustic bird activity in the managed site was not evident. Therefore, our results suggests that the "silent forest" effect was not reversed in the Ark in the Park site.

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 shortly after pest eradication. Long-term acoustic monitoring will reveal if the pest control will be capable of reversing the "silent forest" effect in the Ark in the Park area.

In our data, intense acoustic activity seems to be missing from the Waitakere soundscape in the acoustic regions that encompass predawn and night times (see Fig. 3). One explanation for this observation is that native species that used to exhibit acoustic behaviour within these acoustic regions are now extinct in the region. Extant bird species occupying these acoustic niches in New Zealand forest habitats with vocalizations within the range of 0 kHz–10 kHz (Bell et al., 2013; Corfield et al., 2008) include kiwi (*Apteryx spp.*), weka (*Gallirallus australis*), and kākāpō (*Strigops habroptilus)*. The local extinction of these once-common nocturnal birds in the Waitakere Ranges could explain the quietness of the acoustic regions that encompass predawn and night times. Another species that possibly once occupied this niche was the laughing owl (*Sceloglaux albifacies*), extinct by 1914 (Worthy, 1997). Unfortunately, it is a much harder task to understand what role the 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.

The main goal of monitoring programmes is to detect states and trends (Lee et al., 2005). Therefore, a monitoring approach should be capable of detecting changes in a soundscape through time or between two soundscapes. For a monitoring perspective, the highest differences detected are relevant. The detected differences may not be the ecologically most important events in a given ecosystem. However, we do advocate that a non-biased approach is important for detecting unpredicted outcomes of conservation programmes. Special focus on groups pre-defined as relevant can always be given if the acoustic regions are designed to capture the most relevant acoustic events in the soundscape.

In our study, we use acoustic indices to unveil invasive mammal sounds as being the main differences between soundscapes from sites with different levels of pest management. This result reinforces the importance of pest control and enlarges the range of impacts these species have on New Zealand environments. Our results also support the spring season as the most important for bird monitoring in New Zealand. Acoustic indices analysis did not detect a reversal of the "silence forest" effect in the site with high level of pest management. A longer time frame monitoring will unveil if the pest management will be capable of reverting the "silence forest" effect in the Ark in the Park site.

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Declaration of Competing Interest

None.

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