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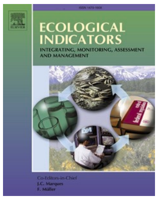

Assessing the potential of acoustic indices for protected area monitoring in the *Serra do Cipó* National Park, Brazil

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ABSTRACT

Protected areas (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 and associated acoustic index analysis an increasingly suitable method for PAs monitoring. Acoustic indices are mathematical filters that can provide standardised comparative information about the acoustic energy, which can be applied to compare communities. In this study we test whether acoustic indices are sufficiently sensitive to detect differences in the soundscape within each of the four seasons between a PA (the *Serra do Cipó* National Park, Brazil) and a surrounding farmland area. Statistical analysis of results from 12 acoustic indices is used to identify which of 20 acoustic regions, defined by frequency range and time period, present the greatest differences between the two sites. The soundscapes of the two sites differed most in autumn within the acoustic region 6, representing 05:30 – 09:00am and a range of 0.988–3.609 kHz. This acoustic region exhibited significant differences for all the 12 indices tested. Visual examination of 65 long-duration false-colour (LDFC) spectrograms resulted in the selection of 865 (from 1365) sound files with acoustic events within the range of acoustic region 6. Sonotype analysis of the 865 files showed that the soundscape outside the park is strongly influenced by human activity, with domestic animals rare in the park soundscape (1% of the sound files), but very common in the surrounding farmland environment (63% of the sound files). The main goal of monitoring programmes detecting biodiversity trends across space and time, which is here achieved via passive acoustic monitoring and acoustic indices. This confirms the utility of the techniques used here for PA monitoring, especially for detecting trends in anthropogenic disturbance, which is a common threat to natural habitats in parks and reserves in the tropics.

1. Introduction

Protected areas (PAs) such as national parks and reserves are crucial for sustaining 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, and places for outdoor activities (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 the protection of 17% of terrestrial and

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inland water ecosystems and 10% of marine and coastal ecosystems globally (CBD, 2010). However, despite their overwhelming importance, robust information on the status and vulnerability of PAs for biodiversity conservation and wildlife communities is rare.

One reason for the shortage of reliable information about how PAs contribute to biodiversity conservation is the difficulty of carrying out long-term monitoring in protected areas. Monitoring programmes need to be sensitive enough to measure trends in biodiversity, and to report on condition and change (Lee, McGlone & Wright, 2005), which is very challenging to achieve with any sampling protocol. Ideally, monitoring should be broad enough to provide a comprehensive picture of biodiversity, and capable of providing information at different levels (populations, species, communities) and different temporal and spatial frames (Schmeller et al., 2017). Traditionally, monitoring of animal diversity is performed 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 and time-consuming, and require specialist training. Furthermore, these techniques can only be deployed for limited time periods, so they might not record rare species. Invasive methods such as trapping, or methods that involve habitat disturbance, also have implications for animal welfare and conservation efforts for populations that are often already at-risk (Putman, 1995; Iossa et al., 2007).

Additionally, animal behaviour commonly changes across seasons, so monitoring protocols should also be able to report on a seasonal scale. In practice, 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 biodiversity monitoring is the use of acoustic recordings, where automatic recordings are made of the natural soundscape and used to infer a component of the general biodiversity. Acoustic information is well-known to vary throughout the day, among seasons, and spatially (Fuller et al., 2015; Phillips et al., 2018; Campos et al., 2019). Passive acoustic sampling protocols can synthesize information on diversity for a wide range of animal species in a non-invasive manner (Sugai et al., 2018). However, the amount of acoustic information that can be analysed by a researcher listening to the files is limited.

A key innovation in acoustic analysis is the development of acoustic indices that extract specific features from the acoustic information (Pieretti et al., 2011; Sueur et al., 2014). These acoustic indices calculate aspects of how the acoustic energy is distributed in time and frequency in a sound file. Such features can be compared between recordings made at various times and locations. In this way, they can be used to provide standardised comparative information about the acoustic activity of animal communities. These standardised measurements can be used not only to detect differences of acoustic activity within a day (e.g., dawn and dusk chorus) (Pieretti et al., 2015), but they can also be sensitive to soundscape change across seasons and years (Phillips et al., 2018).

There is much active research into acoustic indices (Sueur, 2018). The Acoustic Complexity Index (ACI) (Pieretti et al., 2011) and Temporal Entropy (ENT) (Sueur et al., 2014) are sensitive to biophony. The Acoustic Complexity Index (ACI) (Pieretti et al., 2011) measures the amplitude oscillation in each frequency bin, which makes it sensitive to biophony. 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 present greater variability in intensity modulation (Farina et al., 2018). The Temporal Entropy (ENT – also called H) (Sueur et al., 2014) is sensitive to the temporal dispersal of the energy in a sound file. It is expected that the more species emitting sounds, the larger 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 commonly-used acoustic indices for ecological studies (Tucker et al., 2014; Towsey et al., 2014a, 2014b, 2014c; Fuller et al., 2015; Harris et al., 2016; Ferreira et al., 2018).

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., 2014a, 2014b, 2014c), maqui shrubland in Mediterranean Italy (Farina & Pieretti, 2014), tropical forest in Tanzania (Sueur et al., 2008), neotropical forest in French Guiana (Rodriguez et al., 2014), and tropical savannah (Cerrado) in Brazil (Machado et al., 2017; Ferreira et al., 2018). Acoustic indices are also applicable to marine environments (Harris et al., 2016; Buscaino et al., 2016). Studies using acoustic indices commonly aim to extract biological information from data sampled by passive acoustic monitoring 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), more recently termed ecoacoustics (Sueur & Farina, 2015).

The identification of acoustic events in large data sets of index calculations is a challenge that has been addressed by different approaches. Farina et al. (2016), Farina et al. (2018) apply the Ecoacoustic Event Detection and Identification (EEDI) to overcome this obstacle. EEDI uses environmental variables, ACI measurements and a library of predefined acoustic signatures to classify important events in a given soundscape. Phillips et al. (2018) use the interpretation of indicés clusters to extract ecological information from passive acoustic recordings. Gasc et al. (2018) develop the Sonic Timelapse to explore long-term acoustic data sets. Towsey et al. (2014a); Towsey et al. (2014b) and Towsey et al. (2014c) create long-duration false-colour (LDFC) spectrograms, where a single image represents three different indices using the RGB colour model, with each index assigned to a different colour: red, green or blue. LDFC spectrograms have shown to be a useful tool for visualization of acoustic events in large audio data sets (Towsey et al., 2015) as well as allowing the easy identification of single acoustic events such as frog calls, bat echolocation calls, and calls of Tasmanian Lewin's Rail (*Lewinia pectoralis brachipus*), enabling it to assist in studies involving single or multiple species (Towsey et al., 2018).

Despite the remarkable potential of acoustic indices, their relationship with traditional biodiversity measures can be contradictory (Fuller et al., 2015; Mammides et al., 2017). Eldridge et al. (2018) reported that indices were good indicators of avian species richness in temperate, but not tropical, habitats. Therefore, interpretations of acoustic indices as straightforward biodiversity indicators should be made with caution. Instead, we advocate that for monitoring purposes, it is best to use a combination of acoustic indices in a comparative context. These indices should be used as filters that help to identify which sounds are responsible for significant differences between sites and across time, rather than as direct biodiversity indicators. Because each acoustic index is sensitive to different acoustic features, combining them generates a more holistic representation of the acoustic structure.

Here, we test whether acoustic indices approach is suitable for detecting soundscape differences between sites with different land uses. We performed passive acoustic sampling for four seasons in a protected area (the *Serra do Cipó* National Park, Brazil) and the surrounding regions that are not subject to the same conservation management efforts. We also introduce a novel approach whereby statistical analysis of index measurements is used to identify specific acoustic regions, defined by frequency range and time period, that present the greatest 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 acoustic structure and to facilitate the identification of acoustic events. We then provide sonotype counts to summarize the acoustic events in the soundscape. Instead of using indices as biodiversity indicators, we employ them as filters that help to identify which sounds are driving the significant differences between sites and across time. If the techniques applied here are capable of detecting significant changes in animal activity inside and outside the protected area, then these acoustic analyses could provide useful, low-cost protocols for monitoring at a landscape scale, which could be suitable for detecting long-term changes in biodiversity over space and time resulting from conservation management in protected areas.

2. Material and methods

2.1. 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 km^2, the park was created in September 1984, entirely in the *Minas Gerais* State (Fig. 1). 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 producing cattle and dairy. It is common for small farms also to produce chicken meat, eggs and varied vegetables. Occasionally, farmers enter 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 converted 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. We did not include the field habitats (dirty field, cerrado field, and rocky grasslands), locations greater than 900 m above sea level, or urban areas in this study. Within the remaining areas, we 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 (Fig. 1). The minimum distance between locations was 456 m (between InCipo02 and InCipo04). The minimum distance between a given location outside the National Park and the Parḱs perimeter was 2050 m (for OutCipo01). There are no physical barriers between sites.

Habitat loss is the main source of biodiversity decline 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. We employed spatial replication to sample a range of locations in each site within and outside the Park.

2.2. Recording schedule and settings

The acoustic sensors were programmed to perform 1 min of recording, followed by 9 min 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 min recording schedule has also been used successfully in other studies (Aide

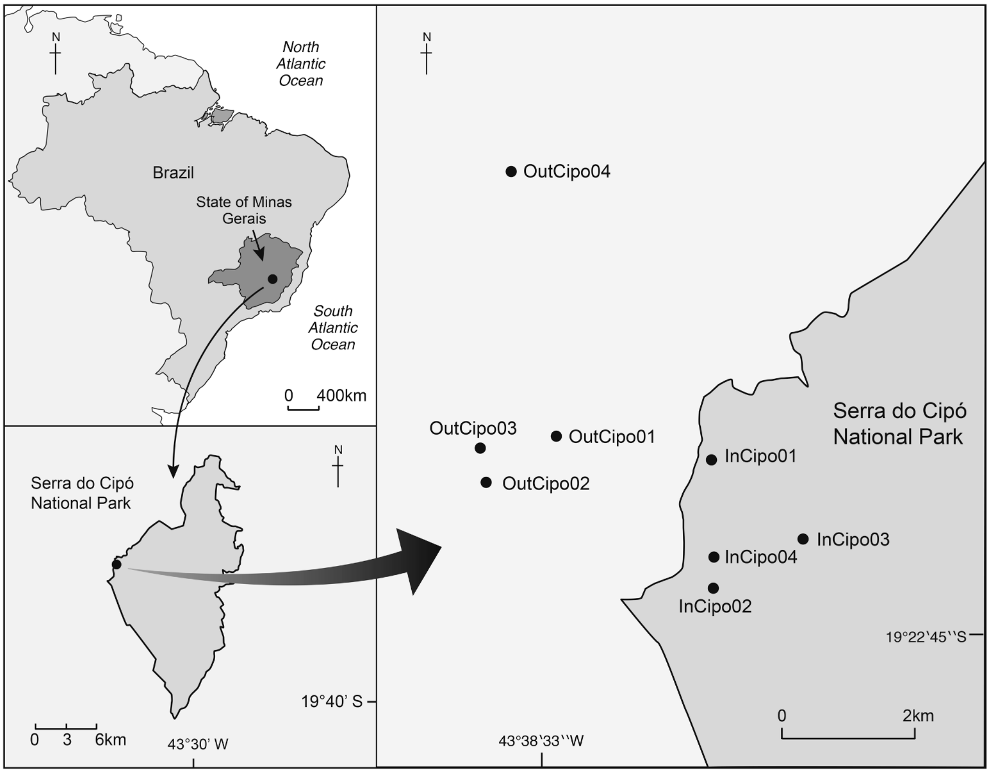

Fig. 1. Serra do Cipó region. Location of eight recorders in the Serra do Cipó region (four recorders inside the protected area and four outside).

et al., 2013, 2017; Ospina et al., 2013; Alvarez-Berríos et al., 2016; Campos-Cerqueira and Aide, 2016; Campos-Cerqueira et al., 2017; Campos-Cerqueira & Aide, 2017).

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

2.3. Acoustic index calculations

First, we mixed down all one-minute files to mono, and down-size them to 22,050 Hz sampling rate (resulting in a effective range of analyses of 0 to 11 kHz), to calculate the indices for each of the 256 frequency bins (each with a bandwidth of ≈43 Hz). The rationale for calculating the 12 indices follows Towsey et al. (2014a), Towsey et al. (2014b), Towsey et al. (2014c), Towsey (2017) and Towsey et al. (2018).

The Acoustic Complexity Index (ACI) measures the amplitude oscillation in each frequency bin (Pieretti et al., 2011). It is calculated from an amplitude spectrogram following the approach of Towsey et al. (2018). It is commonly used as a measure biophony, being among the most widely used acoustic indices among ecologists (Duarte et al., 2015; Fuller et al., 2015; Harris et al., 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, 2014). Here, the converted version of the index provides the “energy concentration”, as calculated by Towsey et al. (2018). The Event Count index (EVN) counts the number of events in each frequency bin per minute (Towsey, 2017).

The Acoustic Cover index (CVR) calculates the fraction of cells in each frequency bin of the noise-reduced spectrogram which surpass 2 dB (Towsey et al., 2014a, 2014b, 2014c). 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).

We also calculated five Ridges Indices, which are derived from the noise-reduced decibel spectrogram according to Towsey (2017). Four indices were calculated corresponding to the four directions of the ridge slope: Ridge Horizontal (RHZ); Ridge Vertical (RVT); Ridge Positive having an upward slope (RPS); and Ridge Negative having downward slope (RNG). Lastly, the Ridge 3 Dimensions (R3D) equals the maximum of RHZ, RPS, and RNG.

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 the ACI, ENT and EVN indices mapped to RGB colours, which are then blended. These three indices are complementary to each other, being sensitive to different aspects of the sound signal, as previously mentioned. The LDFC spectrograms were generated as described by Towsey et al. (2014a), Towsey et al. (2014b) and Towsey et al. (2014c).

2.4. Acoustic region analysis

In order to test for differences inside and outside the park at a more precise and informative scale, we segmented the index values for each day into 20 panels. Each panel corresponds to an acoustic region defined by a specific frequency range (four in total) and period of the day (five), according to the most common acoustic events revealed by the LDFC spectrograms. The four frequency ranges are 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, while the five time periods are 00:00 to 5:29 am; 5:30 to 9:00am; 9:01am to 5:29 pm; 5:30 pm to 8:59 pm; and 9:00 pm to 23:59 pm. Fig. 2 shows an example of an LDFC spectrogram, illustrating the distinctiveness of the 20 acoustic regions.

2.5. Pairwise comparisons of soundscape by acoustic region and season

We normalized the index data following Towsey et al. (2014a), Towsey et al. (2014b) and Towsey et al. (2014c), to reduce outlier effects and facilitate comparisons among different indices. The lowest and highest 1% of values were truncated to the 1% and 99% quantiles respectively, then all values were scaled to the interval from 0 to 1.

The data set comprised over 10 million records for each index. For interpretability, and to avoid the effects of autocorrelation between index calculations corresponding to adjacent times and frequency bins, we summed index values within each acoustic region per day to produce a summary index. For each of the 12 indices, the data for analysis therefore comprised one summary value per day, for each of the eight recording stations and for each of the 20 acoustic regions.

Our aim was to assess differences in soundscape inside and outside the Park, controlling for season effects. A separate analysis was performed for each index and each acoustic region. We fitted an analysis of variance (ANOVA) model to each data set, with the log-transformed index data as response and the interaction between season (autumn, winter, spring, summer) and site (inside or outside the park) as predictors. Normality assumptions were checked using the Shapiro Wilk test and raised no concerns (Appendix A – ENT index models presented for illustration).

Pairwise comparisons of the mean log-index values inside and outside the park were inspected for significance within each season, with p-values adjusted for multiple testing using the Bonferroni correction. These pairwise comparisons were back-transformed to produce a ratio result to reflect the effect size for each index, acoustic region, and season. The ratios can be interpreted as the ratio of median indices inside and outside the park for the corresponding acoustic region and season. We present them as the ratio of the higher to the lower result, marked with a negative sign if the higher result is outside the park, and a positive sign if the higher result is inside the park.

2.6. Analysis of sonotype

To describe the main differences in the types of sounds (sonotypes) between recordings inside and outside the protected area, we visually and aurally scanned the sound files of the season and acoustic region that presented the highest proportion of significant pairwise differences across the 12 indices in the ANOVA analyses. This process was performed in two stages. First, each of the LDFC spectrograms corresponding to the identified season was visually checked to identify acoustic events on the specific acoustic region. 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), but are broader groups used only to provide an overall description of the soundscape. Sonotype examination was performed specifically within the acoustic region (specific time and frequency ranges)

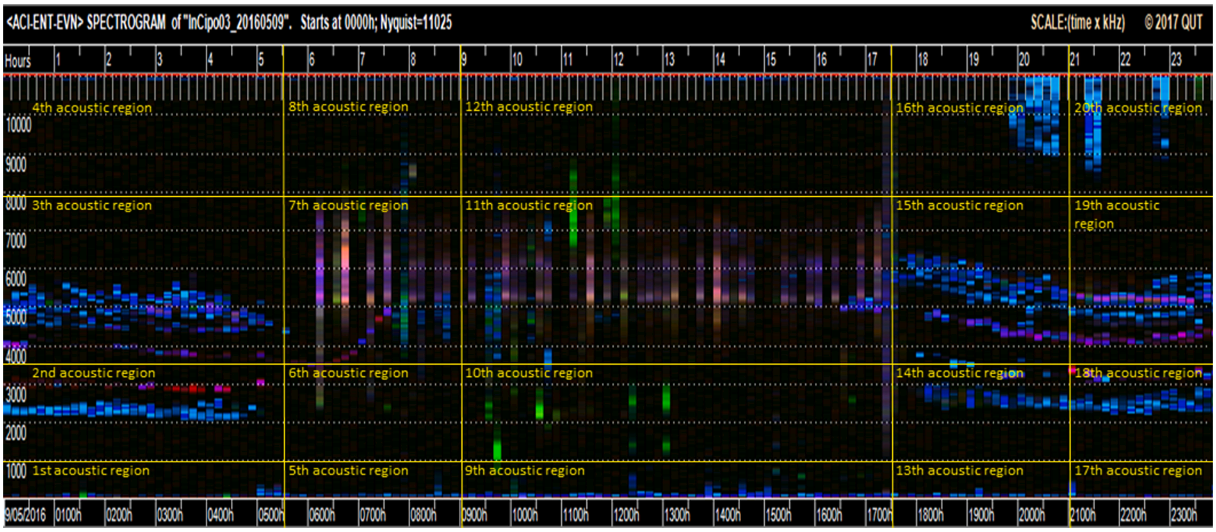

Fig. 2. Illustration of frequency range and time used to define each of the 20 acoustic regions. The indices are mapped to RGB colours (ACI = red; ENT = green; and EVN = blue). Each panel corresponds to one acoustic region. The Long Duration False Colour (LDFC) Spectrogram presented here was created from audio files recorded inside the Serra do Cipó National Park (site: InCipo03) on 9th May 2016, selected as an example of common acoustic events recorded at this site. The y axis represents the frequency varying from 0 to 11 kHz, while the × axis represents time (24 h in total). The yellow lines show the time and frequency chosen as the bounds that define each different panel.

that presented the greatest differences between the recording sites.

3. Results

There were significant differences in the acoustic index values inside and outside the park. The soundscape differed most in autumn, with acoustic region 6 scoring the highest number of indices with a significant difference inside and outside the park (6th Panel – Fig. 2). This corresponds to 05:30 – 09:00am and a range of 0.988–3.609 kHz. The soundscape differed least between sites in acoustic region 15 in winter, representing 17:30–20:59 pm and 3.609–7.906 kHz. This interval scored the fewest significant site differences among the 12 indices.

For each index, we inspected the acoustic region and season involved in the largest of the significant pairwise differences. The largest differences most commonly corresponded to acoustic region 6, followed by region 5, and the autumn season. The same ranking applied to the second largest differences, while the third largest differences most commonly involved acoustic region 7 and the summer season. Conversely, among comparisons with the smallest differences, the most frequently-represented acoustic regions were 15 followed by 19, and the most frequently-represented seasons were spring and winter. Fig. 3 shows the number of times each acoustic region appears within the top 10% highest ratios among all the significant differences between field sites. Appendix S3 presents the p-values and ratios for all 960 pairwise comparisons, corresponding to all combinations of 20 acoustic regions, 12 indices, and 4 seasons.

Fig. 4 illustrates the contrasting patterns presented by acoustic region 6 in autumn (greatest difference between sites) and acoustic region 15 in winter (least difference between sites) for the three indices results ACI, ENT, and EVN, while Table 1 presents the pairwise comparison results for the same acoustic regions for all calculated indices.

All 12 indices presented significant differences for the 6th acoustic region during autumn. The only index that presented significant results for the 15th acoustic region during winter was ENT (ratio −1.2). However, the ratio presented by the same index for the 6th acoustic region during autumn was considerably higher (ratio −5.8, meaning that the

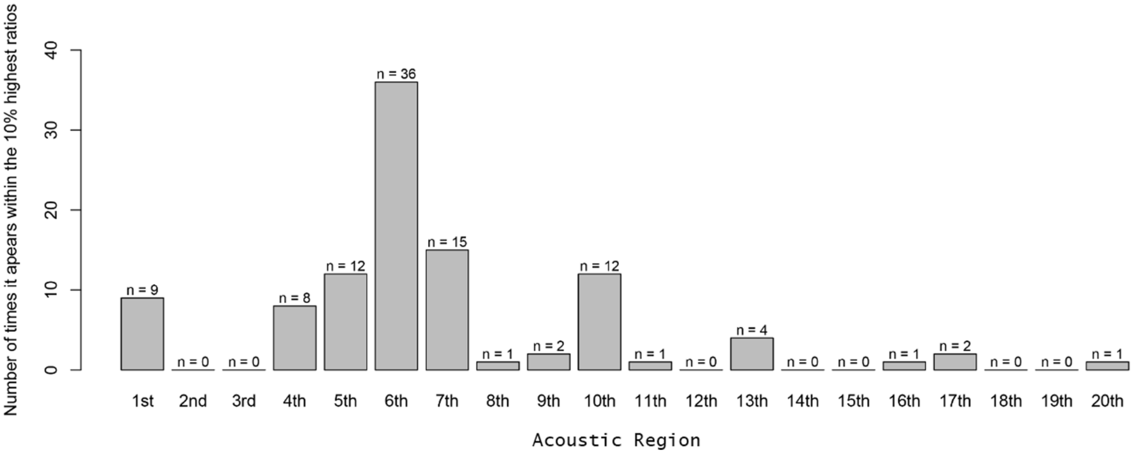

Fig. 3. Acoustic regions that differed most between inside and outside of the National Park. Pairwise comparisons were performed within each of the 20 acoustic regions and four seasons for each index. The number of times each acoustic region appeared in the top 10% highest ratios for each index was counted, and the sum of this count over indices is presented in the histogram. Only the comparisons with significant results were included in this analysis. Acoustic region 6 has the highest count, indicating the greatest differences between field sites. The complete results for all 960 pairwise comparisons are presented in Appendix C.

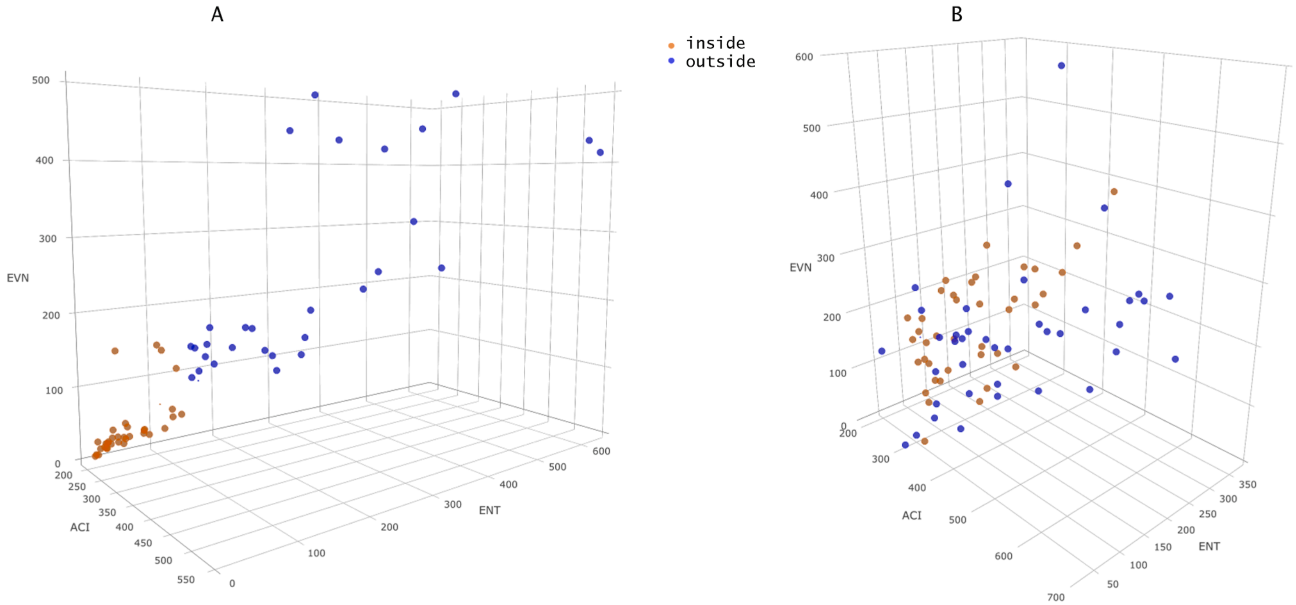

Fig. 4. ACI, ENT and EVN values for acoustic region 6 in autumn and acoustic region 15 in winter. Summary values of Acoustic Complexity Index, Acoustic Entropy Index, and Event Count Index within (A) the 6th acoustic region for each of the days recorded during autumn, when index values differed most; and (B) the 15th acoustic region for each of the days recorded during winter, when index values differed least. Orange dots represent data sampled inside the Serra do Cipó National Park, while blue dots represent data recorded in the non-park sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Pairwise comparisons for the 6th acoustic region in autumn (differs most between sites) and for the 15th acoustic region in winter (more similar) for all the acoustic indices calculated.

6th Acoustic region autumn season			15th Acoustic region winter season		
Index	P value	Ratio	Index	P value	Ratio
ACI	3.34E-06 *	−1.41	ACI	0.13	—
ENT	0*	−5.81	ENT	0.03 *	−1.24
EVN	0 *	−5.94	EVN	0.09	—
CVR	0*	−5.14	CVR	0.27	—
PMN	0*	−4.84	PMN	0.43	—
R3D	0 *	−2.65	R3D	0.46	—
RHZ	0 *	−2.08	RHZ	0.39	—
RNG	0 *	−2.66	RNG	0.99	—
RPS	0 *	−2.62	RPS	0.99	—
RVT	0 *	−2.97	RVT	0.19	—
SPT	0 *	−3.85	SPT	0.71	—
BGN	5.93E-06 *	2.19	BGN	0.96	—

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

ENT measurements were 5.8 times higher outside the park than inside).

Fig. 5 presents the ACI, ENT and EVN measurements for acoustic regions 6, 5 and 15 in all four seasons. Figures in the Appendix B present the ACI, ENT and EVN calculations for each of the 20 acoustic regions in all four seasons. Appendix C presents the complete results for all indices, acoustic regions and seasons.

3.1. Describing the differences: Acoustic events on 6th acoustic region in autumn

Each 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 acoustic region. 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 the park and 543 from outside) were identified as having acoustic events on the 6th acoustic region. Each of these 865 identified files were aurally and visually scanned in order to assign the presence or absence of each of the target sonotypes. Fig. 6 illustrates the identification of acoustic events through LDFC spectrograms, including representations of the highlighted acoustic events on traditional grey-scale spectrograms.

The major differences in the sonotypes identified inside and outside the protected area were clearly related to domestic animals (p-value = 0), and anthrophony (p-value = 0) (Fig. 7). 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. The most common domestic animals identified outside the park were roosters (173 files); cattle (100 files); dogs (94 files); guineafowls (71 files); turkeys (35 files) and horses (6 files). 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 were 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 = 0). Birds were recorded on 218 files from inside the park and 472 files recorded outside (p-value = 0), while insects were recorded on 176 files from inside and 207 files from outside (p-value = 3e-06). Sounds associated with the frog sonotype were scarce both inside (3 files) and outside (19 files); however, significant differences were detected (p-value = 0.04).

The percentage of files including more than one of either bird, insect and/or frog sonotypes was similar inside (31%, 101 files) and outside (34%, 183 files). There was no record of any native mammal species in any of the files that were scanned aurally or visually.

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 acoustic region frequency range. The LDFC spectrograms in which these 11 sound files were represented received a second and more detailed visual

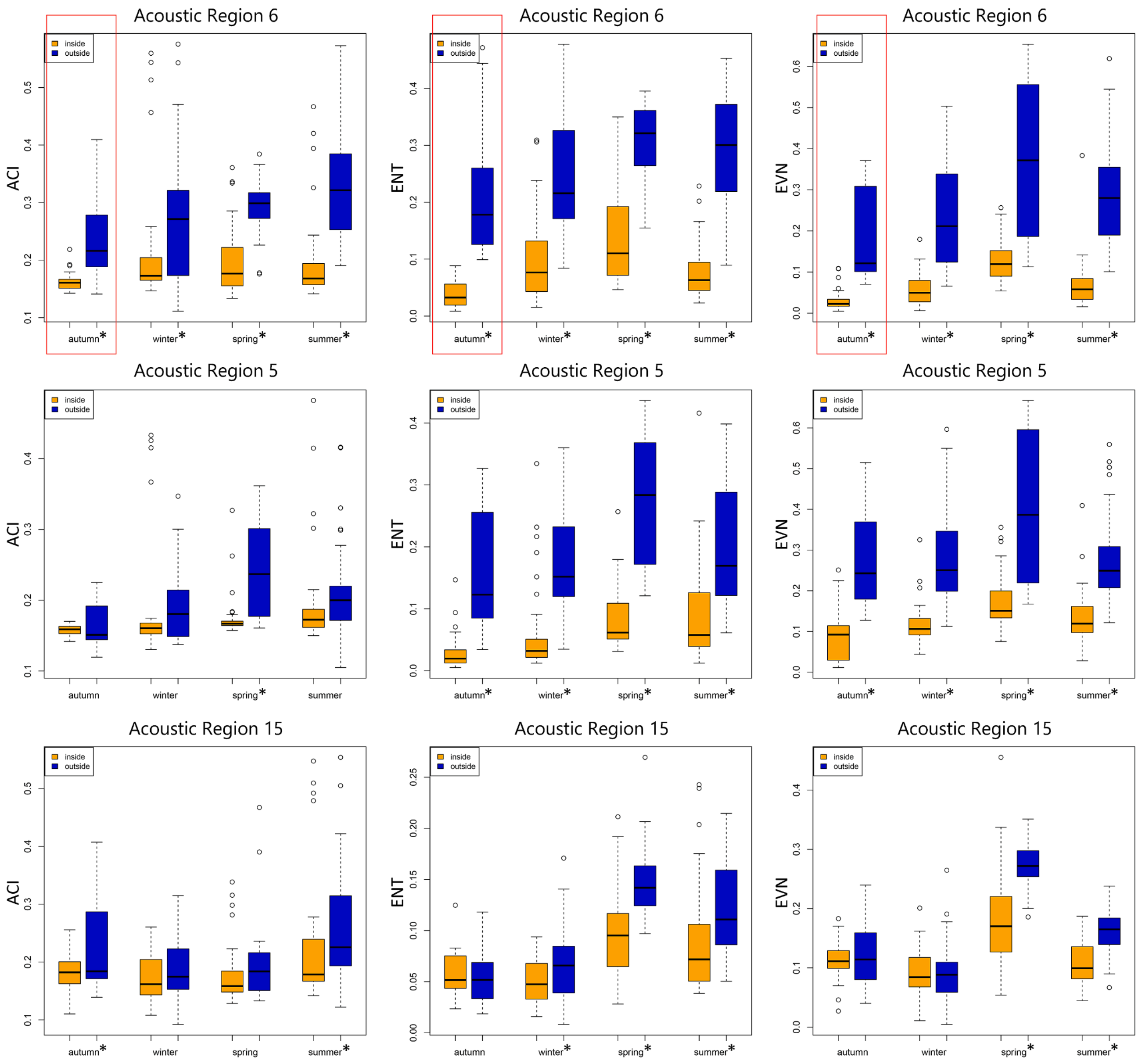

Fig. 5. ACI, ENT and EVN results within acoustic regions 6, 5 and 15 in each season. The values were summed within each acoustic region per day of recording in each of the eight locations. Orange and blue boxplots represent locations inside and outside the park, respectively. Seasons are ordered as autumn, winter, spring, summer. * indicates season with significant differences between inside and outside. The red rectangle indicates acoustic region 6 in autumn, which differed most between inside and outside the park when considering all 12 indices.

examination and the absence of visual signals of acoustic events on the 6th acoustic region was confirmed.

3.2. *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 40,832 one-minute files, with 9403 files recorded in autumn, 11,586 files in winter, 8545 in spring and 11,298 in summer. The differences in the number of files per season are due to few occasional malfunctioning recorders. Two recorders inside the park failed to work for 1, 2, and 5 days dispersed among different seasons, while two recorders outside the park failed for a total of three complete seasons (10 days missing in each case). One of these malfunctions was due to destruction of the microphone by a large animal. Additionally, a malfunctioning acoustic sensor made extra recordings on 12th February 2017, which were excluded from the analysis. The cosine similarity heatmaps generated for ACI, ENT and EVN measurements, which allowed us to identify these extra recordings, are presented in Appendix D.

4. Discussion

Acoustic indices enable researchers to conduct a fast, holistic comparison of soundscapes, without knowing in advance what aspects of the soundscape might differ. This absolves the analyst from the laborious and subjective task of selecting target species or species groups, and training algorithms to detect the corresponding sounds among massive datasets. However, the non-specificity of index calculations makes index comparisons hard to interpret. Here, we have used indices in tandem with a biologically-informative segmentation scheme, to illuminate the time of day and frequency ranges at which soundscapes are most distinguishable. This aids the interpretation of contrasting index results,

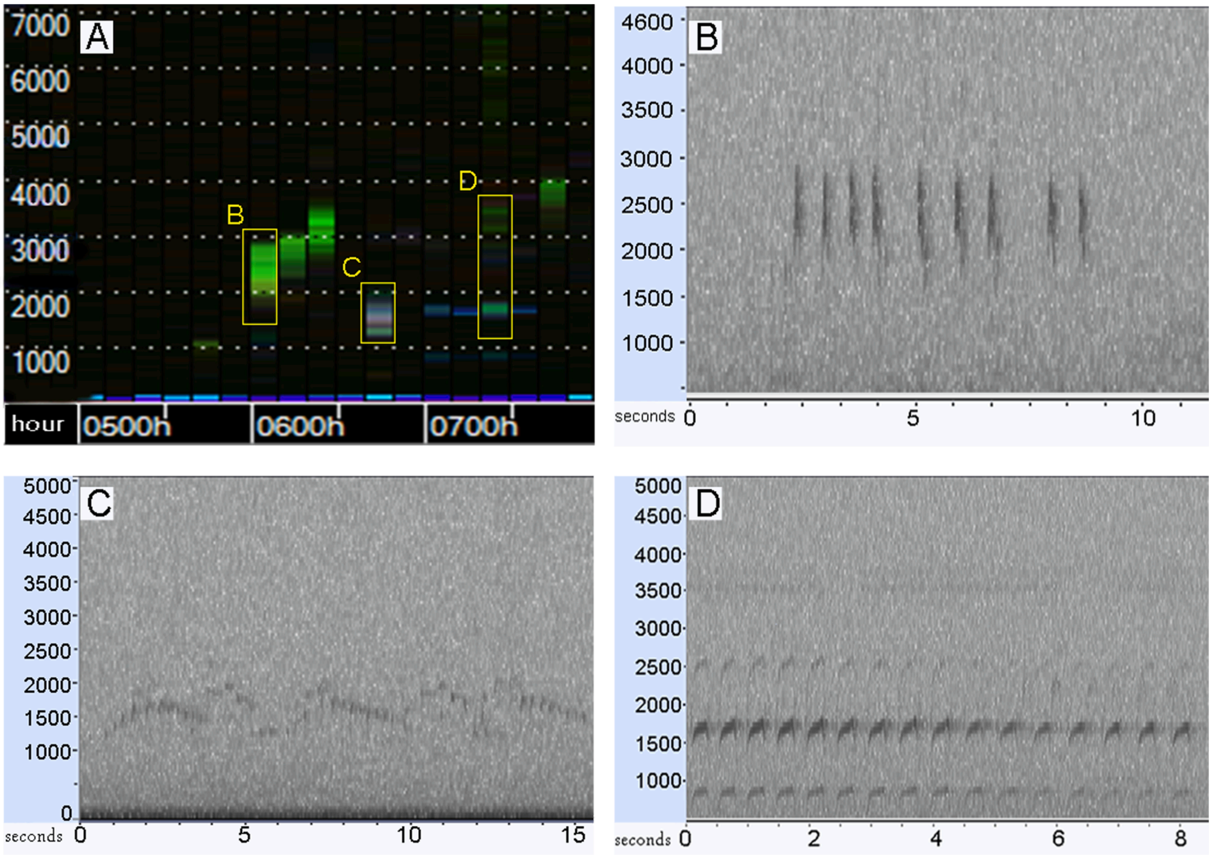

Fig. 6. Example of acoustic events visualization on LDFC spectrograms. (A) Three-hour sample (05:00 to 8:00) from a 24-hour LDFC spectrogram, with yellow rectangles indicating examples of acoustic events. (B), (C), (D) Portions of standard grey-scale spectrograms extracted from the sound files corresponding to events marked B, C, and D on panel A. Events lasted between 8 and 15 s and were each assigned to the bird sonotype. The y axis represents the frequency in Hertz, while the × axis represents time in seconds (B, C and D) and in hours (A).

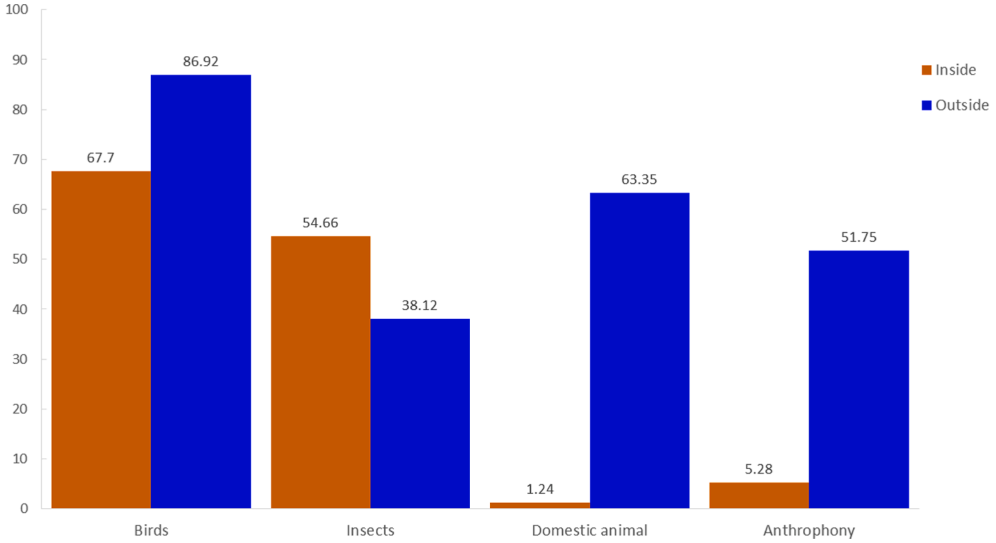

Fig. 7. Sonotypes recorded inside and outside the park within acoustic region 6 in autumn. The proportions specify percentage of presence of each sonotype within the sound files with acoustic events identified inside (total of 322 files with acoustic events) and outside the park (543 files).

and also dramatically reduces the manual work involved in scanning sound files to determine the primary sonotypes driving soundscape differences.

We have also shown the advantages of combining several acoustic indices to detect significant differences in soundscapes between inside and outside the Serra do Cipó National Park. The acoustic region 6 during autumn presented significant differences for all the indices tested (Table 1). This finding enables us to give special focus to the time and sound frequencies encompassed by this acoustic region (05:30 – 09:00am and a range of 0.988–3.609 kHz) when monitoring the soundscape of the National Park. This acoustic region is likely to be optimal for detecting future changes resulting from any increased human activity in the park, associated with reducing the conservation management status of this protected area.

The segmentation of acoustic index data into 20 acoustic regions allowed us not only to identify which acoustic region differs most between sites, but also to compile a shortlist of files to be visually scanned on LDFC spectrograms. This downsized the 40,832 sound files used in this research to only 1,365 (≈ 3.3%) files for scanning using LDFC spectrograms.

The comparative sonotype study confirmed that daily LDFC spectrograms can be used as a tool to indicate 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 acoustic region 6. The 865 sound files aurally and visually scanned using traditional spectrograms corresponded to approximately 2% of the total amount of sound files used in this research. Only 11 of 865 (≈ 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 acoustic region frequency range (0.988–3.609 kHz) that were initially misinterpreted as being within this frequency range.

The sonotype analysis provides a useful complement to the index results, and both show higher acoustic activity outside the park within the 6th acoustic region during autumn. The results show that the soundscape outside the park is strongly influenced by human activity. Domestic animals and anthrophony are rare in the park soundscape, while very common outside of it in the farmland environment. Similar to Ferreira et al. (2018), the analysis presented here only considered presence/absence of a sonotype, and did not consider the dominance by measuring the time length of each sonotype or counting the number of times it appeared in a given sound file. The anthropic influence on the soundscape could 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 acoustic regions 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 acoustic region 6. As well as acoustic region 6, studies aiming to focus specifically on the bird community should also give special attention to the 7th acoustic region, 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 acoustic region is also higher outside the park, as shown for acoustic region 6.

ACI and ENT measurements indicated a higher biophony activity outside the national park, which was confirmed by the sonotype count for acoustic region 6 in autumn. EVN also highlighted 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 regular transient 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) 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 was the only index to achieve higher measurements inside than outside the park, indicating that there was more background noise inside the park than outside within the 6th acoustic region in autumn (see the ratio column 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, i.e. 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 Cipó. 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, rather than determining sound profiles of specific species or groups of species. For this reason, the examination of sonotypes was performed only within the season and acoustic region that presented the largest differences between sites to describe the sound sources responsible for the differences found by the index analysis. Further research can be done to describe the sonotypes and morphospecies composition and expand it to other seasons and acoustic regions. This will provide a better understanding of the measures used and their links with local biodiversity composition and abundance.

4.1. Conclusion

Although we advocate here that acoustic indices and their visualization are a useful tool for biodiversity monitoring, their use as a surrogate for rapid biodiversity assessment should be taken cautiously. Indices provide useful ecological information in different environments worldwide (Depraetere et al., 2012; Towsey et al., 2014b; Duarte et al., 2015; Fuller et al., 2015; Machado et al., 2017; Sueur, 2018), but it is not yet clear what is the relationship between each acoustic index and 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 a major limitation for the use of acoustic indices in protected areas monitoring. The sensitivity of each index to a different aspect of the acoustic energy means they can be used as complementary filters that enable identification of the main differences between seasons and sites, as performed here. We do advocate that passive acoustic monitoring associated with acoustic index analysis should be implemented in protected areas since this monitoring method has been shown to be cost-effective when compared to other traditional surveys methods (Ribeiro et al., 2017; Wrege et al., 2017) and is capable of providing information on different levels (populations, species, communities) and in 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 differences across sites and time (Lee et al., 2005), which we have achieved via passive acoustic monitoring 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 relevant to biodiversity assessment and conservation management. It confirms that passive acoustic monitoring associated with acoustic index analysis is a potential tool for long term monitoring in the Serra do Cipó region, as well as establishing 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 could 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).

CRediT authorship contribution statement

Ivan Braga Campos: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing -

original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Rachel Fewster:** Conceptualization, Writing - review & editing. **Anthony Truskinger:** Formal analysis. **Michael Towsey:** Formal analysis, Writing - review & editing. **Paul Roe:** Resources, Writing - review & editing. **Demival Vasques Filho:** Formal analysis, Writing - review & editing. **William Lee:** Conceptualization, Writing - review & editing. **Anne Gaskett:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106953.

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