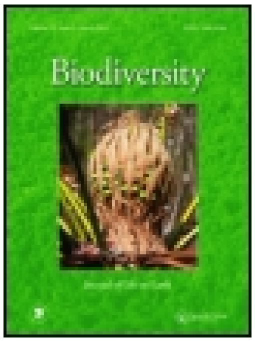

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A soundscape assessment of the Sasso Fratino Integral Nature Reserve in the Central Apennines, Italy

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ABSTRACT
Ecoacoustics investigates natural and anthropogenic sounds and their relationship with the environment. It is a powerful tool for biodiversity monitoring, management and conservation and also with regards to the global climate change issue. This study, based on data collected in 2017, describes for the first time the soundscape of the Sasso Fratino Integral Nature Reserve (INR) in Italy, an area characterised by the almost absence of anthropogenic noise, where we selected three recording sites within and adjacent the reserve. We adopted a double approach: one qualitative, based on visual screening of compact daily spectrograms; the other quantitative, by generating acoustic indices. In general, all sites are characterised by quiet nights and very acoustically dense daylight hours, with a composite biophony occupying the range 1500–9000 Hz. Moreover, the principal component analysis shows that the sites inside and outside the reserve are well differentiated and distinctly clustered, which could be due to their spatial heterogeneity and to the biophony's different contributions. In this case, our results agree with the recognition of sonic patterns, or sonotopes, related to the different overlapping of biotic and abiotic sonic agents. The long-term acoustic data collection allows a reference repository to be built for monitoring the INR's biophony status and evolution: as any human presence or intervention is currently prohibited, only external global changes could be considered as possible factors influencing any shift in the species' presence and distribution inside the reserve.

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Ecoacoustics; acoustic indices; sonotopes; National Park; biodiversity; monitoring

Introduction

Today, one of the most important biodiversity conservation challenges is to manage and mitigate the high rate of species loss caused by the effects of climate change and the long-term impacts of human activities. It is, however, rarely possible to have all the information necessary to make informed decisions and our human understanding of most ecological systems is based on very limited spatial and temporal data coverage (Aide et al. 2013).

Ecoacoustics is an emerging scientific discipline that investigates natural and anthropogenic sounds and their relationship with the environment. In natural habitats, it has the potential to be a powerful tool for management and conservation efforts: from the recognition and monitoring of individual species through to soundscape analysis and description, acoustic data can provide new insights and approaches for science, conservation policies and education (Towsey, Parsons, and Sueur 2014a; Sueur and Farina 2015; Krause and Farina 2016; Farina and Gage 2017a; Pavan 2017; Farina 2019). In particular, passive acoustic monitoring (PAM) allows scientists to record data over large spatial and temporal scales, as well as collecting long-term information on animal distribution and variations in community dynamics, including those driven by anthropogenic activities (Farina and Gage 2017b; Sueur et al. 2008a; Obrist et al. 2010; Marques et al. 2013). Moreover, this method is independent of the observer's presence and numbers, and it allows for monitoring of areas that are difficult to access, whilst also providing collecting quantitative data for the comparison of acoustic variance both intra-site (for monthly or yearly sampling) and inter-sites (for multiple simultaneous locations) (Sueur et al. 2014).

Thanks to the analysis of acoustic data, it is possible to obtain a picture of the soundscape, which is the acoustic expression of the local ecosystem, composed of the sounds produced by the animals (biophony, mainly concentrated in the range 2000–8000 Hz, but including frequencies down to 200 Hz and up to 120 kHz), the sounds produced by atmospheric and physical events (geophony: wind, rain, water, etc., wide frequency range) and by human activity (anthropophony that includes the widely invasive technophony: road traffic, airplanes, railways, generally occupying low frequencies of 20–2000 Hz) (Pijanowski et al. 2011; Gage and Axel 2013; Pavan 2017).

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The different spatial overlap of geophonies, biophonies and anthrophonies creates sonic patterns or sonotopes (Farina 2013). The identification of these sonotopes can be useful for describing and monitoring natural areas, but also for catalysing ecotourism which seeks to enjoy different acoustic experiences, especially in zones where natural sounds largely prevail over anthropophony.

Furthermore, ecoacoustics performs a crucial role in applied ecology and conservation biology to identify and to quantify human-generated noise, in particular the technophony related to transportation infrastructures, considered by the European Environmental Agency (EEA 2014, 2017, 2018) and by the World Health Organization (2018) a danger for human health. As human population and transport infrastructures increase, they have a growing impact on natural ecosystems, and wildlife as well. The European Community (EEA 2014) states that Nature 2000 sites are affected by anthropogenic noise with ecosystem consequences not yet well understood.

In the year 2000, the US National Park Service stated that the acoustic environment is a key component of ecosystems and thus the soundscape must be studied, monitored, protected and even restored when altered by human action (Director's order 47: *Soundscape Preservation and Noise Management*, www.nps.gov).

It is widely documented that sound cues are fundamental for many species' life, promoting information exchanges among individuals intra- and interspecifically (Collias 1960). Several authors have shown that anthropogenic noise may affect mating (Kaiser et al. 2011), feeding (Nedelec et al. 2017), intra- and interspecific communication (Radle 2007; Naguib 2013), anti-predator behaviour (Antze and Koper 2018; La Manna et al. 2016; Simpson, Purser, and Radford 2015; Simpson et al. 2016), environmental sensing (Rosa and Koper 2018; Pavan 2017) and it represents a globally (or ubiquitous) spread source of disturbance even if its effects are lesser studied than those of other human activities (Blickley and Patricelli 2010; Francis and Barber 2013).

Moreover, a soundscape spectrographic analysis and audio listening for recognising various species could serve to build a reference repository of species-specific signatures to create educational materials and to support the future implementation of automatic species recognition algorithms for accurate biodiversity assessments.

This study describes, for the first time, the soundscape of the Sasso Fratino Integral Nature Reserve (INR, located in the Casentinesi Forests National Park, Italy), an area internationally known for its excellent conservation status and high biodiversity. Its peculiar vegetational structure of old growth forest and forest secular management addressed towards a full conservation of the environment, candidate the area to be a suitable model to collect high-quality records of natural habitats.

The data collection is part of the SABIOD (Scaled Acoustic BIODiversity) project designed in 2014 in collaboration with the University of Pavia (Italy), the Italian State Forestry Corp (now Reparto Carabinieri Biodiversità), the University of Toulon (France), and with the support of the French National Centre for Scientific Research (CNRS). The project promotes the recording and investigation of natural sites' soundscapes with different levels of protection and contamination by anthropic noise through the installation of a series of autonomous recorders for a simultaneous and continuous monitoring.

We adopted a double methodological approach based on a qualitative description, with compact daily spectrographic views, and on the application of the quantitative Acoustics Indices (AIs) (Sueur 2018).

PAM generates massive long-term recordings archives that have to be managed and analysed. To support the interpretation of this large amount of information and to reduce the analysis effort, researchers have developed different acoustic indices that summarise and score the structure and the distribution of the acoustic energy, reflecting a correlation with species' diversity and distribution (Towsey et al. 2014b; Sueur et al. 2014; Farina et al. 2014).

For instance, the Bioacoustic Index (BI) aims to quantify biophonic activity by calculating spectral power above a threshold in the frequency range 2000–8000 Hz (Boelman et al. 2007). The Acoustic Diversity Index (ADI) (Villanueva-Rivera et al. 2011) applies Shannon diversity index to the proportion of the signal energy, calculated for each frequency band in which the spectral range of the spectrogram is divided (default 1 kHz steps). The Acoustic Evenness Index (AEI) (Villanueva-Rivera et al. 2011) also considers the distribution of the proportion of signals across the spectrum but uses Gini coefficient to measure how even the occupancy distribution is. The entropy index (H) is the product of two sub-indices, spectral (H_f) and temporal entropy (H_t), computed, respectively, on average frequency spectrum and on the Hilbert amplitude envelope of the raw bioacoustic signal (Sueur et al. 2008a). The Acoustic Complexity Index (ACI) measures the variation in intensity by calculating level changes in frequency bands (Pieretti, Farina, and Morri 2011) and the Normalised Difference Soundscape Index (NDSI), that is indicative of the level of anthropogenic disturbance, by calculating the ratio of the dominance of low frequencies (between 1 and 2 kHz, usually technophony signals) and higher frequencies (2–8 kHz, strictly related to biophonies) (Kasten et al. 2012).

Materials and methods

Study area

The study was conducted in the Sasso Fratino INR inside the National Park of the Casentinesi Forests (on the Tuscan-Romagnolo Apennines, Italy), which is an area designated as SCI-SPA IT4080001 within the European Natura2000 Network of Protected Areas (http://ec.europa.eu/environment/nature/natura2000). We selected three recording sites: one nearby and two within the Sasso Fratino INR borders, site A and sites B–C, respectively (see Figure 1 and the following data collection section for more details). Established in 1959 as the first Italian strict Nature Reserve, the Sasso Fratino INR is an area of 800 ha characterised by complete prohibition of access and of any anthropic action. The negligible human disturbance through the last centuries is due to a lack of access roads, the presence of steep slopes and the extremely bumpy morphology of the site. The Sasso Fratino INR is surrounded by other nature reserves (biogenetic reserves) and all these features have allowed the development of an old-growth forest (very rare in Italy due to the strong anthropogenic pressure on forests for the past millennia) characterised by high biomass (above 1000 mc/ha) and a rich biodiversity (Bianchi et al. 2011).

From a vegetational point of view, there are mixed forests containing beech (*Fagus sylvatica*) and white firs (*Abies alba*) covering the slopes up to 1250 m. Above this altitudinal threshold, the forest is composed only of beech (Padula 1985).

In 1985, the Sasso Fratino INR was awarded the European Diploma for Protected Areas due to its importance and uniqueness as an ecosystem and then, in 2017, it was included by UNESCO within the list of '*Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe World Heritage*' (https://whc.unesco.org).

Data collection

Data collection was carried out through on-site positioning of Wildlife Acoustics SM3 autonomous recorders, which are programmed with Song Meter SM3 Configuration Utility software (Wildlife Acoustics, Inc.). They were set up to record 10 min every 30 min, for 24 h a day, in a synchronous and continuous way from 8 May to 10 June 2017. High pass filters were set to 220 Hz to reduce low-frequency noise mainly due to wind. Digital recordings were set at a sampling rate of 48 kHz and saved in the audio file format Microsoft .wav, stereo 16 bit uncompressed, yielding a total of 45,600 min of recording (about 15,200 min for each of the three sites), and then stored in the sound repository of the Interdisciplinary Centre for Bioacoustics and Environmental Research (CIBRA) of the University of Pavia, Italy (http://www.unipv.it/cibra).

The geographical position of each recorder has been marked with a handheld GPS and then saved as a .kmz file. Three main monitoring sites have been identified: the first site (A) is located in La Lama (at

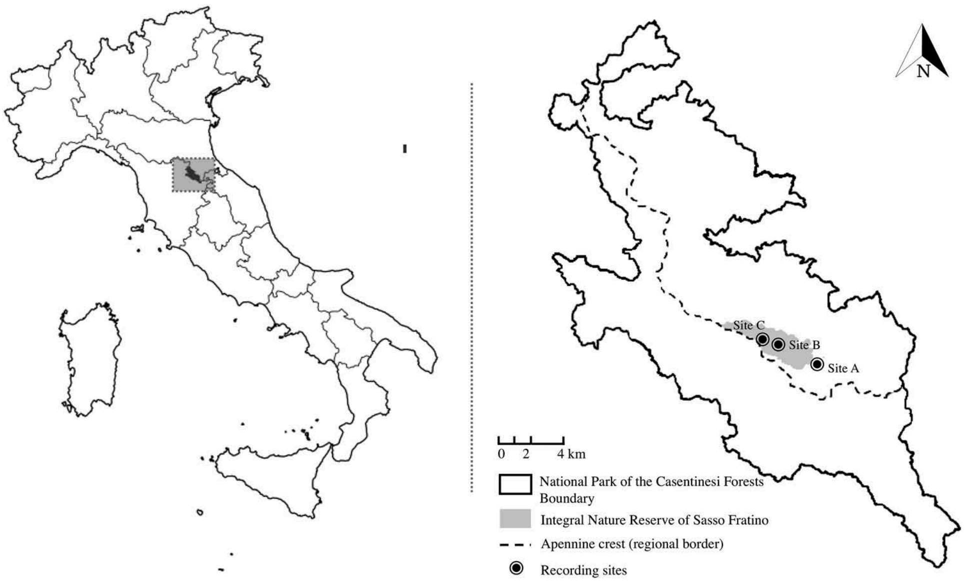

Figure 1. Distribution of acoustic data recording sites. The left-hand side shows the geographic location of the Casentinesi Forests National Park within Italian territory; and the right focuses on the National Park's boundaries and the Sasso Fratino INR with the three sampled sites.

700 m a.s.l.), a flat-plain area at the southern boundary outside the Sasso Fratino INR, but included in the adjoining Biogenetic Reserve of Badia Prataglia-Lama, that is accessible only through cycle-pedestrian paths and by forest service vehicles. The other two sites (B, 950 m a.s.l. and C, 1400 m a.s.l.) are in the core area of the dense forest, deep within the Sasso Fratino INR, where human access is forbidden except for scientific purposes.

Daily spectrograms

To obtain a general overview of the daily acoustic pattern as a single spectrographic image, we generated packed spectrograms for each day and site (see Figure 2), by using the software SeaProSabiod, developed at CIBRA (Pavan 2016).

Packed spectrograms provide a graphical 'summary' of what acoustically happened day to day, and show acoustic scenes relating to biophony, geophony and anthropophony/technophony.

Packed spectrograms can represent long periods (10 min to several days) by packing together consecutive short time spectra. The spectrogram size (512–1024 pixels in vertical, 1600–5120 pixels in horizontal, depending on the available screen resolution) is set first and then the traditional sound analysis parameters are fixed according to the sound contents to be analysed. The FFT size (1024 or 2048 samples) is set according the vertical spectrogram size; the window shape is usually set to the traditional Hanning function; the window size and the overlap ratio are set according to the sound contents, usually, for bioacoustic sounds, 512 or 1024 samples with 50% overlap. The dynamic range is set to 96 dB to show all the possible variations from background noise to the loudest sounds recorded; the time packing factor is set according to the time extension (number of files/frames) to be shown and display size.

To plot a one-day spectrogram, composed by 48 frames of 10 min each, on an 1800 pixels wide spectrogram we use FFT = 1024, window = 1024, overlap 50%, and a packing factor of 1500. The spectrogram is computed with a traditional SFFT method, but each vertical line of pixels is computed by packing together 1500 consecutive spectra. Three packing methods are available, Min, Mean, Max. The two most useful are the Mean and the Max method.

With the Mean mode the mean value of the 1500 spectra is plotted, bin by bin. With the Max method, for each frequency bin the maximum value of the 1500 spectra is plotted. Since the Mean method shows the average level of each frequency bin, it underestimates short acoustic events and transients; e.g. a single short shot that affects few consecutive spectra get underestimated or may disappear. On the contrary, the Max method retains even the shortest acoustic events and appears to provide a more useful and rich representation of all acoustic events, regardless of their duration.

We used the Max method; with the chosen parameters all the 48 daily files are plotted in sequence on 1800 pixels, with each pixel column representing, frequency bin by frequency bin, the maximum energy recorded in a 16 s time frame.

By visual screening of packed spectrograms, we received a general picture of the daily soundscape features and we verified that all days were completely and correctly recorded. Then, we proceeded with the acoustic analysis and statistical exploration.

Listening with simultaneous real-time high-resolution spectrographic display (FFT = 1024, window = 512 samples with Hanning shape, overlap = 25% or 50%) was performed with the software SeaPro (Pavan 2016) to identify species and visualise acoustic events in the details. Clip extraction was performed with Adobe Audition 3.0; no editing was performed on the recordings.

All indices and statistical analyses were computed using the computing language R v. 3.4.2 (R Core Team 2017). The Rscript developed for this task is composed of two parts, one (file analysis) aimed to investigate the acoustic files and produce a table of quantitative indices, the other (result processing) dedicated to exploiting and analysing the table to generate statistics and plots. The analyses were performed on Microsoft Windows 10 operating system with a desktop PC with Dual Xeon CPU; however, no parallelisation of the code was performed.

Acoustics indices

To reduce computation time, for each 10 min file recorded, one minute has been extracted in a random way, achieving $N = 48$ 1 min frames for each sampling day and site.

Six AIs (BI, ADI, H, AEI, NDIS and ACI) were calculated for each 1 min frame using the Soundecology (Villanueva-Rivera and Pijanowski 2018) and Seewave packages for R (Sueur, Aubin, and Simonis 2008b).

Additionally, we calculated the acoustic energy concentrated in the frequency bands that characterise the biophony (hereafter named BIOPHONY), by adapting the function '*meanspec*' of Seewave package in order to obtain the mean relative amplitude for only the frequency range 1500–9600 Hz.

For all AIs, including BIOPHONY, we used default parameters. To compare the AIs' distribution for each of the three sampling sites, all the hourly values computed day by day were averaged across the whole recording period to obtain the mean values per month per site.

Statistical analyses

A Shapiro–Wilk test for normality revealed that data was not normally distributed. The monthly average values for each AI were compared among the three different sites. To test differences within intra sites, we averaged the variables for each site in two subsets according to local sunrise and sunset (day: 05:00 a.m. to 09:00 p.m.; night: 09:30 p.m. to 04:30 a.m.).

A Kruskal–Wallis test and subsequent Wilcoxon rank sum (Bonferroni corrected) tests were applied to compare AI's differences among sites, while a Mann–Whitney was used to compare daily and night distribution at each site (specifically, 'dplyr' and 'factoextra' packages were used to compute statistics and 'ggplot2' package to visualise data).

Additional test

We also investigated the presence of some potential sources of variation related to weather conditions, and for this purpose we compared our results with a filtered dataset. To test the influence of bad weather events, we manually identified (by listening and spectrogram observation) and excluded the files containing wind or rain and recalculated the biophony spectral energy band (BIOPHONY) for each site.

Results

We collected 488.30 GB of acoustic data (about 5.14 GB of data per sampling day/site) and thus we analysed a total of 4560 recording files, that are 48-files per sampling day/site (Site A = 31 recording days/1488 files, Site B = 33 recording days/1584 files, Site C = 31 recording days/1488 files, respectively).

In general, daily packed spectrograms show that all sites are characterised by quiet nights and very acoustically dense daylight hours (dawn to dusk), with a complex and composite biophony mostly occupying the range 1500–9000 Hz and few species vocalising in the range 400–1500 Hz. The technophony component is due to high altitude airplane overflights that appear in the lower part of the spectrograms (Figure 2) with a well recognisable amplitude and spectral pattern below 500 Hz.

AI and BIOPHONY distributions among sites are shown in Figure 3.

BI, ADI, ACI and NDIS exhibited a similar pattern with two main peaks in the morning (dawn, from 5 am to

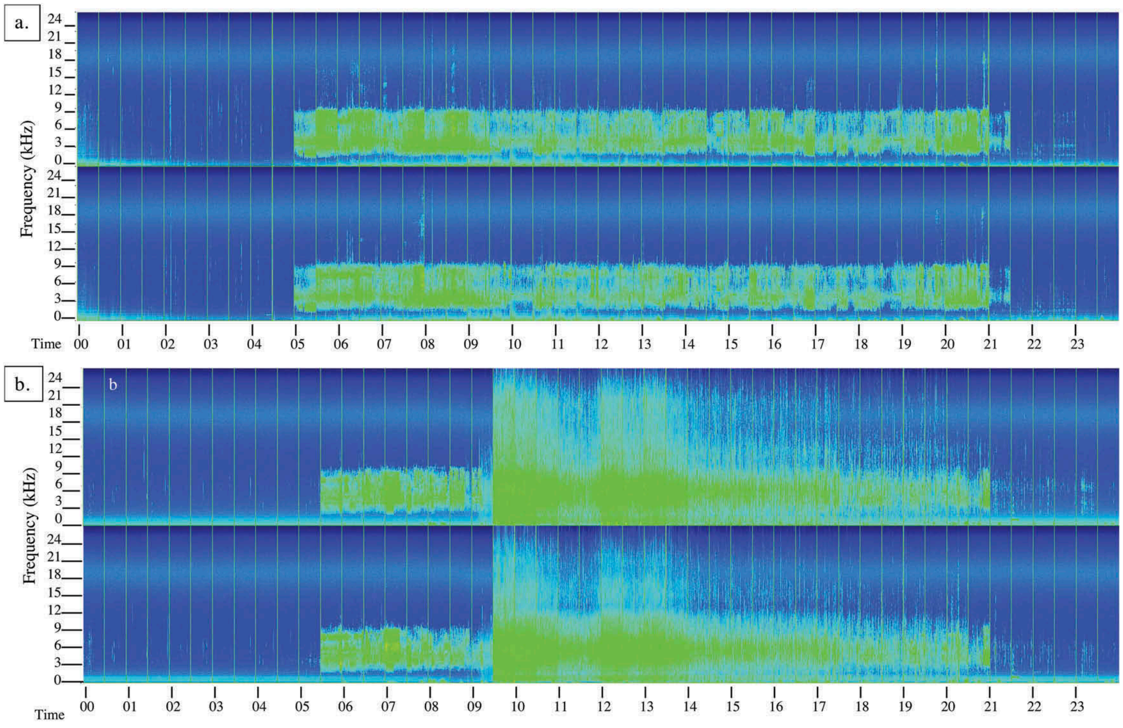

Figure 2. Examples of a packed spectrogram of a one day recording in Sasso Fratino INR, 10 min every half-hour (48 frames/day), x-axis 24 h, y-axis 24 kHz. Stereo is represented in the left channel above and the right channel below, respectively. Spectrogram (a) represents an example of a good weather day (2017-05-25): showing sharp transitions at dawn and dusk and a high density of biological acoustic activity in between, while airplanes produce the traces on the x-axis; and (b) represents an example of bad weather conditions (day: 2017-05-09): showing rain/wind events in the central part of the day.

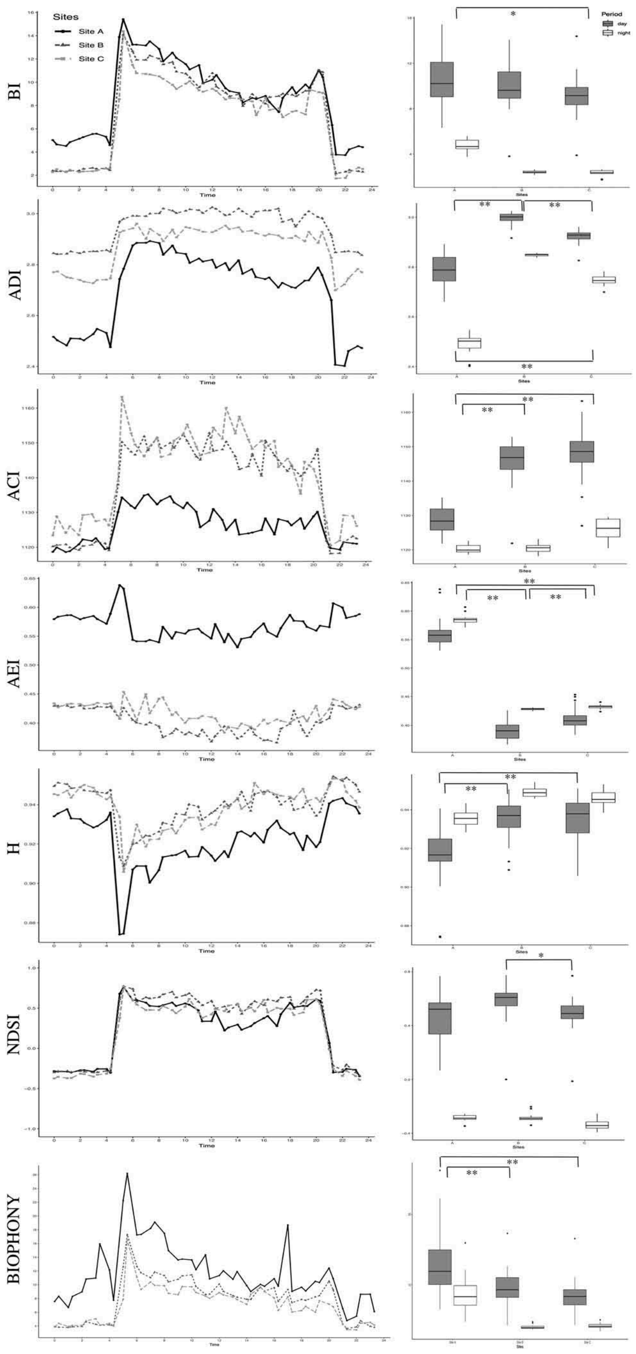

Figure 3. The left represents distribution plots of average monthly trends of three sample sites (A, B and C) for the six acoustic indices (in order BI, ADI, ACI, AEI, H and NDSI) and for the BIOPHONY parameter. The right represents boxplots of the three sites with the separation of the day files (from 05:00 a.m. to 09:00 p.m.) and night recordings (from 09:30 p.m. to 04:30 a.m.). The asterisks indicate the significance of the Wilcoxon rank sum tests (** stands for $p < 0.001$, * stands for $p < 0.05$).

6 am), and in the evening (dusk, from 7 pm to 8 pm), respectively, and all had higher values during the day and lower values in the night. H showed an inverse pattern indicating the lowest value at dawn and the highest in the night. Lastly, AEI is characterised by nocturnal values higher than diurnal ones, suggesting higher nocturnal evenness (and during dawn and dusk choruses) while the daylight hours are more heterogeneous.

Intra-site variability

The 24 h distributions are well differentiated in all three sites, with very active days and generally quiet nights. All six AI results showed significant differences between daily and nocturnal values; all Mann–Whitney Wilcoxon test p values are <0.001.

Inter-site variability

BI and NDSI indices confirmed a clear diel pattern with higher acoustic energy in the daily hours and quieter nights at all three sites.

For the other four indices, all Kruskal–Wallis tests resulted in $p < 0.001$, df = 2, {Nday = 33; Nnight = 15} × 3 sites, (ADI: $p < 2.200^{-16}$; ACI $p < 6.404^{-08}$; H $p < 4.304^{-11}$; AEI $p < 2.2^{-16}$, respectively), indicating a significant difference among sites. In particular, a pairwise Wilcox's test confirmed for ACI and H the difference is statistically marked between the site outside the reserve (site A) and the others inside (sites B and C) (ACI: site A vs site B: $p = 4.800^{-4}$, site A vs site C: $p = 4.050^{-8}$; H: site A vs site B: $p = 5.700^{-9}$; site A vs site C: $p = 1.000^{-8}$).

A principal component analysis (PCA) for the six AIs revealed a difference between sites inside the reserve (site B and C) and the one outside (site A). The first two dimensions of PCA explained around 58% and 35% of the variance in the data set, respectively (see Figure 4). In particular, ADI and BI contribute positively to the first dimension while the second component has large negative associations with H index.

Additional test

The exclusion of files with rain or wind events (specifically, $N = 618$ discarded files, about 13.6% of the total, see Figure 5(a) to see how many files have been discarded for each time interval for the sample site A) had a more evident impact on the night values in which the outlier points found in the previous analysis no longer appear; the patterns follow relatively constant values for overall night and two peaks of bioacoustics activity emerge concurrently with the morning and evening choruses, just after dawn (around 5:30 am) and just before dusk (around 7:30 pm), respectively (see Figure 5(b)).

Discussion

The baseline natural sound conditions of Sasso Fratino INR have been measured. In detail, the two sites (B and C),

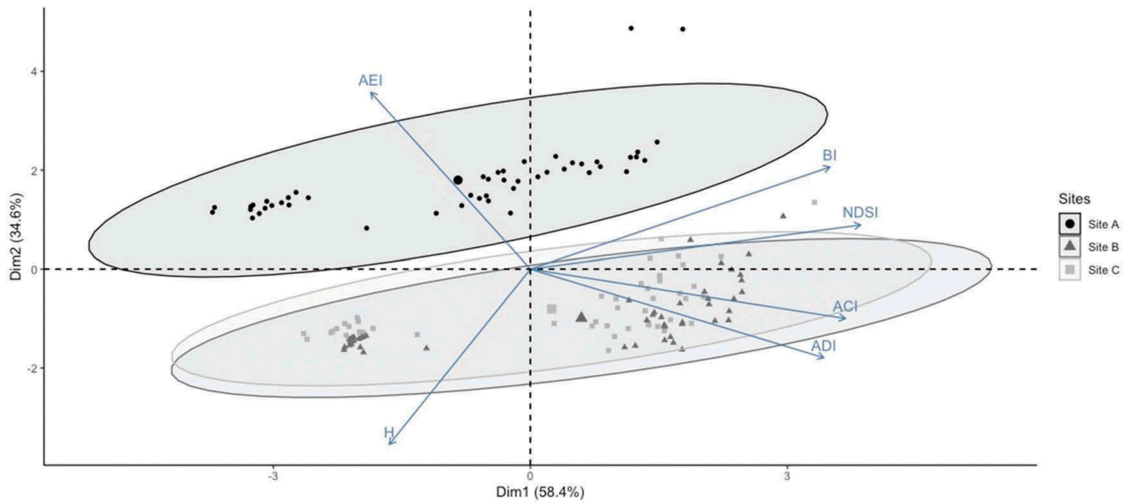

Figure 4. Principal component analysis for the three sites (A, B and C) and six AIs (H, BI, ADI, ACI, NDSI and AEI). The first two dimensions explain 93% of the variance and the analysis highlights the difference between the area around the reserve (site A) and that which is inside the Sasso Fratino INR.

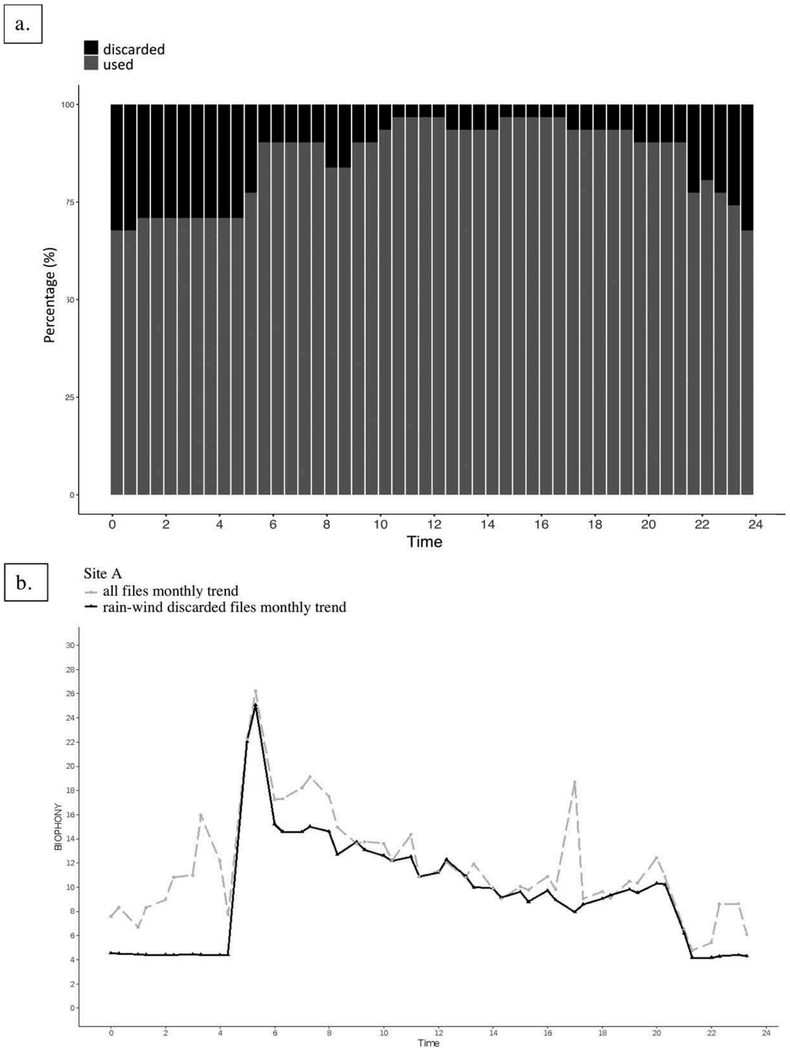

Figure 5. Additional test figures: (a) the percentage of rain/wind files discarded for each time interval in sample site A; (b) mean monthly BIOPHONY trend for site A for the dataset including all recorded files (dashed grey line) compared with the dataset with rain/wind files discarded (solid black line).

properly inside Sasso Fratino INR, are more acoustically homogeneous and similar to each other, while the site A – which is marginal the INR but included in the adjoining biogenetic reserve of Badia Prataglia-Lama – presents its own soundscape, perhaps due to the fact that it is a more open transition area from the forest to a clearing and has a greater tree heterogeneity (mix of beeches and white firs).

Literature (Bottacci 2009) lists 52 censused species of birds for the Sasso Fratino INR, but the information is not up to date and no information is available about communities in the different habitats of the area.

The enrichment of biodiversity monitoring with the ecoacoustic approach (by spectrograms and by acoustic indices) allows information to be obtained not only relating to the diversity of species but also on the density of the biophonic component, which, in this study case, results to be predominant and continuous for all daylight hours in the three sites.

Moreover, the analysis of the monthly average values of the indices by hour of day shows a clear daylight/night pattern with a steep increase of bioacoustic indices at dawn and decrease at dusk. However, during daylight the hourly trends in the three recording sites are different.

Excluding anthropogenic influences, this difference is likely dependent on environmental factors that can affect acoustic structure of avian vocalisations (Acoustic Adaptation Hypothesis: Morton 1975; Boncoraglio and Saino 2007; Ey and Fischer 2009). Namely, temperature and daily lighting cycles, both known to drive animal activity and vocal expression (Bruni, Mennill, and Foote 2014; Hasan and Badri 2016).

These results indicate the need to have more information of environmental parameters at very local levels and thus the need to add at least light, temperature, humidity and wind sensors to acoustic recorders.

Other differences among the recording sites are related to the contents of low frequency noise. In other soundscape studies (Farina and Gage 2017c), the level of low frequency components is usually attributed to the noise of human activities, in particular, to the technophony component of the anthropophony. Car traffic, even from distant sources, contributes to the background noise at even great distances due to high propagation of low frequencies. However, in this case, the study area is characterised by the complete absence of car traffic and only overhead flights were detected. With the exception of airplanes, low frequency sound in the area is only due to natural sources.

Overall, NDSI did not perform as well as expected; it was not able to correctly discriminate the biophonic and anthropophonic components. Although we clearly identified airplane passages both visually, in the lowest part of packed spectrograms, and by listening, they do not seem to heavily influence the index's trend and there was no vehicle traffic at all nor other human-associated sounds (besides very occasional passages of motor vehicles of the forestry service in site A, but at several hundreds of metres from the recorder). As recommended also by Ferreira et al. (2018), NDSI seems to not be suitable for soundscape analyses of sites characterised by low technophony, as also low frequency biophony and geophony can be wrongly included in the anthropogenic component of the index.

In our sites, recurrent low frequency noise comes only from airplanes flying at high altitude and their noise at ground level largely exceeds the naturally quiet background below 500 Hz. Flights are clearly visible in the lowest part of the packed spectrograms, however in the present study this noise has not been taken into consideration, and a dedicated study is in progress.

The differences in ACI and ADI indices among the three sites, and especially during nocturnal hours, show a greater sensitivity to low frequencies in sites B and C, probably because it is more elevated and windier. An anemometer should be used to correlate low-frequency noise to wind speed, in particular, to reveal wind conditions that may determine louder low-frequency noise, but also increase the high-frequency noise generated by the rustling of leaves moved by the wind.

Ecoacoustic indices reveal themselves to be powerful tools for a rapid assessment (Sueur et al. 2008a) of the biodiversity and richness (Wimmer et al. 2013) of a given habitat, whilst also providing cues to recognise the presence of different sonotopes. However, it is difficult to interpret the indices and the cause of sonotope diversity without a complete knowledge about the local communities and the many environmental parameters that may drive animal activity and vocalisation (e.g. temperature, humidity, solar energy flux according to terrain slope, orientation and foliage coverage). Acoustic monitoring should be associated with a greater control of environmental conditions at different scales, possibly including remote sensing imagery to associate seasonal variations of the vegetation coverage with the acoustic expression of the animal communities.

Another positive result of ecoacoustic indices is the ability to provide a cue about the overall acoustic quality of a soundscape to be perceived by human visitors by providing an index of the ratio among biophony and technophony. Unfortunately, current indices, e.g. NDSI, consider the low frequency components as strictly related with technophony and can be fooled by low frequency components generated by some animals (e.g. ungulates in the reproductive period) or by geophony (variable noise from running water after rainy periods, breeze and wind).

After a rapid evaluation of the global acoustic characteristics, the complete understanding of the bioacoustic indices cannot disregard an analytical approach to identify and recognising all the components of the acoustic environment, whether they are natural or anthropogenic.

This still requires a 'human expert approach' to analyse recordings based on listening and contextual high resolution spectrographic visualisation. With the huge amount of recordings made available by autonomous recorders, this is not completely feasible without the support of smart automated sound analysis approaches that are still under development (Ulloa et al. 2016; Stowell and Plumbley 2014; Stowell et al. 2019). In some cases, specific algorithms can help in finding the occurrences of a given sound sample across thousands of recorded files; however an easy and reliable solution to this big data problem is still unavailable.

In light of this, systematic and synchronous recording collection in multiple sites of the Sasso Fratino INR and in adjacent areas can become a promising tool for the acoustic recognition of the current vocal species and provide new information on their ecology, as well as a tool for the monitoring of changes, seasonal shifts and the disappearance or arrival of species, including invasive ones. Extending the monitoring to other areas with different levels of protection will also provide clues about the gradients and effectiveness of the conservation efforts. The emerging use of automatic recognition algorithms will make acoustic monitoring easier, however it is important to consider that the 'human expert approach' to analyse recordings, with listening and contextual spectrographic visualisation, is still required in order to gain a complete understanding of the relationships among the recorded soundscape and the related ecosystem.

Conclusion

This is the very first assessment of the soundscape of an INR characterised by the absence of anthropogenic noise, with the exception of high-altitude overhead flights of airplanes. Both packed spectrogram visualisation and indices interpretation show quiet nights and very acoustically dense daylight hours, with a complex and composite biophony mostly occupying the range 1500–9000 Hertz, with few species vocalising in the range 400–1500 Hz.

This pilot study has paved the way for future insights on the Sasso Fratino INR's animal community, integrating the collection of acoustic data with other valuable auxiliary ecological information (wind, temperature, humidity, light) that can influence the activity and vocal expression of vocal species. The integration of remote sensing imagery can provide additional information to track seasonal variations in the vegetation coverage that may drive the activity of the animal communities.

A species recognition approach is also envisaged to better understand the AIs results and connect them to the acoustic community composition.

The dataset used in this study is part of the SABIOD project, started in 2014 with a two-year long exploratory phase based on random recordings in multiple sites. Data collected since then represent a reference collection for the study of the INR's biophony ecosystem and it is advised to continue with long term monitoring in order to promptly highlight variations in the soundscape composition, especially those related to climate change. As the reserve and the adjacent buffer areas will maintain their protected status, and thus will not be directly altered by human actions, we have to consider global changes as the possible main factors influencing this local ecosystem in the long term.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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