SCUOLA DI ALTA FORMAZIONE DOTTORALE

MACRO-AREA SCIENZE E TECNOLOGIE

Dottorato di Ricerca in Scienze della Terra e dell'ambiente

Roberta Righini

Development of an eco-acoustic research protocol and its application for monitoring the acoustic environment in the Integral Nature Reserve of Sasso Fratino (Italy)

Anno Accademico 2018-2019

Ciclo XXXII

Coordinatore
Prof. Roberto Sacchi

Tutor
Prof. Pavan Gianni

Co-tutor
Prof. Glotin Hervé

To my father

and his unconditional love

CONTENTS

ACKNOWLEDGEMENTS/ RINGRAZIAMENTI

The research is supported by CNRS (Project SABIOD in cooperation with University of Toulon, within the framework of the MASTODONS project on Big Data Processing), providing remote autonomous recorders (three SM3 and two SM4, one SM4bat).

The field data collections were performed with the permits to access to the Sasso Fratino Integral Nature Reserve; many thanks to Maggiore Paola Ciampelli, Brig. Capo Antonio Zoccola, Car. Sc. Barbara Rossi, Brig. Loris Gelli, App. sc. Silvia Bertinelli and the whole Reparto Carabinieri Biodiversità of Pratovecchio and National Park Service of Casentinesi Forests for technical and logistical support.

Furthermore, thanks to Favaretto Andrea, Pesente Marco and Cateni Perla for their support in identifying the songs. A due acknowledgment also to Spectra and PCB Piezotronics for the availability of measuring instruments.

A special thanks to my tutor Pavan Gianni for the wealth of advice and feedback he gave me during my research and support to overcome the various obstacles found, both for collecting data in the field and for their analysis.

Thanks also to the members of the Ph.D. commission Marchini Agnese, Martinoli Adriano, Favaro Livio who made themselves available to reviewee the progressing work for the all three years and, helped to improve project with constructive comments.

Finally, thanks also to Professor Farina Almo for his suggestions and encouragement to continue in the field of eco-acoustic research.

Un ringraziamento alla mia famiglia che mi ha sostenuto e incoraggiato durante tutto il percorso, prima di studi e poi di dottorato.

Un grazie a mio marito Samuele: sei presente fin dalle pagine della tesi triennale e con gli anni siamo passati dall'essere coppia a famiglia, e chissà ora cosa ci riserva il futuro!

Un grazie alla mamma Ambrogina e ai miei fratelli Luca e Valentina, e anche a chi si è aggiunto nel tempo, Marina, Gianfranco, Federica, Rossella e Achille, un grazie a tutti che, nonostante il sospetto che non vi sia ancora del tutto chiaro cos'è l'ecoacustica e il mio campo di ricerca, dimostrate sempre interesse ai miei eventi divulgativi, ai libri e agli articoli scritti.

Development of an eco-acoustic research protocol and its application for monitoring the acoustic environment in the Integral Nature Reserve of Sasso Fratino (Italy)

Abstract

The sound plays a fundamental role in many different aspects of animal species (mating, sociality, alarms, recognition of other individuals belonging to the same species, passive sensing of the environment, active sensing of the environment through echolocation).
The study of target species sounds (Bioacoustics) and, increasingly, of all sounds that constitute the whole acoustic environment of an ecosystem (Ecoacoustics) has proved to be a valid and powerful tool for the monitoring and conservation of biodiversity and the assessment of habitat quality, collecting long-term information on animal distribution and variations in community dynamics, including those driven by anthropogenic activities.
The main purpose of Ecoacoustics is the analysis of the Soundscape and of the acoustic environment (beyond human perception): it explores natural and anthropogenic sounds and their relationship with the environment, on a wide range of spatial and temporal scales and at different levels (individual, community and up to population ones).
Through Passive Acoustic Monitoring (PAM) of a habitat, it is possible to obtain a picture of the soundscape that consists of three different components: the sounds produced by animals (biophony, generally between 2,000-8,000 Hz), the sounds of atmospheric and physical events (geophony: wind, rain, running waters, etc.) and the noises linked to the presence of man (anthropophony: cars, airplanes and other human activities, generally occupying the low frequencies: 20 - 2,000 Hz; the term technophony is used in situations in which electromechanical noise is dominant).
But if on the one hand, the PAM allows new research perspectives for the biodiversity monitoring, since it is possible to record continuously and simultaneously different locations, on the other one, it generates a huge quantity of data that needs to be analyzed and interpreted, implying great time and knowledge efforts to get useful information.
The new challenge is to draw up an analysis methodology to optimize resources both in the field (saving memory cards and batteries) both in the lab, reducing time and effort of analyses, while maintaining high the accuracy of the information.

The aim of this Ph.D. project is to define the methodological and analytical Research Protocol to investigate the Soundscape at multi time and space scales with ecoacoustic analysis procedures.
This elaborated protocol is composed of four main sections:

1. selection of surveys sites;
2. data collection (devices programming and sampling methodology);

3. qualitative analysis of acoustic data (generation of compact daily spectrograms);
4. quantitative analysis of acoustics data (bioacoustic analysis and sound identification; ecoacoustic indices and statistical analysis).

By the application of this protocol, it is possible to describe the soundscape of a well-protected integral nature reserve internationally known for its conservation and biodiversity.
From a five-year SABIOD's archive of sound recordings, collected in the Integral Natural Reserve of Sasso Fratino and surrounding areas of Casentinesi Forests National Park (Italy), acoustic data are compared with cross-sections (horizontal) and time series (vertical) analyses in order to explore the soundscape's spatial-temporal dynamics across different scales. All sites are characterized by quiet nights and very acoustically dense daylight hours, with a composite biophony occupying the range 1500 to 9000 Hz. But, although the acoustics indices trends are similar, the statistical Principal Component Analysis shows that the sites inside and outside the reserve are well differentiated and distinctly clustered in distinct sonotopes, and this could be due to biophony's different components and to their ecological and spatial heterogeneity.
The building of acoustic data repository will contribute to monitoring natural areas' biophony: especially for integral nature reserve sites, where the human presence is prohibited, any shift in species' presence and distribution could be driven by external global changes.
Moreover, the enrichment of biodiversity monitoring with the ecoacoustic approach allows to obtain information not only about the diversity of species but also on the density of the biophonic component, which, in the study case of Sasso Fratino Integral Nature Reserve, results to be predominant and continuous for all daylight hours

Besides to be a tool for research and conservation, the soundscape can also be considered as an object of study.
Hence, the analysis of the single components of the Soundscape (geophony, biophony and anthropophony) is performed separately. Each of them represents an important and rich source of information in the environmental acoustic recording.
For example, improving the knowledge on the natural sounds of an environment becomes important to understand the background environment that contributed to the evolution of specific acoustic signals in the various species, which have had to adapt to a specific environment to communicate efficiently. Moreover, the knowledge of geophony allows to better discrimination of recordings according to different weather conditions and this can contribute to reducing analyses time for large size of data (e.g. by discarding rainy days).

Studying and monitoring of biophony increases the information concerning the biodiversity of an environment, the presence of vocalizing target species, but also, the abundance and distribution of individuals and the way in which species interact with each other and with their environment.
Finally, the analysis of anthropophony aims to estimate the level of disturbance, or more specifically for the project dataset (since the sampling sites are within an integral reserve) the level of silence that has been recorded. This also allows to get a model of the pristine acoustic environment in which species have developed their communication skills and features.

In conclusion, Ecoacoustics turns out to be a powerful instrument for several kinds of environmental investigations and analyses at multiple time and spatial scales. For its great potential is urgent that eco-acoustic monitoring is considered and included in the management plans of the protected natural areas network.

CHAPTER 01

INTRODUCTION

This chapter provides a
general overview of Ecoacoustics
as a new science and the
SABIOD project is introduced.

Ecological and conservation framework

Nowadays, one of the most important biodiversity conservation challenges is to manage and mitigate the threats of climate change and the high rates of biodiversity loss caused by it and by direct habitat destruction. Notwithstanding this, a common limit is that, it is rarely possible to have the information needed to make informed decisions because the understanding of most biological systems is based on very limited spatial and temporal coverage (Aide et al., 2013).

In this context, Ecoacoustics is an increasingly emerging interdisciplinary science that investigates natural and anthropogenic sounds and their relationship with the environment. By the use of Passive Acoustic Monitoring (PAM), data over large spatial and temporal scales can be recorded and long-term information on animal distribution and variations in community dynamics for anthropogenic activities can be collected (Sueur et al., 2008).

Human populations are increasing, and so is their impact on wildlife. For this, another emerging aspect in applied ecology and conservation biology is to identify and to quantify the human-generated noise. Noise is a spatially extensive pollution with consequences on organisms and communities in both terrestrial and marine environment (Goines and Hagler, 2007). It is also an evolutionarily novel source of acoustic interference for many species and a potentially significant force that influences the ecology and evolution of many animals (Francis & Barber, 2013). Several studies have shown how anthropogenic noise may affect mating, communication and antipredator behaviour (Lengagne, 2008; Mockford and Marshall, 2009; Halfwerk and Slabbekoorn, 2013; Kunc at al., 2013; Simpson et al., 2015).

ECOACOUSTICS AS A NEW SCIENCE

Ecoacoustics is the ecological investigation and interpretation of environmental sound, identified as ‘soundscape’. It is defined as soundscape ecology, since it merges bioacoustics and ecology (Pijanowski et al. 2011).

Ecoacoustics can be also described as an emerging interdisciplinary science that investigates natural and anthropogenic sounds and their relationship with the environment on a wide range of scales of study, both spatial and temporal, at the individual level, community level and population (Farina and Gage, 2017).

The soundscape (what perceived by human beings) and the acoustic environment (including frequencies beyond human hearing limits, e.g. infrasounds and ultrasounds), consists of three main components: sounds produced by the animals (biophony), sounds produced by natural elements (rain, wind, thunder, etc., which describes the geophony) and, finally, sounds and noises linked to human presence (anthropophony), and these can become source of disturbance and pollution, dangerous to the ecosystem and to humans (Krause, 1987; Pavan, 2015; see the Chapter 2 for more details about soundscape). Often the soundscape is considered as including all the frequencies, including infrasounds and ultrasounds transmitted by the air or by the water, but not including the vibrations transmitted through the substrate (soil, leaves, trees, etc.) that are the topic of another new discipline called Biotremology (Cocroft et al., 2014.; Hill and Wessel, 2016).

By the analysis of field-recorded data, it is possible to obtain the description of the soundscape (at different levels) and this approach can uncover both broad and fine-scale ecological details (Sugai et al., 2019).

But to get data and useful results in management and conservation projects, it is needed an analytic approach to process huge amounts of acoustic data and it is fundamental to define a standard protocol that optimizes the effectiveness of the samples and avoids time- and resource-consuming analyses (Marques et al., 2013).

Advantages of Ecoacoustics Approach

The study of the whole acoustic environment becomes 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, and education (Farina and Gage, 2017, Gibb et al., 2019).

In particular, the Passive Acoustic Monitoring allows the collection of data over large spatial and temporal scales and long-term information on animal distribution and variations in community dynamics, including those driven by anthropogenic activities (Sueur and Farina, 2015; Deichmann et al., 2018).

Ecoacoustics studies widely range from the biodiversity assessments with the detection of the occurrence of species of interest (Bardeli et al, 2010) and the estimation of temporal and spatial variability of animal acoustic diversity (Rodriguez et al, 2014) to habitat assessments with the monitoring of how quality habitat affects sound production in animal species (Piercy et al., 2014); other kinds of studies focus on community ecology, estimating the species density and variability (Laiolo et al., 2008; Lucas et al., 2015) and on landscape ecology with an analysis the variability in soundscapes along an urban–rural gradient (Joo et al., 2011), to conservation biology by the estimation of the effects of noise on acoustic communities (Pieretti and Farina, 2013).

Moreover, this method is independent of the observer’s presence (increasing the likelihood of detecting more cryptic species) and it eases to monitor places that are difficult to access. moreover,

ecoacoustic researches can be carried out in all kinds of ecosystem, from aquatics (both freshwater and marine) to terrestrial ones (Farina and Gage, 2017).
Lastly, a long-term data collection and the building of acoustic data repository provides collecting quantitative data for the comparison of acoustic variance both intra-site (for monthly or yearly sampling) and inter sites (for multiple simultaneous locations) (Kasten et al, 2012).

Bioacoustics vs Ecoacoustics

The Sound is studied by both Bioacoustics and Ecoacoustics.
Bioacoustics derived from biological and acoustics science. It is characterized by a species analytic approach and aims at investigating sound production, dispersion and reception in animals.
Bioacoustics studies focus on a target species and develope the analyse of large datasets in order to explore animals intra- and inter- species communication, to identify the presence of target species in the environments and also the identification of invasive species (Laiolo, 2010).
Ecoacoustics derived from bioacoustics and ecology sciences. It is characterized by a global descriptive approach and aims at investigating natural and anthropogenic sounds and their relationship with the environment (Pijanowski et al., 2011; Farina, 2014).
Ecoacoustics studies can be performed in different ecosystems (terrestrial and aquatic) and allow monitoring of habitat quality and biodiversity assessment at different time and space scales. And this brings an additional advantage: starting from the recordings of a wider frequencies range (the soundscape as a whole), it is also possible to concentrate the study only on a part of frequencies, specific of the target singing species (Pavan, 2017).

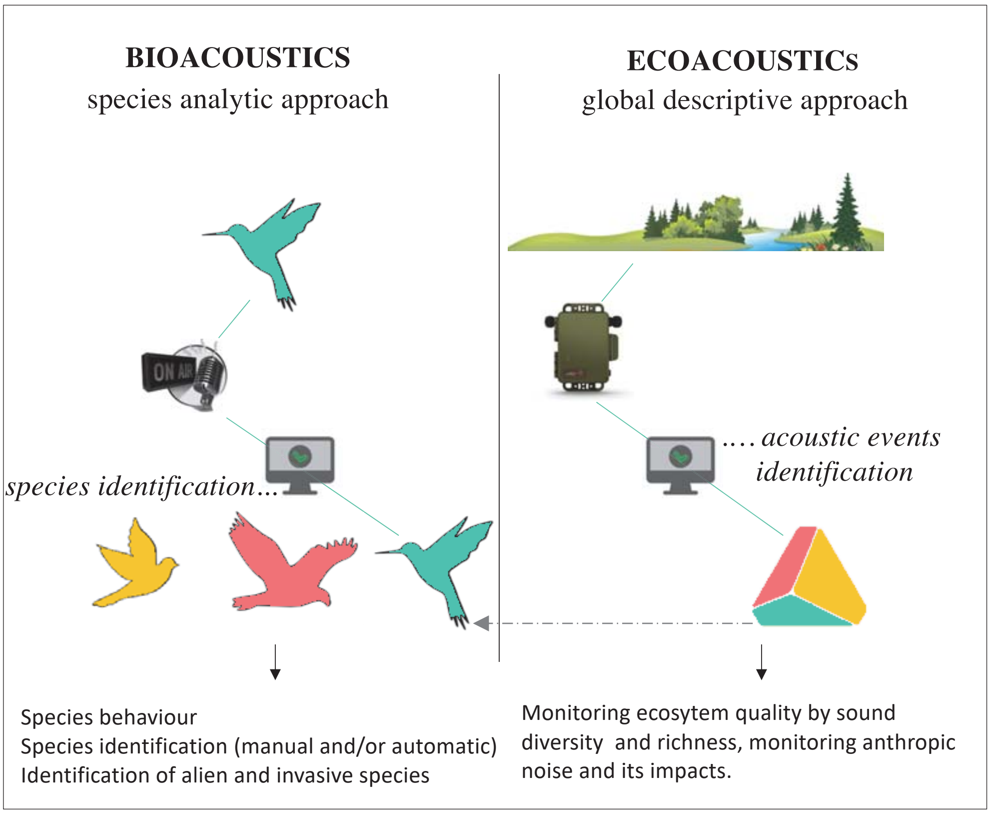


Figure 1.1 Schematic description and difference between Bioacoustics and Ecoacoustics.

The Sounds as a research target

Sounds play a crucial role in many organisms, promoting exchanges of information among individuals intra- and inter-specifically. With acoustic data, it is also possible to implement the knowledge on the behaviour and biological dynamics related to oral communication, as well as the way in which individuals interact with each other and with the environment in which they live. For this, species-specifics sounds can be recorded and investigated in order to detect, on the one hand, their properties and functions in different sympatric species and, on the other, how different environmental pressures affect the vocalization of animal communities (Pavan, 2015; Farina and Gage, 2017).

The Sounds as a research tool

Sounds results to be useful tools for studying and monitoring the biodiversity of an environment. The vocalization analysis allows gathering information on the target species' presence, distribution and abundance. (Frommolt, 2008; Farina and Gage, 2017).

In this way, Ecoacoustic approach could become a valuable tool for both research and management, particularly in extended and remote habitats, and could increase the detection of rare and elusive species, and also for the early detection of alien species potentially invasive.

The use of passive acoustic monitoring could prove to be a powerful tool for scoring the acoustic quality of habitats affected by anthropogenic noise, analysing the level and structure of the noise, assessing the impact on animal communities, and possibly design and implement mitigation actions. Anthropogenic noise has an increasing role in disrupting the natural acoustic habitats, either terrestrial or marine. Noise generated by road traffic, rail or air transport, industrial activity, ship traffic, offshore construction, oil and gas exploration, and sonar operations can mask crucial acoustic cues and elicit behavioural responses with the potential to cause chronic physiological stress on the individuals and devastating effects on a population (Shannon et al., 2016).

2020 will be the International Year of Sound (sound2020.org), an innovative global initiative aimed at highlighting the importance of sound (at all levels of the community) and promoting the development of sciences and technologies related to its study.

Ecoacoustics Indices

An index is a mathematical function designed to describe the distribution of a given character within the sample of analysed data.

Passive acoustic monitoring generates massive long-term recordings databases that have to be managed and analysed. To support the interpretation of this large amount of information and to reduce the analysis effort, researchers are being developing different acoustic indices that summarize and score the structure and the distribution of the acoustic energy, reflecting a correlation with species' presence and distribution (Towsey et al., 2014).

In general, the ecological indices can be divided into two large groups: α indices, which estimate the differences within groups, and β indexes, which compare the differences between different groups.

The acoustic metrics developed respond to different needs, from the general estimates of biodiversity in certain environments compared (H, index for acoustic entropy and D, index of acoustic similarity (Sueur et al., 2008); AR, index for acoustic richness (Depraetere et al., 2012); ACI, an index of complexity (Pieretti et al., 2011) to determine the level of anthropic disturbance by comparing the relationship between biophony and anthropo- phony in a given environment, called the NDSI index (Kasten et al., 2012).

Recently, the indexes proposed in the literature have been varied and different, aiming to describe the variability of the acoustic structures produced by both biotic and abiotic sounds (Sueur et al., 2014). However, the indices present the weakness of attempting to reduce a very complex phenomenon, consisting of several variables that interact with each other, to a single numerical indicator. Efforts in the bioacoustic and eco-acoustic fields are more and more aimed at developing an analytical process

that completely summarizes all the acoustic components of the sound environment and allows them to be compared quickly and easily (Towsey et al., 2014; Bradfer-Lawrence et al., 2019).
This belongs to new disciplines called computational bioacoustics and computational ecoacoustics aimed at developing new instruments and new algorithms to process acoustic data at different levels within the framework of Big Data Science themes.

*

In conclusion, for all above mentioned reasons and its wide applications, the use of Passive Acoustic Monitoring (PAM) could become a valuable tool for both research and management, especially in wide and remote habitats, and could increase the detectability of rare and elusive species, and even of the presence of alien species. In fact, besides to being studied as an object of ecological research, sounds can also be considered as useful tools for studying and monitoring the biodiversity of an environment, the presence of a particular (vocalizing) species and, sometimes, the abundance and distribution of individuals who vocalize, behaviour, biological dynamics and the way in which species interact with each other and with the environment in which they are found.
By the acoustic monitoring of habitats, it is possible collecting information about the presence of vocalizing animals and, on the other hand, about the level of noise related to human activities.
In other words, we can have a continuum among bioacoustics monitoring, mainly addressed at individual species in given periods of their life cycle, and ecoacoustic monitoring addressed at the whole acoustic habitat with the aim of getting “indices” or “scores” about its richness, diversity, and quality intended as low contamination by anthropogenic noise.

THESIS OUTLINE

The aim of this Ph.D. project is to define the methodological and analytical Research Protocol to investigate the Soundscape at multi time and space scales with ecoacoustic analysis procedures.

In Chapter 2, Soundscape concept is introduced and the three main components (geophony, biophony and anthropophony) of Sasso Fratino's soundscape are described and analyzed in detail.
In Chapter 3, the Research Protocol developed is described and presented in its theoretical and methodological parts. The Research Protocol is organized in four main sections (selection of surveys sites; data collection; qualitative and quantitative analyses of acoustic of acoustics data) and each of them is introduced and exanimated in detail.
Finally, in Chapter 4 the protocol is tested and applied to the study of the Sasso Fratino Integral Nature Reserve. The analysis is performed at multi -time and -space scales and the Acoustic Indices' *intra-site* and *inter-sites* variability is explored.
The manuscript concludes with a summary of main findings of the project and offers an overview of the current possibilities that acoustic monitoring represents for biodiversity assessment and environmental monitoring as well as a valid tool for conservation and management projects, especially in natural areas.

- Righini R., Pavan G. (2019). A soundscape assessment of the Sasso Fratino Integral Nature Reserve in the Central Apennines. Biodiversity Journal. (**published**)

- Pavan G., Righini R., Priori P, Scaravelli D. (2018). Il Paesaggio Sonoro. **Chapter** of the book "The Nature Integral Reserve of Sasso Fratino in National Park Forests", published by Rep Biodiversity of Carabinieri (Pratovecchio Office, 2018).

- the section *Focus on the anthropophony (or low frequency band sounds)* in Chapter 2 is part of a paper in preparation.

References

Aide T. M., Corrada-Bravo C., Campos-Cerqueira M., Milan C., Vega G., Alvarez R. (2013). *Real-time bioacoustics monitoring and automated species identification*. PeerJ, 1 e103. http://doi.org/10.7717/peerj.103.

Bardeli, R., Wolff, D., Kurth, F., Koch, M., Tauchert, K. H., & Frommolt, K. H. (2010). *Detecting bird sounds in a complex acoustic environment and application to bioacoustic monitoring*. Pattern Recognition Letters, 31(12), 1524-1534.

Bradfer-Lawrence T., Gardner N., Bunnefeld L., Bunnefeld N., Willis S. G., & Dent, D. H. (2019). *Guidelines for the use of acoustic indices in environmental research*. Methods in Ecology and Evolution.

Cocroft R.B., Gogala M., Hill P.S.M. and Wessel A., (2014). Studying Vibrational Communication ed Springer;

Deichmann J. L., Acevedo-Charry O., Barclay L., Burivalova Z., Campos-Cerqueira M., d'Horta F., ... & Linke, S. (2018). *It's time to listen: there is much to be learned from the sounds of tropical ecosystems.* Biotropica, 50(5), 713-718.

Depraetere M., Pavoine S., Jiguet F., Gasc A., Duvail S., Sueur J., (2012). *Monitoring animal diversity using acoustic indices: Implementation in a temperatewoodland*. Ecol Indic, 13: 46–54.

Farina A. (2014). Soundscape Ecology. Springer Netherlands

Farina, A., and Gage S.H. (2017). *Ecoacoustics A new science.* In Ecoacoustics: The Ecological Role of Sounds, edited by A. Farina and S. H. Gage, 1-11. Oxford, UK: Wiley-Blackwell.

Francis C.D., and Barber J.R. (2013). *A framework for understanding noise impacts on wildlife: an urgent conservation priority*. Frontiers in Ecology and the Environment, 11:6, 305-313.

Frommolt K.H., Bardeli R., Clausen M., (2008). *Computational bioacoustics for assessing biodiversity*, in Proceedings of the International Expert meeting on IT-based detection of bioacoustical patterns, BfN-Skripten., 234.

Gibb R., Browning E., Glover-Kapfer P., & Jones K. E. (2019*). Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. Methods in Ecology and Evolution*, *10*(2), 169-185.

Goines L., and Hagler L. (2007). *Noise pollution: a modern plague*. Southern Medical Journal-Birmingham Alabama, 100(3), 287.

Halfwerk, W., and Slabbekoorn, H., (2013). *The impact of anthropogenic noise on avian communication and fitness.* Avian urban ecology: 13nalyse1313131 and physiological adaptations, 84-97.

Hill P.S.M., and Wessel A., (2016). *Biotremolgy.* Current Biology 26, R181–R191.

Joo, W., Gage, S. H., & Kasten, E. P. (2011). *Analysis and interpretation of variability in soundscapes along an urban–rural gradient*. Landscape and Urban Planning, 103, 259–276.

Kasten, E. P., Gage, S. H., Fox, J., & Joo, W. (2012). *The remote environmental assessment laboratory's acoustic library: An archive for studying soundscape ecology*. Ecological Informatics, 12, 50-67.

Krause B., (1987) *Bioacoustics, habitat ambience in ecological balance*. Whole Earth Review, 57: 14–18.

Kunc, H. P., McLaughlin, K. E., and Schmidt, R. (2016). *Aquatic noise pollution: implications for individuals, populations, and ecosystems*. Proceedings of the Royal Society B: Biological Sciences, 283(1836), 20160839.

Laiolo P., Vögeli M., Serrano D., and Tella J. L. (2008). *Song diversity predicts the viability of fragmented bird populations.* PloS One, 3, e1822.

Laiolo, P. (2010). *The emerging significance of bioacoustics in animal species conservation*. Biological conservation, 143(7), 1635-1645.

Lengagne, T. (2008). *Traffic noise affects communication behaviour in a breeding anuran*, Hyla arborea. Biological conservation, 141(8), 2023-2031.

Lucas T. C. D., Moorcroft E. A., Freeman R., Rowcliffe J. M., and Jones K. E. (2015). *A generalised random encounter model for estimating animal density with remote sensor data*. Methods in Ecology and Evolution, 6, 500–509.

Marques T.A., Thomas L., Martin S. W., Mellinger D. K., Ward J. A., Moretti D.J., Tyack P. L. (2013). *Estimating animal population density using passive acoustics*. Biological Reviews, 88: 287–309.

MockfordE. J., Marshall R. C. (2009). *Effects of urban noise on song and response behaviour in great tits.* Proceedings of the Royal Society B: Biological Sciences, 276(1669), 2979-2985.

Pavan G., (2015) *Bioacustica e Ecologia 13nalyse13*. In "ACUSTICA. Fondamenti e applicazioni", Renato Spagnolo (a cura di), UTET Università, Torino, pp. 803-828.

Pavan G., (2017). *Fundamentals of Soundscape Conservation*. In book: Fundamentals of Soundscape Conservation, Editors: Farina A., Gage S.H.

Piercy, J. J. B., Codling, E. A., Hill, A. J., Smith, D. J., & Simpson, S. D. (2014). *Habitat quality affects sound production and likely distance of detection on coral reefs.* Marine Ecology Progress Series, 516, 35–47.

Pieretti N., Farina A., Morri D. (2011). *A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI).* Ecol Indic, 11: 868–223.

Pieretti, N., & Farina, A. (2013) *Application of a recently introduced index for acoustic complexity to an avian soundscape with traffic noise*. Journal of the Acoustical Society of America, 134, 891–900.

Pijanowski B.C., Farina A., Gage S.H., Dumyahn, S.L., Krause, B.L. (2011). *What is soundscape ecology? An introduction and overview of an emerging new science*. Landscape Ecology, 26, pp. 1213-1232.

Rodriguez, A., Gasc, A., Pavoine, S., Grandcolas, P., Gaucher, P., & Sueur, J. (2014). *Temporal and spatial variability of animal sound within a neotropical forest.* Ecological Informatics, 21, 133-143.

Simpson, S. D., Purser, J., & Radford, A. N. (2015). *Anthropogenic noise compromises antipredator behaviour in European eels*. Global change biology, 21(2), 586-593.

Shannon, G., McKenna, M. F., Angeloni, L. M., Crooks, K. R., Fristrup, K. M., Brown, E., ... & McFarland, S. (2016). *A synthesis of two decades of research documenting the effects of noise on wildlife*. Biological Reviews, 91(4), 982-1005.

Sueur J., Pavoine S., Hamerlynck O., Duvail S., *Rapid Acoustic Survey for Biodiversity Appraisal*. PloS ONE, 3, 12 (2008) e4065.

Sueur, J., Farina, A., Gasc, A., Pieretti, N., and Pavoine, S. (2014*). Acoustic indices for biodiversity assessment and landscape investigation*. Acta Acustica united with Acustica, 100(4), 772-781.

Sueur J., and Farina A. (2015). *Ecoacoustics: the ecological investigation and interpretation of environmental sound*. Biosemiotics, 8(3), 493-502.

Sugai L. S. M., Desjonquères C., Silva T. S. F., & Llusia D. (2019). *A roadmap for survey designs in terrestrial acoustic monitoring*. Remote Sensing in Ecology and Conservation.

Towsey M., Parsons S., Sueur J. (2014). *Ecology and acoustics at a large scale*. Ecological Informatics, 21:1–3.

Associazione Italiana di Acustica
44° Convegno Nazionale
Pavia, 7-9 giugno 2017

BIOACUSTICA E ECOACUSTICA PER LO STUDIO E LA CONSERVAZIONE DELLA BIODIVERSITÀ

Gianni Pavan (1), Roberta Righini (2)

1) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
Email gianni.pavan@unipv.it
2) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
Email roberta.righini@gmail.com

SOMMARIO

La bioacustica e l'ecoacoustica sono discipline emergenti e innovativi strumenti per la scienza, la conservazione e l'educazione. Il paesaggio sonoro rappresenta una componente essenziale degli ecosistemi, sia naturali che antropizzati, e deve essere monitorato, conservato e ripristinato qualora alterato dalle attività umane. La relazione presenta le linee di sviluppo dell'analisi acustica orientata allo studio e alla tutela della biodiversità e della qualità acustica degli ambienti naturali.

1. Introduzione

Al giorno d'oggi, una delle più grandi sfide per la conservazione della biodiversità è gestire e mitigare le minacce determinate dal cambiamento climatico e ridurre l'alto tasso di perdita di specie da esso causato.

Nonostante ciò, molto spesso è difficile avere un quadro generale completo che permetta di prendere decisioni efficaci, in quanto la comprensione della maggior parte dei sistemi biologici è basata su una copertura di dati limitata sia spazialmente che temporalmente [1].

In questo contesto si inserisce l'Ecoacustica, una scienza interdisciplinare sempre più emergente che indaga i suoni naturali e antropici e il loro rapporto con l'ambiente [2]. Grazie all'utilizzo del monitoraggio acustico passivo (PAM), è possibile registrare dati su grande scala spaziale e temporale e si possono raccogliere informazioni a lungo termine sulla distribuzione delle specie animali e sulle variazioni nelle dinamiche delle comunità biologiche a causa delle attività antropiche [3].

1.1 Il paesaggio sonoro

Il paesaggio sonoro, o ambiente acustico, si definisce costituito da tre componenti principali: suoni di natura biologica (biofonia), rumori prodotti da elementi naturali (pioggia, vento, tuoni, ecc., che formano la geofonia) e, infine, suoni e rumori legati alla presenza umana (antropofonia), che possono diventare fonte di disturbo e di inquinamento, per cui dannosi per l'ecosistema e per l'uomo [2,4]. Tramite l'analisi dei dati registrati, è possibile ottenere la descrizione del paesaggio sonoro, sia nel suo complesso che nel dettaglio delle singole componenti.

Ma affinché ciò accada, è necessario un approccio analitico per elaborare le enormi quantità di dati acustici ed è fondamentale definire un protocollo standard che ottimizzi l'efficacia dello sforzo di campionamento e riduca i costi, in termini di tempo e di risorse, per l'analisi dei dati e l'elaborazione di risultati utilizzabili in progetti di conservazione [5].

1.2 I suoni come *oggetti* di ricerca

Attraverso il monitoraggio acustico degli habitat, è possibile raccogliere informazioni sulla qualità biologica di un ambiente e, al tempo stesso, sul livello di rumore generato dalle attività umane.

I suoni svolgono un ruolo cruciale in molti organismi, consentendo scambi di informazioni, intra- e inter- specifici, tra gli individui. In questa prospettiva, è importante tenere in considerazione l'ambiente acustico, in quanto può condizionare in modo considerevole i sistemi di comunicazione. L'evoluzione di un segnale acustico è legata ad un determinato ambiente con degli specifici suoni di fondo naturali (ad esempio, vento o pioggia, acqua corrente, ecc.) a cui gli organismi adattano il loro comportamento acustico (*Acoustic Adaptation Hypothesis*) [6,7].

Il rumore antropogenico ha un ruolo crescente nel disturbare gli habitat acustici naturali, sia in acqua che in aria. Il rumore generato dal traffico stradale, il trasporto ferroviario e aereo, le attività industriali, le piattaforme offshore per l'esplorazione del petrolio e del gas e le operazioni di sonar, sono elementi sonori definibili come tecnofonia in quanto propriamente prodotti da macchine, che possono avere grande diffusione, soprattutto in ambiente acquatico. Si tratta di rumori che, in ambito aereo, sono riconosciuti per l'impatto che hanno sull'uomo [8]. In aria e in acqua possono mascherare segnali acustici cruciali per la riproduzione e la sopravvivenza delle specie, provocare risposte comportamentali particolari, causare uno stress psicofisico cronico sugli individui e conseguentemente anche determinare effetti dannosi a livello di popolazione [9].

1.3 I suoni come *strumenti* di ricerca

L'impiego del PAM potrebbe diventare uno strumento prezioso sia per la ricerca che per la gestione, in particolare negli habitat estesi e lontani, e potrebbe aumentare la rintracciabilità di specie rare ed elusive, e anche rilevare precocemente la presenza di specie aliene e potenzialmente invasive. Infatti, oltre ad essere studiato come oggetto della ricerca ecologica, i suoni possono essere considerati anche come strumenti utili per studiare e monitorare la biodiversità di un ambiente, la presenza di una determinata specie (vocalizzante) e, talvolta, l'abbondanza e la distribuzione degli individui che vocalizzano, il comportamento, le dinamiche biologiche e il modo in cui le specie interagiscono tra di loro e con l'ambiente in cui si trovano [10].

2. Lo sviluppo di indici di stima

Un indice è una funzione matematica progettata per descrivere la distribuzione di un determinato carattere all'interno del campione di dati analizzati. In generale, gli indici ecologici si possono dividere in due grandi gruppi: indici α, che stimano le differenze all'interno di gruppi, e indici β, che confrontano le differenze tra gruppi diversi.

Associazione Italiana di Acustica, 2017
ISBN: 978-88-88942-54-4

Recentemente, sono stati vari e diversi gli indici proposti nella letteratura che mirano a descrivere la variabilità delle strutture acustiche prodotte sia da suoni biotici che abiotici [11]. Le metriche acustiche sviluppate rispondono ad esigenze diverse, dalle generali stime di biodiversità di determinati ambienti a confronto (H, indice per l'entropia acustica e D, indice di similarità acustica [12]; AR, indice per la ricchezza acustica [13]; ACI, indice di complessità [14]) al determinare il livello di disturbo antropico confrontando il rapporto tra biofonia e antropofonia in un determinato ambiente, definito indice NDSI [15].

Tuttavia, gli indici, finora proposti, presentano la debolezza di tentare di ridurre ad un unico indicatore numerico un fenomeno assai complesso e costituito da più variabili che interagiscono tra di loro. Gli sforzi in campo bioacustico ed ecoacustico sono, quindi, ora volti a sviluppare un processo analitico che sommarizzi in modo completo tutte le componenti acustiche dell'ambiente sonoro e che permetta di confrontarle in modo veloce e facile [16].

3. Il progetto SABIOD-Italy

Il progetto SABIOD (Scaled Acoustic Biodiversity) è parte di un più ampio programma sulle tematiche della Big Data Science denominato MASTODONS, finanziato dal CNRS francese. SABIOD-Italy è svolto in collaborazione con il laboratorio DYNI-LSIS dell'Università di Tolone, con l'obiettivo di raccogliere dati e sviluppare metodi di analisi per descrivere l'ambiente acustico, o paesaggio sonoro, di ambienti naturali sottoposti a diversi livelli di impatto antropico, dalle aree protette [17], lontane da ogni disturbo antropico, alle aree più antropizzate e agli agroecosistemi. In questo ambito riveste un ruolo particolare lo studio di aree con un livello di rumore antropico molto basso [18, 19] al fine di definire un modello di riferimento di ambiente acustico assimilabile all'era pre-industriale.

4. Prospettive future

L'impiego dell'analisi bioacustica ed ecoacustica per il monitoraggio della biodiversità e della qualità ambientale sia per fini gestionali che conservazionistici, si è rivelato e continua ad essere un potente strumento ma ancora con dei limiti sia per quanto riguarda la rapida analisi dell'enorme quantità di dati che si registra, sia per l'efficacia dell'uso di indici che tengano in considerazioni le numerose variabili e le diverse condizioni ambientali in cui i dati vengono raccolti.

Si prospetta quindi la realizzazione di un frame work che possa permettere sia l'analisi completa e generale delle caratteristiche acustiche di un ambiente che quelle più specifiche di ciascuna delle tre componenti, geofonia, biofonia e antropofonia.

5. Bibliografia

[1] Aide T. M., Corrada-Bravo C., Campos-Cerqueira M., Milan C., Vega G., Alvarez R., *Real-time bioacoustics monitoring and automated species identification*. PeerJ, **1** (2013) e103. http://doi.org/10.7717/peerj.103

[2] Pavan G., *Bioacustica e Ecologia acustica*. In "ACUSTICA. Fondamenti e applicazioni", Renato Spagnolo (a cura di), UTET Università, Torino (2015), pp. 803-828

[3] Sueur J., Pavoine S., Hamerlynck O., Duvail S., *Rapid Acoustic Survey for Biodiversity Appraisal*. PLoS ONE, **3**, 12 (2008) e4065

[4] Krause B., *Bioacoustics, habitat ambience in ecological balance*. Whole Earth Review, **57** (1987), pp. 14–18

[5] Marques T.A., Thomas L., Martin S. W., Mellinger D. K., Ward J. A., Moretti D.J., ..., Tyack P. L., *Estimating animal population density using passive acoustics*. Biological Reviews, **88** (2013), pp. 287–309

[6] Hansen, P., *Vocal learning: its role in adapting sound structures to long-distance propagation and a hypothesis on its evolution*. Animal Behaviour **27** (1979), pp. 1270–1271

[7] Morton, E.S., *Ecological sources of selection on avian sounds*. American naturalist, **109** (1975), pp. 17-34

[8] EEA, *Noise in Europe*, Report No 10/2014, European Environment Agency, Copenhagen, (2014)

[9] Barber J.R., Burdett C.L., Reed S.E., Warner K.A., Formichella C., Crooks K.R., ..., Fristrup K.M., *Anthropogenic noise exposure in protected natural areas: estimating the scale of ecological consequences*. Landscape ecology, **26** (2011), pp. 1281–1295

[10] Frommolt K.H., Bardeli R., Clausen M., *Computational bioacoustics for assessing biodiversity*, in Proceedings of the International Expert meeting on IT-based detection of bioacoustical patterns, BfN-Skripten., **234** (2008)

[11] Sueur J., Farina A., Gasc A., Pieretti N., Pavoine S., *Acoustic indices for biodiversity assessment and landscape investigation*. Acta Acustica united with Acustica, **100** (2014), pp. 772–781

[12] Sueur J., Pavoine S., Hamerlynck O., Duvail S., *Rapid acoustic survey for biodiversity* appraisal. PloS One, **3** (2008) e4065.

[13] Depraetere M., Pavoine S., Jiguet F., Gasc A., Duvail S., Sueur J., *Monitoring animal diversity using acoustic indices: Implementation in a temperate woodland*. Ecol Indic, **13** (2012), pp. 46–54

[14] Pieretti N., Farina A., Morri D., *A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI)* Ecol Indic, **11** (2011), pp. 868–223

[15] Kasten E.P., Gage S.H., Fox J., Joo W., *The remote environmental assessment laboratory's acoustic library: An archive for studying soundscape ecology*. Ecological Informatics, **12** (2012), pp. 50–67

[16] Towsey M., Parsons S., Sueur J., *Ecology and acoustics at a large scale*. Ecological Informatics, **21** (2014), pp. 1–3

[17] Pavan G., Favaretto A., Bovelacci B., Scaravelli D., Macchio S., Glotin H., *Bioacoustics And Ecoacoustics Applied To Environmental Monitoring And Management*. Rivista Italiana di Acustica, **39-2** (2015), pp. 68-74

[18] Pavan G., *Il rumore negli ambienti naturali. Misura e interpretazione*. Atti 43° Convegno AIA (2016)

[19] EEA, *Quiet areas in Europe. The environment unaffected by noise pollution*. EEA Report No 14/2016, European Environment Agency, Copenhagen (2016)

Associazione Italiana di Acustica
44° Convegno Nazionale
Pavia, 7-9 giugno 2017

COMPUTATIONAL BIOACOUSTICS, UN APPROCCIO INFORMATICO A BIOACUSTICA ED ECOACUSTICA

Simone Clemente (1), Roberta Righini (1), Virginia Sciacca (2), Gianni Pavan (1)

1) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali
Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
& CONISMA, Italia. clementesimone71@gmail.com, roberta.righini01@universitadipavia.it, gianni.pavan@unipv.it
2) INFN-LNS di Catania, Italia & CONISMA, Italia, vsciacca@unime.it

SOMMARIO

Con questa presentazione si vuole fornire un panorama dettagliato delle metodologie analitiche e le linee di ricerca più promettenti per l'analisi bio/ecoacustica su Python, MATLAB ed R. Partendo dalle tecnologie ad oggi disponibili per la raccolta di dati sul campo, si cercherà di far luce su potenzialità e limiti dei diversi strumenti, proponendo un framework che possa essere implementato in futuro per creare applicazioni di facile utilizzo nell'analisi del paesaggio sonoro.

1. Introduzione

La ricerca nel campo dei sistemi automatici di registrazione ha permesso di arrivare, ad oggi, a disporre di strumenti in grado di effettuare campionamenti acustici di lunga durata e per un'ampia gamma di frequenze [1], permettendo di esplorare gli ambienti, sia terrestri che marini, secondo nuovi modelli di ricerca e raccolta dati [2], consentendo il monitoraggio anche in luoghi un tempo difficilmente raggiungibili a causa dei limiti dell'operatore [1] e aprendo nuove interessanti sinergie tra ecologia, bioacustica, ecoacustica e *big data science* [3]. Quest'enorme capacità di campionamento dovrebbe quindi permettere di produrre una visione completa del *soundscape* [4] nell'insieme delle sue diverse componenti. Tuttavia, a tale rapido sviluppo tecnologico, non è corrisposto un analogo sviluppo di metodi analitici che soddisfino le esigenze di ricerca. Questo determina un significativo rallentamento nello studio delle tematiche e nella piena comprensione delle potenzialità della nascente ecoacustica e della *soundscape ecology* [4].

In questo lavoro si è focalizzata l'attenzione sugli strumenti analitici a disposizione dei ricercatori per effettuare analisi di tipo bioacustico/eco-acustico, con particolare riferimento agli ambienti di *R* [5], di *Python* [6] e di MATLAB® [7], al fine di elaborare una proposta di *framework* implementabile e riproducibile per studi futuri.

2. Metodologie disponibili

2.1 R

Le librerie presenti in *R* per l'analisi di dati bioacustici sono varie e dal loro uso combinato è possibile elaborare un primo piano di lavoro esplorativo. La problematicità maggiore è invece legata alla sintassi del linguaggio stesso, spesso difficilmente accessibile ai non programmatori esperti, che limita la possibilità di interpretazione e di adattamento degli script, condizione indispensabile per meglio configurare le proprie analisi e manipolare efficacemente i propri dati.

Le librerie *TuneR* [8], *seewave* [9], *MonitoR* [10] e *Soundecology* [11] costituiscono al momento la base per ogni tipo di analisi bioacustica in R. Tramite queste è possibile, ad esempio, ricavare informazioni sui componenti spettrali del segnale, ricercare similitudini tra spettrogrammi e ottenere indici acustici che stimino in modo rapido il livello di biodiversità e di qualità ambientale. È inoltre interessante la possibilità in *MonitoR* di creare dei *templates* di segmenti acustici e di operare l'individuazione automatica di questi all'interno di uno o più file audio. Altre librerie consentono specifiche funzioni di interesse, ad esempio in *WarbleR* [12] il *core* della libreria è quello di confrontare la similarità tra vocalizzazioni di conspecifici e ricercare pattern ripetitivi all'interno di queste. Infine *Signal* [13] è una trasposizione in R di alcune funzioni per il *signal processising* sviluppate su *MATLAB* e *Octave.*

2.2 Python

Per la semplicità della sua sintassi *Python* si sta velocemente affermando come ambiente di calcolo e sviluppo anche da parte di "non-programmatori". La semplicità nella struttura dei suoi codici fa sì che essi possano essere facilmente interpretati e utilizzati anche quando scritti da terzi. Permette inoltre una facile gestione e manipolazione dei dati in forma matriciale o di *dataframe.* Al momento, il limite più grande è dato dal numero ridotto di librerie precostituite per l'analisi bioacustica, fattore che ne restringe l'utilizzo.

Le librerie base di riferimento sono *numpy* e *scipy* [14], che sono l'ossatura per il calcolo scientifico in *Python,* incluso il *signal processing*. *Librosa* [15] è una libreria molto vasta ideata per l'analisi e la produzione musicale, le sue funzionalità vanno dall'analisi spettrale al rilevamento di eventi acustici a determinate intensità. Particolarmente interessante è ancora *pyAudioAnalysis* [16], che dà modo di effettuare analisi spettrali, e restituisce in forma matriciale i valori dei descrittori spettrali, rendendoli immediatamente disponibili per vari tipi di analisi su di essi. Inoltre, presenta dei *templates* utilizzabili per compiere calcoli di regressione e classificazione con algoritmi di *Machine Learning.*

2.3 MATLAB

MATLAB è certamente uno dei più diffusi ambienti di calcolo e programmazione nel campo della bioacustica e dell'acustica ambientale. Il vantaggio dato dall'utilizzo di questo software risiede principalmente nella possibilità di utilizzare diversi toolbox per le analisi di dati acustici e più in generale per il *signal processing*. Tra gli strumenti fondamentali per analisi di dati acustici in MATLAB, citiamo il *Signal Processing Toolbox* [17] (SPT). SPT consente di generare, misurare, trasformare, filtrare, ricampionare e visualizzare segnali. Il toolbox, può essere utilizzato per analizzare e confrontare segnali nel dominio del tempo e della frequenza, per sviluppare modelli e per individuare trend. Inoltre, le funzioni disponibili in SPT possono es-

Associazione Italiana di Acustica, 2017
ISBN: 978-88-88942-54-4

sere utilizzate per sviluppare algoritmi personalizzati. Tra i software MATLAB per bioacustica disponibili on-line ricordiamo, ad esempio, Triton [18], che fornisce una intuitiva interfaccia utente GUI e tool specifici per l'analisi di *big data series*, come la funzione LTSA (Long-Term Spectral Average). LTSA consente di analizzare rapidamente serie storiche di dati, ricercare e identificare eventi acustici significativi ed eventuali trend, in un dato arco temporale. Pochi software MATLAB specifici per studi di bioacustica sono tuttavia facilmente reperibili on-line. Le numerose funzioni messe a disposizione a pagamento da MATLAB vengono infatti generalmente utilizzate in algoritmi custom, sviluppati ad-hoc sulle caratteristiche del dataset a disposizione. Fa eccezione il pacchetto XBAT, sviluppato dalla Cornell University, che incorpora molteplici possibilità operative, anche di ricerca di eventi su collezioni di files consecutivi. E' tuttavia da notare che XBAT non viene aggiornato da diversi anni e, oltra a diversi bug, mostra problemi di compatibilità fra le diverse versioni di Matlab che sono difficilmente risolvibili dall'utente finale. E' infine da segnalare l'eccellente libro di Zimmer [19] che illustra con segmenti di codice Matlab le tecniche di analisi applicate allo studio della bioacustica dei cetacei.

3. Possibili frameworks e prospettive future

In Python un modello di framework può essere dato dall'integrazione di librerie concepite per lavorare in diverse aree del *signal processing*. Ad esempio, la ricerca di un determinato evento acustico in una registrazione può essere concepito anche come la ricerca di una determinata immagine all'interno di uno spettrogramma. Per tale approccio si può fare affidamento a librerie come *opencv* [20] (Figura 1), specifiche per l'*image processing*. O ancora, l'integrazione di *feature extraction* automatica e *machine learning* può divenire uno strumento molto potente nello studio e nella valutazione qualitativa del paesaggio sonoro e delle sue componenti.

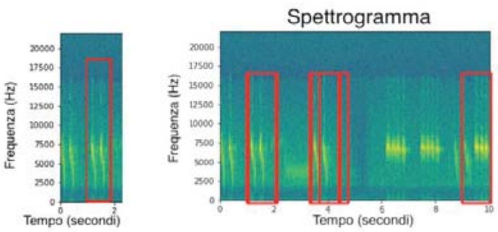


Figura 1 Esempio di *pattern recognition* con *opencv* in *Python*. A sinistra l'evento ricercato all'interno dello spettrogramma; sulla destra il risultato dell'analisi.

In conclusione, in *Python*, ad oggi, si necessita la presenza di una libreria integrata, dedicata nello specifico alle analisi bioacustiche ed ecoacustiche. Lo sviluppo di strumenti che sopperiscano a tale mancanza in questo contesto può aprire spazi di ricerca interessanti, soprattutto doterebbe i ricercatori impegnati in questo campo di maggiore autonomia, limitando il tempo impiegato nella creazioni di algoritmi *ad hoc* ai casi di più stretta necessità. Più in generale, un punto di incontro tra *Python* ed *R* potrebbe essere dato dalla creazione di strumenti per rappresentare spettrogrammi compatti di registrazioni di lunga durata o stime percentili dello spettro di potenza, strumenti che permetterebbero una maggiore comprensione del *soundscape* nelle sue componenti di bio-, geo- e antropofonia.

4. Bibliografia

[1] Acevedo M.A., Villanueva-Rivera L.J., *Using automated digital recording systems as effective tools for the monitoring of birds and amphibians.* Wildlife Society Bulletin, **34** (2006) pp 211–214.

[2] André M., Van der Schaae M., Zaugg S, Houégnigan I., Sànchez A. M., Castell J. V.. *Listening to the deep: live listening of ocean noise and cetacean acoustic signals.* Marine Pollution Bulletin. **63** (2011) pp 18-26.

[3] Stowell D., Plumbley M.D., *Large-scale analysis of frequency modulation in birdsong data bases.* Methods in Ecology and Evolution, **5** (2014) pp 901-912.

[4] Farina A., Pieretti N., Piccioli L. *The soundscape methodology for long-term bird monitoring: A Mediterranean Europe case-study. Ecological Informatics*, **6** (2011) pp 354-363.

[5] R Core Team. *R: A language and environment for statistical computing.* (2013).

[6] Python Core Team. Python*: A dynamic, open source programming language. Python Software Foundation.* (2015).

[7] http://www.mathworks.com/

[8] Ligges U., Krey S., Mersmann O., Schnackenberg S. *tuneR: Analysis of music*. (2016) URL: http://r-forge.r-project.org/projects/tuner/.

[9] Sueur J., Aubin T., Simonis C.. *Seewave: a free modular tool for sound analysis and synthesis*. Bioacoustics, **18**, (2008) 213-226.

[10] Hafner S., Katz J. *monitoR: Acoustic template detection in R. R package version 1.0.5 (2017).* http://www.uvm.edu/rsenr/vtcfwru/R/?Page=monitoR/monitoR.htm.

[11] Villanueva-Rivera L.J., Pijanowsk B.C. Doucette j., Pekin B. *A primer of acoustic analysis for landscape ecologists*. Landscape Ecology **26** (2011) pp 1233-1246.

[12] Araya-Salas M., Smith-Vidaurre G., *warbleR: an r package to streamline analysis of animal acoustic signals*. **8** (2016) pp 184-191.

[13] Signal developers. *signal: Signal processing.* (2013) URL: http://r-forge.r-project.org/projects/signal/.

[14] Van der Walt S., Colbert S. C., Varoquaux G. *The NumPy Array: A Structure for Efficient Numerical Computation,* Computing in Science & Engineering, **13** (2011) pp 22-30.

[15] McFee B., McVicar M., Nieto O., Balke S., Thome C., Liang D, Lee H. *librosa 0.5.0* (2017), Zenodo. http://doi.org/10.5281/zenodo.293021

[16] Giannakopulos T. *pyAudioAnalysis: An Open-Source Python Library for Audio Signal Analysis*. PLoS ONE **10** (2015) 12:e0144610.

[17] https://it.mathworks.com/products/signal.html

[18] Wiggins S.M., Roch M.A., Hildebrand J.A. *TRITON software package: analyzing large passive acoustic monitoring data sets using MATLAB.* J. Acoust. Soc. Am., 128 (2010) http://doi.org/10.1121/1.3508074

[19] Zimmer W.M.X. *Passive Acoustic Monitoring of Cetaceans*, Cambridge Press (2011)

[20] Bradsky G. *The opencv library*. Doctor Dobbs Journal **25** (2000) pp 120-126.

Associazione Italiana di Acustica
45° Convegno Nazionale
Aosta, 20-22 giugno 2018

LE FONOTECHE PER DOCUMENTARE LA COMPLESSITA' DEL PAESAGGIO SONORO FRA BIOFONIA E ANTROPOFONIA

Gianni Pavan (1), Roberta Righini (1), Elisa Salvalaggio (2)

1) Università di Pavia, Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia, Pavia, gianni.pavan@unipv.it, roberta.righini01@universitadipavia.it

2) Archivista libero professionista, Istituto piemontese per la storia della Resistenza e della società contemporanea "Giorgio Agosti", Torino, elisa.salvalaggio@gmail.com

SOMMARIO

Le fonoteche raccolgono, conservano e valorizzano documenti sonori di diversa origine a testimonianza di un mondo naturale e di una società umana in continua evoluzione. Le fonoteche zoologiche e naturalistiche documentano le voci di specie e ambienti sonori in progressiva riduzione a causa delle attività umane. In ambito umanistico raccolgono testimonianze culturali di varia natura, interviste, musiche, suoni e rumori di ambienti culturali diversi. E' auspicabile riflettere sulle modalità di conservazione, fruizione e utilizzazione di questi patrimoni documentali anche suggerendo nuove convergenze di interessi e di approcci multidisciplinari.

1. Approccio scientifico al paesaggio sonoro

Il concetto di paesaggio sonoro (*soundscape*), nato in ambito perlopiù musicale e antropologico con il lavoro di Schafer [1], si è ampiamente sviluppato anche in ambito ecologico e zoologico negli ultimi venti anni.

Il paesaggio sonoro, anche riconosciuto come "ambiente acustico", è l'insieme di suoni e rumori che nascono dall'ambiente fisico, dalla comunità di animali che lo abitano [2] e anche dalla presenza e attività dell'uomo, ad esempio con i suoni di una festa di paese o i rumori delle attività lavorative.

Il paesaggio sonoro è quindi una espressione dell'ambiente che possiamo considerare sul piano estetico, ma che ha anche un grande valore scientifico per la comprensione dei fenomeni naturali e antropici che vi si sviluppano sia a breve che a lungo termine. In ambito ecologico, nel momento in cui si riconosce il paesaggio sonoro come espressione della struttura e diversità di un ambiente, come ampiamente anticipato da Carson [3], i suoni e i rumori diventano uno strumento di studio e monitoraggio dell'ecosistema. L'esigenza di ricondurre il tema entro binari scientifici e rigorosi ha portato allo sviluppo di nuove discipline, come l'ecologia acustica e, più recentemente, la *soundscape ecology* [4-7] da cui poi è nata l'ecoacustica [8].

2. Bioacustica ed ecoacustica

La bioacustica studia i suoni prodotti dagli animali per comunicare e, nei pipistrelli e nei cetacei, per ecolocalizzare ostacoli e prede, e indaga come gli animali percepiscono i suoni e i rumori dell'ambiente e come reagiscono al rumore e al disturbo antropico [6]. L'ecoacustica deriva dalla relazione fra bioacustica ed ecologia: studia tutti i suoni che compongono il paesaggio sonoro in una ampia gamma di frequenze, dagli infrasuoni agli ultrasuoni, e il loro rapporto con l'ambiente fisico e biologico in un ampio intervallo di scale di studio, sia spaziali che temporali, a livello individuale, comunitario e di popolazione.

Nel paesaggio sonoro riconosciamo tre componenti principali: i suoni biologici (*biofonia*), più propriamente oggetto della bioacustica, i rumori generati dai fenomeni naturali quali pioggia, vento, tuoni, ecc. (*geofonia*), e infine i suoni e rumori prodotti dall'uomo (*antropofonia*). Recentemente si tende a distinguere i rumori antropici più propriamente considerati espressione del lavoro dell'uomo, della cultura e delle tradizioni locali, identificabili come *antropofonia culturale*, dalla *tecnofonia*, ovvero dai rumori portati dalle *macchine* con l'era industriale e generati principalmente dai sistemi di trasporto (strade, ferrovie, aerei, navi) e da attività industriali. La *tecnofonia* è soprattutto costituita da rumore continuo con componenti a bassa frequenza che si propagano su lunghe distanze, soprattutto in ambiente acquatico, e che risultano presenti e invasivi, considerati inquinamento acustico, anche lontano dalle aree urbane o prettamente industriali [9-11]. Nel paesaggio sonoro urbano predominano antropofonia e tecnofonia, in un intreccio complesso di suoni e rumori, mentre la biofonia rappresenta una componente minore ma sempre apprezzata.

3. Le fonoteche

Nella seconda metà del Novecento le fonti sonore sono divenute strumento indispensabile per la ricerca e lo studio in moltissimi settori del sapere, sia in ambito umanistico (storia contemporanea, scienze linguistiche, sociologia, antropologia, etnomusicologia e altre), sia nelle discipline scientifiche ambientali (bioacustica ed ecoacustica). In un'epoca di forti cambiamenti ambientali e di un allarmante e sempre più veloce declino della biodiversità, primariamente causati dall'azione dell'uomo, la registrazione, lo studio e la conservazione dei paesaggi sonori è diventato un tema di grande interesse internazionale [12-14].

Gli archivi sonori sono di grande importanza sia per la conservazione che per la gestione delle risorse e delle aree naturali, e talvolta rappresentano l'unica traccia di specie e comunità ormai scomparse o in corso di deterioramento ed estinzione; a questo proposito, Bernie Krause [2] afferma che quasi il 50% dei paesaggi sonori che ha registrato nel corso di numerosi decenni sono ormai scomparsi o profondamente alterati.

4. Suoni e voci umane

Le discipline umanistiche si occupano di produrre e conservare documenti sonori sin dalla fine dell'Ottocento, a partire dall'invenzione del primo fonografo. Dal Novecento riceviamo in eredità cospicue quantità e tipologie eterogenee di documenti sonori, custoditi da enti pubblici, archivi, biblioteche, imprese, associazioni, nuclei familiari, ricercatori indipendenti e attivi in

Associazione Italiana di Acustica, 2018
ISBN: 978-88-88942-56-8

seno alle più svariate istituzioni, una su tutte la ex Discoteca di Stato (oggi Istituto centrale per i Beni sonori e audiovisivi) voluta e istituita nel 1928 da Vittorio Emanuele III. Negli ultimi vent'anni sono state molte le operazioni di censimento delle fonti sonore e orali condotte sia a livello regionale che nazionale. Nel 1991-92 fu indetto un censimento delle fonti orali, in ambito nazionale, condotto dal Ministero per i Beni culturali attraverso la rete delle soprintendenze archivistiche [15]. Nel 2002 Amedeo Benedetti ha pubblicato i risultati di un censimento dei materiali musicali [16]; nel 2015, viene pubblicato l'*Atlante degli archivi fotografici e audiovisivi italiani digitalizzati*, all'interno del progetto M9-Museo del Novecento della Fondazione di Venezia, sostenuto dalla Regione Veneto e dal Ministero per le Attività culturali e del turismo [17].

A livello regionale, in Piemonte, nel 1992 viene avviato un primo censimento dei fondi sonori e dal 1999 quello delle fonti musicali [18-19]; nel 2007 in Toscana è stato pubblicato un primo censimento delle fonti orali [20]. Nel 2016 è avviato il Progetto Archivi sonori del Piemonte promosso dall'Istituto piemontese per la Storia della Resistenza e della Società contemporanea "Giorgio Agosti", in collaborazione con la Soprintendenza archivistica e bibliografica del Piemonte e della Valle d'Aosta e sostenuto dalla Regione Piemonte. Il nuovo censimento si conclude nel 2018 e i primi risultati sono stati recentemente presentati al Salone Internazionale del Libro di Torino.

5. Paesaggio sonoro naturale e antropico

I suoni prodotti dall'uomo possono integrarsi al paesaggio sonoro arricchendolo di componenti informative, ma possono anche interferire con esso e diventare una forma di inquinamento con effetti negativi sia sull'uomo che sulla fauna. L'antropofonia è un intreccio di suono e rumore che può essere espressione di azione, di cultura, di lavoro, di tradizioni, di lingue, di religioni ma anche diventare un fattore di criticità quando la componente di tecnofonia diventa prevalente [9-11]. Al di fuori degli ambienti di lavoro, nei quali le criticità acustiche possono essere controllate e confinate, la principale sorgente di rumore è rappresentata dai sistemi di trasporto, strade, ferrovie, metropolitane, traffico aereo, che investe costantemente una grande percentuale di popolazione con effetti significativi sulla salute [11].

L'approccio scientifico a queste tematiche richiede di registrare, analizzare e catalogare le varie manifestazioni acustiche e, attraverso il loro studio, discernerne le componenti positive e negative, per quanto riguarda discipline di tipo ambientale, o per conservare la memoria privata e istituzionale dell'attività dell'uomo, per quel che riguarda le discipline umanistiche. In questo ambito hanno grande importanza le fonoteche, gli archivi e le raccolte di documenti sonori, che hanno il compito di preservare e conservare le collezioni di registrazioni delle espressioni acustiche dell'uomo e della natura, che sono espressione e testimonianza di storia e cultura.

6. Conclusioni

Da tutto questo nasce la necessità di conservare e utilizzare le fonti sonore con un approccio multidisciplinare condivisibile. Appare peraltro ovvio che tutti questi diversi tipi di "suoni" e "rumori" (e le loro registrazioni) non sono assimilabili sul piano del contenuto e le varie discipline interessate hanno infatti affinato nel tempo precise tecniche per la gestione e lo studio dei documenti sonori di rispettiva pertinenza.

È tuttavia possibile comprendere in un discorso unitario tali documenti, almeno dal punto di vista "tecnico", assimilandoli proprio per la loro natura di "registrazioni". Una convergenza di discipline di diversi ambiti è sempre più auspicabile per riflettere sulle modalità di conservazione, fruizione e utilizzazione di questo patrimonio sonoro anche suggerendo nuovi approcci multidisciplinari. Le testimonianze del nostro patrimonio naturale e culturale meritano di essere individuate, catalogate e conservate attraverso idonee fonoteche regionali e nazionali. In particolare è da notare che in Italia non esiste alcuna fonoteca naturalistica o fonoteca zoologica nazionale. È pertanto auspicabile che si compia uno sforzo di recupero del patrimonio di informazioni sonore ora disperso e spesso dimenticato negli archivi di istituzioni di ricerca e di privati che nel corso degli anni hanno effettuato pregevoli e non replicabili registrazioni sonore di singole specie o di ambienti sonori sia naturali che antropici.

Se non si interviene tempestivamente, si corre il rischio che il patrimonio di registrazioni effettuate nel corso degli ultimi decenni da molti ricercatori e appassionati, che hanno documentato la ricchezza e la diversità degli ambienti naturali e culturali del nostro paese, venga perso e che la testimonianza di tali suoni scompaia come stanno scomparendo gli ambienti e le specie, ma anche le culture e le tradizioni umane.

Purtroppo, molte registrazioni preziose sono ancora conservate in archivi privati con il rischio non solo che se ne perda la memoria ma che subiscano deterioramenti irreversibili. In alcuni casi è anche da considerare il rischio di non avere più disponibili gli strumenti e le informazioni per leggerle correttamente.

7. Bibliografia

1. Schafer R.M., *The tuning of the World*, Knopf New York (1977).
2. Krause B., *The great animal orchestra*. Profile Books, London, (2012).
3. Carson R., *Silent Spring*, Houghton Mifflin, Boston, (1962).
4. Pijanowski B.C., Farina A., Gage S.H., Dumyahn S.L., KrauseB.L., *What is soundscape ecology? An introduction and overview of an emerging new science*, Landscape Ecology, 26, (2011), pp. 1213–1232.
5. Pijanowski B.C., Villanueva-Rivera L.J., Dumyahn S.L., Farina A., Krause B.L., Napoletano B.M., Gage S.H., Pieretti N., *Soundscape Ecology: The Science of Sound in the Landscape*, BioScience, 61/3, (2013), pp. 203-216.
6. Pavan G., *Bioacustica e Ecologia acustica*, In: Spagnolo R. (a cura di), "Acustica. Fondamenti e applicazioni", UTET, (2015), pp. 803-828.
7. Farina A., *Soundscape Ecology. Principles, Patterns, Methods and Applications*, Springer, (2014).
8. Farina A., Gage S.H., *Ecoacoustics. The ecological role of sound*, Wiley, (2017).
9. Pavan G., *Fundamentals of Soundscape Conservation*, In: Farina A., Gage S.H. (Editors), "Ecoacoustics. The ecological role of sound", Wiley, (2017), pp. 235-258.
10. Pavan G., *Il rumore negli ambienti naturali. Misura e interpretazione*, Atti 43° Convegno AIA, (2016).
11. EEA, *Noise in Europe*, Report No 10/2014, European Environment Agency, Copenhagen, (2014).
12. Ranft R., *Capturing and preserving the sounds of nature*, in: A Linehan (Editor), "Aural history: essays on recorded sound", The British Library, London, (2001), pp. 65-78.
13. Ranft R., *Natural sound archives: past, present and future*, Anais da Academia Brasileira de Ciências, 76 /2, (2004), pp. 455-465.
14. Marques P.A.M., Magalhaes D.M., Pereira S.F., Jorge P.E., *From the Past to the Future: Natural Sound Recordings and the Preservation of the Bioacoustics Legacy in Portugal*, PLoS ONE, 9/12, (2014), e114303.
15. Barrera G., Martini A., Mulè A. (a cura di), *Fonti orali. Censimento degli istituti di conservazione*, Roma, Ministero per i Beni culturali e ambientali-Ufficio centrale per i Beni archivistici, (1993).
16. Benedetti A., *Gli archivi sonori. Fonoteche, nastroteche e biblioteche musicali in Italia*, Genova, Erga Edizioni, (2002).
17. Sergio G. (a cura di), *Atlante degli archivi fotografici e audiovisivi italiani digitalizzati*, Venezia, Fondazione di Venezia-Marsilio, (2015).
18. *Archivi sonori. Atti dei seminari di Vercelli (22 gennaio 1993), Bologna (22-23 settembre 1994), Milano (7 marzo 1995)*, Roma, Ministero per i Beni e le Attività Culturali-Ufficio centrale per i Beni archivistici, (1999)
19. *Le fonti musicali in Piemonte*, Lucca, LIM-Libreria musicale italiana [per i vol. 3-4: Torino, Regione Piemonte], 2006-2014 (Istituto per i beni musicali in Piemonte, *Cataloghi di fondi musicali del Piemonte*, 4 vol.).
20. Andreini A., Clemente P. (a cura di), *I custodi delle voci. Archivi orali in Toscana. Primo censimento*, Firenze, Centro stampa Regione Toscana, (2007).

SABIOD PROJECT

The SABIOD project (Scaled Acoustic Biodiversity) is part of a bigger program on the issues of Big Data Science named MASTODONS, funded by the French CNRS (www.sabiod.univ-tln.fr).
Begun in 2014 and developed in collaboration with the lab CIBRA (Interdisciplinary Center for Bioacoustics and Environmental Research) of the University of Pavia (Italy) and the University of Toulon (France), SABIOD provides for the installation of remote autonomous sound recorders in natural habitats to collect long-term environmental acoustic records and to develop analysis methods to describe the acoustic environment, or soundscape, of natural areas characterized by different levels of anthropic impact, from protected areas (Pavan et al., 2018) far or almost far from any noise disturbance, to more anthropized areas and agro-ecosystems. In this context, the study of areas with a very low level of noise pollution (Pavan 2016; EEA 2016) plays a particular role in order to define a reference model of an acoustic environment similar to the pre-industrial era.

Concerning data collection and analysis, SABIOD is divided in three main levels:

i. research: detection, clusterization and indexation of acoustic Big Data for qualitative and quantitative multilevel analyses;
ii. conservation: the soundscape is considered as a key component of the ecosystems and thus it must be studied, monitored, conserved and even restored when altered by human action (habitat degradation, noise pollution).
iii. education: elaboration of info panels and dissemination documentation; soundscape valorisation of soundscape component for touristic attraction in natural areas.

In particular, the SABIOD-Italia section aims to record soundscapes of natural sites of international importance with different levels of protection and contamination by anthropic noise (www-3.unipv.it/cibra).
In this regard, the decision to focus on the soundscape of the Sasso Fratino Integral Nature Reserve (Italy) is of great importance.
Sasso Fratino's peculiar vegetational structure of old-growth forest and the forest secular management addressed toward a full conservation of the environment (see Chapter 4 for more details about Sasso Fratino) and all these features candidate this area to be an important case of wilderness and a suitable model to collect high-quality records of natural habitats.
The SABIOD project is still undergoing within the larger frame of the French CNRS MASTODONS, MADICS (Masses de Données, Informations et Connaissances en Sciences) and EADM

(Environmental Acoustic Data Mining) projects (http://www.madics.fr/actions/actions-en-cours/eadm/).

and the partner laboratories:

References

EEA, (2016) *Quiet areas in Europe. The environment unaffected by noise pollution*. European Environment Agency, Report No 14/2016, Copenhagen.

Pavan G., Favaretto A., Bovelacci B., Scaravelli D., Macchio S., Glotin H., (2015). *Bioacoustics and Ecoacoustics applied to environmental monitoring and management*. Rivista Italiana di Acustica, 39-2 (2015), pp. 68-74.

Pavan G., (2016). *Il rumore negli ambienti naturali*. *Misura e interpretazione*. Atti 43° Convegno AIA.

www.sabiod.univ-tln.fr

www-3.unipv.it/cibra

Proceedings (ita)

Progetto SABIOD (Scaled Acoustics BIODiversity) 2014-2019: sfide vinte, sfide non (ancora) vinte e le nuove sfide (AIA, 2019)

Associazione Italiana di Acustica
46° Convegno Nazionale
Pesaro, 29-31 maggio 2019

PROGETTO SABIO (SCALED ACOUSTIC BIODIVERSITY) 2014-2019: SFIDE VINTE, SFIDE NON (ANCORA) VINTE E LE NUOVE SFIDE

Roberta Righini (1), Gianni Pavan (2)

1) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
E-mail: roberta.righini01@universitadipavia.it
2) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
E-mail: gianni.pavan@unipv.it

SOMMARIO

Lo studio del paesaggio sonoro rappresenta uno strumento innovativo per caratterizzare uno specifico ambiente e delinearne i suoi cambiamenti su diverse scale temporali e spaziali. La seguente relazione si propone di descrivere i primi cinque anni di campionamento e analisi dei dati raccolti all'interno del progetto SABIOD, sviluppato dal CIBRA a partire dal 2014, con lo scopo di documentare e descrivere i paesaggi sonori di specifici habitat e di sviluppare nuovi protocolli di analisi e classificazione multilivello sempre più automatizzata.

1. Introduzione

Al giorno d'oggi, una delle più grandi sfide per la conservazione della biodiversità è gestire e mitigare le minacce determinate dal cambiamento climatico e ridurre l'alto tasso di perdita di specie da esso causato.
Nonostante ciò, molto spesso è difficile avere un quadro generale completo che permetta di prendere decisioni efficaci, in quanto la comprensione della maggior parte dei sistemi biologici è basata su una copertura di dati limitata sia spazialmente che temporalmente [1].

La necessità di ottenere dati di sintesi che permettano analisi rapide e confronti a larga scala nonché l'avanzamento tecnologico nel settore degli strumenti di registrazione acustiche, hanno contribuito allo sviluppo della recente scienza definita *Ecoacustica* [2] un filone di ricerca interdisciplinare che ha come fine lo studio e la descrizione del paesaggio sonoro ovvero dei suoni naturali e antropici e la loro relazione con l'ambiente, diventando uno strumento sempre più valido e potente per la conservazione della biodiversità e la stima della qualità ambientale. Attraverso il monitoraggio acustico passivo di un habitat, è possibile ottenere un'immagine del paesaggio sonoro nelle sue diverse tre componenti, i suoni prodotti dagli animali (*biofonia*, generalmente compresa tra 2.000-8.000 Hz, i rumori caratteristici di eventi atmosferici e fisici (*geofonia*: vento, pioggia, acque correnti, ecc.) e i rumori legati alla presenza dell'uomo (*antropofonia*: automobili, aeroplani e altre attività antropiche, generalmente occupanti le basse frequenze: 200 – 2.000 Hz (in situazioni in cui il rumore elettromeccanico sia dominante si utilizza il termine *tecnofonia*) [3].

In particolare, la registrazione dell'ambiente acustico rappresenta uno strumento innovativo per caratterizzare uno specifico paesaggio e delinearne i suoi cambiamenti su diverse scale temporali, dai cambiamenti giornalieri a quelli stagionali nonché, attraverso la costituzione di un archivio sonoro, con essa si ha anche la possibilità di conservare le serie annuali e confrontarle tra loro.
In questo nuovo filone di ricerca è nato, nel 2014, il progetto SABIOD (Scaled Acoustic BIODiversity) in collaborazione con l'Università di Tolone (LSIS-DYNI) e supportato anche dal CNRS con lo scopo di documentare e descrivere i paesaggi sonori di specifici habitat e di sviluppare nuovi protocolli di analisi e classificazione multilivello sempre più automatizzata per di ambienti naturali sottoposti a diversi livelli di impatto antropico, dalle aree protette [4], lontane da ogni disturbo antropico, alle aree più antropizzate e agli agroecosistemi. In questo ambito riveste un ruolo particolare lo studio di aree con un livello di rumore antropico molto basso [5, 6] al fine di definire un modello di riferimento di ambiente acustico assimilabile all'era preindustriale.

Il lavoro proposto presenta lo sviluppo e l'avanzamento della sezione del progetto SABIOD-Italy nei suoi primi cinque anni (2014-2019), attraverso la descrizione dei suoi obiettivi inziali, dei problemi tecnici affrontati (sia per la raccolta che l'analisi dei dati acustici), la sperimentazione di algoritmi di analisi automatica, nonché l'organizzazione di un protocollo che dallo specifico caso studio possa venire applicato a più ambienti terrestri (forestali).

Verranno presentati i risultati della prima analisi effettuata sul paesaggio sonoro della Riserva Naturale Integrale del Sasso Fratino (nel Parco Nazionale delle Foreste Casentinesi, Italia), un'area caratterizzata dalla quasi assenza di rumore antropogenico (ad eccezione dei sorvoli aerei), dove sono stati collocati, in punti diversi, tre registratori al fine di ottenere registrazioni audio sincrone e continue. Per la successiva fase di analisi dei dati acustici, si è adottato un doppio approccio, uno qualitativo basato sullo screening visivo degli spettrogrammi giornalieri compatti e l'altro quantitativo mediante la stima degli indici acustici e l'analisi dell'energia dello spettro per ciascun intervallo di 1000 Hz (da 0 a 24 kHz).

Tale studio rappresenta anche un riferimento per il monitoraggio dello stato di biofonia dell'INR: infatti, poiché l'acceso all'uomo è vietato cosi come interventi di alterazione dell'ambiente, i cambiamenti globali potrebbero essere considerati come possibili fattori che influenzeranno future modificazioni nella presenza e distribuzione di specie all'interno della riserva.

2. Metodi

2.1 Area di studio

L'area di studio si trova all'interno del Parco Nazionale delle Foreste Casentinesi (sull'appennino tosco-romagnolo, Italia) e in particolare nella Riserva Integrale di Sasso Fratino: istituita nel 1959, la RNI di Sasso Fratino è caratterizzata da uno

Associazione Italiana di Acustica, 2019
ISBN: 978-88-88942-59-9

scarso livello di intervento antropico grazie alla mancanza di vie di accesso, alla presenza di forti pendii rocciosi e all'accidentalità del sito e tutto ciò ha permesso lo sviluppo di un ecosistema forestale evoluto e con struttura di *old-growth*, ossia di bosco vetusto. Tali popolamenti, rarissimi in Italia a causa della forte pressione che da millenni l'uomo esercita sulle foreste, sono caratterizzati da elevate biomasse (superiori ai 1000 mc/ha) e biodiversità [7].

Dal punto di vista vegetazionale, si trova un bosco misto di faggi e abeti bianchi fino alla quota di circa 1250 m a.s.l., mentre al di sopra di tale soglia altitudinale la composizione diviene di solo faggio [8].

2.2 Raccolta dati

A partire da maggio 2014, la raccolta dei dati è avvenuta tramite il posizionamento in loco di registratori remoti autonomi Wildlife Acoustics SM3 e SM4 (da giugno 2017) programmati per registrare 10 minuti ogni 30 minuti, 24 ore al giorno, in modo sincrono e continuativo; le registrazioni digitali sono state effettuate ad una frequenza di campionamento di 48 kHz o 24kHz (per testare la maggiore durata temporale delle batterie e delle schede di memoria) memorizzate nel formato di file audio .wav, per un totale giornaliero di 5.6 GB.

La posizione di ciascun registratore è stata contrassegnata tramite GPS Garmin e quindi salvata come file .kmz.

Sono stati individuati 12 siti principali di monitoraggio: sei siti sono compresi nella *core area* della foresta densa, propriamente all'interno della RNI di Sasso Fratino, dove l'accesso è interdetto, e sei si collocano in un'area marginale della riserva, ma pur sempre all'interno dei confini del Parco Nazionale, dove l'acceso è possibile solo attraverso la sentieristica ciclo-pedonale e alle autovetture del Corpo forestale dello stato, ora Arma dei Carabinieri.

Il dislivello altitudinale che caratterizza il campione dei siti si estende dai circa 750 m s.l.m. fino a circa 1400 m s.l.m..

I dati registrati sono stati salvati in formato .wav su schede di memoria estraibili e da queste trasferiti nell'archivio del laboratorio CIBRA (Università di Pavia), catalogati e preparati per le successive analisi.

2.3 Analisi dei dati

La prima fase di analisi comporta la generazione di spettrogrammi giornalieri compatti per ciascuna giornata di registrazione tramite l'uso del software SeaPro sviluppato dal CIBRA (http://www-3.unipv.it/cibra/) al fine di valutare la correttezza e la completezza delle giornate registrate [Figura 1].

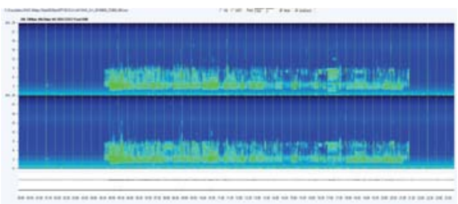


Figura 1 - Esempio di uno spettrogramma compatto giornaliero di una registrata stereo effettuata nella Riserva Naturale di Sasso Fratino mediante l'uso di un registrato SM3 programmato per registrare 10 minuti ogni 30 (48 sezioni al giorno). Emerge una chiara transizione all'alba e al tramonto caratterizzati, un'intensa biofonia nelle ore diurne e la notte più silenziosa.

La successiva fase di analisi prevede l'estrazione di un minuto random (per ogni file di 10 minuti) e quindi la misurazione di parametri acustici eseguita mediante l'uso dell'ambiente R e di diverse librerie, tra cui Soundecology e Seewave, che consentono di ottenere sia parametri generali, come per esempio il valore dell'energia spettrale (minimo, massimo, medio), e sia specifiche metriche acustiche per stimare le differenze nel panorama sonoro, come gli indici H e D [9], rispettivamente per l'entropia acustica e la dissimilarità, AR [10] per la ricchezza acustica, ACI [11] per l'indice di complessità acustica, calcolati sia sull'interna banda di frequenza (0-24.000 Hz) che su bande di frequenza specifiche (intervalli di 1000 Hz).

I dati ottenuti dall'analisi acustica sono stati organizzati in tabelle in cui oltre ai valori sono stati aggiunti anche (per ogni file) degli attributi quali il nome univoco del sito campionato, il tipo di registratore usato (SM3 o SM4), il mese, l'anno, e l'ora.

Si è proceduto a creare dei grafici sintetici che permettessero il più possibile la visione di insieme dell'andamento dei vari indici al fine di ottenere una descrizione del paesaggio sonoro sia nel tempo che nello spazio.

3. Risultati

Con oltre più di 77.000 file di 10 minuti analizzati che si traducono in circa 9 terabyte di materiale archiviato in circa cinque anni di campionamento, i risultati che si possono ottenere da questo protocollo di analisi possono essere di vario genere, possono essere di vario genere, con diversi livelli di precisone ed estensione temporale (a seconda che si filtri i dati di un solo sito, che si prenda in considerazione la media mensile per confrontare l'andamento annuale o le singole giornate per vedere le differenze che gli indici assumono durante le varie ore). L'aspetto più interessante è il quadro generale che si può ottenere sui paesaggi sonori che caratterizzano i siti del parco, la possibilità di confronto e monitoraggio degli andamenti annuali, la capacità di evidenziare anomalie anche meteo dipendenti (vento e pioggia).

4. Bibliografia

[1] Aide T. M., Corrada-Bravo C., Campos-Cerqueira M., Milan C., Vega G., Alvarez R., *Real-time bioacoustics monitoring and automated species identification,* PeerJ, **1** (2013) e103

[2] Pavan G., *Bioacustica e Ecologia acustica*. In "ACUSTICA. Fondamenti e applicazioni", Renato Spagnolo (a cura di), UTET Università, Torino (2015), pp. 803-828

[3] Sueur J., Farina A., Gasc A., Pieretti N., Pavoine, S., *Acoustic indices for biodiversity assessment and landscape investigation*, Acta Acustica United with Acustica, **100**, (2014), pp 772–781

[4] Pavan G., Favaretto A., Bovelacci B., Scaravelli D., Macchio S., Glotin H., *Bioacoustics and Ecoacoustics applied to environmental monitoring and Management*. Rivista Italiana di Acustica, 39-2 (2015), pp. 68-74

[5] Pavan G., *Il rumore negli ambienti naturali. Misura e interpretazione*. Atti 43° Convegno AIA (2016)

[6] EEA, Quiet areas in Europe. *The environment unaffected by noise pollution*. EEA Report No 14/2016, European Environment Agency, Copenhagen (2016)

[7] Bianchi L., Bottacci A., Calamini G., et al., *Structure and dynamics of a beech forest in a fully protected area in the northern Apennines (Sasso Fratino, Italy)*, iForest - Biogeosciences and Forestry **4** (2011), pp.136-144

[8] Padula M., *La riserva naturale di Sasso Fratino nelle foreste demaniali casentinesi (Appennino tosco – romagnolo)*, Ministero dell'Agricoltura e Foreste, parchi nazionali – riserve integrali, Forlì, 1985

[9] Sueur J., Pavoine S., Hamerlynck O., Duvail S., *Rapid acoustic survey for biodi-versity appraisal*, PloS one, **3.12,** (2008), e4065

[10] Depraetere M., Pavoine S., Jiguet F., Gasc A., Duvail S., Sueur J., *Monitoring animal diversity using acoustic indices: implementation in a temperate woodland*, Ecol. Indic., **13** (2012), pp. 46-54

[11] Pieretti N., Farina A., and Morri D., *A new methodology to infer the singing activity of an avian community: the Acoustic Complexity Index (ACI),* Ecological Indicators **11.3** (2011), pp 868-873

CHAPTER 02

THE SOUNDSCAPE

In this chapter, the Soundscape is described and the three main components of Sasso Fratino's soundscape are analysed in detail.

The Soundscape is the acoustic expression of an ecosystem.

It's composed of three main components (Pijanowski et al., 2016):

- *biophony*: it comprises all sounds produced by animals (generally between 2,000-8,000 Hz) to communicate with each other (vocal signals play a crucial role in several activities, including mating rituals, warning calls, conveying the location of food sources, and social learning);
- *geophony*: it comprises all sounds produced by atmospheric and physical events that characterize an environment;
- *anthropophony*: they are all noises associated with the human presence and the other anthropic activities and they generally are at low frequencies: 20 - 2,000 Hz, but may extend to 5000 Hz and more; in situations where electromechanical noise is dominant, e.g. noise from transportation infrastructures or industries, the term technophony is preferred.

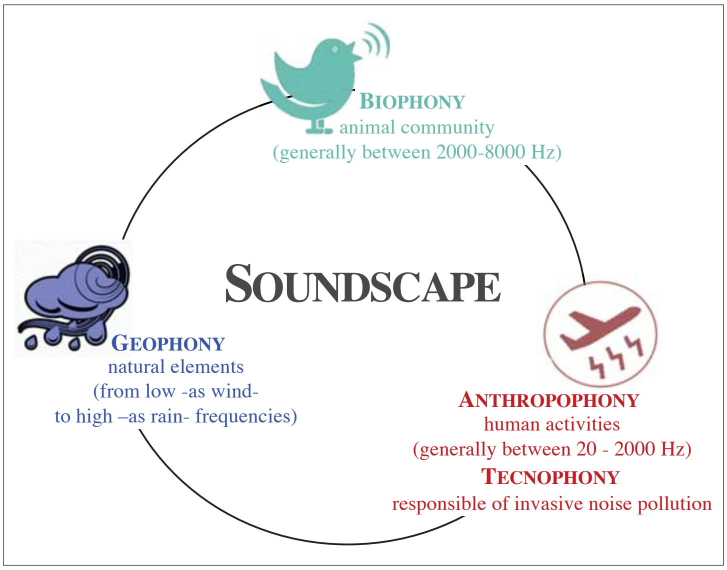


Figure 2.1 Schematic description of Soundscape and its three main components.

Since 2000s, the soundscape has been recognized to be a key component of the ecosystem by the National Park Service of the United States of America and thus a structured program aimed to study, the monitoring, the protection and restoration of different soundscape for all national parks has been promoted (Director's order 47: *Soundscape Preservation and Noise Management*, www.nps.gov).

In the following sections, each of the three components is analyzed separaterly.

FOCUS ON THE GEOPHONY

Aim

Focus the analysis on natural background noise in order to investigate the acoustic characteristics of a natural environment in different weather conditions (good, wind or rainy conditions).

Moreover, since passive acoustic monitoring generates large data sets of audio recordings that have to be stored and processed, the possibility of discriminating the recordings according also to different weather conditions, would contribute to make more manageable the processing time and to reduce analysis effort.

Methods

The study area is located within the National Park of the Casentinesi Forests (on the Tuscan-Romagnolo Apennines, Italy) and in particular in the Sasso Fratino Integral Nature Reserve: established in 1959, Sasso Fratino is characterized by a low level of anthropic intervention due to the lack of access roads, the presence of strong rocky slopes and the accidentality of the site and all these conditions has allowed the development of an evolved forest ecosystem with an old-growth structure. These populations, very rare in Italy cause the strong anthropic pressure exerted on forests for millennia, are characterized by high biomasses (above 1000 m^3 / ha) and biodiversity (Bianchi et al. 2011). From a vegetational point of view, there is a mixed wood of beeches (*Fagus sylvatica*) and white firs (*Abies alba*) up to the altitude of about 1250 m a.s.l., while above this altitudinal threshold the composition becomes only beech (Padula, 1985).

Three monitoring sites have been identified: two sites (q700 and q1400) are included in the core area of the dense forest, properly within the Sasso Fratino Integral Nature Reserve, where access is forbidden (except for scientific reasons) while the third site (La Lama) is located in a marginal area of the reserve, but still within the boundaries of the National Park, where access is only possible through cycle-pedestrian pathways and to vehicles authorized by the State Forestry Corps, now Arma dei Carabinieri, Reparto Biodiversità.

Data collection was carried out through the local positioning of three remote autonomous Wildlife Acoustics recorders (one SM3 and two SM4) programmed to record 10 minutes every 30 minutes, 24 hours a day, synchronously and continuously (in general, batteries and memory cards allow at least two months of data); digital recordings were made at a sampling rate of 48 kHz and stored in the audio file format .wav, for a total of 5.6 GB per day.

The position of each recorder has been marked with GPS Garmin and then saved as a .kmz file.

The recorded data were saved on memory cards and transferred from these to the archive of the CIBRA (University of Pavia) laboratory, then catalogued and prepared for subsequent analyses.

The selected period was from 10th May to 30th June 2017 because synchronous registrations were available for all the sampled sites and by visual screening of compact daily spectrograms, model days characterized by only good weather or with rain and/or wind were identified.

By visual screening of compact daily spectrograms of June 2017 (see Figures 2.2-2.4), reference days characterized by only good weather or with rain and/or wind were identified. Within these, they were randomly selected, including both the day and night time hours (day: 5:30-21:00; night: 21:01- 5:29), a total of 75 files (of 10 minutes each) of good quality that exhibit only one of the following atmospheric events: good weather (N = 22), rain (N = 22), wind (N = 31). Each 10-minute file has been divided into ten single-minute files, for a total of 750 cases, categorized into six groups according to the atmospheric event that characterized it (day-good, day-rain, day-wind, night-good, night-rain, night-wind).

This subset of data was proceeded with the acoustic analysis performed using the R environment and several libraries, including Soundecology and Seewave, which allow to obtain both general acoustic parameters, such as the spectral energy value (minimum, maximum, average), and both acoustic metric specifications to estimate the differences in the sound structure, such as the H and D indices (Sueur et al., 2008), respectively for acoustical acoustics and dissimilarity, AR (Depraetere et al., 2012) for the acoustic richness, ACI (Pieretti et al., 2011) for the Acoustic Complexity Index, calculated both on the whole frequency band (0-24.000 Hz) and on five specific frequency band range: 0-250 Hz, 250-1,500 Hz, 1,500-9,000 Hz, 9,000-20,000 Hz, 10,000-15,000 Hz.

The mean spectrum energy distributions were also explored.

Since the analysed records were collected in areas where the human presence is low or null, the geophonic component is expected to be especially evident and dominant in the frequency bands above and below the biophony.

The mean spectrum energy was extracted at three different frequency ranges:

- *low*, from 0 to 1500 Hz: at low frequencies geophonic sounds (linked in particular to the wind) were expected;
- *medium*, from 1500 to 9000 Hz: a greater predominance of biophony is expected in this frequency range;
- *high,* 10000 to 15000 Hz: in this range above the biophonic band, mainly geophonic sounds due to the presence of rain were expected.

Subsequently, the statistical analysis was performed to identify the indices or pairs of indices that could better explain the difference in the distribution of the six groups.

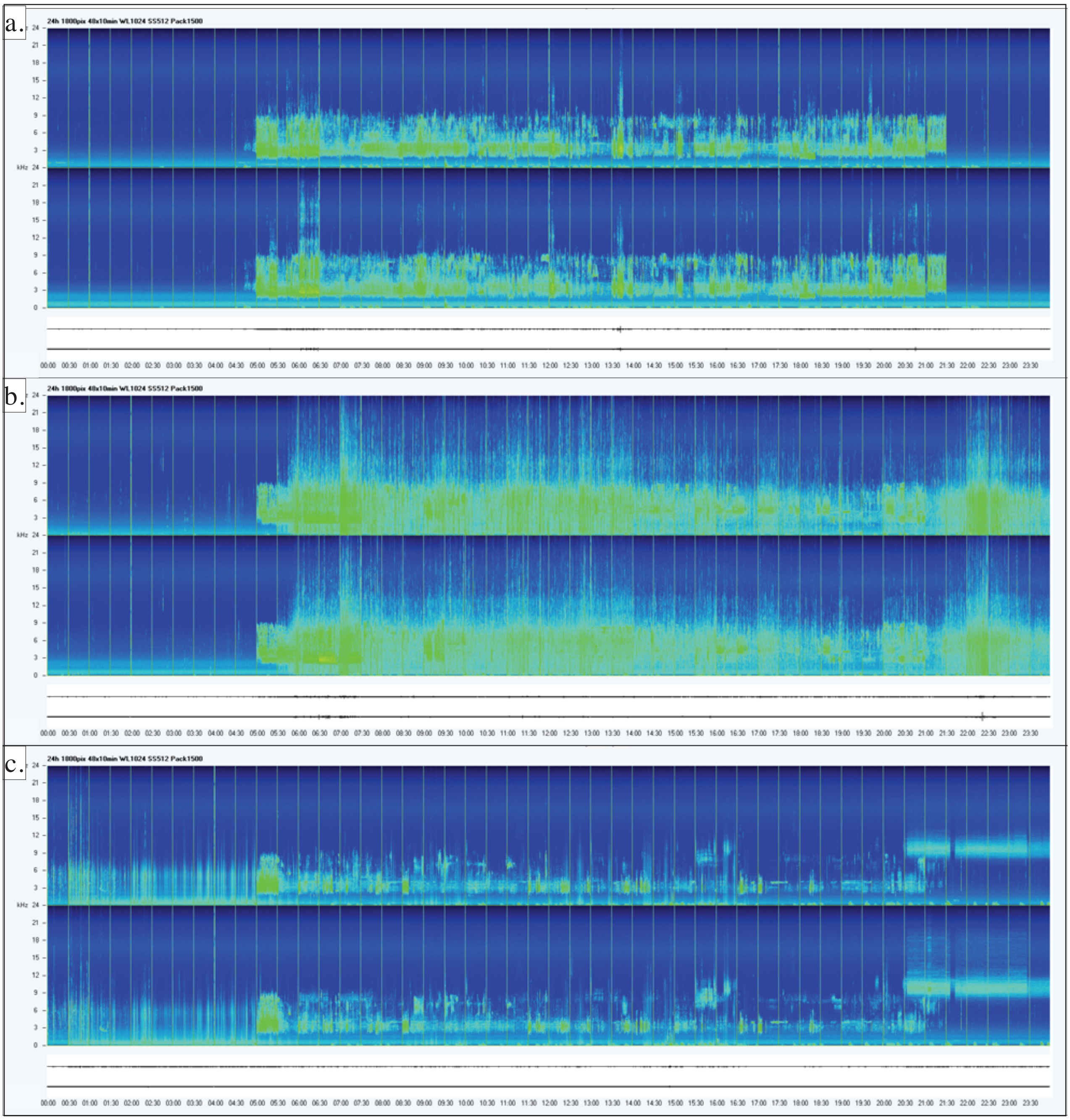


Figure 2.2 Examples of compact spectrograms for La Lama site with good weather conditions, rain and wind events, a. b. and c., respectively.

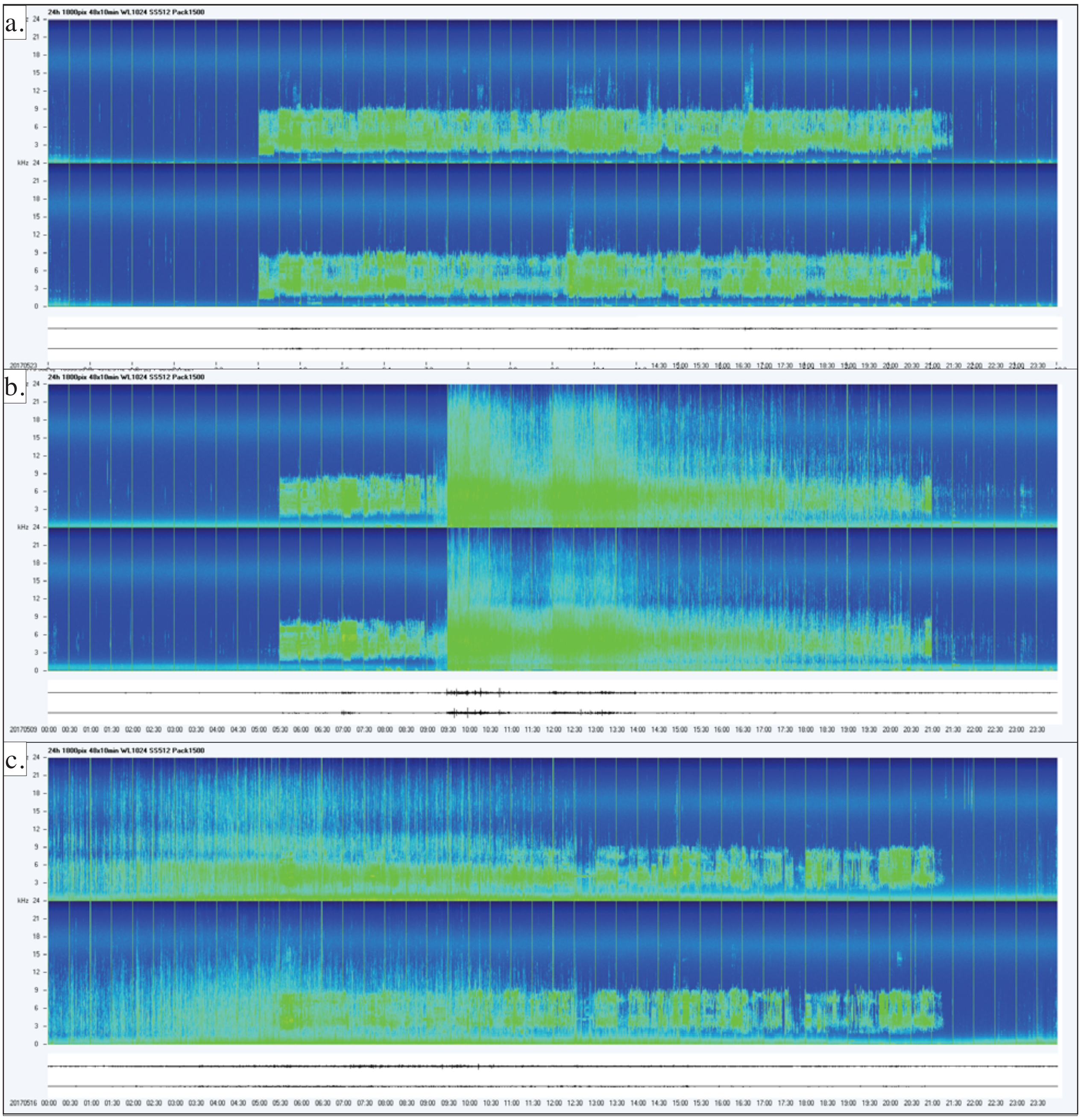


Figure 2.3 Examples of spectrograms for q700 site with good weather conditions, rain and wind events, a. b. and c., respectively.

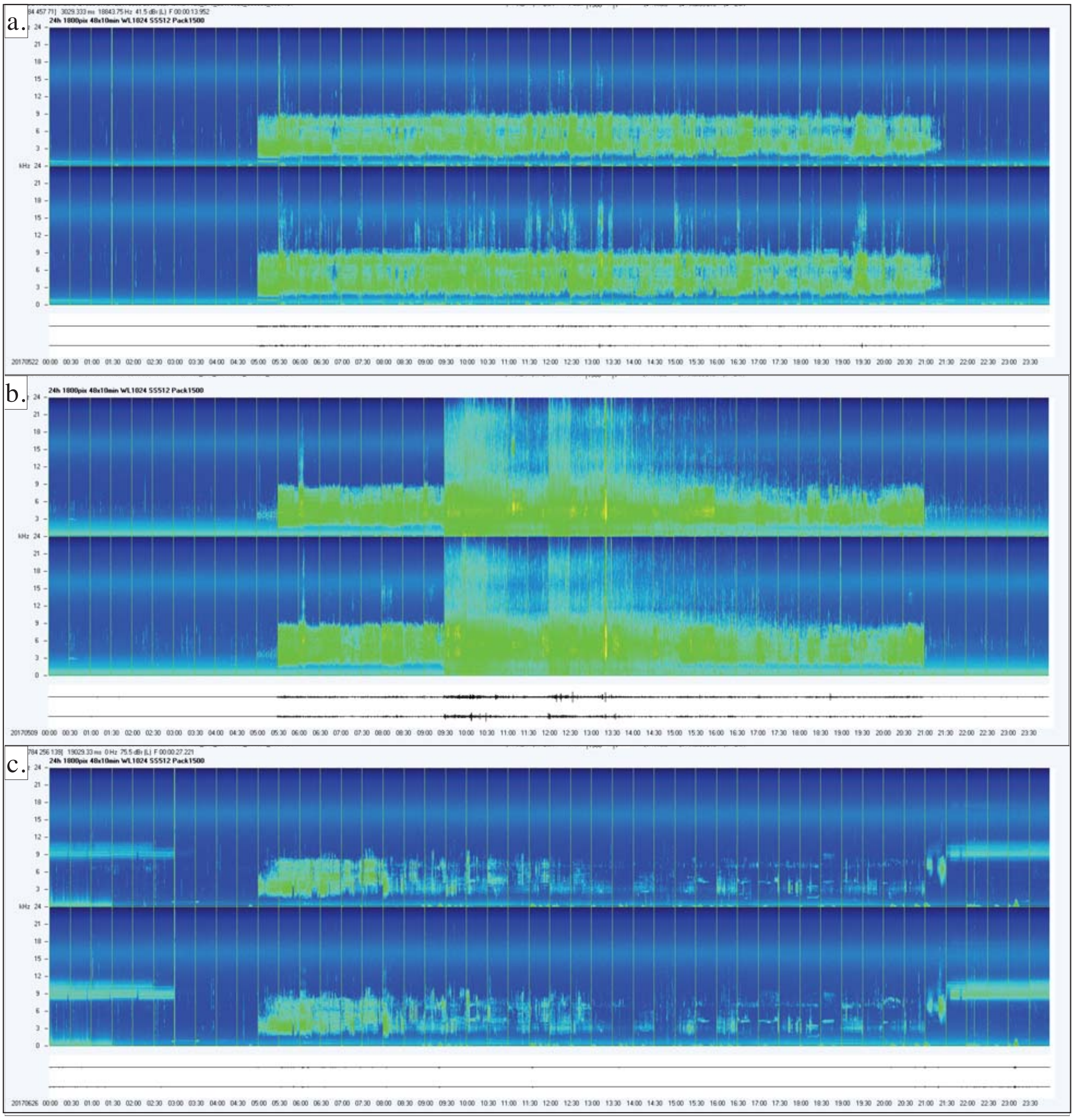


Figure 2.4 Examples of spectrograms for q1400 site with good weather conditions, rain and wind events, a. b. and c., respectively.

Results

Kruskal Wallis test showed ACI a strong discriminating power in grouping the files in the different categories (day-good, day-rain, day-wind, night-good, night-rain, night-wind); this acoustic index was calculated for five different frequency ranges, respectively: ACI: 0-250 Hz ($F = 85.15$, $P < 0.001$); ACI: 250-1,500 Hz ($F = 236.4$, $P < 0.001$); ACI: 1,500-9,000 Hz ($F = 234.7$, $P < 0.001$), ACI: 9,000-20,000 Hz ($F = 311.6$, $P < 0.001$); ACI: 10,000-15,000 Hz ($F = 321.4$, $P < 0.001$).

The post hoc Tukey test for the comparison of ACI values in the 9.000-20.000 Hz frequency range confirms a difference in ACI values in files classified as rain (both day and night) compared to the others (good and wind) (good vs rain: $P < 0.001$, rain vs wind: $P < 0.001$, good vs wind: $P = 0.99$) (Figure 2.5).

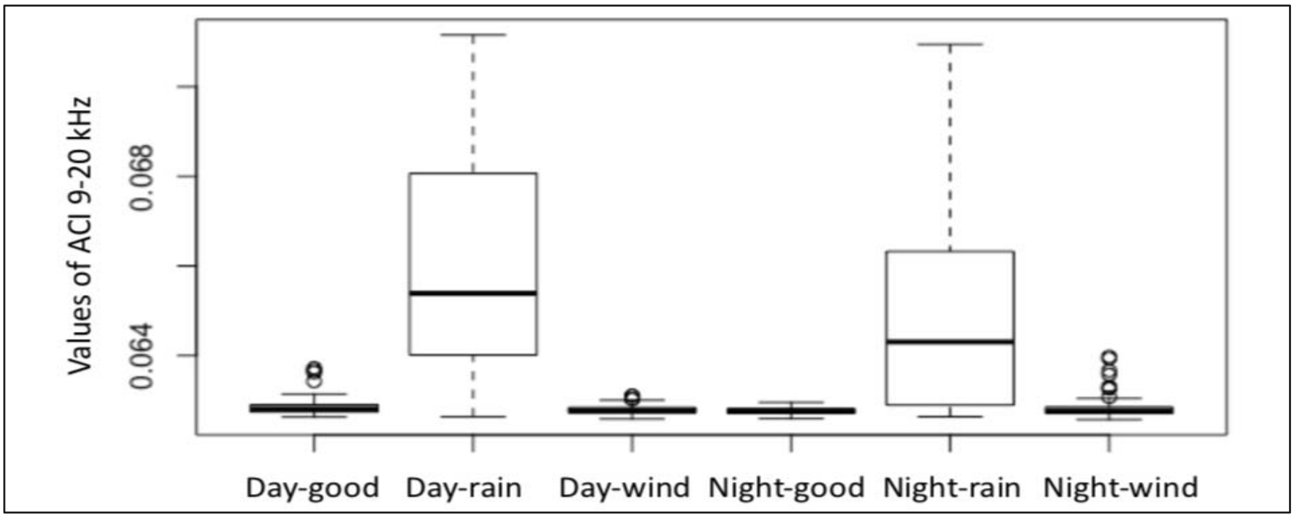


Figure 2.5 Example of distribution of the values of Acoustic Complexity Index (ACI) calculated in the frequency range 9 kHz – 20 kHz; the categories day/rain and night/rain differ significantly from the others.

A second parameter is the ratio of the spectral energy calculated in the frequency ranges 0-1.500 Hz (*low*), 1.500-9.000 Hz (*medium*) and 10.000-15.000Hz (*high*). The ratio between the values of the *low* and *medium* ranges, in particular, indicates positive values only for files belonging to the 'good' category (Figure 2.6).

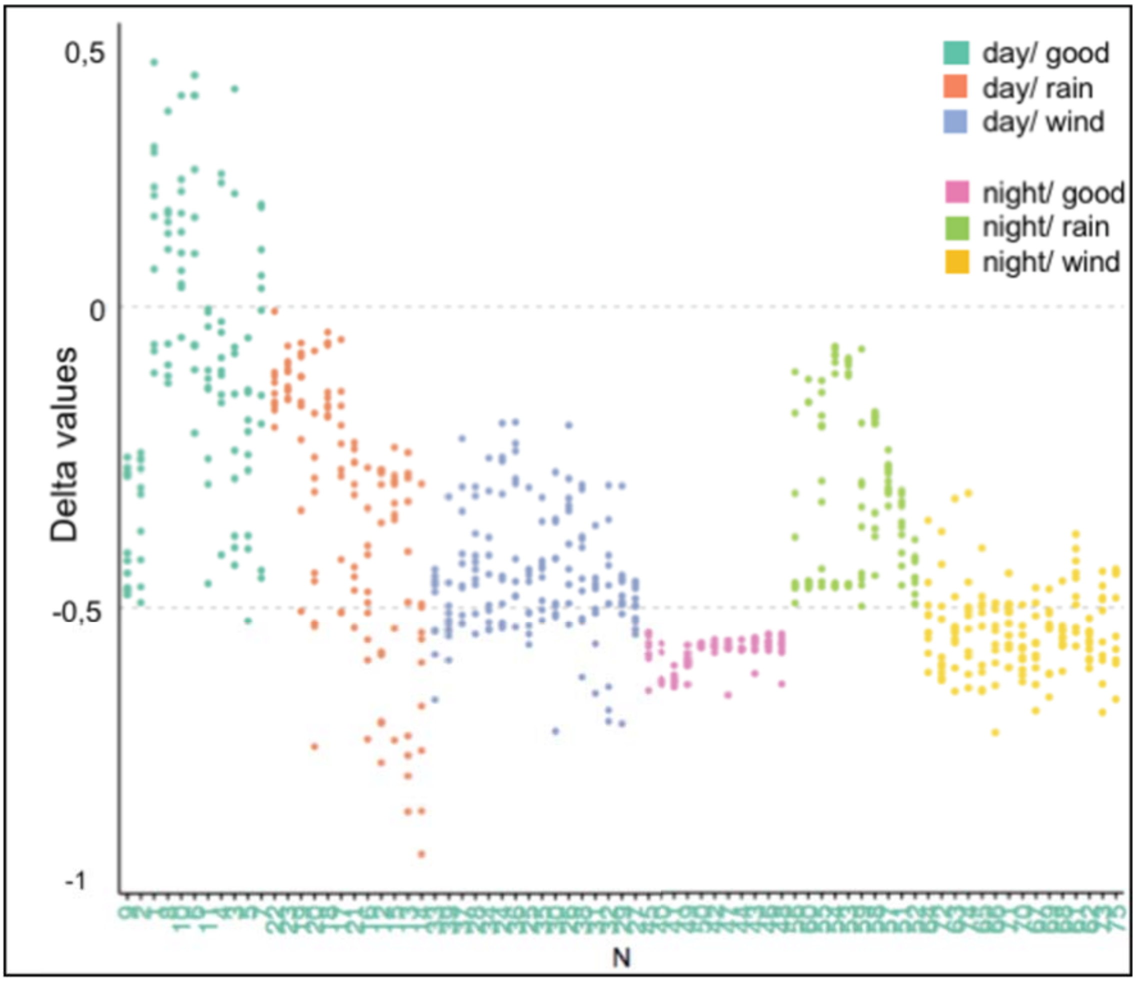


Figure 2.6 Delta values distribution for the ratio of Mean Spectrum Energy (0-1.5 kHz) on Mean Spectrum Energy (1.5- 9 kHz), for (β - ᵭ)/(β +ᵭ), with ᵭ < β.

Proceedings of the 10th International Conference on Ecological Informatics

Focus on geophony: what weather sounds can tell

***Roberta Righini*[1] *and Gianni Pavan*[1]**

[1]*University of Pavia, Italy*

Corresponding author e-mail: roberta.righini01@universitadipavia.it

ABSTRACT:

Nowadays, one of the most important biodiversity conservation challenges is to manage and mitigate the threats of climate change and the high rate of species loss caused by it.

In this context, Ecoacoustics is an increasingly emerging interdisciplinary science that investigates natural and anthropogenic sounds and their relationship with the environment. It can become a powerful tool for management and conservation efforts. By the use of passive acoustic monitoring of a habitat, it is possible to get a picture of its soundscape, that is composed of the sounds produced by the animals (biophony), the noise produced by atmospheric and physical events (geophony: wind, rain, water, etc..) and by human activity (anthropophony: cars, airplanes, etc..; other activities to be referred as technophony, if electro-mechanical noise overbears).

But, if on the one hand, there are more and more studies concerning the analysis of the biophony component that are translated into the detection new indices for the determination of different bio-diversity and bio-richness levels in different habitat, and, more recently, a great attention is paid to the human-activity sounds, on the other hand, the third main soundscape component, geophony, is a rich but still unexplored source of information in the environmental acoustics recordings.

The aim of the work is to focus the analysis on natural background noise of recording collected in an Italian National Park in order to investigate the acoustic characteristics of a natural environment in different weather conditions (good, wind or rainy conditions).

Moreover, since passive acoustic monitoring generates large data sets of audio recordings that have to be stored and processed, the possibility of discriminating the recordings according also to different weather conditions, will contribute to make processing time manageable and to reduce analysis effort.

KEYWORDS: Ecoacoustics, Soundscape ecology, Geophony, Rain, National park

From the visual and listening analysis of the recordings of 15 days of sampling (from 1st to 15th of June 2014), 44 species (from the thesis of Cateni, 2018) were identified through the recognition of their song (out of 52 species of birds surveyed by traditional on-site listening census carried out in previous years on a wider area) (Cursano & Lucchesi, 2009).

The analysis with automatic detection algorithms has been the most challenging issue.

Starting from audio files in which the target species had already been identified, acoustic templates valid for the identification of bird species were created and organized in a reference library; automatic algorithms were tested for woodpeckers and tawny owls (Figures 2.7-2.8).

It was a pilot study to test the possibility of creating an archive with most of the species present in the recordings in order to develop, in future, increasingly automatic recognitions as the base of continuous monitoring.

The possibility of identifying the species in the recordings (especially in the automatic mode through reference samples) will be opening new perspectives for biodiversity studies aiming to elaboration of species' presence/absence tables at a daily/hourly or area level of detail (for example) or focalizing to more elusive vocalizing species.

Methods

The search for species-specific sound patterns for automatic identification was performed with the monitoR Studio package that allows to create patterns for automatic detection and to perform a spectrogram cross correlation. The analysis is a main three-step process:

1. create a correlation template (or a list that contains multiple templates) of the target acoustic event, by setting time and frequency limits in a sample file;
2. calculate correlation score between the spectrogram of the template and of each time bin in the survey file;
3. identify ‘peaks’ in the scores to find best matches with target acoustic event and setup the score cutoff to balance false and positive ids.

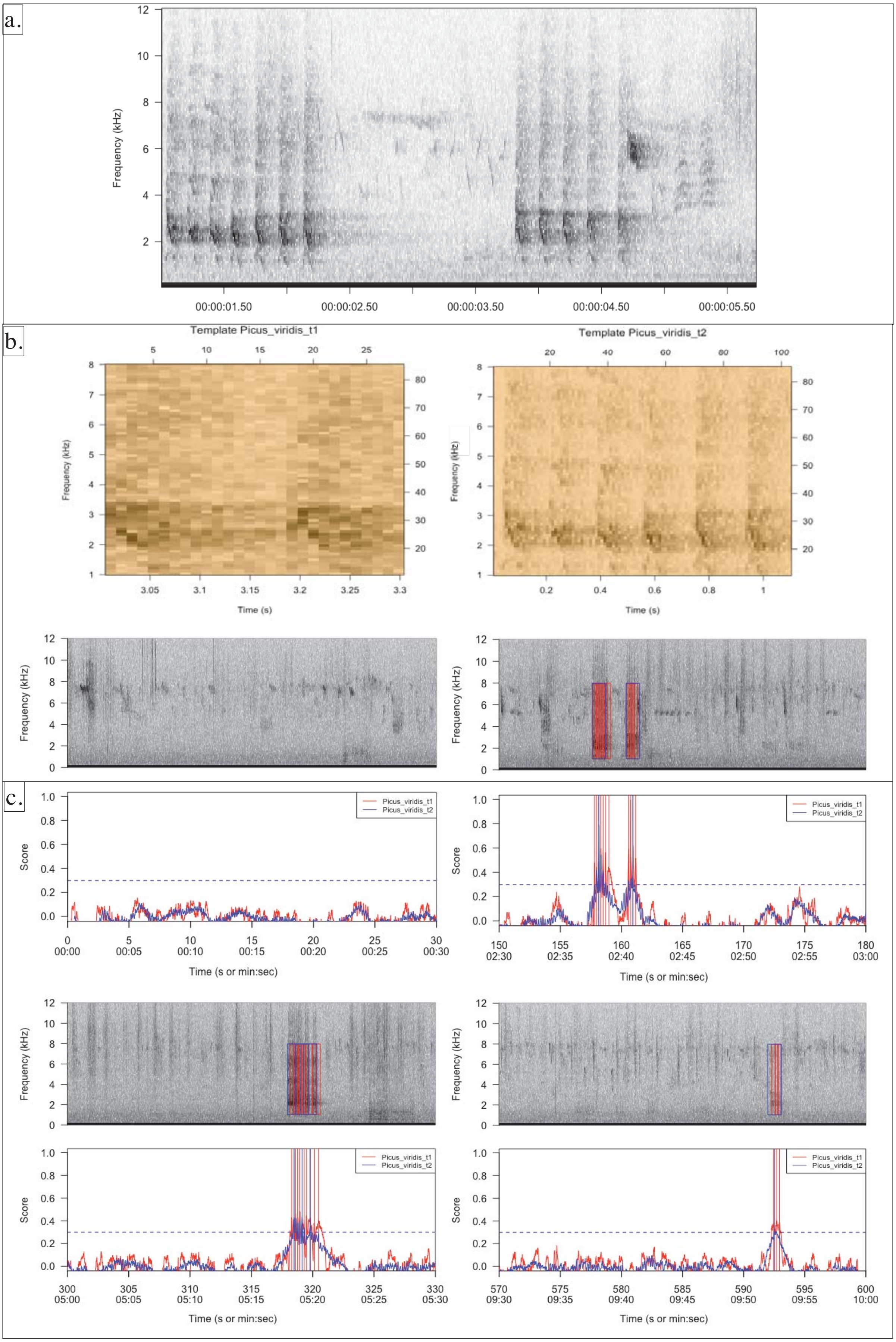


Figure 2.7 Example for automatic identification of the green woodpecker *(Picus viridis*). **a.** target species' vocalization; **b.** different kind of templates for detection; **c.** testing of different time/frequency parameter templates (blue, red and green) for the automatic identification

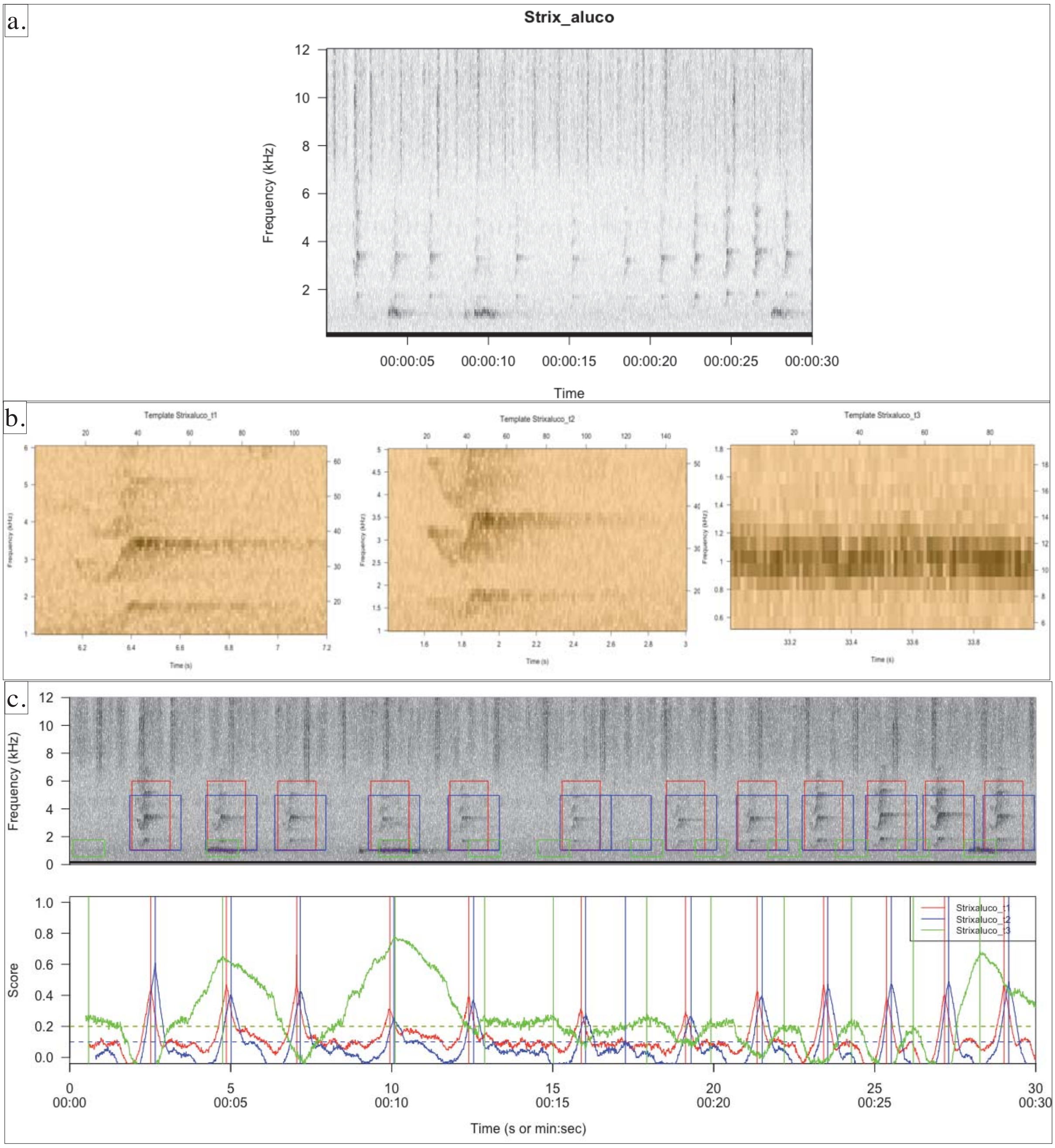


Figure 2.8 Example for automatic identification the tawny owl (*Strix aluco*). **a.** target species' vocalization; **b.** different kind of templates for detection; **c.** testing of different time/frequency parameter templates (blue, red and green) for the automatic identification.

FOCUS ON THE ANTHROPOPHONY (OR LOW FREQUENCY BAND SOUNDS)

(Paper in preparation, see preliminary results in Pavan, 2016)

Anthropogenic noise has an increasing role in disrupting the natural acoustic habitats. Noise generated by road traffic, rail or air transport, industrial activities, and, in the sea, shipping, offshore construction, oil and gas exploration, and sonar operations can mask crucial acoustic environmental cues and communication signals and elicit behavioral responses with the potential to cause chronic physiological stress on the individuals and devastating effects on a community or population.

The use of passive acoustic monitoring could prove to be a powerful tool for analysing the level of the noise, scoring habitats affected by anthropogenic noise and assessing the impact on animal communities.

Methods

A general analysis of the records collected at different points in the Casentinesi Forests National Park (especially inside or adjacent to the Sasso Fratino Integral Nature Reserve) show overall full band Sound Level Measure around 30 dB(z) and 25 dB(A) in slow mode. Both A and Z weighting were considered, the A curve relates to human perception of the sound levels, but the Z curve provides an objective measure regardless of the human hearing limits (Figure 2.9).

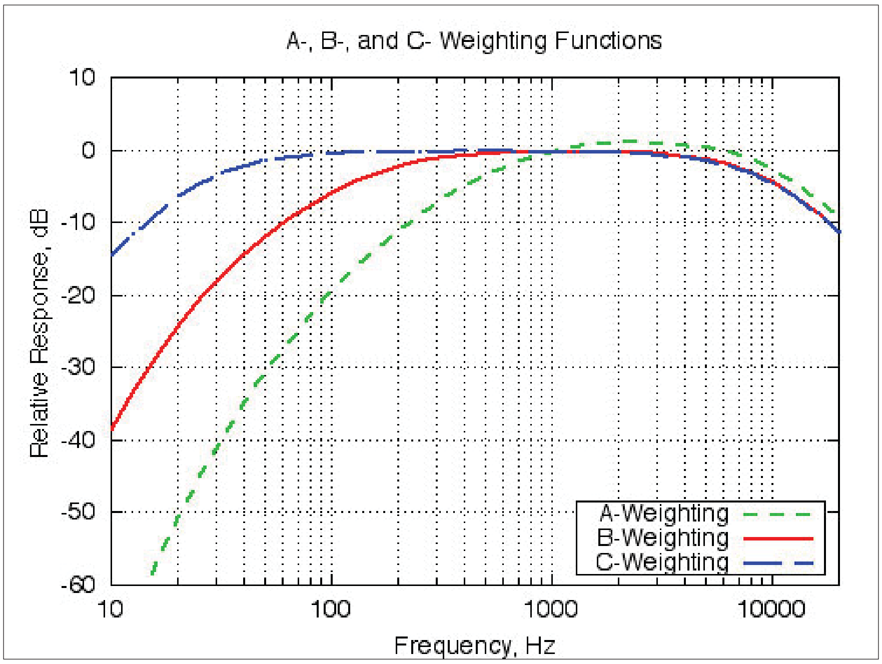


Figure 2.9 Weighting curves. The A curve is usually used for providing noise levels in relation to the human hearing sensitivity. The Z curve, also called flat or unweighted, is completely flat across the whole measuring spectrum regardless of the human limits.

Worth to mention that in most 5 minutes samples of quiet days, the recorded noise levels in 1/3 octave bands (no weighting) show the L50 and L95 percentiles always below 20 dB (without wind), exceeding 10 dB only in the range 100 Hz to 2 kHz because of the texture of little noises and insects' hums and buzzes. The L5 percentile exceeds 20 dB only in the range 100 Hz – 2 kHz, and never reach 30 dB. (Figure 2.10).

High levels of anthropogenic noise are only due to airplane overflights. Even flights at 9000m altitude do produce a highly noticeable increase of low frequency noise, up to 56 dB(z) in the overall level and in 1/3 octave bands below 500 Hz, as shown in Figure 2.11.

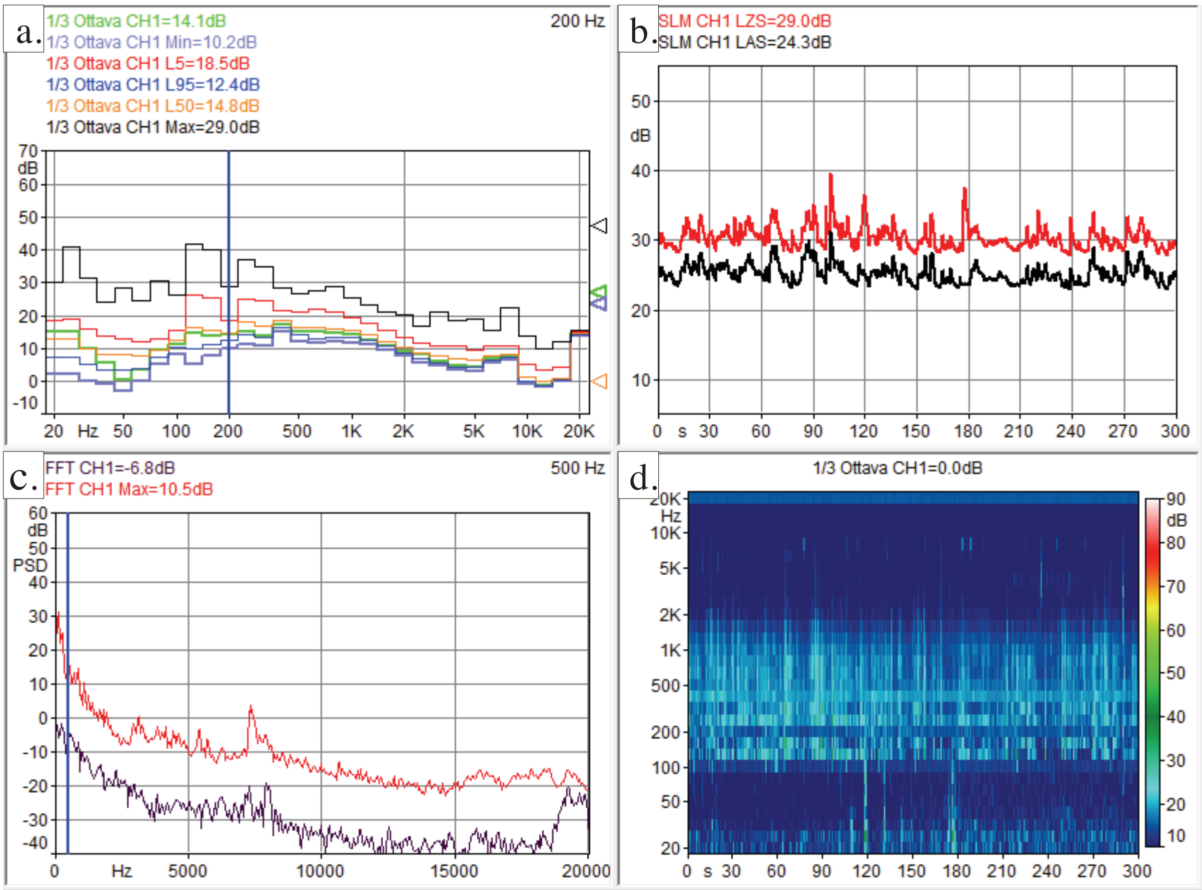


Figure 2.10 Example of recording in conditions of low environmental noise (no wind, no birds singing). Measurements taken with a low-noise microphone Piezotronics PCB 378A45 connected to SINUS Harmony acquisition system with SINUS SAMURAI software. Graph **a.** shows unweighted (z) 1/3 octave bands with selected percentiles and in **b**. the overall (full band) SLM (Sound Level Measure) with both A and Z weighting in Slow mode over a 300 seconds time period. In **c.** the FFT based PSD (Power Spectral Density) and in **d.** the 1/3 octave spectrogram over a 300 seconds time period. In D the visible sound traces are mainly due to the buzzing of insects in flight and to small noises from the forest that determine the sound levels between 100 Hz and 2 kHz.

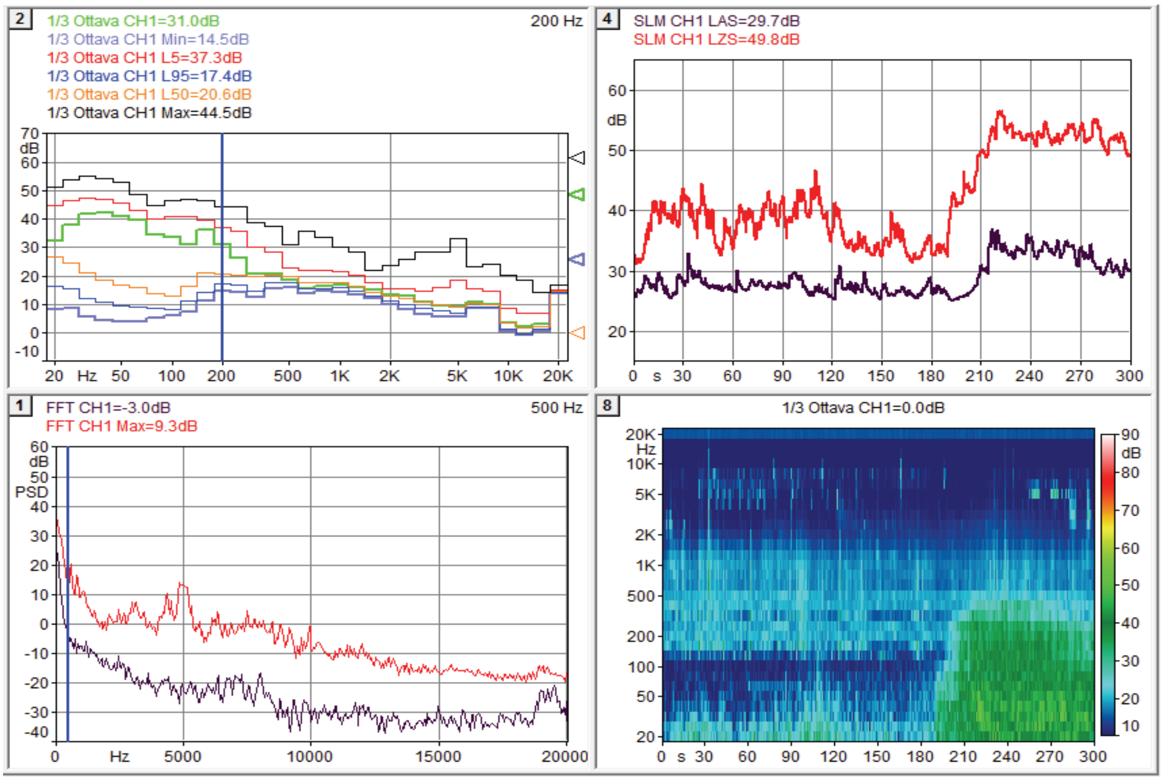


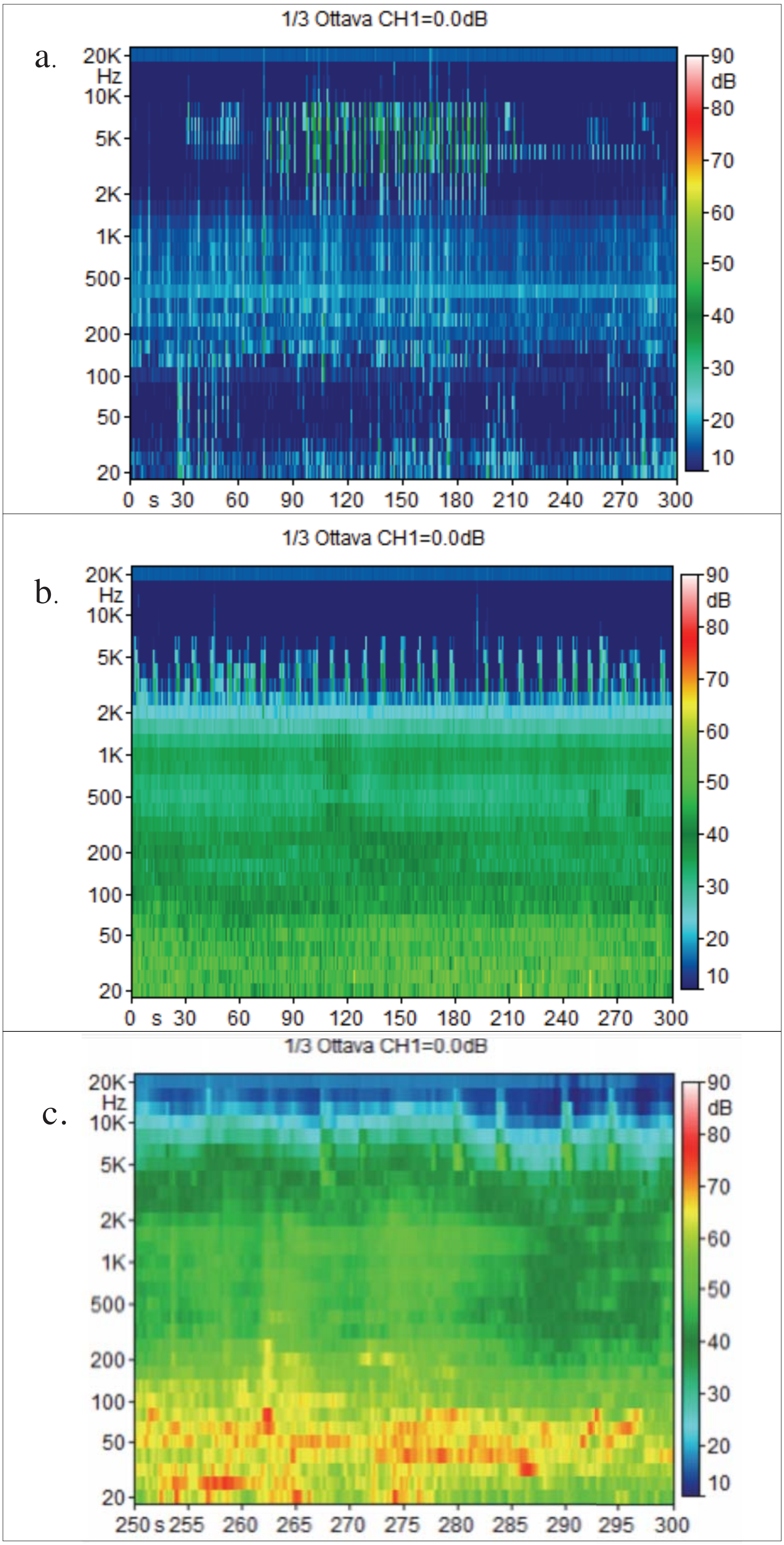
Figure 2.11 Airplane overflight produces a 50 dB increase in 1/3 octave frequency bands below 500 Hz.

Another interesting result is that with 1/3 octave band analysis, the low frequency bands (below 100 Hz), the level (L95) is close to 0 dB and the MIN goes below 0 dB, indicating a significant lack of continuous anthrophony component (continuous low frequency noise, e.g. due to car traffic in a range of several km) (Figure 2.12).

Roads, railways, and airplanes are the most common noise sources that spread low frequency noise, that propagates very well compared to higher frequency components, over large distances. In the Sasso Fratino INR only airplanes do produce recurrent low frequency technophony.

Figure 2.12 (in the following page) 1/3 octave spectrograms of three different sites. **a.** shows the 1/3 octave spectrogram of 300 seconds recorded in the Sasso Fratino in conditions (no wind) similar to those in Figure X but with some birds singing revealed by traces up to 60 dB in the range 2-8 kHz. **b.** shows the recording in the garden of a residential area on the boundaries of Pavia where the 1/3 octave bands of the background level below 2 kHz are constantly above 30 dB e above 45 dB below 100 Hz.

Figure **c.** is even more dramatic as it shows the high noise level recorded in the garden of Cibra lab with noise bands below 200 Hz extending up to 80 dB and more. Low frequency components below 200 Hz are mostly due to motor vehicles engines.


1/3 Ottava CH1=0.0dB
a.
20K
Hz
10K
5K
2K
1K
500
200
100
50
20
0 s 30 60 90 120 150 180 210 240 270 300
90
dB
80
70
60
50
40
30
20
10
1/3 Ottava CH1=0.0dB
b.
20K
Hz
10K
5K
2K
1K
500
200
100
50
20
0 s 30 60 90 120 150 180 210 240 270 300
90
dB
80
70
60
50
40
30
20
10
1/3 Ottava CH1=0.0dB
c.
20K
Hz
10K
5K
2K
1K
500
200
100
50
20
250 s 255 260 265 270 275 280 285 290 295 300
90
dB
80
70
60
50
40
30
20
10

References

Cateni P. (2018). *Uso di registratori automatici programmabili per lo studio acustico dell'avifauna di una Riserva Naturale Integrale*. LT in Scienze Ecologiche e della Biodiversità. University of Pisa. Relators Giunchi D. & Pavan G.

Pavan G., (2016). Il rumore negli ambienti naturali. Misura e interpretazione. Atti 43° Convegno AIA. CN43071.

Associazione Italiana di Acustica
45° Convegno Nazionale
Aosta, 20-22 giugno 2018

FOCUS SULLA GEOFONIA: STUDIO PRELIMINARE DELL'IMPATTO DEGLI AGENTI ATMOSFERICI SULLE REGISTRAZIONI AUDIO NEL PARCO NAZIONALE DELLE FORESTE CASENTINESI (TOSCANA, ITALIA)

Roberta Righini (1), Gianni Pavan (2)

1) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
Email: roberta.righini01@universitadipavia.it

2) Centro Interdisciplinare di Bioacustica e Ricerche Ambientali, Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia
Email: gianni.pavan@unipv.it

SOMMARIO

Il paesaggio sonoro è costituito da tre componenti principali: geofonia, biofonia e antropofonia. Oltre alla stima della ricchezza e della biodiversità e ai diversi livelli di impatto antropico che caratterizzano una determinata area di studio, l'analisi dell'ambiente acustico può essere concentrata sui dati geofonici ovvero quelli connessi ai suoni di origine naturale che rappresentano una fonte di informazione ricca ma ancora poco esplorata.

1. Introduzione

Al giorno d'oggi, una delle più grandi sfide per la conservazione della biodiversità è gestire e mitigare le minacce determinate dal cambiamento climatico e ridurre l'alto tasso di perdita di specie da esso causato.

In questo contesto si inserisce l'Ecoacustica come un filone di ricerca interdisciplinare sempre più emergente che indaga i suoni naturali e antropici e la loro relazione con l'ambiente, diventando uno strumento valido e potente per la conservazione della biodiversità e la stima della qualità ambientale. Attraverso il monitoraggio acustico passivo di un habitat, è possibile ottenere un'immagine del paesaggio sonoro nelle sue diverse tre componenti, i suoni prodotti dagli animali (*biofonia*, generalmente compresa tra 2.000-8.000 Hz [1], i rumori caratteristici di eventi atmosferici e fisici (*geofonia*: vento, pioggia, acque correnti, ecc.) e i rumori legati alla presenza dell'uomo (*antropofonia*: automobili, aeroplani e altre attività antropiche, generalmente occupanti le basse frequenze: 200 – 2.000 Hz [3]; in situazioni in cui il rumore elettromeccanico sia dominante si utilizza il termine *tecnofonia*).

Ci sono sempre più studi sull'analisi della componente di biofonia che vengono tradotti nell'individuazione di nuovi indici per la determinazione di diversi livelli di biodiversità e bio-ricchezza in habitat diversi, e più recentemente una grande attenzione è stata posta sull'analisi dei suoni delle attività umane, la terza componente principale del paesaggio sonoro, la geofonia, rimane una fonte di informazioni ricca ma ancora inesplorata nelle registrazioni di acustica ambientale.

Lo scopo del lavoro è di focalizzare l'analisi sul rumore di fondo naturale al fine di indagare le caratteristiche acustiche di un ambiente naturale in diverse condizioni meteorologiche (condizioni di vento, pioggia o buone condizioni).

Inoltre, poiché il monitoraggio acustico passivo genera ampie serie di dati di registrazioni audio che devono essere memorizzate ed elaborate, la possibilità di discriminare le registrazioni in base anche alle diverse condizioni meteorologiche, contribuirà a selezionare le registrazioni migliori e a diminuire il tempo di elaborazione dei dati raccolti in campo riducendo lo sforzo di analisi.

2. Metodi

2.1 Area di studio

L'area di studio si trova all'interno del Parco Nazionale delle Foreste Casentinesi (sull'appennino tosco-romagnolo, Italia) e in particolare nella Riserva Integrale di Sasso Fratino: istituita nel 1959, la RNI di Sasso Fratino è caratterizzata da uno scarso livello di intervento antropico grazie alla mancanza di vie di accesso, alla presenza di forti pendii rocciosi e all'accidentalità del sito e tutto ciò ha permesso lo sviluppo di un ecosistema forestale evoluto e con struttura di *old-growth*, ossia di bosco vetusto. Tali popolamenti, rarissimi in Italia a causa della forte pressione che da millenni l'uomo esercita sulle foreste, sono caratterizzati da elevate bio-masse (superiori ai 1000 mc/ha) e biodiversità [2].

Dal punto di vista vegetazionale, si trova un bosco misto di faggi e abeti bianchi fino alla quota di circa 1250 m a.s.l., mentre al di sopra di tale soglia altitudinale la composizione diviene di solo faggio [3].

2.2 Raccolta dati

La raccolta dei dati è avvenuta tramite il posizionamento in loco di 3 registratori remoti autonomi Wildlife Acoustics SM3 programmati per registrare 10 minuti ogni 30 minuti, 24 ore al giorno, in modo sincrono e continuativo per il periodo compreso dal 10 maggio al 30 giugno 2017; le registrazioni digitali sono state effettuate ad una frequenza di campionamento di 48 kHz e memorizzate nel formato di file audio .wav, per un totale giornaliero di 5.6 GB.

La posizione di ciascun registratore è stata contrassegnata tramite GPS Garmin e quindi salvata come file .kmz.

Sono stati individuati 3 siti principali di monitoraggio: due siti (Q1000 e Q1400) sono compresi nella *core area* della foresta densa, propriamente all'interno della RNI di Sasso Fratino, dove l'accesso è interdetto, mentre il terzo sito (La Lama) si colloca in un'area marginale della riserva, ma pur sempre all'interno dei confini del Parco Nazionale, dove l'acceso è possibile solo attraverso la sentieristica ciclo-pedonale e alle autovetture del Corpo forestale dello stato, ora Arma dei Carabinieri.

I tre siti di campionamento si differenziano per altitudine e più precisamente: La Lama a circa 750m, Q1000 a circa 1000m e Q1400 a circa 1400m.

Associazione Italiana di Acustica, 2018
ISBN: 978-88-88942-56-8

I dati registrati sono stati salvati in formato .wav su schede di memoria estraibili e da queste trasferiti nell'archivio del laboratorio CIBRA (Università di Pavia), catalogati e preparati per le successive analisi.

2.3 Analisi dei dati

Al fine di concentrarsi sulla componente della geofonia, una prima fase di analisi ha riguardato la generazione di spettrogrammi giornalieri compatti per ciascuna giornata di registrazione tramite l'uso del software SeaPro (sviluppato dal CIBRA, [4]), e mediante il loro screening visivo effettuato dall'operatore, sono state individuate delle giornate modello caratterizzate da solo bel tempo, da pioggia, dalla presenza di vento. All'interno di queste, sono stati selezionati, in modo random ma che comprendessero sia le ore diurne (intervallo temporale calcolato con le effemeridi del mese di giugno, giorno 5:30-21:00) che notturne (notte: 21:01- 5:29), un totale di 75 file (di 10 minuti ciascuno) di buona qualità che presentassero uno solo dei seguenti eventi atmosferici: tempo sereno (N= 22), pioggia (N=22), vento (N=31).

Ogni file di 10 minuti è stato suddiviso in altrettanti file da 1 singolo minuto, per un totale di 750 casi, categorizzati in sei gruppi (*giorno-sereno, giorno-pioggia, giorno-vento, notte-sereno, notte-pioggia, notte-vento*).

Su questo subset di dati si è poi proceduto con l'analisi acustica eseguita mediante l'uso dell'ambiente R e di diverse librerie, tra cui Soundecology [5] e Seewave [6], che consentono di ottenere sia parametri acustici generali, come per esempio il valore dell'energia spettrale (minimo, massimo, medio), e sia specifiche metriche acustiche per stimare le differenze nel panorama sonoro, come gli indici H e D [7], rispettivamente per l'entropia acustica e la dissimilarità, AR [8] per la ricchezza acustica, ACI [9] per l'Indice di Complessità Acustica, calcolati sia sull'interna banda di frequenza (0-24.000 Hz) che su bande di frequenza specifiche: 0-250 Hz, 250-1.500 Hz, 1.500-9.000 Hz, 9.000-20.000 Hz, 10.000-15.000 Hz.

Successivamente si è eseguita l'analisi statistica per individuare gli indici o coppie di indici che meglio potessero spiegare la differenza della distribuzione dei sei gruppi.

3. Risultati

A partire dalle analisi statistiche effettuate sul set di dati categorizzato a priori (ovvero di cui per ogni file si conosceva l'evento atmosferico che lo caratterizzava), risulta avere un forte potere discriminante nel raggruppare i file nelle diverse categorie l'ACI (Indice di Complessità Acustica), calcolato in diversi intervalli di frequenza,, rispettivamente: ACI: 0-250 Hz (F=85.15, P < 0.001); ACI: 250-1.500 Hz (F= 236.4, P <0.001); ACI:1.500-9.000 Hz (F=234.7, P < 0.001), ACI: 9.000-20.000 Hz (F=311.6, P< 0.001); ACI: 10.000-15.000 Hz (F=321.4, P < 0.001). L'applicazione del post hoc test di Tukey per il confronto dei valori dell'ACI nell'intervallo di frequenza 9.000-20.000 Hz, conferma una differenza dei valori dell'ACI nei file categorizzati come pioggia (sia giorno che notte) rispetto agli altri ovvero sereno e vento (vedi Figura 1: pioggia-sereno: P<0.001; pioggia-vento: P<0.001; vento-sereno: P=0.99).

Un secondo parametro è il rapporto dell'energia spettrale calcolata negli intervalli di frequenza 0-1.500 Hz (*low*), 1.500-9.000 Hz (*medium*) e 10.000-15.000Hz (*high*). Il rapporto tra i valori degli intervalli *low* e *medium*, in particolare, indica valori positivi solo per i file appartenenti alla categoria 'sereno'.

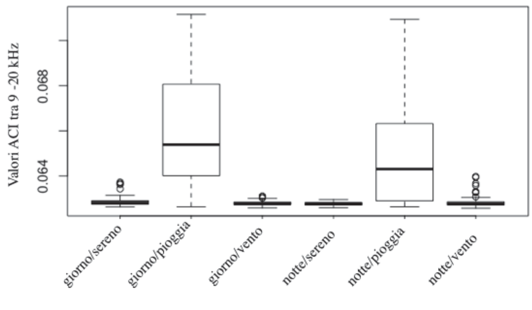


Figura 1 – Esempio di distribuzione di valori dell'Indice di Complessità Acustica (ACI) calcolato nell'intervallo di frequenza 9.000 Hz – 20.000 Hz, le categorie giorno/pioggia e notte/pioggia differiscono significativamente dalle altre.

4. Discussione

In questo studio viene presentata l'analisi preliminare sui dati audio al fine di individuare i parametri o l'insieme di indici che meglio si prestano per indicare la presenza di pioggia (e in parte vento) nelle registrazioni ottenute tramite l'uso di registratori automatici remoti all'interno del Parco Nazionale delle Foreste Casentinesi.

L'analisi statistica mostra un potere discriminativo di indici che, seppur propriamente sviluppati per indagare la biofonia, possono essere adattati allo studio anche della componente geofonica.

Tra questi, emerge l'applicazione dell'ACI calcolato in specifiche bande di frequenza, ovvero al di sopra di 9.000 Hz, la soglia che la bibliografia indica come limite per la biofonia.

Una seconda via di indagine si concentra nella formulazione di un nuovo indice che tenga conto invece dei diversi valori che assume l'energia spettrale nelle bande di frequenza.

È auspicabile ora l'applicazione di tali analisi su un dataset più ampio per testare la validità del metodo, e su registrazioni audio provenienti anche da ambienti caratterizzati da paesaggi sonori diversi da quello in studio, in cui la componente antropofonica è minima e la biofonia è costituita essenzialmente dall'avifauna.

5. Bibliografia

[1] Sueur J., Farina A., Gasc A., Pieretti N., Pavoine, S., *Acoustic indices for biodiversity assessment and landscape investigation*, Acta Acustica United with Acustica, **100**, (2014), pp 772–781

[2] Bianchi L., Bottacci A., Calamini G., et al., *Structure and dynamics of a beech forest in a fully protected area in the northern Apennines (Sasso Fratino, Italy)*, iForest - Biogeosciences and Forestry **4** (2011), pp.136-144

[3] Padula M., *La riserva naturale di Sasso Fratino nelle foreste demaniali casentinesi (Appennino tosco – romagnolo)*, Ministero dell'Agricoltura e Foreste, parchi nazionali – riserve integrali, Forlì, 1985

[4] http://www.unipv.it/cibra/

[5] http://ljvillanueva.github.io/soundecology/

[6] Sueur J., Aubin T., Simonis C., *Seewave, a free modular tool for sound analysis and synthesis*, Bioacoustics **18.2** (2008) pp 213-226

[7] Sueur J., Pavoine S., Hamerlynck O., Duvail S., *Rapid acoustic survey for biodiversity appraisal*, PloS one, **3.12,** (2008), e4065

[8] Depraetere M., Pavoine S., Jiguet F., Gasc A., Duvail S., Sueur J., *Monitoring animal diversity using acoustic indices: implementation in a temperate woodland*, Ecol. Indic., **13** (2012), pp. 46-54

[9] Pieretti N., Farina A., and Morri D., *A new methodology to infer the singing activity of an avian community: the Acoustic Complexity Index (ACI)*, Ecological Indicators **11.3** (2011), pp 868-873

CHAPTER 03

THE RESEARCH PROTOCOL

In this chapter, the research protocol developed is described and presented in its theoretical and methodological part.

The Research Protocol developed consists of four main parts (Figure 3.1):

1. selection of surveys sites;
2. data collection;
3. qualitative analysis of acoustic data (generation of compact daily spectrograms);
4. quantitative analysis of acoustics data (bioacoustic analysis and sound identification; ecoacoustic indices and statistical analysis).

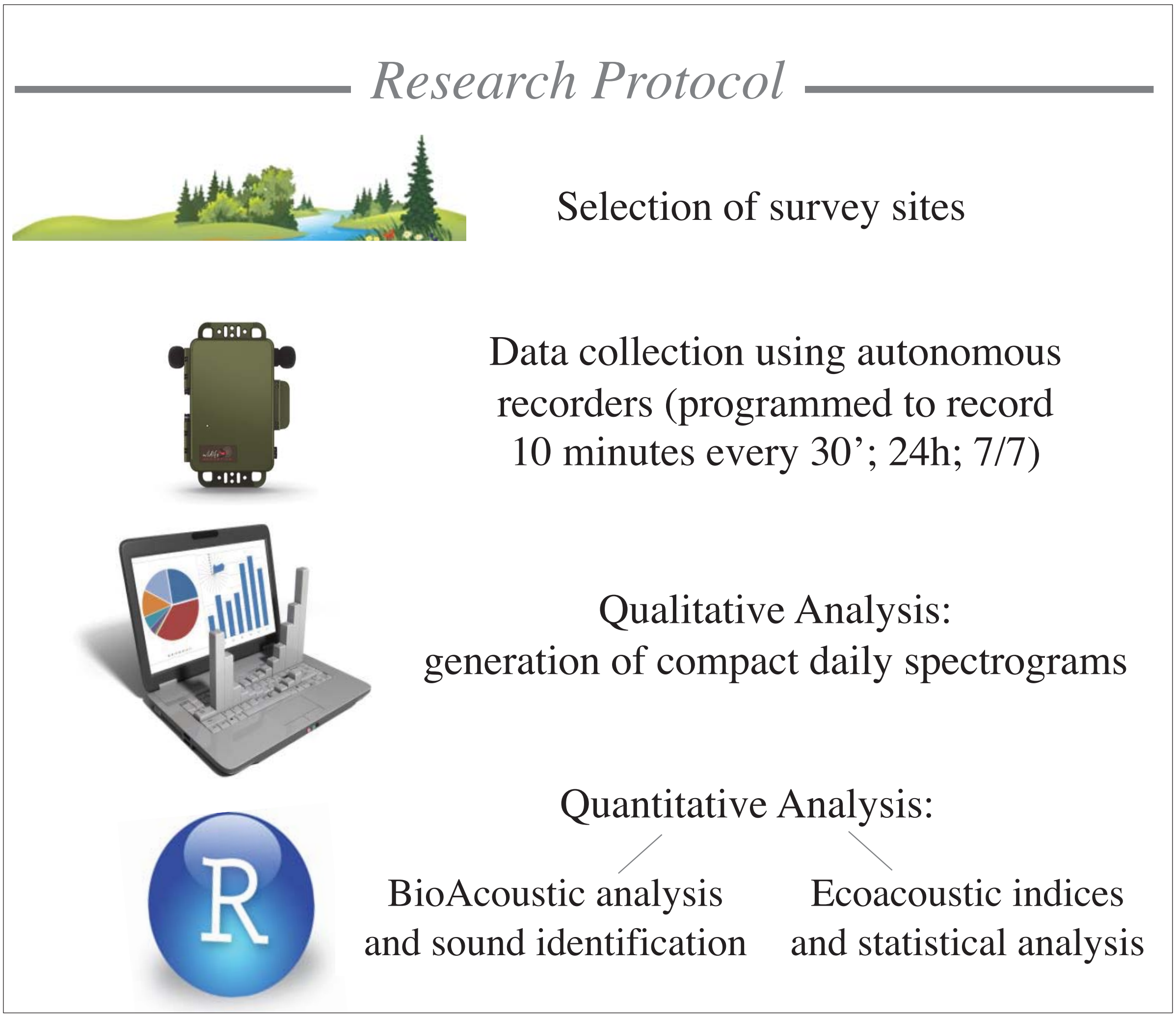


Figure 3.1. Graphic representation of the protocol divided into its four main parts.

1. Selection of survey sites

Ecoacoustics monitoring provides quantitative data over large spatial and temporal scales for the comparison of acoustic variance both intra-site (for monthly or yearly sampling) and inter sites (for multiple simultaneous locations).

The selection of sites to monitor is a very important phase. It is recommendable to identify sites that can be monitored in simultaneous and in continuous to increase a reference acoustic data archive.

In this case, a long-term acoustic data collection allows to build a pivotal repository for monitoring the Sasso Fratino's biophony status and evolution due to climatic changes: as it is prohibited any human presence or intervention, only external global alterations could be considered as possible factors influencing any shift in the species' presence and distribution inside the reserve.

Considering its biodiversity, ecological integrity, and lack of anthropogenic noise sources, we consider the area as a reference site for ecoacoustic studies (see following section for more details about Sasso Fratino Integral Nature Reserve).

2. Data collection

2a. In field

Data collection is carried out through the on-site positioning of remote autonomous Wildlife Acoustics Song Meters recorders (models SM3 and SM4, see Figure 3.2).

The recorder should be placed on the trunk of a tree, with even just plastic strips, at about 2 m in height (but also at a higher level if necessary to prevent damage or theft).

The GPS position, altitude, orientation and other useful information must be collected and provide a description of the surrounding environment (possibly with photographs).

The recorder should be placed in areas far from sources of noise (rivers, waterfalls, tourist paths, etc..), unless the study includes a focus especially on these acoustic elements.

Acoustic recordings should be integrated with an extensive data logging of weather conditions, temperatures, precipitation, and solar radiation because these parameters may drive animals' behaviour and their production of sounds (Brumm, 2004).

Finally, it is possible to integrate the study of the soundscape by placing integrative tools aimed at recording ultrasounds, e.g. emitted by insects and by echolocating bats and eventually the use of hydrophones for the monitoring of water environments (for amphibians, for example).

Monitoring the presence of bats has been done at different altitudes and in different habitats, but it is not included in this thesis work.

a. b. c.

Figure 3.2 Different examples of Wildlife Acoustics Song Meter Recorders currently available: a. SM3 Acoustic Recorder with stereo microphones (older model); b. SM4 Acoustic Recorder with stereo microphones; SM4 BAT Full-Spectrum Ultrasonic Recorder (for only bat species) with a single microphone for ultrasounds.

Each recorder is programmed to recording up to 24 kHz (sampling at 48 kHz, 16-bit, stereo) for 10 minutes every 30 minutes, 24 hours a day, in a synchronous and continuous way (archiving about 5.6GB/day, 170GB/month).

The efficacy of recording 10 minutes every is tested and it results to be a good compromise that optimizes the effectiveness of the samples and avoids time- and resource-consuming analyses (see the section "*comparison between different time-size samples"* for more details).

The programming of the SM4 can be made directly on the unit by using the on-board screen and buttons, however the best way is to use the SM4 configuration utility and save the programming file on a SD card for subsequent uploading on all the recorders used. Then, on each recorder it is required to perform the microphone calibration with a suitable calibrator (1 kHz 94 dBSPL tone) and, at the onsite installation it is important to record the GPS position by connecting the Wildlife Acoustics GPS to the recorder. This way all the recorders can memorize their accurate position and time synchronization.

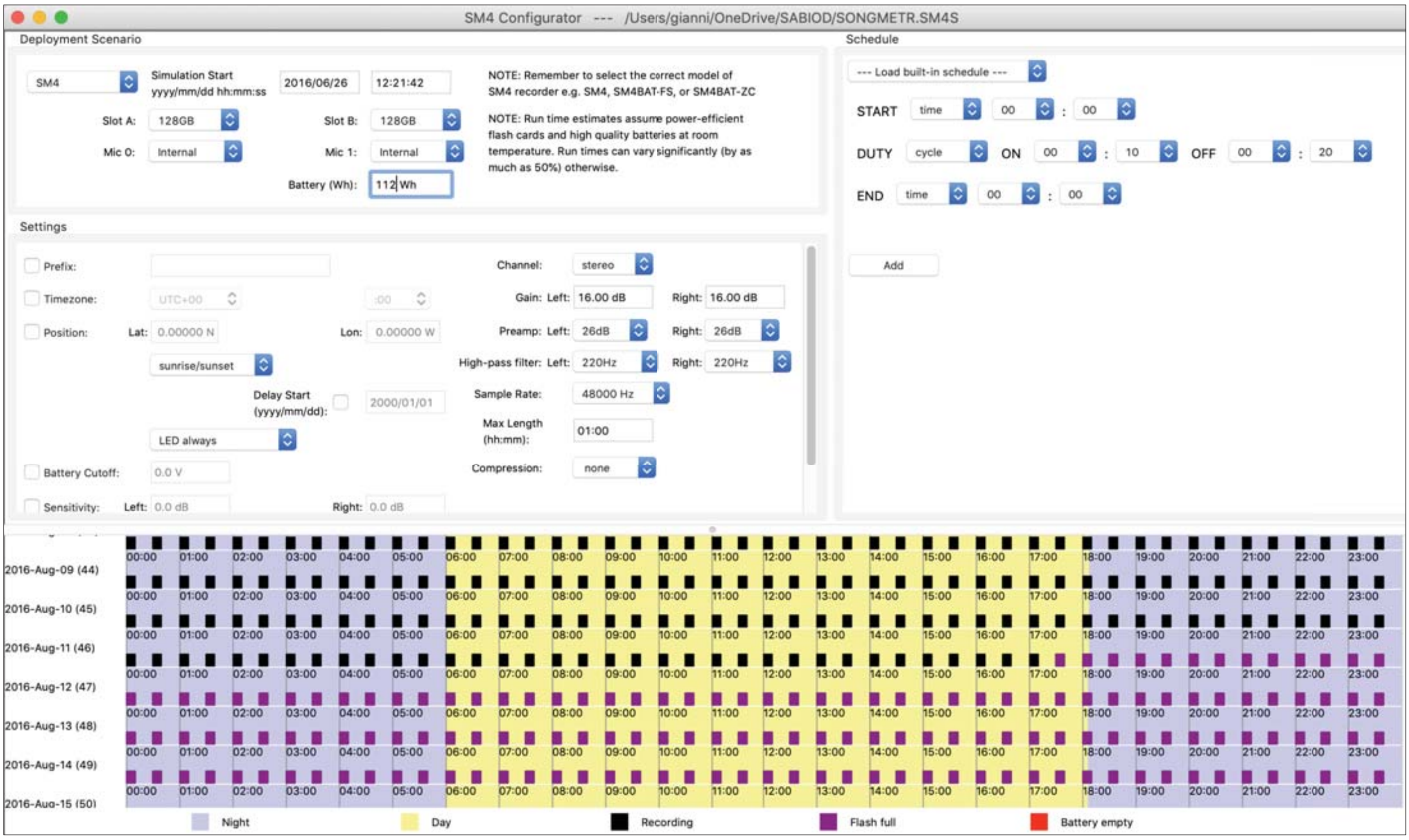


Figure 3.3 Use of the SM4 Configurator software to program settings and schedules from a computer. Graphic visualization of the time schedule; by scrolling the map of the recording periods it is possible to check the changes of the sunrise and sunset times (yellow band) and verify the total recording duration according to the recording settings (number of channels, sampling frequency, compression factor) and capacity of batteries and memories installed.

For example, with a two 128GB memory cards, and with 4 internal D-type batteries (torch) of 1.5V and 19 Ah capacity, it is possible to record 10 minutes every 30, 2 channels at 48 kHz, for about 30 - 35 days (depends on temperature); by installing an external car battery (12V and 40 Ah), the recorder can work for about six to nine months (also depending on the temperature) and the limit becomes the availability of memory; with a 12V / 40 Ah battery and two 512 GB cards it records for six months and four days in uncompressed .wav format which can become over 9 months with lossless compression (proprietary format, similar to FLAC).

2b. In laboratory

The recorded data are saved as .wav files on memory cards inside the recorders and then the files are transferred to the archive of the CIBRA's laboratory (University of Pavia), then catalogued, organized in site specific folders, and prepared for subsequent analyzes (Figures 3.4-3.5).

When using normal audio recorders, each file should be renamed to include the following pieces of information to make subsequent cataloguing and browsing files easier:

- unique code that identifies the sampling site;
- model of the used recorder (and the code linked to each recorder if multiple tools are used simultaneously);
- the number of microphones (mono or stereo) in which the recording was made;
- date (yy / mm/ dd);
- hour (hh: mm: ss);

In case a Wildlife Acoustics instruments are used, the filenames contain all the above information in the format RECORDERID_CHANNELS_DATE_TIME.

Nome	Data di modifica	Dimensioni
SM3D_0+1_20151112_000000.wac	12 novembre 2015 00:10	64,8 MB
SM3D_0+1_20151112_003000.wac	12 novembre 2015 00:40	64,8 MB
SM3D_0+1_20151112_010000.wac	12 novembre 2015 01:10	64,8 MB
SM3D_0+1_20151112_013000.wac	12 novembre 2015 01:40	64,8 MB
SM3D_0+1_20151112_020000.wac	12 novembre 2015 02:10	64,8 MB
SM3D_0+1_20151112_023000.wac	12 novembre 2015 02:40	64,8 MB
SM3D_0+1_20151112_030000.wac	12 novembre 2015 03:10	64,9 MB
SM3D_0+1_20151112_033000.wac	12 novembre 2015 03:40	64,9 MB
SM3D_0+1_20151112_040000.wac	12 novembre 2015 04:10	64,9 MB
SM3D_0+1_20151112_043000.wac	12 novembre 2015 04:40	64,9 MB
SM3D_0+1_20151112_050000.wac	12 novembre 2015 05:10	64,9 MB
SM3D_0+1_20151112_053000.wac	12 novembre 2015 05:40	64,9 MB
SM3D_0+1_20151112_060000.wac	12 novembre 2015 06:10	64,9 MB
SM3D_0+1_20151112_063000.wac	12 novembre 2015 06:40	64,9 MB
SM3D_0+1_20151112_070000.wac	12 novembre 2015 07:10	64,9 MB
SM3D_0+1_20151112_073000.wac	12 novembre 2015 07:40	65,2 MB
SM3D_0+1_20151112_080000.wac	12 novembre 2015 08:10	65,1 MB
SM3D_0+1_20151112_083000.wac	12 novembre 2015 08:40	65 MB
SM3D_0+1_20151112_090000.wac	12 novembre 2015 09:10	64,9 MB
SM3D_0+1_20151112_093000.wac	12 novembre 2015 09:40	65,4 MB
SM3D_0+1_20151112_100000.wac	12 novembre 2015 10:10	64,9 MB
SM3D_0+1_20151112_103000.wac	12 novembre 2015 10:40	64,9 MB
SM3D_0+1_20151112_110000.wac	12 novembre 2015 11:10	65 MB
SM3D_0+1_20151112_113000.wac	12 novembre 2015 11:40	64,9 MB
SM3D_0+1_20151112_120000.wac	12 novembre 2015 12:10	65,2 MB
SM3D_0+1_20151112_123000.wac	12 novembre 2015 12:40	65,2 MB
SM3D_0+1_20151112_130000.wac	12 novembre 2015 13:10	64,9 MB
SM3D_0+1_20151112_133000.wac	12 novembre 2015 13:40	65,1 MB
SM3D_0+1_20151112_140000.wac	12 novembre 2015 14:10	64,8 MB
SM3D_0+1_20151112_143000.wac	12 novembre 2015 14:40	65,5 MB
SM3D_0+1_20151112_150000.wac	12 novembre 2015 15:10	65 MB
SM3D_0+1_20151112_153000.wac	12 novembre 2015 15:40	64,8 MB
SM3D_0+1_20151112_160000.wac	12 novembre 2015 16:10	64,8 MB
SM3D_0+1_20151112_163000.wac	12 novembre 2015 16:40	64,8 MB

SSD5 › Data A

1.864 elementi, 1,88 TB disponibili

Figure 3.4 An example of file listing of recordings made with an SM3 recorder, unit D, both channels (0+1) active, date and time of each file, wac format (a lossless compression format used in early stages of the research).

Lama_SM3_0+1_20140926_060000 deers barking and roaring.wav
Lama_SM3_20141017_183000 heavy rain and wind.wav
Lama_SM3_20141125_220000 running water noises of wild pigs moving.wav
Lama_SM3_20141126_020000 rain.wav
Lama_SM3_20141128_113000 noise birds running water.wav
Lama_SM3_20150401_093000 birds airplanes.wav
TEST_SM3_20140530_050000 birds at dawn.wav
TEST_SM3_20140530_053000 birds at down.wav
TEST_SM3_20140530_060000 birds at dawn.wav

Figure 3.5 Selection of files with specific contents, useful for demonstration and training purposes.

The acoustic data analysis is then performed with a multiple level approach:

- a qualitative description of soundscape based on the generation of compact daily spectrographic views;
- listening of selected files to get a better understanding of the sound contents of the recordings;
- generation of sample spectrograms of selected sound scenes;
- selection of files representative of sound scenes or species of interest;
- a quantitative investigation based on the generation and the application of the acoustics indices and their statistical analyses.

3. Qualitative analysis of acoustic data (generation of compact daily spectrograms)

Packed spectrograms provide a "summary" of what acoustically happened day by day, and show acoustic scenes related with biophony, geophony and anthropophony/technophony (Figure X).
In general, daily compact spectrograms are generated to show the soundscape features throughout 24 hours; listening and detailed spectrographic analysis are performed with the software SeaProSabiod developed at Cibra (Pavan, 2016). All the analysis parameters (FFT, WL, WT, OVL) can be set to optimize spectrographic view.
Packed spectrograms can show long periods (10 minutes to several days) by packing together consecutive spectra. Once the spectrogram size (512 to 1024 pixels in vertical, 1600 to 5120 pixels in horizontal) and traditional sound analysis parameters are set, namely the FFT size (1024 or 2048 samples), the window size (512 samples), the window shape (Hanning), the overlap ratio (50%), and the dynamic range (0 to 96 dB), the packing factor is set according to the time extension (number of files/frames) to be shown.
To plot a one-day 1800 pixels wide spectrogram with the above parameters, a packing factor of 1500 is required. The spectrogram is computed with a traditional SFFT method, but each vertical line of pixels is computed by packing together 1500 spectra. Three packing methods are available, Min, Mean, Max.
With the Min method, for each frequency bin the minimum value of the 1500 spectra is plotted.
With the Mean method, for each frequency bin the mean value of the 1500 spectra is plotted.
With the Max method, for each frequency bin the maximum value of the 1500 spectra is plotted.
The Mean method shows the average level of each frequency bin and thus underestimate the short acoustic events and transients. E.g. a single short shot that affects few consecutive spectra may disappear.

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 decided to use the Max method because it shows all acoustic events regardless of their duration. With the chosen parameters each 10 minutes file is plotted on 38 pixels, with each pixel column representing, frequency bin by frequency bin, the maximum energy recorded in a 16 seconds time frame.
By visual screening of packed spectrograms, we verify that all days are completely and correctly recorded, and we get an overview of what happened "acoustically" in the recorded period. Then we proceed with the acoustic and thus statistical exploration.
Recordings can be browsed and listened to identify acoustic events related to geophony, to biophony and to human presence. By overview visual inspection, patterns of most relevant events for each day (e.g. rain, wind, dawn bird choruses, diurnal and nocturnal birds, airplanes, etc…) are identified and then analyzed in greater detail.
The spectrographic display can be designed at different time scales:
from the overview of all 48 daily files to obtain a daily compact spectrogram, showing what acoustically happened in a single day, to a more and more detailed views, e.g. 10 minutes, 1 minute, 10 seconds, 1 second, to examine sound series or specific acoustic details (Figures 3.6-3.8).
Some spectrograms that well represent specific soundscapes or specific acoustic events can be used as typical spectrograms that well represent specific soundscapes or specific acoustic events that can be collected and stored as references:

- intra sites variability: for the same site, models representing days with different weather conditions (to highlight scenes of good weather/rain/wind) or models showing how the soundscape of an area changes with the succession of hours (in a day) or of seasons (in a year) or between different years;
- inter sites variability: for the same day, models of different sites' compact spectrograms can be stored to compare their variability.

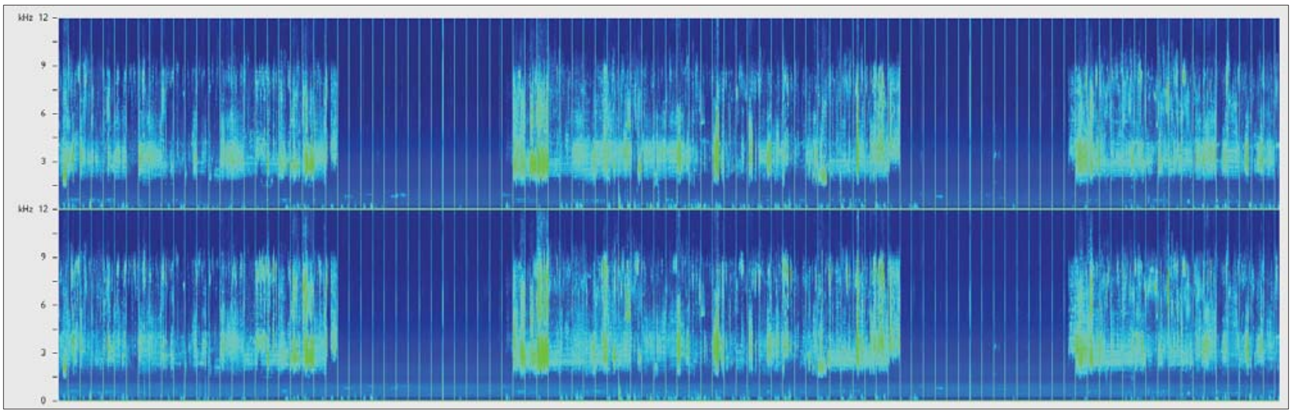


Figure 3.6 Compact spectrogram view of 3 days. The day/night alternance is clearly visible.

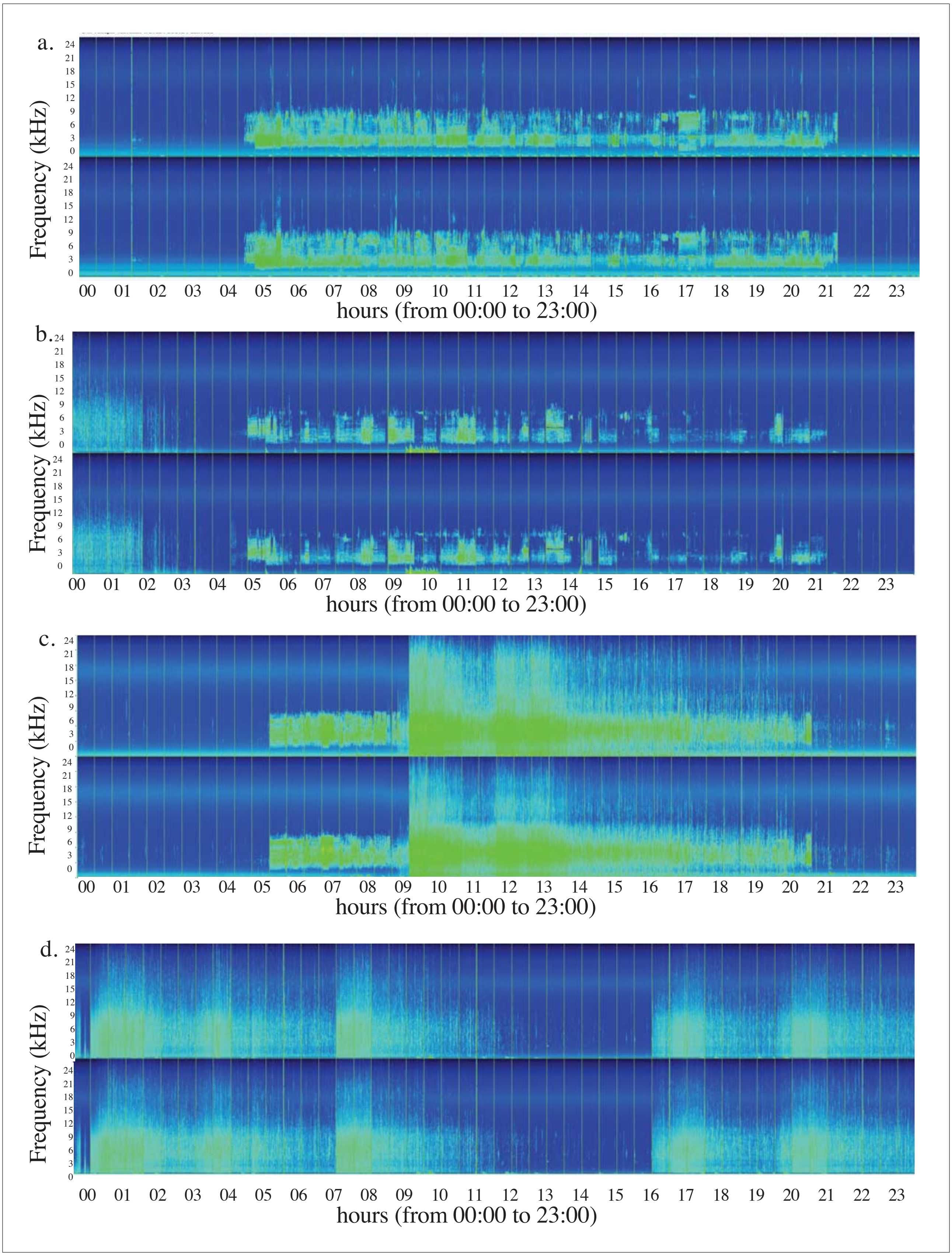
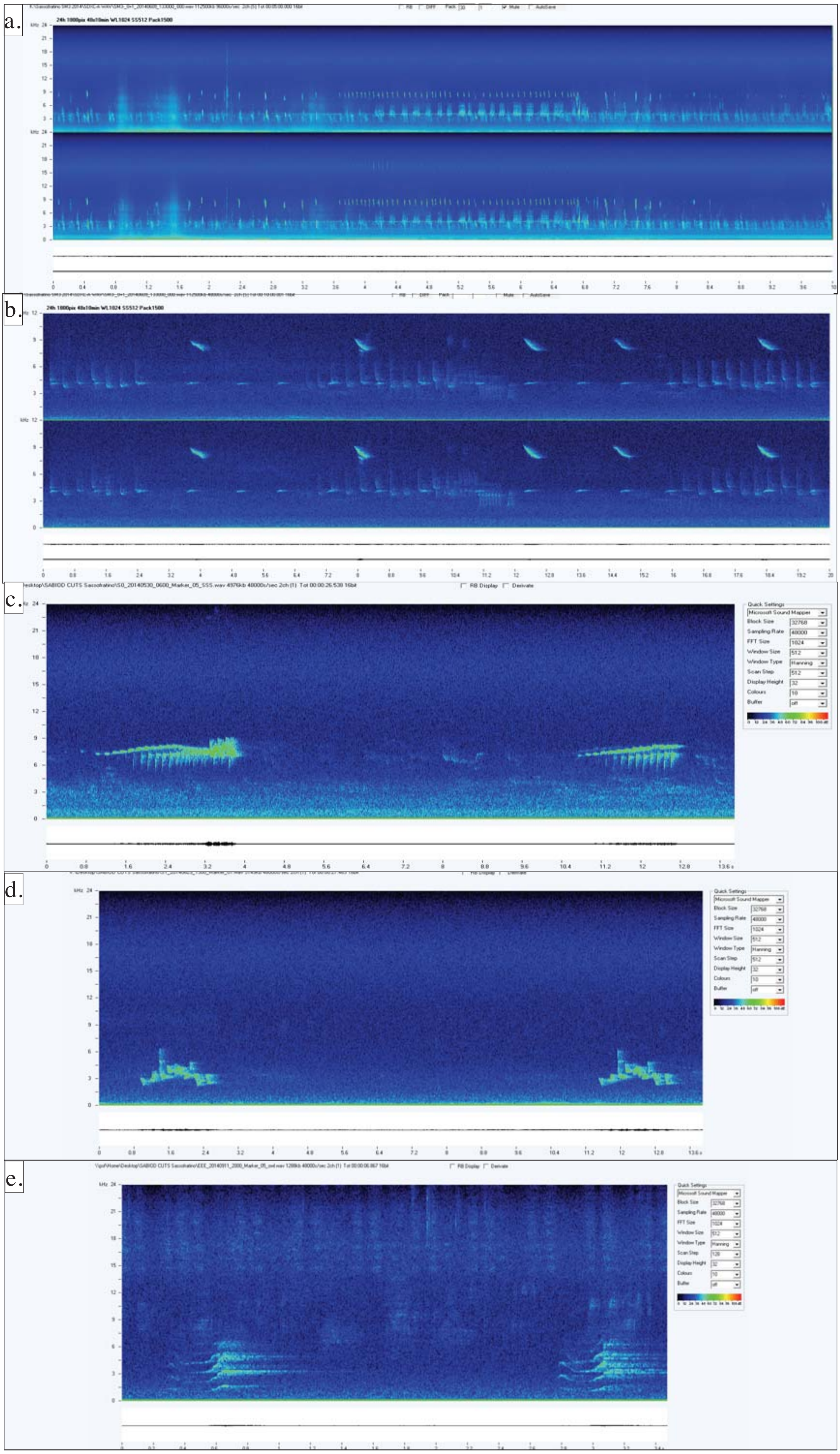

a.
Frequency (kHz)
hours (from 00:00 to 23:00)
b.
Frequency (kHz)
hours (from 00:00 to 23:00)
c.
Frequency (kHz)
hours (from 00:00 to 23:00)
d.
Frequency (kHz)
hours (from 00:00 to 23:00)

Figure 3.7 (in the previous page). Daily packed spectrograms: examples of different weather condition days (good and rain/wind) recording 10 min every half-hour (48 frames/day); acoustic energy is in green and its intensity depends on spectral energy values. In **a**. there is a good weather day, the visual predominant component is biophony and there are clear sharp transitions at dawn and dusk with (biological) acoustic energy mainly concentrated between 1500 and 9000 Hz; **b.** is a day characterized by less biophonic acoustic activity during the day and presence of wind during the night; **c.** is an example of a rain/wind day, the visual predominant component is geophony and acoustic energy is distributed over wider frequency ranges; **d.** is a day dominated by rain and wind, no biophony is recorded. The uniform band between 15 and 22 kHz is the noise floor of the SM3 recorder; the newer SM4 recorder, on the contrary, has a flat noise floor.

Figure 3.8 (in the following page). Examples of possible spectrogram at different time scale precision: **a.** Spectrogram of a 10 minutes frame. At this time scale the biophony composition becomes clearly composed by different components, however it is not possible to discriminate the structure of different species' song. In the first two minutes are clearly visible the bunches of wideband noise generated by leaves moved by some breeze shots. **b.** Spectrogram of a 20 seconds frame. **c.**Spectrogram (0-24 kHz – 14 secondi) with a time resolution suitable for the recognition of the song structure of the "common firecrest". **d.** Spectrogram (0-24 kHz – 14 secondi) of the song of the "Eurasian blackcap". **e.** Spectrogram (0-24 kHz – 3.5 secondi) of calls emitted by a female tawny owl (*Strix aluco*).


a.
b.
c.
d.
e.

4. Quantitative analysis of acoustic data

Due to the huge amount of data that the (long-term) ecoacoustic monitoring allows collecting, a multi time scale approach is elaborated to obtain information at different levels of precision based on the use of annual series, monthly, daily up to the minute files (Figure 3.9).

The analysis can be addressed to explore the variability intra-site and inter-sites at difference time scales.

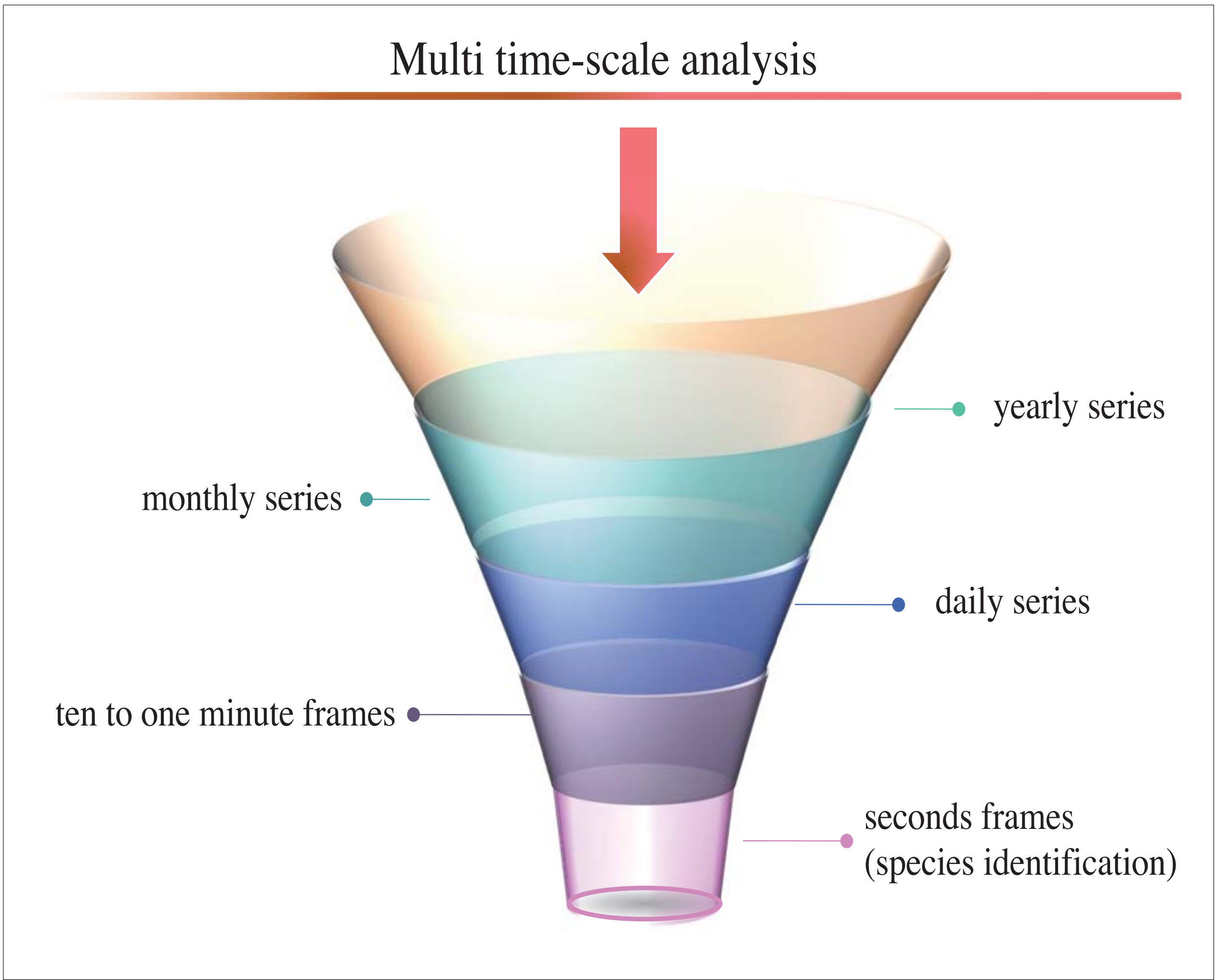


Figure 3.9 A schematic representation of the multi-time scale approach elaborated that allows performing data exploration at different levels of detail, from the overview soundscape description to recognition and monitoring of vocalizing species.

COMPARISON BETWEEN DIFFERENT TIME-SIZE SAMPLES

We also tested the analysis of different recording schedules to identify the best compromise between the completeness of the results, the memory and battery requirements, and the processing time to elaborate the data in order to possibly reduce the recording intervals to save battery and memory space and thus to allow more extended recording period for each deployment.

Data collection

A period of ten days was selected, from 29 September to 8 October 2017, during which a continuous 24 hours recording sample was performed. Adopting a continuous sampling, the time range was limited by batteries' and memory cards' efforts.

The collected acoustic data were organized in 10-minute files each (00:00 - 00:10; 00:10-00:20; 00:20-00:30, etc...).

Data analysis

The quantitative analysis of acoustic values was performed at three levels of sample size:

a. *all minutes*: all minutes were considered for analysis as single units (N = 1440 / day);
b. *10-total*: each whole 10-minute file was considered as a single unit (N = 144 / day);
c. *1-random*: only one random minute for each 10-minute file was considered as a unit (N = 144 / day).

For all units, six Acoustic Indices were extracted using R's Soundecology and Seewave packages: Entropy Index (H), Bioacoustic Index (BI), Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), Normalized Difference Soundscape Index (NDSI) and Acoustic Evenness Index (AEI); and the mean trends were calculated.

The same computer and the same computational procedure were used to get fully comparable results. For statistical analysis, all AIs' mean trends were compared each other: Kruskall Wallis Wilcox test and the pairwise comparison with Wilcoxon rank sum test (P value adjustment method: Bonferroni) tests were applied.

Results

The first notable result was the different time required to complete the analysis procedure with a standard desktop Windows 10 PC with Intel iCore7 cpu, R Studio, R 3.2, without any parallelization of the code (Table 3.1).

Sample Size	Total units analysed	Time required for analysis
a. all minutes	N=14000 (1440units / day * 10 days)	145h 28' (6days, 1hours, 28 minutes)
b. 10-total	N=1400 (144 units / day * 10 days)	149h 43' (6days, 5 hours, 43 minutes)
c. 1-random	N=1400 (144 units / day * 10 days)	15h 19'

Table 3.1 Results for analysed units and required time for analysis of the three different sample size datasets.

It is clearly evident the huge amount of time required to analyse the dataset, even if only 10 days were considered. This is due by the slow computational speed of R, that is a (slow and inefficient) interpreter; the problem can be partially solved by parallelizing the code and to use multicore/multicpu computers.

Kruskal-Wallis Test was conducted to examine the differences on AIs values according to the size of samples. No significant differences were found among H, BI and ADI while the sample size resulted to affect the mean trend for ACI, NDSI and AEI ($p< 0.01$) (see Table 3.2 for more details).

Acoustic Index	χ^2	df	p-value
H	1.2635	2	0.5317
BI	7.569	2	0.02272
ACI	12.585	2	**0.00185**
ADI	0.84593	2	0.6551
NDSI	13.572	2	**0.00113**
AEI	189.1	2	**< 2.2e-16**

Table 3.2 Results for the Kruskal Wallis Test; in bold are reported p value < 0.01.

In particular, the following pairwise comparison with Wilcoxon for ACI, NDSI and AEI showed a significant difference between the use of *10-total* vs *1random* sample size and *10-total* vs *all minutes* but not between the use of *all-minutes* vs *1-random* sample size (see Table 3.3 for detailed p-values and the Figures 3.10-3.11 to see the mean trends of all AIs calculated for the three different sample sizes).

Acoustic Index		p-value	
		1-random	All minutes
H	All minutes	1	-
	10-total	1	0.78
BI	All minutes	1	-
	10-total	0.45	0.061
ACI	All minutes	1	-
	10-total	**0.0058**	**0.0074**
ADI	All minutes	1	-
	10-total	1	1
NDSI	All minutes	1	-
	10-total	**0.0089**	**0.0020**
AEI	All minutes	0.7	-
	10-total	**$<2e^{-}16$**	**$<2e^{-}16$**

Table 3.3 Results for the pairwise comparison with Wilcoxon rank sum test; in bold are reported p value < 0.01.

Discussion

Passive acoustic monitoring generates large data sets of sound recordings that have to be stored and analysed. In this context, it is crucial the elaboration of a research protocol that optimizes the effectiveness of the samples and avoids time- and resource-consuming analyses.

Continuous field sampling for 24 hours involves the use of enormous amounts of batteries and memory cards, as well as the need to retrieve on-site data at short intervals (about every 10 days) by an operator.

It is more appropriate to schedule shorter recording intervals (for example 10 minutes every 30 minutes) that allow having a valid global daily view. The 10/30 solution appears to be a good compromise also considering the need of analysing the recordings for species and acoustic event detection and identification. Ten minutes of recording allows to get a short history around each event and to understand more of the time relations among acoustic events (e.g. series of songs or of calls, response of calling animals to non-biological events such as anthropogenic noise or geophonic events).

Likewise, the analysis effort and computation time are also influenced by the amount of data. For example, for a 10-day sampling, using all minutes (N = 144000 files) the analysis time was found to be longer than 6 days while it is considerably reduced to 15 hours and 19 minutes if 1-random minute every 10 is used (N = 14400 files); moreover the average trend of the indices does not appear to be significantly different.

Finally, the test using *10-total* requires the longest analysis time, but the average distributions are significantly different, both vs the subset of all minutes and vs that of 1random.

For this, if the Acoustic Indices' mean trend is considered, the analysis of 1-random minute for each 10-minute files results to be a reliable compromise for the general analysis of a soundscape.

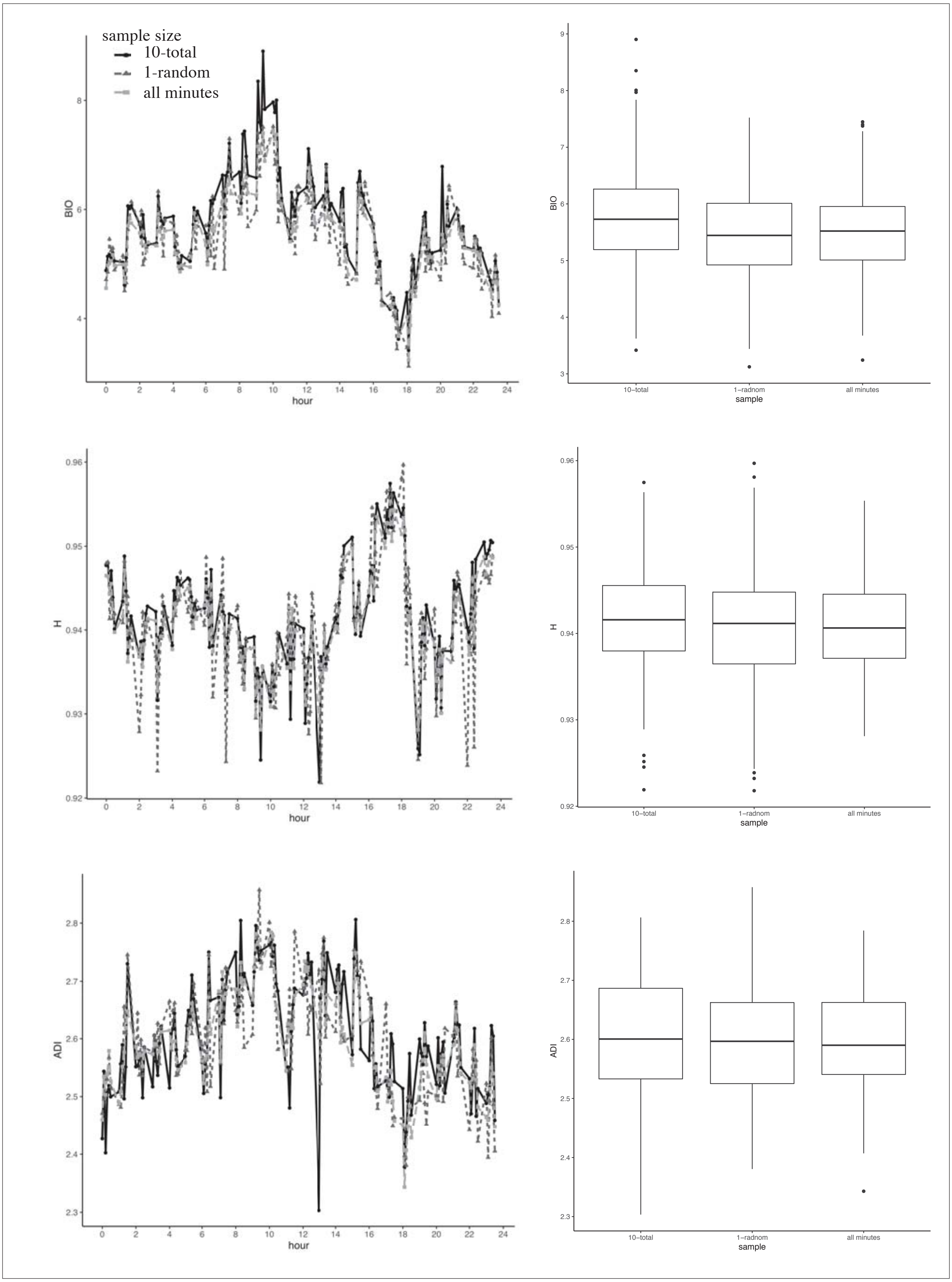


Figure 3.10 10-day mean trends of the following Acoustic indices: Bioacoustic Index (BIO), Entropy (H) and Acoustic Diversity Index (ADI) calculated for the three different sample sizes (10-totals, 1-random and all minutes, respectively). On the left: AIs' mean trends distribution plots; on the right: AIs' mean values box plots.

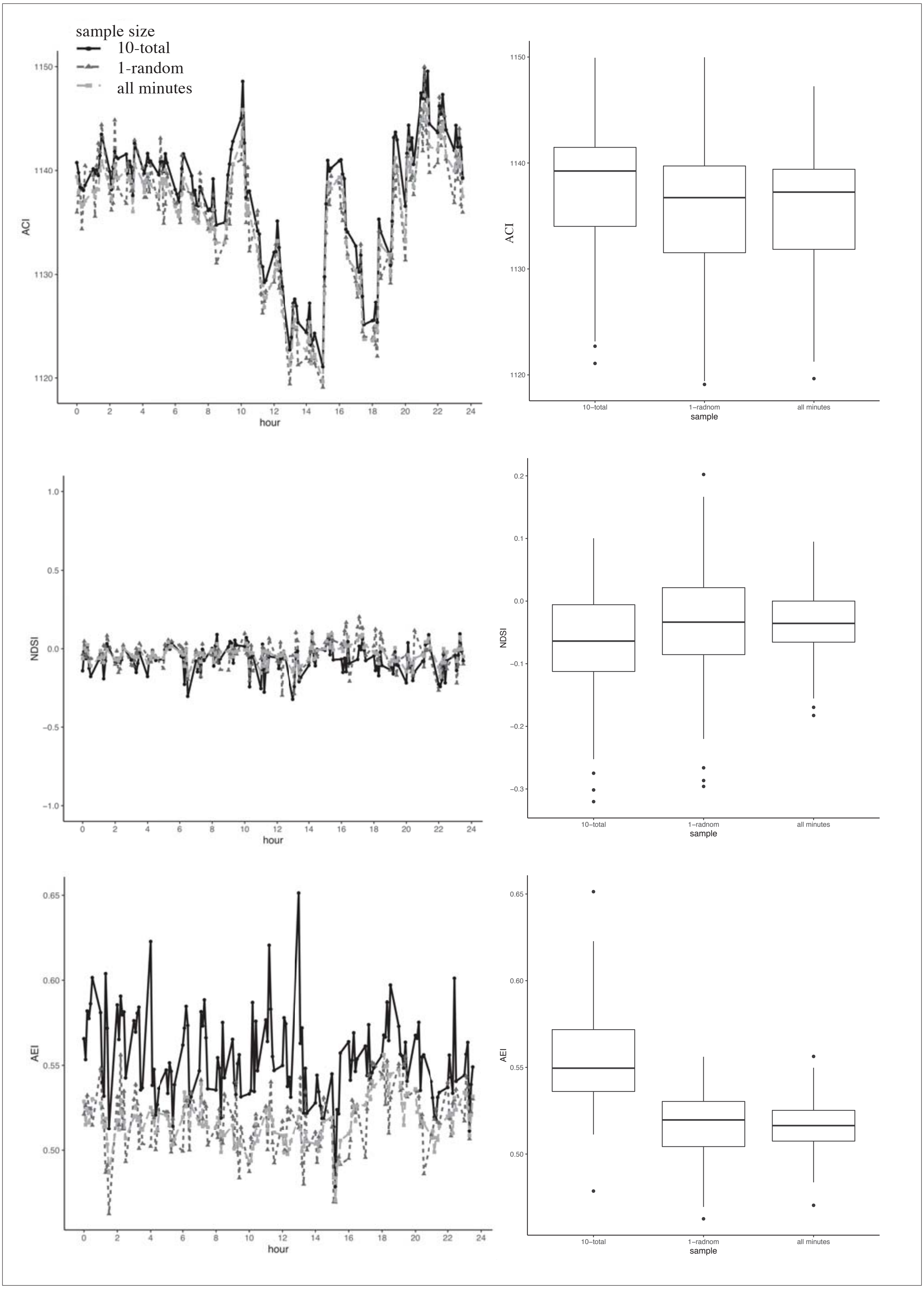


Figure 3.11 10-day mean trends of the following Acoustic indices: Acoustic Complexity Index (ACI), Normalized Difference Soundscape Index (NDSI) and Acoustic Evenness Index (AEI) calculated for the three different sample sizes (10-totals, 1-random and all minutes, respectively). On the left: AIs' mean trends distribution plots; on the right: AIs' mean values box plots.

CHAPTER 04

THE SOUNDSCAPE OF SASSO FRATINO INTEGRAL NATURE RESERVE IN THE NATIONAL PARK OF FORESTE CASENTINESI

In this chapter, the research protocol is applied to monitoring the soundscape of Sasso Fratino

The Research Protocol (application)

The protocol elaborated is applied for the first monitoring of the soundscape of the Integral Nature Reserve "Sasso Fratino" in the Casentinesi Forests National Park (Italy).

1. **Selection of survey sites**

The study area is located within the National Park of the Casentinesi Forests (on the Tuscan-Romagnolo Apennines, Italy) and in particular in the Integral Nature Reserve of Sasso Fratino, comprised in the Natura2000 Network Sites (IT4080001- SCI and SAC).

Established in 1959, the Integral Nature Reserve of Sasso Fratino is characterized by a low level of anthropic intervention due to the lack of access roads, the presence of strong rocky slopes and the accidentality of the site and all this has allowed the development of an evolved forest ecosystem with an old-growth structure, that is of old wood. These populations, very rare in Italy due to the strong pressure that man has exerted on forests for millennia, are characterized by high biomasses (above 1000 m3 / ha) and biodiversity (Bianchi et al., 2011).

After being awarded with the European Diploma since 1985 for Protected Areas, for its importance and singularity, in 2017 the Sasso Fratino Integral Nature Reserve has also been included by UNESCO in the list of "Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe World Heritage" (https://whc.unesco.org) (Figures 4.1-4.2)

From a vegetational point of view, there is a mixed wood of beeches and white firs up to the altitude of about 1250 m a.s.l., while above this altitudinal threshold the composition becomes only beech (Padula, 1985).

Sasso Fratino's peculiar vegetational structure of old-growth forest and the forest secular management addressed toward a full conservation of the environment (in fact, for this it earned first the award of European Diploma and then it has also been included in the UNESCO list) and all these features candidate this area to be an important case of wilderness and a suitable model to collect high-quality records of natural habitats.

Some survey sites are chosen outside the reserve (but still within the boundaries of the Casentinesi Forests National Park) in order to compare the results with areas managed by the national park service and assigned to productive and touristic functions.

Figure 4.1 Sasso Fratino Integral Nature Reserve.

Figure 4.2 Inspection for the renewal of the European Diploma Awarded to the Integral Natural Reserve of Sasso Fratino 2020 with the European Commission's delegate, July 2019, National Park of Casentinesi Forests (Italy). Ph: Pavan G.

2. Data collection

Data collection was carried out through the local positioning of autonomous Wildlife Acoustics both older SM3 models and newer SM4 recorders (from in 2017) programmed to record 10 minutes every 30 minutes, 24 hours a day, synchronously and continuously (in general, batteries and memory cards allow at least two months of data); digital recordings were made in stereo at a sampling rate of 48 kHz with a high-pass filter set at 200Hz, to get the frequency range from 180 Hz to 24 kHz, and stored in the audio file format .wav, for a total of 5.6 GB per day/recorder (Figure 4.3).

Figure 4.3 On-site positioning of remote autonomous Wildlife Acoustics recorders (model SM3 on the left and SM4 on the right, respectively) inside Sasso Fratino Integral Nature Reserve.
In the left photo, the acoustic sampling has been completed with the placement of a camera trap and external batteries for both the recorder and the camera trap in order to prolong the recording time.

The position of each recorder has been marked with GPS Garmin and then saved as a .kmz file. Since the beginning of the SABIOD project (May 2014, see Table 4.1) 12 different monitoring sites have been identified and tested (Figure 4.4): six sites are included in the core area of the dense forest, properly within the Integral Nature Reserve of Sasso Fratino, where access is forbidden, and the other six located outside Sasso Fratino, but in the adjacent Nature Reserve La Lama, still within the boundaries of the National Park, where access is only possible through the cycle-pedestrian path and to the forest service's.

The altitude range that characterizes the sample of the sites extends from approximately 750 m a.s.l. up to about 1400 m a.s.l. The recorded data was saved in .wav format on removable memory cards and then transferred to the CIBRA laboratory archive (University of Pavia), catalogued and prepared for subsequent analysis.

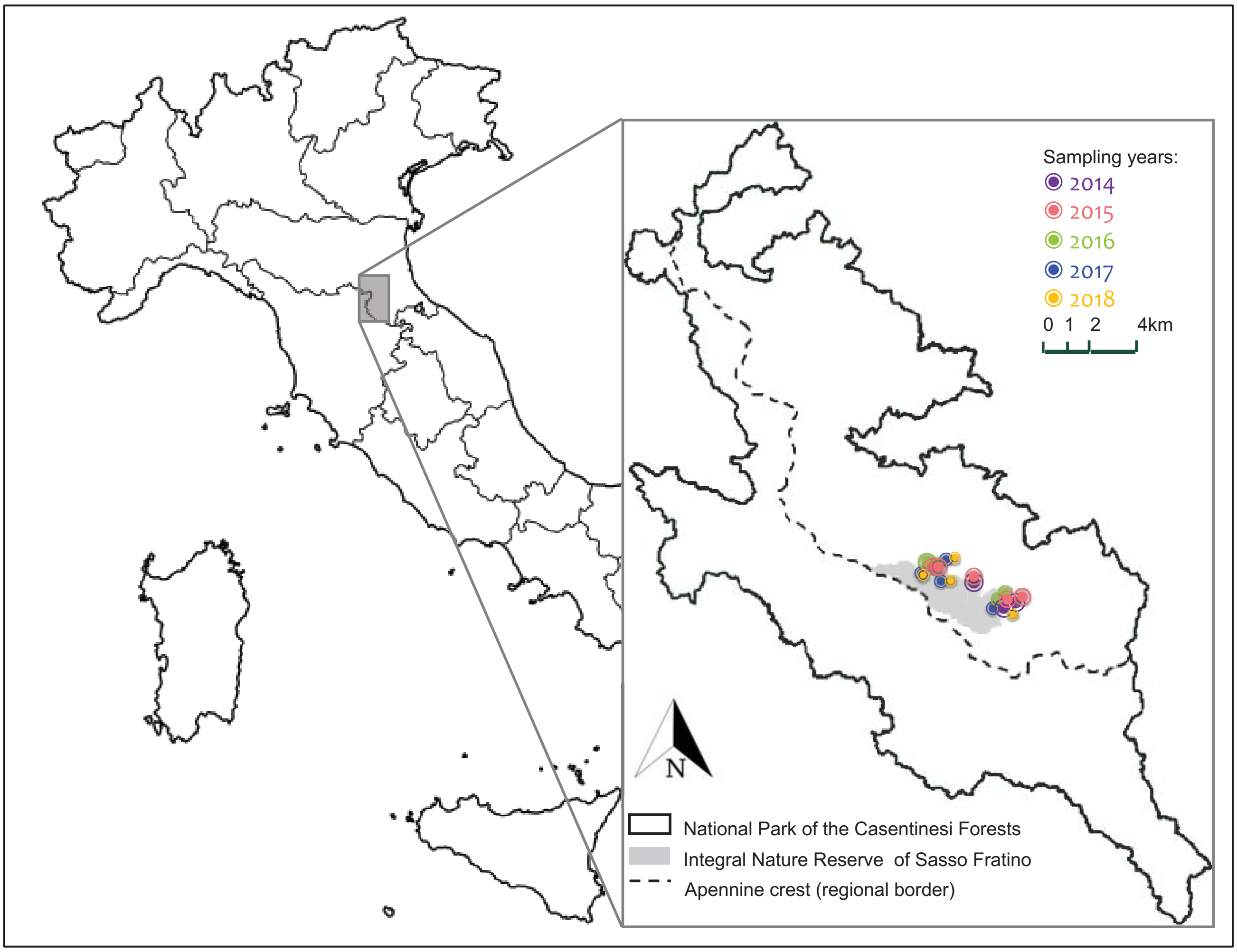


Figure 4.4 Distribution of acoustic data recording sites. In details, on the left the geographic location of the Casentinesi Forests National Park on Italian territory; on the right the focus on the NP's boundaries and of the Integral Nature Reserve of Sasso Fratino's area with the sampled sites for each years from the beginning of the project of SABIOD project (2014-2018).

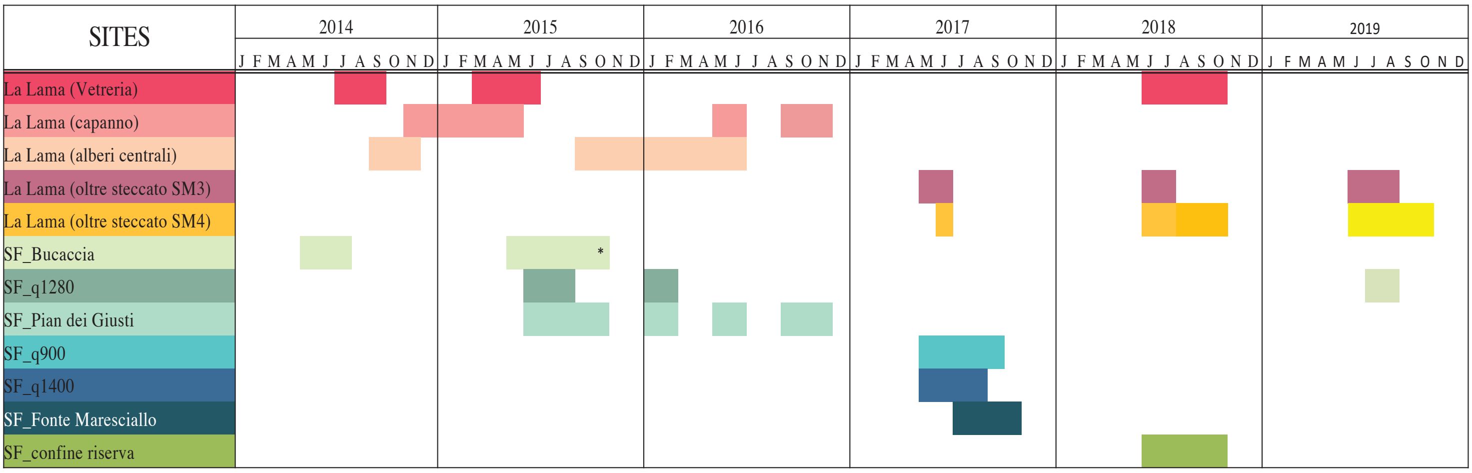


Table 4.1 A summary table that shows the monthly/year data availability in the SABIOD archive for the period 2014-2019, respectively for each recorder placed in the National Park of the Casentinesi Forests National Park and within Sasso Fratino Integral Nature Reserve, properly (marked by the initial "SF_" before the name site); * indicates the theft of the recorder in the site.

In addition to technical difficulties regarding data collection (battery and memory space limit), the impossibility of physically reaching the study area for several months a year (due to snow and landslide danger) must also be considered.

**

A double approach, one qualitative, based on visual screening of compact daily spectrograms, and the other quantitative, by processing data with the acoustic indices was adopted.

3. Qualitative analysis of acoustic data (generation of compact daily spectrograms)

The generation of compact daily spectrograms for each recording period by using the SeaPro software developed by CIBRA (http://www-3.unipv.it/cibra/) was performed in order to assess that recorded days were all corrected and complete days and to provide an overview of each recorded day.

4. Quantitative analysis of acoustic data

77122,00 of 10-minute files have been collected, that is approximately 9 terabytes of digital audio archived in about five years of monitoring.

By applying the elaborated protocol, the results can range on several analyses with different temporal and spatial scales. On the one hand, the continuous sampling of 10 minutes every 30 guarantees the building of a modular database that allows time analyzes from single minutes to daily trends, but also

to the hourly, monthly, and annual average. On the other hand, simultaneous sampling in more sites allows the possibility of comparing trends across multiple sites.
The quantitative analysis begun with the extraction of a random minute (for each 10-minute file) and therefore the measurement of acoustic parameters performed using the R environment and various libraries, including Soundecology and Seewave, that allow obtaining both general parameters, such as the value of the spectral energy (minimum, maximum, average), and both specific acoustic metrics to estimate the differences in the soundscape.
In a preliminary phase, the main acoustic indexes found in the literature for monitoring the terrestrial acoustic environment (Sueur, 2018) were tested on a subset of data (30 days in three sites) and up to 33 variables were obtained, from the combination of the indices calculated both on the entire frequency band (180-24.000 Hz) and on bands of specific frequencies (1000 Hz intervals).
To reduce the analysis effort and time, six Acoustic Indices (AIs) were selected and extracted for all files recorded. The following AIs resulted to be more suitable for the exploration of soundscape:

- BI: Bioacoustic Index (Boelman et al. 2007);
- H: Entropy (Sueur et al. 2008);
- ADI: Acoustic Diversity Index (Villanueva-Rivera et al. 2011);
- AEI: Acoustic Evenness Index (Villanueva-Rivera et al. 2011);
- ACI: Acoustics Complexity Index (Pieretti et al. 2011);
- NDSI: Normalized Difference Soundscape Index (Kasten et al. 2012).

Additionally, a new parameter was calculated: the acoustic energy concentrated in the frequency bands that characterize 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 from 1500 to 9600 Hz.
The data obtained from the acoustic analysis were organized in tables in which, in addition to the values, attributes were added (for each file) such as the unique name of the sampled site, the type of recorder used (SM3 or SM4), the month, year, and time.

The quantitative analysis can be addressed to describe and to explore the acoustic variance both intra-site (for monthly or yearly samplings of a site) and inter-sites (for multiple simultaneous locations).

4a. Intra-site acoustic variability

The Soundscape is the acoustic expression of an ecosystem: in a site, it is not static but is linked to environment's fluctuation (for example temperature and light affect the behaviour of vocalizing species; rain, wind, snow and other geophonic events are more concentrated in a period).

Because of Acoustic Indices aim to describe the different components of the Soundscape and for this, they are expected to assume different values for different conditions.

Analyzing temporal variation of acoustic indices and identifying acoustic-environmental relationships is important to understanding how soundscapes are characterized over space and time. The intra-site variability has been explored at multi-scale time levels to compare how each index in a site changes over the time from an annual overview to a daily detailed one:

- 4a.1: intra-sites variability at yearly range: mean values plotted per sampling month/site for each sampling year;
- 4a.2: intra-sites variability at specific time range: daily values plotted per sampling month/site for a single sampling site;
- 4a.3: intra-sites variability at daily range: exploration about how acoustic indices vary during the different phases of the day.

4a.1: intra-sites variability at yearly range

The average monthly trend of six Acoustic Indices was calculated for all sampling sites and then plotted together to get a general overview of how the indices change monthly over the years (Figures 4.5a-f).

Using the R's ggplot2 package (Wickham, 2016), a facet plot was created for each acoustic index (H, BI, ADI, NDSI and ACI). The facet approach partitions a plot into a matrix of panels and each panel shows a different subset of the data, in this case a subset for each sampling year (from 2014 to 2018).

Figures 4.5a-f (in the following pages). Representation of yearly intra-site variation for the following Acoustic Indices: Entropy Index (a), Bioacoustic Index (b), Acoustic Diversity Index (c), Normalized Difference Soundscape Index (d), Acoustic Complexity Index calculated for the frequency range from 1500 to 9000 Hz (in which main biophony component is focus) (e), Acoustic Complexity Index calculated for the frequency range from 9000 to 12000 Hz (f). All mean values were plotted per sampling month/site. Because of problems with recorders, memories and accessibility of the sites, a complete coverage of all sites and years has not been available.

Entropy Index

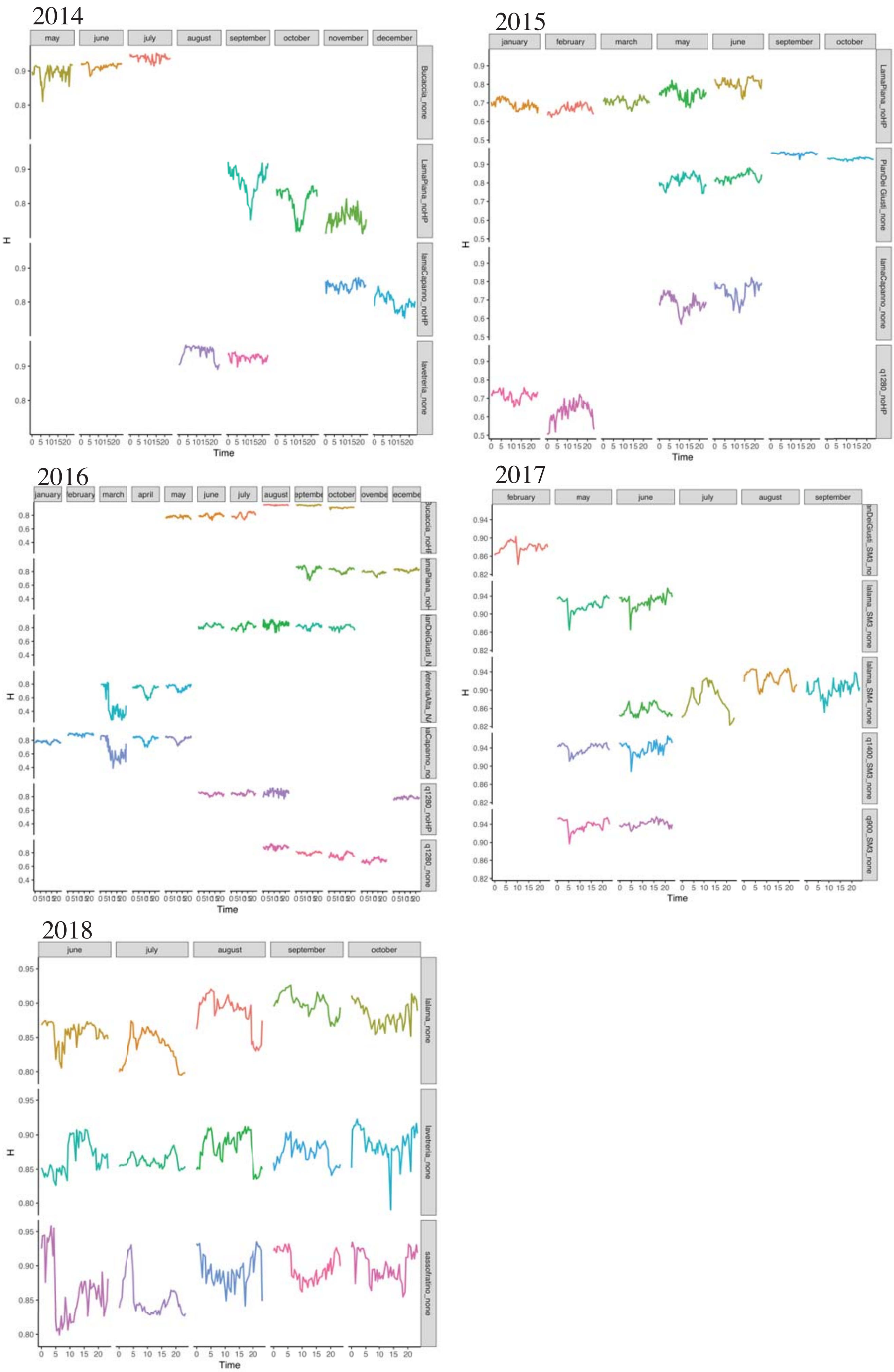


Figure 4.5a Intra-site variation of the Entropy Index.

Bioacoustic Index

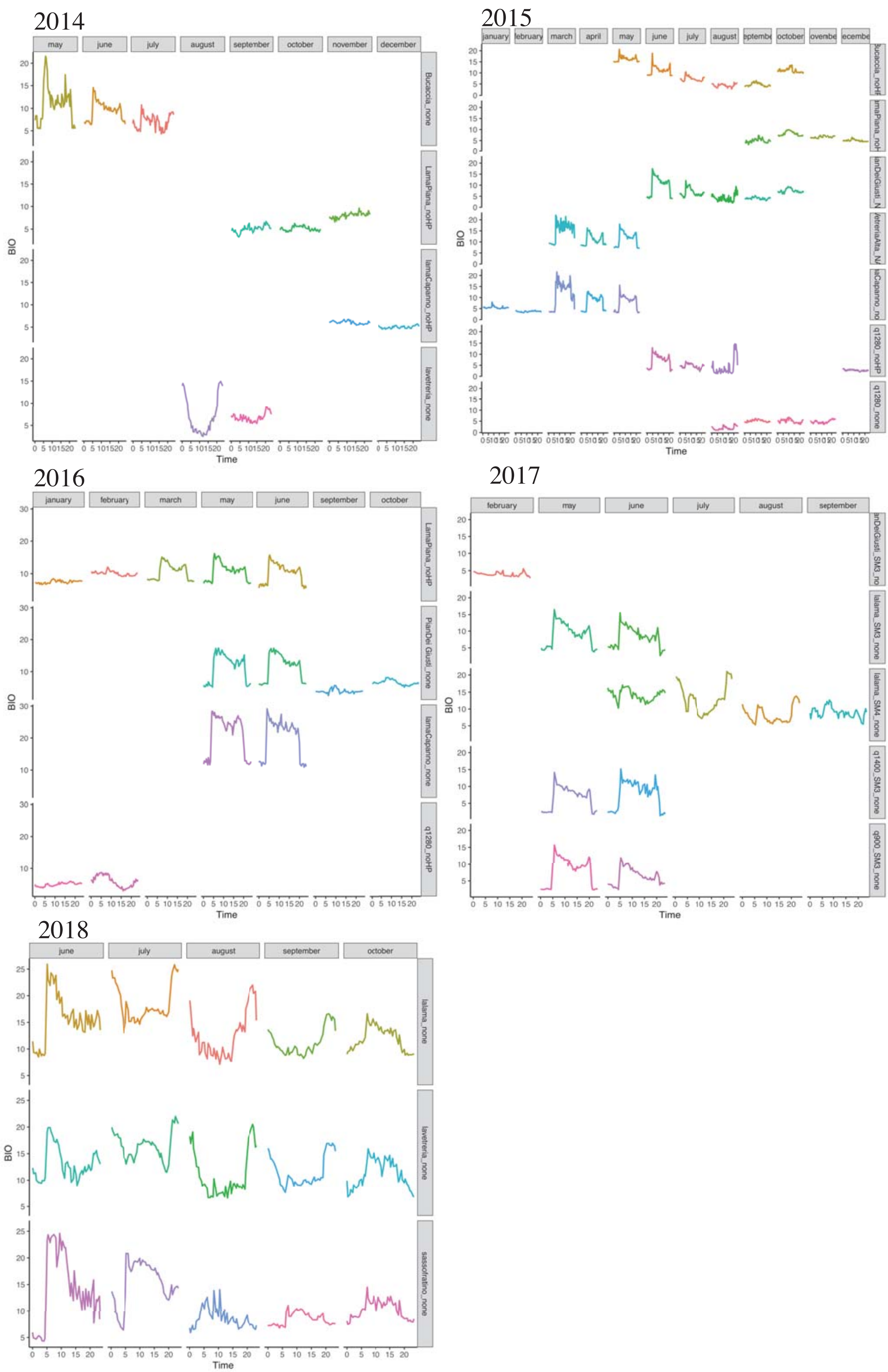


Figure 4.5b Intra-site variation of the Bioacoustic Index.

Acoustic Diversity Index

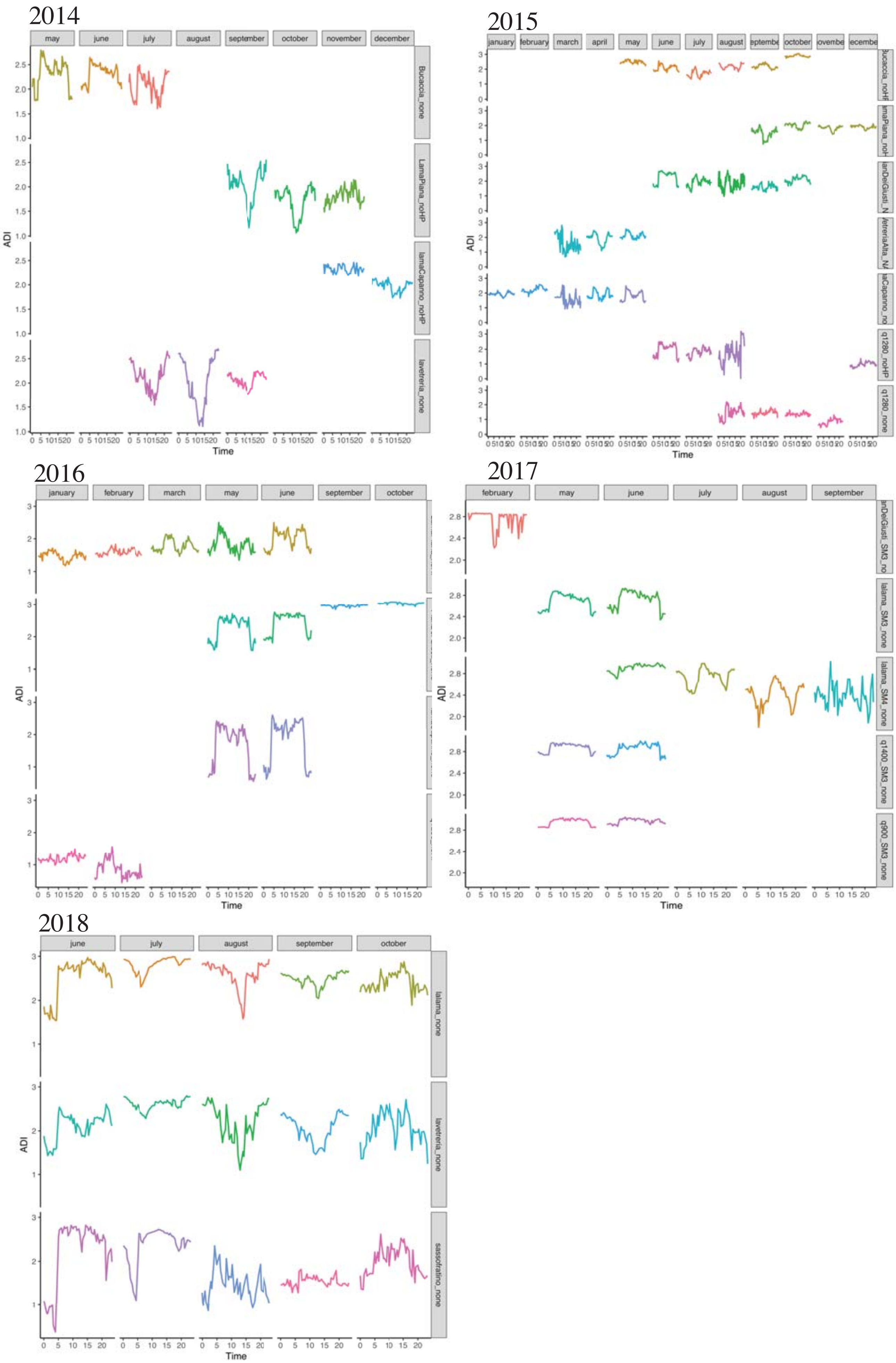


Figure 4.5c Intra-site variation of the Acoustic Diversity Index.

Normalized Difference Soundscape Index

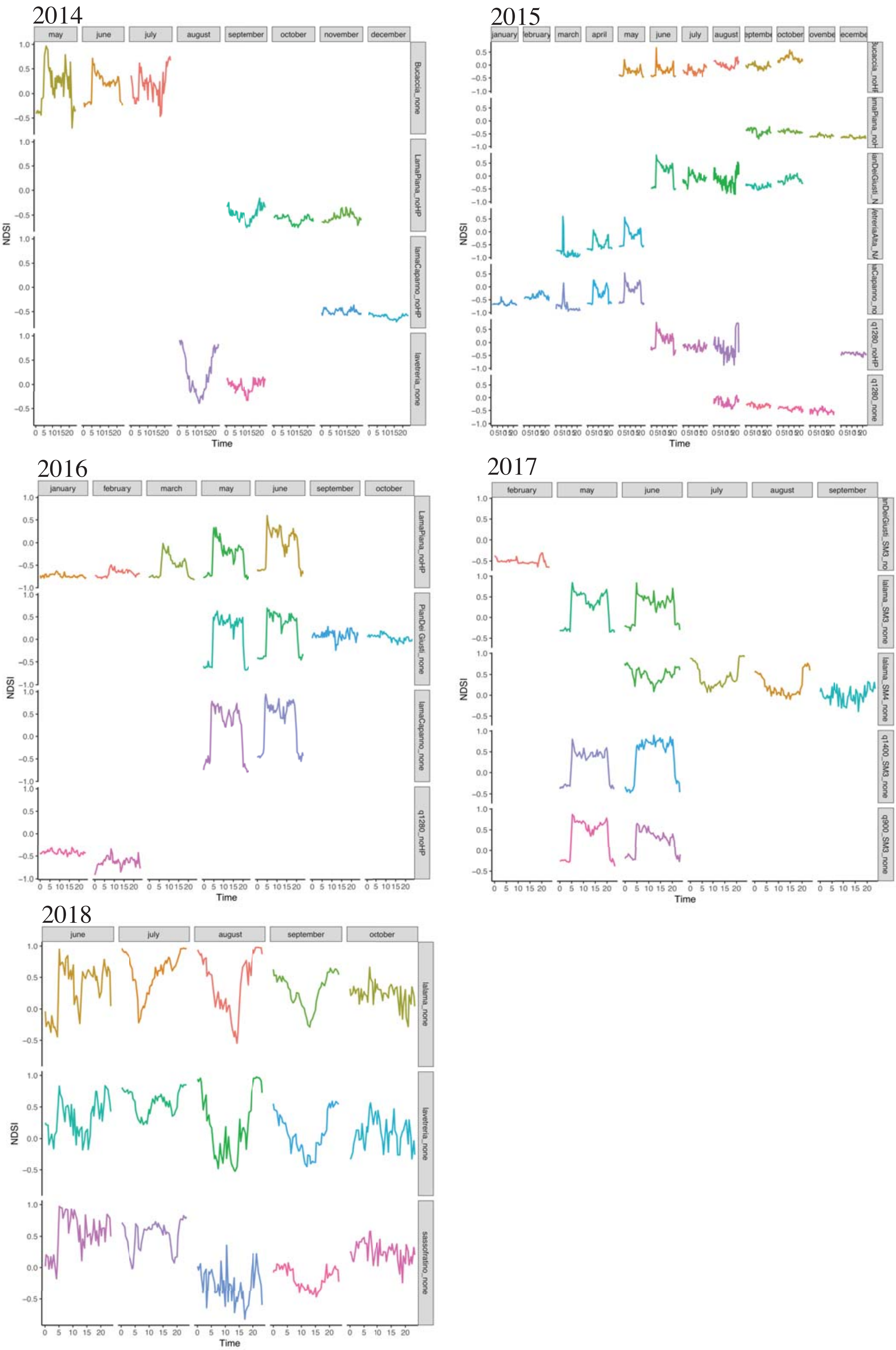


Figure 4.5d Intra-site variation of the Normalized Difference Soundscape Index.

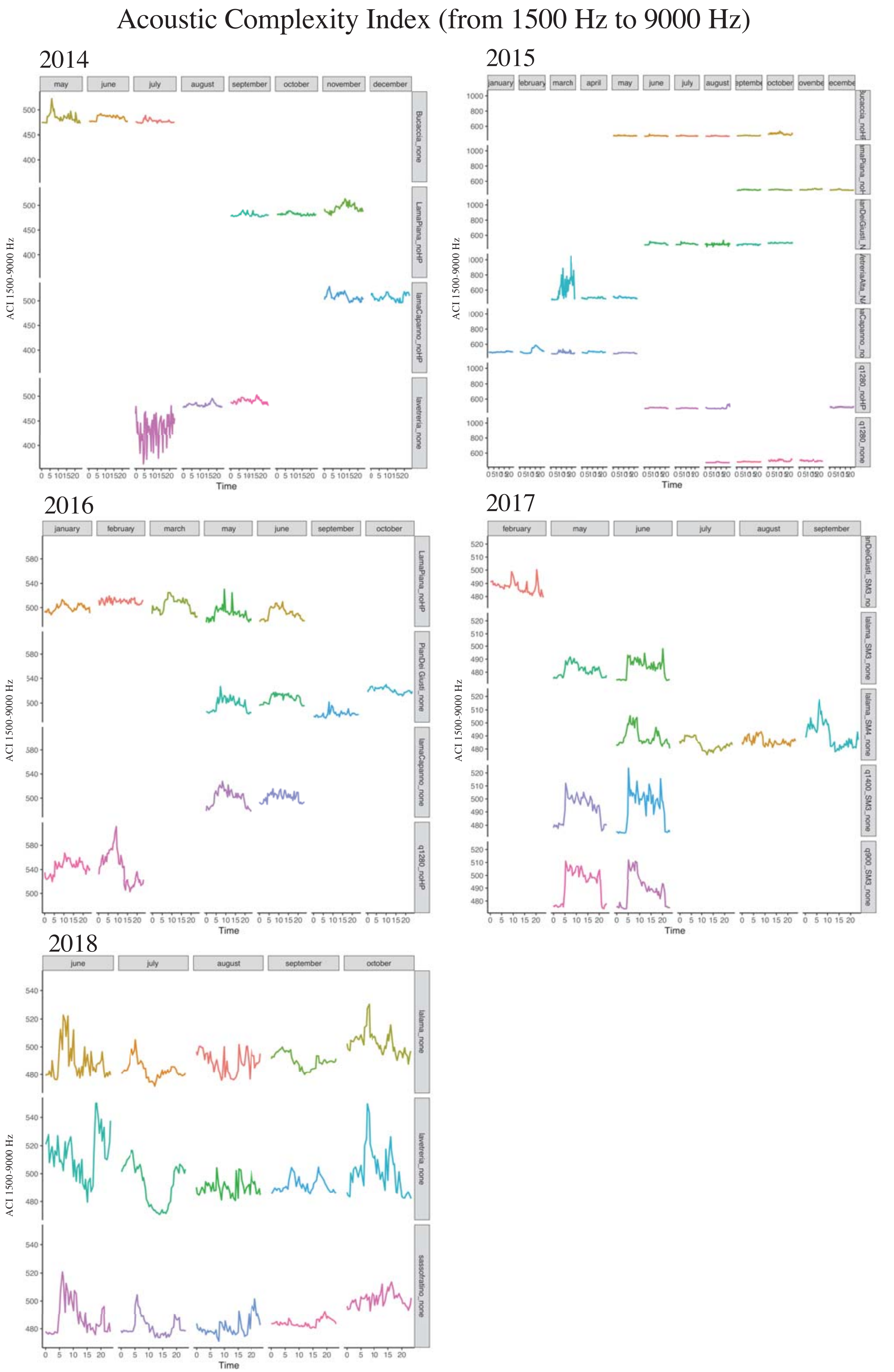


Figure 4.5e Intra-site variation of the Acoustic Complexity Index calculated for the frequency range from 1500 Hz to 9000 Hz.

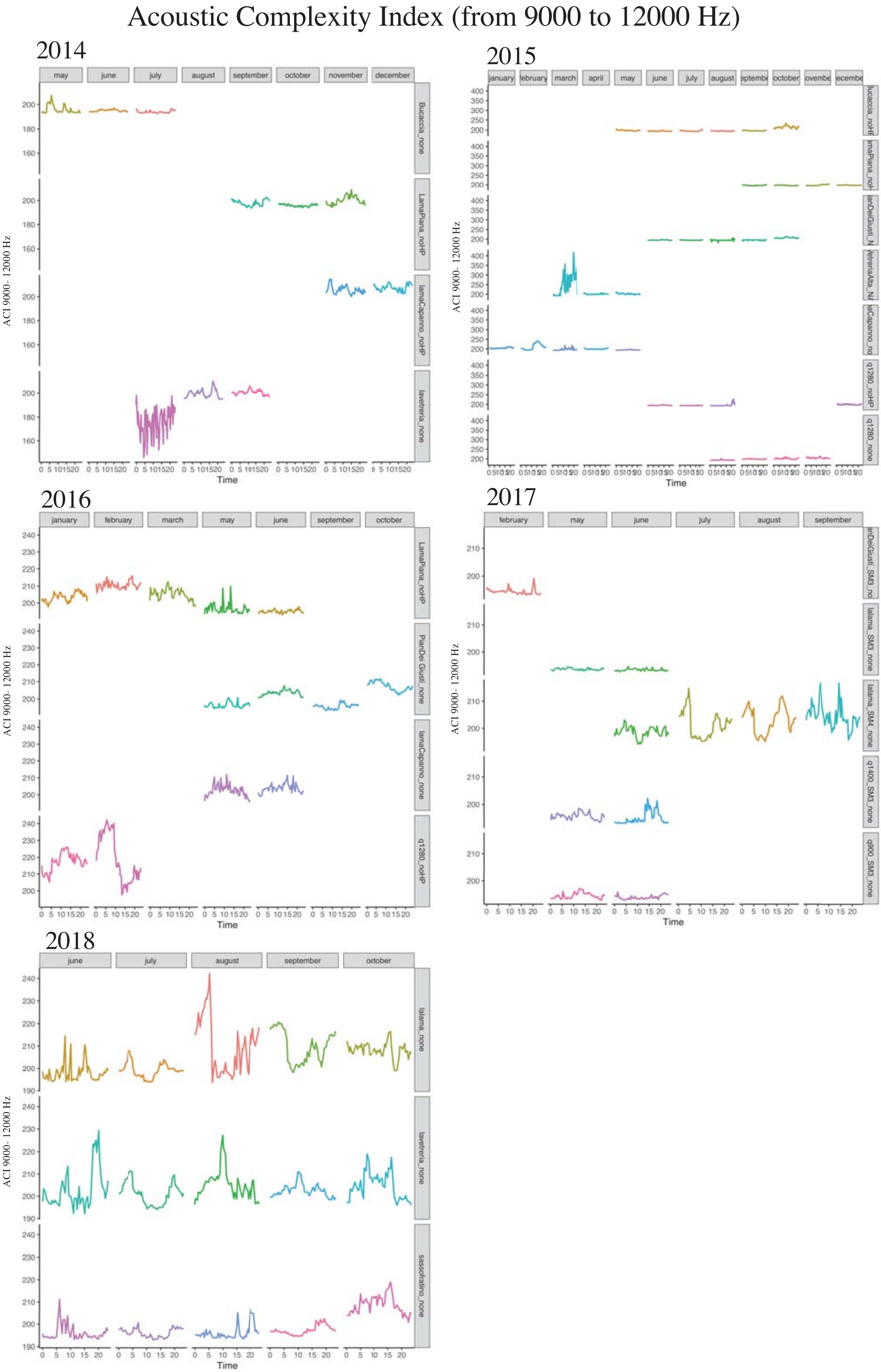


Figure 4.5f Intra-site variation of the Acoustic Complexity Index calculated for the frequency range from 9000 Hz to 12000 Hz.

4a.2: intra-sites variability at specific time range

It is possible to have a finer level of vision of intra-site variability by zooming more and more and using the single daily values recorded in each 10minute files.

In particular, the analysis was addressed to explore variation of the site La Lama (at the southern boundary outside the reserve) for the time period of data available, between from May 2017 to September 2018.

At the moment, the sample of data recorded in La Lama site is the temporally longest: since it is not properly inside the reserve but still inside the National Park, it is more easily accessible during the year and a car battery as an aid to the recorder's internal batteries has been located thanks to the logistical support of the Carabinieri.

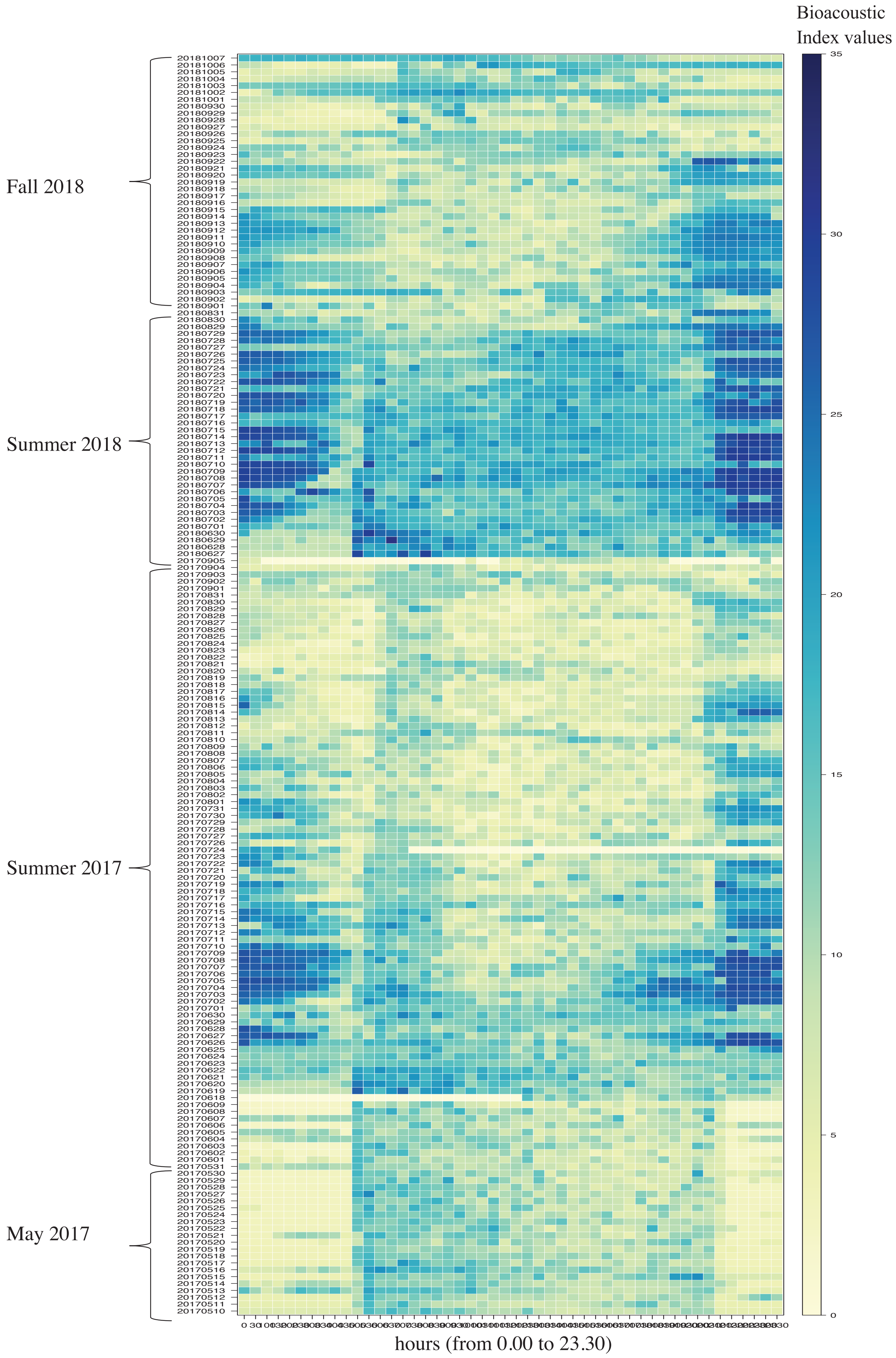
Using the R's ggplot2 package (Wickham, 2016), Bioacoustic Index's time series were plotted with each 24-hour values on the x-axis and all sampled single day on the y-axis (Figure 4.6).

In this way, monthly and seasonally variance becomes clearer and more evident:

during the period of May 2017, BI is the constant and dominant during the daytime, from the dawn (around 5:30 am) and to the dusk (around 7:30 pm), and BI has general lower values in the night (lighter colour).

If the focus is on the summer period (both summer 2017 and 2018), besides bioacoustic values during the day hours, higher values were also detected during nighttime, probably due to the main presence of insects.

Figure 4.6 (in the following page). Representation of daily intra site variation for the Bioacoustic Index: hourly values were plotted together, and each line is a day of a single sampling site (La Lama 2017-2018). The graph shows the variation of the ephemerids, the time of dawn and dusk, that delimit the daylight biophony mainly. Night-time biophony has greater variations, mainly due to singing insects in warmer months and roaring deers in late September.


Bioacoustic
Index values
35
30
25
20
15
10
5
0
Fall 2018
Summer 2018
Summer 2017
May 2017
hours (from 0.00 to 23.30)

4a.3: intra-sites variability at daily range

The intra-site variability was also analysed at the level of daily performance.

A period of 30 days (from 8 May to 10 June 2017) for the La Lama site was selected and the distributions of the AIs' average values were compared, labelling as 'day' the files from 05:00 a.m. to 09:00 p.m., and as 'night' ones from 09:30 p.m. to 04:30 a.m.

All six AIs' results showed significant differences between daily and nocturnal values, all Mann Whitney Wilcoxon test's p are < 0.001 (Figures 4.7-4.8).

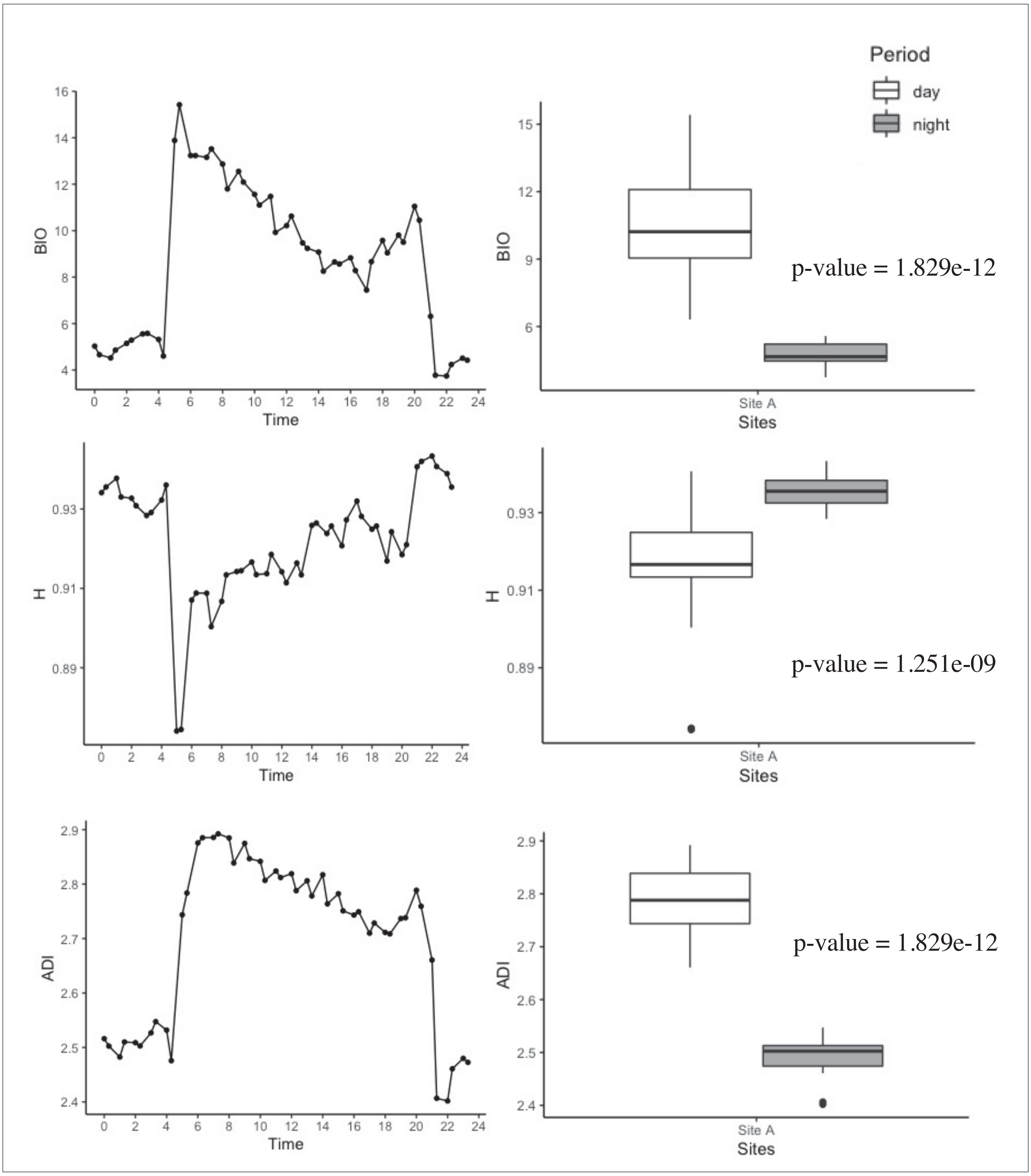


Figure 4.7 30-day mean trends of the following Acoustic indices: Bioacoustic Index (BIO), Entropy (H) and Acoustic Diversity Index (ADI) calculated for the La Lama site. On the left: AIs' mean trends distribution plots; on the right: AIs' mean values box plots comparing files labelled as 'day' (from 05:00 a.m. to 09:00 p.m.) and as 'night' (from 09:30 p.m. to 04:30 a.m.).

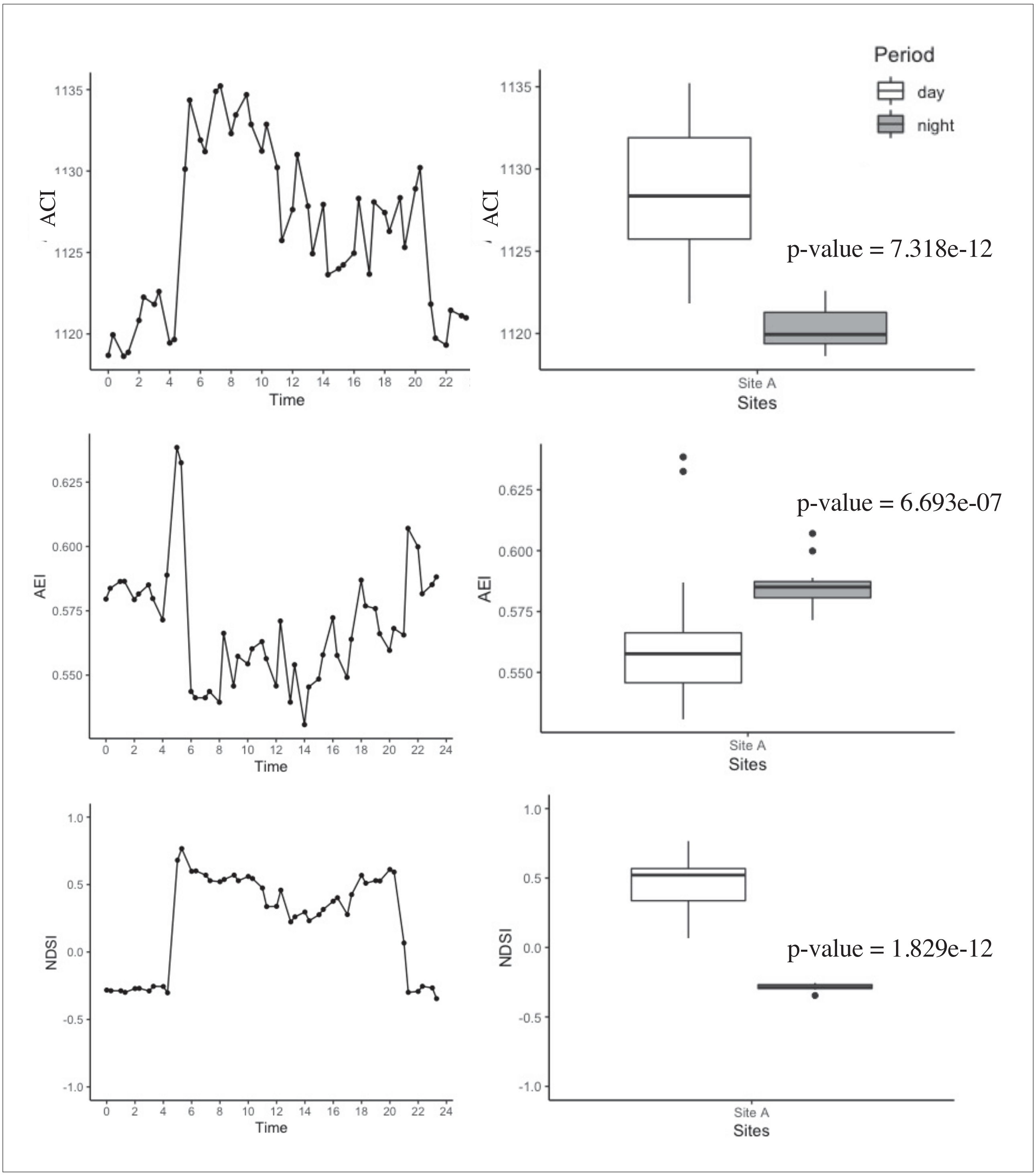


Figure 4.8 30-day mean trends of the following Acoustic indices: Acoustic Complexity Index (ACI), Acoustic Evenness Index (AEI) and Normalized Difference Soundscape Index (NDSI) calculated for the La Lama site. On the left: AIs' mean trends distribution plots; on the right: AIs' mean values box plots comparing files labelled as 'day' (from 05:00 a.m. to 09:00 p.m.) and as 'night' (from 09:30 p.m. to 04:30 a.m.).

References

Bianchi L., Bottacci A., Calamini G., et al. (2011) *Structure and dynamics of a beech forest in a fully protected area in the northern Apennines (Sasso Fratino, Italy)*, iForest – Biogeosciences and Forestry 4:136-144.

Boelman, N.T., G.P. Asner, P.J. Hart and R.E. Martin. (2007). "Multi-trophic invasion resistance in Hawaii: bioacoustics, field surveys, and airborne remote sensing." *Ecological Applications* 17: 2137-2144.

Kasten, E. P., S. H. Gage, J. Fox, and W. Joo. (2012). "The remote environmental assessment laboratory's acoustic library: an archive for studying soundscape ecology." *Ecological Informatics* 12: 50–67.

Padula M. (1985). *La riserva naturale di Sasso Fratino nelle foreste demaniali Casentinesi (Appennino tosco – romagnolo)*. Ministero dell'Agricoltura e Foreste, parchi nazionali – riserve integrali, Forlì.

Pieretti N., Farina A., and Morri D. (2011). "A new methodology to infer the singing activity of an avian community: the Acoustic Complexity Index (ACI)." *Ecological Indicators* 11: 868-873.

Sueur, J., S. Pavoine, O. Hamerlynck, and S. Duvail S. (2008) "Rapid acoustic survey for biodiversity appraisal." *PloS ONE* 3: e4065.

Sueur, J. (2018). *Sound analysis and synthesis with R*. Culemborg, the Netherlands: Springer.

Villanueva-Rivera, L.J., and Pijanowski B. C. (2018). *Soundecology: Soundscape Ecology*. R package version 1.3.3.

Wickham H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York

90

Multi-scale ecoacoustic analysis of natural soundscapes within the INR of Sasso Fratino (Italy)

Roberta Righini

Department of Earth and Environmental Sciences, University of Pavia, Italy

Co-author
Gianni Pavan

Ecoacoustics is an increasingly emerging interdisciplinary science that investigates natural and anthropogenic sounds and their relationship with the environment. But if on the one hand, it allows a great opportunity to monitor a habitat because, by the placement of many sensing devices it is possible to record continuously and simultaneously different locations, on the other hand, it is generated a huge quantity of data that needs to be archived and analysed. The new challenge is to draw up a scaled analysis methodology to optimise resources both in the field (saving memory cards and batteries) both in the lab, reducing time and effort of analyses, while maintaining high the accuracy of the information. This work focuses on the testing of scaled multi-view analyses that are both qualitative, based on visual screening of compact daily spectrograms, and quantitative, by the estimation of the acoustics indices and the analysis of spectrum energy for each 1000 Hz range (from 0 to 24 kHz). A further level of analysis is the identification of species by listening to the sounds and observing high-resolution real-time spectrograms, possibly driven by automatic detection tools. On a five-year archive of acoustic data collected in the Integral Natural Reserve of Sasso Fratino (Italy), we operated cross-section (horizontal) and time series (vertical) analyses to explore its soundscapes' spatial-temporal dynamics across different scales.

PEER REVIEWED PAPER:

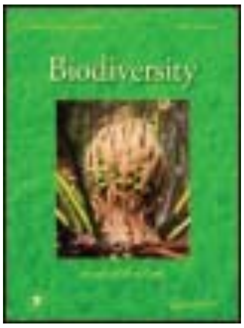
A SOUNDSCAPE ASSESSMENT OF THE SASSO FRATINO INTEGRAL NATURE RESERVE IN THE CENTRAL APENNINES, ITALY

Roberta Righini[1], Gianni Pavan[1]

[1]Department of Earth and Environmental Sciences, University of Pavia (Italy)

keywords: Ecoacoustics, Acoustic Indices, Sonotopes, National Park

accepted by Biodiversity Journal



Taylor & Francis
Taylor & Francis Group

Biodiversity

ISSN: 1488-8386 (Print) 2160-0651 (Online) Journal homepage: https://www.tandfonline.com/loi/tbid20

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

Roberta Righini & Gianni Pavan

BIODIVERSITY
https://doi.org/10.1080/14888386.2019.1696229

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

Roberta Righini and Gianni Pavan

Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy

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.

ARTICLE HISTORY
Received 2 July 2019
Accepted 19 November 2019

KEYWORDS
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).

CONTACT Roberta Righini roberta.righini01@universitadipavia.it Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy

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

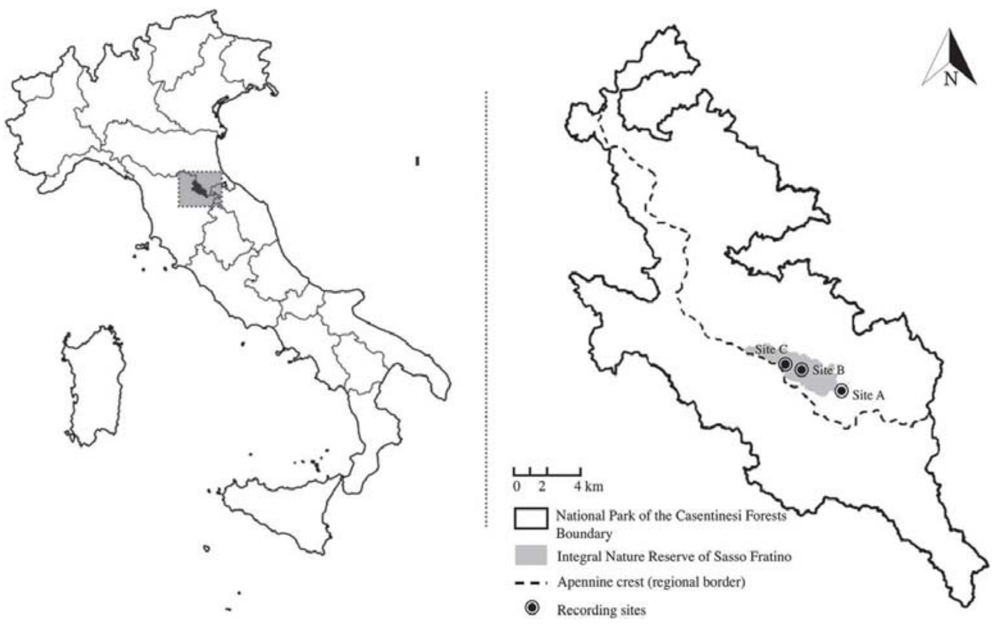


Figure 1. Distribution of acoustic data recording sites. The left-hand side shows the geographic location of the Casentinesi Forests National Park within Italian territory; and the right focuses on the National Park's boundaries and the Sasso Fratino INR with the three sampled sites.

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

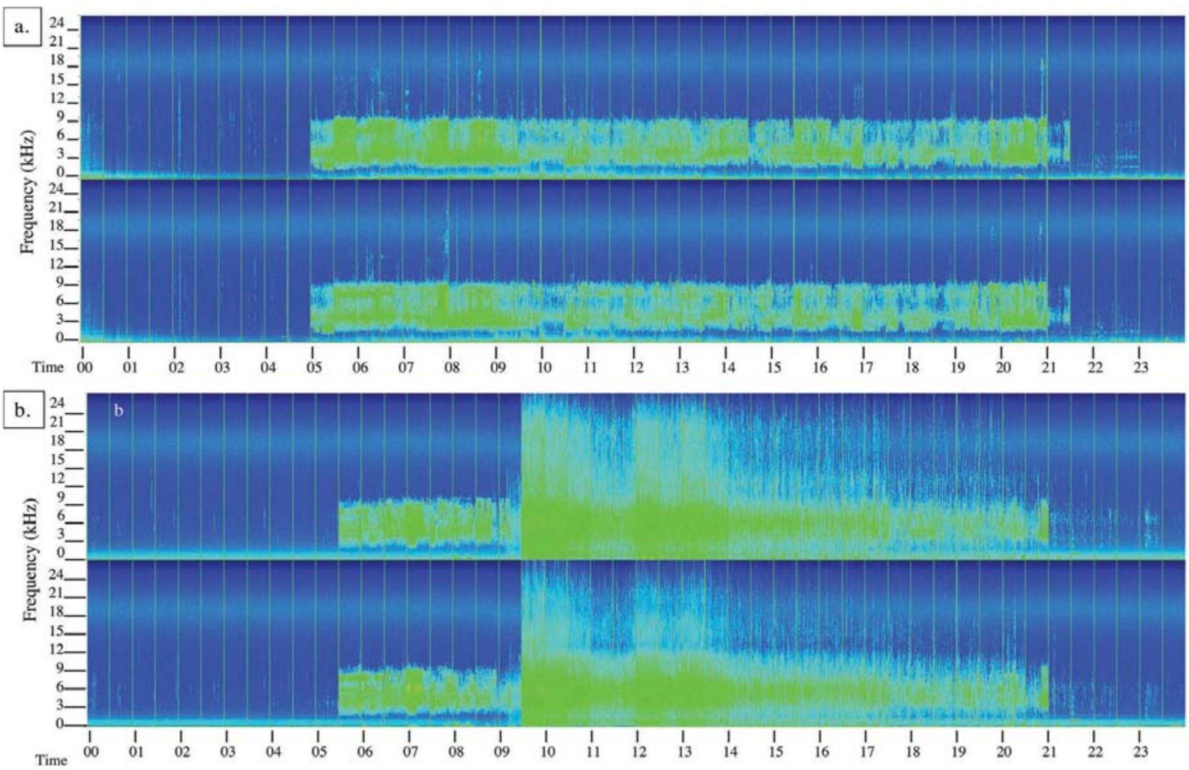


Figure 2. Examples of a packed spectrogram of a one day recording in Sasso Fratino INR, 10 min every half-hour (48 frames/day), x-axis 24 h, y-axis 24 kHz. Stereo is represented in the left channel above and the right channel below, respectively. Spectrogram (a) represents an example of a good weather 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.

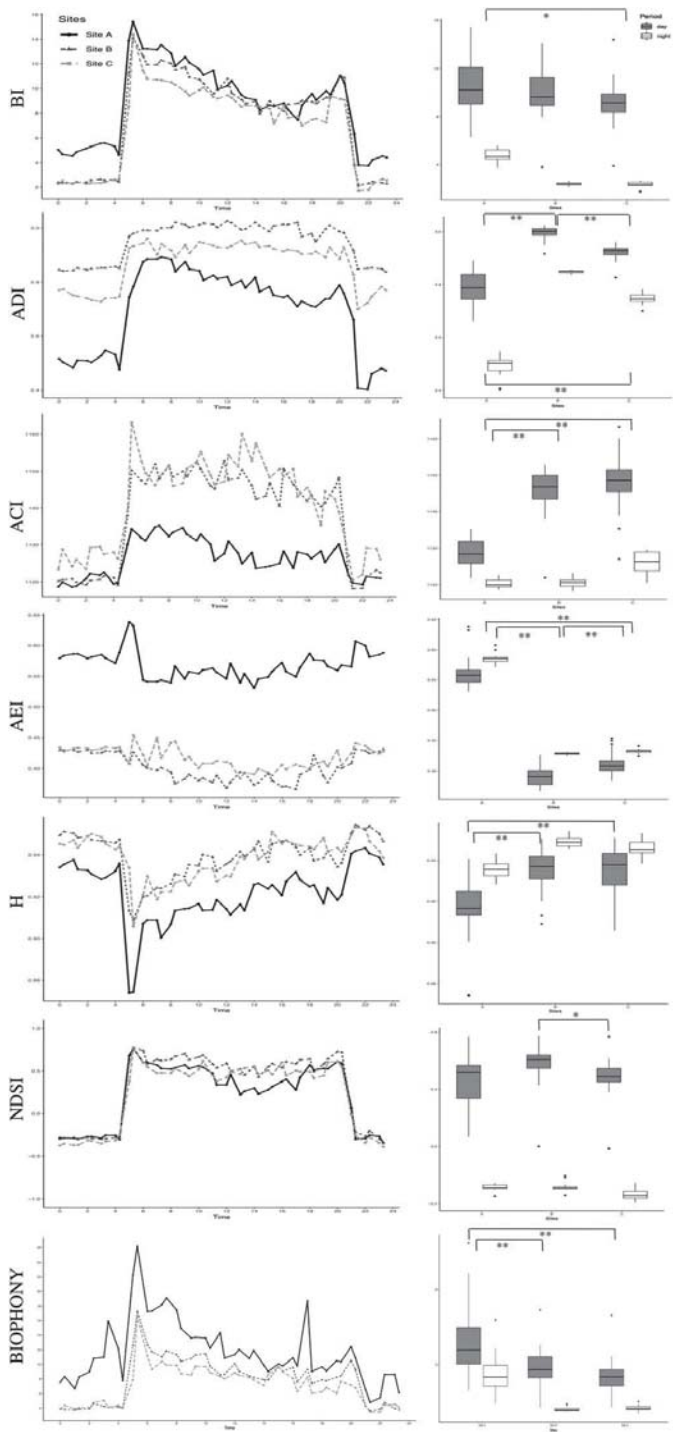


Figure 3. The left represents distribution plots of average monthly trends of three sample sites (A, B and C) for the six acoustic indices (in order BI, ADI, ACI, AEI, H and NDSI) and for the BIOPHONY parameter. The right represents boxplots of the three sites with the separation of the day files (from 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),

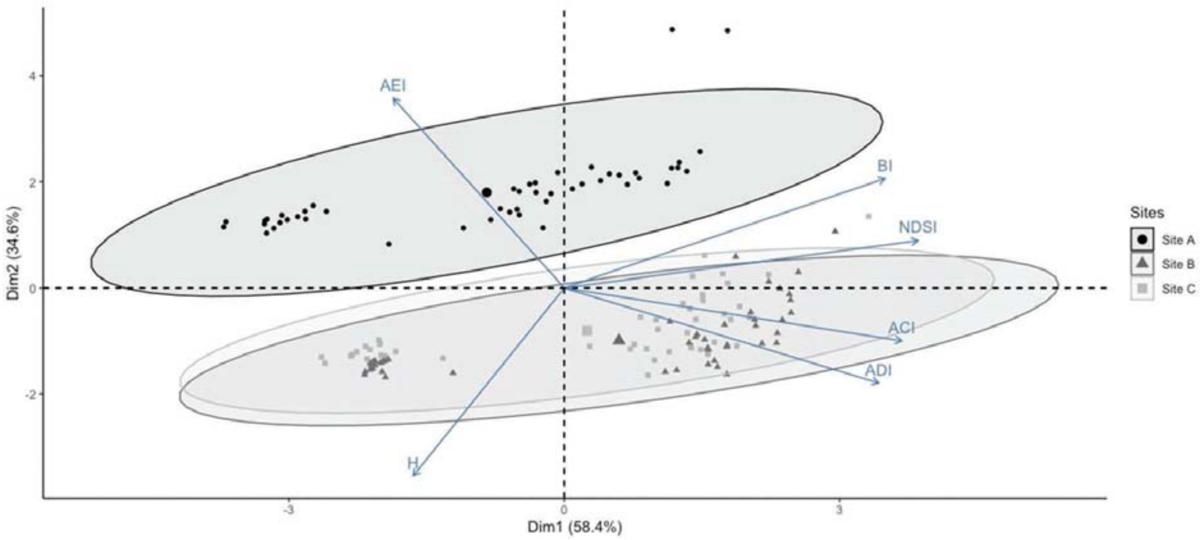


Figure 4. Principal component analysis for the three sites (A, B and C) and six AIs (H, BI, ADI, ACI, NDSI and AEI). The first two dimensions explain 93% of the variance and the analysis highlights the difference between the area around the reserve (site A) and that which is inside the Sasso Fratino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

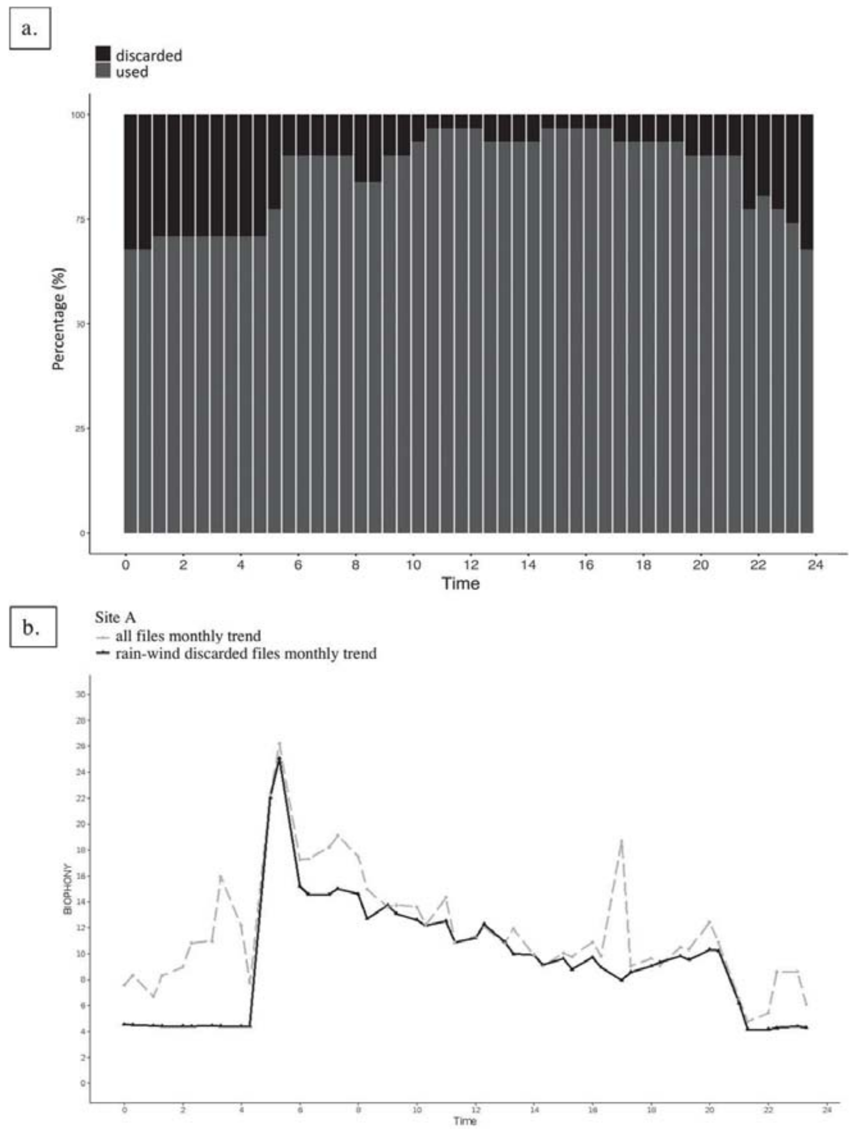


Figure 5. Additional test figures: (a) the percentage of rain/wind files discarded for each time interval in sample site A; (b) mean monthly BIOPHONY trend for site A for the dataset including all recorded files (dashed grey line) compared with the dataset with rain/wind files discarded (solid black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

Acknowledgements

The study of Sasso Fratino's soundscape is a part of the project SABIOD that now belongs to the EADM (Environmental Acoustics Data Mining) action within MADICS (MAsses des Données, Informations and Connasiances en Science) of CNRS (F). EADM is coordinated by H. Glotin and M. Asch.

We thank H.Glotin (LSIS, University of Toloun) for the financial support of the initial stages of SABIOD-Italy (2014–2016) and a special thank is due to 'Reparto Carabinieri per la Biodiversità' of Pratovecchio (AR, Italy) for their support in data collection and for the permits to access the INR.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Roberta Righini has a master's degree in natural sciences and she is now completing a doctoral project at the University of Pavia (Italy) about the application of ecoacoustic monitoring in terrestrial natural areas for the biodiversity conservation.

Gianni Pavan runs the Interdisciplinary Center for Bioacoustics and Environmental Research at the Dept. of Hearth and Environment Sciences of the University of Pavia, Italy, since 1989. He also teaches Ecology and Bioacoustics at the same University. Current research topics span from bioacoustics to ecoacoustics in both terrestrial and marine environments with a special focus on the application of these disciplines to the monitoring and conservation of natural ecosystems.

References

Aide, T. M., C. Corrada-Bravo, M. Campos-Cerqueira, C. Milan, G. Vega, and R. Alvarez. 2013. "Real-time

Bioacoustics Monitoring and Automated Species Identification." *PeerJ* 1: e103. doi:10.7717/peerj.103.

Antze, B., and N. Koper. 2018. "Noisy Anthropogenic Infrastructure Interferes with Alarm Responses in Savannah Sparrows (*Passerculus sandwichensis*)." *Royal Society Open Science* 5 (5): 172168. doi:10.1098/rsos.172168.

Bianchi, L., A. Bottacci, G. Calamini, A. Maltoni, B. Mariotti, G. Quilghini, F. Salbitano, A. Tani, A. Zoccola, and M. Paci. 2011. "Structure and Dynamics of a Beech Forest in a Fully Protected Area in the Northern Apennines (Sasso Fratino, italy)." *iForest - Biogeosciences and Forestry* 4: 136–144. doi:10.3832/ifor0564-004.

Blickley, J. L., and G. L. Patricelli. 2010. "Impacts of Anthropogenic Noise on Wildlife: Research Priorities for the Development of Standards and Mitigation." *Journal of International Wildlife Law & Policy* 13: 274–292. doi:10.1080/13880292.2010.524564.

Boelman, N. T., G. P. Asner, P. J. Hart, and R. E. Martin. 2007. "Multi-trophic Invasion Resistance in Hawaii: Bioacoustics, Field Surveys, and Airborne Remote Sensing." *Ecological Applications* 17: 2137–2144. doi:10.1890/07-0004.1.

Boncoraglio, G., and N. Saino. 2007. "Habitat Structure and the Evolution of Bird Song: A Meta-analysis of Evidence for the Acoustic Adaptation Hypothesis." *Functional Ecology* 21: 134–142. doi:10.1111/j.1365-2435.2006.01207.x.

Bottacci, A., editor. 2009. *La Riserva naturale integrale di Sasso Fratino: 1959–2009. 50 anni di conservazione della biodiversità*. Pratovecchio, Arezzo: CFS/UTB.

Bruni, A., D. J. Mennill, and J. R. Foote. 2014. "Dawn Chorus Start Time Variation in a Temperate Bird Community: Relationship with Seasonality, Weather, and Ambient Light." *Journal of Ornithology* 155: 877–890. doi:10.1007/s10336-014-1071-7.

Collias, N. E. 1960. "An Ecological and Functional Classification of Animal Sounds." In *Animal Sounds and Communication*, edited by W. E. Lanyon and W. N. Tavolga, 368–391. Washington: American Institute of Biological Sciences.

EEA. 2014. *Noise in Europe 2014*. EEA Report No 10/2014. Copenhagen, Denmark: European Environment Agency.

EEA. 2017. *Managing Exposure to Noise in Europe*. EEA Briefing No 01/2017. Copenhagen, Denmark: European Environment Agency.

EEA. 2018. *Population Exposure to Environmental Noise*. Copenhagen, Denmark: European Environment Agency.

Ey, E., and J. Fischer. 2009. "The 'acoustic Adaptation Hypothesis' - a Review of the Evidence from Birds, Anurans and Mammals." *Bioacoustics* 19: 21–48. doi:10.1080/09524622.2009.9753613.

Farina, A. 2013. *Soundscape Ecology: Principles, Patterns, Methods and Applications*. Dordrecht, Netherlands: Springer Science & Business Media.

Farina, A. 2019. "Ecoacoustics: A Quantitative Approach to Investigate the Ecological Role of Environmental Sounds." *Mathematics* 7 (1): 21. doi:10.3390/math7010021.

Farina, A., and S. H. Gage. 2017a. "Ecoacoustics A New Science." In *Ecoacoustics: The Ecological Role of Sounds*, edited by A. Farina and S. H. Gage, 1–11. Oxford, UK: Wiley-Blackwell.

Farina, A., and S. H. Gage. 2017b. *Ecoacoustics: The Ecological Role of Sounds*. Oxford, UK: Wiley-Blackwell.

Farina, A., and S. H. Gage. 2017c. "The Ecological Effects of Noise on Species and Communities." In *Ecoacoustics: The Ecological Role of Sounds*, edited by A. Farina and S. H. Gage, 95–108. Oxford, UK: Wiley-Blackwell.

Farina, A., P. James, C. Bobryk, N. Pieretti, E. Lattanzi, and J. McWilliam. 2014. "Low Cost (Audio) Recording (LCR) for Advancing Soundscape Ecology Towards the Conservation of Sonic Complexity and Biodiversity in Natural and Urban Landscapes." *Urban Ecosystems* 17: 923–944. doi:10.1007/s11252-014-0365-0.

Ferreira, L. M., E. G. Oliveira, L. C. Lopes, M. R. Brito, J. Baumgarten, F. H. Rodrigues, and R. S. Sousa-Lima. 2018. "What Do Insects, Anurans, Birds, and Mammals Have to Say about Soundscape Indices in a Tropical Savanna." *Journal of Ecoacoustics* 2: 1–17. doi:10.22261/jea.pvh6yz.

Francis, C. D., and J. R. Barber. 2013. "A Framework for Understanding Noise Impacts on Wildlife: An Urgent Conservation Priority." *Frontiers in Ecology and the Environment* 11 (6): 305–313. doi:10.1890/120183.

Gage, S. H., and A. C. Axel. 2013. "Visualization of Temporal Change in Soundscape Power of a Michigan Lake Habitat over a 4-year Period." *Ecological Informatics* 2: 100–109.

Hasan, N. M., and M. Badri. 2016. "Effect of Ambient Temperature on Dawn Chorus of House Sparrows." *Environment and Ecology Research* 4: 161–168. doi:10.13189/eer.2016.040308.

Kaiser, K., D. Scofield, M. Alloush, R. Jones, S. Marczak, K. Martineau, M. A. Oliva, and P. Narins. 2011. "When Sounds Collide: The Effect of Anthropogenic Noise on a Breeding Assemblage of Frogs in Belize, Central America." *Behaviour* 148 (2): 215–232. doi:10.1163/000579510X551660.

Kasten, E. P., S. H. Gage, J. Fox, and W. Joo. 2012. "The Remote Environmental Assessment Laboratory's Acoustic Library: An Archive for Studying Soundscape Ecology." *Ecological Informatics* 12: 50–67. doi:10.1016/j.ecoinf.2012.08.001.

Krause, B., and A. Farina. 2016. "Using Ecoacoustic Methods to Survey the Impacts of Climate Change on Biodiversity." *Biological Conservation* 195: 245–254. doi:10.1016/j.biocon.2016.01.013.

La Manna, G., M. Manghi, F. Perretti, and G. Sarà. 2016. "Behavioral Response of Brown Meagre *(Sciaena umbra)* to Boat Noise." *Marine Pollution Bulletin* 110 (1): 324–334. doi:10.1016/j.marpolbul.2016.06.045.

Marques, T. A., L. Thomas, S. W. Martin, D. K. Mellinger, J. A. Ward, D. J. Moretti, D. Harris, and P. L. Tyack. 2013. "Estimating Animal Population Density Using Passive Acoustics." *Biological Reviews* 88: 287–309. doi:10.1111/brv.2013.88.issue-2.

Morton, E. S. 1975. "Ecological Sources of Selection on Avian Sounds." *The American Society of Naturalists* 109: 17–34.

Naguib, M. 2013. "Living in a Noisy World: Indirect Effects of Noise on Animal Communication." *Behaviour* 150: 1069–1084. doi:10.1163/1568539X-00003058.

Nedelec, S. L., A. N. Radford, L. Pearl, B. Nedelec, M. I. McCormick, M. G. Meekan, and S. D. Simpson. 2017. "Motorboat Noise Impacts Parental Behaviour and Offspring Survival in a Reef Fish." *Proceedings of the Royal Society B: Biological Sciences* 284 (1856): 20170143. doi:10.1098/rspb.2017.0143.

Obrist, M. K., G. Pavan, J. Sueur, K. Riede, D. Llusia, and R. Marquez. 2010. "Bioacoustics Approaches in Biodiversity Inventories." *Abc Taxa* 8: 68–99.

Padula, M. 1985. *La riserva naturale di Sasso Fratino nelle foreste demaniali casentinesi (Appennino tosco – romagnolo)*. Forlì: Ministero dell'Agricoltura e Foreste, Parchi Nazionali – Riserve Integrali.

Pavan, G. 2016. "SeaPro SABIOD Software." http://www.unipv.it/cibra/seapro.html

Pavan, G. 2017. "Fundamentals of Soundscape Conservation." In *Ecoacoustics: The Ecological Role of Sounds*, edited by A. Farina and S. H. Gage, 235–258. Oxford, UK: Wiley-Blackwell.

Pieretti, N., A. Farina, and D. Morri. 2011. "A New Methodology to Infer the Singing Activity of an Avian Community: The Acoustic Complexity Index (ACI)." *Ecological Indicators* 11: 868–873. doi:10.1016/j.ecolind.2010.11.005.

Pijanowski, B., L. J. Villanueva-Rivera, S. L. Dumyahn, A. Farina, B. L. Krause, B. M. Napoletano, S. H. Gage, and N. Pieretti. 2011. "Soundscape Ecology: The Science of Sound in the Landscape." *Bioscience* 61: 203–216. doi:10.1525/bio.2011.61.3.6.

R Core. 2017. *TeamR: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Radle, A. L. 2007. "The Effect of Noise on Wildlife: A Literature Review." In *World Forum for Acoustic Ecology Online Reader*, 1–16.

Rosa, P., and N. Koper. 2018. "Integrating Multiple Disciplines to Understand Effects of Anthropogenic Noise on Animal Communication." *Ecosphere* 9 (2): e02127. doi:10.1002/ecs2.2127.

Simpson, S. D., J. Purser, and A. N. Radford. 2015. "Anthropogenic Noise Compromises Antipredator Behaviour in European Eels." *Global Change Biology* 21 (2): 586–593. doi:10.1111/gcb.12685.

Simpson, S. D., A. N. Radford, S. L. Nedelec, M. C. Ferrari, D. P. Chivers, M. I. McCormick, and M. G. Meekan. 2016. "Anthropogenic Noise Increases Fish Mortality by Predation." *Nature Communications* 7: 10544. doi:10.1038/ncomms10544.

Stowell, D., and M. D. Plumbley. 2014. "Automatic Large-scale Classification of Bird Sounds Is Strongly Improved by Unsupervised Feature Learning." *PeerJ* 2: e488. doi:10.7717/peerj.488.

Stowell, D., M. D. Wood, H. Pamuła, Y. Stylianou, and H. Glotin. 2019. "Automatic Acoustic Detection of Birds through Deep Learning: The First Bird Audio Detection Challenge." *Methods in Ecology and Evolution* 10 (3): 368–380. doi:10.1111/2041-210X.13103.

Sueur, J. 2018. *Sound Analysis and Synthesis with R*. Culemborg, the Netherlands: Springer.

Sueur, J., T. Aubin, and C. Simonis. 2008b. "Seewave: A Free Modular Tool for Sound Analysis and Synthesis." *Bioacoustics* 18: 213–226. doi:10.1080/09524622.2008.9753600.

Sueur, J., and A. Farina. 2015. "Ecoacoustics: The Ecological Investigation and Interpretation of Environmental Sound." *Biosemiotics* 8 (3): 493–502. doi:10.1007/s12304-015-9248-x.

Sueur, J., A. Farina, A. Gasc, N. Pieretti, and S. Pavoine. 2014. "Acoustic Indices for Biodiversity Assessment and Landscape Investigation." *Acta Acustica United with Acustica* 100: 772–781. doi:10.3813/AAA.918757.

Sueur, J., S. Pavoine, O. Hamerlynck, and S. Duvail. 2008a. "Rapid Acoustic Survey for Biodiversity Appraisal." *PloS One* 3: e4065. doi:10.1371/journal.pone.0004065.

Towsey, M., S. Parsons, and J. Sueur. 2014a. "Ecology and Acoustics at a Large Scale." *Ecological Informatics* 21: 1–3. doi:10.1016/j.ecoinf.2014.02.002.

Towsey, M., J. Wimmer, I. Williamson, and P. Roe. 2014b. "The Use of Acoustic Indices to Determine Avian Species Richness in Audio-recordings of the Environment." *Ecological Informatics* 21: 110–119. doi:10.1016/j.ecoinf.2013.11.007.

Ulloa, J. S., A. Gasc, P. Gaucher, T. Aubin, M. Réjou-Méchain, and J. Sueur. 2016. "Screening Large Audio Datasets to Determine the Time and Space Distribution of Screaming Piha Birds in a Tropical Forest." *Ecological Informatics* 31: 91–99. doi:10.1016/j.ecoinf.2015.11.012.

Villanueva-Rivera, L. J., and B. C. Pijanowski. 2018. *Soundecology: Soundscape Ecology*. R package version 1.3.3.

Villanueva-Rivera, L. J., B. C. Pijanowski, J. Doucette, and B. Pekin. 2011. "A Primer of Acoustic Analysis for Landscape Ecologists." *Landscape Ecology* 26: 1233–1246. doi:10.1007/s10980-011-9636-9.

Wimmer, J., M. Towsey, P. Roe, and I. Williamson. 2013. "Sampling Environmental Acoustic Recording to Determine Bird Species Richness." *Ecological Applications* 22: 1419–1428. doi:10.1890/12-2088.1.

World Health Organization. 2018. *Environmental Noise Guidelines for the European Region*. https://www.eea.europa.eu

Book's Chapter:

Il Paesaggio Sonoro

Gianni Pavan[1], Roberta Righini[1], Pamela Priori[2], Dino Scaravelli[3]

[1]Department of Earth and Environmental Sciences, University of Pavia (Italy)

[2]Museo Ornitologico "F. Foschi" e STERNA, Forlì (Italy)

[3]IUCN Bat Specialist Group, Department of Veterinary Medical Sciences, University of Bologna (Italy).

chapter of the book "The Nature Integral Reserve of Sasso Fratino in National Park Forests", published by Rep Biodiversity of Carabinieri (Pratovecchio Office, 2018).

La Riserva Naturale Integrale di

Sasso Fratino

CARABINIERI

BIODIVERSITÀ

RAGGRUPPAMENTO CARABINIERI BIODIVERSITÀ

REPARTO BIODIVERSITÀ
PRATOVECCHIO

Il paesaggio sonoro

Gianni Pavan, Roberta Righini, Pamela Priori, Dino Scaravelli

La Riserva Naturale Integrale di Sasso Fratino offre un paesaggio visivo estremamente ricco che nasce dallo sviluppo indisturbato di tutte le componenti dell'ecosistema e dalla mancanza dei segni della presenza umana. Ma, oltre a un complesso paesaggio visuale, la Riserva offre anche un paesaggio sonoro ricco e articolato che nasce dall'insieme di suoni e rumori generati dall'ambiente fisico e dalla comunità di animali che lo abitano. A tutto questo si aggiungono gli alberi che, con lo stormire delle foglie e lo scricchiolare dei tronchi, contribuiscono a costruire uno specifico e riconoscibile ambiente acustico, a seconda dei luoghi arricchito dal rumore delle acque correnti.
Il paesaggio sonoro è una espressione dell'ambiente che possiamo considerare sul piano estetico, ad esempio per il piacere che proviamo nell'ascoltare i suoni e i rumori della natura, ma che ha anche un grande valore scientifico per la comprensione dei fenomeni che vi si sviluppano sia a breve che a lungo termine (Schafer, 1985; Krause, 2002; Pavan, 2012; Farina, 2014; Farina & Gage, 2017).

I suoni prodotti dagli animali, come il canto degli uccelli o il gracidare delle rane, un tempo considerati espressione della "forza vitale" o più poeticamente espressione della "gioia di vivere", sono riconosciuti come funzionali allo svolgimento di molteplici funzioni vitali, quali l'accoppiamento e la riproduzione, il coordinamento dei comportamenti individuali e sociali, la caccia e la ricerca del cibo, la percezione dell'ambiente. La bioacustica studia i suoni prodotti dagli animali per comunicare e, nei Chirotteri e nei Cetacei, per individuare, con l'ecolocalizzazione, ostacoli e prede (Griffin, 1958). Studia anche come gli animali recepiscono e interpretano i suoni e i rumori dell'ambiente e anche come reagiscono al rumore e al disturbo prodotto dalle attività umane (Pavan, 2015, 2017, 2018).

L'ecoacustica ha come oggetto principale di ricerca il paesaggio sonoro, definito anche ambiente acustico, ovvero l'insieme dei suoni e rumori, di origine naturale e antropica che caratterizzano un determinato ambiente. In generale, il paesaggio sonoro è costituito da tre componenti, i suoni prodotti dalla comunità biologica (*biofonia,* oggetto di studio condiviso anche con la bioacustica), i rumori generati da fenomeni naturali (pioggia, vento, tuoni, acque correnti, ecc.) che rappresentano la *geofonia*, e i suoni e rumori prodotti dall'uomo (*antropofonia*) che in alcune situazioni possono avere effetti negativi e pertanto essere considerati come "inquinamento acustico" (Pavan, 2017, 2018).

La bioacustica e l'ecoacoustica sono discipline emergenti e in rapido sviluppo nelle scienze della biodiversità e della conservazione: dal riconoscimento e monitoraggio delle singole specie fino allo studio del paesaggio sonoro, forniscono nuove informazioni e strumenti per la scienza, la conservazione e l'educazione (Laiolo, 2010; Obrist et al., 2010; Favaretto et al., 2011; Pijanovsky et al., 2011; Pavan, 2015; Pavan et al., 2015). L'ecoacoustica deriva dalla relazione fra bioacustica ed ecologia; studia i suoni naturali, biologici e di origine antropica e il loro rapporto con l'ambiente fisico in un ampio intervallo di scale di studio, sia spaziali che temporali, a livello individuale, comunitario e di popolazione. L'ecoacoustica considera tutti gli ecosistemi terrestri e acquatici, estendendo il campo di applicazione della bioacustica e dell'acustica, e fornisce nuovi strumenti per il monitoraggio, la gestione e la conservazione dell'ambiente.

La Riserva Naturale Integrale di Sasso Fratino è un esempio di ambiente naturale in cui

paesaggio visivo e paesaggio sonoro si fondono per dare una completa percezione di ambiente naturale. A questa percezione contribuisce in modo significativo la quasi totale mancanza di rumore di origine antropica.
Lo studio e la conservazione dei paesaggi sonori hanno molteplici implicazioni, sia per la conservazione dell'ambiente naturale e delle sue funzioni, sia per offrire al visitatore attento e consapevole il ristoro dato dal silenzio e da un ambiente ricco di stimoli con le continue variazioni dei suoni naturali. Attraverso le loro manifestazioni sonore il visitatore percepisce la vita degli animali che lo circondano, anche quando

Fig. 1 - Registratore Wildlife Acoustics SM3 collocato ai margini di Pian dei Giusti, nel cuore della RNI. La batteria esterna consente il funzionamento per circa 90 giorni. In anni successivi sono stati affiancati i nuovi modelli SM4.

non visibili, e la ricchezza e biodiversità dell'ambiente naturale. I sentieri naturalistici adiacenti alla Riserva possono anche divenire percorsi di ascolto (Pavan & Pinoli, 2007) e contribuire alla formazione di una più ampia consapevolezza della ricchezza, diversità, e complessità degli ambienti naturali, ma anche della loro vulnerabilità al rumore prodotto dall'uomo.

IL MONITORAGGIO ACUSTICO DELLA RISERVA

Per le sue caratteristiche peculiari, si è avviato nella Riserva un progetto di ricerca sul paesaggio sonoro estendendolo alle frequenze ultrasoniche che, non percepibili dall'uomo, sono usate dai Chirotteri per volare nella completa oscurità e cacciare le loro prede, perlopiù insetti in volo, durante le ore notturne. Il programma di ricerca nasce dal progetto SABIOD (*Scaled Acoustic BIODiversity*) delle Università di Pavia e di Tolone (Francia) per lo studio del paesaggio sonoro in ambienti naturali a diverso grado di integrità e di tutela, dalle riserve naturali integrali alle aree più soggette ad attività antropiche (Pavan et al., 2015). Il progetto è anche collegato al tema delle "quiet areas" (EEA, 2016) e all'importanza del silenzio, inteso come assenza del rumore delle attività umane, soprattutto dovute ai trasporti (traffico stradale, ferroviario e aereo), che ha un impatto negativo sulla salute umana (EEA, 2014), sugli animali e sugli ecosistemi (Fristrup et al., 2012; McGregor et al., 2013; Pavan, 2015, 2017, 2018). A partire dal 2014 sono stati installati nel cuore della Riserva e in aree adiacenti diversi registratori autonomi (Figura 1), programmati per registrare il paesaggio sonoro 10 minuti ogni mezz'ora, per periodi estesi da 45 a 90 giorni consecutivi (Pavan et al., 2015). Questi strumenti registrano su memorie a stato solido che periodicamente, al cambio delle batterie del registratore, vengono estratte e copiate su computer per essere successivamente archiviate, catalogate e analizzate.

AVIFAUNA

L'analisi del paesaggio sonoro udibile fornisce un quadro dell'ambiente acustico principalmente dominato, nelle ore diurne, dai canti di numerose specie di uccelli canori.

Lo studio delle registrazioni, che richiede l'ascolto dei canti e l'analisi delle immagini spettrografiche che mostrano la struttura dei suoni, è ancora in corso ma già consente di avere una visione della ricchezza di specie presenti.

L'analisi delle registrazioni viene effettuata a diversi livelli, dapprima una visione generale del paesaggio sonoro giornaliero con spettrogrammi compatti (ovvero la rappresentazione grafica dell'intensità di un suono in funzione del tempo e della frequenza, Figura 2), che rappresentano 24 ore e che costituiscono una sorta di "indice" attraverso il quale si cercano "pattern sonori" ripetitivi e riconoscibili (Pavan et al., 2015), quindi l'analisi si focalizza su dettagli sempre più particolari, da periodi di 10 minuti (Figura 3) fino a frammenti temporali di pochi secondi (Figura 4), per il riconoscimento specifico dei vari canti o di altri eventi sonori. Un diverso approccio fornisce invece "indici" di ricchezza, di diversità sonora e di rumore antropico, prescindendo dal riconoscimento delle specie ma fornendo invece dei valori che consentono di valutare la qualità sonora ambientale dell'area studiata (Sueur et al., 2008).

La Figura 2 mostra i suoni registrati in una intera giornata (10 minuti di registrazione ogni mezz'ora) e, pur non consentendo la visione dei suoni nel dettaglio, evidenzia la diversità di bande di frequenza, la densità e la durata delle vocalizzazioni; le figure successive (Figure 3 e 4) mostrano invece analisi con maggiore risoluzione temporale che consentono di evidenziare e riconoscere le strutture acustiche delle varie specie. Il riconoscimento delle specie, che richiede il supporto di esperti ornitologi, viene anche verificato attraverso la consultazione delle fonoteche zoologiche, archivi sonori internazionali che conservano e catalogano le registrazioni delle varie specie animali fornite da studiosi di tutto il mondo. In questo lavoro vengono anche sperimentati e perfezionati software che riconoscono l'occorrenza di "modelli", ma la supervisione di un esperto rimane essenziale.

L'analisi specifica rivela la presenza di diverse specie di allegato I della direttiva 79/409 ed esempio certo più tipico per l'ambito forestale è dato dalla presenza del Picchio nero, *Dryocopus martius* che trova qui uno dei pochi punti di presenza al di fuori delle Alpi (Campedelli et al., 2014). Ma oltre a questi elementi faunistici rari, nel bosco si trovano altre decine di specie che possono sopravvivervi per i numerosi microambienti e le reti trofiche ancora complesse

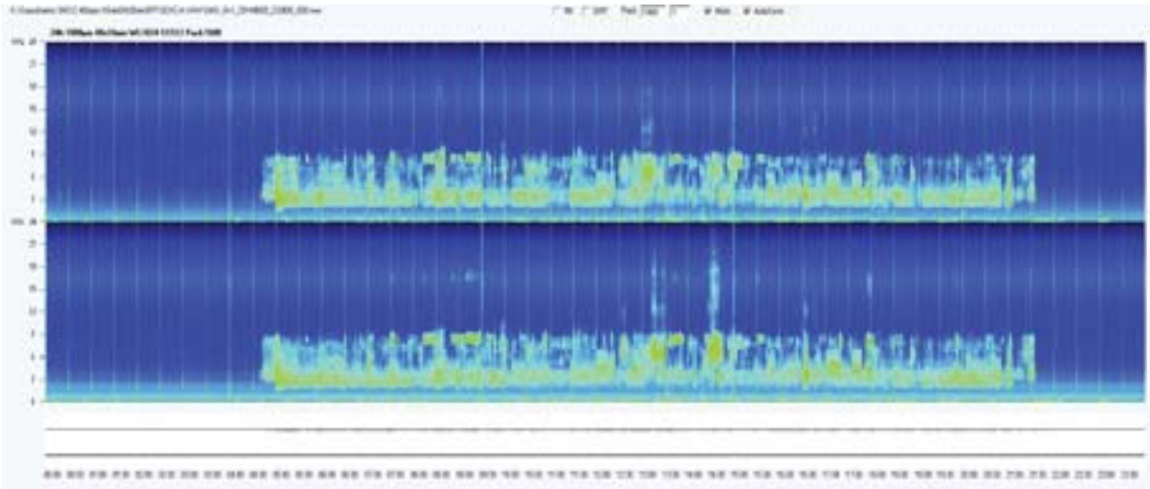


Fig. 2 - Spettrogramma compatto di un giorno di registrazione in Sasso Fratino, località la Bucaccia (2014-06-09), costituito da 10 minuti ogni mezz'ora (48 sezioni). L'immagine mostra una netta transizione all'alba e al tramonto con una intensa *biofonia* nelle ore diurne che si concentra fra 1.5 e 9 kHz. Le tracce a frequenze molto basse rappresentano il passaggio di aerei (asse x 24 ore, asse y 0-24 kHz). La figura è composta dalla rappresentazione grafica di 2 canali di registrazione.

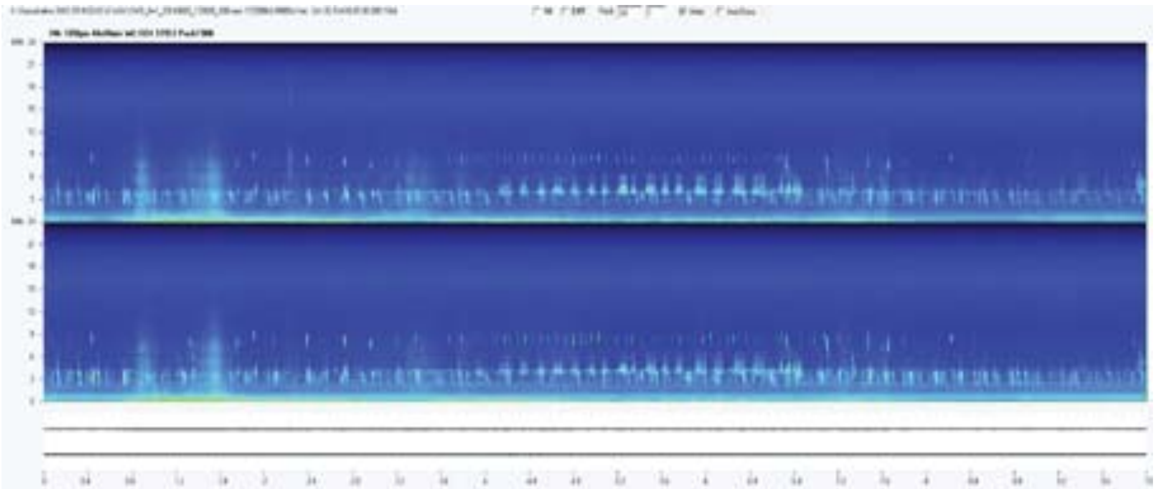


Fig. 3 - Spettrogramma compatto di 10 minuti di registrazione (2014-06-09 alle 13:30). Si notano le tracce di richiami e canti che si ripetono più volte. A sinistra il vento produce rumore sia a bassa frequenza che a larga banda, quest'ultimo generato dalle foglie mosse. (asse x 10 min, asse y 0-24 kHz, 2 canali).

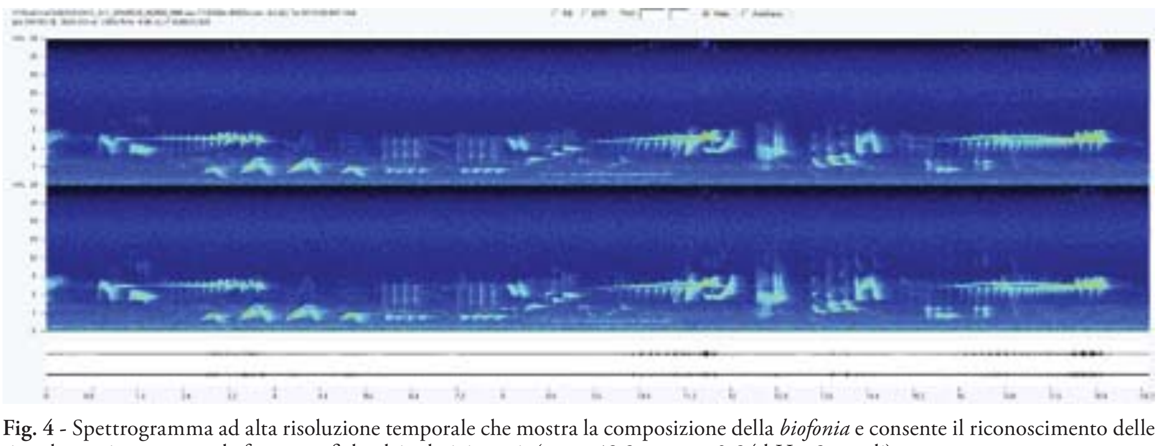


Fig. 4 - Spettrogramma ad alta risoluzione temporale che mostra la composizione della *biofonia* e consente il riconoscimento delle singole specie attraverso le forme grafiche dei relativi canti. (asse x 19.2 s, asse y 0-24 kHz, 2 canali).

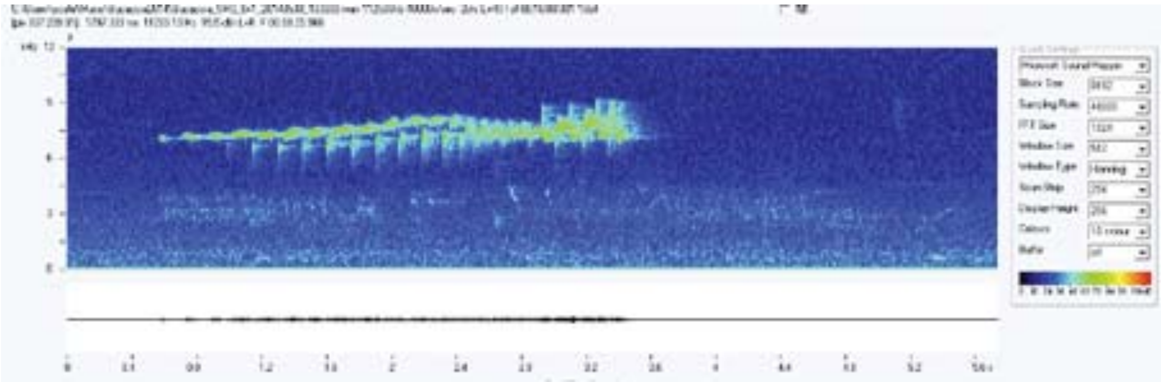


Fig. 5 - Spettrogramma ad alta risoluzione del canto di fiorrancino. (asse x 5.6 s, asse y 0-12 kHz).

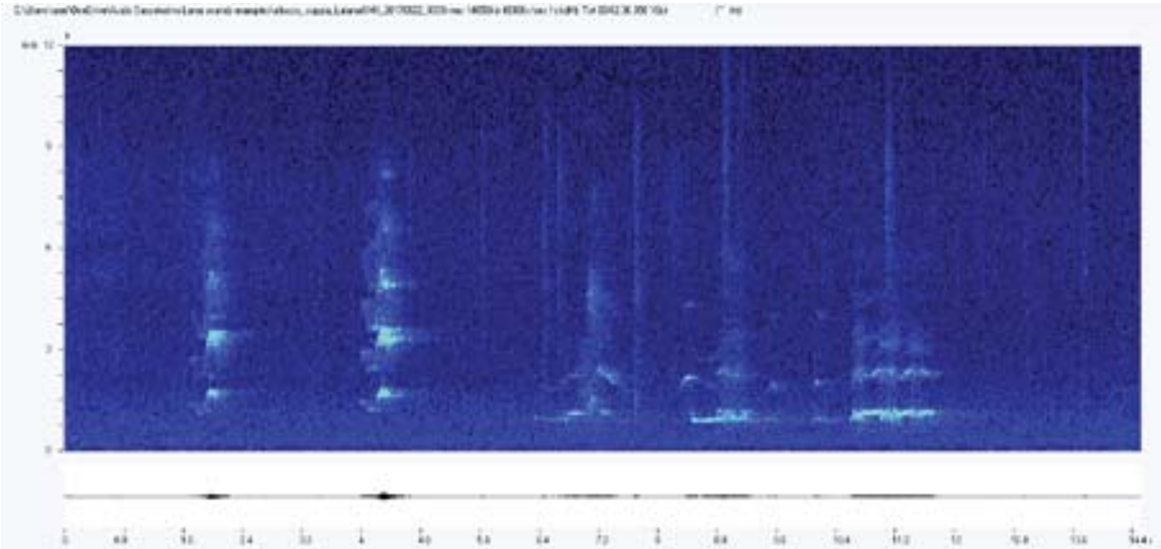


Fig. 6 - Spettrogramma ad alta risoluzione della vocalizzazione di una coppia di allocchi. (asse x s, asse y kHz). In particolare, nella specie *Strix aluco* è possibile distinguere acusticamente (e visivamente sullo spettrogramma) il verso della femmina, i primi due a sinistra, da quello del maschio, a destra.

e diversificate. Vi sono specie dai canti molto fievoli e ad alta frequenza come Fiorrancino *Regulus ignicapilla* (Figura 5), e poi Regolo *Regulus regulus*, Rampichino alpestre *Certhia familiaris,* Luì piccolo *Phylloscopus collybita* e Luì verde *Phylloscopus sibilatrix*, Usignolo *Luscinia megarinchos* e molti altri. Nelle notti silenziose emergono frequenti le note dell'Allocco *Strix aluco* (Figura 6) . L'insieme di queste voci compone l'immagine di Figura 2 e indica la grande ricchezza e diversità sonora del bosco.

I CHIROTTERI E IL PAESAGGIO SONORO ULTRASONICO

I Chirotteri hanno una grande importanza per gli equilibri biologici e sono ottimi indicatori di integrità ambientale. La loro presenza testimonia la complessità e il livello di conservazione degli ambienti che abitano; tuttavia, in molti ambienti, questi mammiferi sono in pericolo per le molteplici pressioni dovute alle attività umane proprio nei loro ecosistemi, sia naturali che variamente antropizzati, come aree urbane, periurbane, e agricole.

Per volare e catturare le prede nell'oscurità usano l'ecolocalizzazione, un sofisticato sistema di orientamento basato sull'emissione di brevi segnali ultrasonori e sulla capacità di percepire gli echi di ritorno che permette all'animale di valutare la distanza dall'oggetto colpito dall'ultrasuono oltre che ad avere informazioni sul suo movimento, dimensioni e caratteristiche (Griffin, 1958). Tutte le informazioni sonore vengono captate ed elaborate da specifiche unità del sistema nervoso centrale per la creazione di un'immagine "sonora" molto dettagliata dell'ambiente circostante e delle possibili prede (Schnitzler & Kalko, 2001).

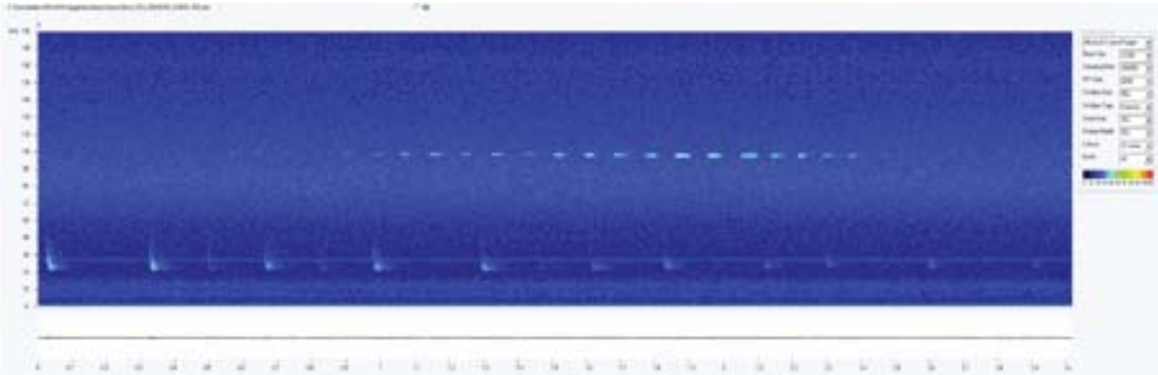


Fig. 7 - Spettrogramma di sequenze di ecolocalizzazione di due specie di Chirotteri, a circa 25 kHz e a 108 kHz; la più alta in frequenza è tipica di *Rhinolophus hipposideros* (asse x, 3 secondi; asse y 0-192 kHz). La registrazione è stata effettuata con registratore Wildlife Acoustics SM4BAT-FS.

Le specie forestali e montane sono tra le meno conosciute, sia in termini di distribuzione altitudinale sia come presenza e diversità di specie, anche nel panorama europeo. La collocazione in diversi siti, fino a 1400 metri di quota, di un registratore a loro dedicato ha fornito dati sorprendenti che indicano una diversità e una attività inattese e superiori alle aspettative. La Figura 7 mostra sequenze di ecolocalizzazione di alcune delle specie registrate nella piana della Lama, adiacente alla Riserva, con registratori programmati per registrare nelle ore notturne quando vi siano segnali in banda ultrasonica (Fig. 8). L'analisi esclusivamente acustica non sempre consente una accurata identificazione di tutte le specie registrate (Russo & Jones, 2002; Obrist et al., 2004) e solo la verifica diretta dei siti di rifugio o la cattura temporanea di esemplari consente la certezza di riconoscimento, soprattutto delle specie con caratteristiche acustiche e spettrografiche meno studiate in letteratura o che si sovrappongono come avviene con le specie del genere *Myotis*. Tuttavia, il metodo acustico fornisce una prima prova della loro presenza e, con l'analisi delle bande di frequenze usate, che si estende da circa 20 kHz a oltre 110 kHz, una preliminare stima di abbondanza e di diversità specifica.

Le ricerche tradizionali hanno evidenziato la presenza da tempo di una comunità molto ricca (Agnelli et al., 1998 e 1999) che oggi conta tra le specie di particolare rilevanza per la conservazione (in allegato II della direttiva Habitat) *Rhinolophus ferrumequinum* Rinolofo maggiore, *Rhinolophus hipposideros* Rinolofo minore (visibile in figura 7), *Rhinolophus euryale*, Rinolofo mediterraneo, *Barbastella barbastellus* Barbastello, *Myotis emarginatus* Vespertilio smarginato, *Myotis myotis* Vespertilio maggiore, *Myotis blythii* Vespertilio di Blyth e *Miniopterus schreibersii* Miniottero. Inoltre, vi sono riscontri per le specie *Myotis daubentonii* Vespertilio di Daubenton, *Pipistrellus pipistrellus* Pipistrello nano, *Pipistrellus pygmaeus* Pipistrello pigmeo, *Pipistrellus kuhlii* Pipistrello albolimbato, *Hypsugo savii* Pipistrello di Savi, *Nyctalus leisleri* Nottola di Leisler, *Nyctalus noctula* Nottola comune, *Eptesicus serotinus* Serotino comune, *Plecotus austriacus* Orecchione grigio, *Plecotus auritus* Orecchione bruno, *Tadarida teniotis* Molosso di Cestoni. Per alcune di queste, con metodi bioacustici si sono determinati anche preferenze ambientali e determinanti ecologici (Campedelli et al. 2015 e 2016). Recentemente il valore della conservazione non solo della foresta ma anche degli edifici, storici e non, gestiti in seno alla compagine alberata, è stato oggetto di valutazione con la valorizzazione dell'importanza ai fini della conservazione di specie a rischio come i rinolofidi o il Vespertilio smarginato (Scaravelli e Priori 2016a, 2016b).

SILENZIO E RUMORE ANTROPICO

Anche i suoni e i rumori di origine antropica contribuiscono alla composizione e alla caratterizzazione di un paesaggio sonoro (Pavan, 2018), ma possono anche diventare invasivi fino ad essere considerati inquinamento acustico con un effetto negativo sia sull'uomo (EEA, 2014, 2016) che sulle comunità animali (McGregor et al., 2013; Pavan, 2015, 2017).

L'ambiente della RNI di Sasso Fratino è particolarmente silenzioso (Pavan, 2016), i suoni che vi si sentono sono essenzialmente i suoni della natura, canti di uccelli, insetti nei periodi più caldi, i bramiti dei cervi a settembre, il vento con lo stormire delle foglie, lo scrosciare delle acque, e i rumori generati da fenomeni atmosferici (vento, pioggia, temporali). Nonostante la presenza di questi suoni e rumori naturali, si ha la percezione di profondo silenzio, dovuta alla mancanza del costante rombo a bassa frequenza del traffico stradale al quale siamo ormai assuefatti nella vita urbana (Pavan, 2017, 2018). I suoni di origine antropica sono praticamente assenti, l'unica strada nella valle è chiusa al traffico e l'ambiente è ben schermato dalle montagne circostanti coperte di foresta densa. L'unico rumore antropico ricorrente è il passaggio degli aerei ad alta quota che, nel silenzio, appaiono molto più invasivi rispetto alle normali situazioni in cui li udiamo, immersi nel rumore tipico dell'ambiente urbano (Pavan, 2016).

Per effettuare accurate misure di rumore sono stati necessari strumenti fonometrici con microfono a basso rumore. Nel perseguire questo obiettivo il vento è stato il problema principale, in un ambiente non pervaso dal rumore del traffico stradale vicino e lontano, anche solo con una leggera brezza si sente il fruscio generato dalle foglie mosse (Figura 3). Per questo motivo non è stato facile trovare periodi sufficientemente lunghi con assenza di vento, e con insetti e uccelli in silenzio, e quindi le misure utili per determinare i livelli di massima silenziosità sono state possibili solo per brevi periodi.
La RNI di Sasso Fratino è risultata un'area naturale con elevata ricchezza e diversità di suoni biologici, concentrati dall'alba al tramonto, e particolarmente silenziosa per quanto riguarda il rumore di origine antropica. Nelle registrazioni più silenziose le misure mostrano livelli di rumore nei terzi di ottava inferiori a 100 Hz molto bassi, prossimi a 0 dB, talvolta inferiori. Nelle bande superiori, fra 200 Hz e 2 kHz, il livello è compreso fra 10 dB e 20 dB per il 95% del tempo (percentile 95).
Le misure visibili nella Figura 9, riferite a un periodo di 5 minuti, rappresentano:
1 Spettro in terzi di ottava (costante di tempo 100ms) con presentazione dei minimi, dei massimi, della media, e dei percentili 5, 50 e 95
2 Andamento temporale del livello sonoro con

Fig. 8 - Registratore Wildlife Acoustics SM4BAT-FS installato nella piana della Lama a una altezza di circa 2.5 metri.

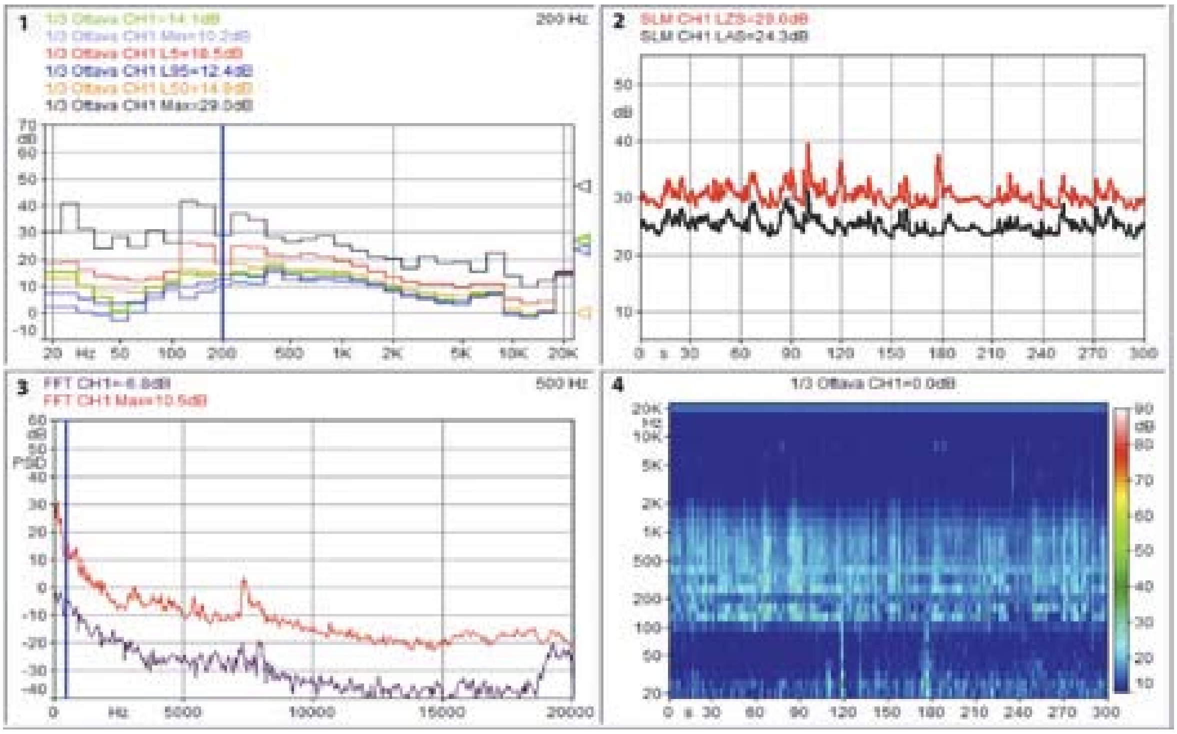


Fig. 9 - Registrazione in condizioni di basso rumore ambientale. Le tracce sonore visibili nello spettrogramma (4) sono prevalentemente dovute al ronzio degli insetti in volo e ai piccoli rumori provenienti dal bosco che determinano i livelli sonori fra 100 Hz e 2 kHz nel grafico 1 e il livello complessivo nel grafico 2. Le misure sono state effettuate con microfono a basso rumore PCB Piezotronics 378A45 collegato a sistema di acquisizione SINUS Harmony con software SAMURAI, al fine di rilevare livelli sonori inferiori a 0 dB, che è il livello minimo percepibile dall'orecchio umano.

e senza pesatura, LAS e LZS

3 Spettro lineare con indicazione del minimo e del massimo livello
4 Spettrogramma in terzi di ottava con scala colori da 10 dB a 90 dB

Nell'area delle riserve della Lama e di Sasso Fratino, lontani dal traffico stradale e da aree abitate, si ha una profonda e continua percezione di silenzio nonostante i ronzii degli insetti in volo, il rumore dello stormire delle foglie mosse dal vento, e il rumore delle acque correnti percepibile quando ci si avvicina ai corsi d'acqua. Dalle misure effettuate emerge un basso livello di rumore nelle frequenze più basse, usualmente prodotte dal traffico stradale, e sembra che questo sia fondamentale nel generare la percezione di "profondo silenzio". La scelta dei punti di misura non è banale; la presenza pressoché continua di suoni e rumori di origine biologica e geofisica, quale lo scorrere di acque presenti ovunque, pone la necessità di misure estese nel tempo per avere un preciso quadro spettro-statistico dell'ambiente acustico.

In questo contesto emerge il rumore prodotto dai sorvoli degli aerei che pervade anche le aree naturali più remote. Sulle rotte più frequentate la frequenza dei passaggi aerei è molto elevata e ciascun passaggio aereo diventa particolarmente avvertibile a causa del basso rumore naturale a bassa frequenza. Nei vari passaggi aerei si nota una grande diversità di livello e composizione spettrale con un contrasto dinamico che talvolta supera i 60 dB nelle bande inferiori a 500 Hz. Da notare che il livello di rumore degli aerei ad alta quota è raramente percepito negli ambienti antropizzati perché si confonde con il rumore a bassa frequenza che può raggiungere livelli di oltre 70 dB nelle aree con traffico più intenso.

CONCLUSIONI

La RNI di Sasso Fratino è risultata un'area naturale con elevata ricchezza e diversità di suoni biologici e particolarmente silenziosa per quanto riguarda il rumore di origine antropica. In questo contesto particolare si possono effettuare studi sulle distanze di comunicazione degli animali, uccelli in particolare, sulla capacità del bosco di attenuare il rumore antropico e quindi ridurre la propagazione dell'inquinamento acustico all'interno delle aree protette, e sul disturbo dovuto a eventi transienti quali i

passaggi aerei. Con la registrazione sistematica del paesaggio sonoro della Riserva si costruisce un archivio di riferimento per valutare, in futuro, eventuali cambiamenti nella composizione della fauna canora.
È infine da considerare che le aree protette circostanti la RNI ne tutelano la silenziosità e offrono al visitatore un ricco paesaggio sonoro e un profondo silenzio antropico.

RINGRAZIAMENTI
Un particolare ringraziamento è dovuto al Reparto Carabinieri Biodiversità di Pratovecchio e al personale di Camaldoli e Badia Prataglia per la preziosa collaborazione e il sempre cordiale supporto alle nostre necessità di ispezione ai siti di registrazione all'interno della Riserva.
Si ringraziano Andrea Favaretto, Marco Pesente, Marco Dragonetti e Perla Cateni per il prezioso supporto nell'identificazione dei canti. Si ringraziano inoltre le ditte Spectra e PCB Piezotronics per la disponibilità degli strumenti di misura.

Bibliografia

- Agnelli P., Scaravelli D., Bertozzi M., Crudele G., 1998. Studio e conservazione dei Chirotteri nelle Riserve Biogenetiche del Parco Nazionale delle Foreste Casentinesi Monte Falterona e Campigna. Atti II° Congresso Italiano di Teriologia – Varese.
- Agnelli P., Scaravelli D., Bertozzi M., Crudele G., 1999. Primi dati sui Chirotteri del Parco Nazionale delle Foreste Casentinesi, M. Falterona e Campigna. Atti del I° Convegno Italiano sui Chirotteri. Castell'Azzara (GR).
- Campedelli T., Tellini Florenzano G., Londi G. e Cutini S., 2014. Avifauna nidificante nella Riserva Naturale Integrale di Sassofratino – Risultati dei censimenti 2013. Report.
- Campedelli T., Londi G., Cutini S., Scaravelli D., Priori P., Tellini Florenzano G., 2015. Composizione forestale e comunità di Chirotteri nel Parco Nazionale delle Foreste Casentinesi, Monte Falterona e Campigna: il ruolo dei boschi di conifere. Abstr. III Conv. Ital. Chirotteri, Trento 9-11/10/2015: 18.
- Campedelli T., Londi G., Cutini S., Scaravelli D., Priori P., Tellini Florenzano G., 2016. Chirotteri e boschi di conifere: il caso del Parco Nazionale delle Foreste Casentinesi, Monte Falterona e Campigna. In Pavan G. e D. Scaravelli (edts), 2016. Workshop "Bioacustica ed Ecoacustica per il Monitoraggio Acustico Ambientale", 11-12/6/2016 Badia Prataglia (AR): 17-20.
- EEA, 2014. Noise in Europe. European Environmental Agency, Report 10/2014: 1-68
- EEA, 2016. Quiet areas in Europe. The environment unaffected by noise pollution. European Environmental Agency, Report 14/2016: 1-80.
- Farina A., 2014. Soundscape Ecology. Principle, Patterns, Methods and Applications. Springer: 315pp.
- Farina A., Gage S.H. (Editors), 2017. Ecoacoustics. The ecological role of sound. Wiley: 352pp.
- Favaretto A., Salogni G., Pavan G., De Battisti R., 2011. Sistemi automatici di registrazione: nuove metodologie bioacustiche applicate a indagini ornitologiche in alcuni siti della Rete Natura 2000 del Veneto. Risultati e prospettive, Atti Conv. Faunisti Veneti 2010, «Bollettino del Museo di Storia Naturale di Venezia», 61: 118-123.
- Fristrup K.M., Mennitt D., 2012. Bioacoustical monitoring in terrestrial environments, Acoustics Today, 8-3: 16-24
- Griffin D.R., 1958. Listening in the dark, Yale University Press
- Krause B., 2002. Wild soundscapes: Discovering the voice of the natural world, Wilderness Press, Birmingham
- Laiolo P., 2010. The emerging significance of bioacoustics in animal species conservation, Biological Conservation, 143: 1635-1645
- McGregor P.K., Horn A.G., Marty L. Leonard M.L., Thomsen F., 2013. Anthropogenic Noise and Conservation, in "Animal Communication and Noise", Brumm H. Editor, Springer: 409-444
- Obrist M.K., Boesch R., Flückiger P.F., 2004. Variability in echolocation call design of 26 Swiss bat species: consequences, limits and options for automated field identification with a synergetic pattern recognition approach. Mammalia, 68 (4): 307-322
- Obrist M.K., Pavan G., Sueur J., Riede K., Llusia D. and Márquez R., 2010. Bioacoustic approaches in biodiversity inventories. In: Manual on Field Recording Techniques and Protocols for All Taxa Biodiversity Inventories, Abc Taxa, 8: 68-99
- Pavan G., 2012. Paesaggi sonori terrestri e marini. In: "Filogenesi e ontogenesi della musica", a cura di Avanzini G., Longo T., Majno M., Malavasi S., Martinelli D., pp 45-54. Franco Angeli Editore
- Pavan G., 2015. Bioacustica e Ecologia acustica. Cap. 18. Pp 803-828. In: Renato Spagnolo (a cura di), "ACUSTICA. Fondamenti e applicazioni", UTET Università: 1-1582
- Pavan G., 2016. Il rumore negli ambienti naturali. Misura e interpretazione. Atti 43° Convegno AIA. CN43071.
- Pavan G., 2017. Fundamentals of Soundscape Conservation. In: "Ecoacoustics. The ecological role of sound" (Farina A. & Gage S.H., editors). Wiley: 235-258.
- Pavan G., 2018. I suoni naturali dell'antropocene. Bollettino Ingegneri, Anno LXVI - n. 1: 15-17.
- Pavan G., Favaretto A., Bovelacci B., Scaravelli D., Macchio S., Glotin H., 2015. Bioacoustics and Ecoacoustics applied to environmental monitoring and management. Rivista Italiana di Acustica, 39: 68-74
- Pavan G., Pinoli G., 2007. Paesaggi Sonori. Suoni e rumori nella foresta della Valsolda. ERSAF Itinerari Tematici, 7: 1-38
- Pijanowski B.C., Villanueva-Rivera L.J., Dumyahn S.L., Farina A., Krause B.L., Napoletano B.M., Gage S.H., Pieretti N., 2011. Soundscape Ecology: The Science of Sound in the Landscape, BioScience, 61-3: 203-210.
- Russo D., Jones G., 2002. Identification of twenty-two bat species (Mammalia: Chiroptera) from Italy by analysis of time-expanded recordings of echolocation calls. J. Zool., 258: 91-103
- Scaravelli D. e P. Priori, 2016a. La gestione forestale per i Chirotteri: dalle teorie alla pratica. In Pavan G. e D. Scaravelli (editors), 2016. Workshop "Bioacustica ed Ecoacustica per il Monitoraggio Acustico Ambientale", 11-12/6/2016 Badia Prataglia (AR): 15-165
- Scaravelli D. e P. Priori, 2016b. Nota di studio sulla chirotterofauna e suoi rifugi nelle Foreste Casentinesi. Report ufficio UTB Pratovecchio
- Schafer R.M., 1985, Il paesaggio sonoro (The tuning of the World, 1977), Unicopli, Milano
- Schnitzler H.-U., Kalko E.K.V., 2001. Echolocation by insect-eating bats. Bioscience, 51: 557-569
- Sueur J., Pavoine S., Hamerlynck O., Duvail S., 2008. Rapid acoustic survey for biodiversity appraisal, «PloSONE», 3, e4065

Siti web

- Cibra, Università di Pavia (http://www.unipv.it/cibra)
- Fonoteca Zoologica della British Library (http://sounds.bl.uk/Environment)
- Fonoteca Zoologica di Berlino (http://www.tierstimmenarchiv.de)
- Fonoteca Zoologica Xeno Canto (http://www.xeno-canto.org)
- Fonoteca Zoologica Cornell University (http://macaulaylibrary.org)
- Fonoteca Zoologica di Madrid (http://www.fonozoo.com)
- World Forum for Acoustic Ecology (http://wfae.proscenia.net)
- Nature sound map (http://www.naturesoundmap.com)
- Global soundscapes (http://globalsoundscapes.org)
- Wild Echoes (http://www.wildechoes.org)
- Martyn Stewart (http://www.naturesound.org)
- Bernie Krause (http://www.wildsanctuary.com)

GENERAL CONCLUSIONS & FUTURE PERSPECTIVES

The present Ph.D. project is aimed at validating the descriptive power of acoustic environment's analysis as a useful tool to describe temporal and structural characteristics of a particular habitat and to obtain a valid animal diversity/richness assessment and potential indicators of its status.
The main result is the elaboration of the methodological and analytical research protocol (sampling, archiving and analysis) and the development of a multi-scale time ecoacoustic analysis procedure applied to the biodiversity monitoring in protected areas that can be adopted by park authorities for a national and European monitoring network.
In addition to this, a new perspective of investigation has been initiated for the quantifying of the anthropogenic noise levels impacting a natural environment in order to build a reference archive that will score habitats and will contribute to assessing the habitat quality and biodiversity status.

The ecoacoustic analysis was developed with a double approach, one focusing on each of the three components of the Soundscape separately (*chapter 2*) and one based on a global synthetic description based on “indices”, providing the elaboration of a standard research protocol (*chapter 3*, for the theory and methodology part, and *chapter 4* for the practical application of the protocol to the study of the soundscape of the Sasso Fratino Integral Nature Reserve).

In the *Chapter 2*, the Soundscape has been analysed by considering its three components separately.

Geophony – It is a rich but still unexplored source of information in the environmental acoustic recording.
In fact, although there are more and more studies concerning the analysis of the biophony component that are translated into the creation of new indices for the determination of different bio-diversity and bio-richness levels in different habitats, and, more recently, a great attention is paid to the human-activity sounds, the geophony results to be the less known but also the most difficult component to study, due to the diversity of sources and types of natural sounds. Moreover, since passive acoustic monitoring generates large data sets of audio recordings that have to be stored and processed, the possibility of discriminating the recordings according also to different weather conditions, will contribute to make processing time manageable and to reduce analysis effort.
Concerning the geophony, the preliminary analysis of the audio data is presented in order to identify the parameters or the indices most suitable to indicate the presence of rain (and partly wind) in an acoustic dataset.

Among Acoustic Indices, the Acoustic Complexity Index showed a good discriminative power, in particular calculated in specific frequency bands, i.e. above 9,000 -12000 Hz in which the acoustic index presented values with statistically significant distribution in the files classified as rain (both day and night) compared to the others (good and wind).
A second parameter investigated is the different distribution that the spectral energy assumes in selected frequency bands. Three main frequency ranges were considered, concentrating in the intervals above, central and below the typical frequencies of biophony: 0-1.500 Hz (low), 1.500-9.000 Hz (medium) and 10.000-15.000Hz (high), respectively; the ratio between the values of the low and medium ranges, in particular, indicated positive values only for files belonging to the 'good weather' category.

Biophony - In long real field recordings, the automatic species sound detection results to become a useful and promising method for acoustic monitoring of wildlife animals, in synergy with the more traditional techniques (as listening points census). The goal of automatic identification is to process huge amounts of recordings to find when and where the target species sang. But the whole process is still based on the initial expert classifications of the targets to set the auto-id process, that must be tuned accurately case by case. For this, the main challenge is to develop machine learning techniques that allow, on the one hand, the elaboration of species specific pattern for automatic identification and, on the other one, the processing large amounts of data in less time in order to enable that automatic detection can be integrated into remote monitoring projects.

Anthropophony - For conservation and monitoring projects, the study of anthropogenic sounds and their relationship with the environment, and in particular with the animal communities, allows increasing knowledge about habitat quality. In this context, the study of areas with a very low level of anthropic noise plays a special role in order to define a reference model of an acoustic environment similar to the pre-industrial era.
By the analysis of the several calibrated recordings collected at different points in the National Park (especially inside or adjacent to the INR of Sasso Fratino), the recorded noise levels in 1/3 octave bands lower than 1 kHz show L95 and L5 percentiles below 20 dB (without wind). Another interesting result is that, focusing on the low-frequency bands (below 200 Hz), the background noise level (percentile L95) is close to 0 dB and sometimes lower, and this indicates a significant lack of anthrophony component (continuous low-frequency noise due to transportation infrastructures).

A global descriptive ecoacoustic approach as long term biodiversity and environment' monitoring has different advantages:

- 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, and education;
- qualitative and quantitative data: acoustic sampling provides qualitative and quantitative data for the comparison of acoustic variance both intra-site (for monthly or yearly sampling) and inter sites (for multiple simultaneous locations);
- data over large spatial and temporal scales: the recording of the acoustic environment allow to characterize a specific habitat and to outline its changes on different time scales, from daily changes to seasonal ones and, through the creation of an acoustic repository, it also has the possibility of preserving the annual series and comparing them with each other to study long term trends related with climate change pressures;
- remote and passive: it results to be a non-invasive method and it is independent of the observer's presence (increasing the likelihood of detecting rare, cryptic or alien species) and it eases to monitor places that are difficult to access. Future developments of data transmission networks will allow continuous real-time monitoring of acoustic events, also for surveillance purposes.

The new challenge is to draw up an analysis methodology to optimize resources both in the field (saving memory cards and batteries) both in the lab, reducing time and effort of analyses, while maintaining high the accuracy of the information.
For this, it is required the elaboration of a standard Research Protocol (*Chapter 3*) which defines an effective procedure from data collection to their storage and analysis; the analysis works at different time and space scales and with multiple approach, in particular one qualitative based on visual screening of compact spectrograms and the other quantitative by the estimation of the acoustics parameters and indices and their statistical analysis.

In *Chapter 4*, the application of the Research Protocol is applied and validated. For the first time it is described the soundscape of the Sasso Fratino Integral Nature Reserve, a well-protected area internationally known for its conservation level and biodiversity, and of some areas of the Casentinesi Forests National Park, that surrounds the Reserve. On a five-year archive of acoustics data collection,

variability cross-section (horizontal) and time series (vertical) was investigated to explore its soundscape's spatial-temporal dynamics across different scales.
Ecoacoustic monitoring provides quantitative data over large spatial and temporal scales for the comparison of acoustic variance both *intra-site* (for monthly or yearly sampling) and *inter-sites* (for multiple simultaneous locations).

The intra-site variability was explored at different time scale levels:
the Acoustic Indices' monthly average distributions were compared to describe how the soundscape in a site changes from month to month (and therefore from year to year); the Acoustic Indices' daily values were compared to highlight the soundscape's minor variations day by day and finally the comparison of the values' distributions that Acoustic Indices assume in daylight and night hours were used to indagate the intra-site variability at daily precision
The *inter sites* variability was investigated comparing the Acoustic Indices' trends in three sites (two inside Sasso Fratino and one outside the Reserve) for a selected 30-day continuous and synchronous recording period. In general, all sites are characterized by quiet nights and very acoustically dense daylight hours, with a composite biophony occupying the range 1500 to 9000 Hz. But, although the acoustics indices trends are similar, the Principal Component Analysis shows that the sites inside and outside the reserve are well-differentiated and distinctly clustered, and this could be due to the spatial and ecological heterogeneity that drive the biophony's different contributions.

Future perspectives

Ecoacoustics is an emerging scientific discipline that investigates natural and anthropogenic sounds and their relationship with the environment. Since few years, the more urgent need to obtain summary data that allows rapid analysis and comparisons on a large scale as well as the technological advancement in the field of acoustic recording instruments, have contributed to the development of acoustics analysis.
Data collected since 2014 represent a reference collection for the study of the Integral Nature Reserve's biophony ecosystem and it would be advised to continue with long term monitoring in order to promptly highlight variations in the soundscape composition, especially those related to climate changes. 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 the local ecosystems in the long term.

In this way, systematic and synchronous recordings collection in multiple sites in the Casentinesi Forests National Park can also become a promising tool for the acoustic recognition of the current avian species and can provide new information on the ecology of soniferous species, as well as tools for the monitoring their changes, e.g. seasonal shifts and both the disappearance of species and the arrival of new species, including invasive ones. Extending the monitoring to other areas with different levels of protection will also provide cues about the gradients and effectiveness of the conservation efforts.

Finally, it's crucial to continue to document and describe soundscape of specific habitats and to develop new analytical protocols and multilevel classification (more and more automated) of natural environments under the effect to different levels of anthropic impact, from protected areas, far from any anthropic disturbance to the most populated areas and agro-ecosystems.

Considering the technological evolution of instruments and the expanding market of ecoacoustic instrumentation and software, in a near future it will be possible to build low cost interconnected multisensorial monitoring networks with real-time communication capabilities. This will also require the development of both supervised and unsupervised analytical tools to promptly provide responses (acoustic scene classification, acoustic events detection and classification, species recognition, robust ecological indices generation) to data feeds. However, many limitations will prevent the real implementation of monitoring networks in most remote areas where providing energy and wireless data transmission is not easily feasible.