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Methodological Approach for Recognition of Species from 0 kHz – 12 kHz Nocturnal PAM Recordings – the case of Orthoptera

Abstract: The fortuitous discovery of *Acheta pantescus* Massa, Cusimano, Fontana, Brizio, 2022, born from the observation of an unknown cricket song during the review of passive acoustic monitoring (PAM) recordings, disclosed the potential of unsupervised recorders as tools for the assessment of orthopteran diversity. This case study, based on a one-month, nightly PAM campaign in two Apulian locations, covers the issues of orthopteran species recognition by bioacoustical means and outlines an analysis and diagnosis workflow for contested soundscapes, with special reference to the medium-quality record settings (24 kHz sampling frequency, 0 kHz - 12 kHz band), chosen as the best compromise between quality and storage capacity. At the price of substantial labour, the method proved suitable for a preliminary assessment of the diversity of the night-singing orthoptera. Results include several lessons learned, a list species observed and some novel observations.

Key words: Apulia; diversity; Orthoptera; Mediterranean; bioacoustics; Passive Acoustic Monitoring

Riassunto: La scoperta fortuita di *Acheta pantescus* Massa, Cusimano, Fontana, Brizio, 2022, nata dall'osservazione di un canto di grillo non riconosciuto durante la revisione di registrazioni di monitoraggio acustico passivo (PAM), ha rivelato il potenziale dei registratori non supervisionati come strumenti per la valutazione della diversità degli ortotteri. Questo studio, basato su una campagna PAM notturna di un mese in due località pugliesi, copre le problematiche del riconoscimento delle specie di ortotteri mediante mezzi bioacustici e delinea un flusso di lavoro di analisi e diagnosi per paesaggi sonori contestati, con particolare riferimento a registrazioni di media

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qualità (frequenza di campionamento di 24 kHz, banda 0 kHz - 12 kHz), scelte come il miglior compromesso tra qualità e capacità di archiviazione. Al prezzo di un significativo impiego di tempo, il metodo si è dimostrato adatto per una valutazione preliminare della diversità degli ortotteri a canto notturno. I risultati includono diverse lezioni apprese, un elenco delle specie osservate e alcune nuove osservazioni.

Parole chiave: Puglia; diversità; Ortotteri; Mediterraneo; bioacustica; Monitoraggio acustico passivo.

1. Introduction

Fortuitous discoveries may be very rewarding, but the concept of serendipity itself and the underlying cognitive biases are as much uneasy to describe, as they are uneasy to control (Brizio *et al.*, 2020). Yet, in some cases, serendipitous discoveries may spark methodological advances. This study, taking place in Apulia (Italy) is primarily aimed at testing whether the collection of evenly timed recordings, taken at night by a passive wildlife recorder equipped with an omnidirectional microphone, may provide information at a level of detail sufficient for a preliminary census of the Orthoptera species singing in the investigated location, despite a compromisory quality setting (a sampling frequency of 12 kHz). Considering that the Apulian orthopterofauna is still not fully known, a secondary but nevertheless important objective is to check whether such an unfocused method may reveal the presence of species previously unreported for the recording area, or may collect songs that cannot be attributed to any known species, as in the case occurred in Pantelleria in April-May 2022 when *Acheta pantescus* Massa, Cusimano, Fontana, Brizio, 2022 was discovered during an ornithological bioacoustical survey, in which its previously unknown song happened to be collected by the same equipment adopted in this study.

2. Materials and Methods

2.1 A simple and affordable approach

Obrist *et al.* (2010), citing previous works by Brandes (2008), Hobson *et al.* (2002), Rempel *et al.* (2005) and Frommolt *et al.* (2008) clarified that autonomous recording devices could reduce person-hours spent in the field, and lead to a major breakthrough in acoustic monitoring of a wide variety of species, particularly in combination with species recognition algorithms and expert listeners. Such a bold assertion is tenable only as long as the passive autonomous recording devices obtain optimal or slightly suboptimal recordings of well-known species, in such a way that both the recognitions by suitably trained software applications and those by expert listeners do not require a relevant effort.

This study, driven forward without economic support by any institution, was born out of our curiosity about the possible outcome of a zero-budget investigation based just on our commitment and on the interactive software we currently use for the expert analysis of insect songs (details hereunder). We forewent any kind of machine-aided recognition or automated signal extraction, that in turn would have required designing and suitably training the machine-learning components: in that respect, even if more economical and technological resources were available, most probably we couldn't train a machine-learning system in such a way that allows the extraction and the recognition of specific songs from suboptimal-quality recordings where up to around ten species sing simultaneously.

Even though it disregards some of the technological advances of the last decades, such an approach suits the needs of anybody wishing to engage in low-tech, low-budget bioacoustic research, as in the case of developing countries or underfunded scientific institutions.

2.2 Terminology

2.2.1 General

The term "soundscape" is adopted in the acceptation by Truax (1978), as commonly used in ecoacoustics, to refer to the immersive natural acoustic environment. We define soundscapes as either "permissive", when the song of only one individual clearly emerges with no, or with minimal, disturbance by noise and by heterospecific or homospecific songs, or "contested" when noise or homospecific / heterospecific songs collide in time or frequency.

The acronym PAM, for Passive Acoustic Monitoring, will refer to the deployment in natural settings of unsupervised, temporised digital recorders, capable of collecting omnidirectional soundscape recordings (PAM recordings).

Acoustic phenomena are here studied, compared and presented in the following forms:

- concerning the time history of sound pressure, in the form of Time/Pressure Envelopes (also known as "Oscillograms" or "Sonograms"), referred to by the acronym TPE;

- concerning the time history of frequencies, in the form of Time/Frequency Spectrographic Images (also known as "Spectrograms"), referred to by the acronym TFSI;
- concerning pressure distribution at the different frequencies during a given amount of time, in the form of Frequency/Pressure Analyses, referred to by the acronym FPA.

Baker, Chesmore (2020) standardised the bioacoustic terminology for insects pointing at the contradictions about the concepts of "pulse", "pulse train", and "bout". For the sake of clarity, we will strive to adhere to the terminology they propose and, in song descriptions, we will restrain to the following terms:

- **Tooth impact**: minimal and indivisible unit of sound. The count of tooth impacts determines the frequency pattern observed in the sound analyses.
- **Syllable**: first-order assemblage of tooth impacts. It coincides with a single complete stridulatory movement (the opening and closing of the elytra in Ensifera, the up and down motion of the femora against the elytra in some Acrididae).
- **Echeme**: first-order assemblage of syllables.
- **Echeme-Sequence**: first-order assemblage of echemes (may include individual syllables that precede or follow the echeme).

The term "**Tick**" will be used in its commonplace acceptation of "very short syllable". Furthermore, we will use the following unambiguous terms from Buzzetti, Barrientos-Lozano (2011), some of which are also cited by Baker, Chesmore (2020) as conveying meaning (particularly for human identification by ear) but are not recognized as part of their controlled vocabulary:

- **Buzz:** Unaided human ear detection of high syllable repetition rate in which the individual syllable cannot be resolved.
- **Tick sequence:** Unaided human ear detection of very low syllable repetition rate in which the individual syllable can be resolved and counted.
- **Zip:** Unaided human ear resolution of a short buzz, less than 1 sec in duration.
- **Trill:** a more or less long echeme made by subequal, closely spaced syllables.

The term "**volume**" will be used with reference to the recorded sound pressure, and to the namesake setting of recorder input sensitivity. Thus, a distant sound source with high intrinsic amplitude may get recorded at a low volume.

The term “**track**” applies to an audio file loaded in the memory of the audio analysis software: many tracks can be simultaneously loaded and separately played. A new or an edited track can be saved to a separate audio file.

2.2.2 Definition of Q

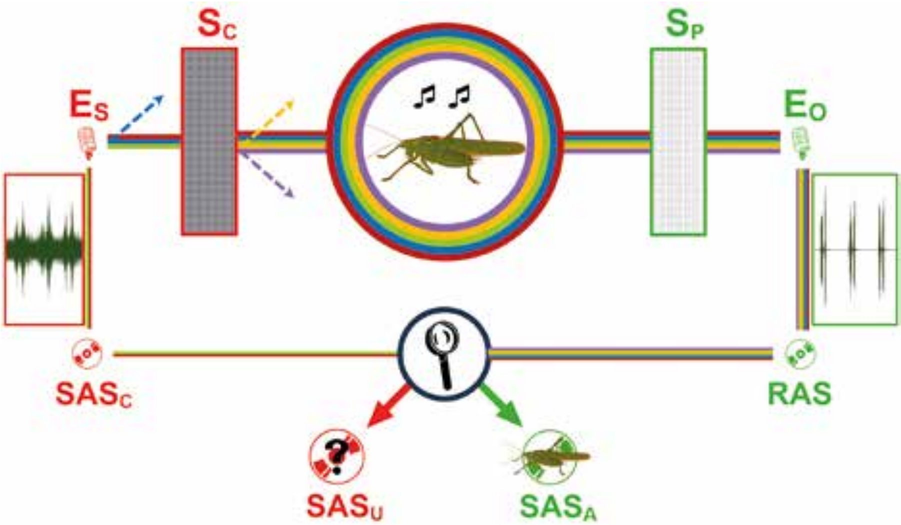
Recurring reference will be made to the quality factor Q, the dimensionless parameter that describes how underdamped an oscillator or resonator is. Two definitions of Q have prevailed in literature since its first appearance in 1914 (see Green, 1955). They become approximately equivalent as Q becomes larger and damping decreases. In terms of frequency-to-bandwidth ratio, Q is defined as

$$Q \stackrel{\text{def}}{=} \frac{f_r}{\Delta f} = \frac{\omega_r}{\Delta \omega}$$

where fr is the resonant frequency, Δf is the resonance width or full width at half maximum i.e. the bandwidth over which the power of vibration is greater than half the power at the resonant frequency, ωr = 2π fr is the angular resonant frequency, and Δω is the angular half-power bandwidth. The other common nearly equivalent definition for Q is the ratio of the energy stored in the oscillating resonator to the energy dissipated per cycle by damping processes:

$$Q \stackrel{\text{def}}{=} 2\pi \times \frac{\text{energy stored}}{\text{energy dissipated per cycle}} = 2\pi f_r \times \frac{\text{energy stored}}{\text{power loss}}$$

High-Q sound (Elsner, Popov, 1978; Montealegre-Zapata, Morris, 1999) results, e.g., in Gryllidae, in one or more isolated peaks of frequency, clearly distinguishable from the rest of the frequency emission. On the other hand, “wide band” or “low-Q” sound gives a wide spectrogram trace, in which sometimes is possible to distinguish spectral subpeaks. The distinction may be blurred for those low-Q songs that include well-defined, narrow-band frequency components.



1. Fig. 1 Relations among Reference Audio Samples (RAS) and Surviving Acoustic Signatures (SAS). The song emitted by the singing orthopteran contains both robust characters, that will remain available in the SAS, and fragile characters that are obliterated by the contested soundscape or by the equipment suboptimality. SC and SP are respectively the contested and the permissive soundscape. Dashed arrows mark the characters that are lost for signal degradation or by inadequacies in the recording equipment and settings. RAS is the Reference Audio Sample. ES and EO are respectively the suboptimal and the optimal combination of equipment and settings. SASC, SASU and SASA are the Surviving Acoustic Signatures, respectively in candidate, unassigned and assigned state, the two latter resulting from the comparison process (symbolised by the lens) between the candidate SAS and the RAS.

2.2.3 Definition of Reference Audio Sample (RAS)

The term "sample" in the locution "Reference Audio Sample" refers to an exemplary audio file, not to unitary samples with reference to the sampling frequency of the recorder. In this study, reference audio files for the Italian species were obtained from the accompanying DVD of Massa *et al.* (2012), from the accompanying CD of Fontana *et al.* (2002), from the Xeno-canto online repository (see the References) and from the personal collection of the authors.

Typically, a Reference Audio Sample (RAS) is obtained under ideal conditions that include a permissive soundscape and optimal equipment/recording conditions, and is able to provide the full array of acoustic characters that define the species-specific song. Consequently, its informative content includes both the robust characters that may be found in a Surviving Acoustic

Signature (SAS, see below), and the characters obliterated by signal degradation and suboptimal equipment or settings (see Fig. 1).

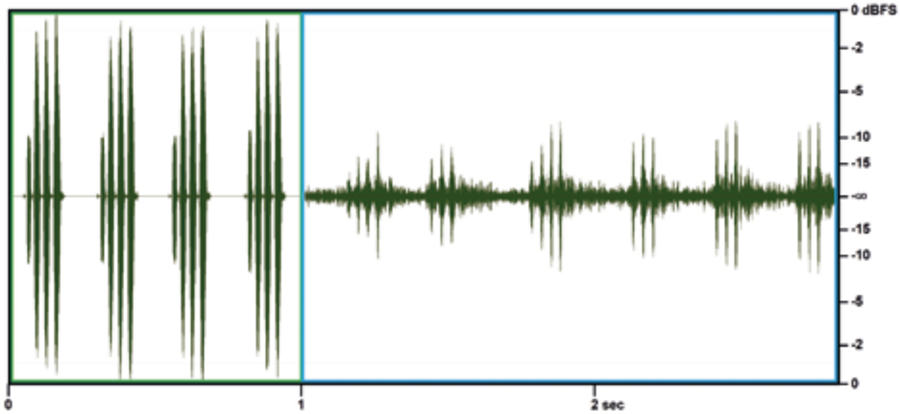
2.2.4 Definition of Surviving Acoustic Signature (SAS)
In a contested soundscape, and in suboptimal recording conditions, we define as "Surviving Acoustic Signature" (SAS) of a species any set of species-specific *robust bioacoustic characters*, that…

- "survive" the suboptimal recording settings,
- "survive" the intrinsic limitations of PAM recording and omnidirectionality (low volume, low discrimination of sound sources),
- "survive" the competition with noise and heterospecific songs,
- "survive" the invasive post-production activities, that necessarily include one or more frequency filtering sessions, and that may include amplification and noise reduction,
- contain diagnostic features (such as typical TPE or TFSI patterns) that allow the unambiguous recognition of a species.

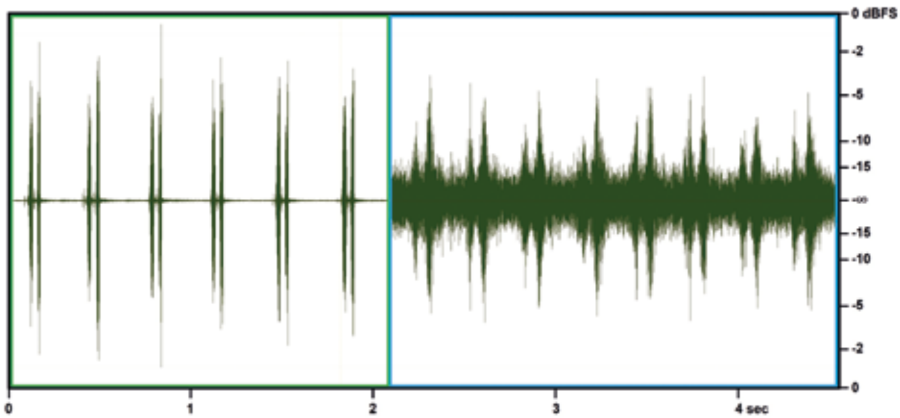
The locution will also be used as a synecdoche, to describe any audio excerpt containing the SAS. Such an excerpt, instead of showing the full set of typical characteristics of a reference audio sample for the species, may contain just one, or a few characters as shown in Fig. 1. Summarising, a SAS audio excerpt of a species may be largely suboptimal, and remain acceptable insofar as at least one "highly survivable" robust characters, whether in the time or in the frequency domain, allow species recognition.

Figg. 2-5 show the TPE and the TFSI of four examples of high-Q and low-Q SAS', side by side with their respective RAS.

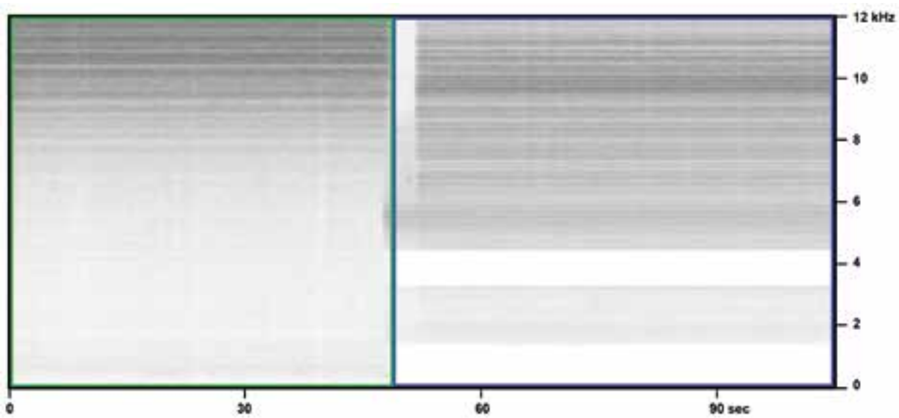
For the same species, SAS' derived from different recordings may differ, depending on the degree of clarity and the level of conflict with heterospecific songs observed in each recording. As an example, in some recordings a species may be recognizable thanks to some salient detail in the TFSI; in others, that same species may be recognizable thanks to traces of its typical pattern in the TPE. The quality of a SAS is high when it includes a wide frequency band of the interesting song, when no overlapping songs occur, or at least when their volume is decidedly lower than that of the interesting song, and when its temporal pattern clearly emerges from the bottom noise in the TPE. The analysis and diagnosis workflow includes the steps needed to improve the quality of the SAS' and the generation of more than one SAS per species is encouraged.



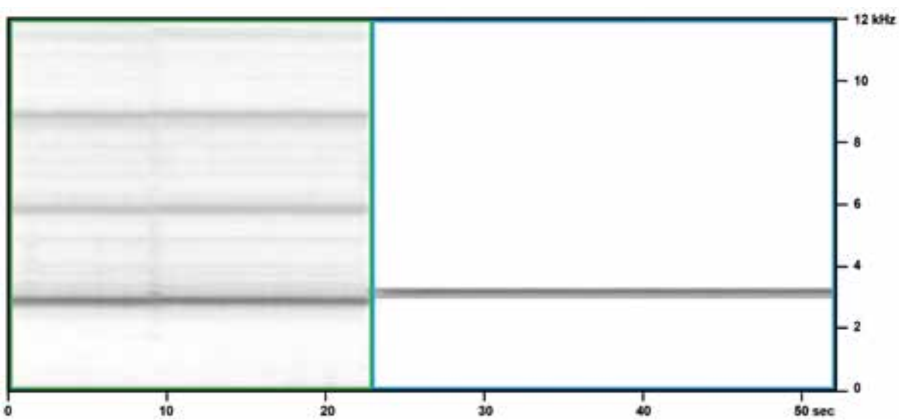
2. Robust characters in the time/pressure domain (amplitude patterns): the quadrisyllabic echeme of *Gryllus campestris*; Green inset: RAS from Massa et al., 2012; Blue inset: band-pass filtered and de-noised SAS from a recording taken on 22 July.



3. Robust characters in the time/pressure domain (amplitude patterns): the disyllabic echeme of *Platycleis intermedia*; Green inset: RAS from Massa et al., 2012; Blue inset: band-pass filtered SAS from a recording taken on 23 July.



4. Robust characters in the time/frequency domain (frequency patterns): the low-Q, continuous rattling sound of *Tettigonia viridissima*; Green inset: RAS from Massa et al., 2012; Blue inset: high-pass and band-stop filtered SAS from a recording taken on 19 July.



5. Robust characters in the time/frequency domain (frequency patterns): the high-Q song of *Oecanthus pellucens*; Green inset: RAS from Massa et al., 2012; Blue inset: band-pass filtered SAS preserving the fundamental band from a recording taken on 23 July (frequency shift is due to higher temperature).

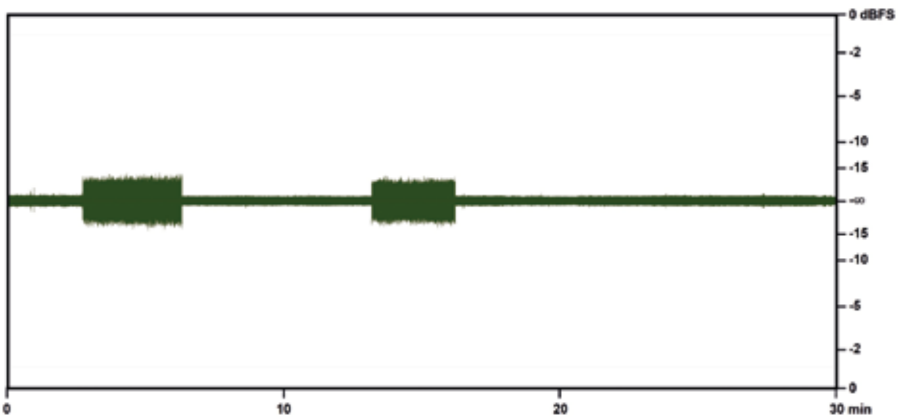
2.2.5 Definition of Salient Feature

By “ambience” we indicate both the background soundscape where no song occurs, and the corresponding volume in a digital recording. More laxly, the ambience may also include indistinct, feeble background songs that may, or may not, be recognizable, but that do not interfere destructively with the songs being analysed.

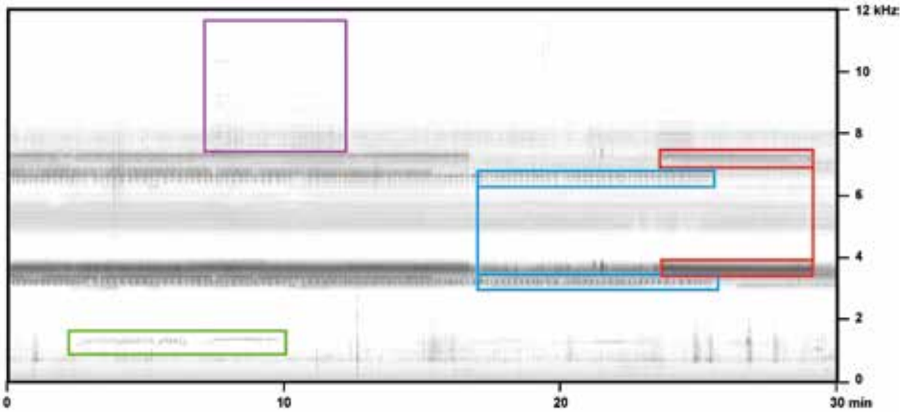
With reference to the full-breadth on-screen visualisation of a 30 minutes recording, by “salient feature” we mean any bioacoustical activity clearly standing out, in time or frequency, above the ambience.

When observed in a TPE, salient features may look like in Fig. 6, showing the favourable situation of a high-amplitude song at a short distance with low-volume ambience: features may also be much less conspicuous. Minor volume peaks may be investigated by zooming-in on the envelope, selecting the interesting peak, and verifying by ear: most of the short, isolated salient features are the fruit of noise and may include impacts of the recorder, shaken by occasional wind gusts or by other disturbances. In other cases, zoom-in on a minor peak may reveal insect songs.

When in doubt about the presence or absence of salient features, the visualisation is put in TFSI mode, with results similar to those shown in Fig. 7: spectral view is decisive for ascertaining the presence of songs deserving investigation. Visually, salient features are the fruit of coalescent patterns, whose investigation usually requires zooming-in in time or frequency but that, with experience, may also be recognized at first glance in the full-breadth TFSI.



6. TPE of a 30-minutes recording. Salient feature in the time domain: the song of *Tettigonia viridissima* stands out clearly above the ambience. The informative content of such a registration is obvious.



7. Contrast-enhanced spectrogram of a 30-minutes recording. Salient feature in the frequency domain: coloured insets mark some among the most evident patterns attributable to bioacoustic sources. Green: Scops Owl *Otus scops*; Purple: *Decticus albifrons*; Light blue: fundamental and first harmonic band by *Oecanthus pellucens*; Red: fundamental and first harmonic band by *Oecanthus dulcisonans*. Wide background continuous bands may be tentatively assigned to distant low-Q songs that may include those by Platycleis intermedia.

2.3 Hardware and software

2.3.1 Recording Equipment and Settings

A Wildlife Acoustics Song Meter Micro wildlife recorder was placed by A. Di Palma in two locations near Vieste (Apulia, Italy):

- From 19 July 2023 to the early morning of 3 August 2023: Ranch dell'Ambrenella, at the approximate decimal georeference of 41.87995N, 16.12276E (in a lot adjacent to an agritourism, near an olive grove); for brevity, it will be referred to as "Location 1".
- From the evening of 3 August 2023 to 25 August 2023: Azienda agricola Olivieri, at the approximate decimal georeference of 41.84222N, 16.08052E (in an olive grove that includes a small pond). The last recording before complete storage depletion started on 20 August 2023 at 00:51. It will be referred to as "Location 2".

The recorder was set for timed, automated recording in bouts of ten 30-minutes sessions per day, with 60-minute intervals among sessions starts, and the first daily session starting at 20:27 on 19 July 2023.

On average, the internal clock of the recorder anticipated the initial recording by 70 (seventy) seconds each day, so that the recordings on 19 August started at 19:51. The engagement of the 7 pm hourly bracket resulted in one more recording per day, starting on 13 August. Overall, 322 30-minutes recordings were obtained, 144 of which in the first location.

Such an extended and repetitive time coverage serves both the primary and the secondary objectives elucidated in the Introduction. Both the exhaustiveness of the survey of resident species, and the probability to intercept non-resident taxonomic entities, geometrically increases with recording time.

The recorder, whose technical specifications are available on the manufacturer's website (listed in the references) is equipped with an omnidirectional microphone, and generates uncompressed monophonic 16-bit PCM wav files that are stored on a micro-SD card.

Despite the availability of a 96 kHz sample rate, the recorder was set at a sampling frequency of 24 kHz that, following the Whittaker–Nyquist–Shannon cardinal theorem of interpolation (Nyquist 1928, Shannon 1949), results in a recorded bandwidth of 12 kHz starting at 0 Hz.

Although representing just one quarter of the device's potential, the choice of a 12 kHz bandwidth is a frequently adopted compromise, capable to ensure a sufficient quality for a human-supervised review of the recordings by the unaided ear or by audio software, while saving storage space thus ensuring a longer coverage in time before depletion of storage. The default microphone gain setting was left unaltered at 18 dB.

2.3.2 Ideal recording parameters in digital audio

In the nature recordists community, and in the wider audio practitioner community in general, there is general consensus about the fact that record settings should engage the full dynamic range of the equipment, thus optimising signal-to-noise ratio, and at the same time they should leave some headroom for post production intervention that may include amplification. As reported in many sources including a post of sound engineer "Mojo" on Medium (see references) the *vox populi* standard is setting microphone gain and (where available) recording volume so that:

- the peaks are kept away from the destructive clipping threshold of 0 dBFS, and do not exceed -6 dBFS / -5 dBFS;
- the average volume of the interesting sound is at least at -15 dBFS.

The first requirement is particularly difficult to fulfil in the context of PAM, where the distance between the microphone and the singing insect is unknown and may vary at any time (more comments about this issue will be provided in the Conclusions): to avoid destructive clipping of the song by the insects nearer to the microphone that, thanks to the short distance, will get recorded with the highest clarity, we left unchanged the recorder's default gain setting of 18 dB.

While our decision was completely successful in ensuring that no relevant destructive clipping occurred in any recording, such a setting was so conservative that, generally, the recordings showed a volume that was lower than desirable: in absence of wind, average ambience rarely exceeded -40 dBFS and frequently the salient features were under -25 dBFS.

Any quality evaluation performed at such a low volume would be misleading: in fact, on the basis of volume only, most if not all the non-windy recordings should have been discarded. An adequate volume can be restored by digital amplification: even though the amplified recording lacks the low-amplitude songs and feebler frequency bands that would have been recorded at a higher gain setting, for the aims of this study and in the context of suboptimal recording conditions, post-production amplification increases decisively the number and the quality of SAS that can be observed. For that reason, amplification is an integral part of the analysis and diagnosis workflow.

2.3.3 Analysis Hardware and Software

Sound description includes TPE's (relative pressure in dB Full Scale), TFSI's, and FPA's, generated on an Intel NUC 5i3RYH desktop computer by Adobe Audition 1.0 software running under Windows 10 64-bit operating system. FPA's were generated by scanning the entire interval of time considered and averaging pressure data through the interval - punctual distribution of pressure in each tempuscule is considered as uninformative. Adobe Audition was used to support the entire analysis workflow, including the application of frequency filters usually set at the maximum available order[1] (18^{th}).

Analysis and recognition as proposed here are vision-intensive processes, and a good computer monitor is of paramount importance. We used a Dell P2416D 24" LCD monitor. A Dell AY410 2.1 Computer Speaker System was used for audio playback.

The screenshots obtained from Adobe Audition were post-produced with Adobe Photoshop Elements, by converting them in black and white and, where requested, by increasing contrast. To ensure readability of the downsized images appearing in this article, MS-Paint was used to add horizontal / vertical reference rulers. Those interventions did not alter the data nor the analysis results.

[1] Digital filtering algorithmically simulates the application to the input signal of a resistor/ condenser network: for each subsequent order, the band roll-off (representing the steepness of the filtering function) will be twice the preceding order filter (Shenoi, 2005).

2.4 The analysis and diagnosis workflow

2.4.1 Overview

To allow a more effective description of the analysis and diagnosis workflow, any detail that lends itself to be treated as part of the Discussion is covered in the namesake section. The flexibility of the workflow impedes its exhaustive depiction as a flowchart: Fig. 8 shows a simplified backbone of the workflow, that may be adapted to different needs.

The massive number of recordings available allowed a very strict selection process. In different situations, criteria for rejection would have been more relaxed.

Unless otherwise noted, the sense of hearing is not engaged in the process of analysis and specific diagnosis. Actions are described in present tense. We indicate the individual engaged in the analysis as "the analyst".

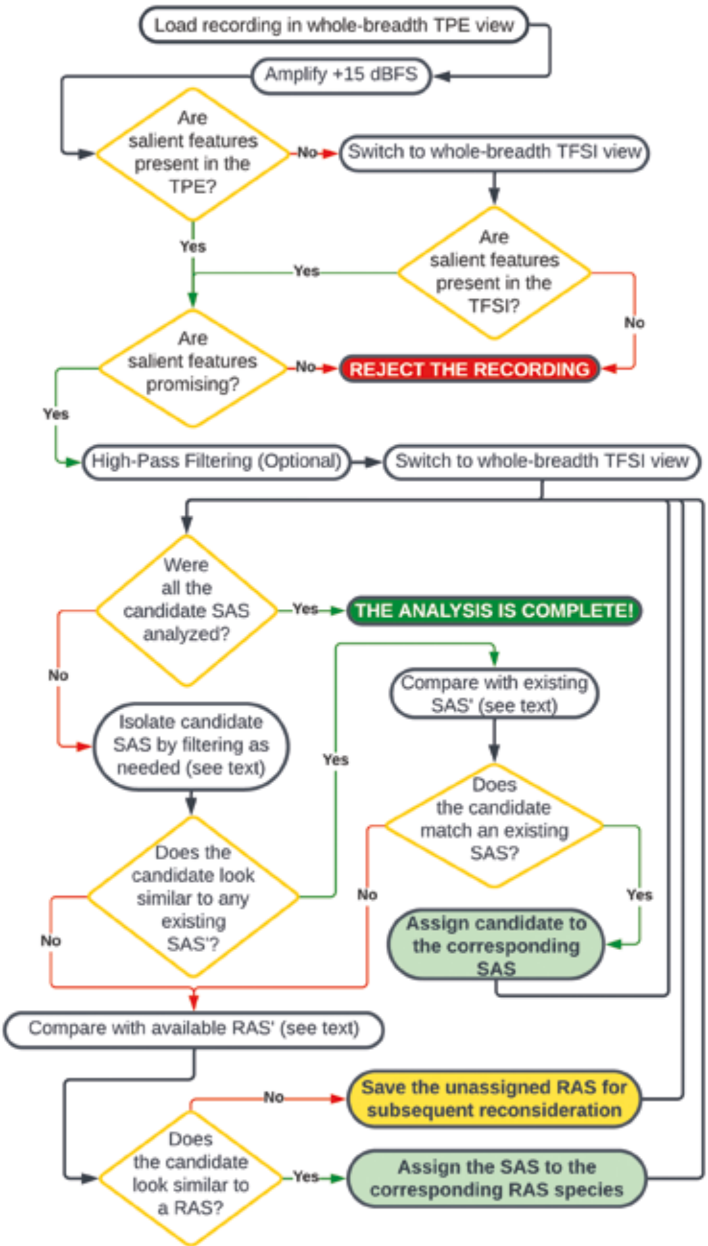
The filename automatically assigned by the recorder is self-explanatory and includes date and time. If applying the workflow to recordings of different origin, one should ascertain that naming policies are unambiguous and ease the identification of each recording.

The workflow steps include digital filtering when required: we advise against the adoption of more sophisticated post production steps, such as denoising or hiss removal. Providing guidelines on noise reduction by digital means is outside the scope of this paper: such interventions may optionally be adopted only if the analyst is fully aware of their effects. Suffice to say that the selection of the portions of the recording to be used as noise samples should be very accurate, and that attention should be paid to the parameters for the application of noise reduction: repeated comparisons by ear should avoid the formation of artefacts and, in any case, the degree of application should not exceed the "medium" setting of the audio analysis software.

Before analysis, all the recordings from a campaign should be stored in the same, aptly named folder. After analysis, the recordings should be sorted in different folders, according to their quality: as an absolute minimum, two destination folders should exist, for rejected and analysed recordings respectively. It would be advisable to store separately the recordings of outstanding quality (low noise, fewer collisions, good volume), that will be the preferential subject of recursive review as described at point 2.4.9.

2.4.2 Initial loading and generalised amplification

As a first step, the recording is loaded in the analysis software that, by default, shows a whole-breadth (in our case, 30 min) TPE. The entirety of the recording is selected and amplification is applied (see point 2.3.2).



8. The main steps in our analysis and diagnosis workflow for contested soundscapes, including main alternatives and optionalities.

The ideal amount of amplification was determined empirically by trial and error, and is equal to +15 dBFS, limited to +10 dBFS where the salient features are near or above -15dBFS. Optionally, lower or higher amounts may be adopted, at the discretion of the analyst.

2.4.3 Rejection by absence of salient features

In line of principle, any song whose TFSI lacks obvious salient features should be rejected. To avoid the rejection of potentially interesting recordings that may contain feeble traces of recognisable frequency patterns, visualisation is set to whole-breadth (30 min) TFSI: if neither the spectrogram shows promising features, the recording is rejected.

2.4.4 Rejection by unpromisingness

The abundance of recordings promoted a policy of early rejection of all unpromising recordings. We immediately discarded with no further analysis most of the recordings that:

- were taken before 21:00[2],
- regardless of recording time, showed obvious signs of cicada songs, whose presence can be quickly verified by ear,
- were obviously affected by wind or other adverse weather conditions: also, this can be verified by ear, but normally is very evident for the disordered and ubiquitous presence of irregular strong peaks in the TPE.

Exceptions exist: recordings whose TFSI seem to include interesting frequency patterns are not rejected, regardless of their unpromisingness.

2.4.5 High-pass filtering (optional)

As a general rule, save unusually near songs with high (> -12 dBFS) volume, and with the exception of the rumbling sound generated by *Meconema thalassinum* by drumming on the substrate with the hind legs, record settings didn't allow the recording of any meaningful insect signal under 1000 Hz - 1500 Hz. Furthermore, at the temperatures encountered during the recording campaign, no high-Q species' song engages lower frequencies, and the songs of low-Q species may not engage that frequency band at all, or engage it imperceptibly. Instead, the 0 Hz - 1500 Hz band is the most prone to naturogenic noise including wind, distant bird songs, distant amphibian

[2] The exact hour/minute of probable termination of cicada songs in the evening wasn't known when the time parameters of the recorder were set: another lesson learnt is to delay the beginning of the first recording session.

songs, dogs barking, and to anthropogenic sounds that may include distant voices, vehicles etc.

When looking at the TFSI, zooming to the frequency range from 0 Hz to 4000 Hz, if regular features tentatively attributable to insect songs seem to extend in the lower frequency band, the cut-off frequency is reconsidered consequently, after zooming to the time range pertaining to the lowest-frequency songs. Otherwise, the cut-off frequency may safely be put at 1500 Hz or higher, depending on spectrogram observation.

In a situation like that portrayed in Fig. 7, cut-off frequency could be put at 2500 Hz with no adverse effects on the subsequent steps.

In any case, the removal of the lowest few hundred Hertz, capable of excluding most non-insectogenic sounds, is strongly advised.

The removal is performed by high-pass filtering the entire recording, or its relevant parts, above the chosen cut-off frequency. By comparing the time/amplitude envelope before and after filtering, a drastic decrease in ambience volume and a clearer evidence of song structures should be evident.

2.4.6 Iterative (for each SAS) activities

An iterative set of steps aimed at song recognition (see the Discussion) ensues. The activities are performed in TFSI view.

Considering that the objective is not a punctual census of all the species singing in each recording, but rather the compilation of a list of distinct recognizable species met during the entire recording campaign, the analyst may disregard any positively identified song (optionally, he may write down the species observed in each recording), and concentrate on the identification of new, or potentially new, songs, in other words, on any song that he does not immediately recognize. For each such song, a relevant duration of the least-conflicted part of the song (the part with the fewest collisions, or possibly with no collision) is selected and the following steps are performed. We will refer to the selected part of the recording as "the selection".

2.4.7 Isolation of the candidate SAS

The isolation of the candidate SAS from the selection may be more or less challenging, depending on the number and the intensity of the collisions as described in the Discussion. In order of increasing complexity, the commonest cases among those more exhaustively covered in the Discussion:

- *No collision:* the most favourable case, coincident with a permissive soundscape. The selection contains just the interesting song, or the interesting song's volume is high enough that colliding songs are negligible. In that case, the selection coincides with the candidate.

- *The entirety of the candidate SAS can be isolated via a single filtering action (low-pass, high-pass or band-pass filter):* in this case, the analyst needs only to define the low and high cut-off frequencies, that can be ascertained by suitably zooming-in the spectrogram, so that any spectrogram area attributable to the song is included. Then, the suitable filter is applied.
- *Multiple filtering options are required for isolation:* a typical case for wide-band low-Q songs, that may need the exclusion of colliding high-Q or anyway narrow-band songs. A sequence of high-pass and band-stop filters may be required.

The effects of each filtering operation described in the Discussion should be verified both on screen and by ear, in particular to ascertain that the cut-off frequencies are properly chosen. As an example, in case of a band-pass and band-stop filters, a good idea may be setting the cut-off frequencies inclusively (with some slack), then refine the filtering with a second pass, if needed. On screen verification should be performed in the two views:

- *spectrogram*, where the disappearance of the cut-off portions gives an idea of the result, without forgetting the intrinsic low resolution in time of any spectrographic view, due to the FFT size;
- *time/amplitude envelope:* a proper filtering action results in a sharper and cleaner echeme structure, without forgetting that low-Q species may emit buzzing or swishing sound that may not show well-defined peaks.

Verification by ear consists in the playback of the selection before and after filtering: obviously, after the application of filters, the song should be perceptibly clearer.

We refer to the filtered (and, if need be, denoised) selection as "the candidate". The candidate should be selected for playback. It's up to the analyst whether or not to copy and paste the candidate as a new track / new audio file, so that it is already separately stored. The alternative is maintaining the candidate inside the current recording, and access it simply by selecting its relevant portion.

Only in case that, in the same time interval of the current recording, two candidates co-exist in different frequency bands, it is mandatory to save the first candidate as a separate track / audio file. In fact, the isolation of the first candidate filters destructively any other candidate from the same time interval of the current track. Once the first candidate is ready, it should be copied and pasted in a new track or saved as a separate audio file. Then, the filtering actions are reversed, restoring the current recording to its previous state, and the complementary filtering actions needed to extract the second candidate are performed.

2.4.8 Comparison with extant SAS'

If the candidate looks familiar, it may well be attributed to an extant SAS, and it is compared with the extant SAS' audio files. Possible results include:

- The candidate is recognized as an extant SAS. If a list of species is kept for each recording, a note is written down. Depending on the quality of the candidate…
  - If poorer than the extant SAS audio file, the candidate is discarded;
  - If better than the current SAS, the audio file of the current SAS is overwritten with the candidate;
  - If quality is comparable, the analyst may decide to save another audio file and keep more audio files of the same SAS.
- If the optional comparison with extant SAS' brings no result, the candidate should be assigned to a species unheard before, as described in the next step. Otherwise, the search for candidates resumes at step 2.4.6.

2.4.9 Generalities about the comparison process

Whether in the form of an on-screen selection within the current recording or as a separate track, the candidate is now the analyst's first term of comparison. Second terms of comparison may include:

- *Already available SAS'*, whenever the analyst suspects that the candidate is another instance of an extant SAS and wishes to disambiguate;
- *External Reference Audio Samples*, for the Attribution of the candidate to a species unheard before. The candidate will thus become the first SAS audio file for that species.

While the first analyses provide the opportunity to collect new SAS', after the first dozen instances, the analyst has grasped the look of the commonest and clearest SAS'. See e.g. Fig. 12 for a synoptical view of spectral patterns. Any comparison may be performed:

- *visually*, e.g., by counting the syllables or comparing the echeme structure in the time/amplitude envelope (high-resolution zoom on the TPE may be indispensable to disambiguate the attribution of clicks and short zips, as when separating the echemes of *Decticus albifrons* from those by *Eupholidoptera garganica*, sometimes uneasy to distinguish by ear or from longer sections of TPE's), or by checking commonalities in the spectrogram: the aid of a "spectrogram catalogue" similar to Fig. 12 (see point 2.4.10 more under) can greatly help both the recognition of already available SAS' and the candidacy of previously unobserved spectral patterns;
- *by ear*: we can never stress enough how any comparison of two recordings, candidate (first term) and reference (second term), strictly requi-

res the alternated listening to the candidate recording, and to each reference. Severe ineffectiveness arises whenever two candidates are listened to, without interposing one more hearing of the reference recording. An effective trick applicable when using a computer involves copying and storing in the memory clipboard (an operation usually performed with the Ctrl+C keypress) a short excerpt from the candidate recording, that is temporarily pasted (Ctrl+V) into a suitable position of each reference recording. That way, it will be possible to hear immediately in a single audio track the candidate and the reference, thus expediting the comparisons. The altered version of the reference recording obviously shan't be saved.

Signal degradation has a different influence on the comparison between a candidate and an extant SAS, than on the comparison between a candidate and a RAS recorded in more favourable conditions:

- in the first case, considering that both the candidate and the SAS are extracted from the recordings, it can be expected that signal degradation equally affects both terms: usually, this result in an immediate recognition of the candidate as a species whose SAS is already available;
- instead, when comparing a candidate and an external RAS that may differ in bandwidth and in recording conditions, recognition may be much more complicated. For reasons more extensively commented at point 3.3 in the Discussion, whenever the RAS is recorded at a wider bandwidth than the candidate, two operations are required:
  - it's advisable to low-pass filter the RAS at 12 kHz, particularly for comparisons by ear. The downgrading to 12 kHz bandwidth occurs automatically when pasting excerpts from higher-quality samples into the recording;
  - the RAS should be subject to the same filtering process adopted for the candidate SAS: consistent filtering of the two terms of comparison may improve their similarity in a decisive way.

In the Discussion, more details are provided. Candidate SAS and RAS should be recognized as similar based on the observation of common patterns in the TPE and in the TFSI, as well as by ear. As explained in the Discussion, FPA comparison may be indecisive due to the radical differences in the dynamic response of the microphones and to the different recording conditions.

2.4.10 The birth of a new SAS

Associating a candidate to a species, thus creating a new SAS, implies the comparison of the candidate with external audio files. As explained in the Discussion, conclusions may be drawn via an exclusively visual comparison (e.g., by syllable count and echeme structure, plus spectrogram comparison) and may involve alternated listening. Hints about the SAS characters recognised in the reference audio appear in the "Results" section. Considering the immutability of the recorder's position, the intensity (visual/aural detectability) of the time and frequency feature of the song are strictly dependent from the distance. Tab. 2 lists the characters of each SAS emerging from this study. It's advisable to add a fixed duration, e.g., 30 sec, from the new SAS to an audio file that will grow in time and contain a collection of all the current SAS'. A screenshot of the time/frequency spectrogram from that file will look like Fig. 12. Such an image is an invaluable reference for the analyst who visually scans the spectrogram of a new recording, and will allow to understand quickly whether it may include the songs of a species unobserved before. Missed recognition may assume two forms:

- indecision among two or more reference audios
- objective novelty of the candidate. In that case, pending further investigations, the candidate is assigned to an unknown species with a progressive number.

If not done before, the candidate (now, an SAS proper) should be saved in an aptly named[3] PCM Wav audio file. If the candidate was already in the form of an audio file, the name of that file should be changed accordingly.

Once the new SAS is created, the search for candidates resumes at step 2.4.6. Both indecision and missed identification…

- may stem from the low quality of the candidate audio;
- should be honestly declared in the results;
- should promote the search for better, decisive candidates for the same species.

2.4.11 Degree of uncertainty of the specific Attributions

The highest degree of uncertainty results from the lack of comparable audio samples at the end of the preceding step. This amounts to a missed identification, that may be most parsimoniously explained by the poor quality of the SAS. Yet, if the SAS does not show particular quality problems, an alternative hypothesis arises: a species, or at least a song pattern, never reported before for the Italian territory was recorded. Our fear of false alarms abundantly outweighs our desire for newly discover: as pre-emptive measures to avoid missed identifications,

- we discarded the unmatched SAS' whose quality was deemed too low to ensure any decision;

[3] The filename should obviously include the species name and, if desired, the recording date or an identifier of the recording from which it was extracted.

- for all the SAS' of acceptable quality, we tried as hard as we could to find a match with an existing audio sample;
- we clearly reported alternative candidates in a special column of Tab. 2.

The degree of certitude is roughly directly proportional to the SAS quality, and is defined as follows:

- *maximum* when, thanks to the good quality of the SAS, most of the typical song features of the candidate species can be observed in the song, when the candidate species is already reported for the area of study, and when the song by the candidate species is clearly distinct from that by other species[4];
- *high* when the SAS quality leaves something to desire yet, as in the case of *T. viridissima*, a plausible candidate can be easily recognised by a few song characters in time or frequency;
- *good* when the SAS quality is just acceptable, or when – regardless of its quality – the SAS resembles the song of several species (this is particularly common with zips and ticks).

2.4.12 The recursive review of recordings

As explained at point 2.4.8, new and better SAS' may replace or flank the existing ones. The availability of a new SAS, including those indecisive or unassigned, should promote a process of review involving also the recordings previously analysed: in fact, any new or better SAS' may provide a new awareness capable of increasing the analyst's resolving power. Furthermore, any recursive review may help disambiguate the indecisions. As an example, an exceptionally good recording of *O. dulcisonans* may show the first harmonic band, unobserved before. The analyst may notice that an unassigned SAS corresponds exactly with that first harmonic band, previously unrecognised as such because extracted from a recording where the fundamental band of *O. dulcisonans* was covered by another louder song. Considering the massive number of recordings, in our case the advantageous process of recursive review wasn't systematic but limited to peculiar situations and to the better-quality recordings.

[4] Exceptions apply: the song of the Italian *Eupholidoptera* species is uneasy to separate, *E. garganica* is currently the only *Eupholidoptera* reported from Apulia, so it's a natural candidate for an *Eupholidoptera* song recorded in Apulia, even if *E. danconai* could be also present in Apulia. Besides that, maximum-pressure frequency in the SAS coincides with the RAS by *E. garganica*.

2.5 Time committed to work and cost-effectiveness

Whether or not a more sophisticated technology would have provided better results in our complex scenario is an open question, but for sure we can estimate how much time was required to obtain and substantiate our findings.

Even though the recognition abilities of the analyst improved drastically with time, the onset of unpredictable conditions prevented any clear-cut conclusion to be drawn about the average duration of the analysis of a 30 minutes recording. We can safely state that the recognition and quick rejection of a recording unsuitable for analysis required more than five minutes in the first instances, a time which, with experience, was reduced to around two minutes in the last weeks of analysis.

It's much more difficult to provide an estimate of the time required for the analysis of an acceptable recording. In general terms, after the commonest SAS' were collected, a recording of sufficient quality containing only the already known SAS' could be recognised as such by a relatively quick visual scan on the full-breadth TFSI. Including the preliminary operations (amplification, TFSI generation) the no-novelty recording could be examined in less than two minutes, with the help of Fig. 12 and Tab. 2 from the Results section.

In fact, our approach was very conservative: as a rule, whenever a TFSI feature was reminiscent of, but not fully coincident with, an extant SAS, it was prudently extracted as a candidate, and compared with existing SAS to our satisfaction. Such a high standard implied that no-novelty recordings may have required up to 20 or more minutes before the recognition of a new species was excluded. In many of those cases, one more SAS audio file for the species was added for completeness, and provided another term of comparison in subsequent searches.

Whenever a good-faith new SAS emerged, the ensuing research of comparable material required unpredictable, and wildly varying, amounts of time, from 30 minutes to several hours, also due to the optimality of the RAS': even when downgraded to a bandwidth of 12 kHz and filtered consistently with the candidate, they remained drastically richer in temporal and frequency details, often sharply contrasting with the degraded SDF audio, and requiring multi-faceted comparisons via TPE, TFSI and FPA.

The emergence of a new SAS (compliant with Step 2.4.10) also required time for the recursive review of past SAS', assigned and unassigned. On average, in 5 hours the analyst could examine from 5 (worst case) to 30 (best case) recordings. Furthermore, the Figg. and the Tabb. appearing in this paper were constantly created or edited as required. To provide an order of magnitude of the overall effort, we may state that 322 recordings were analysed at the average rhythm of 12 every 5 hours, including the drafting of this paper, for a total of around 130 man/hours.

To evaluate even in very general terms the cost-effectiveness of the results obtained, we should ask ourselves whether, and how, we could obtain an equally reliable, or even better, record of the 19 species observed, with the two alternative methods: conventional (by capture) or bioacoustical by supervised recordings, not forgetting that our work was aimed at the species that sing at night.

While vindicating the intrinsic advantages of the bioacoustical methods, by which the presence of a species out of the collector's reach can be ascertained, we cannot exclude that the approach based on specimen search and collection (that, at night, may include the usage of light traps) may prove more cost-effective, inasmuch as the species can be detected and collected without any bioacoustical aid. Considering that the PAM recordings covered the night hours, it's uneasy to say whether all the recorded species could have been physically captured.

About the supervised bioacoustical approach, based on our experience in field recording, we can safely state that the amount of time needed to extract viable audio from the PAM recording compares very favourably with the time that would have been required to obtain separate supervised recordings of each species. The latter would probably have attained a better reliability, and their quality would have ensured a quicker recognition, apart providing the opportunity for specimen capture, but – unless the nature recordist would have invested a comparable number of hours in a similar interval of dates – it's undemonstrated that the coverage of species could be as extended, as that granted by the PAM campaign. On the other side, the supervised recording method, especially if supported by a higher sampling frequency and by directional microphones, would have been capable to intercept those species whose song engages the band above 12 kHz, outside the reference settings of this study.

3. Discussion on the methodology

3.1 Generalities on the analysis of overlapping acoustic phenomena

Even in a permissive soundscape, signal degradation (mostly, attenuation by divergence, selective atmospheric absorption and by adverse effects of naturogenic or anthropogenic noise) hampers song recognition by conspecific individuals (Catchpole, Slater, 2008, chapter 4.5). Furthermore, at any time, one can reasonably expect that different singing species are competing in time and frequency against each other, as well as against noise (Catchpole, Slater, 2008, chapter 4.4), a competition that typifies a contested soundscape. An important evolutionary drive, competition for audibility, is driven by the fact that, as a general rule, when two or more bioacoustic signals overlap, the obstruction usually results in an irreversible obliteration of their informative content that may compromise all, or just some, of the concurrent signals. The best possible outcome of the collision is the survival of some diagnostic feature that can be traced back to a specific song.

Descriptively, bioacoustic phenomena may be referred to the three physical domains of time, amplitude and frequency, that provide three axes of analysis. Considering that in periodic phenomena frequency is the number of occurrences of a repeating event for a unit of time, and amplitude of a periodic variable is a measure of its change in an unit of time, it's very obvious that time, amplitude and frequency are linked inextricably. As a purely narrative device, to allow a more ordered discussion, we deem it better to separately cover three contexts of competition: amplitude, time and frequency that, in actuality, cannot be separated squarely.

3.1.1 Amplitude-based competition: the loudest takes it all (…for each frequency band!)

In a contested soundscape, the songs by any two sources are characterised by their intrinsic amplitude and are necessarily emitted from different positions with reference to the microphone. The microphone itself, with its typical sensitivity pattern (in our case, omnidirectional) may exhibit higher sensitivity in specific directions (as in the case of directional microphones). Regardless of the cause, it can be expected that any two different songs reach the microphone with different amplitudes, as they would do with a conspecific or heterospecific receiver.

Such an amplitude-based competition occurs separately for any frequency band. Also, very feeble songs may get recorded, as long as they engage frequency ranges radically different from those engaged by louder songs: in that case, the possibility to recover useful information even from destructively clipped audio files was recently discussed in Brizio (2023).

Yet, in the bioacoustic scenario, whenever a feeble (low-amplitude) and a strong (high-amplitude) song compete at the same time[5] for the same frequency range, their collision will be destructive: the feebler song will be

[5] Considering that this paragraph is dedicated to overlap in amplitude, the competition here described happens simultaneously for frequency and for time. It's clear that if two equally loud sources engage the same frequency range at different times, as in the case of intermeshing series of echemes, no conflict occurs.

annihilated or obliterated beyond recognition by what will be recorded as "foreground sound" on a purely quantitative amplitude basis (e.g., a high-amplitude song may completely obliterate a feebler song even though the latter is emitted nearer to the microphone).

Such obliteration by *force majeure* is the main cause of the Lombard effect, particularly studied in birds (e.g., Potash, 1972; Cynx *et al.*, 1998; Pytte *et al.*, 2003): the singing animal perceives noise and increases the song amplitude by the amount needed to make the song emerge above the noise.

Another very relevant effect of the destructive competition in the amplitude domain is the coevolutionary emergence, as clarified e.g. by Siegert *et al.* (2013), of species-specific partitioning of the soundscape. Among the commonplace examples, many people know by personal experience that it's easy to hear distinctly and simultaneously the song of crickets and the song of other families of Ensifera[6], because the higher-amplitude parts of their songs engage different frequency bands.

By applying mathematical methods such as the Fast Fourier Transform (Blackman, Tukey, 1958; Harris, 1978), the soundscape can be analysed in the frequency domain, and the Inverse Fast Fourier Transform can be used to restore an audio wave after selective interventions on some of its constituent frequencies, such as when applying a band filter.

Yet, those relatively simple methods cannot restore any signal to its unperturbed state before collision. Only sophisticated algorithms, fed with exhaustive and very detailed data about both the competing signals before collision, or with equally detailed data of the recorded signal and of one of the competing signals, may in fact deconvolve the two input signals, insofar as no destructive clipping occurs: approaches based on the usage of Hidden Markov Models (Brandes, 2008) or deep neural networks (Bermant, 2021) can provide effective results, respectively, on the fronts of signal separation and automated recognition. Furthermore, Blind Source Separation (BSS), the task of separating a set of source signals from mixed signal without (or with very little information) of both the sources and the mixing process, was successfully demonstrated in the field of bioacoustics, employing methods such as Independent Component Analysis (ICA), Principal Component Analysis (PCA) and Non-Negative Matrix Factorization (NMF) (Hassan, Ramli, 2018).

In our operational context, where suboptimal recording conditions coe-

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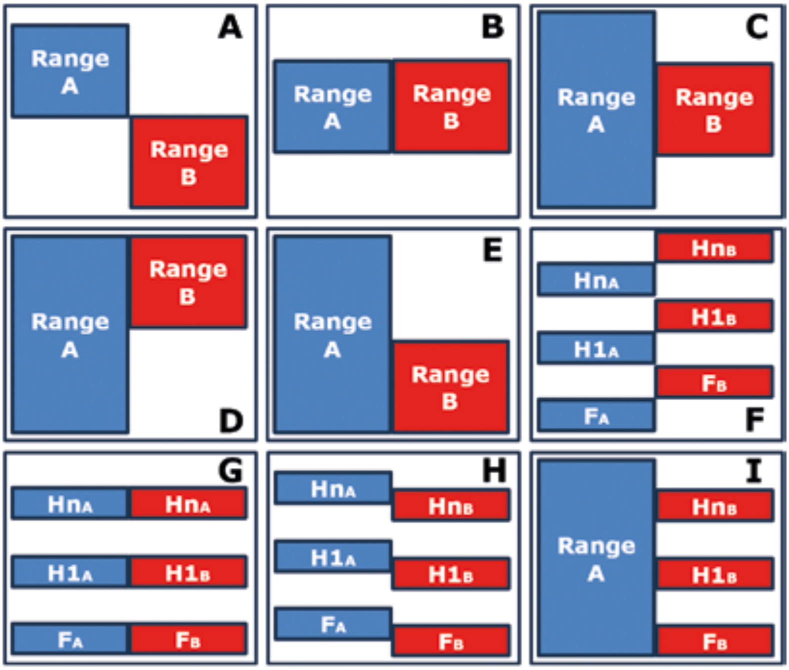
[6] That subjective perception does not imply that the identification of concurrent Orthoptera songs is hassle-free: in fact, the song structure is much more complex than what one gets by ear, and much more species are singing than one expects, including inaudible or poorly audible species.



9. Example scenarios of frequency collision of Range A (blue, lower amplitude) and Range B (red, higher amplitude). For clarity, the superposed ranges are represented side by side, but comments provided describe a full overlap (superposition). A-E, between low-Q songs; F-H, between high-Q songs; I, between low-Q and high-Q songs. IN F-I, FB is the fundamental band, and the H-bands are its harmonic frequencies. The coverage of scenarios is not exhaustive. See Tab. 1 for comments.

xist with hardware and software devices not capable to set the stage for signal deconvolution (Comon, 2004) nor for the application of the advanced techniques cited above, we can safely postulate that direct conflicts in the domain of amplitude will necessarily have destructive results, and collisions in each frequency band may be envisioned in purely mechanical terms of *force majeure*. With no means to intervene retroactively upstream of the microphone, with no provision for *ex post* signal separation, without pre-emptive measures to avoid collisions by increasing sound source selectiveness such as the mechanical aids and the design features that improve microphone directionality, we can state that – for the scope of this study – in the amplitude domain there is no remedy for the disappearance of feeble songs due to the preponderance of higher-am-

Kind of overlap	Q level		Scenario in Fig. 9 LP Low pass	Portion preserved after filtering				Notes
				HP High pass	BP Band pass	BS Band stop	BS Band stop	
None	Range A	Low	A	None	Entire	n/a	n/a	The entirety of each range can be preserved by HP and LP respectively.
	Range B	Low		Entire	None	n/a	n/a	
Full	Range A	Low	B	Ineffective				Frequency filtering is ineffective.The recognition of Range B (higher amplitude) may be possible, e.g. in a TPE (see "Time Overlap" more under).
	Range B	Low						
Middle	Range A	Low	C	n/a	n/a	None	Partial	Range B, overlapping the middle section of Range A, can be entirely preserved by a BP filter. A BS filter may preserve the remaining part of Range A.
	Range B	Low		n/a	n/a	Entire	None	
Top	Range A	Low	D	None	Entire	n/a	n/a	Range B, overlapping the upper section of Range A, can be entirely preserved by a HP filter. A LP filter may preserve the lower part of Range A.
	Range B	Low		Lower part	None	n/a	n/a	
Low	Range A	Low	E	None	Higher part	n/a	n/a	Range B, overlapping the lower section of Range A, can be entirely preserved by a LP filter. A HP filter may preserve the remaining part of Range A.
	Range B	Low		Entire	None	n/a	n/a	
None	Range A	High	F	Moderately effective, when harmonic bands are absent, scenario A applies Entire		Entire	Entire	Even though the ranges are not overlapped, they are intermeshed. Iterative band stop or band pass can preserve the entirety of each range. If only the fundamental band is present, scenario A applies.
	Range B	High				Entire		
Full	Range A	High	G	Ineffective				Frequency filtering is ineffective to separate fully overlapping high-Q ranges, but BP and BS filters may be used to clean Range B from noise.
	Range B	High						
Partial, high-Q	Range A	High	H	For each conflicting band, filtering as described for scenarios C, D or E may be applied				If only the fundamental band is present, scenario E or D apply, depending on which fundamental frequency is higher
	Range B	High						
Mixed Q	Range A	Low	I	Iterative recursion of C and D scenarios, E scenario if only the fundamental band is present				The recursive application of BS or LP filters may preserve the entirety of Range B, but leave Range A in an unrecognisable state. If only the fundamental band of Range B is present, scenario E applies.
	Range B	High						

Tab. 1. Examples of filtering strategies for de-collision of overlapping frequency ranges (Range B has a higher amplitude than Range A), with reference to the scenarios exemplified in Fig. 9.

plitude songs in the same time and frequency range. That is the exact reason why recording in the hours where cicadas are singing, or recording near any anthropogenic noise source of unpredictable amplitude, is highly inadvisable.

3.1.2 Frequency-based competition: strategies of de-collision
Confliction for frequencies may happen in many ways: its occurrence is also influenced by the nature, high-Q or low-Q, of the colliding songs. While the latter, epitomised by wide-band white noise, tend to show an irregular, continuous frequency/power spectrum, the TFSI of high-Q songs shows a harmonic structure divided in discrete bands: the lowest and usually loudest fundamental frequency, plus one or more (depending on the species, on microphone dynamic response and on the recording distance) harmonic bands, whose variable intensity is affected by the structure of the resonating tegmina.

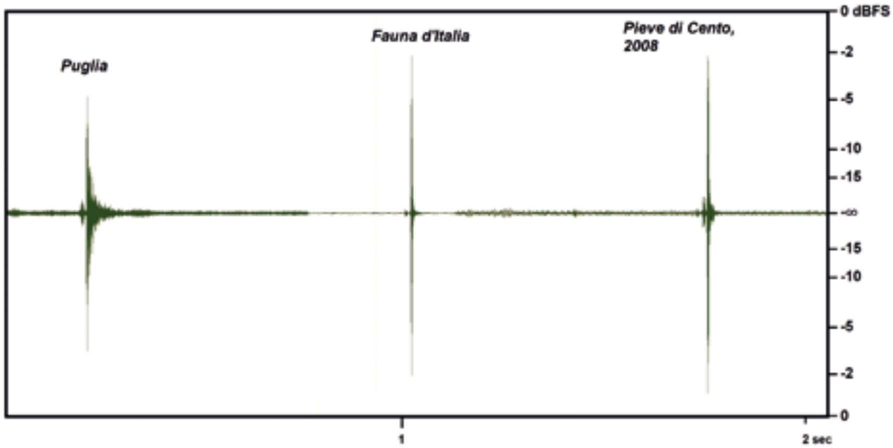
In the low-volume, unfocused recording scenario covered by this study, with few exceptions (e.g., some songs by *Oecanthus pellucens* and by *Oecanthus dulcisonans*) the harmonic bands are usually obliterated by attenuation, and we may consider the high-Q songs as restricted to the fundamental band.

Some scenarios of collision between songs with different amplitudes are summarised in Fig. 9, where the overlapping frequency ranges are shown side by side for clarity: the illustration does not cover all the possible scenarios, but exemplifies the typical collisions observed in this study. Tab. 1 provides idealised indications about the relevant filtering strategies and their results. Needless to say, the actual soundscape is much more complex, and the method application will never be as straightforward and effective as illustrated in Tab. 1.

3.1.3 Time-based competition: losing the tempo
In line of principle, excluding other adverse factors in other domains, echemes occurring in different moments (non-time-colliding) remain recognisable. In absence of frequency collision, recognisability may be granted as long as a sufficient part of a diagnostic echeme, or a sufficient number of syllables where the syllables suffice for recognition, is not overlapped by any other echeme / syllable.

In actuality, even in case when the elements (echemes, syllables…) of heterospecific songs are fully superposed in time, one, or both, the songs may remain visually recognizable in a TPE, as long as their amplitude is sufficient to grant the emergence of a species-specific pattern in the TPE. As an example, the tetrasyllabic echeme of *G. campestris,* if sufficiently loud, survives the collision, as does the disyllabic echeme of *P. intermedia* (see Fig. 7 and Fig. 9).

As it will be illustrated more under, visual recognition of species-specific

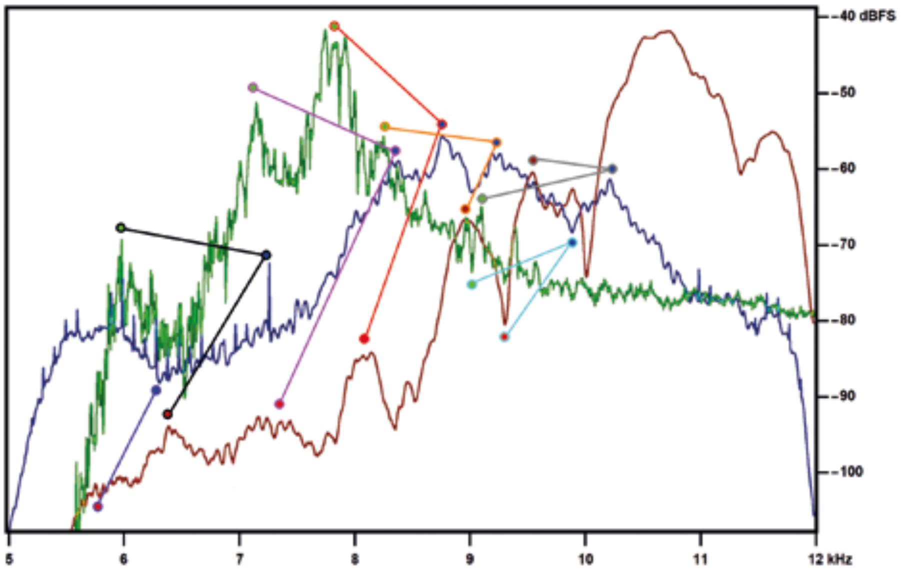


10. Effects of the different dynamic responses of the microphones and different recording conditions on the TPE of an echeme by *Decticus albifrons*, limited to the 5 kHz - 12 kHz band by high-pass filtering. Puglia: PAM recording from this study; *Fauna d'Italia*: an echeme from the accompanying DVD of Massa *et al.* (2012); Pieve di Cento (Emilia-Romagna, Italy), August 2008: an echeme from a recording obtained with the built-in microphone of an Edirol R-09 digital recorder. The two latter reference samples were downgraded to 12 kHz by pasting them into our recording.

TPE patterns greatly helps the identification. TFSI's are not equally effective in the recognition of time-related features, being unavoidably affected by the loss of time resolution inherent in the FFT algorithm, a loss directly proportional to the FFT size (see e.g., Brizio, 2023).

3.2 Comparing digital recordings: effects of different quality

Normally, the RAS is usually recorded at a wider bandwidth than the SAS candidate with which it's being compared: as explained at point 2.4.9, comparison is easier when the RAS is downgraded to the 12 kHz bandwidth. Particularly in case of comparison by ear, reference audio samples should be subject to the same filtering process adopted for the candidate: in fact, an unfiltered reference audio sample may be perceived as very different, only because it contains frequency bands not available anymore in the candidate. Consistent filtering of the two terms of comparison may improve their similarity in a decisive way. Another relevant difference between candidate SAS and RAS is related to the recording process. In most cases, reference audio samples are obtained in better, or even in ideal, conditions, including a proper recording distance. Even disregarding noise and any conflicting song, a



11. Effects of the different dynamic responses of the microphones and different recording conditions on the FPA of a song by *Decticus albifrons*, limited to the 5 kHz - 12 kHz band by high-pass filtering. FFT size = 8192 samples. Green line, built-in microphone of the Wildlife Acoustics Song Meter Micro recorder used in this study, excerpt from a PAM recording; Blue line, built-in microphone of an Edirol R-09 digital recorder, Pieve di Cento (Emilia-Romagna, Italy), August 2008; Red line, Sennheiser K6-module with ME67 condenser Microphone, recording by Baudewijn Odé, Maimone (Sardinia, Italy) on Tascam DA-P1 (DAT), August 1999 from the accompanying CD of Fontana *et al.* (2002). Blue and Red reference samples were downgraded to 12 kHz by pasting them into our recording. Coloured lines join tentatively homologous features in the three FPA's, marked by dots whose fill colour identifies each recording. For each recording, the FPA is based on an interval of around 30 sec. Differences in air temperature account for the frequency shift of homologous features.

relevant effect of the wider subject-microphone distance and of the lack of directionality is the selective attenuation of higher frequencies, that sums with the low sampling rate in returning a poorly recognisable acoustic image, particularly for those species that engage the higher frequency bands (in our case, we may cite *Poecilimon superbus* and *Yersinella raymondii*) and – after consistent filtering of the two terms of comparison – provide only a narrow high frequency range to compare. It should be remembered that any alteration in frequency / pressure composition affects also the TPE: combined with the other disturbances, filtering results in a more or less relevant reshaping of the TPE, that can completely obliterate the feebler components of the echeme (see Fig. 10). In any such case, a combined approach may be necessary: TPE comparison at different time resolutions, TFSI comparison by zooming on the bands that survived filtering, and band – wise FPA comparison – the latter may be indecisive due to the different dynamic response of the PAM microphone and of the microphone used to obtain the reference audio sample (see Fig. 11). Comparison should be based on degree of similarity rather than on equality (the latter is never granted), and decision should be based on the consensus of at least two approaches, plus confirmation by ear.

3.3 The quasi-ancillary role of hearing in the recognition process

Entering the realm of psychoacoustics (for a compelling overview, see Lemaitre *et al.*, 2018) is decidedly outside the scope of this paper, yet we would like to declare our full awareness of the subjective and potentially contentious nature of species recognition by the unaided ear. The reliability of any such recognition is severely compromised by the combination of the suboptimal nature of the PAM recording as considered in this study, and by the further signal degradation inherent in the process of extraction of audio excerpts.

Furthermore, the effectiveness of the ear-plus-brain machinery may be radically different in the two cases of recognition by immediate comparison, and of recognition without comparison.

When the audio of a song is played as first term of comparison, and the second term of comparison is provided by the memory of the listener, the concept of "familiarity" and its associated cognitive biases are brought into play (the work by Lavan *et al.*, 2016 addresses the issue in the context of human voice recognition). With some simplification, it can be said that the way we memorise phenomena (including songs) is necessarily non-exhaustive, but reductive, and is mostly based on a limited number of salient characters, and on the relations among those characters. When a high-fidelity representation of a known phenomenon is shown to us (e.g., a recording made under ideal conditions, or a high-resolution photo), if the memory is efficient, recognition (e.g., of the song, or of the person portrayed in the photo) occurs almost unavoidably. When signal degradation occurs (low resolution, blurred pictures, or degraded, partial audio signals – the only kind of signals that the approach adopted in this study can provide), performing recognition by memory may pose an insurmountable problem. In actuality, that was our case: even though the pool of authors may boast several decades of field and lab experience in the field of Orthoptera songs, commonplace species such as *Gryllus campestris* or *Tettigonia viridissima* proved difficult to identify by ear, due to the combination of distance and overlapping heterospecific songs. The several hours of coverage of a common species such as *Oecanthus dulcisonans*, almost ubiquitous in most recordings, included also previously unreported echeme-sequences of paucisyllabic, *Acheta*-like echemes that caused considerable perplexities until some unmistakable *Oecanthus dulcisonans* songs including such echemes were detected. Obviously, some commonplace and loud songs are so clearly sculpted in one's mind, that an effective recognition may take place despite degradation: yet, methodologically, we must discourage any instinctive approach and must require anybody, who wishes to work along the lines sketched by this paper, to question his/her self reliance.

Although letting the sense of hearing out of the door, we bring it back through the window as an invaluable aid when recognition by immediate comparison is performed. Our workflow includes at least two steps in which two-terms immediate comparison by ear occurs:

- *during the Attribution of an SAS to a species*: the alternated hearing[7] of – on one side – reference, optimal quality audio samples of definite attribution and – on the other side – an SAS audio excerpt may quickly provide a single candidate species, or a shortlist of candidates. Besides temporal features such as rhythm of echemes or other temporal patterns such as trills, a multifaceted and frequency-based subjective element is called into play: timbre. In each comparison, the recognition of some degree of commonality in rhythm and timbre between the SAS excerpt and the current reference audio sample helps to discriminate between candidate species.
- *when checking the effectiveness of the application of digital filters*: as an example, when a band-stop filter is applied to exclude a narrow-band rhythmic song (such as the fundamental band of a cricket song), listening to the song before and after the application of the filter allows ascertaining that the desired obliteration is complete, or that a wider band should be stopped because remnants of the rhythmic pattern are still audible after filtering.

Anyway, even the most straightforward conclusions drawn by ear shall be verified as illustrated at point 2.4.9.

[7] See also point 2.4.9 "Generalities about the comparison process"

4. Results

4.1 Species-specific SAS' emerging from this study

Tab. 2 lists the main robust characters used as SAS' in this study. As a general rule, high-Q songs may be well recognizable in both time and frequency domains due to the coexistence of a well-defined and often species-specific echeme structure (we may say that echeme structure is the most robust character in time), and of a clear partitioning in more or less narrow frequency bands (the fundamental being the most robust character in frequency), often repeated in a harmonic series.

Devoid of well-defined features in the frequency domain, unless their wide-band song includes typical pressure peaks at special frequencies (those peaks may provide some robust grasp for recognition), low-Q songs may show species-specific amplitude patterns in the time domain. Again, echeme structure is potentially highly survivable: yet, it's more prone to degradation because its components are often more poorly defined in frequency than the high-Q syllables. Furthermore, short amplitude patterns, in particular short zips and ticks, are not species-specific unless the whole spectral information is considered, which is impossible in our case, due to the restriction to 12 kHz of the usable frequency band. Anyway, it should not be forgotten that intergrades may exist and also low-Q songs may include some well-defined frequency component, and lend themselves to an easier recognition.

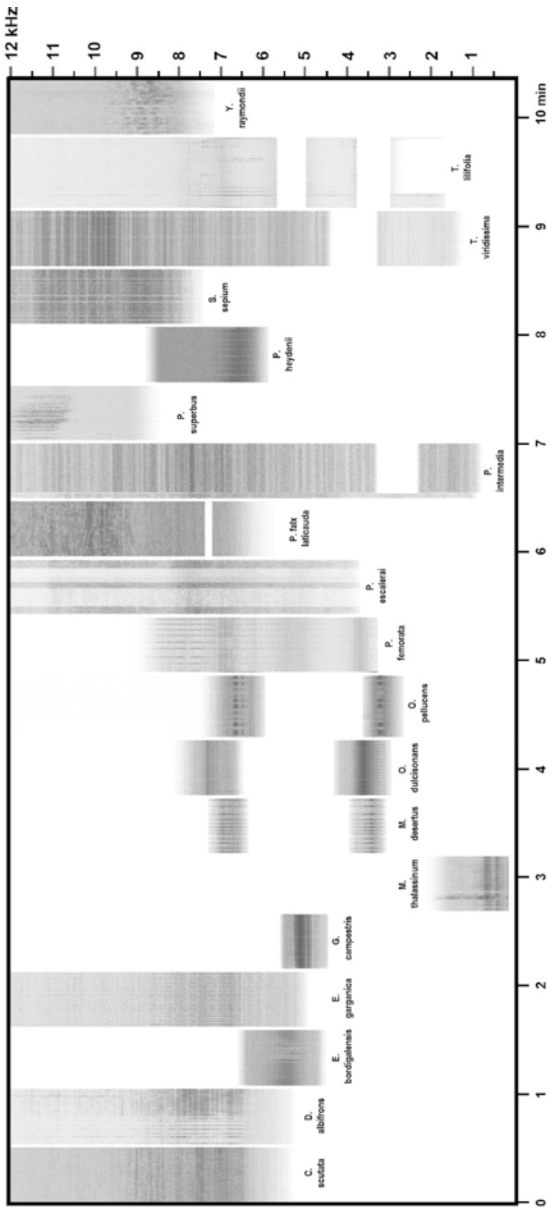
Fig. 12 provides a synopsis of the frequency range of the clearest SAS' emerging from this study, listed in Tab. 3. On purpose, we omit illustrating them in individual images: the extent, the frequency range, and the clarity of the SAS' audio files is the fruit of unpredictable combinations of songs and noise conditions, and may vary wildly among different recordings, so their TPE's or TFSI's wouldn't be useful for any comparative purpose outside of this study. For high-Q songs, the SAS' may include only the highly survivable fundamental band, except in a few cases where the first harmonic band was observed.

SURVIVING ACOUSTIC SIGNATURES AS OBSERVED IN THE RECORDINGS

N	Species Alphabetical order	Q	Degree of certainty	Alternative identification	Typical pattern in time	Most robust frequency features	Notes for comparison by ear with reference songs
	Cyrtaspis scutata Charpentier, 1825	Low	Good	None	Echeme-sequence of very short sounds, regularly emitted at a rate of around 3 per seconds.	Observed in the 6000 Hz - 7000 Hz frequency band.	Regular emission helps identification, short sounds look all similar.
	Decticus albifrons Fabricius, 1775	Low	Maximum	None	Tick sequences emitted at a gradually increasing rate, then constantly at the highest rate of about 8 echemes/sec.	Loudest band is at least 3 kHz wide, centred around 7500 Hz.	Variable number of syllables per echeme. Increasing echeme rate must be considered.
	Eumodicogryllus b. bordigalensis Latreille,1804	High	Maximum	None	2-4 echemes/sec of 15-20 subequal syllables.	Multicusped, wide (>2 kHz) fundamental band peaking at around 5400 Hz.	Regular "krees", sometimes with a typical lower pitched swishing sound among echemes.
	Eupholidoptera garganica La Greca, 1959	Low	Maximum	None	1-4 echemes every 2 sec.	Maximum pressure at around 8 kHz.	Short "tsip" sounds. Vaguely similar to D. albifrons. Check echeme in TPE.
	Gryllus campestris Linnaeus, 1758	High	Maximum	None	Quadrisyllabic echemes, first syllable feebler.	Medium-width (1400 Hz) fundamental band peaking at around 5200 Hz.	An unmistakable species.
	Meconema thalassinum De Geer, 1773	Low	High	None, anthropogenic sounds	Up to 30 vibrating percussions on the substrate per sec, in bursts of a few seconds, reminiscent of a distant engine idling.	Percussive rumble in the 500 - 1500 Hz band, with the highest pressure concentrated in a narrow band at around 600 Hz.	Based on comparison with XenoCanto (see references).
	Melanogryllus desertus Pallas, 1771	High	High	Another Gryllinae	Short, subequal trills with a volume crescendo	Fundamental at around 3500 Hz. First harmonic band observed in one instance.	Very feeble song in the recording, well-matching an equally filtered reference audio sample
	Oecanthus dulcisonans Gorochov, 1993	High	Maximum	None	Continuous trill. May include shorter, interrupted trills ("Mode 2" song.	Narrow (800 Hz) fundamental band peaking at around 3600 Hz.	May display 1st harmonic.
	Oecanthus pellucens Scopoli, 1763	High	Maximum	None	Short, subequal trills, never continuing for more than a few seconds.	Narrow (800 Hz) fundamental band peaking at around 3200 Hz.	May display 1st harmonic.
	Pholidoptera femorata Fieber, 1853	Low	Good	See "Notes" column	Trisyllabic zip, increasing volume of the three close-packed syllables, the first feeble, the last loudest.	Wide band, most relevant between 3500 Hz and 6500 Hz.	By ear, *Phaneroptera falcata* sounds similar, but the syllable structure is radically different.

N	Species Alphabetical order	Q	Degree of certainty	Alternative identification	Typical pattern in time	Most robust frequency features	Notes for comparison by ear with reference songs
	Platycleis escalerai Bolivar, 1889	Low	Good	*Platycleis affinis* Fieber, 1853	Echeme-sequences (a few tens of buzzing echemes followed by around 10 quick clicks) similar to those by *P. affinis*. Reference audio samples for *P. escalerai* looked overall more similar, including the higher number of final clicks.	Wide band, starting above 4 kHz. Highest pressure bands centered at 7700 and 10500 Hz.	The reference audio sample, most probably taken at a higher air temperature, was quicker than what was observed on 14 August.
	Platycleis falx laticauda Brunner von Wattenwyl, 1882	Low	Good	*Platycleis escalerai* Bolivar, 1899; *Platycleis affinis* Fieber, 1853	Quick, fluttering sound. Syllable structure unclear in the recordings, due to low volume and competing noise. Echeme-sequences lack the final clicks typical of *P. escalerai* and *P. affinis*.	Wide band, starting above 6 kHz. Highest pressures between 9500 Hz and 10500 Hz. Barely audible without extreme amplification.	At least two species of *Platycleis* in the area deliver similar songs. Clickless echeme-sequence structure is more akin with *P. falx laticauda*.
	Platycleis intermedia Serville, 1839	Low	High	*Sepiana sepium* (Yersin, 1854)	2-3 Short, disyllabic sounds per second.	Most relevant band 4 kHz wide centred at around 6000 Hz. Many peaks between 6.5 kHz and 8 kHz.	"dzi" sounds.
14.	***Poecilimon superbus*** Fischer, 1854	Low	Good	*Leptophyes laticauda* (Frivaldsky, 1867)	Quiet and short tick sequences with one tick every few seconds. Short groups repeated at an interval of 30 sec or more	The song is definitely ultrasonic, and faint traces of the ticks may be found above 10 kHz	Syllable structure and number of echemes in a bout seems more similar to *P. superbus* than to *L. laticauda*.
	Pteronemobius heydenii Fischer, 1853	High	Maximum	None	45/50 sharp syllables per sec, typical, slow pressure crescendo in trills up to 4 sec.	Fundamental band centred at around 7000 Hz	The crescendo survives signal degradation. The number of syllables per second is diagnostic.
16.	***Sepiana sepium*** Yersin, 1854	Low	High	*Platycleis intermedia* (Serville, 1839)	Short, disyllabic sounds (100 msec for two syllables). Irregular sequence of short (3-6 echemes) and long (8-20 or more) echeme-sequences.	The surviving elements are very high-pitched (> 7500 Hz) due to the need of a high-pass filter to separate them from concurrent songs.	Within each echeme-sequence, the intervals are almost equal, resulting in a very regular rhythm.
	Tettigonia viridissima Linnaeus,1758	Low	High	None	Disyllabic, continuous rattling sound.	Very wide band, from 1500 Hz up to 12000 Hz. Many regularly spaced peaks from 9.5 kHz to 10 kHz.	"Machine gun" rhythm.
	Tylopsis lilifolia Fabricius, 1793	Low	Good	See "Notes" column	Short tick sequences of 1-5 ticks, long intervals between tick sequences.	Very wide band, the loudest starting at 1500 Hz and up to 12000 Hz.	Ambiguity with other ticking songs. Check monosyllabic structure.
	Yersinella raymondii Yersin, 1860	Low	Good	*Phaneroptera falcata* (Poda, 1761)	Isolated short monosyllabic echemes, usually 1 to 3 every 10 sec	Observed above 7000 Hz, conflicting with the 1st harmonic frequency of *O. dulcisonans*.	Squeaking zips. Syllable structure unclear in the recordings.

Tab. 2. Specific SAS' used in this study, in alphabetical order of scientific name. The column "Typical pattern in frequency" refers to the particular, unrecorded temperature conditions encountered during the recordings.



12. Synopsis of 30” highest-quality SAS’ listed in Tab. 3. The illustration shows the TFSI of the clearest, least degraded acoustic signatures obtained for each species, depending on concurrent songs. In less ideal conditions, only the most robust frequency features cited in the special column of Tab. 2 were visible for each species.

POSITION OF THE HIGHEST-QUALITY SPECIFIC SAS IN THE RECORDINGS

Species	Recording date	Recording time	Starts at (min:sec)
Cyrtaspis scutata (Charpentier, 1825)	23 July	21:23	24:40
Decticus albifrons Fabricius, 1775	26 July	02:22	23:42
Eumodicogryllus bordigalensis (Latreille,1804)	30 July	23:17	05:19
Eupholidoptera garganica La Greca, 1959	26 July	21:21	10:16
Gryllus campestris Linnaeus, 1758	22 July	21:24	24:37
Meconema thalassinum (De Geer, 1773)	10 August	20:03	(many excerpts)
Melanogryllus desertus (Pallas, 1771)	15 August	00:58	00:00
Oecanthus dulcisonans Gorochov, 1993	21 July	02:26	25:35
Oecanthus pellucens (Scopoli, 1763)	21 July	02:26	16:50
Pholidoptera femorata (Fieber, 1853)	23 July	01:23	27:13
Platycleis escalerai Bolivar, 1889	14 August	20:58	00:28
Platycleis falx laticauda Brunner von Wattenwyl, 1882	26 July	02:22	25:20
Platycleis intermedia (Serville, 1839)	10 August	00:05	05:22
Poecilimon superbus (Fischer, 1854)	5 August	21:10	25:49
Pteronemobius heydenii (Fischer, 1853)	30 July	00:18	20:37
Sepiana sepium (Yersin, 1854)	4 August	01:12	00:14
Tettigonia viridissima (Linnaeus,1758)	19 July	23:27	02:40
Tylopsis lilifolia (Fabricius, 1793)	29 July	22:18	05:55
Yersinella raymondii (Yersin, 1860)	24 July	22:22	24:13

Tab. 3. Position of the highest-quality SAS' (see Fig. 12) in the recordings.

The following species were recognised with at least a good degree of certainty, by comparison with available reference recordings (mostly, with Massa *et al.*, 2012) and by the adoption of the analysis protocol described in the "Materials and methods" section: all were already reported for the study area, except when otherwise noted.

- *Cyrtaspis scutata* (Charpentier, 1825), Location 1
- *Decticus albifrons* Fabricius, 1775, Location 1 & 2
- *Eumodicogryllus b. bordigalensis* (Latreille, 1804), Location 1 & 2
- *Eupholidoptera garganica* La Greca, 1959, Location 1 & 2
- *Gryllus campestris* Linnaeus, 1758, Location 1 & 2
- *Meconema thalassinum* (De Geer, 1773), Location 1 & 2 – besides the typical song of *M. thalassinum*, a long lasting series of regularly spaced

(typically, 1100 msec; minimum and maximum interval around 700 msec and 1600 msec respectively) double impacts, reminiscent of those by *Meconema meridionale* (A. Costa, 1860) was observed in Location 2, but neither their regularity nor the two distinct hits in each double impact match the song of this species, that is made by small groups (2-10) of leg impacts, lasting about 2-5 sec at the rate of 2 or 3 per second, spaced by intervals of 10 to 20 seconds. Parsimoniously, while the existence of a previously unreported song mode by *M. thalassinum* may be suspected, the song is not formally attributed to any Orthopteran species.

- *Melanogryllus desertus* (Pallas, 1771), Location 2
- *Oecanthus dulcisonans* Gorochov, 1993, Location 1 & 2
- *Oecanthus pellucens* (Scopoli, 1763), Location 1 & 2
- *Pholidoptera femorata* (Fieber, 1853), Location 1
- *Platycleis escalerai* Bolivar, 1889, Location 2
- *Platycleis falx laticauda* Brunner von Wattenwyl, 1882, Location 1
- *Platycleis intermedia* (Serville, 1839), Location 1 & 2
- *Poecilimon superbus* (Fischer, 1854), Location 1 & 2
- *Pteronemobius heydenii* (Fischer, 1853), Location 1 & 2 - **never reported before for the area**
- *Sepiana sepium* (Yersin, 1854), Location 2
- *Tettigonia viridissima* (Linnaeus,1758), Location 1
- *Tylopsis lilifolia* (Fabricius, 1793), Location 1 & probably Location 2 - Evidence from Location 2 is robust but indecisive.
- *Yersinella raymondii* (Yersin, 1860), Location 1 & 2

4.2 Faunal differences in the two locations

The two locations, separated by a mere 5200 metres in a straight line, did not show any significant difference in altitude, ecology, vegetational cover and orography, and there was no reason to expect that different species may have been intercepted and, in fact, 10 species were observed in both locations. In hindsight, although observed diversity didn't drastically change, Location 2 provided a more monotonous soundscape, overwhelmingly dominated by the songs from *Platycleis intermedia*. Furthermore, Location 2 resented more heavily from noise factors including grazing sheep, and its weather conditions looked overall less favourable, complicating the analyses (where they were possible) but at the same time resulting in a high rate of early rejection (step 2.4.2 of the workflow): blowing wind and temperature drop with decrease or disappearance of insect songs were observed in the majority of the recordings there taken.

Tylopsis lilifolia, whose high-pitched zips may have been obliterated by the dominant songs of *P. intermedia*, was indecisively observed also in Location 2. Species observed only in Location 1 included:

- *Cyrtaspis scutata*, observed in several recordings;
  Pholidoptera femorata, that was observed in Location A in two instances in the nights between 24 and 26 July;
- *Platycleis falx laticauda*, that was observed in Location A in a single instance in the night between 25 and 26 July;
- *Tettigonia viridissima*, that was observed in Location A in a single instance on July 20.

We cannot exclude that the unobserved species in location 2 weren't absent, but may simply have ended their calling season before the repositioning of the recorder in Location 2, or that the less favourable weather conditions may simply have prevented or discouraged their song. One last element emerging in Location 2 were the strong and widespread songs by *Platycleis intermedia*, whose very wide band has surely obscured any feebler concurrent song.

Species present only in location 2 included:

- *Melanogryllus desertus*, which was observed in a single instance at 11 pm on August 13;
- *Platycleis escalerai*, which was observed in a single instance at 9 pm on August 14;
- *Sepiana sepium*, which was observed in a single instance at 1 am on August 4.

4.3 Generalities about the soundscape evolution during the night

In retrospect, recurring acoustic phenomena showed quite regular patterns that will be considered in future similar PAM campaigns. We cite the most relevant for the geographical area and for the July/August period.

- Roughly 85% of the Orthoptera songs effectively analysed were observed between 21:00 and 03:00. If the recordings would have taken place just in the 21:30-02:30 time band, most if not all the species would have been observed.
- Depending on air temperature and weather conditions, cicada songs may be present until 21.30.
- The first rooster crows may occur as early as 3:30 am.
- The barking of the dogs was completely unpredictable, and the only possible mitigation would have been placing the PAM recorders as far away as possible from houses with dogs.
- The songs by the Scops owl *Otus scops* were regularly present for the enti-

rety of July.

- Sheep flocks or cow herds moving or grazing at night were observed in roughly the same time bands. It could have surely been possible to obtain information about such movements before deploying the PAM recorders.
- When no disturbance occurred, the quietest time band was from 3 am to 5 am.
- Since 5 am, early bird songs emerge as the only relevant natural element in the soundscape.
- Often, a sudden decrease of the wind was observed in the last part of the night: it's perfectly possible that five or more recordings, unusable for excessive wind noise overlapped by intense, concurrent songs, are followed by one or more late night/early morning recording that is unusable for opposite reasons (insufficient volume).

4.4 The dual-mode song by Oecanthus dulcisonans *and* Oecanthus pellucens

The concurrent song of the two species of *Oecanthus* observed in our recordings was already reported for Spain by Gorochov, Llorente (2001) and for Italy (Parco del Circeo, Lazio) by Schmidt (1996). More recently, it was observed in Sardinia by Brizio, Buzzetti (2014) and was comparatively studied by Cordero *et al.*, 2009. In this study, both species were recorded delivering two song modes that were assigned to each species based on syllable structure and by comparison with reference audio samples.

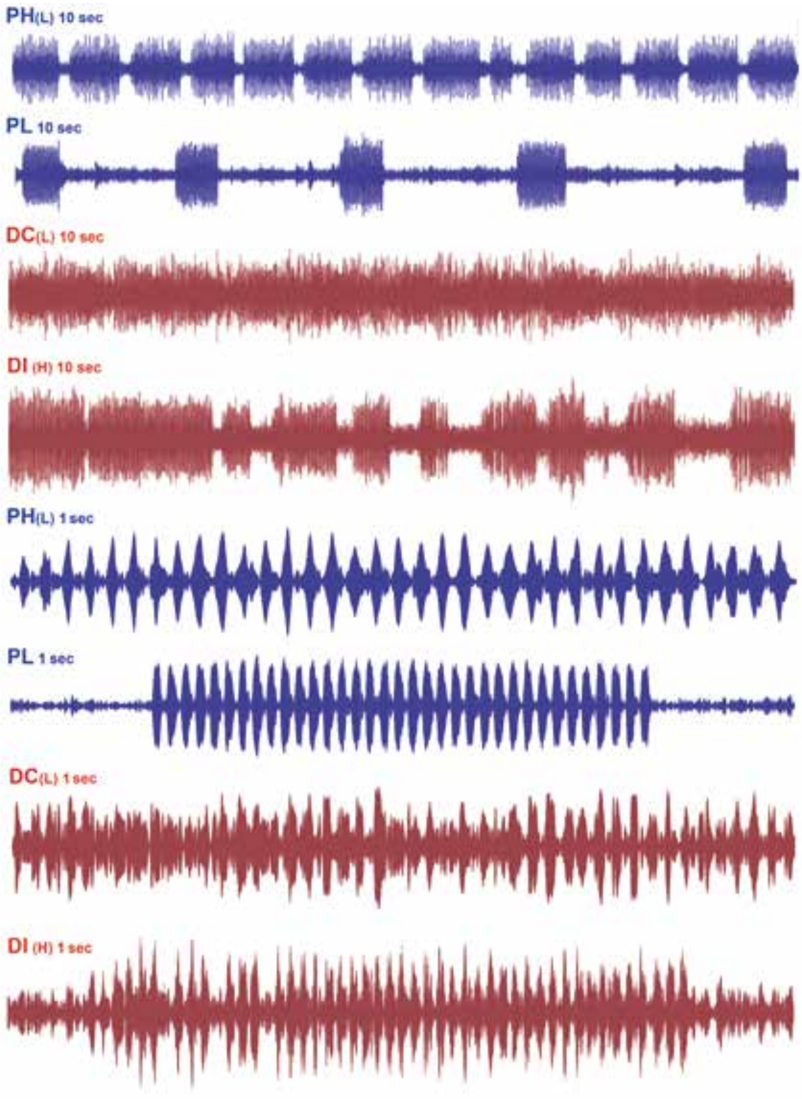
The regular mode coincides, with a few variations, with the advertising song reported in literature for each species and, as usual for any Orthoptera song, is emitted at frequencies that increase with temperature, while syllable duration may decrease:

- for *O. pellucens*, a series of closely packed subequal echemes, in our case of 20-45 syllables (with the exceptional insertion of shorter echemes of around 10 syllables), with a short interval of around 150 msec between echemes. The number of echemes per seconds depends on the syllable count and often is around three echemes every two seconds. Depending on temperature conditions, usually the fundamental band was centred around 3100 Hz, in which case the commonest syllable duration is around 30 msec. In the TPE, syllables show a regular contour in which a longer and stronger syllable body is immediately followed by, and often merged with, a short and feeble tail. Regardless of echeme duration, the consistent duration of the intervals gives an impression of regularity to the song;
- for *O. dulcisonans*, a seldom interrupted continuous trill that may last for minutes, made by irregular, multi-cusped syllables: in the TPE, the

adjacent syllables look different in volume and duration. In the same temperature conditions, the fundamental band by *O. pellucens* is centred at around 300 Hz below that by *O. dulcisonans*: as an example, at around 3100 Hz and 3500 Hz respectively, in which case syllable rate is around 50 syllables / second and syllable duration is around 20 msec.

The alternative song modes maintain the same syllable structure described above for each species, can be emitted while other conspecifics persist in the regular advertising songs, and remain discernible because they may engage different frequency bands, and because they are sparser and more interrupted.

- for *O. pellucens*, the alternative mode is characterised by a rarefaction of the echemes, that look louder and of more consistent duration than in the standard advertising song: the echeme rate may be as low as three echemes every 10 seconds, with intervals of two seconds or more. The alternative song mode engages a higher frequency band (e.g. its fundamental may be centred at 3500 Hz, around 400 Hz above the standard song: as a consequence, it may interfere with the advertising song of *O. dulcisonans*), and the duration of the syllables is visibly reduced, even under 20 msec. Considering that the alternative mode was observed in presence of an unusually high background noise (ambience at around -30 dBFS with loud songs by P. intermedia, wind gusts up to -15dBFS, occasional noise by the bells of a herd of sheep), it may be an expression of the Lombard effect, (Cynx *et al.*, 1998; Potash, 1972; Pytte *et al.*, 2003): noise perception induces a frequency shift and an amplitude increase to make the song emerge above the noise. While the required frequency shift was clearly observed, the amplitude increase can be subjectively perceived by the unaided ear, but cannot be measured conclusively, because of the impossibility to extract sufficiently clean echemes from the background noise. In this case, also echeme rarefaction and increased regularity may contribute to mitigate signal degradation in noisy conditions. The Lombard effect is still poorly studied in insect songs, as noticed by Gomes *et al.* (2022), who cite the study by Duarte *et al.* (2019) on cricket song variations in presence of the noise by mining trucks, while Lampe (2012, 2014) described the effects of roadside noise on grasshopper songs;
- for *O. dulcisonans*, the alternative song is emitted in the same frequency band as the advertising song, that as usual varies with temperature, is broken in echeme-sequences of very variable duration, and completely lacks the regularity of the song by *O. pellucens*. The interrupted song may be emitted immediately following a regular song and vice versa. It's much too obvious that, without human presence during the recording phase, no behavioural

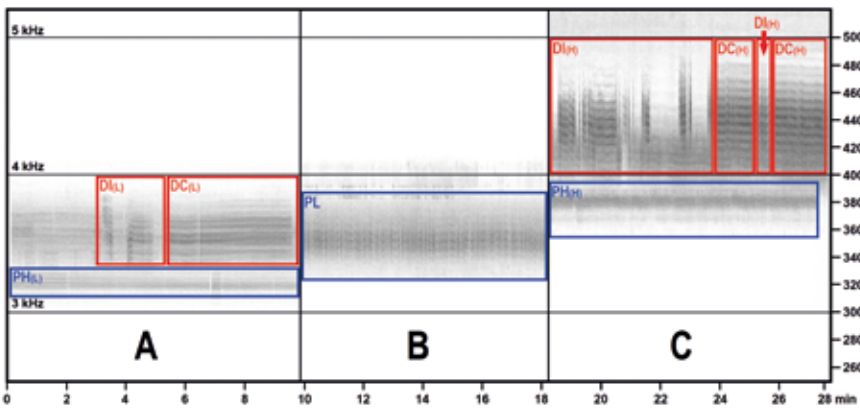


13. 10-sec and 1-sec TPE's of some different song modes observed for the *Oecanthus* species reported in this study. Blue TPE's = *O. dulcisonans*, red TPE's = *O. pellucens.* The first letter in the acronym is the initial of the species name, the second letter specifies the song mode: C = continuous; I = interrupted (may occur both in the lower and in the higher frequency range of the species, see Fig. 14); H = high echeme repetition rate; L = low echeme repetition rate, accompanied by an increase in frequency (shorter syllables) if compared to PH(L). The letter in round brackets refers to the lower (L) or higher (H) frequency range in which the song mode was observed. Probably, the PL song by *O. pellucens* is an example of the Lombard effect (see text).

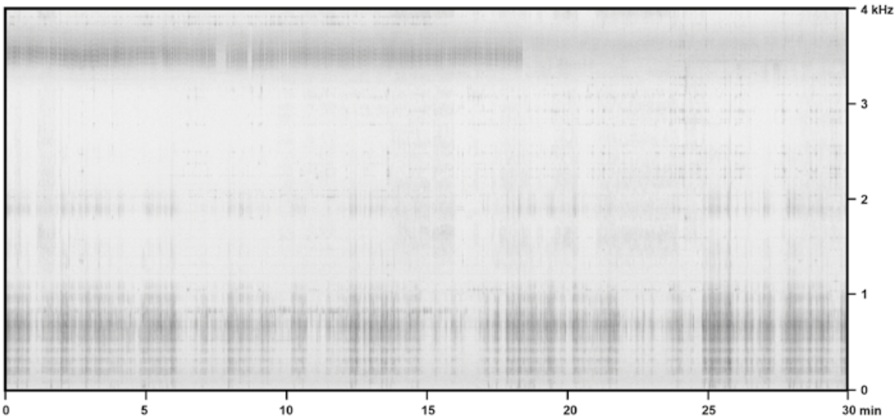
inductions would be reasonable, and we may just state that it may serve other non-advertising biological purposes, that may include rivalry or courtship.

The coexistence and the possible frequency overlap of the two song modes by the two species may cause doubts that the TFSI and the FPA may not solve: conclusions can be drawn only when the TPE of a band-pass filtered excerpt shows the syllable structure with enough clarity. Comparison by ear may be indecisive: the song by *O. pellucens* may be perceived as slightly clearer and feebler, the song by *O. dulcisonans* may be perceived as stronger and slightly uneven or coarser, but no decisions should be based only on those impressions.

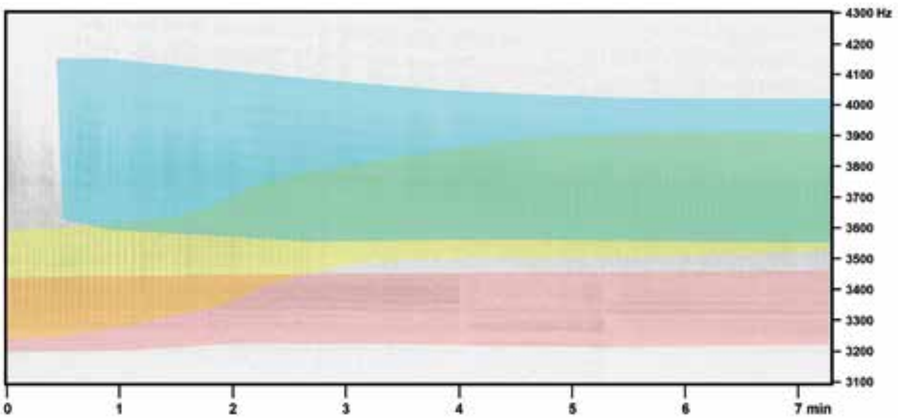
Figs. 13 and 14 provide a visual proof of the difference among the song modes cited above. Fig. 15 shows the noise condition during the emergence of the alternative mode song of *O. pellucens*, while Fig. 16 shows a case of frequency shift of the Mode 2 song band centre from approximately 3200 Hz to approximately 3600 Hz, a possible further expression of the Lombard effect.



14. Example TFSI's of the different song modes observed for the *Oecanthus* species reported in this study in three different dates. Blue frames = *O. pellucens*, red frames = *O. dulcisonans.* Column A = most frequent temperature and background noise conditions; Column B = high noise in the 0 Hz - 3000 Hz band; Column C = unusually high temperature conditions. First letter in the acronym is the species (D for *O. dulcisonans*, P for *O. pellucens*). Second letter specifies the song mode: C = continuous; I = interrupted; H = high echeme repetition rate; L = low echeme repetition rate. The letter in round brackets refers to the lower (L) or higher (H) frequency range in which the song mode was observed. Probably, the PL song by *O. pellucens* is a case of the Lombard effect (see text).



15. Noise condition under 3 kHz during the emergence of the alternative song mode of *O. pellucens*, a possible case of the Lombard effect. The lower frequency range of the soundscape was heavily affected by a flock of sheep with bells and by frequent wind gusts.



16. *O. pellucens*: transition of low echeme rate song (yellow overlay) from the fundamental band of the advertising song (red overlay), centred at around 3300 Hz, to the band of the advertising song of *O. dulcisonans* (blue overlay) centred at around 3600 Hz - 3700 Hz.

5. Conclusions

The deployment of PAM recorders as instruments for punctual biodiversity assessment proved useful but – in some cases – not entirely decisive: its cost-effectiveness may be questioned on the basis of the unordered amount of work that – depending on unpredictable circumstances – may be required to extract useful information from a contested soundscape. Success may be increased by accurate preliminary planning, taking advantage of predictive methods such as the Encounter Predictability Scorecard (Brizio *et al.*, 2020). Yet, the intrinsic unselectiveness of omnidirectional PAM recorders, especially when coupled with suboptimal sampling frequency, will require extensive manpower to provide meaningful results. In that respect, the main lessons learnt include the following.

- **PAM night recording by omnidirectional microphones proved effective in the detection of a relevant sample of Orthoptera diversity**: without the countercheck of a supervised night recording campaign at the same location, the relative merits of passive and active, supervised recordings remain open to discussion. The optimal recording distance and the directionality of the latter come at the price of a substantial expenditure of time in the field, and active recording may be unable to grant the extended coverage in time of a fixed-location automated recorder. At the same time, the wider coverage of species of any automated recorder comes at the price of suboptimal quality, which in turn may complicate the analyses and quickly bring them beyond the threshold of cost-effectiveness.
- **Any species offering to the recorder a set of robust "Surviving Acoustic Signatures" remained recognizable regardless to the signal degradation**: the 24 kHz sampling frequency, that made the recorder entirely deaf to the songs higher than 12 kHz, proved capable to engage also the lower range of very high-pitched songs such as those by *Poecilimon superbus*.
- **The equipment and the analysis workflow proved capable of revealing some previously unreported phenomena**, including the presence of *Pteronemobius heydenii* in the area, a higher diversity of *Oecanthus* songs, and the possible influence of the Lombard effect on the song of *O. dulcisonans*.
- **Even though the two locations explored were near (5 km in a straight line) and in a substantially identical landscape, location-typical species were recorded**: for a proper evaluation of actual faunal differences, one recorder should have been deployed contemporaneously in each location. We cannot exclude that the singing season of the unobserved species was nearing its end during the deployment in Location 1, nor that the missing

observations were due to the overall noisier setting of Location 2, which was affected by worse weather conditions.

- **Brute force, massive PAM recording campaigns, while ensuring an extended coverage in time, are not necessarily information-rich**: even though the dataset is too scanty to allow any meaningful statistical analysis, the acoustic landscape in consecutive days is subequal and very consistent, casting doubt on the opportunity to repeat the recording session for more of two or three days in a row in any given station. Yet, when the objectives include the possible interception of a rarely emitted song, repeated recordings in the same place, at the same time, may be justified, especially when the location and the period are based on well-founded guesses.
- **It's advisable to investigate and to make agreements with the owners of the plot of land where the PAM recorder will be placed**: grazing sheep, agricultural works and other foreseeable causes of noise should be considered before deciding the placement position.
- **It's advisable to check the recordings obtained during the first few days of deployment**: if necessary, gain settings, recording volume (if available) and recorder positioning can be reconsidered consequently.
- **The recorder should be fastened firmly to the chosen support (tree, pole, wall…), possibly interposing some elastic padding element, e.g., foam rubber) in between**, to limit the amount of vibration that may be transmitted to the recorder itself. Any wobbling or rattling of the recorder must be prevented, taking into account adverse weather conditions.
- **Further care should be put in avoiding that the support itself does not receive impacts**: as an example, if the recorder is solidly fixed to a tree branch in such a way that it doesn't rattle and does not get direct hits, one should check that the branch itself may not get hit by other branches in windy conditions. Besides that, any care put in a correct placement of the recorder may be nullified by slamming or rattling objects (gates, loose fencing) in the immediate vicinity, as well as by crunchy substrates such as dead leaves or twigs when the passage of animals may be expected.
- **If the dominant wind direction is established, the recorder should be placed with the microphone pointing leeward.**
- **The volume (recorded pressure) of PAM recordings is necessarily lower than desirable**: the unpredictability of the nature, number and distance of the singing specimens requires a prudent, low setting of the gain and of the recording volume (when available), to avoid destructive clipping in case of near, high amplitude songs. It's better to amplify a low-volume recording, than to discard a clipped recording altogether. Anyway, it should not be for-

gotten that low microphone gain and sound source distance lower the signal/noise ratio and increase the adverse effects of attenuation by divergence and by atmospheric absorption, to a point that may prevent recognisability.

- **PAM recordings may not necessarily provide decisive results**, but may prove useful for assessing the presence of the most recognisable species.
- **Species delivering similar songs may be impossible to separate, regardless of the quality of the recording**: some uncertainty remains about the songs attributed to *Platycleis escalerai*, that may also match those by *P. affinis*. *P. falx laticauda*, whose echeme-sequences lack the final clicks, poses less problems, even though the clickless echeme-sequences by *P. escalerai* and *P. affinis* are very similar.
- **PAM recordings are a surrogate, not a substitute of field investigations**, and may just be used as a preliminary assessment tool. Both the uncertain identifications based on SAS', the identification of a species never reported for the area and the unrecognised songs may require the collection of physical specimens to corroborate the conclusions.
- **Omnidirectional microphones have pros and cons**: while omnidirectionality may allow intercepting a wider range of singing individuals, and consequently a higher number of species, it's an attack to audio source selectivity. Omnidirectional microphones increase the probability of collisions. To our best knowledge, a rotating directional microphone that can be linked to a wildlife recorder is still unavailable. A remedy may consist in the manual periodical reorienting of a directional microphone between consecutive PAM recording sessions.
- **An extended time bracket (e.g., from 9:30 p.m. to 05:30 a.m.) may be useful for an exhaustive coverage of the specific diversity**, considering that some species were observed just in one, or in very few, recordings in each daily bracket.
- **For the detection of Orthoptera, it's mandatory to exclude from the recordings the hours when cicadas are singing**: the low-Q, the wide frequency range and the loudness of cicada songs compromise any possibility to extract useful information from the concurrent Orthoptera songs.
- **In a contested soundscape, it may be impossible or unusually difficult to recognise even the commonest song by listening with the unaided ear to the playback of a PAM recording**, as exemplified by perplexities initially arising even with common species of crickets, initially mistaken for entities never heard heard-before.
- As a consequence, to take into account echeme structure, syllable duration and exact frequency structure, **comparison among audio samples should be mostly or entirely performed on screen rather than by ear**.

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