Biodiversity Journal, 2020, 11 (2): 443–496 https://doi.org/10.31396/Biodiv.Jour.2020.11.2.443.496

Beyond the audible: wide band (0-125 kHz) field investigation on Italian Orthoptera (Insecta) songs

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ABSTRACT In recent years, several species of Orthoptera were field recorded by the authors by using a low cost USB microphone with a sampling frequency up to 250 kHz. Here for the first time we propose a comprehensive review of the audio samples obtained, including envelopes, spectrograms and frequency analyses, to reveal their extension into the ultrasonic domain. Our research both extends previous similar efforts, such as the paper by Heller (1988) and covers for the first time several species for which ultrasound recordings are not reported in scientific literature.

KEY WORDS Ultrasound; Bioacoustics; Ultramic.

Received 12.01.2020; accepted 12.01.2020; published online 29.05.2020

INTRODUCTION

Importance of bioacoustic studies is manifold and increasing, primarily in taxonomy and systematic (Tishechkin, 2014), conservation (Laiolo, 2010) and biodiversity research (Obrist et al., 2010; Sugai & Llusia, 2018).

The Orthoptera fauna of Italy is summarized in Massa et al. (2012), with information on acoustic emissions limited to audible frequencies. In the early 2010's, field recording techniques were revolutionized by the emergence of low-cost, highly portable USB microphones with a sampling rate of 250 kHz, and thus capable to provide monophonic recordings in the 1- 125 kHz range. Since then, in the spirit of Dave Gray's Liminal Thinking (Gray, 2016), the authors - in the steps of Heller (1988) and of all the investigators who ventured in the inaudible realm in the last thirty years - have been constantly trying to overcome anthropocentric cognitive and perceptive biases, by aiming at an objective representation of animal sounds thanks to the deployment of the flexible and relatively cheap field recording apparatus mentioned above, that allows a much wider frequency range extended in the inaudible ultrasonic range.

Based on field recordings obtained with the Ultramic 250 by Dodotronic, our previous papers (Brizio & Buzzetti, 2014; Brizio, 2018; Buzzetti et al., 2019), illustrated some technical limitations of Ultramic 250 (including the emergence of characteristic, extremely narrow intrinsic noise bands for USB cable lengths higher than 50 cm), and defined a protocol for the comparison of digital audio recordings taken at 250 kHz and digital recordings obtained at any lower sampling frequency, down to 44.1 kHz sampling. Those previous works confirmed the consistency of the results obtained with both techniques, and the possibility to identify different species on the basis of their song, as well as to derive novel information from an analysis of the high frequency components of the songs, some of which previously unreported in the scientific literature.

Our exploration of the inaudible range builds upon well-known foundations, such as the monograph by Heller (1988). If compared to that reference book, this paper includes previously uncovered species, particularly of infraorder Gryllidea. Even though it covers just a small fraction of the species covered by Heller (1988), this paper investigates a range up to 125 kHz, provides better quality illustrations of the frequency analyses, as well as time/frequency spectrograms, and in that respect it improves the results in Heller's monograph.

The instrumentation used for our work is far cheaper and easier to use than the bulky, complex and expensive equipment used by Heller (1988). The technological development of the last 30 years allow a new and easier approach to full bandwidth recording of Orthopterans, to better investigate in the intimate structure of their sounds and also to open new questions.

It should be noted that this paper should be viewed primarily as a commented field report. Our research is primarily focused on field recording and on the spectral characterization of the songs of Orthopteran species.

We didn't investigate issues such as propagation distance of the inaudible components as a whole, or of specific narrow inaudible bands, compared to the propagation distance of audible frequencies. From basic acoustic principles, it can be expected that – besides to the 1/r law of distance damping - the absorption of high frequencies, exhaustively covered e.g. by Vladišauskas & Jakevičius (2004), and by Bass et al. (1984) rises with frequency, temperature and humidity - indicatively, in standard atmosphere it may amount to 5 dB/m for frequencies in the order of magnitude of 100 kHz. We included a column in Table 2, "Recording Distance", from which this datum can be appreciated. Operatively, knowing that the highest frequencies are more sensible to atmospheric dumping, during our field recordings, we strived to get as close as possible to the singing specimens, but we didn't systematically take recordings at different distances for comparative purposes.

It's beyond the scope of this paper to ascertain which parts of the whole spectra effectively engage the hearing apparatus of conspecifics, are heard and consequently elicit a behavioral response. The selective laboratory tests needed, besides the anatomical investigations on a microscopic scale to describe the hearing apparatus, should include a series of experiments to expose living specimens to band-pass filtered versions of the song, a procedure that may allow to determine which frequencies are perceived and which not.

Such investigations may require unaffordable amounts of time, and may pose logistic difficulties for the collection and rearing of a statistically significant number of specimens (no less than 10 or 12 per species, as usual for qualitative analyses - see Shetty, 2019). For those reasons, with the primary aim to provide without any further delay the novel data that we collected, we will restrain the scope of our research to the description of the songs, that will be separately investigated in future species-specific articles.

MATERIAL AND METHODS

All the species listed in Table 1 were recorded in Italy. With the exception of audio samples of *Isophya modestior*, *Barbitistes vicetinus*, *Pholidoptera littoralis littoralis*, *Eupholidoptera* sp. (recorded in the town of Battaglia Terme) and *Uromenus annae*, all the recordings were obtained in nature. Specimens recorded by FMB are deposited in the collection of Fondazione Museo Civico di Rovereto, specimens recorded by CB were identified in the field but not captured.

Ultrasound monophonic recordings at 250 kHz sampling rate were obtained by using a Dodotronic Ultramic 250 microphone connected via USB cable to the recording apparatus, that included, for Author 2, an Asus Eee PC 1000HE notebook PC, a cell phone Samsung Galaxy S5 2014 and an Asus MemoPad ME172V tablet; for CB an Asus Eee PC 1225B notebook pc, using SeaWave software by CIBRA, developed by Author 3, with Windows 7 64-bit. SeaPro software by CIBRA (Pavan, 2017) was used for continuous long time recording on the notebook PC, this feature being very useful for those species with very faint sound emission and singing during nighttime.

Brizio & Buzzetti (2014) addressed in more detail some technical requirements of Ultramic 250 and proposed a specific operating protocol to ensure comparison between Ultramic recordings and audio range recordings available in literature.

Brizio (2015) described in more detail the challenges of ultrasound field recording and the requirements to obtain a recording as close as possible to the singing animal, to avoid the attenuation of faint high-order components. To ensure consistency with our previously published analyses, we applied the same methods here.

The first two Authors worked independently to collect the recordings to be used for the present work. When more recordings of a same subject or species were available, one of them was selected according to the following criteria:

- lowest disturbance from concurrent songs, wind and anthropogenic / technogenic noise;

- lowest distance between the microphone and the singing specimen, and thus better S/N ratio and highest number of feeble components recorded;

- appropriate gain setting of the microphone – in a general sense, among the three possible settings of Ultramic 250 (low, medium and high), medium gain provided the best results.

From the recordings of each species, several audio samples were selected and analyzed, choosing the clearest in the spectral structure of the song, that was analyzed and here illustrated and discussed. The position within the selected recordings, as well as the duration, of the selected audio samples were determined considering factors including:

- need to select a section unaffected, or minimally affected, by the disturbances cited above;

- nature of the song: trills, such as in *Ruspolia nitidula* and *Gryllotalpa gryllotalpa* may just require a selection of few syllables, while structured echemes with unequal syllables may require the selection of one or more full echemes (see below for terminology);

- interference by concurrent overlapping songs (either homo or heterospecific).

Field recordings face with real-world situations with the target songs often overlapped by environmental noise and/or by other songs. Concurrent songs occurred in several recording stations, and in some cases the resulting sound samples were unsuitable for a reliable analysis: in those cases, the species is not included in this paper (as in the case of *Euchorthippus declivus*, whose recording was inextricably overlapped by the songs of *Cicada orni* (Homoptera Cicadidae), or in the case of accidentally saturated recordings due to improper gain setting or unexpected level of the ultrasonic components). Whenever the concurrent songs did not overlap (for example, in the case of a background of far Gryllidae songs and a Tettigoniidae species in the foreground), as long as the lowest frequencies of the foreground songs where above the highest frequencies of the background songs, the frequency / level analysis window simply didn't include the band where interference by the heterospecific song was observed. In other cases of songs overlapping in the same frequency ranges, the echeme(s) used for the analysis were carefully selected by examining both the spectrogram and the envelope, to choose one or more echemes that didn't overlap. For example, this was the case of *T. tessellata*: in all the audio samples obtained, that included the concurrent song of up to four different species, only few echemes were deemed to fit for the analysis in several minutes of four different audio takes.

Even though we are perfectly aware of the poor frequency response of Ultramic 250 in the audible range, leading to waveforms that may slightly differ from those obtained by other types of microphone, we decided anyway to provide highly detailed waveforms and envelopes to facilitate comparisons with Ultramic recordings that other researchers may obtain.

Envelopes, spectrograms and frequency analysis plots were generated by Adobe Audition 1.0 software. Sound level is on an arbitrary scale, expressed in dB ref Full Scale Level. No real sound pressure level can be extrapolated. Spectrograms (normalized spectral energy) were generated with the following parameters: FFT and Window size 8192 samples, Windowing function Welch (Gaussian), logarithmic energy plot, sound level expressed in dB ref Full Scale Level.

Frequency analyses were made with the same parameters with Blackman-Harris windowing function.

The illustrations of frequency analyses were generated with a scan of the whole audio sample reported in Table 3. FFT-based analyses were performed on the sections shown in envelope or spectrogram views in two different ways:

- instantaneous (SPOT), on the time frame located at the current cursor position: although providing information at the smallest possible time scale, this may be useful e.g. to ascertain the emergence of different transient frequencies in different portion of the syllable; as a drawback, the instantaneous peaks of the analysis cannot necessarily match the features portrayed in the time-frequency spectrogram;

- by scanning (SCAN) a larger time frame, selected by dragging the cursor across the target piece of the envelope/spectrogram: in this way, all the sound elements in the selection are analyzed, thus providing a more general analysis, whose peaks more easily match the features in time-frequency spectrogram.

All the analyses provided, were obtained by scanning whole echemes or sequences of syllables.

The screenshots obtained from Adobe Audition were then post-produced with Adobe Photoshop Elements, by converting them in black and white and removing the background grid, and finally horizontal / vertical reference rulers were manually added with MS-Paint. Those intervention did not alter the data nor the analysis results.

It's well known (Welch et al., 2012; National Instruments Corporation, 2012) that the frequency resolution of FFT-based analyses is directly proportional to FFT size: higher FFT sizes lead to prickly frequency/level curves, lower sizes lead to smoother yet less precise depiction, but higher time resolution.

Considering the expected size of the pictures in this article and previous suggestions by reviewers of Brizio & Buzzetti 2014, we chose an FFT size of 8192 samples as an acceptable compromise between detail and smoothness of the picture.

To optimize the visualization and deliver optimal analyses, even though the whole 0-125 kHz frequency range was analyzed, the illustrations of analyses are limited to the frequency and level ranges where characteristic features, depending from the species, can be observed:

- the observation window of each spectral analysis was limited at the top by the highest level observed, and at the bottom by the highest level uniformly present at any frequency (that can be defined as "floor noise at any frequency");

- considering the frequency range, the recording bandwidth largely encompasses the range of frequencies emitted by the species; the upper limit in the figures was chosen to include, species by species, all the relevant components attributed to the singing animal.

The choice to optimize the frequency/level observation window for each species allowed us to exclude the noisy regions from the analyses, avoiding the noise peaks unless they overlapped the song.

Even though not particularly relevant, the noise of the AD converter may appear in the noise floor profile as a wide, ill-defined hump centered at around 50 kHz and extending between 40 and 60 kHz. This feature may become evident in the analyses of some recordings, such as those of Gryllidea where no wide-band components of the song overlap the same frequency interval.

Especially in urban areas or in the vicinity of high voltage transmission lines, Ultramic can record technogenic high frequency noise, such as continuous signals at 51 kHz or 61 kHz.

Where relevant, in the illustrations those spurious peaks are marked with a small circle.

In some analyses, the same mark above a narrow and well-defined peak indicates an artefact: narrow band noise, appearing in the spectrograms as thin, barely visible continuous lines at 1 kHz, 10 kHz or at some integer multiples of 1 kHz (such as 2, 3, 5 and 7 kHz), may be generated by Ultramic 250 as a side effect of the use of USB cables longer than 30 / 50 cm, as described in Brizio & Buzzetti, 2014. Species recorded with a longer USB cable are marked with an asterisk in Table 1.

Only in the case of *G. gryllotalpa*, a 18th order Butterworth band stop filter was successfully applied to the artefact peaks, encompassing the following frequencies: 990 Hz to 1010 Hz; 1990 Hz to 2010 Hz; 9990 Hz to 10010 Hz.

As a general rule no noise reduction was performed in post processing to avoid artefacts.

Table 2 summarizes the results of the analyses: a reference grid wasn't superposed on the figures provided in this paper because, considering their size, it would have hampered rather than facilitated their reading.

To give more evidence to the fainter significant spectral components, some of time/frequency spectrograms were contrast-enhanced with Adobe Photoshop Elements 4.0 without affecting the accuracy of rendering.

When describing songs, a useful distinction can be based on 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 approximatively equivalent as Q becomes larger and damping decreases. In terms of frequency-to-bandwidth ratio, Q is defined as

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

where fr is the resonant frequency, Δf is the resonance width or full width at half maximum (FWHM) 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:

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

High-Q sound (Elsner & Popov 1978; Montealegre & Morris 1999) results in one or more (e.g. Gryllidae) 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 band spectrogram traces, in which sometimes is possible to distinguish spectral subpeaks.

For what concerns audible sound description we use an array of terms from sources including Buzzetti & Barrientos (2011), Moore (1989) and Ragge & Reynolds (1998):

- Syllable (or phonatome): a short, clearly definable sound, produced by a complete opening and closing movements of the tegmina (or upward and downward movements of hind legs). In this case two subunits (hemisyllables) are clearly recognizable, usually characterized by pulses with opposite phases. In some cases the units are symmetrical, in other cases one of the sub units can be clearly different or barely visible, depending on the contact of the moving parts;

- Hemisyllable: distinct sound generated by each one-way movement of the stridulatory apparatus. A more loose definition may refer to any regularly recurring subdivision of a syllable;

- Zip: short syllable - the term may refer to short isolated pulses, as well as to the unitary elements in a quick series of pulses, that result in a short buzz;

- Trill: a long, regular series of uniform (equal or subequal), tightly packed syllables, dominated by a single frequency (Morris et al., 1988);

- Echeme: most basic and simple assemble of syllables.

To provide a general overview of the current knowledge of Italian Orthopterans in the inaudible range, Table 2 includes also the five Orthopteran species cited in our previous articles (Brizio & Buzzetti, 2014; Brizio, 2018).

Song descriptions and species distribution are excerpted from Cigliano et al., 2019 and Massa & al., 2012 - species are treated in the systematic order proposed by the latter monograph. Even though song description focuses on the subjective/perceptive aspect, rather than on technical and impersonal language, we consider that any doubt caused by the descriptive lexicon can be easily solved by reference to the figures, that provide no less than four, and often more, unambiguous illustrations for each species considered.

RESULTS AND DISCUSSION

Infraorder Gryllidea (general remarks). As expected from previous experiences and from bioacoustic literature, as a general rule Gryllidea emit high-Q song with a more or less pronounced harmonic structure. Our analyses confirmed that, while some species' song seems restricted to the lowest part of the inaudible range, the general rule applies also to the inaudible part of the song, with "harmonics" (integer multiples of the fundamental carrier frequency, in arithmetical progression) that in some cases, e.g. *G. gryllotalpa*, may be recognizable up to the 40th order or above.

Often, the dominant iterative harmonic structure coexists with secondary peaks or more or less pronounced wide bands, and may display selective amplification (e.g. the silenced 3rd harmonic of the marsh cricket *Pteronemobius concolor* usually fainter than the 4th) or obliteration of harmonics by secondary peaks or bands. In other words, the same phenomena determining the timbre and the color of audible sounds, selectively amplified or muffled by the vibrating structures of the tegmina (harp, chord, mirror and flexible region, see Montealegre et al., 2011), influence sound formation also in the inaudible region, where those complex interaction continue to occur, and where almost unexpectedly high order harmonics may reappear above apparently unstructured frequency bands.

In the case of the cricket *E. bordigalensis bordigalensis*, the analysis showed selective amplification and damping of some frequencies in the song of a specimen singing from under a manhole cover, with the cavity operating as a sound box. A second analysis of the species' typical song is provided, based on a specimen singing on open grassy ground. As expected, the differences observed confirm that closed cavities may significantly alter the spectral structure of the song, and in line of principle the analysis of such songs may lead to questionable results. It is also important to note that high frequencies are more directive than low frequencies and thus the recorded level of high components may also be influenced by the distance and orientation toward the microphone.

Other families (general remarks). For those families whose stridulatory apparatus lack structures, as those of Grylloidea, that preserve a good degree of spectral purity (Montealegre et al., 2011) or where those structures are much reduced, the inaudible portion of the song may consist in one or more repetition of ill-defined, more or less wide, frequency bands, with narrow or wide frequency peaks. Single peaks or whole bands may reappear at higher frequencies in a repetitive pattern, with a geometrical energy decrease proportional to the frequency.

In other cases the song may simply consist (especially in the case of "zips") in an uniform energy distribution: fading at frequency extremes, and covering the entire frequency range. In those cases, the song remains more or less unstructured throughout its full extension, and frequency analyses don't reveal any pattern except one or a few ill-defined bands.

Considering that in any Low-Q songs the narrow frequency peak corresponding to the highest volume may not coincide with the exact center of the loudest band, Table 2 includes two separate columns:

- For all the songs analyzed, "Peak Frequency", the exact frequency corresponding to the highest volume – its value is influenced by any parameter, such as FFT size, that affects frequency resolution;

- For the Low-Q songs only, "Low-Q main band center", the approximate frequency marking the graphical center of the loudest band - this more robust and more approximate value, less affected by FFT size, is provided to ease visual comparison with existing and future analyses obtained with different equipment and settings.

During our work, additional results - not described here - were obtained:

- novel discoveries emerged about *B. vicetinus* Galvagni et Fontana, 1993, *Anonconotus italoaustriacus* Nadig, 1987 and *Isophya modestior modestior* (Brunner von Wattenwyl, 1882), made possible by the analysis of their inaudible emissions: all those species show a previously unreported frequency shift among different syllables, between hemisyllables or among different parts of the echeme;

- it was confirmed that the different species of *Eupholidoptera* cannot be resolved on bioacoustic base only.

As stated above, this paper concentrates on a general description of the songs, and the novelties cited above will be the subject of separate future publications: further investigation may reveal whether sex-specific targeting of the different parts of each echeme, as reported e.g. for the amphibian *Eleutherodactylus coqui* Thomas, 1966 (Narins & al., 1976), is present also in Orthopterans.

Phaneroptera nana Fieber, 1853

Distribution. Europe, Middle East and North Africa.

Song description. It sings mainly in the evening and the night. The song consists of series of irregularly repeated short sounds of different character. High-pitched clicks (syllables) are mixed with short "zb"-sounds (syllables). The latter resemble the sounds of *P. falcata*. Syllables seem never to be grouped in echemes.

Analyses. Band spectrum, mostly sonic, peak at 19830 Hz (Table 2, Fig. 1).

Tylopsis lilifolia (Fabricius, 1793)

Distribution: from southern Europe and North Africa to Middle East.

Song description. The song consists of short groups of about 3 (1–5) short ticks (syllables). These groups are repeated with intervals about 10s up to more than a minute. The song is mainly produced during the day.

Analyses. Band spectrum, mostly ultrasonic, peak at 23160 Hz (Table 2, Fig. 2).

Isophyia modestior modestior (Brunner, 1882)

Distribution. Balkans and East Alps.

Song description. The song consists of sharp buzzing syllables of 150–200ms, repeated every 2–5s. A short and sharp tick at some distance follows many of these syllables. The song of specimens from Veneto seems different from the song of Serbian specimens, as described by Heller (1988). Further research in the ultrasonic range is necessary on Italian and Balkan populations.

Analyses. Band spectrum, mostly ultrasonic, peak at 24890 Hz (Table 2, Fig. 3).

Barbitistes vicetinus Galvagni et Fontana, 1993

Distribution. Italian endemic, the range being confined to the pre-alps of Veneto and Trentino.

Song description. The song is produced mainly in the evening and night. It consists of a sequence of quiet ticks (syllables), lasting for about 8–25s. Ticks are grouped in series of 10–25, with the exception of the last group, that usually only consists of 1–2 ticks. Sequences are separated by intervals of about 10s or more.

Analyses. Band spectrum, mostly ultrasonic, peak at 24530 Hz (Table 2, Fig. 4).

Leptophyes laticauda (Frivaldszky, 1868)

Distribution. Central-eastern Europe to the Balkans.

Song description. This species sings in the afternoon, evening and night. The song consists groups of 1–3 very faint ticks (syllables). Groups are repeated more or less regularly, at a minimum interval of about 1s. The faint song can hardly be heard with the unaided ear, but the species is easily traced with a bat detector, tuned at 20 kHz (ultrasonic).

Analyses. Band spectrum, mostly ultrasonic, peak at 31430 Hz (Table 2, Fig. 5).

Polysarcus denticauda (Charpentier, 1825)

Distribution: from Central Europe to the Balkans.

Song description. It sings during the day and has a song with a characteristic sequence of different sounds. The first part of the song consists of a ticking/buzzing sound that can last for minutes. It merges into a more fast and high-pitched buzzing sound. This buzzing is suddenly followed by 1–3 loud ticks. After that the singing returns to the first part of the song. The male walks around when singing.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 26510 Hz (Table 2, Fig. 6).

Anisoptera fusca (Fabricius, 1793)

DISTRIBUTION. Widespread in the whole of Italy.

SONG DESCRIPTION. It mainly sings in the daytime. The song consists of a faint ticking/ rustling sequence, often lasting for minutes. The sequence is rarely interrupted by or ending with a more loose ticking sound for 0.5s or less.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 29020 Hz (Table 2, Fig. 7).

Ruspolia nitidula (Scopoli, 1786)

DISTRIBUTION. from Europe and North Africa to Central Asia.

SONG DESCRIPTION. The song is a continuous, very loud metallic buzz that can be heard in the night. The wings move very fast, and syllables are repeated at the rate of about 70–100/s.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 16290 Hz (Table 2, Fig. 8).

Tettigonia cantans (Fuessly, 1775)

DISTRIBUTION. From Central Europe to Central Asia.

SONG DESCRIPTION. This species starts singing in the afternoon and continues until late at night. In the daytime the song consists of an echeme of 1–5s, with a crescendo in the early part of each echeme. At high temperatures the song may sound sibilant, while at low temperatures in the evening it sounds vibrating and may last for more than one minute.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 8331 Hz (Table 2, Fig. 9).

Tettigonia viridissima (Linnaeus, 1758)

DISTRIBUTION. Palaearctic region.

SONG DESCRIPTION. As the congeneric *T. cantans*, this species sings in the afternoon, evening and night. The song is a very loud continuous rattling sound. Every element of the song (echeme) consists of two syllables that give a special quality to the rhythm of the song.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 41530 Hz (Table 2, Fig. 10).

Decticus albifrons (Fabricius, 1775)

DISTRIBUTION. From southern Europe and North Africa to south-western Asia.

SONG DESCRIPTION. This species sings during the day and in the evening. The song consists of sharp loud single ticks (syllables), with a certain resemblance to chirps of a bird. Ticks are repeated more or less regularly with a repetition rate between 2–10/s, typically about 5/s.

ANALYSES. composite spectrum, mostly ultrasonic, peak at 8300 Hz (Table 2, Fig. 11).

Decticus verrucivorus verrucivorus (Linnaeus, 1758)

DISTRIBUTION. From Europe to Siberia across Caucasus.

SONG DESCRIPTION. It has a loud song that is produced during the day. It consists of a sequence of sharp "zrrt"-sounds (echemes), often lasting for minutes. Characteristic is the increasing echeme repetition rate during a sequence, starting with isolated echemes, gradually increasing to about 10 echemes/s. Every echeme consists of four louder elements (syllables).

ANALYSES. Band spectrum, mostly ultrasonic, peak at 4660 Hz (Table 2, Fig. 12).

Platycleis affinis affinis (Fieber, 1853)

DISTRIBUTION. From Europe and North Africa to Central Asia.

SONG DESCRIPTION. It sings mainly in the afternoon and evening. The song is a faint echeme of variable duration (0.5–5s) that ends with a series of 2–9 short ticks (microsyllables). The first part of the echeme consists of macrosyllables, repeated at the rate of about 10–20/s.

Analyses. Band spectrum, mostly ultrasonic, peak at 23800 Hz (Table 2, Fig. 13).

Tessellana tessellata tessellata (Charpentier, 1825)

Distribution. From around the Mediterranean and Canary Is. to Caucasus.

Song description. It sings in the afternoon, evening and night. The song consists of a series of faint ticks (syllables), repeated irregularly at the rate of about 2/s, but sometimes regularly at the rate of about 7/s for a long period.

Analyses. Band spectrum, mostly ultrasonic, peak at 31150 Hz (Table 2, Fig. 14).

Bicolorana bicolor bicolor (Philippi, 1830)

Distribution. Species with Euro-Asiatic distribution, from France to Siberia and Mongolia.

Song description.This species mainly sings in the daytime. The song consists of a long sequence with a ticking/buzzing sound. Every element of the song (echeme) consists of three syllables that give a special quality to the rhythm of the song. Echemes are repeated at the rate of 15–25/s.

Analyses. Band spectrum, mostly ultrasonic, peak at 21660 Hz (Table 2, Fig. 15).

Pholidoptera aptera aptera (Fabricius, 1793)

Distribution. From Central Europe to the Balkans.

Song description. The song can be heard in the afternoon, evening and night. It consists of sequences of 5–40 short and loud, almost melodious "prri"-sounds (echemes). Sequences are repeated at intervals of about 5–10s and last for about 1–5s, but may last for 20s at low temperatures.

Analyses. Composite spectrum, mostly ultrasonic, peak at 25840 Hz (Table 2, Fig. 16).

Pholidoptera littoralis littoralis (Fieber, 1853)

Distribution. From the Balkans to North-East Italy.

Song description. Its song can be heard in the afternoon and evening. It consists of a 1–4s long, loud and almost melodious "trrrri"-sound (echeme). The syllables are quiet in the first part of the echeme, but reach maximum intensity in the course of the echeme. Echemes are repeated at intervals of about 5–10s. There is some variability in the song of this taxon (Massa et al., 2012).

Analyses. Composite spectrum, mostly ultrasonic, peak at 25200 Hz (Table 2, Fig. 17).

Eupholidoptera chabrieri chabrieri (Charpentier, 1825)

Distribution. From western and central Alps to northern Apennines and eastern France.

Song description.The song cannot be diagnostic in *Eupholidoptera*. Çiplak et al. (2009) have synonymized many Italian taxa. We retain here the original status of the Italian species and subspecies, awaiting more (molecular) research (see Allegrucci et al., 2013). This species sings both during the day and at night. The song consists of short "tsip"-sounds (syllable), that are at maximum repeated fairly regularly at the rate of about 0.5–2/s. The frequency spectrum shows a maximum at about 7–9 kHz. The song can hardly be distinguished from the song of other species of *Eupholidoptera*.

Analyses. Band spectrum, mostly ultrasonic, peak at 38900 Hz (Table 2, Fig. 18).

Eupholidoptera schmidti (Fieber, 1861)

Distribution. From northern Balkans, to North-East and Central Italy.

Song description. This species sings both during the day and at night. The song consists of short "tsip"-sounds (syllable), that are at maximum repeated fairly regularly at the rate of about 0.5–2/s. The frequency spectrum shows a maximum at about 7–9 kHz. The song can hardly be distinguished from the song of other species of *Eupholidoptera*.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 38290 Hz (Table 2, Fig. 19).

Eupholidoptera sp. (specimens recorded in the towns of Battaglia Terme and Chiampo)

ANALYSES. See Table 2 and figures 20, 21.

Anonconotus italoaustriacus (Nadig, 1987)

DISTRIBUTION. The genus *Anonconotus* is endemic of the Alps and the Apennines, this being the most eastern species in the Alps, occurring in Italy and Austria. It occupies a rather large range, but is quite scarce.

SONG DESCRIPTION. It sings in the afternoon, with a very faint rustling sound (echeme) of about 1–2.5s with about 24–55 syllables. Echemes are repeated irregularly at intervals of 5–30s. The song can be heard with bat detector, tuned at 30 kHz.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 36430 Hz (Table 2, Fig. 22).

Rhacocleis germanica (Herrich-Schäffer, 1840)

DISTRIBUTION. From southern Europe to the Balkans.

SONG DESCRIPTION. It mainly sings at night. The song consists of rustling/buzzing sounds (echemes) of 0.2–0.7s, repeated fairly regular at intervals of about 1–3s. The song can hardly be heard without bat detector, tuned at about 30kHz.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 28250 Hz (Table 2, Fig. 23).

Rhacocleis neglecta neglecta (Costa A., 1863)

DISTRIBUTION. From Italy to the North Balkans. Cited for Algeria in Cigliano et al., 2019.

SONG DESCRIPTION. The calling song is produced at night. It consists of an echeme of about 150-220ms ("zr"), repeated at the rate of 1–3/s in series 4s or longer. It consists of about 3–5 syllables, repeated at the rate of about 25/s.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 46690 Hz (Table 2, Fig. 24).

Antaxius difformis (Brunner, 1861)

DISTRIBUTION. Central European species, from Switzerland to Slovenia along the Alps.

SONG DESCRIPTION. It sings in the daytime, but also in the evening. The song consists of quiet rustling sounds (echeme sequences) of about 0.4s, repeated at intervals of about 1–3s. The echeme sequence has a variable and complex structure, but partly consists of paired syllables.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 27700 Hz (Table 2, Fig. 25).

Uromenus annae (Targioni-Tozzetti, 1881)

DISTRIBUTION. Endemic of Sardinia.

SONG DESCRIPTION. The male calling song (Fig. 30) consists of a series of syllables, with a repetition rate of 3.3 to 3.5 syllables/ sec. Each syllable lasts 0.278 sec (0.25–0.3, n=10). Main frequency between 11 and 32.5 kHz, with peak at 22.17 kHz (19.89–23.89, n=10).

ANALYSES. Band spectrum, mostly ultrasonic, peak at 24070 Hz (Table 2, Fig. 26).

REMARKS. This species was thought to be extinct while in the last decades few specimens from scattered populations have been collected. The Fondazione Museo Civico di Rovereto and the CNR of Sassari are running a joint research project on evaluation of the status of the populations and any conservation actions. This species has been the subject of a recent paper (Buzzetti et al., 2019)

Nemobius sylvestris sylvestris (Bosc, 1792)

DISTRIBUTION. West and South-central Europe.

Song description. It sings both in the daytime and during the night. The song consists of a series of quiet melodious, churring "prree"-sounds (echemes), repeated irregularly. Echemes can be very short, but can last up to 3s. In the presence of a female the male produces a courtship song with an alternation of periods with very short echemes and periods with very long echemes, lasting up to 5s.

Analyses. Composite spectrum, mostly sonic, peak at 3997 Hz (Table 2, Fig. 27). Specimen recorded with long USB cable (150 cm), artefact peaks are clearly marked in the frequency analysis.

Pteronemobius heydenii heydenii (Fischer, 1853)

Distribution. Europe and the Balkans.

Song description. It sings both in the daytime and during the night. The song consists of a series of quiet melodious, high-pitched churring "prree"-sounds (echemes) with a marked crescendo, lasting 1–4s and repeated at intervals of about 1–2s. Courtship song is unknown.

Analyses. High-Q spectrum, mostly sonic, peak at 7293 Hz, see also Tab. 2 and Fig. 28. Specimen recorded with long USB cable (150 cm), artefact peaks are clearly marked in the frequency analysis.

Gryllus bimaculatus (De Geer, 1773)

Distribution. Africa, Asia and Mediterranean Europe.

Song description. It sings especially during the night. The song consists of a series of loud melodious "kre"-sounds (echemes), repeated very regularly at the rate of about 1–4/s. All echemes in a series are equal, consisting of about 4–5 syllables. Males produce a courtship song in the vicinity of a female. It consists of a continuous rustling mixed with loud, high-pitched ticks.

Analyses. High-Q spectrum, mostly sonic, peak at 4913 Hz (Table 2, Fig. 29).

Gryllus campestris (Linnaeus, 1758)

Distribution. Europe, Western Asia and North Africa. Quite frequent in Italy, especially in the northern-central regions.

Song description. the song can be heard from May until August. It sings at daytime and during the night. The song consists of a series of loud melodious "kre"-sounds (echemes), repeated very regularly at the rate of about 1–4/s. All echemes in a series are equal, consisting of about 4 syllables, the first of which is usually emitted at a slightly lower volume. Males produce a courtship song in the vicinity of a female. It consists of a continuous rustling mixed with loud, high-pitched ticks.

Analyses. High-Q spectrum, mostly sonic, peak at 3723 Hz (Table 2, Fig. 30).

Remarks. two different analyses are provided, both from specimens recorded in the open at the same location and at the same temperature (16.3°C), to show that - despite a remarkable similarity in fundamental and main frequency peaks, different individuals may display, even to the unaided ear, significant timbre modification, with softer or sharper songs emitted in the same environmental conditions.

Brachytrupes megacephalus (Lefèvre, 1827)

Distribution. North Africa, Sicily, Sardinia.

Song description. It sings during the evening and night, usually just in front of its burrow, ready to flee inside at the slightest disturbance. The calling song is a continuous series of syllables repeated very fast (about 130/s). The peak frequency of the song is around 6kHz.

Analyses. High-Q spectrum, mostly sonic, peak at 5920 Hz (Table 2, Fig. 31).

Remarks. This is the biggest European cricket and as reported by Brizio (2018) it has a high-order harmonic structure. Given the rarity of this species, the song detection could be useful in adding new distribution data. This could be important, being a species included in the Habitat Directive.

Eumodicogryllus bordigalensis bordigalensis (Latreille, 1804)

DISTRIBUTION. Mediterranean Region.

SONG DESCRIPTION. It sings in the evening and during the night. The song consists of a series of loud melodious, rolling krrree-sounds (echemes), repeated regularly at the rate of about 2–4/s. The echemes consist of about 14–20 syllables. A courtship song is unknown.

ANALYSES. High-Q spectrum, mostly sonic peak at 5737 Hz (Table 2, Fig. 32).

Oecanthus pellucens pellucens (Scopoli, 1763)

DISTRIBUTION. From Europe and North Africa to Central Asia, across Arabian Peninsula and Caucasus.

SONG DESCRIPTION. It sings in the evening and at night. This is the cricket song of warm summer evenings. The song consists of a series of loud melodious “tree”-sounds (echemes), lasting 0.5–1s and repeated very regularly at the rate of about 0.5–2/s. All echemes in a series are equal, consisting of about 15–30 syllables.

ANALYSES. High-Q spectrum, mostly sonic, peak at 3479 Hz (see also Table 2, Fig. 33).

REMARKS. For the song comparison with the congeneric *O. dulcisonans*, see Brizio & Buzzetti (2014), the ecology of the two spp. in southern Italy is discussed in Labadessa & Todisco (2016). Data in Table 2 are based on new recordings in the same station of the 2014 paper, taken in July 2019 under more favorable conditions, and displaying a more complex harmonic structure than previously reported.

Gryllotalpa gryllotalpa (Linnaeus, 1758)

DISTRIBUTION. From Europe and North Africa to Middle Asia.

SONG DESCRIPTION. The song consists of a continuous loud melodious rattle (echeme). Syllables are repeated regularly at the rate of about 30–50/s.

ANALYSES. High-Q spectrum, mostly sonic, peak at 1434 Hz (Table 2, Fig. 34).

Euthystira brachyptera (Ocskay, 1826)

DISTRIBUTION. From Europe to Asia.

SONG DESCRIPTION. It sings in the daytime. The song consists of high pitched short quiet sounds (echemes), consisting of about 4–7 syllables. Echemes are repeated more or less regularly at minimum intervals of about 2–4s.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 29050 Hz (Table 2, Fig. 35).

Chorthippus (Chorthippus) dorsatus dorsatus (Zetterstedt, 1821)

DISTRIBUTION. Widely distributed from Europe to Siberia.

SONG DESCRIPTION. *C. dorsatus dorsatus* sings by day. The song consists of a series of short scratching/rustling sounds (echemes) lasting about 0.8–1.5s and repeated regularly at intervals of about 1–3s. The echeme consists of about 3–7 clear scratching syllables, followed by a short rustling sound. In situations of social interaction of two males (rivalry) the rustling part of the song remains, while the scratching syllables are left out.

ANALYSES. Band spectrum, mostly ultrasonic, peak at 22790 Hz (Table 2, Fig. 36).

Chorthippus (Chorthippus) parallelus parallelus (Zetterstedt, 1821)

DISTRIBUTION. From Europe to Siberia.

SONG DESCRIPTION. It sings by day, but might easily be heard during warm evenings. The song consists of a series of short scratching sounds (echemes) lasting about 1–2s and repeated regularly at intervals of about 3–5s. The echeme consists of about 10–20 clear scratching syllables, repeated at the rate of about 4–6/s. In situations of social interaction of two males (rivalry) the echemes are shortened and sound different, more rustling, like *C. d. dorsatus* or *C. dichrous*.

ANALYSES. Composite spectrum, mostly ultrasonic, peak at 29930 Hz (Table 2, Fig. 37).

N.	Sub-family	Species	Rec. Date/Time yyyymmdd-hhmmss	Recording locality	Lat-Long	Specimen observed
1	PHA	*Phaneroptera nana* Fieber, 1853	20140822-212018	Poggio Renatico	44.762,11.475	Yes
2	PHA	*Tylopsis lilifolia* (Fabricius,1793)	20150726-210335	Bologna, Parco Villa Ghigi	44.475,11.325	Yes
3	PHA	*Isophya m. modestior* (Brunner, 1882)	20180818-203000	Passo Croce d'Aune	46.052,11.841	Yes
4	PHA	*Barbitistes vicetinus* Galvagni & Fontana,1993	20130629-212429	Via S.G. in M.te,Colli Berici	45.442,11.563	Yes
5	PHA	*Leptophyes laticauda* (Frivaldszky,1868)	20120808-210041	Madonna dell'Acero	44.148,10.821	Yes
6	PHA	*Polysarcus denticauda* (Charpentier, 1825)	20130907-(unav.)	PNDB Vette Feltrine	46.093,11.844	Yes
7	CON	*Anisoptera fusca* (Fabricius, 1793)	20180725-191748	Marina Romea	44.524,12.269	No
8	CON	*Ruspolia nitidula* (Scopoli,1786)	20120729-001551	Poggio Renatico	44.762,11.475	Yes
9	TET	*Tettigonia cantans* (Fuessly,1775)	20120807-182648	Madonna dell'Acero	44.148,10.821	Yes
10	TET	*Tettigonia viridissima* (Linnaeus,1758)	20130629-212525 20120807-230257 20130829-223308	Colli Berici, Tr. Vecia Priara Madonna dell'Acero Sardegna, Fluminimaggiore	39.447,08.461 44.148,10.821 45.454,11.556	Yes
11	TET	*Decticus albifrons* (Fabricius,1775)	20120718-105942	Ferrara	44.809,11.597	Yes
12	TET	*Decticus v. verrucivorus* (Linnaeus,1758)	20120813-124321	Madonna dell'Acero	44.148,10.821	Yes
13	TET	*Platycleis a. affinis* Fieber, 1853	20180725-212909	Marina Romea	44.499,12.283	No
14	TET	*Tessellana t. tessellata* (Charpentier,1825)	20150726-210335	Bologna, Parco Villa Ghigi	44.475,11.325	Yes
15	TET	*Bicolorana b. bicolor* (Philippi, 1830)	20120813-130104 20180813-(unav.)	Madonna dell'Acero PNDB Monte Grave	44.148,10.821 46.089,11.928	Yes
16	TET	*Pholidoptera a. aptera* (Fabricius,1793)	20130713-214504 20130629-212429	Madonna dell'Acero Colli Berici	44.148,10.821 45.442,11.563	No
17	TET	*Pholidoptera l. littoralis* (Fieber, 1853)	20180618-(unav.)	Colli Berici, Pianezze	45.486,11.559	Yes
18	TET	*Eupholidoptera c. chabrieri* (Charpentier, 1825)	20151024 141824	Passo della Raticosa	44.195,11.358	Yes
19	TET	*Eupholidoptera schmidti* (Fieber,1861)	20120717-225522	Poggio Renatico	44.762,11.475	Yes
20	TET	*Eupholidoptera* sp. Battaglia	20180618-2015	Colli Euganei, Battaglia	45.292,11.773	Yes
21	TET	*Eupholidoptera* sp. Chiampo	20180713-1942	Chiampo	45.534,11.306	Yes
22	TET	*Anonconotus italoaustriacus* Nadig,1987	20130816-082000	PNDB Vette Feltrine	46.093,11.844	Yes
23	TET	*Rhacocleis germanica* (Herrich-Schäffer,1840)	20150726-204011	Marina Romea	44.475,11.325	Yes
24	TET	*Rhacocleis n. neglecta* (Costa & A.,1863)	20151024-141824	Passo della Raticosa	44.195,11.358	No
25	TET	*Anthaxius difformis* (Brunner, 1861)	20130910-(unav.)	PNDB Vette Feltrine	46.075,11.842	Yes
26	BRA	*Uromenus annae* (Targioni-Tozzetti,1881)	20180801-235237	Crastazza, Mamone	40.586,09.410	Yes
27	NEM	*Nemobius s. sylvestris* (Bosc, 1792) *	20180722-141134	M.te Pigna,S. Lucia,Vergato	44.308,11.037	No
28	NEM	*Pteronemobius h. heydenii* (Fischer,1853)*	20150726-210335	San Pietro in Casale	44.675,11.422	No
29	GRY	*Gryllus bimaculatus* De Geer, 1773	20150825-121424	Cala Domestica	39.373,08.379	No
30	GRY	*Gryllus campestris* Linnaeus, 1758	20190427-225055	Gherghenzano	44.676,11.382	No
31	GRY	*Brachytrupes megacephalus* (Lefèvre, 1827)	20180422-205622	Capo Pecora, Sardinia	39.450,08.396	Yes
32	GRY	*Eumodicogryllus b. bordigalensis* (Latreille,1804)	20180728-220303	Poggio Renatico	44.762,11.475	No
33	OEC	*Oecanthus p. pellucens* (Scopoli, 1763)	20180802-010021	S.Benedetto, S. Pietro in C.	44.697,11.376	Yes
34	GTL	*Gryllotalpa gryllotalpa* (Linnaeus,1758)*	20180529-235220	San Pietro in Casale	44.681,11.439	No
35	GOM	*Euthystira brachyptera* (Ocskay, 1826)	20180813-143000	PNDB Monte Grave	46.085,11.934	Yes
36	GOM	*Chorthippus (C.) d. dorsatus* (Zetterstedt,1821)	20140817-(unav.)	Castelcerino (VR)	45.462,11.241	Yes
37	GOM	*Chorthippus (C.) p. parallelus* (Zetterstedt,1821)	20120812-174718	Madonna dell'Acero	44.148,10.821	Yes

Table 1. Comprehensive list of the species exained and recording localities (all in Italy). Exact hour/minute of recording could not be ascertained in the sases marked with (unav.). Subfamily legend: PHA: Tettigoniidae Phaneropterinae. CON: Tettigoniidae Conocephaline. TET: Tettigoniidae Tettigoniinae. BRA: Tettigoniidae Bradyporinae. NEM: Gryllidae Nemobiinae. GRY: Gryllidae Gryllinae. OEC: Gryllidae Oecanthionae. GTL: Gryllotalpidae Gryllotalpinae. GOM: Acrididae Gomphocerinae. *USB cable length = 150 cm (30 or 50 cm in all the other case).

Family Subfamily	Species	Spectrum type	Most relevant emission	Recording distance cm (*)	Peak frequency Hz	Low-Q main band center kHz	Highest kHz emitted	Highest harmonic (High-Q)
Tettigoniidae Phaneropterinae	*P. nana*	Band	sonic	200	19830	20	45	n/a
	T. lilifolia	Band	ultrasonic	400	23160	25	80	n/a
	I. m. modestior	Band	ultrasonic	30	24890	24	75	n/a
	B. vicetinus	Band	ultrasonic	50	24530	24	60	n/a
	L. laticauda	Band	ultrasonic	100	31430	31	55	n/a
	P. denticauda	Band	ultrasonic	50	26510	24	70	n/a
Tettigoniidae Conocephalinae	*A. fusca*	Band	ultrasonic	100	29020	29	100	n/a
	R. nitidula	Band	ultrasonic	400	16290	15	75	n/a
Tettigoniidae Tettigoninae	*T. cantans*	Band	ultrasonic	50	8331	9	70	n/a
	T. viridissima	Band	ultrasonic	100	41530	40	90	n/a
	D. albifrons	composite	ultrasonic	300	8300	38	85	7 - 8
	D. v. verrucivorus	Band	ultrasonic	200	4.660	44	85	n/a
	P. a. affinis	Band	ultrasonic	200	23800	27	110	n/a
	T. t. tessellata	Band	ultrasonic	250	31150	33	85	n/a
	B. b .bicolor	Band	ultrasonic	100	21660	22	85	n/a
	P. a. aptera	composite	ultrasonic	100	25840	28	75?	n/a
	P. l. littoralis	composite	ultrasonic	50	25200	35	80	12
	E. c. chabrieri	Band	ultrasonic	300	38900	35	90	n/a
	E. schmidti	Band	ultrasonic	50	38290	44	75	n/a
	Eupholidoptera sp. (Euganei Battaglia)	Band	ultrasonic	50	21540	35	85	n/a
	Eupholidoptera sp. (Chiampo)	Band	ultrasonic	50	39090	40	85	n/a
	A. italoaustriacus	Band	ultrasonic	30	36430	45	80	n/a
	R. baccettii **(a)**	Band	ultrasonic	200	51000	28	105	n/a
	R. germanica	Band	ultrasonic	150	28250	27	85	n/a
	R. n. neglecta	Band	ultrasonic	250	46690	46	90	n/a
	A. difformis	Band	ultrasonic	50	27700	28	65	n/a
Tettigoniidae Bradyporinae	*U. annae*	Band	ultrasonic	50	24070	22	65	n/a
	U. brevicollis insularis **(a)**	Band	sonic	200	13450	12	41	n/a
Gryllidae Nemobiinae	*N. s. sylvestris*	composite	sonic	50	3.997	n/a	60	3
	P. h. heydenii	High-Q	sonic	100	7.293	n/a	50	6
Gryllidae Gryllinae	*G. bimaculatus*	High-Q	sonic	100	4.913	n/a	60	11
	G. campestris	High-Q	sonic	80	3.723	n/a	70	19
	B. megacephalus **(b)**	High-Q	sonic	50	5.920	n/a	121.7	21
	S. p. palmetorum **(a)**	High-Q	sonic	20	6.317	n/a	32	5
	E. b. bordigalensis	High-Q	sonic	30 / 100	5.737	n/a	45	6 - 8
Gryllidae Oecanthinae	*O. dulcisonans* **(a)**	High-Q	sonic	50	2.960	n/a	44.7	15
	O. p. pellucens	High-Q	sonic	10	3.479	n/a	65	18
Gryllotalpidae	*G. gryllotalpa*	High-Q	sonic	20	1.434	n/a	55	38
Acrididae Gomphocerinae	*E. brachyptera*	Band	ultrasonic	50	29050	29	60	n/a
	C. (C.) d. dorsatus	Band	ultrasonic	50	22790	25	65	n/a
	C. (C.) p. parallelus	composite	ultrasonic	50	29930	28	65	n/a

Table 2. Synopsis of the ultrasound components of the species examined. Shaded lines mark species treated in separate papers: a) *O. dulcisonans*, *R. baccettii*, *S. p. palmetorum*, and *U. b. insularis* from Brizio & Buzzetti, 2014, integrated by recordings in July 2019 (*O. dulcisonans*) and August 2019 (*R. baccettii*), b) *Brachytrupes megacephalus*, data from Brizio, 2018. (*) Approximate distance between the microphone and the singing insect during recording.

Sub-family	**Species**	**Audio File Name**	**Analyzed section (Min:sec.msec)**			**Highest kHz emitted**
			From	**To**	**Length**	
PHA	*Phaneroptera nana*	Phaneroptera nana Poggio_20140822 212018.wav	1:04.527	1:22.035	17.508	45
PHA	*Tylopsis lilifolia*	Tylopsis Lilifolia estratto zip non saturi VillaGhigi_20150726 210335.wav	0	0.201	0.201	80
PHA	*Isophya m. modestior*	Isophya modestior e Poecilimon ornatus SeaPro PNDB Passo Croce d'Aune july18_MONO.wav	2:35.732	2:50.800	15.068	75
PHA	*Barbitistes vicetinus*	Barbitistes vicetinus Euganei Madonna Pholidoptera littoralis Berici Pianezze june18.wav	12.496	14.195	1.698	60
PHA	*Leptophyes laticauda*	Leptophyes_laticauda_Madonna_Acero_Pattern_1_5_MedGain_20120808_204915_1CH250K16.wav	1:35.729	1:44.308	8.579	55
PHA	*Polysarcus denticauda*	Polysarcus denticauda Vette Feltrine 7sept2013.wav	48.404	51.464	3.06	70
CON	*Anisoptera fusca*	*Anisoptera_fuscus*_sinonimo_*Xiphidion_discolor*_FORSE_Marina_Romea_20180725 191748.wav	2:04.662	2:19.077	14.414	100
CON	*Ruspolia nitidula*	Ruspolia_nitidula_Circonvallazione_Poggiorenatico_20120729_001732_1CH250K16.wav	4.091	6.335	2.244	75
TET	*Tettigonia cantans*	Tettigonia_cantans_Madonna_Acero_MedGain_20120807_182648_1CH250K16.wav	1:32.769	1:37.030	4.261	70
TET	*Tettigonia viridissima*	Tettigonia_viridissima_Madonna_Acero_MedGain_20120807_230257_1CH250K16.wav	15.533	21.818	6.284	90
TET	*Decticus albifrons*	Decticus_albifrons_RedTurtle_ok_SeaPro_20120718_105942_1CH250K16.wav	21.556	22.457	0.901	85
TET	*Decticus v. verrucivorus*	Decticus_verrucivorus_Madonna_Acero_20120813_124321_1CH250K16.wav	1:34.011	1:37.791	3.779	85
TET	*Platycleis a. affinis*	Platycleis_affinis_affinis_MIGLIORE_Marina_Romea_20180725 212909.wav	1.475	5.558	4.082	115
TET	*Tessellana t. tessellata*	ESTRATTO R_germanica_T_tessellata_T_lilifolia VillaGhigi_20150726 211922.wav	18.632	18.724	0.096	85
TET	*Bicolorana b. bicolor*	Bicolorana_bicolor_Madonna_Acero_LoGain_20120813_130104_1CH250K16.wav	1:21.937	1:28.075	6.138	85
TET	*Pholidoptera a. aptera*	Pholidoptera aptera aptera_Madonna_Acero_canone SeaWave_20130713 214504.wav	1:30.979	1:43.153	12.173	65
TET	*Pholidoptera l. littoralis*	Same track as *B. vicetinus*	32.036	34.668	2.632	80
TET	*Eupholidoptera c. chabrieri*	Eupholidoptera chabrieri Raticosa _20151024 144136.wav	22.85	26.022	3.172	90
TET	*Eupholidoptera schmidti*	Eupholidoptera_schmidti_Via_Chiesavecchia_45_Poggio_ok_SeaPro_20120717_225522_1CH250K16.wav	6.13	9.56	3.43	75
TET	*Eupholidoptera* Euganei Battaglia	Eupholidoptera Euganei Battaglia june18	38.927	56.788	17.86	85
TET	*Eupholidoptera* Chiampo	Eupholidoptera Chiampo july13.wav	18.433	21.521	3.087	85
TET	*Anonconotus italoaustriacus*	Anonconotus italoaustriacus Vette Feltrine 16aug2013.wav	1:25.618	1:25.747	0.129	80
TET	*Rhacocleis germanica*	Rhacocleis_germanica_Forse_Marina_Romea_20180725 211926.wav	8.997	9.303	0.306	85
TET	*Rhacocleis n. neglecta*	Rhacocleis neglecta neglecta Raticosa _20151024 142110.wav	6.543	7.16	0.616	90
TET	*Antaxius difformis*	Antaxiusdifformis__20130910_PNDBVetteFeltrineFMB.wav	25.467	26.612	1.145	65
BRA	*Uromenus annae*	Steropleurus annae Crastazza high gain SeaPro_20180801_235237_1CH250K16 (2).wav	22.764	24.725	1.96	65
NEM	*Nemobius s. sylvestris*	Nemobius sylvestris _20180722 141134.wav	17.492	26.025	8.532	65
NEM	*Pteronemobius h. heydenii*	Pteronemobius_concolor_San_Pietro_in_Casale_20180530 001328.wav	6.511	14.951	8.439	50
GRY	*Gryllus bimaculatus*	Gryllus bimaculatus Cala Domestica - SeaWave _20150825 123153.wav	1.66	2.1	0.439	60
GRY	*Gryllus campestris*	Gryllus_campestris_Gherghenzano_SeaWave _20190427 225055	36.493	41.417	4.942	71
GRY	*Gryllus campestris*	Gryllus_campestris_Gherghenzano_SeaWave _20190427 230303	22.181	26.900	4.719	60
GRY	*Brachytrupes megacephalus*	B_megacephalus_C_Pecora_20180422-205622.wav	16.869	19.873	3.003	100
GRY	*Eumodicogryllus b. bordigalensis*	Eumodicogryllus_burdigalensis_PoggioRenatico_20180724 013359.wav	13.057	17.628	4.571	45
OEC	*Oecanthus p. pellucens*	Oecanthus_pellucens_San_Benedetto_20180802 010021.wav	12.86	13.438	0.578	
GTL	*Gryllotalpa gryllotalpa*	Gryllotalpa_gryllotalpa_San_Pietro_in_Casale_20180529 235619.wav	43.073	46.575	3.501	55
GOM	*Euthystira brachyptera*	Euthystira brachyptera Monte Grave PNDB.wav	1:24.675	1:36.358	11.683	60
GOM	*Chorthippus (C.) d. dorsatus*	Chorthippus dorsatus Castelcerino 17aug14FMB.wav	54.337	54.838	0.501	65
GOM	*Chorthippus (C.) p. parallelus*	Chorthippus_parallelus_Madonna_Acero_LoGain_20120812_174718_1CH250K16.wav	1:28.591	1:43.417	14.825	65

Table 3. Details about the audio samples used for the frequency analyses. Subfamily legend: see Table 1.

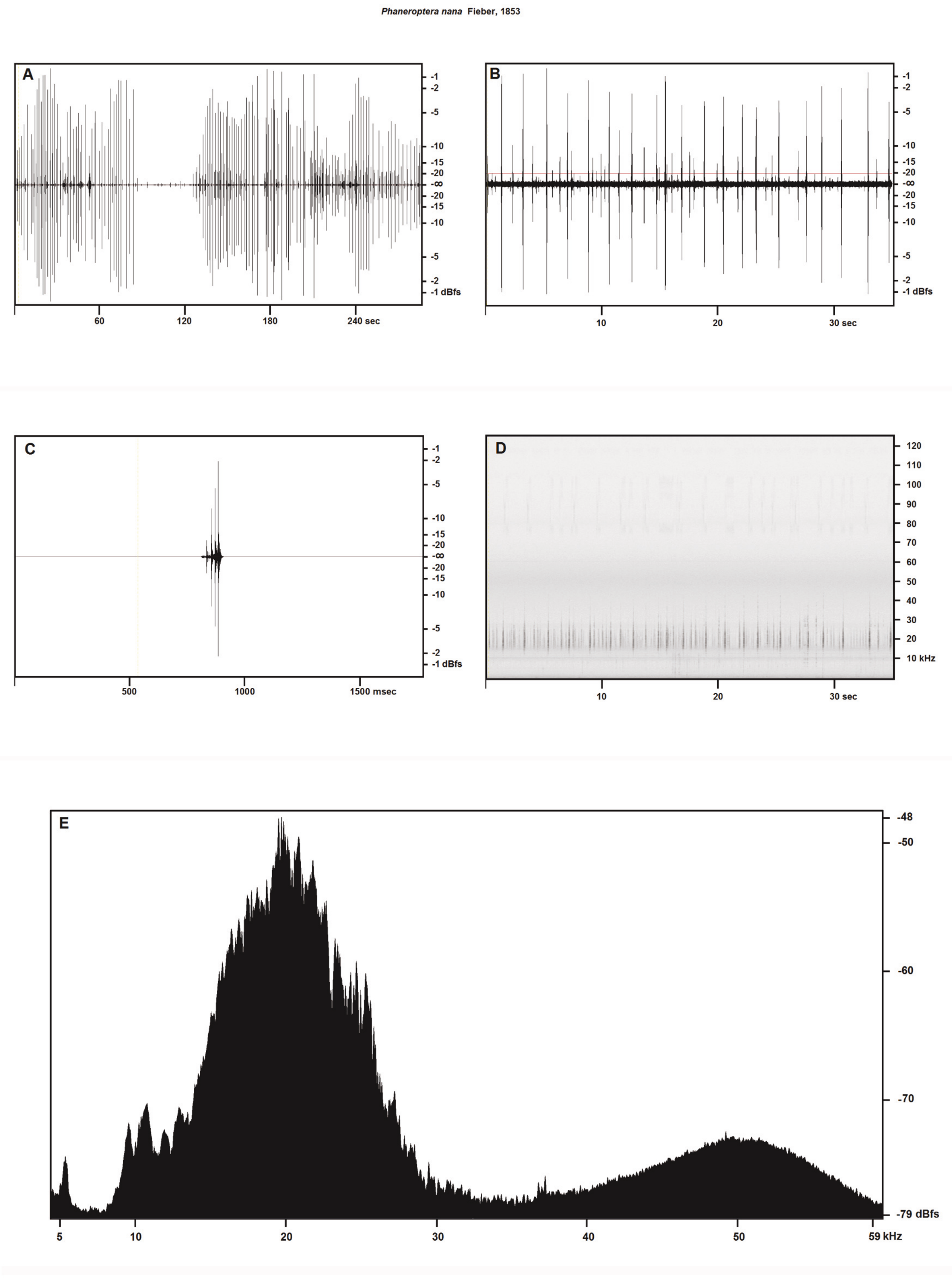


Figure 1. *Phaneroptera nana* Fieber, 1853 – A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 17.508 sec (see Table 3). The components between 40 and 60 kHz are due to the noise of the AD converter, that is visible in other figures.

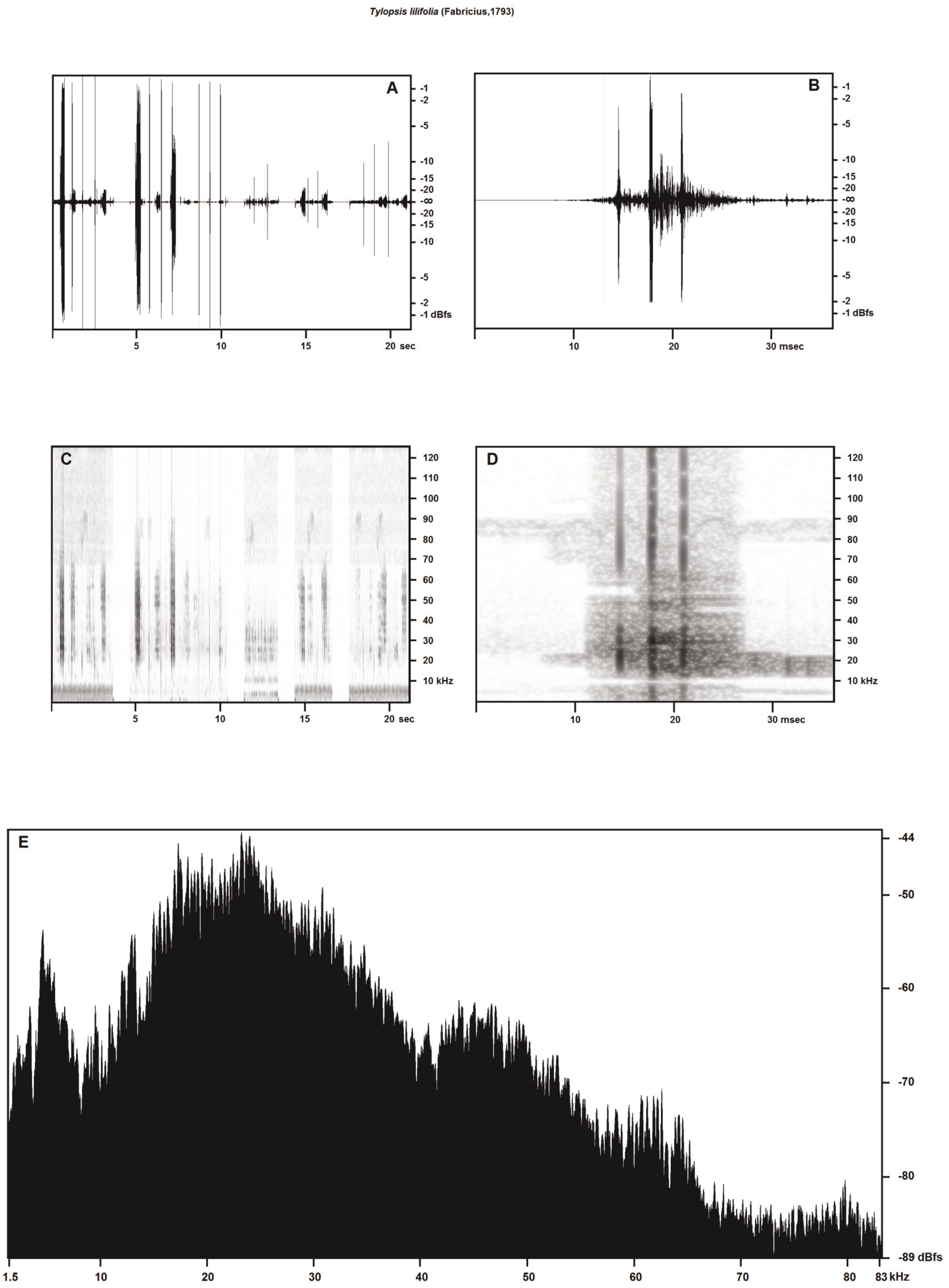


Figure 2. *Tylopsis lilifolia* (Fabricius,1793) - A, B: envelope at two increasing levels of detail, A, C, D: spectrogram at two increasing levels of detail, E: frequency analysis - 0.201 sec (see Table 3).

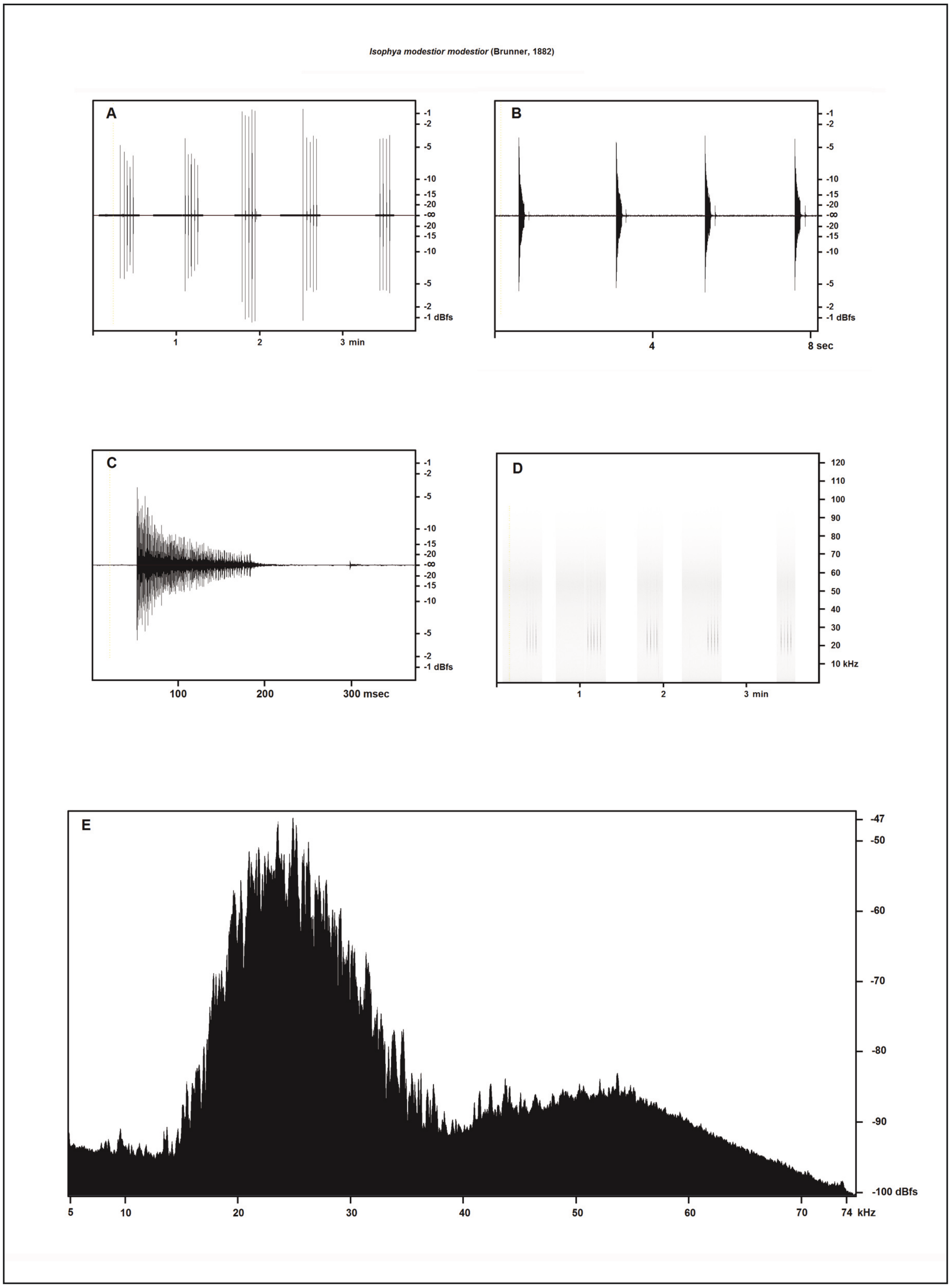


Figure 3. *Isophya modestior modestior* (Brunner, 1882) - A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 15.068 sec (see Table 3).

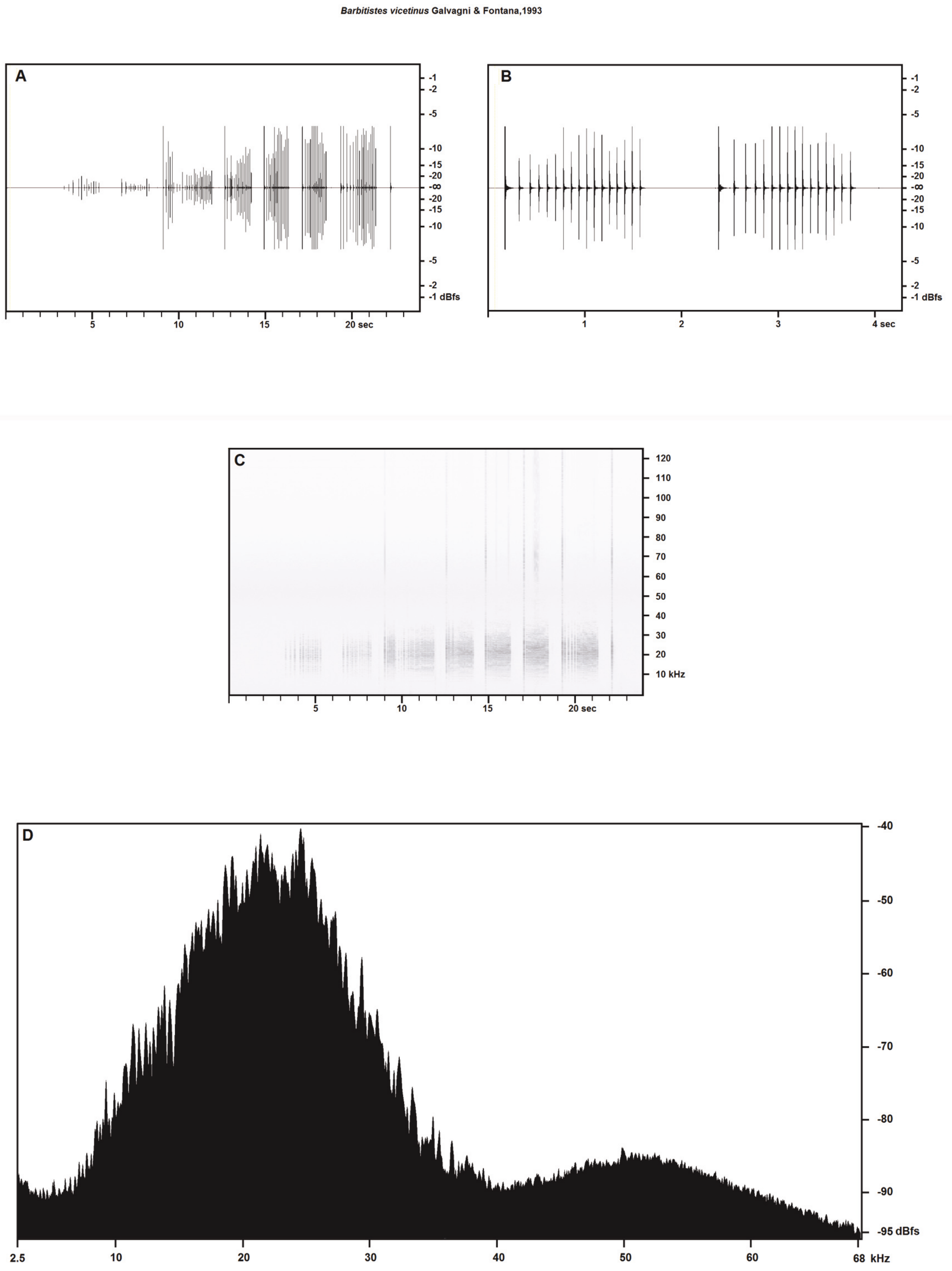


Figure 4. *Barbitistes vicetinus* Galvagni & Fontana,1993 - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 1.698 sec (see Table 3).

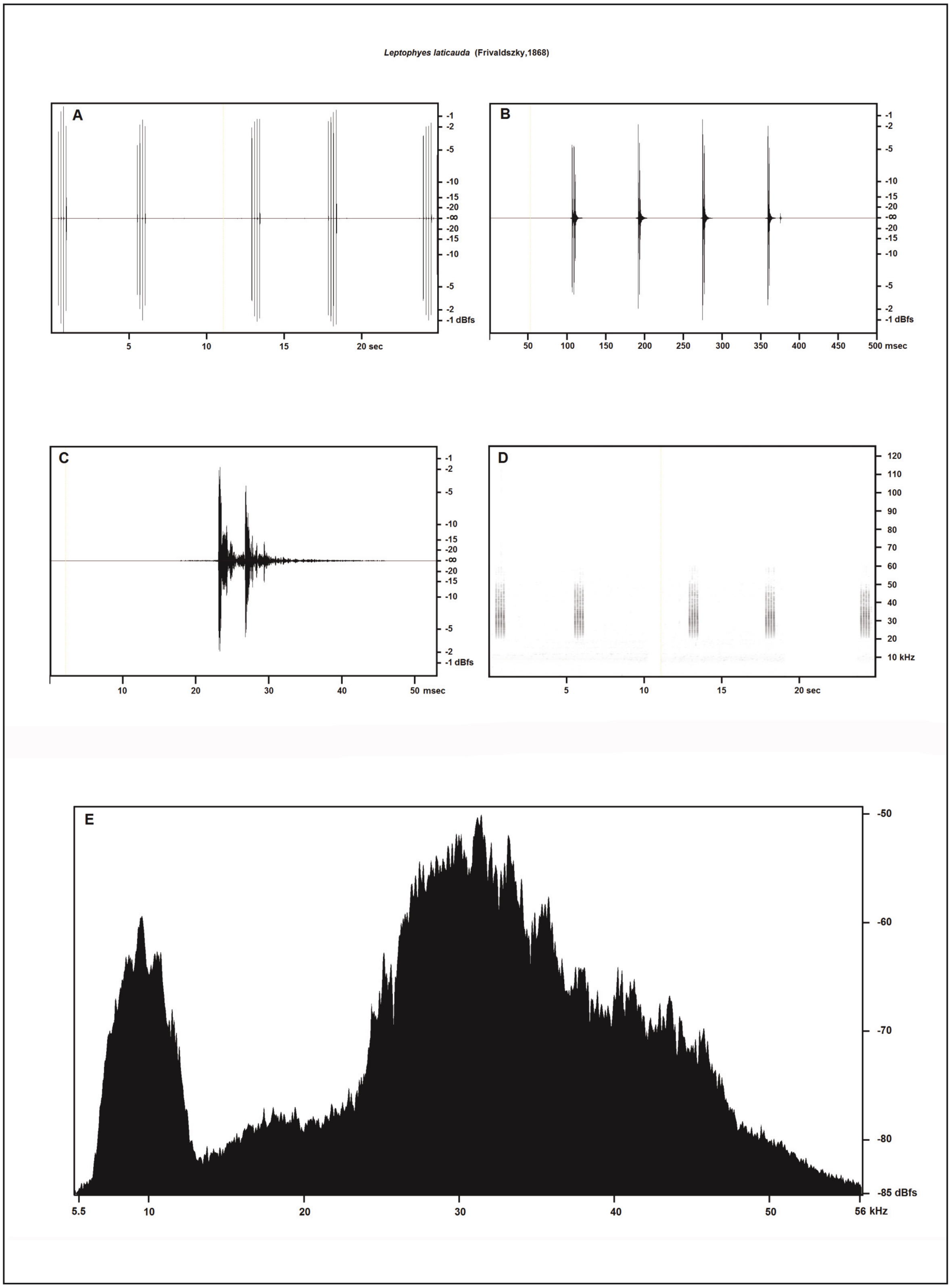


Figure 5. *Leptophyes laticauda* (Frivaldszky,1868) - A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 8.579 sec (see Table 3).

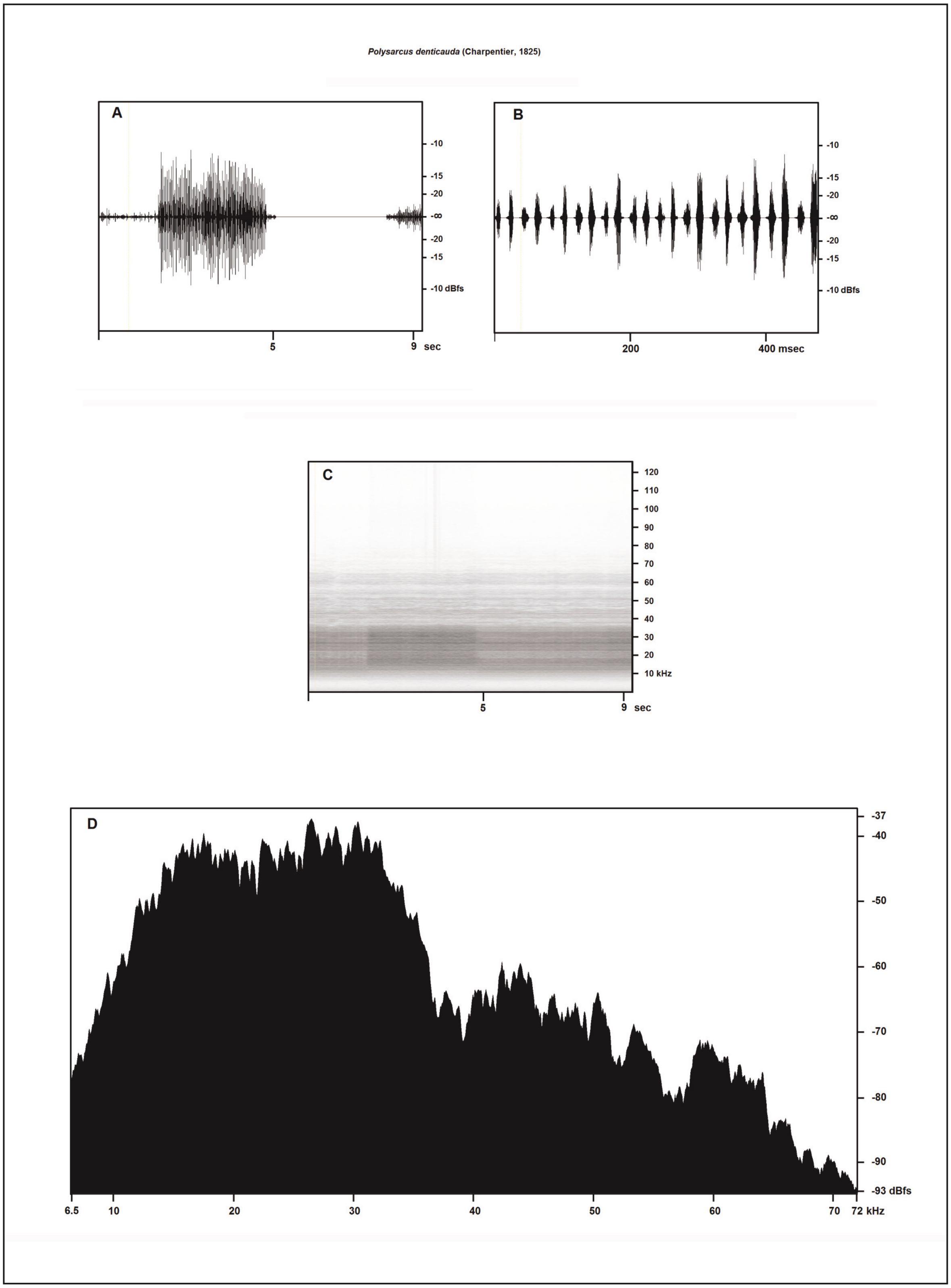


Figure 6. *Polysarcus denticauda* (Charpentier, 1825) - A, B: envelope in three increasing levels of detail, C: spectrogram, D: frequency analysis - 3.060 sec (see Table 3).

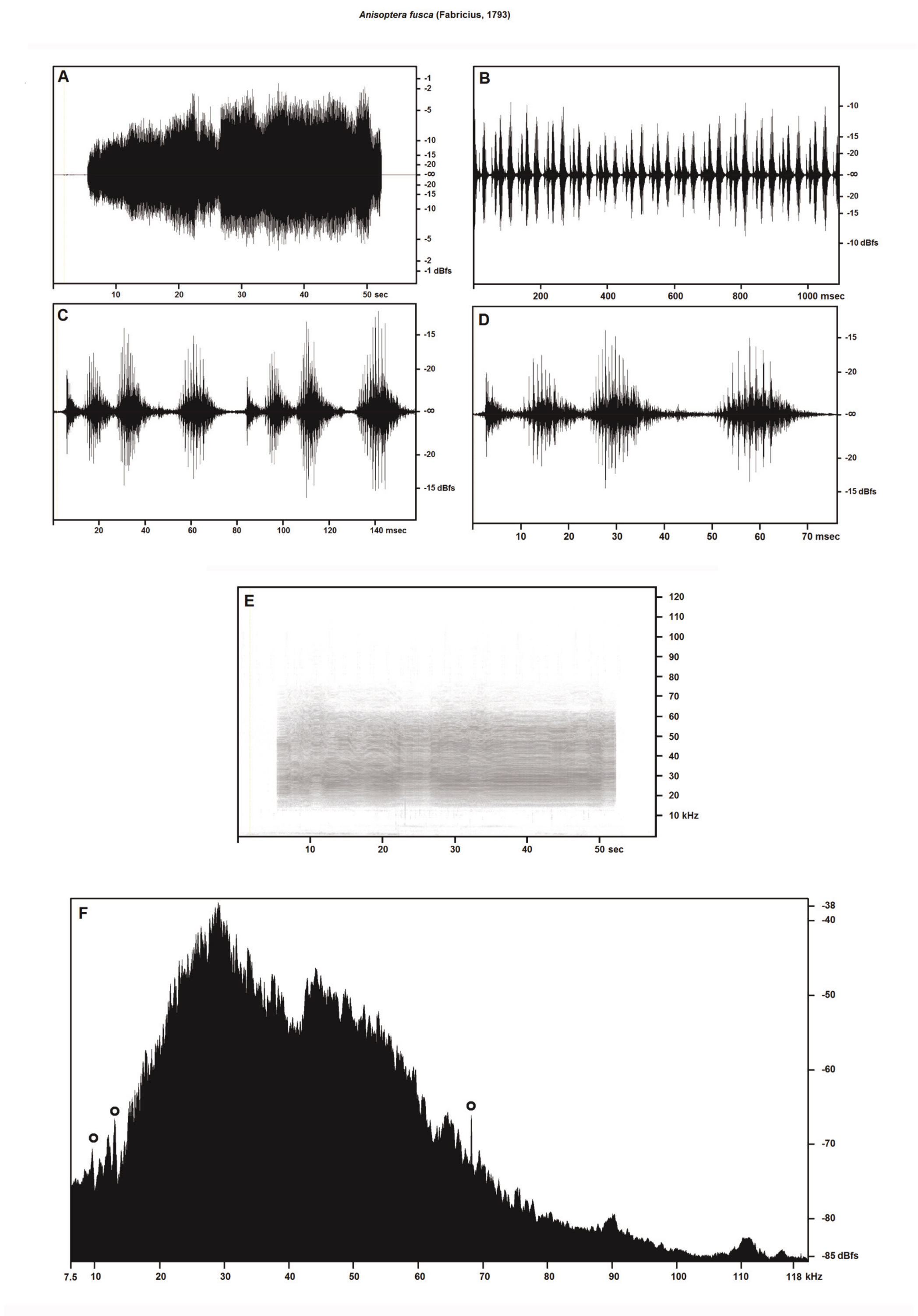


Figure 7. *Anisoptera fusca* (Fabricius, 1793) - A, B, C, D: envelope in four increasing levels of detail, E: spectrogram, F: frequency analysis - 14.414 sec (see Table 3).

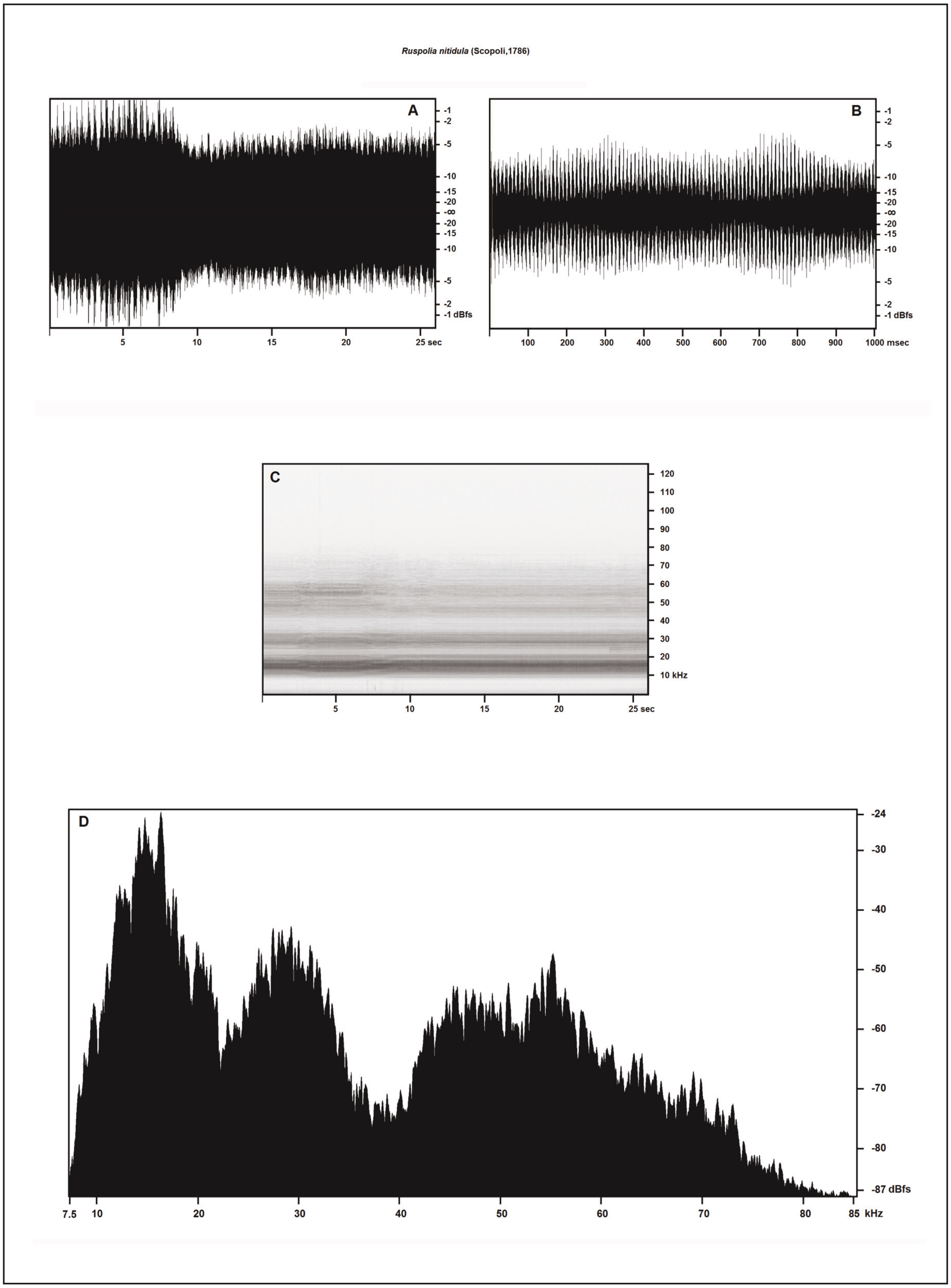


Figure 8. *Ruspolia nitidula* (Scopoli,1786) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 2.244 sec (see Table 3).

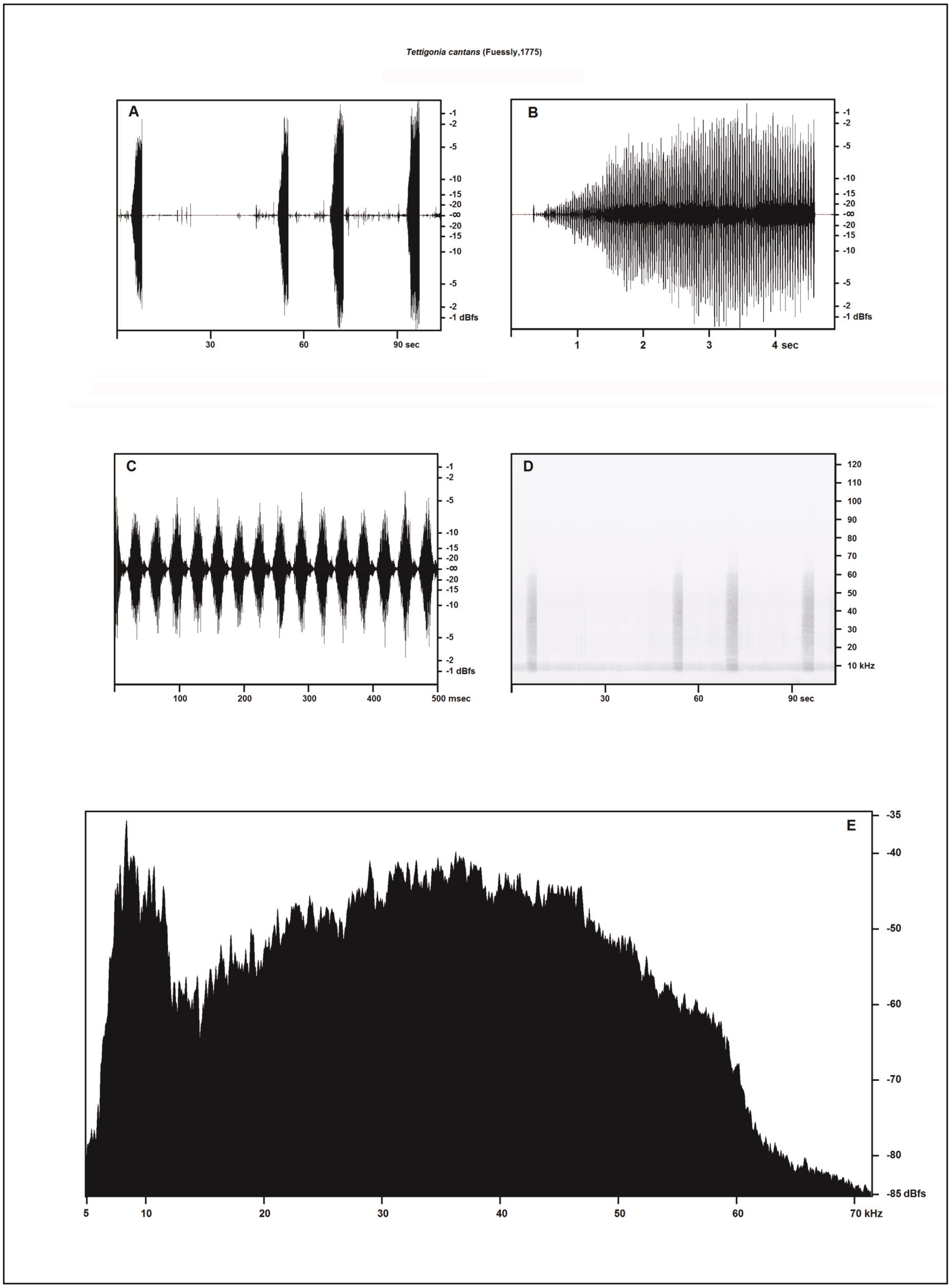


Figure 9. *Tettigonia cantans* (Fuessly,1775) - A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 4.261 sec (see Table 3).

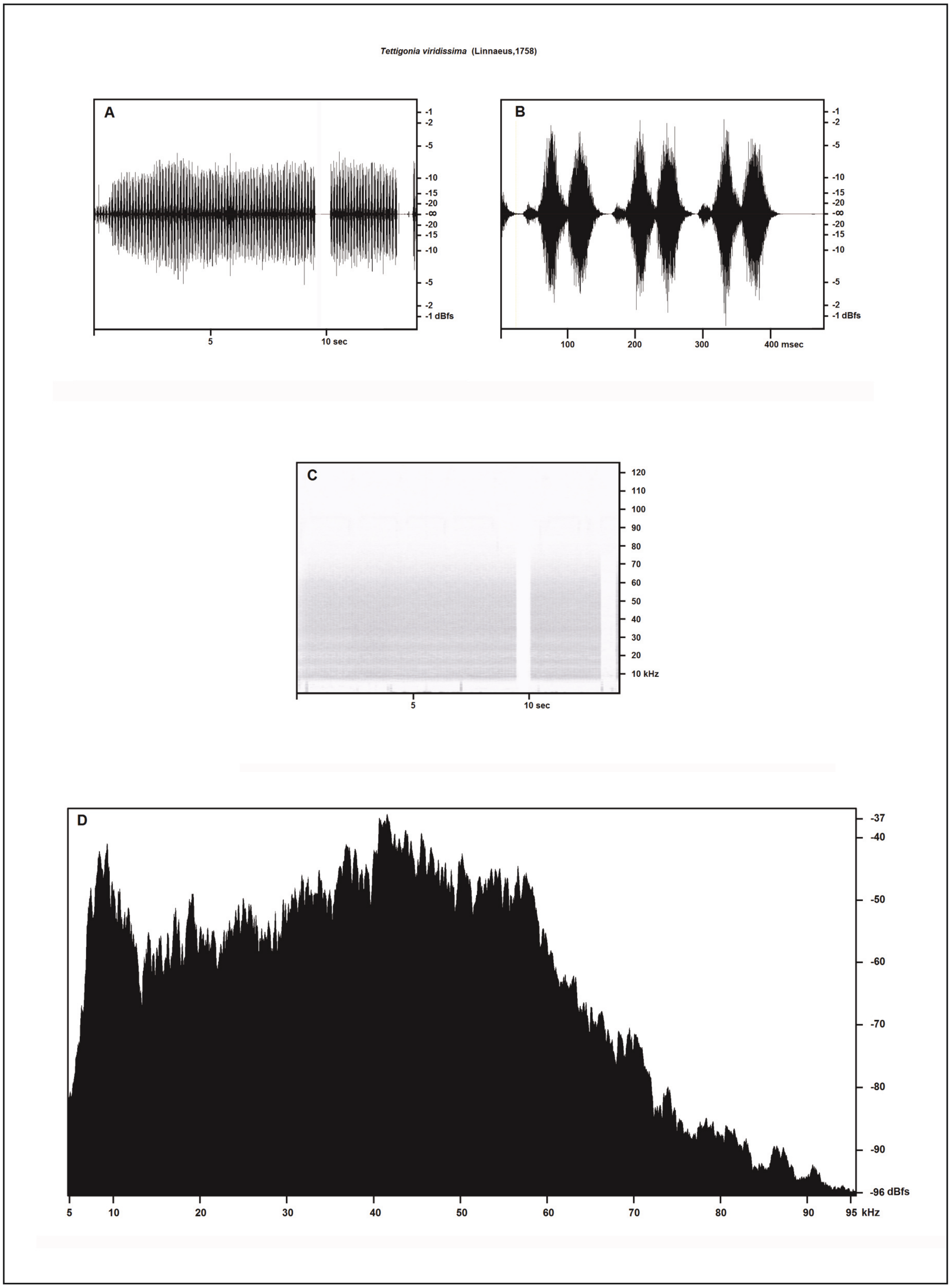


Figure 10. *Tettigonia viridissima* (Linnaeus,1758) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 6.284 sec (see Table 3).

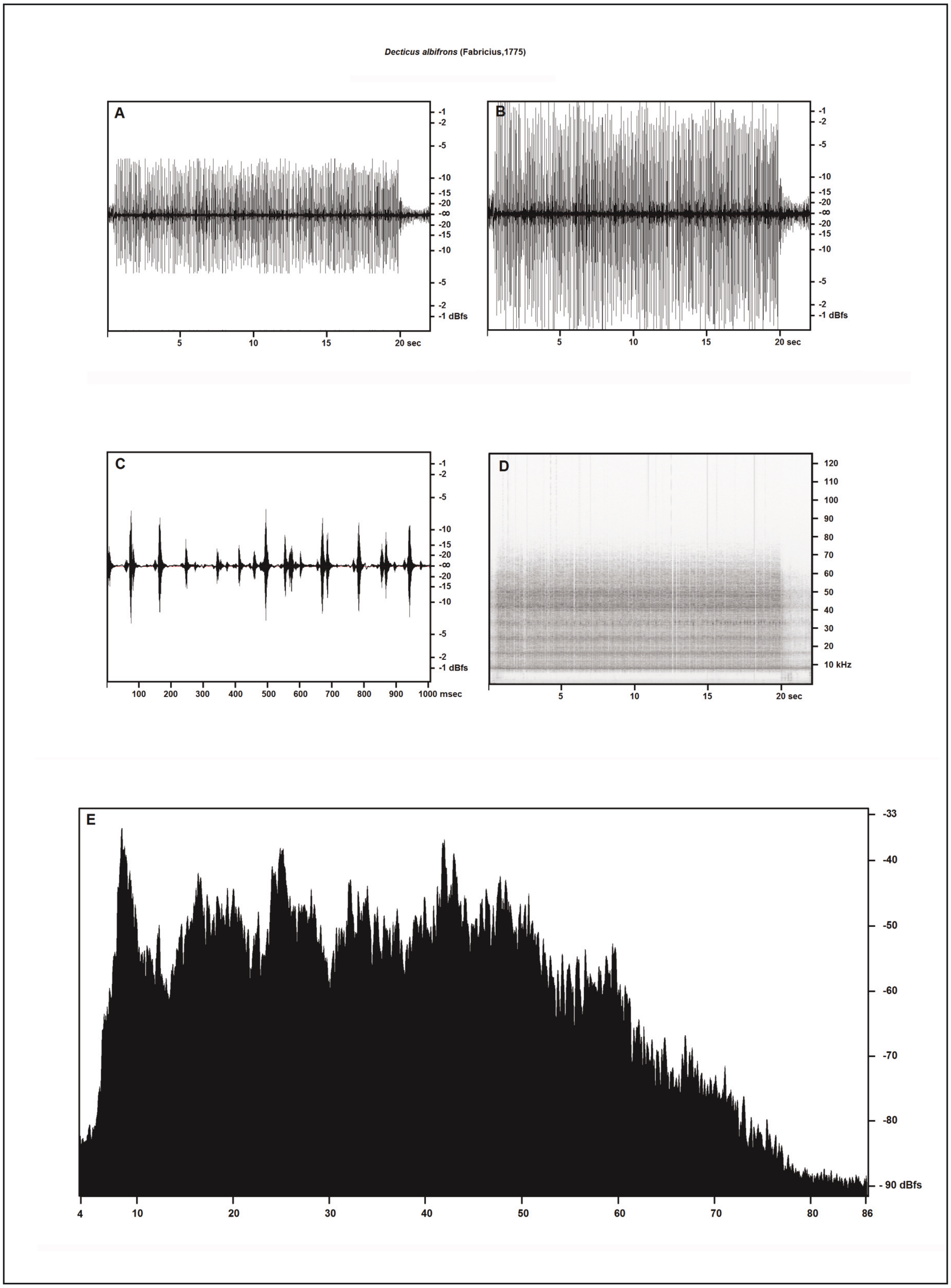


Figure 11. *Decticus albifrons* (Fabricius,1775) - A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 0.901 sec (see Table 3).

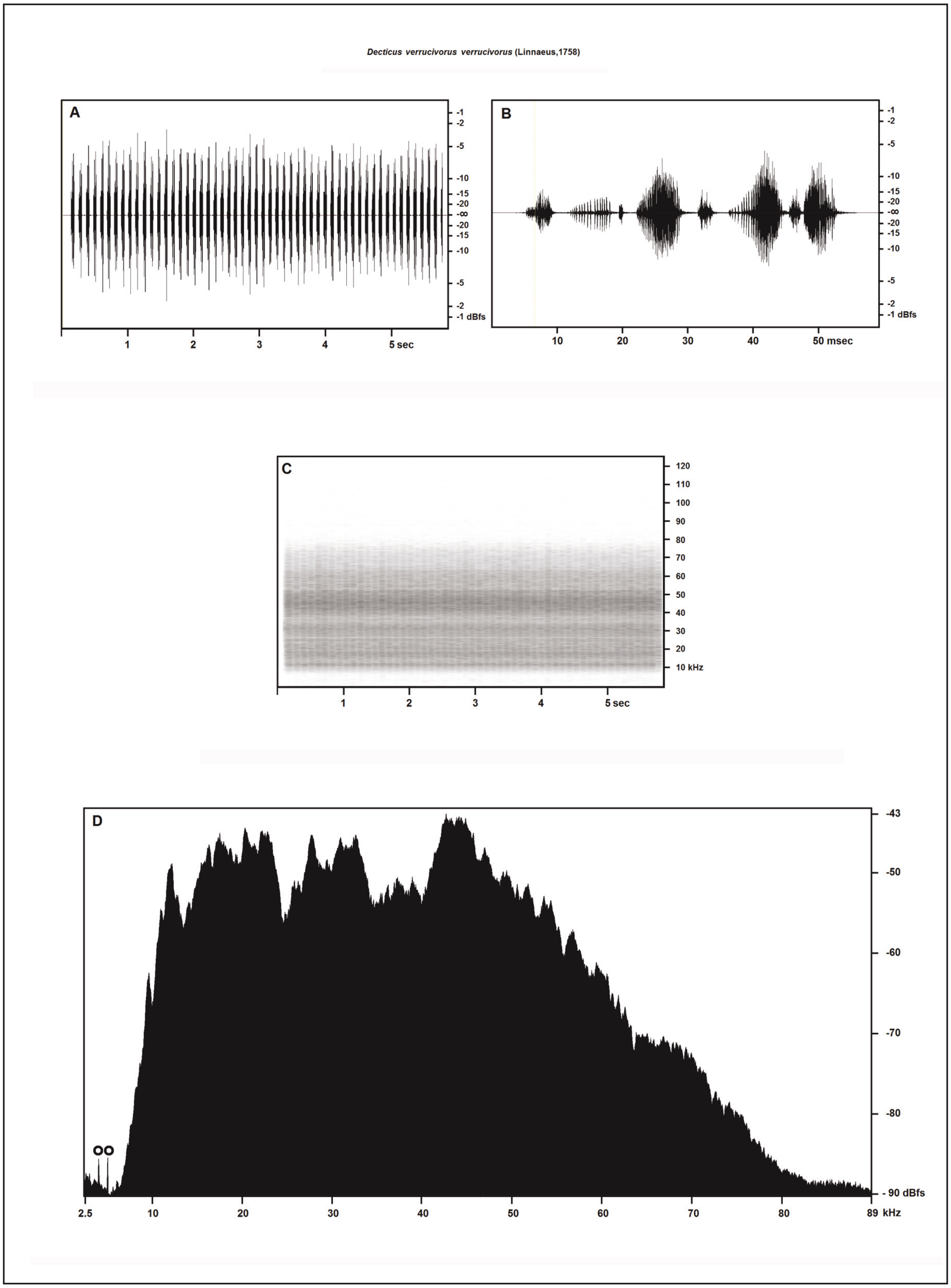


Figure 12. *Decticus verrucivorus verrucivorus* (Linnaeus,1758) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 3.779 sec (see Table 3).

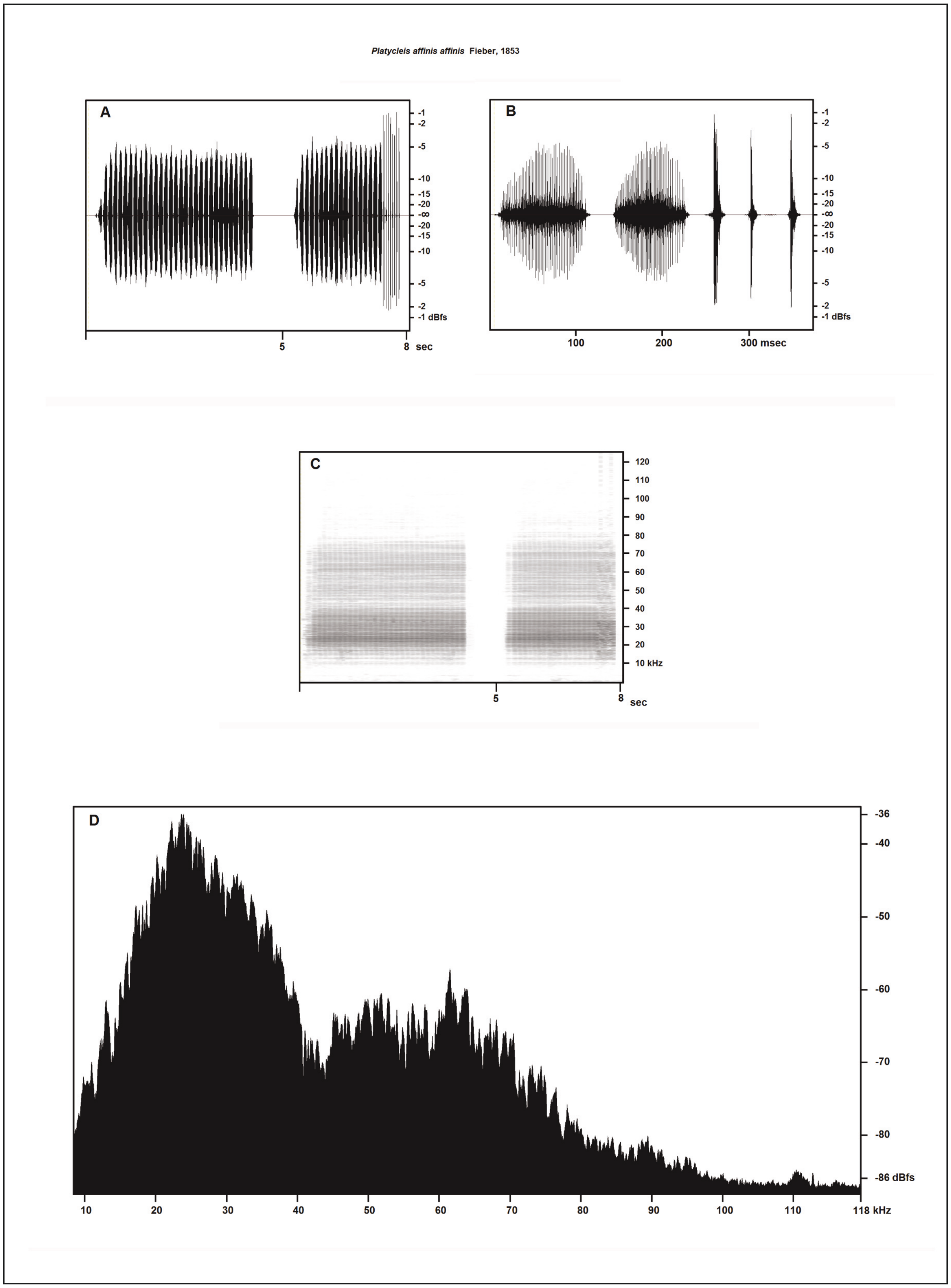


Figure 13. *Platycleis affinis affinis* Fieber, 1853 - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 4.082 sec (see Table 3).

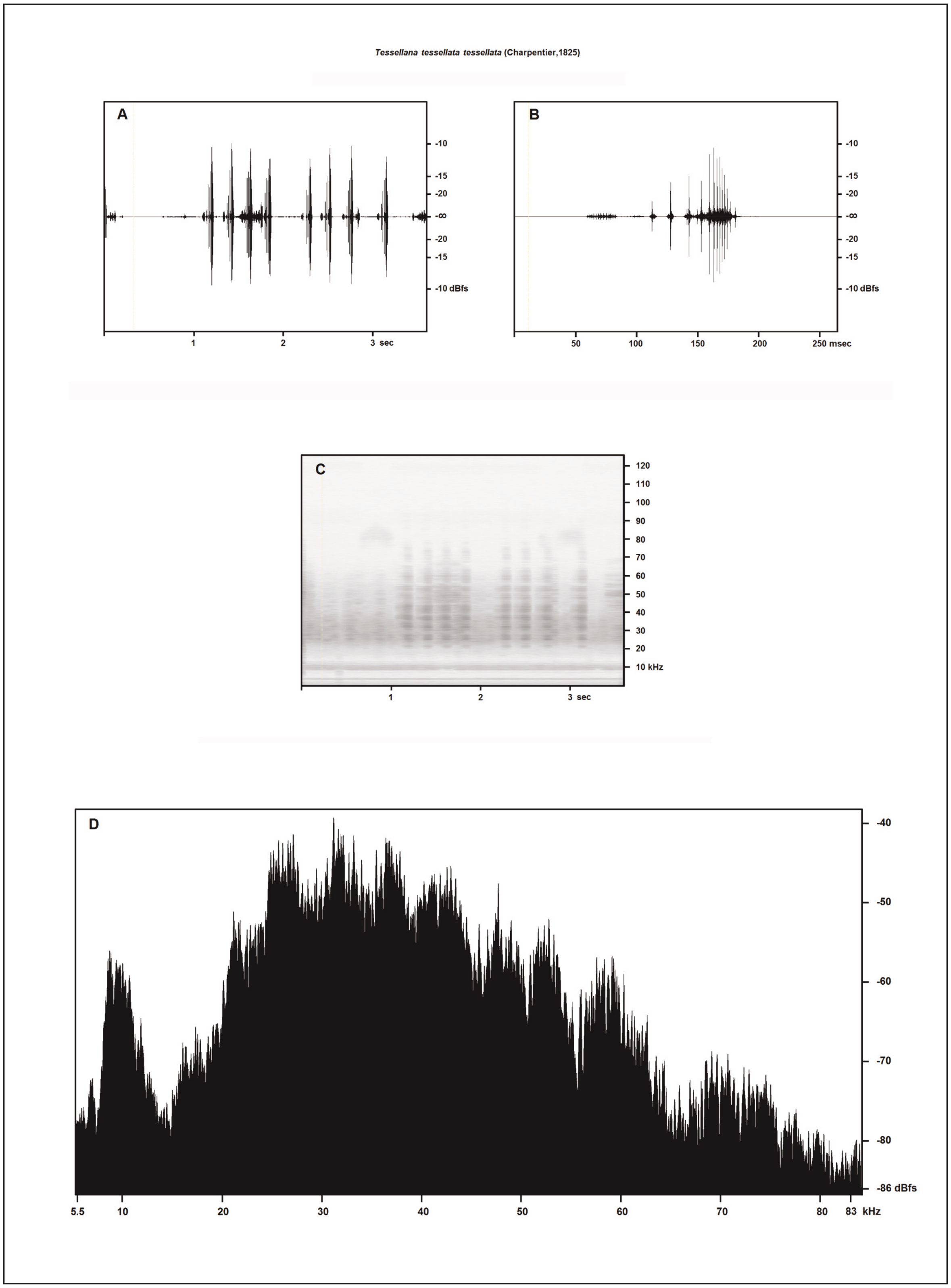


Figure 14. *Tessellana tessellata tessellata* (Charpentier,1825) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 0.096 sec (see Table 3).

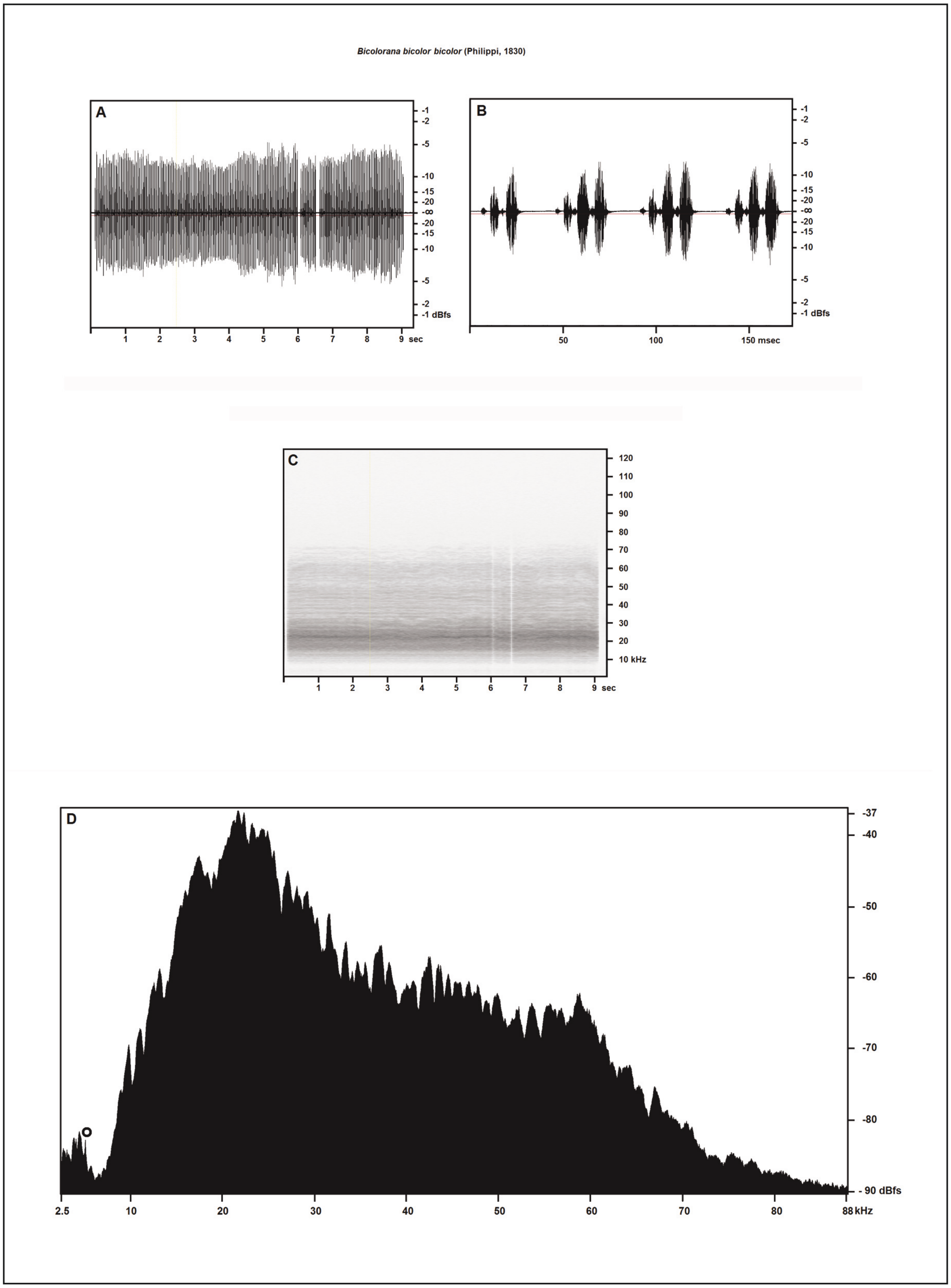


Figure 15. *Bicolorana bicolor bicolor* (Philippi, 1830) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 6.138 sec (see Table 3).

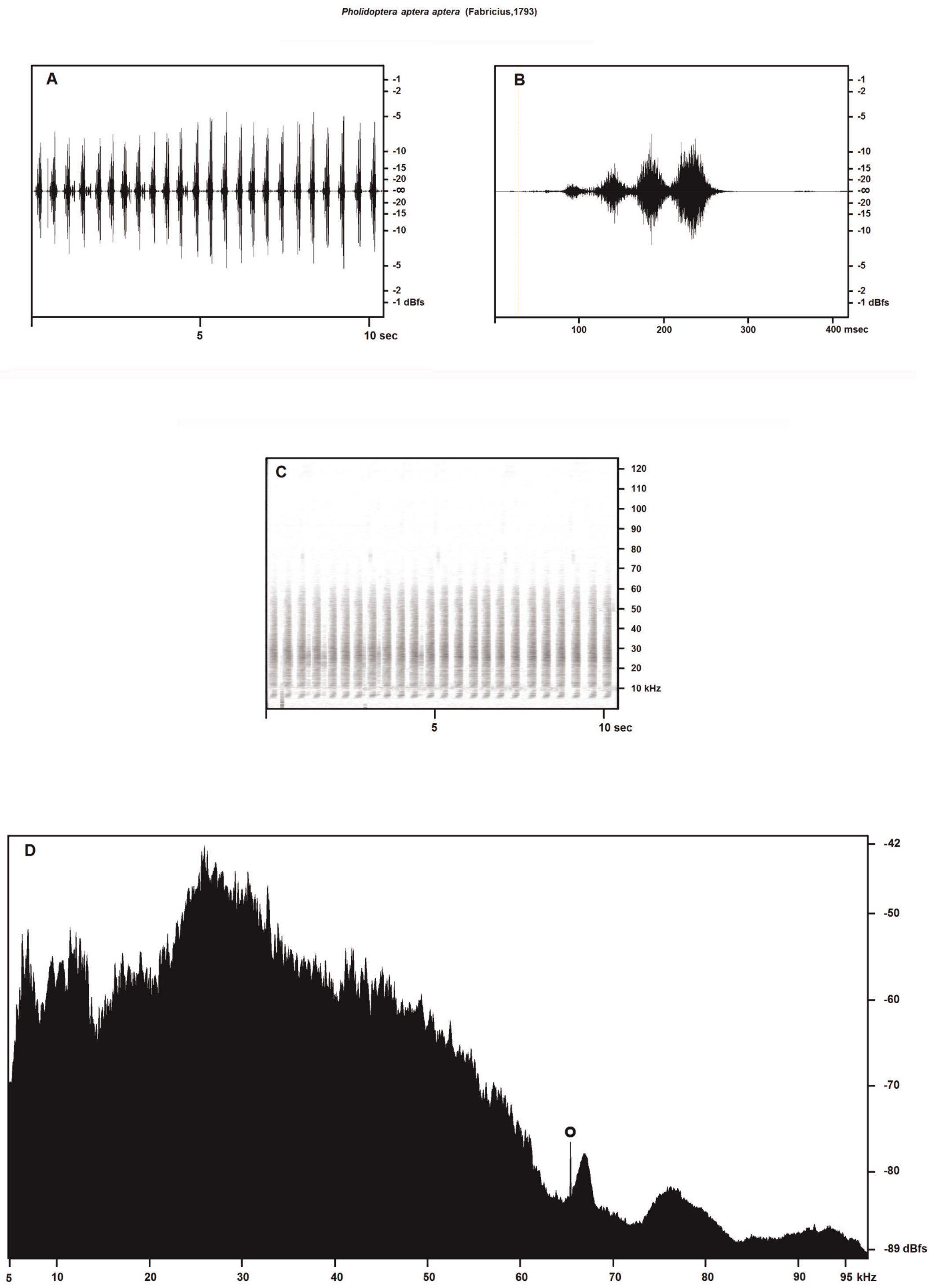


Figure 16. *Pholidoptera aptera aptera* (Fabricius,1793) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 12.173 sec (see Table 3).

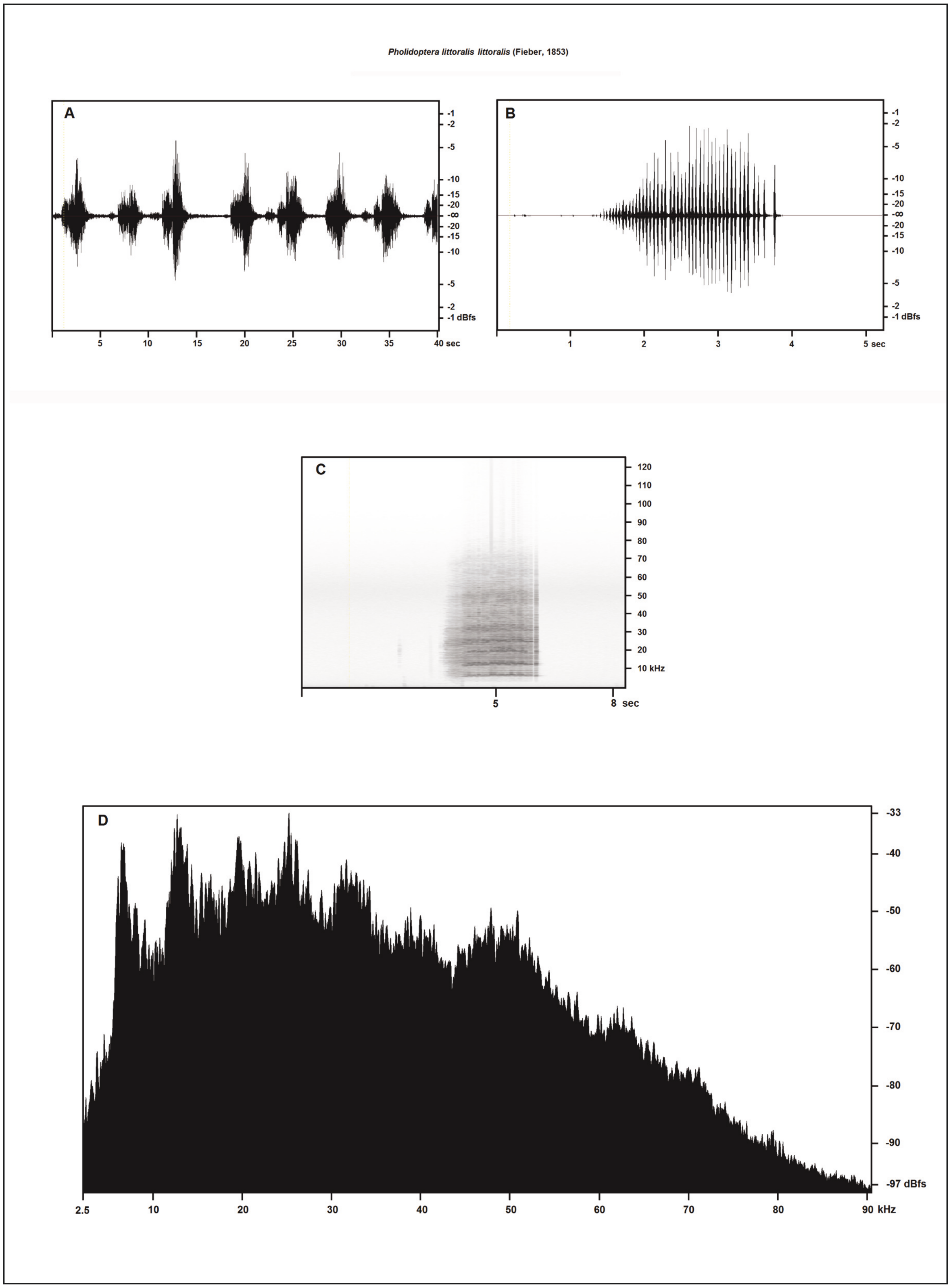


Figure 17. *Pholidoptera littoralis littoralis* (Fieber, 1853) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 2.632 sec (see Table 3).

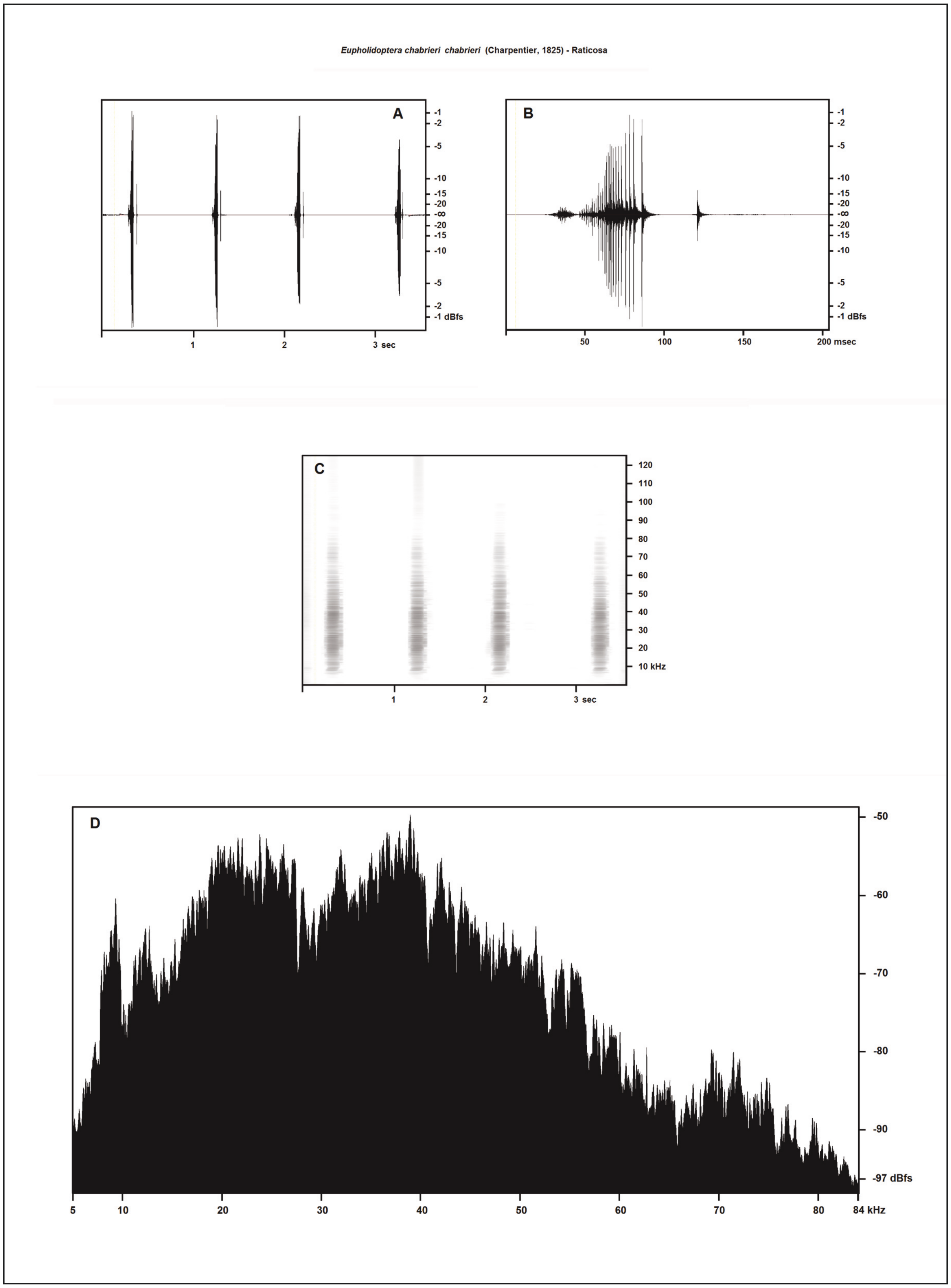


Figure 18. *Eupholidoptera chabrieri chabrieri* (Charpentier, 1825) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 3.172 sec (see Table 3).

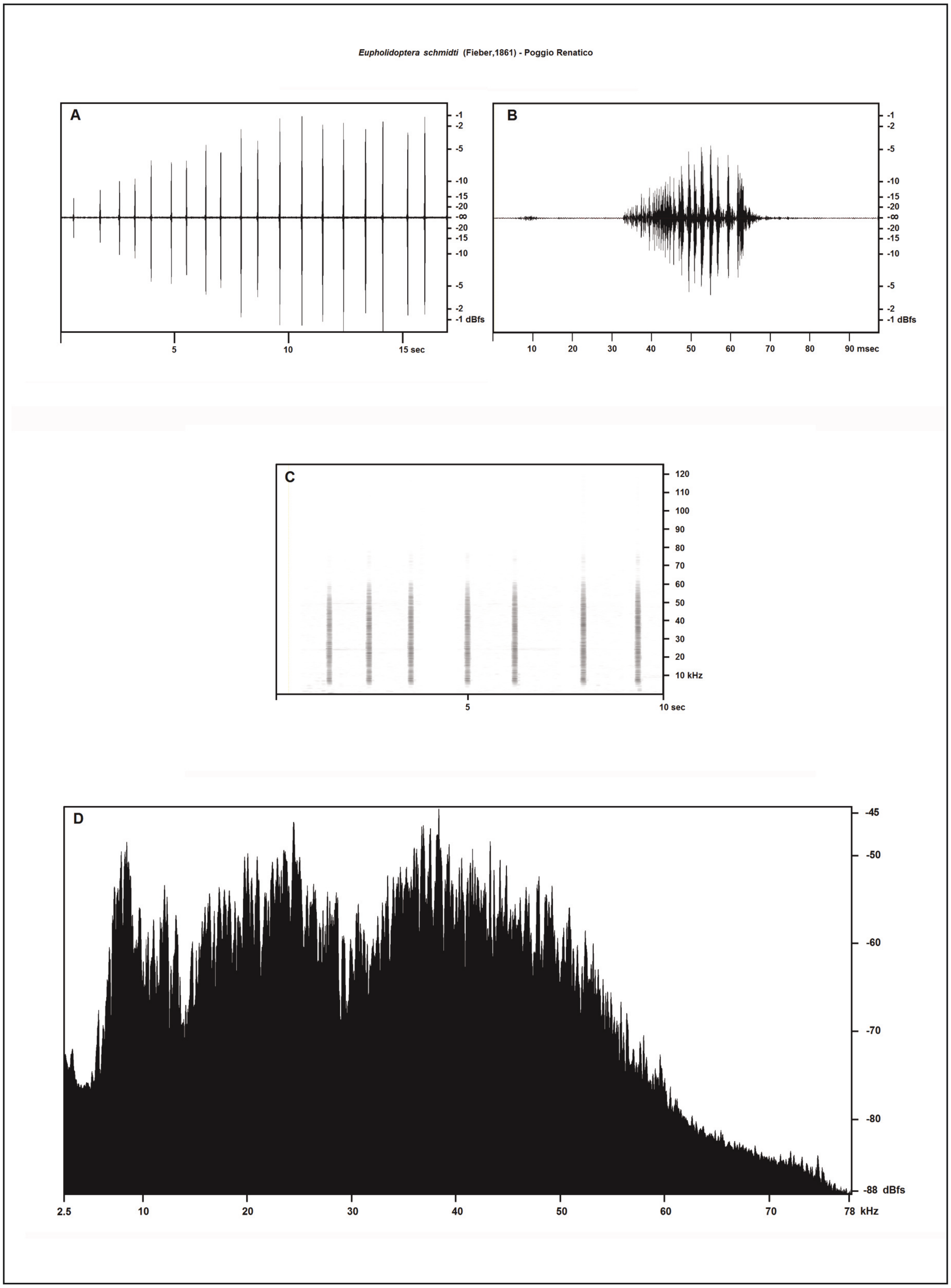


Figure 19. *Eupholidoptera schmidti* (Fieber,1861) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 3.430 sec (see Table 3).

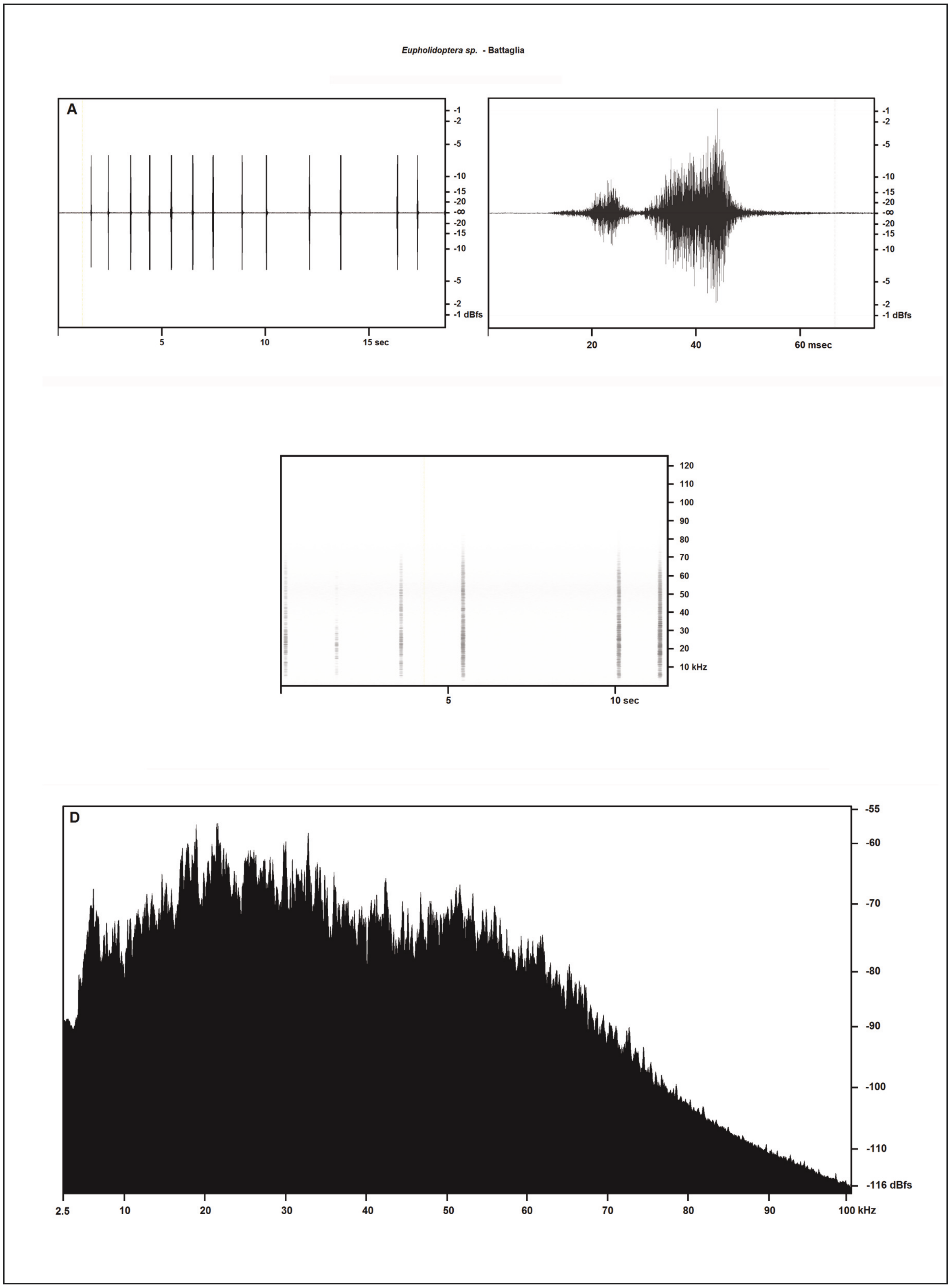


Figure 20. *Eupholidoptera* sp. Battaglia - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 17.860 sec (see Table 3).

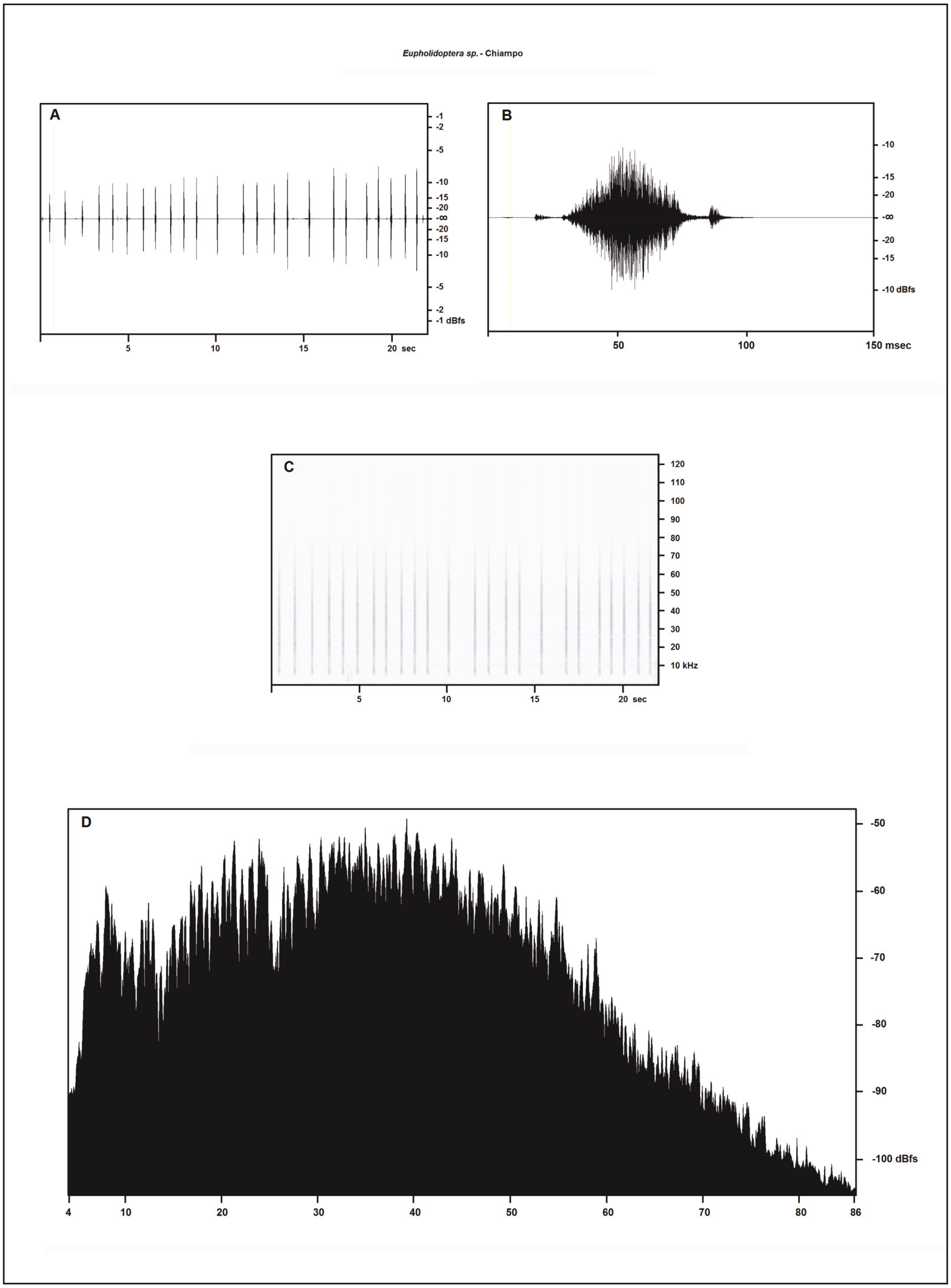


Figure 21. *Eupholidoptera* sp. Chiampo - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 3.087 sec (see Table 3).

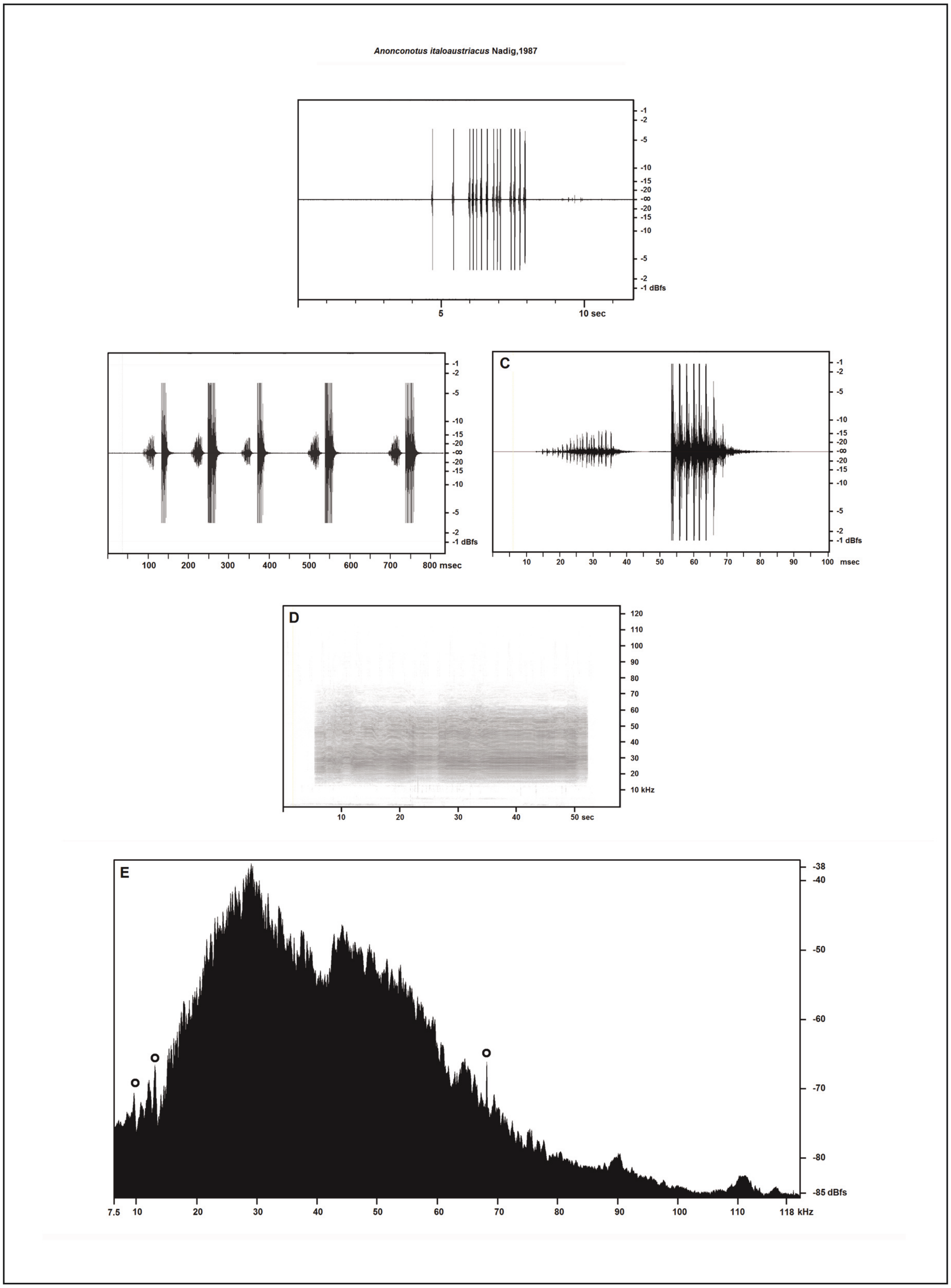


Figure 22. *Anonconotus italoaustriacus* Nadig,1987 - A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 0.129 sec (see Table 3); small circles mark narrow technogenic peaks (see text).

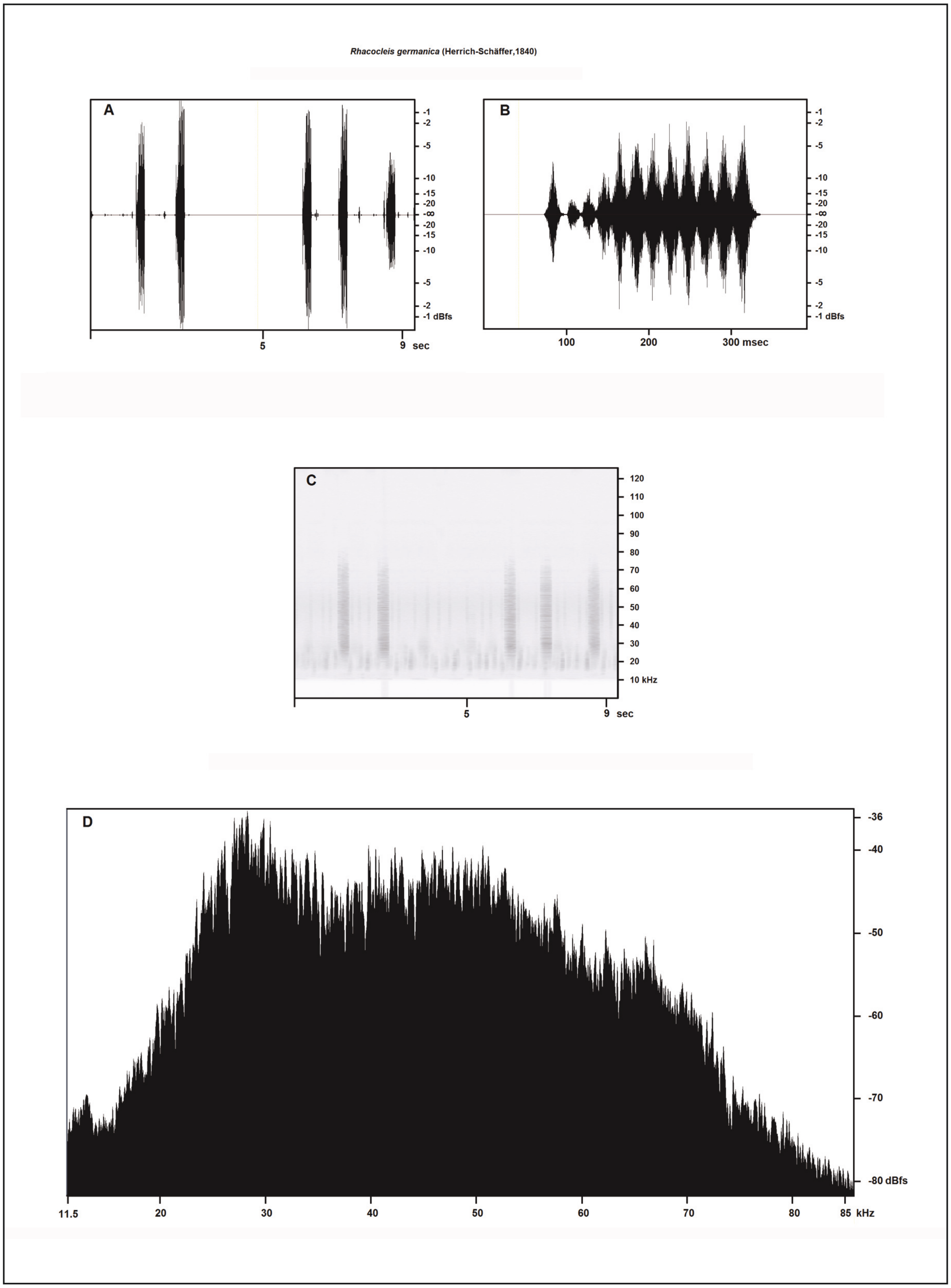


Figure 23. *Rhacocleis germanica* (Herrich-Schäffer,1840) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 0.306 sec (see Table 3).

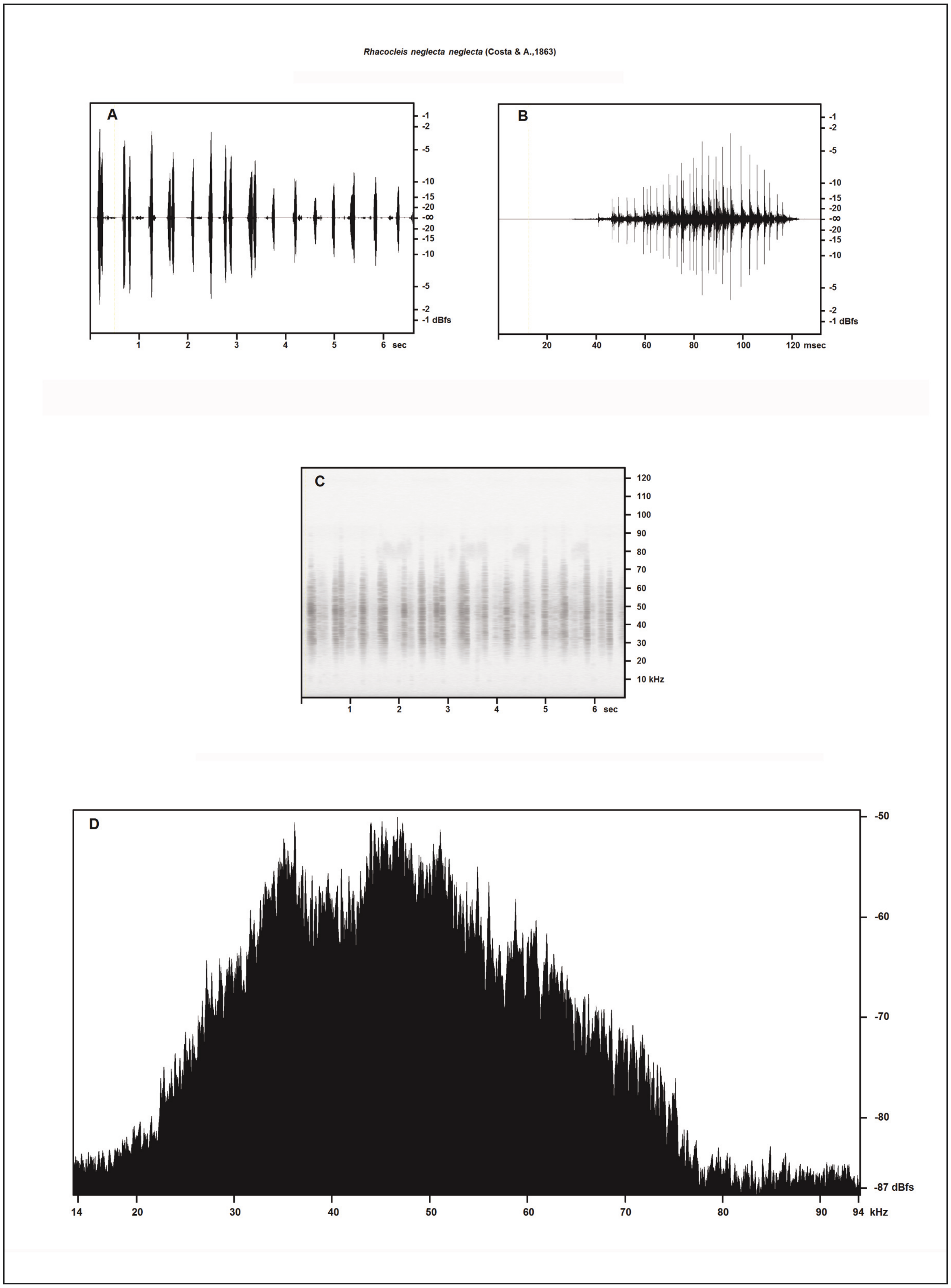


Figure 24. *Rhacocleis neglecta neglecta* (Costa A.,1863) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 0.616 sec (see Table 3).

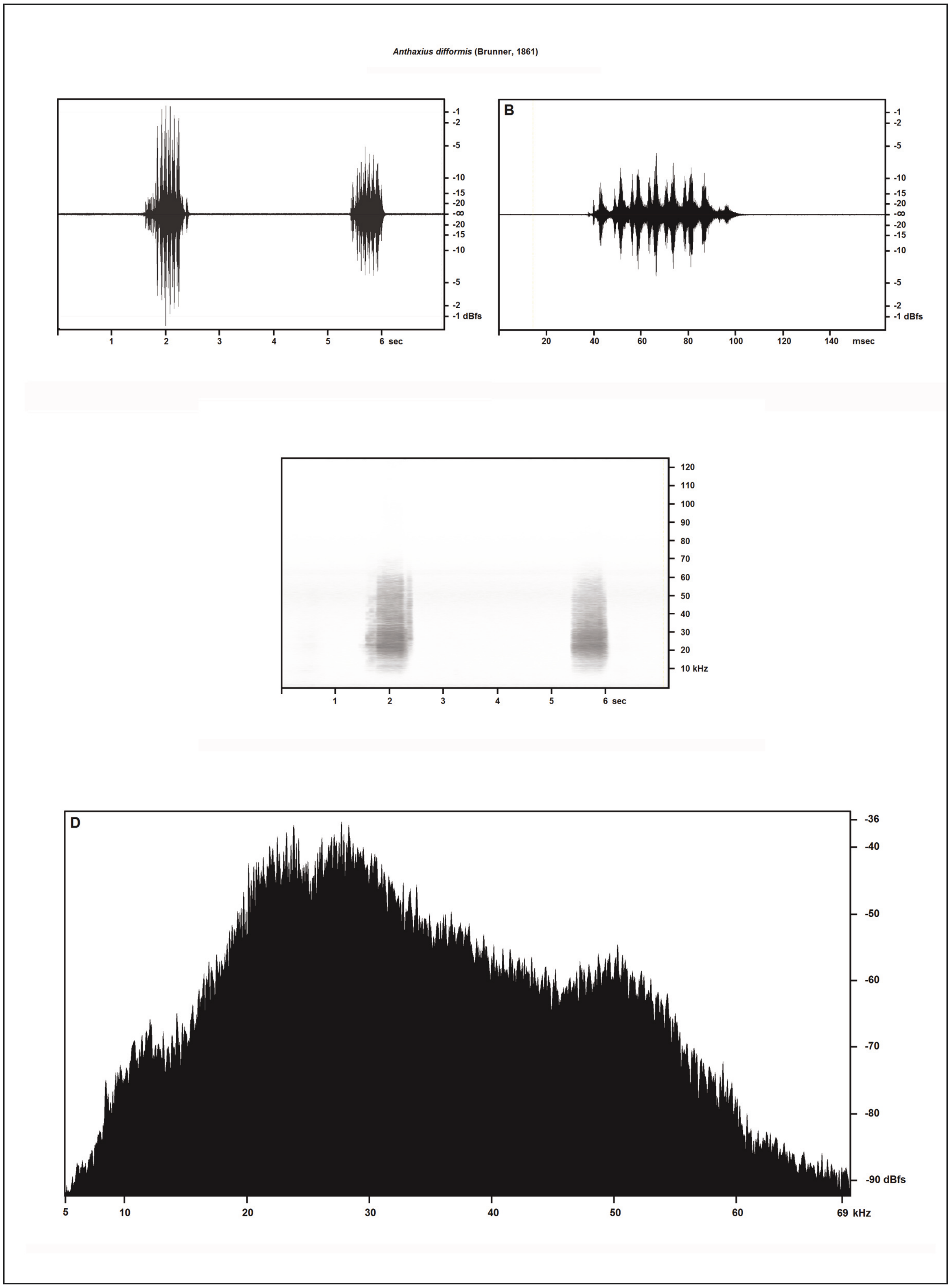


Figure 25. *Anthaxius difformis* (Brunner, 1861) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 1.145 sec (see Table 3).

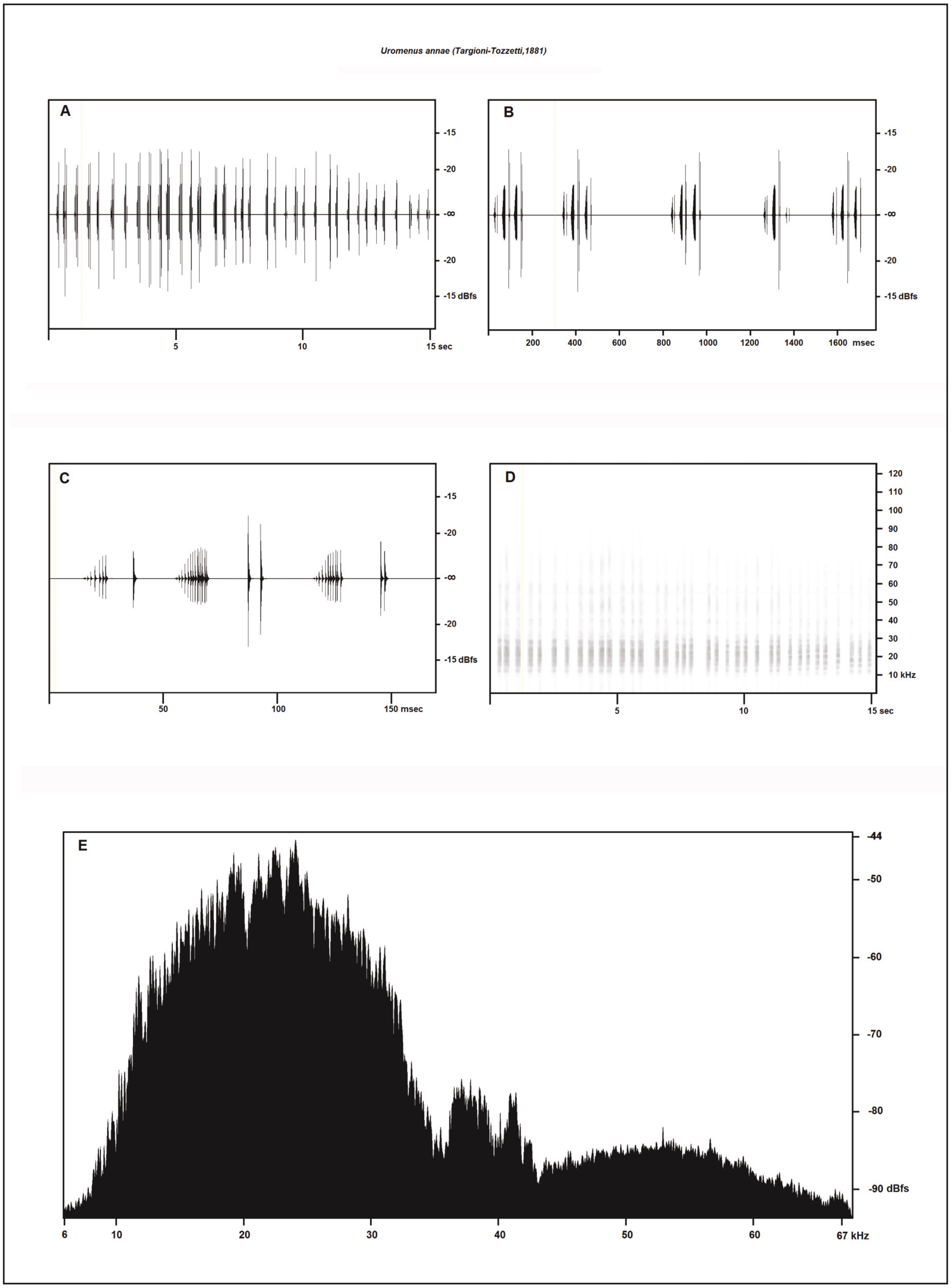


Figure 26. *Uromenus annae* (Targioni-Tozzetti, 1881) - A, B, C: envelope in three increasing levels of detail, D: spectrogram, E: frequency analysis - 1.960 sec (see Table 3).

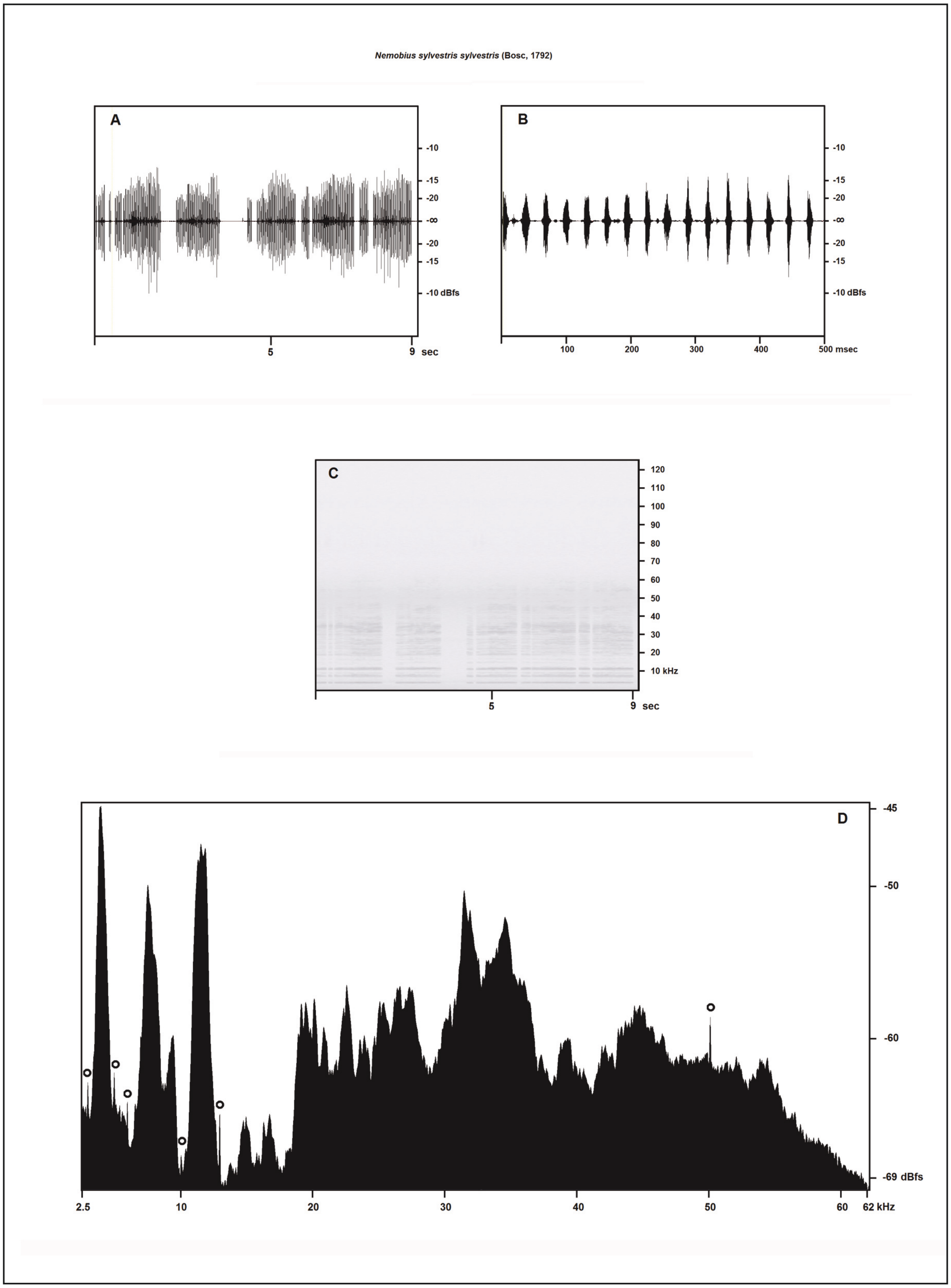


Figure 27. *Nemobius sylvestris sylvestris* (Bosc, 1792) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 8.532 sec (see Table 3); peaks marked with a small circle are artefacts caused by the usage of 150cm USB cable with Ultramic 250.

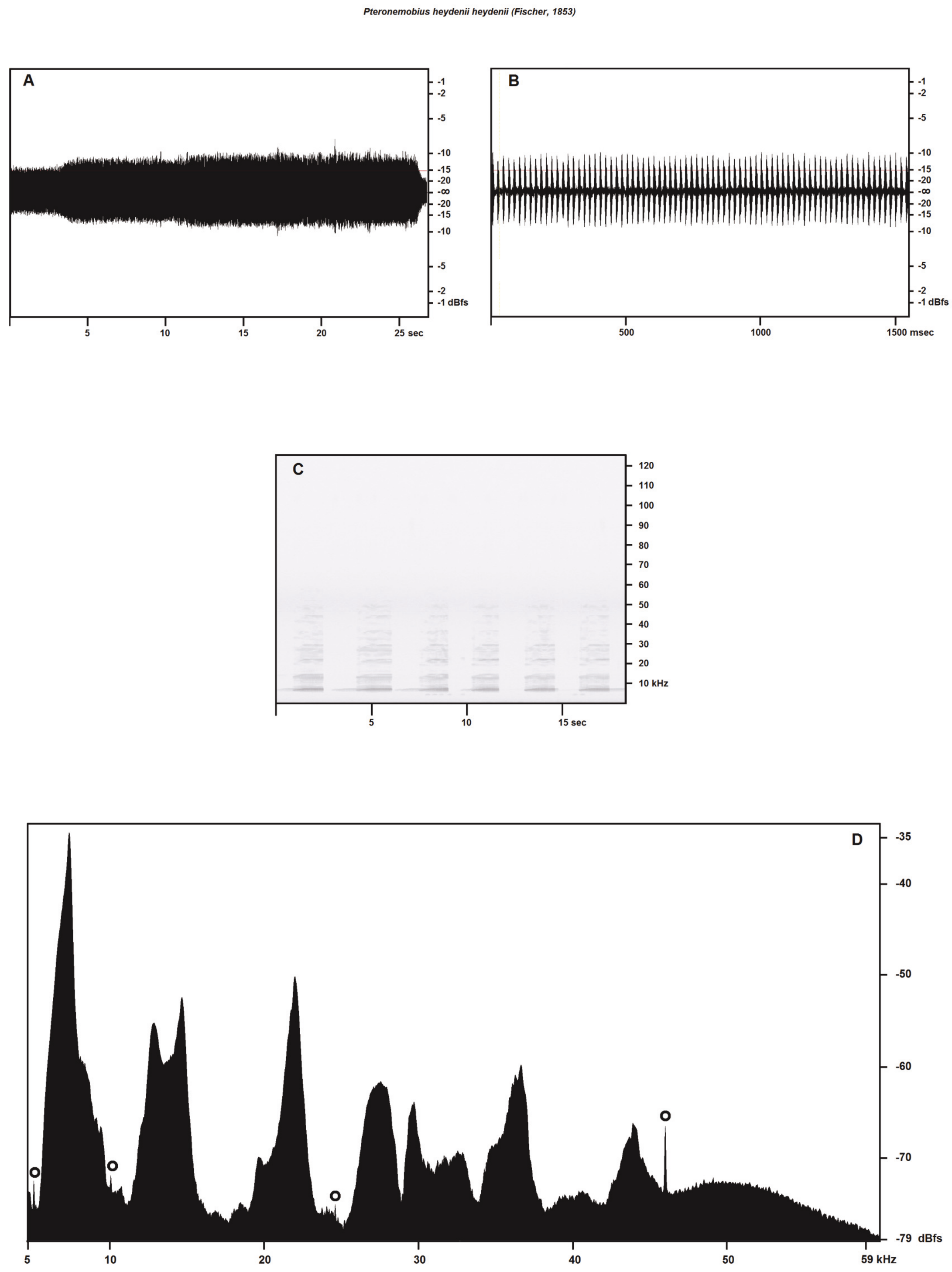


Figure 28. *Pteronemobius heydenii heydenii* (Fischer, 1853) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 8.439 sec (see Table 3); peaks marked with a small circle are artefacts caused by the usage of 150cm USB cable with Ultramic 250.

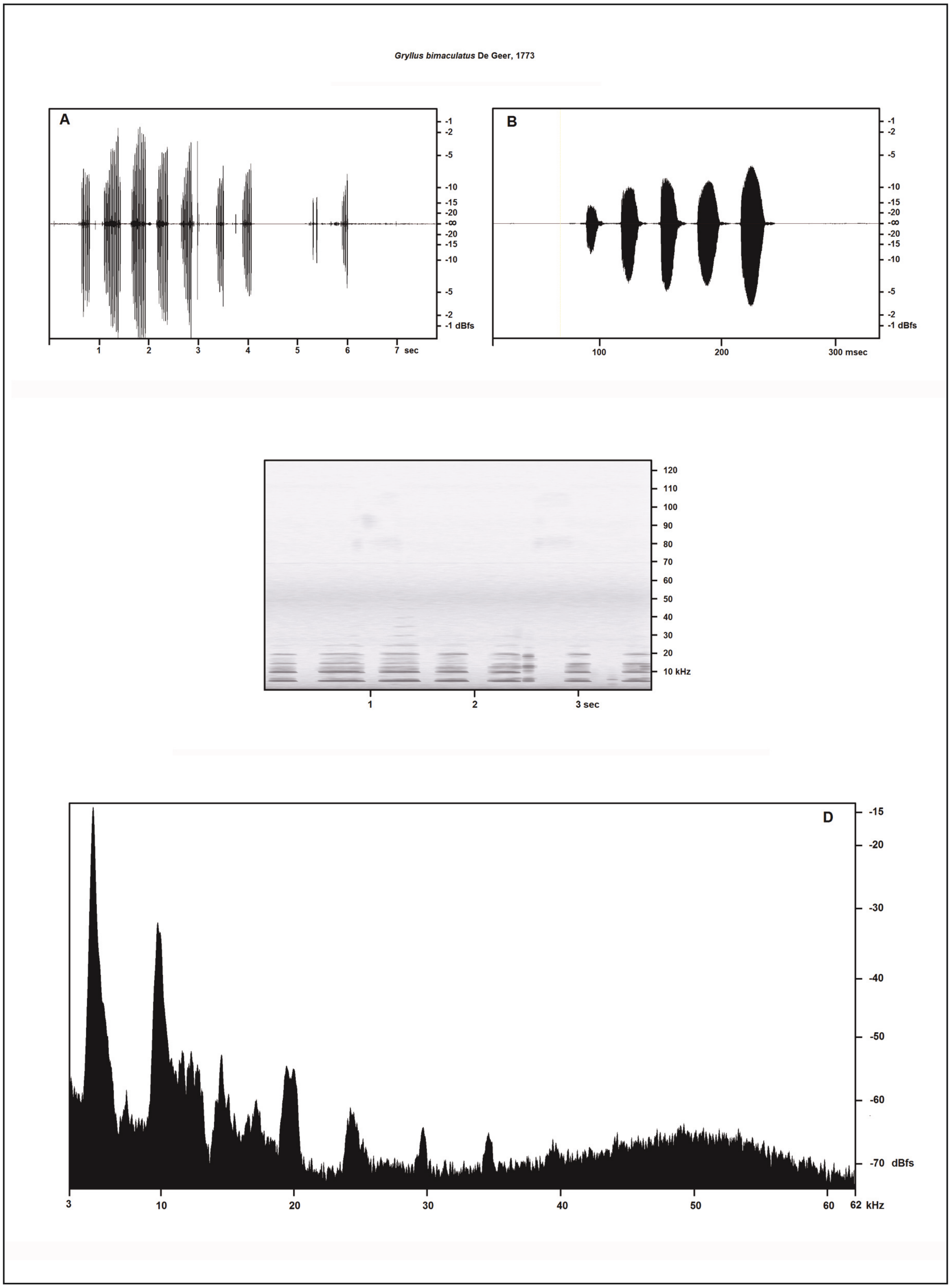


Figure 29. *Gryllus bimaculatus* De Geer, 1773 - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 0.439 sec (see Table 3).

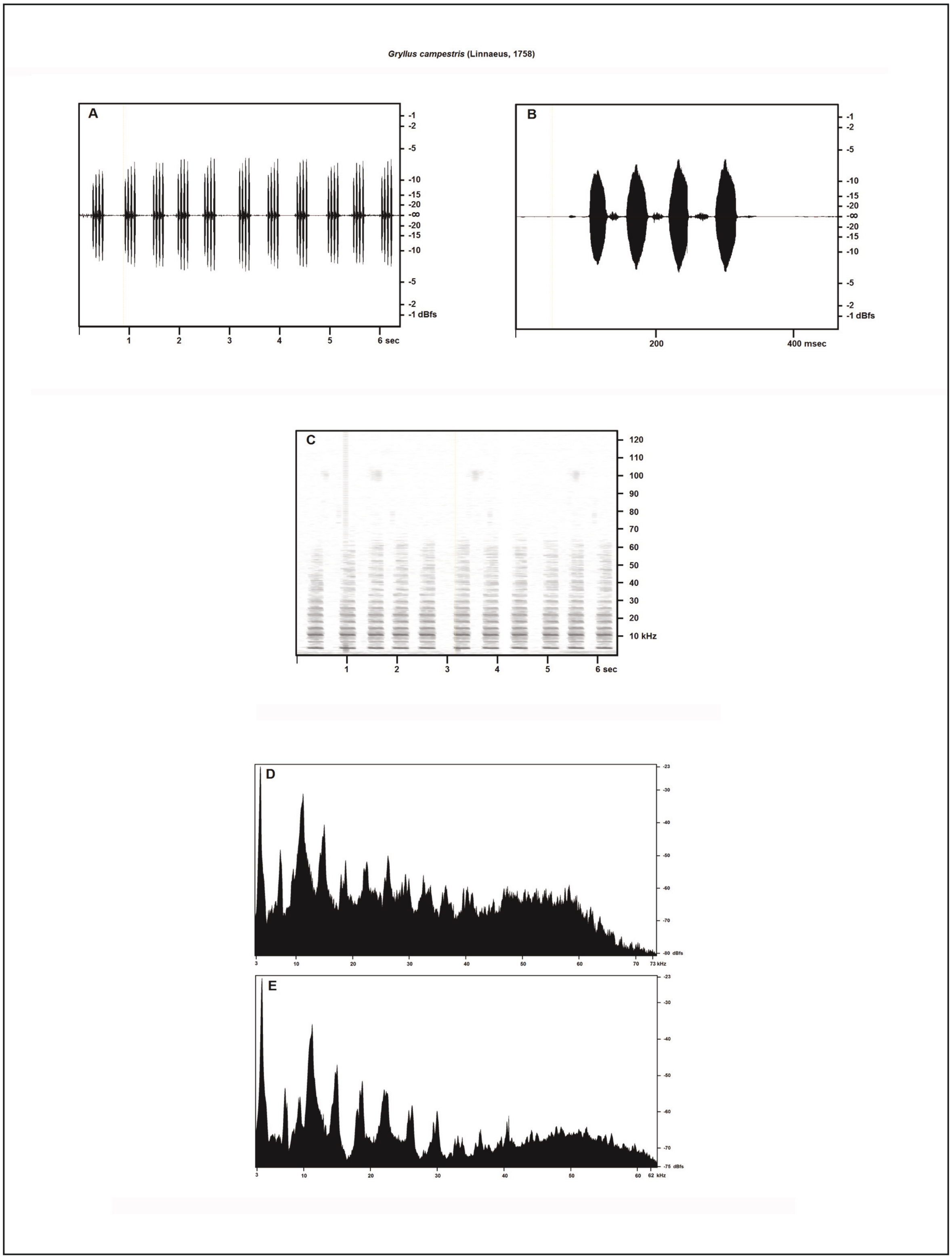


Figure 30. *Gryllus campestris* Linnaeus, 1758 - A, B: envelope at two increasing levels of detail, C: spectrogram, D, E: frequency analyses of two specimens recorded at the same location and at the same time, showing the exact coincidence of fundamental frequency, good correspondence of peaks above 10 kHz, and different timbre in the 5-10 kHz band as well as, respectively, a less or more sharp definition of frequency peaks - respectively, 4.942 and 4.719 sec (see Table 3).

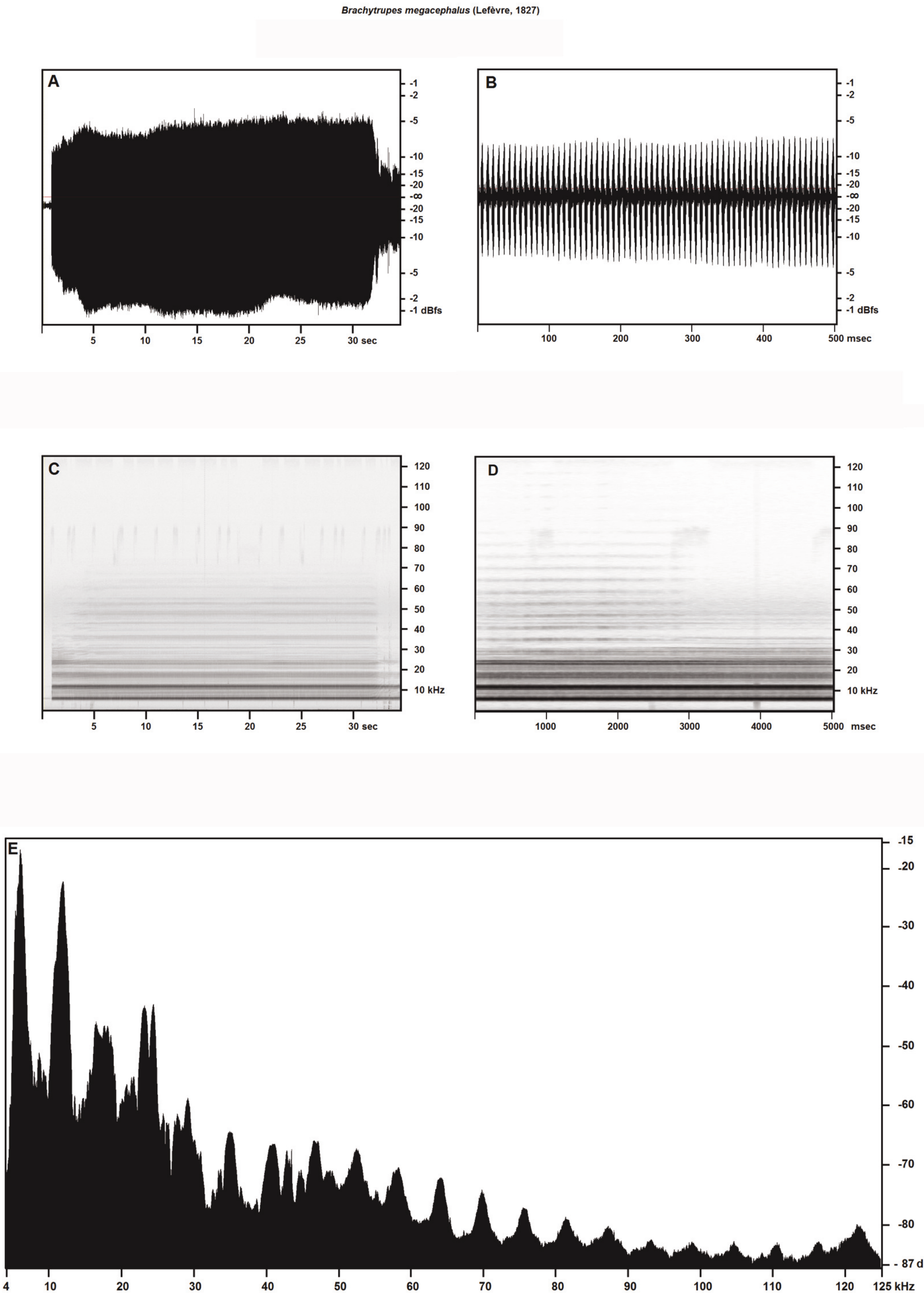


Figure 31. *Brachytrupes megacephalus* (Lefèvre, 1827) - A, B: envelope at two increasing levels of detail, C,D: spectrogram at two increasing levels of detail, E: frequency analysis - 3.003 sec (see Table 3).

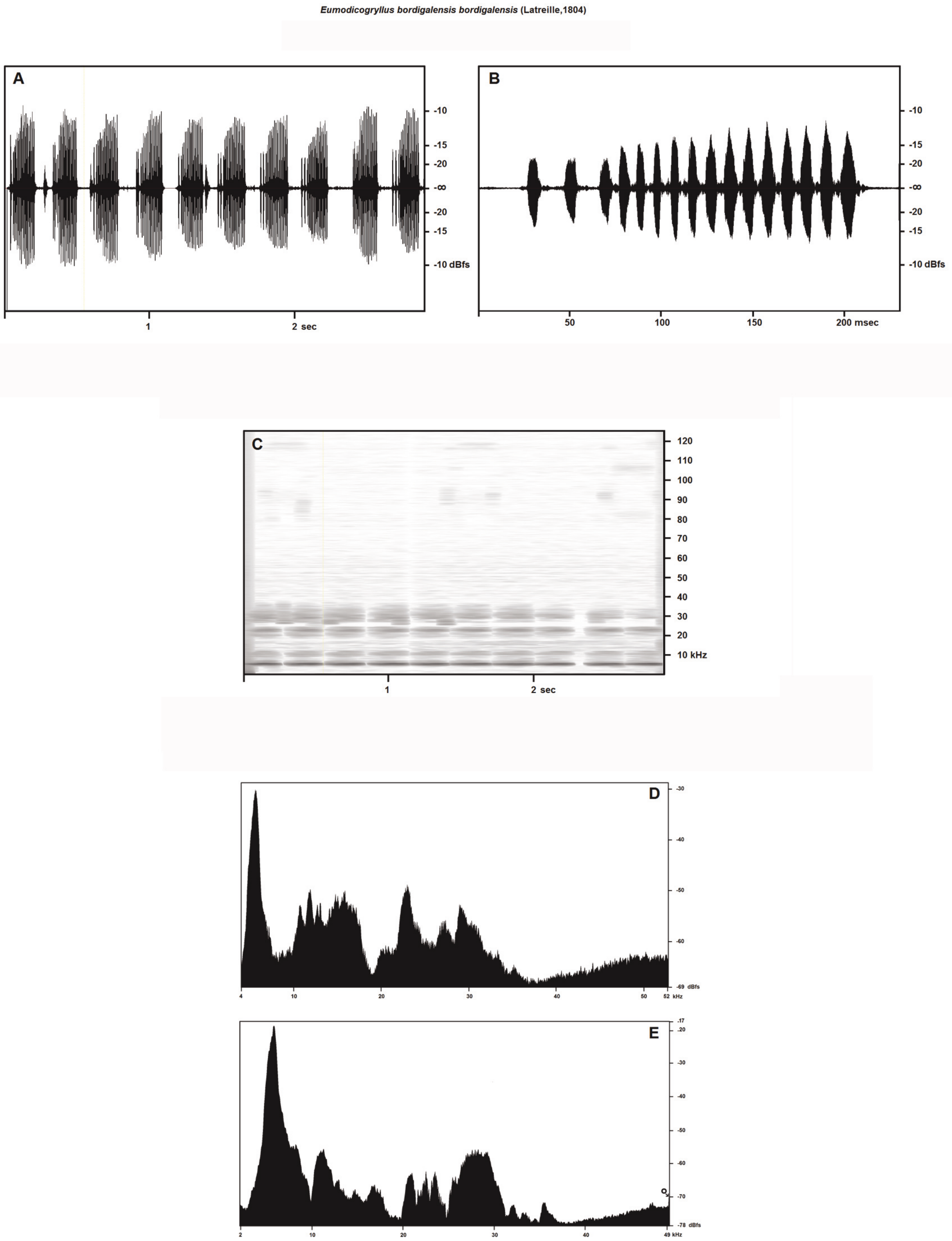
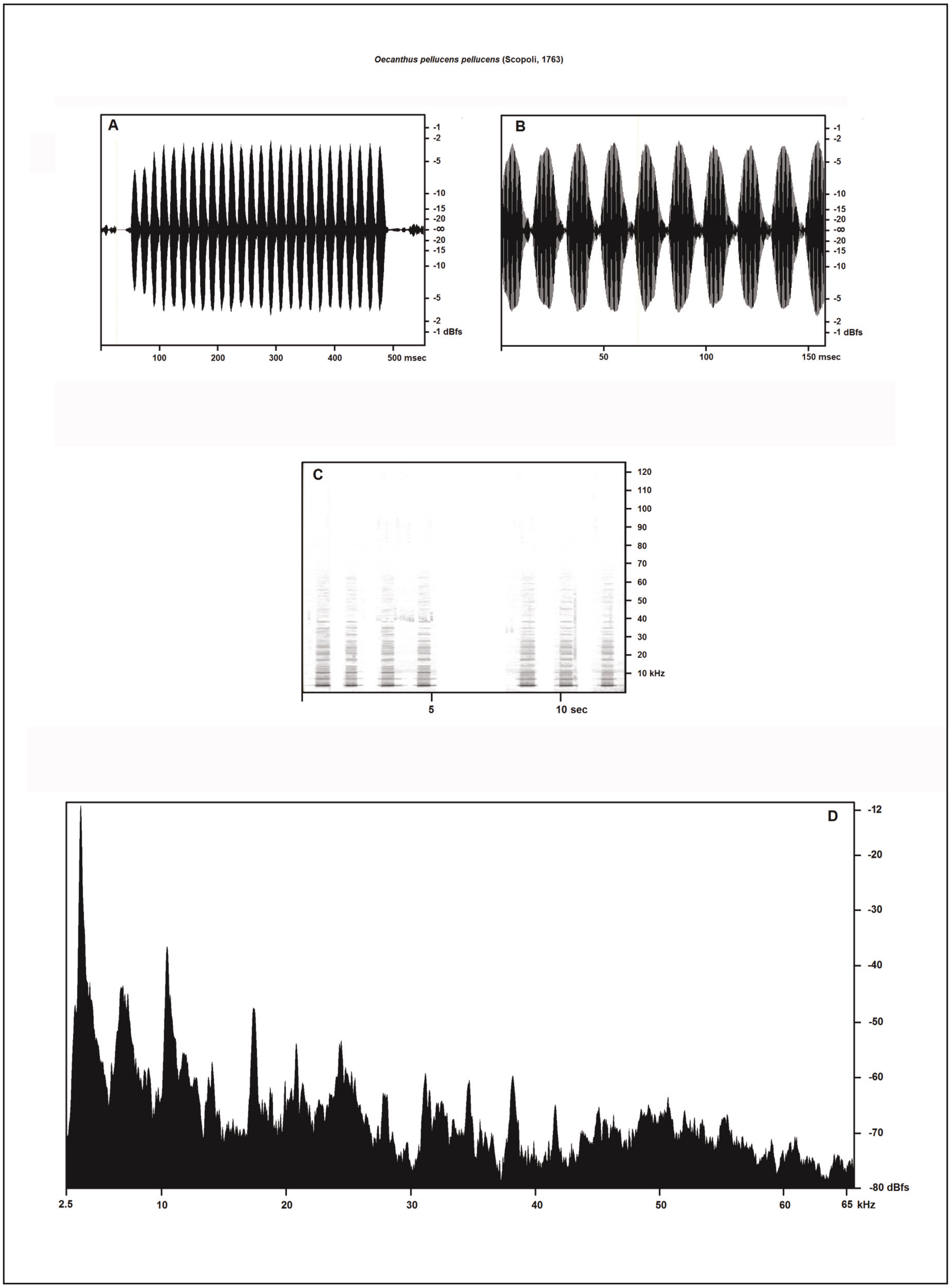


Figure 32. *Eumodicogryllus bordigalensis bordigalensis* (Latreille,1804) - A, B: envelope at two increasing levels of detail, C: spectrogram, D, E: frequency analyses - above, specimen singing in natural conditions on open ground - 4.571 sec (see Table 3); below, specimen singing from under a manhole cover, whose song is affected by selective frequency amplification and damping.



Oecanthus pellucens pellucens (Scopoli, 1763)

Figure 33. *Oecanthus pellucens pellucens* (Scopoli, 1763) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 0.578 sec (see Table 3).

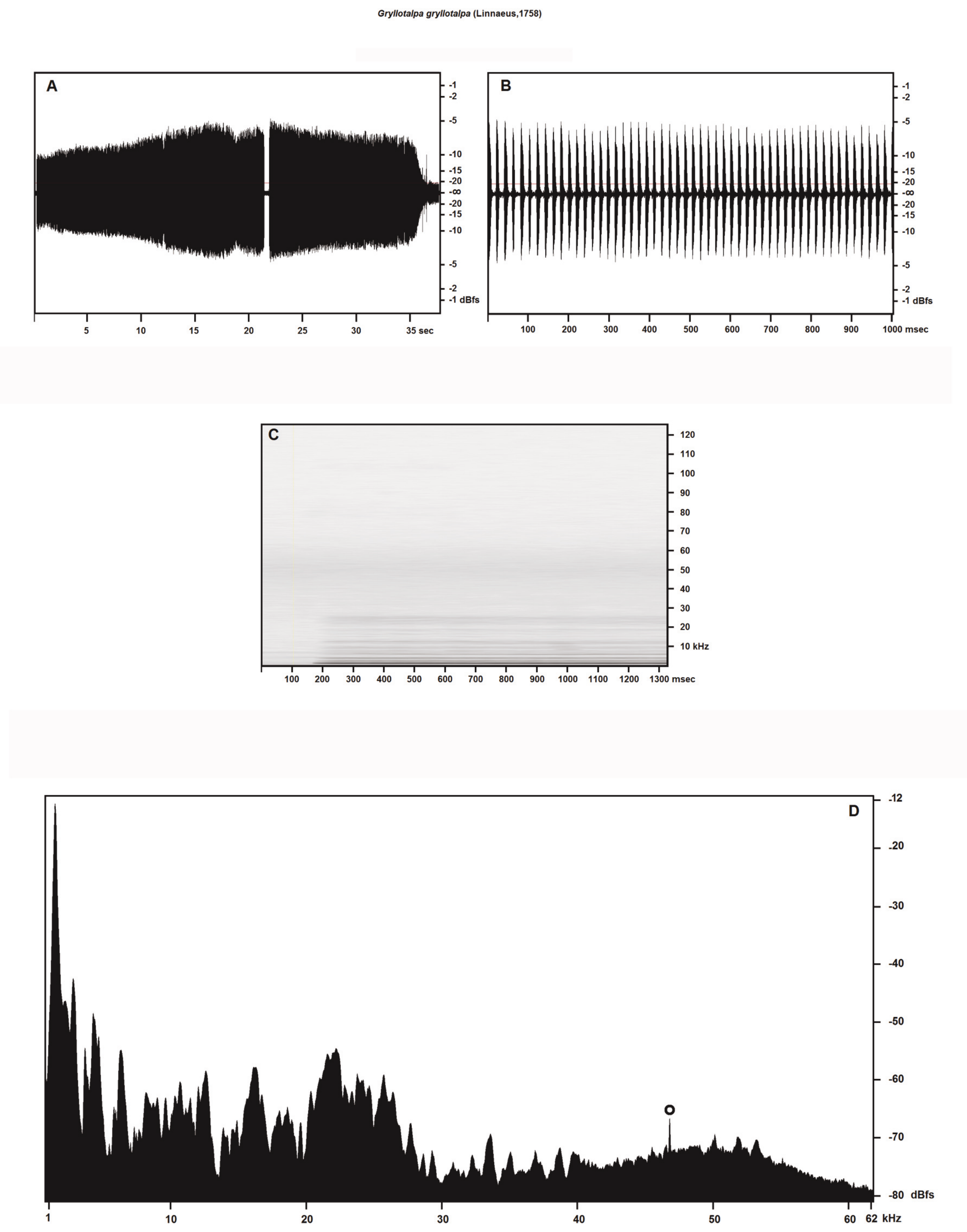


Figure 34. *Gryllotalpa gryllotalpa* (Linnaeus,1758) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 3.501 sec (see Table 3). A few artefacts peaks caused by the usage of 150cm USB cable with Ultramic 250 were eliminated with narrow band-stop filters as described in the text.

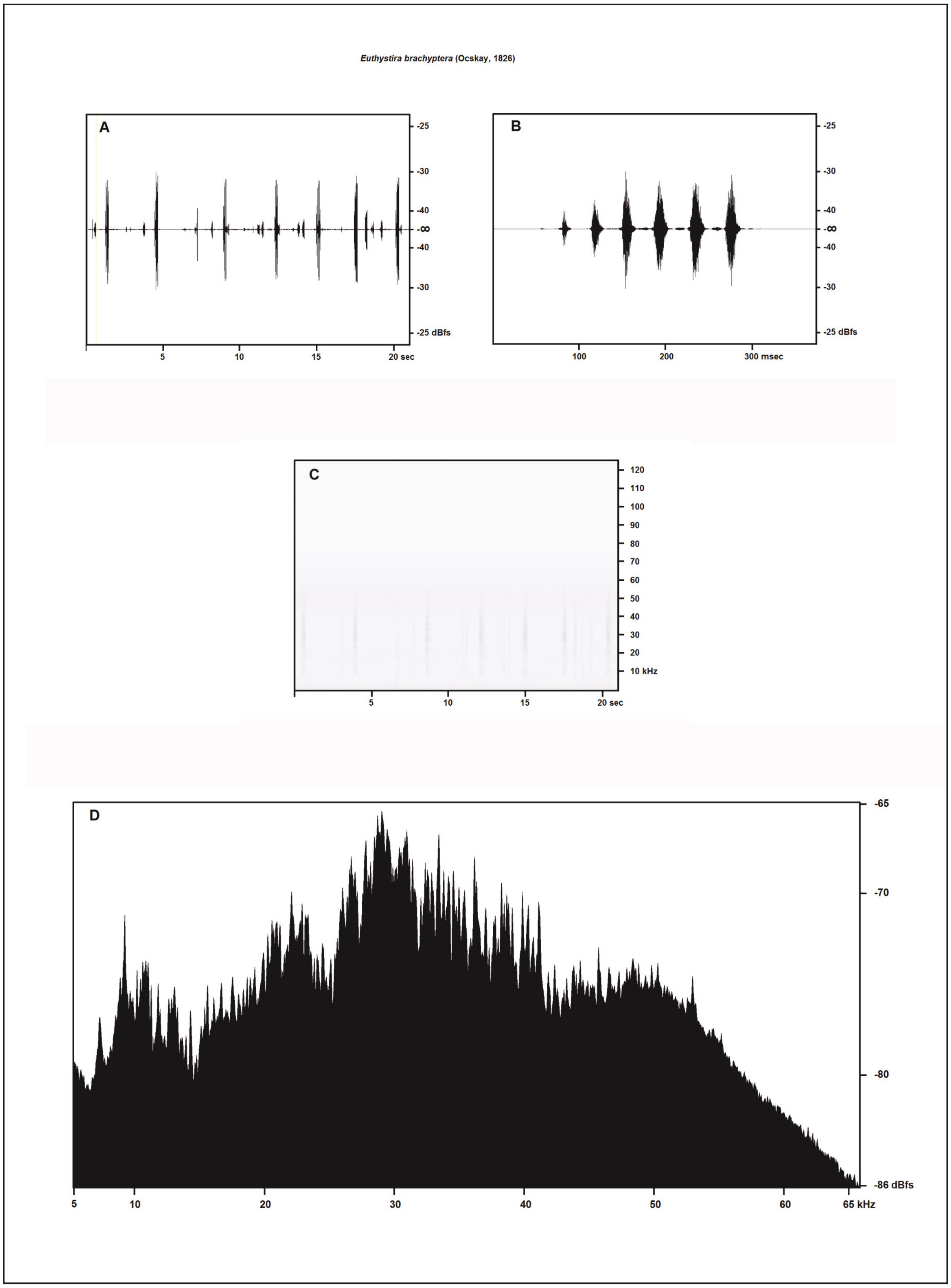


Figure 35. *Euthystira brachyptera* (Ocskay, 1826) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 11,683 sec (see Table 3).

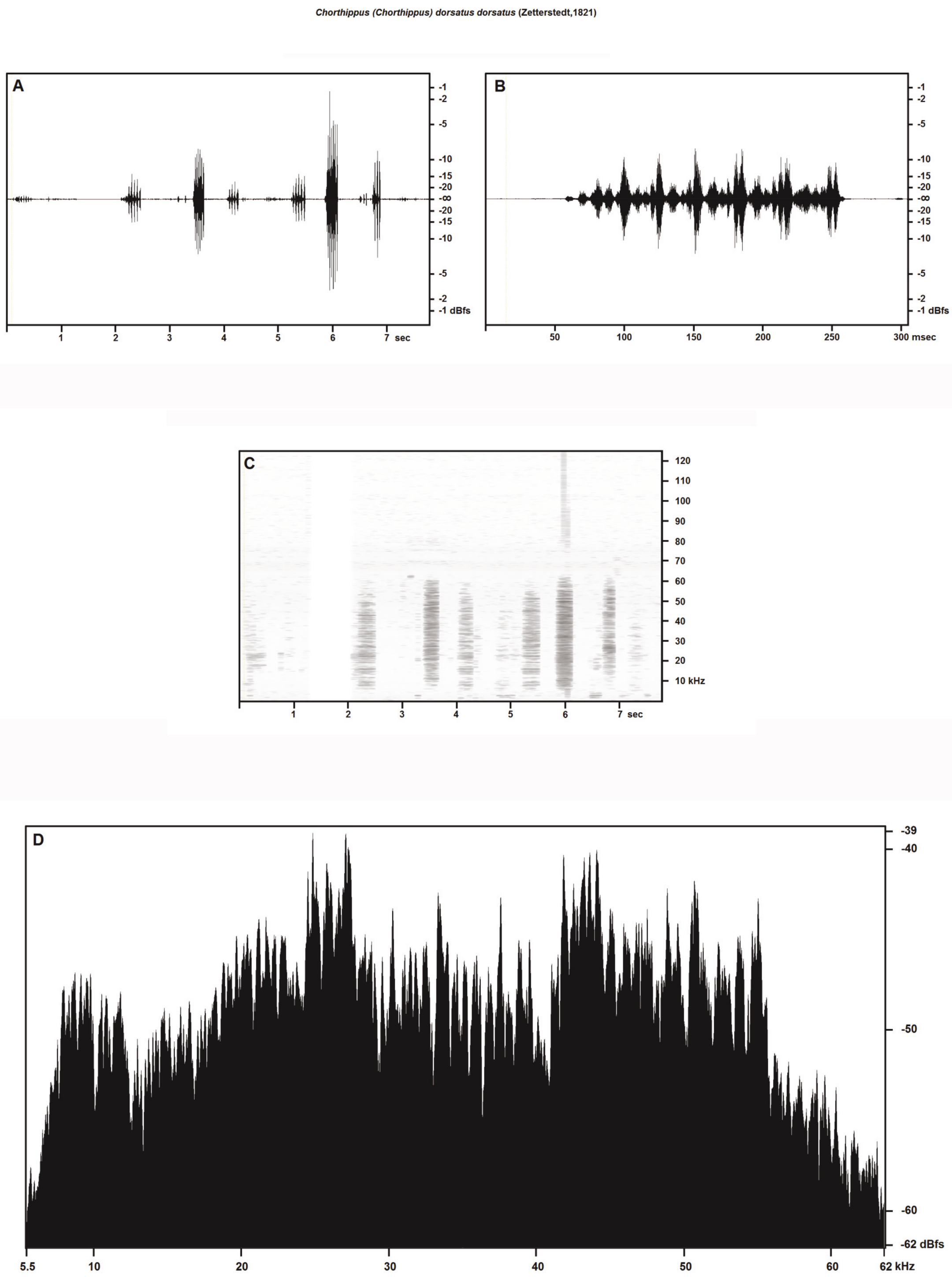


Figure 36. *Chorthippus (Chorthippus) dorsatus dorsatus* (Zetterstedt,1821) - A, B: envelope at two increasing levels of detail, C: spectrogram, D: frequency analysis - 0.501 sec (see Table 3).

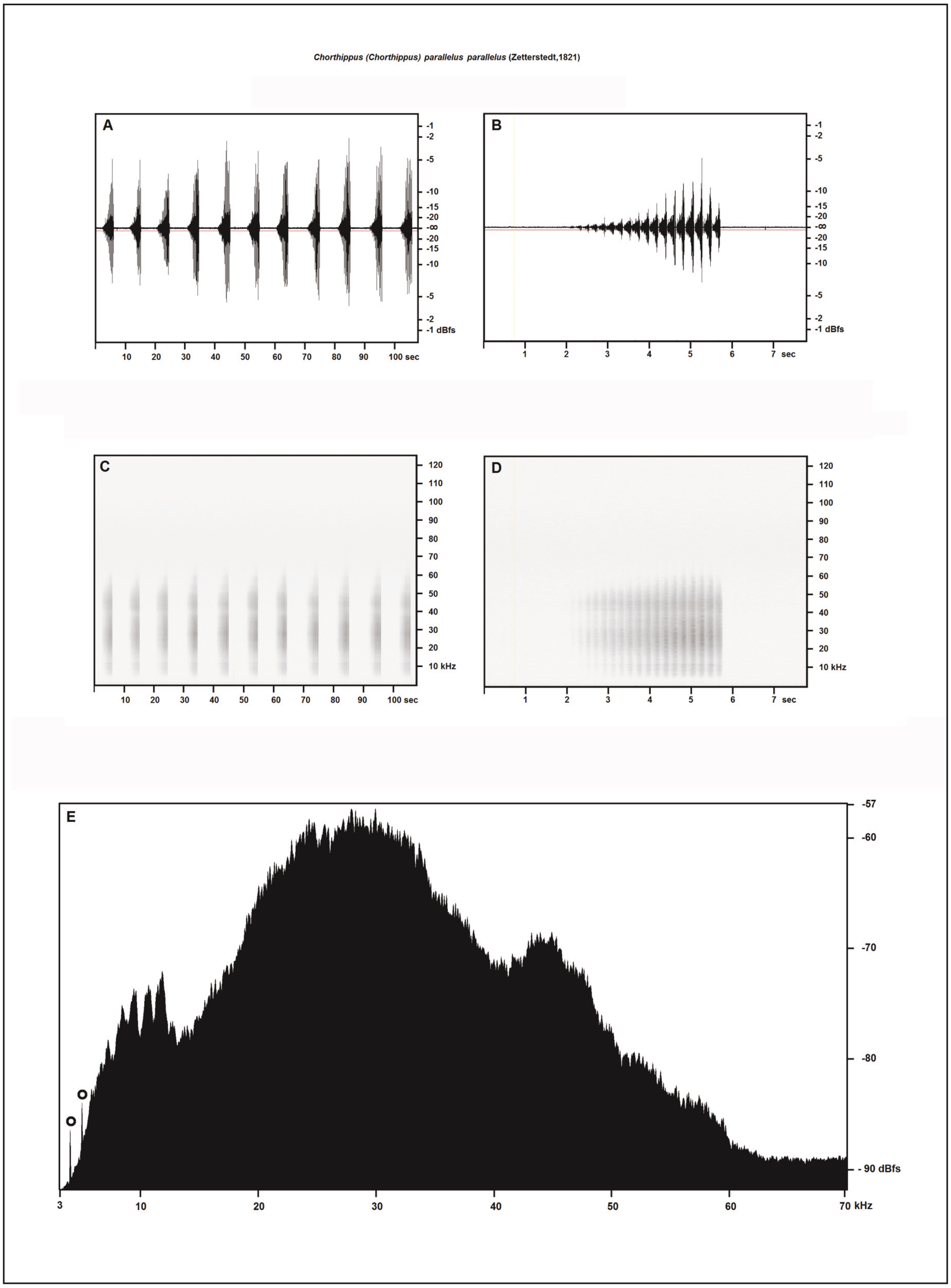


Figure 37. *Chorthippus (Chorthippus) parallelus parallelus* (Zetterstedt,1821) - A, B: envelope at two increasing levels of detail, C, D: spectrogram at two increasing levels of detail, E: frequency analysis - 14.825 sec (see Table 3).

REFERENCES

Allegrucci G., Massa B., Trasatti A. & Sbordoni V., 2013. A taxonomic revision of western Eupholidoptera bush crickets (Orthoptera: Tettigoniidae): testing the discrimination power of DNA barcode. Systematic Entomology, 39: 7–23. http://dx.doi.org/10.1111/syen.12031.

Bass H.E., Sutherland L.C., Piercy J. & Evans L., 1984. Absorption of sound by the atmosphere. In: Physical acoustics: Principles and methods, Vol. 17 (A85-28596 12–71). Orlando, FL, Academic Press, Inc., p. 145–232.

Brizio C., 2015. High frequency components of the songs of two Cicadas (Hemiptera Cicadidae) from Sardinia (Italy) investigated by a low-cost USB microphone. Biodiversity Journal, 6: 41–52

Brizio C., 2018. Bioacoustic evidence of two uncommon crickets from SW Sardinia, including an analysis of the song of *Brachytrupes megacephalus* (Lefèvre, 1827) in the ultrasonic range. Biodiversity Journal, 9: 135–142. https://doi:10.31396/Biodiv.Jour. 2018.9.2.135.142

Brizio C. & Buzzetti F.M., 2014. Ultrasound recordings of some Orthoptera from Sardinia (Italy). Biodiversity Journal, 5: 25–38.

Buzzetti F.M. & Barrientos-Lozano L., 2011. Bioacoustics of some Mexican Orthoptera (Insecta: Orthoptera: Ensifera, Caelifera). Bioacoustics, 20: 193–213. https://doi.org/10.1080/09524622.2011.9753643

Buzzetti F.M., Brizio C., Fontana P. & Massa B., 2019. A new voice from Sardinia: *Uromenus annae* (Targioni-Tozzetti, 1881) (Insecta: Orthoptera: Tettigoniidae: Bradyporinae: Ephippigerini). Zootaxa, 4560: 311–320. http://dx.doi.org/10.11646/zootaxa.4560.2.4

Cigliano M.M., Braun H.D., Eades C. & Otte D., Orthoptera Species File. Version 5.0/5.0. [January 2019]. http://Orthoptera.SpeciesFile.org

Çiplak B., Heller K.G. & Willemse F., 2009. Review of the genus *Eupholidoptera* (Orthoptera, Tettigoniidae): different genitalia, uniform song. Zootaxa, 2156: 1–75.

Elsner N. & Popov A.V., 1978. Neuroethology of acoustic communication. Advances in Insect Physiology, 13: 229–355. https://doi.org/10.1016/S0065-2806(08)60267-2

Gray D., 2016. Liminal Thinking: Create the Change You Want by Changing the Way You Think - Two Waves Books. Paperback: 174 pp.

Green E.I., 1955. The story of Q. American Scientist, 43: 584–594. https://www.jstor.org/stable/27826701?seq=1

Heller K.G., 1988. Bioakustik der europäischen Laubheurschrecken - Verlag Josef Margraf. Paperback: 361 pages.

Labadessa R. & Todisco S., 2016. Patterns of ecology and distribution of the tree crickets *Oecanthus dulcisonans* and *O. pellucens* (Orthoptera: Gryllidae; Oecanthinae) in southern Italy. Zootaxa, 4169: 579–586. http://dx.doi.org/10.11646/zootaxa.4169.3.10

Laiolo P., 2010. The emerging significance of bioacoustics in animal species conservation. Biological Conservation, 143: 1635–1645. 10.1016/j.biocon.2010.03.025.

Massa B., Fontana P., Buzzetti F.M., Kleukers R. & Odé B., 2012. Fauna d'Italia, XLVIII, Orthoptera. Calderini, Bologna, 564 pp.

Montealegre F. & Morris G.K., 1999. Songs and Systematics of Some Tettigoniidae from Colombia and Ecuador I. Pseudophyllinae (Orthoptera). Journal of Orthoptera Research, 8: 162–236.

Montealegre F., Jonsson T. & Robert D., 2011. Sound radiation and wing mechanics in stridulating field crickets (Orthoptera: Gryllidae). Journal of Experimental Biology, 214: 2105–2117. https://doi:10.1242/jeb.056283/-/DC1

Morris G.K., Klimas D.E. & Nickle D.A., 1988. Acoustic Signals and Systematics of False-Leaf Katydids from Ecuador (Orthoptera, Tettigoniidae, Pseudophyllinae). Transactions of the American Entomological Society, 114: 215–263.

National Instruments Corporation., 2018. White Paper 4278. The Fundamentals of FFT-Based Signal Analysis and Measurement in LabVIEW and LabWindows/CVI. http:// www.ni.com/white-paper/4278/en/

Moore T.E., 1989. Glossary of song terms. In: Cricket behavior and neurobiology. Huber F., Moore T.E. & Loher W. (Eds.), Cornell University Press, 485–487. https://trove.nla.gov.au/work/17011465

Narins P.M. & Capranica R.R., 1976. Sexual Differences in the Auditory System of the Tree Frog *Eleutherodactylus coqui*. Science, 192: 378–380. https://doi.org/10.1126/ science. 1257772

Obrist M.K., Pavan G., Sueur J., Riede K., Llusia D. & Márquez R., 2010. Bioacoustic approaches in biodiversity inventories. In: Manual on Field Recording Techniques and Protocols for All Taxa Biodiversity Inventories, Abc Taxa, 8: 68–99. (on-line pdf, available at: http://www.abctaxa.be/volumes/volume-8-manual-atbi/chapter-5/)

Pavan G., 1998–2017. SeaWave software. http://www.unipv.it/cibra/seawave.html

Ragge D.R. & Reynolds W.J., 1998. The songs of the Grasshoppers and Crickets of Western Europe. Harley Books, Colchester, 591 pp.

Shetty S., 2019. Determining Sample Size For Qualitative Research: What Is The Magical Number? InterQ

Research - recovered online, 15 June 2019 - https://interq-research.com/determining-sample-size-for-qualitative-research-what-is-the-magical-number/

Sugai L. & Llusia D., 2018. Bioacoustic time capsules: Using acoustic monitoring to document biodiversity. Ecological Indicators, 99: 149–152. https://doi.org/10.1016/j.ecolind.2018.12.021

Tishechkin D.Y., 2014. The use of bioacoustic characters for distinguishing between cryptic species in insects: potentials, restrictions, and prospects. Entomological Review, 94: 289–309. https://doi.org/10.1134/S0013873814030014

Vladišauskas A. & Jakevičius L., 2004. Absorption of ultrasonic waves in air. ULTRAGARSAS, Nr.1: 46–49.

Welch T.B., Wright Cameron H.G. & Morrow M.G., 2012. Real-Time Digital Signal Processing from MATLAB to C with the TMS320C6x DSPs, Second Edition. CRC Press.

Supporting material

Available at the URL https:// bit.ly/2Mwt8gS includes 38 short excerpts (10 seconds or less) from 37 different species, provided for informative purposes. All the excerpts are extracted from the audio files used for song analysis, whose details are listed in Table 3. The initial number in the file name refers to the systematic order adopted in the paper and in the same table. Excerpts may be shorter portions of the analyzed samples, and in a few cases may not include the exact segment analyzed. The audio sample of *Tessellana tessellata tessellata*, less informative because of its extreme brevity, isn't included.