Acoustic profiling of Orthoptera for species monitoring and discovery: present state and future needs

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Abstract:

Background:

Bioacoustic monitoring and classification of animal communication signals has developed into a powerful tool for measuring and monitoring species diversity within complex communities and habitats. The high number of stridulating species among Orthoptera allows their detection and classification in a non-invasive and economic way, particularly in habitats where visual observations are difficult or even impossible, such as tropical rainforests.

Methods:

Major sound archives where queried for Orthoptera songs, with special emphasis on usability as reference training libraries for computer algorithms.

Results:

Orthoptera songs are highly stereotyped, reliable taxonomic features. However, exploitation of songs for acoustic profiling is limited by the small number of reference recordings: existing song libraries represent only about 1,000 species, mainly from Europe and North America, covering less that 10% of extant stridulating Orthoptera species. Available databases are fragmented and lack tools for song annotation and efficient feature-based search. Results from recent bioacoustic surveys illustrate the potential of the method, but also challenges and bottlenecks impeding further progress. A major problem is time-consuming data analysis of recordings. Computer-aided identification software has been developed for classification and identification of cricket and grasshopper songs, but these tools are still far from practical field application.

Discussion:

A framework for acoustic profiling of Orthoptera should consist of the following components: (1) Protocols for standardised acoustic sampling, at species and community level, using acoustic data loggers for autonomous long-term recordings; (2) Open access to and efficient management of song data and voucher specimens, involving the Orthoptera Species File (OSF) and Global Biodiversity Information Facility (GBIF); (3) An infrastructure for automatised analysis and song classification; (4) Complementation and improvement of Orthoptera sound libraries, using Orthoptera Species File as taxonomic backbone and repository for representative song recordings. Taxonomists should be encouraged to deposit original recordings, particularly if they form part of species descriptions or revisions.

Introduction:

A considerable number of animal species produce species-specific sounds for communication, indicating their presence acoustically. Among the most impressive examples are tropical rainforest insects, producing a huge variety of audible signals, while only very few can actually be seen.

There is a long tradition in ornithology to identify birds by their songs (Parker, 1991). Acoustic assessment forms part of regular censusing (reviewed by Brandes, 2008), or targeted searches for flagship species such as the Ivory Woodpecker (Swiston & Mennill, 2009). Efficiency and reproducibility of human observers can be increased considerably by using powerful directional microphones in combination with cheap portable sound recording devices and bat detectors, allowing monitoring of high frequency or even ultrasound signals (reviewed by Obrist et al. 2010, p. 79). Several research groups developed sophisticated autonomous sound recording and automated classification techniques, facilitating monitoring and inventorying of birds (Celis-Murillo, Deppe & Allen,2009; Haselmayer & Quinn, 2000; but see Hutto & Stutzmann, 2009, for a discussion of limitations), whales (Širović et al., 2009), bats (Jennings, Parsons & Pocock, 2008), frogs (Hu et al., 2009), crickets (Nischk & Riede, 2001; Riede, 1993; Riede et al., 2006), bushcrickets (Penone et al., 2013) and grasshoppers (Chesmore & Ohya, 2004; Gardiner, Hill & Chesmore, 2005).

Due to their small size, seasonal occurrence and often nocturnal activity, insects are particularly difficult to monitor, requiring expensive and frequent sampling of specimens (Gardner et al., 2008). Species-specific songs of (bush)crickets and grasshoppers facilitate acoustic monitoring for non-invasive mapping of species ranges (Penone et al., 2013), discovery of hitherto undescribed, “new” species and detection of endemics, and rapid assessment of community structure and species turnover (Forrest, 1988), particularly in complex habitats with low visibility (Riede, 1993; Diwakar, Jain & Balakrishnan, 2007). In addition, methods for acoustic-based density estimation of marine mammals reviewed by Marques et al. (2013) are applicable to any other sound-producing taxa, including insects.

At present, information on phenology, activity patterns, abundance and community structure is only available for a very small number of insects, but urgently needed to document potentially dramatic effects of global warming and changing land use patterns on insect communities (Parmesan, 2007). The high number of stridulating species among Orthoptera is both opportunity and challenge to compile these highly needed datasets by acoustic profiling.

Besides species discovery, the potential of acoustic monitoring for Environmental Impact Assessments and red-listing of Orthoptera is evident: Cordero et al. (2009) recognized and mapped the rare and endangered silver-bell cricket *Oecanthus dulcisonans* Gorochov, 1993 by its song, which is clearly different from the much more common *O. pellucens* (Scopoli, 1763). At the island of Réunion, several endemic crickets are indicator species for native forest, and acoustic monitoring was applied successfully to survey a reforestation program (Hugel, 2012). The strong ultrasound components of bushcrickets can be detected by ultrasound recorders, thereby minimizing ambient noise, allowing detection of singing specimens even along roadsides (Penone et al., 2013).

Several bioacoustic monitoring studies focusing on Orthoptera applied (semi-)automatic identification (Fischer, 1997; Gardiner, Hill & Chesmore, 2005) illustrating the potential of the method, but also challenges impeding further progress (Riede, 1998; Lehmann et al., 2014). In spite of these promising prospects, the approach did not advance beyond an exploratory stage, due to several shortcomings.

Analyzing the lessons learnt, a strategic framework is presented to establish acoustic profiling as a core element of future biodiversity monitoring schemes, targeting all vocalizing animals within entire soundscapes

2. Methods:

The following analysis is based on data-mining major online sound repositories, searching for Orthoptera sound files. A short review of recording techniques is presented here, to provide a basic understanding of Orthoptera sound recording using analog or digital devices.

2.1 Targeted and passive acoustic recording

2.1.1 Targeted recording

Most repositories of Orthoptera sounds were compiled by targeted recording of individual specimens, either in the field or in the laboratory. Microphones and recording apparatus varies widely, due to considerable technological changes during the last decades, evolving from analog to digital recording. Particularly for tropical Orthoptera, reliable species identification is only possible by determination of a collected voucher specimen, which often turns out to be an unknown species, in need of taxonomic description. Therefore, most tropical Orthoptera are caught and recorded in captivity, to establish a reliable cross-reference between voucher specimen and recording. Besides essential parameters like time, recordist etc. (cf. Table II in Ranft, 2004), temperature has always to be annotated because temporal patterns of Orthoptera songs depend considerably on temperature ("Dolbear's law": Dolbear, 1897; Frings, 1962). Targeted recording was the standard methodology during 20th century insect bioacoustics, resulting in impressive analogue tape archives which often remained with the researcher. There is a high risk of loss of these valuable collections, due to deterioration and misplacement (Marques et al., 2014).

The frequency spectrum of many Orthoptera reaches far into ultrasound, with the recently described, hitherto highest-pitched katydids of the neotropical genus *Supersonus* reaching up to 150 kHz (Sarria-S et al., 2014). Common digital recorders with in-built microphones and 96 kHz sampling rate cover a frequency range up to 30 kHz with sufficient quality. In addition, there is an increasing number of ultrasound recording devices and "bat detectors", reaching far into the ultrasound up to 300 kHz (see Obrist et al. 2010, p. 79), facilitating classification of tettigoniid songs in the field.

2.1.2 Passive acoustic recording

"Passive Acoustic Monitoring (PAM) refers loosely to methods using sounds made by animals to make inferences about their distribution and occurrence over space and time." (Marques et al., 2013, p. 290). There is a rapidly increasing number of acoustic monitoring initiatives recording overall soundscapes by Autonomous Recording Units (ARUs), using custom-built or commercial equipment.

2.2 Data-mining and analysis of available repositories

Traditionally, sounds were stored on analogue tapes and archived in phonotheks (Ranft, 2004). At present, major sound repositories are digitizing and databasing their analogue recordings, making them accessible via the World Wide Web (Baker et al., 2015). The digitization of historic analogue tapes of ultrasound recordings is particularly challenging, because the appropriate recorders for their reproduction are getting rare. The amount of data is growing quickly, because new accessions are already available in digital format (a list of links to major sound libraries is provided by the International Bioacoustic Council: http://www.ibac.info/links.html#libs).

The following comparison of major sound archives focuses on the number of accessible Orthoptera songs, number of species and taxonomic compatibility with the Orthoptera Species File (OSF: Eades et al., 2015), as well as user-friendliness of web interfaces. Connectivity with the Global Biodiversity Information Facility (GBIF: http://www.gbif.org) was analysed by a GBIF query for “Orthoptera”, adding “audio” multimedia type as additional filter criterion.

2.3 Signal analysis software

An adequate classification of Orthoptera songs cannot be achieved by the unaided human ear, but requires visualization and temporal analysis by signal analysis software. A wide variety of programs is now available for Personal Computers (for an extensive list see Obrist et al., 2010), including the Ravenviewer plug-in for Firefox web-browser allowing online analysis (cf. Fig. 1).

Fig 1

3. Results:

3.1 Orthoptera songs as reliable taxonomic features

The analysis of insect sounds started with simple, descriptive verbal descriptions or musical annotation (reviewed by Ragge & Reynolds: p. 64), focusing on their function for intraspecific communication (Faber, 1953). Research about female attraction – phonotaxis – elicited by these stereotyped songs has a long history, reviewed by Weber & Thorson (1989). Some crickets and several gomphocerine grasshoppers species were used as model organisms for sophisticated neuroethological and -biological experiments to unravel underlying neural circuitry (for *Gryllus bimaculatus*, *G. campestris*: Weber & Thorson, 1989; Schöneich, Kostarakos & Hedwig, 2015; for Acrididae: Helversen & Helversen, 1998; Roemer & Marquart, 1984; Ronacher & Stumpner, 1988). It is now widely demonstrated that most Orthoptera songs are inborn, stereotyped and species-specific, providing reliable taxonomic features. Striking differences in song structure of morphologically similar species helped taxonomists to diagnose and describe "cryptic species", many of which cannot be determined without a sound recording. In a seminal paper, Walker (1964) reviewed studies on songs and taxonomy of North American Orthoptera, searching for eventual cryptic species. He concluded that "approximately one-fourth of the species of gryllids and tettigoniids of the eastern United States had never been recognized or had been wrongly synonymized." (l.c., p. 346). His discovery and description of "virtuoso katydids" (*uhleri* group of the genus *Amblycorypha*: Walker, 2004) corroborate this prediction.

Regional faunistic surveys including songs were pioneered by Pierce (1948) and Alexander (1956) for North America, Otte & Alexander (1983) for Australian crickets, and Heller (1988) for European Tettigonioidea. Each of these studies provided graphic representations and comparative analysis of acoustic signatures for hundreds of species, highlighting pronounced interspecific differences in frequency composition and temporal structure.

Most song parameters can be quantified. Cricket songs are particularly "simple" and can be characterized by carrier frequency and pulse rate (Riede et al., 2006; Walker Funk, 2014a). Some publications already include the respective datasets as supplementary material, e.g. the full workbooks published by Walker & Funk (2014b), which illustrate the strong temperature dependence of both pulse rates and carrier frequency, and provide clues as to which additional table and fields should be added to bioacoustic databases.

3.2 Sound repositories and databases: state of the art

Either automatic or expert identification of Orthoptera songs require well-curated reference collections. Song libraries are published as CDs, or stored in public and private sound archives (phonotheks). In addition - and not reviewed here - , an increasing number of recordings is available online as part of citizen science efforts (cf. August et al., 2015; Di Minin, Tenkanen & Toivonen, 2015).

3.2.1 Compilations on Compact Discs (CD)

Since the 1990s, most monographs compiling Orthoptera songs were backed up by recordings on CD, serving as potential acoustic determination guides and targeting a wider audience. Compilations are available for most European Orthoptera species (Ragge & Reynolds, 1997), Italian (Fontana et al., 2002), Central European (Bellmann, 1993), Australian Orthoptera

(Rentz, 1996) and Costa Rica katydids (Naskrecki, 2000). Due to copyright rules, most of these recordings are not publicly available. Nevertheless they can be used for analysis and feature extraction.

3.2.2 Sound archives – from phonotheks to digital repositories

The history of analogue recordings starts in 1889, and major archives of wildlife recordings go back to the 1940s (for a historical synopsis see Ranft, 2004). Several well-organized phonotheks house more than hundreds of thousands of catalogued analog tape recordings of vocalizing animals, such as the Tierstimmenarchiv Berlin (http://www.tierstimmenarchiv.de/), British Library Sound Archive's wildlife collection (https://www.bl.uk/collection-guides/wildlife-and-environmental-sounds) or the Macaulay Library of Sounds (Cornell Lab, 2017; http://macaulaylibrary.org/). The latter provides more than 160,000 playable audio files, and even permits spectrographic online visualization using RavenViewer as a free browser plugin (cf. Fig. 1).

Besides the major sound archives reviewed below, there are important regional archives (reviewed for Latin America by Ranft, 2004). Digitization of existing analogue recordings is under way, but distinct policies on use and dissemination exist. At present, most major sound archives provide searchable catalogues on the World Wide Web (see comprehensive list provided by the International Bioacoustics Council: IBAC, 2013), offering access to subsets of digitized recordings and under varying license agreements.

With more than 40,000 animal sound recording the Borror Laboratory of Bioacoustics archive (http://blb.osu.edu/database/ ; Ohio State University) is among the smaller archives, but contains important historic Orthoptera recordings by R. Alexander and D. Borror, including the few available recordings of North American grasshoppers (Acrididae).

The SYSTAX-DORSA (2017) virtual museum is a repository dedicated to Orthoptera types, song recordings, pictures and voucher specimens from German institutions and private collections. 2229 type specimens are documented by approx. 25000 images (Fig. 2). Analog tapes from widely scattered institutional and private sound archives have been digitized (Ingrisch et al., 2004) and made accessible at http://www.systax.org and via GBIF SysTax - Zoological Collections. Occurrence Dataset (2017).

Fig. 2

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3.3 Orthoptera recordings in and special features of major sound archives

The number of Orthoptera recordings and species for these major sound archives is summarized in Table 1, including comments on accessibility, user-friendliness, and particular issues. Archives differ considerably in taxonomic and geographic coverage. Most archives have several recordings for each species, and each archive has strengths and weaknesses summarized in the last column.

Table 1

While all databases allow extraction of the number of Orthoptera recordings, information about the number of species was not always available. Therefore it was queried from a table downloaded from GBIF (2015).

A close inspection reveals 3 major contributors: Borror Lab, Animal Sound Archive (= TSA), and ZFMK DORSA. Note that GBIF accesses data providers dynamically, and number of records are increasing on a daily basis. While the GBIF (2015) dataset contained 3,973 occurences, a more recent Orthoptera/Audio search (GBIF 2017) results in 4,803 occurences from 119 species. At present, federated bioacoustics datasets downloaded from GBIF have issues resulting from unresolved problems between data providers and GBIF. Macaulay (Scholes III, 2015), Systax (2017) and BioAcoustica (Baker& Rycroft, 2017) are registered, citable GBIF data providers, but occurrences disappear once the multimedia audio filter is applied. The numbers of species covered by each database presented in Table 1 do not add up, because there is a strong overlap between DORSA, Tierstimmenarchiv and OSF, with a strong focus on European species. Exact numbers on SINA are not available, and not every link from OSF to SINA leads to a sound recording. SINA is restricted to North American Ensifera, while Caelifera remain uncovered, apart from some very few historic acridid recordings from the Borror sound archive.

For each species with a DORSA recording, a “typical” song has been transferred to OSF, which by now contains songs for 778 species and subspecies. With a considerable number of recordings imported from DORSA, OSF has a similar bias towards European species. Addition of songs from newly described species will sooner or later compensate this unbalance, but addition of songs from newly described species grows slowly: According to a “complex search” in OSF, from the 857 recent species described since 2014, only 8 sound recordings found their way into OSF: 2 *Neoxabea* spp and 3 Oecanthus spp. described by Collins & van den Berghe (2014), *Tettigonia balcanica* Chobanov & Lemonnier-Darcemont, 2014 (Chobanov et al, 2014), and 2 *Typophyllum* spp described by Braun (2015) (OSF search: “sounds” AND “description date >=2014”, extracted 6/9/2015). For others (Walker & Funk, 2014a; Hemp et al., 2015) the publications contain detailed song descriptions, while the songs are either deposited outside OSF, or not accessible at all (Hemp et al., 2015). However, OSF already contains links, e. g. to Walker´s recordings, and it would be a comparatively easy task to transfer additional songs to OSF. Likewise, editors of Orthoptera song CDs (e.g. Rentz, 1996; Naskrecki, 2000) are actively involved in enrichment of OSF, and probably disposed to contribute their CD recordings. At present. This would be the most straightforward and efficient way to monitor progress of Orthoptera song coverage, and store at least one song recording for each species. The Orthopterist community is small, and given the excellent communication between OSF curators and authors, the easiest way to increase the OSF song repository would be by proactive encouragement of authors to deposit their available recordings in OSF.

In summary, accessibility of Orthoptera song recordings in any format is extremely limited. With a total of 26,000 described Orthoptera species of which a (conservatively!) estimated 10,000 are able to stridulate, we have web access to song recordings for about 1,000 species, i.e. coverage of a meagre 10 percent of all stridulating Orthoptera species. Adding another 1,000 songs scattered in publications, CDs, books and private collections, we might have song data for about 2,000, which is still only 20% of all known stridulating species. If we assume that another 20,000 Orthoptera species still have to be described (again, a conservative estimate, cf. Stork et al., 2015), we get an idea of the task ahead!

3.4 Computer-aided analysis

It is evident that Autonomous recording units (ARUs) could drastically reduce person-hours spent in the field, but the huge amount of data generated by ARUs can only be exploited efficiently in combination with species recognition algorithms. A considerable number of publications report successful algorithmic identification of sets of bat (Jennings, Parsons & Pocock, 2008), bird (Potamitis et al., 2014) and frog (Hu et al., 2009) species within field recordings from certain sites. Unfortunately, in most cases neither recordings nor the software code are available for re-analysis or re-use.

To facilitate multiple use of sound files used for improving algorithms, the respective sound files should be tagged and labelled as a corpus. A wide variety of well-documented corpora is available to be used in computational linguistics and speech recognition. A speech corpus is a well-defined set of speech audio files (Harrington, 2010), and a pre-requisite for reproducible results in classifier and recogniser development. Well-curated corpora are not yet available in bioacoustics, which hampers progress of computer-aided analysis.

In addition, downloading sound files from currently available repositories leads to disintegration of soundfile and sound metadata. The safest way to avoid such disintegration is to store metadata within the soundfile – actually, an announcement of the recordist often contains information about time, place, temperature, microphone and recording conditions. However, if this information is clipped for sake of signal clarity and detectability, a downloaded soundfile cannot be attributed to its source and metadata. For mp3 versions of SYSTAX DORSA sound files , the soundminer software (http://store.soundminer.com/) was used to annotate metadata, showing species name and source when displayed on most devices (Fig. 3).

Fig 3

Embedding metadata within the soundfile creates redundancy which can be used to restore or cross-check the links between the original database storing the metadata and the multimedia object.

3.5 Requirements

A combination of features of all databases reviewed here probably describes best the requirements for an ideal Orthoptera song database, in particular:

– comprehensive metadata for each recording, in particular temperature, microphone with frequency characteristics and distance from specimen, preferably sound intensity at a given distance.
– Cross-reference to voucher specimen.
– User-friendly upload and query interface
– Efficient, reciprocal connection to taxonomic (OSF) and specimen-based federated

specimen databases (GBIF).

– Basket function for download of selected songs and/or corpora, including metadata.

Optional requirements include online visualization of sound files (sonagram/oscillogram), generation of bioacoustic factsheets, open annotation of song parameters, together with query and visualization tools.

3.6 A data warehouse for bioacoustics data

None of the existing databases fulfils all these requirements. Therefore, the way forward is interoperability and federation of existing multimedia databases. Commercial or community multimedia providers like the pioneering peer-to-peer filesharing program Napster (https://en.wikipedia.org/wiki/Napster), itunes or soundcloud (https://soundcloud.com/) demonstrate that efficient, user-friendly data management and federation of sound files is feasible, but not designed for scientific use, requiring annotation, citability and sustainability of repositories. GBIF federates specimen data. It allows filtering for audio data, providing multimedia links, but without any interface for direct listening or bulk download via shopping basket functions.

A scheme illustrating elements and workflows of a bioacoustics data warehouse is presented in Fig. 4

Fig. 4

A fully developed bioacoustic workbench should allow seamless integration of entire soundscape recordings (as generated by ARUs) and tools for managing acoustic scenes, with software for annotation and identification of acoustic snippets (cf. Riede & Jahn, 2013), and reference corpora generated from targeted recordings with taxonomically identified voucher specimens.

A well-designed data warehouse infrastructure is the only way to organize efficient workflows between taxonomists (providing reference sound libraries) and computer scientists developing algorithmic recognition tools. Ideally, code and documentation of recognizer software should be publicly accessible through the (virtual) data warehouse, together with the sound libraries and references to voucher specimens. For the time being, it is suggested to establish OSF as a taxonomic backbone, to host at least one song recording per species, which would allow to verify completeness of bioacoustic coverage of singing Orthoptera species. Every sound file could be associated with a unique Life Science Identifier (LSID), comparable to Digital Object Identifiers (d.o.i.), facilitating the necessary cross reference between names, multimedia files, voucher specimens and eventually genetic sequences. However, at present a functional LSID architecture is jeopardized by lack of standards (cf. Table 1 in Guralnick et al, 2015).

3.7 Acoustic surveys: from acoustic profiling to species identification

Well-documented, comprehensive song libraries are the prerequisite for the next logical step, which consists in acoustic profiling of entire communities. This is particular promising for lesser known tropical faunas, where acoustic recording could accelerate species assessment. Up to now, overall analysis of Orthoptera communities based on entire soundscapes are still limited to very few sites. Lehmann et al. (2014) used ARUs at Hymettos mountain range, Greece. Tropical Orthoptera communities have been assessed in the Western Ghats, India (Diwakar, Jain & Balakrishnan, 2007), Panama (Schmidt, Roemer & Riede, 2013) and Amazonian Ecuador, the latter based exclusively on ethospecies (Riede, 1993). Evidence that ethospecies can be reliably attributed to well-defined morphospecies, was provided by systematic recording of captured individuals in Ecuadorian lowland and mountain rainforests (Nischk & Riede, 2001).

To mobilise the full potential of sound repositories for biodiversity research, innovative query tools are needed to search for sounds. The vision is to upload a sound recording to a data warehouse portal and search for similar acoustic patterns, comparable to the Basic Local Alignment Search Tool (BLAST; Altschul et al. 1990), available as a tool in genetic databases (e.g. National Center for Biotechnology Information advances science and health: NCBI, http://blast.ncbi.nlm.nih.gov/Blast.cgi). The potential of such innovative tools will be further enhanced by federated access to distinct sound archives, using one portal with a unified query tool. As a next step, applications running on portable computers could allow classification and identification of songs in the field. Such an infrastructure sounds demanding, but its elements are already available.

4. Discussion

Otte & Alexander (1983) were the first to point out the enormous potential of communicative signal analysis for understanding the systematics and taxonomy of Orthoptera: "*It must be clear at this point that those systematists who utilize communicative signals and isolating mechanisms as their principal means of locating and recognizing species are not simply studying biology as well as morphology, or simply using a wide variety of characters, as is commonly and justifiably considered desirable in bio-systematic work. Their entire approach, their methods of analysis, and their interpretations of particular kinds of data are all different. Further, and probably most important, their possibilities for rapid and accurate systematic coverage are unparalleled. For this reasons, the groups of animals for which these techniques are possible ought to present unique opportunities for breakthroughs in biogeography and in the study of speciation and other evolutionary phenomena*." (l.c., p. 5). Three decades later, bioacoustic characters of Orthoptera songs frequently form part of species descriptions, taxonomic revisions (e.g. Anatolian *Chorthippus* species: Mol, Ciplak & Sirin, 2003), as well as phylogenetic studies (Desutter-Grandcolas, 2003; Nattier et al., 2011), being a well-established element of a comprehensive, "integrative" taxomomy (Schlick-Steiner et al., 2010).

ARUs in combination with computer-aided algorithms could lead to major progress in species monitoring and discovery, providing the distribution data needed for the envisaged breakthrough in biogeography. But songs have been documented for less than 20% of described species. Reference sound libraries are missing not only for tropical regions, but are incomplete even for well-known faunas, e.g. North American grasshoppers, in spite of comprehensive literature including detailed description of communication and sonograms of songs (Otte, 1981). Unfortunately, available multimedia databases and web interfaces do not fulfil user requirements needed for species discovery: automatic identification of uploaded songs is still science fiction. However, a search for simple features (as for example, a 3 khz song at 50 Hz pulse rate, recorded in Malaysia), resulting in a list of available songs within the range of search criteria, should be easy to implement on top of adequately enriched databases.

It must be doubted that self-organizing scientific routine procedures will suffice to establish the necessary infrastructure sketched here. A strong commitment for data sharing as part of good scientific practice is needed, preferably under leadership of the respective scientific societies such as IBAC or Orthopterist´s Society, together with representatives from major sound archives. In a letter to Science, Toledo, Tipp & Marquez (2015) suggested that scientific journals require deposition of sound files used in publications. Submitting sound as additional online material for publications is certainly a step forward, but will lead to further fragmentation, with valuable sound recordings hidden as supplementary material behind journal paywalls, or distributed over a wide variety of online repositories such as Figshare, Dryad etc. Instead, a longterm, sustainable archival strategy should be centered around memory institutions, which in general have a longer half-life than states or private companies. Therefore, Riede & Jahn (2013) suggested that researchers submit sound recordings and well-annotated corpora to few well-established memory institutions, comparable to common practice in genetics. For Orthoptera, OSF provides an authoritative taxonomic backbone and tools for upload and retrieval of sound files. At present, OSF database managers and editors of the Journal of Orthoptera Research encourage submission of sound files together with manuscripts, but there is no obligation. In contrast, submission of gene sequence data to the National Center for Biotechnology Information (NCBI) is a pre-requisite for publication, resulting in rapid population of gene banks, and impressive advances in molecular biology.

Traditional targeted song recordings of individual Orthoptera species have now been complemented by acoustic profiling using entire soundscapes (*sensu* Schafer, 1994). Soundscapes are recorded routinely for environmental monitoring (Szeremeta & Zannin, 2009) or military uses (Ferguson & Lo, 2004). Sueur et al. (2008) applied signal analysis to entire soundscapes recorded at Tanzanian coastal forests, measuring entropy as a surrogate for biodiversity richness. Further recordings were made at biodiversity hotspots in New Caledonia and French Guiana (reviewed in Sueur et al., 2014). Such overall bioacoustic indices do not provide information about actual Orthoptera species presence and diversity, but informative snippets could be extracted (Riede & Jahn, 2013; Lehmann et al., 2014). This means that post-hoc analysis for Orthoptera presence/absence at an ever-increasing number of acoustic monitoring sites is possible, if soundscape recordings would be made available for re-analysis. At present, the Purdue soundscape server provides unlimited access to an impressive number of high-quality recordings (Pijanowski et al., 2011; Purdue Sound Ecology Project, 2015), while the extensive soundscape collection of Krause (2017) is commercial, but nevertheless available for Orthoptera song data mining (Jones 2017 just reported a complete burndown of Bernie Krause´s archive during 2017 California wildfires. It seems that the data are still available, thanks to backup copies at 2 localities, one in Europe, illustrating the importance of mirror servers).

In spite of promising first results, an efficient connection and data flow between sound archives, museum collections, advanced computational tools and users has not yet been established. Close cooperation of biologists with computer engineers is needed to cope with the data deluge generated by ARUs. Again, well-curated and documented song libraries are a prerequisite to exploit bioacoustic Big Data for further biodiversity assessments

Basically, an efficient acoustic sampling strategy should consist of the following components:

1. Protocols for standardised acoustic recording, at species and community level, using acoustic data loggers for autonomous long-term recordings.
2. Open access to and efficient management of sound recordings, song data and voucher specimens, involving the Orthoptera Species File (OSF: Eades et al., 2015) as a taxonomic backbone, and the Global Biodiversity Information Facility (GBIF) for federation of distinct biodiversity multimedia databases.
3. An infrastructure for automatic analysis and song classification for on-the ground and web-based analysis, including web2.0 applications for user communities and citizen science (see Di Minin, Tenkanen & Toivonen, 2015).
4. A strategic framework for future inventorying and monitoring efforts, including geographic priorities.

Components 1 and 3 involve the entire terrestrial bioacoustics research community, requiring considerable effort to overcome fragmentation between distinct bioacoustic subgroups, clustering around distinct taxa (e.g. frogs, birds etc.). In contrast, 2 and 4 focus on Orthoptera and are feasible, eventually serving as a model for other species groups.

4. Conclusions

Orthoptera songs are reliable taxonomic features which can be quantified by well-defined signal parameters such as carrier frequency and pulse rate. The future challenge is integration of sound archives into the developing biodiversity information infrastructure, to develop the full potential of “integrative taxonomy” (Dayrat 2005). Assessment and monitoring of biodiversity is among the priorities of the Convention of Biodiversity strategic framework program (Aichi Target 19: CBD2010). Acoustic profiling techniques have much to offer, from rapid assessment and species discovery of acoustically active species in remaining wilderness areas to continuous monitoring in managed landscapes. Their full potential can only be developed by cooperative data sharing. For Orthoptera, OSF provides the ideal taxonomic backbone and can serve as a testbed for the development of further innovative query tools. For other vocalizing taxa and soundscapes, the existing well-established sound archives reviewed here could cooperate to create the necessary data-warehouse infrastructure with a workbench providing annotation and query tools. At present, an increased wealth of digitized bioacoustic data leads to confusing fragmentation: without the creation of a data warehouse infrastructure, bioacousticians will lose an excellent opportunity to exploit potential synergies from on-going soundscape monitoring initiatives, and contribute to urgently needed biodiversity assessments. Likewise, without willingness for datasharing, the newly emerging field of ecoacoustics will generate fragmented soundscape monitoring projects.

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Table 1

Table 1: Digitized Orthoptera songs in major sound archives and databases. For further details on issues and special features see text.

Archive[1]	N Orthoptera recordings	N taxa	Taxa	Geographic focus Orthoptera fauna	Issues and special features
Macaulay Cornell Lab	9,282	262[2]	All animals; Ensifera	North America	+ Raven viewer for sound visualization + Basket function for download, annotations (+) GBIF federation with issues - no voucher cross-reference - Temperature missing or comment only
SYSTAX-DORSA	8,669[3]	550	Orthoptera	Europe (Ecuador, South East Asia)[4]	+ Additional user interfaces via Europeana (+) GBIF federation with issues + Additional user interfaces - uploads difficult; completed archive - Temperature in commentary
Tierstimmen-archive	1,093	66	All animals; Orthoptera	World-wide, mainly Europe	+ Full GBIF federation - no voucher cross-reference - temperature missing or hidden in text
BioAcoustica[5]	2,358	556	Orthoptera	World-wide, mainly Europe	+ Graphic display of standard sound analysis + Rapidly growing, allowing user uploads (+) GBIF federation with issues
Borror Sound Archive	1,761	119	All animals; Orthoptera	North America, Australia	+ full GBIF federation
SINA	n.a.	(440)[6]	Ensifera	North America	+ Species fact sheets with sonagrams and songs for download + full tables of song parameters for download[7] + cross-reference to voucher - no database query interface - GBIF
Orthoptera Species File	n.a.	776[8]	Orthoptera	World-wide	+ well-curated, up-to-date taxonomic backbone (+) providing links to additional resources - temperature hidden in commentary
GBIF[9]	4,803	119	Orthoptera	World-wide	- double-entries of specimens from distinct data providers but identical primary source

[1] See References for web addresses and extraction date

[2] Calculated using GBIF download GBIF Occurrence Download 10.15468/dl.xsud5i

[3] Riede K, Ingrisch S, Jahn O (2013)

[4] See map at http://www.gbif.org/dataset/72309d40-0c1f-47d6-8008-33e687b7df7a

[5] http://bio.acousti.ca/analyses

[6] Estimate using complex OSF search for North American Ensifera AND link, most links leading to SINA species fact sheets. Note that not all SINA pages contain a sound recording.

[7] Full workbook: http://entnemdept.ifas.ufl.edu/walker/Buzz/g610ms3.htm showing temperature-dependence of song parameters

[8] Including subspecies.

[9] GBIF Occurrence Download doi:10.15468/dl.psq6q1 accessed via GBIF.org on 03 Nov 2017

Figures and captions

Figure 1

Fig. 1 Web-based sound analysis tool for the Macaulay Sound Library, Cornell Lab (https://www.macaulaylibrary.org). Macaulay library provides more than 120,000 playable audio files (http://macaulaylibrary.org/index.do), and even permits spectrographic online visualization using RavenViewer as a free browser plugin (http://www.birds.cornell.edu/brp/software/sound-analysis-tools). The example shows a recording of a Virtuoso katydid by T. Walker, who provided most of the Orthoptera sound recordings for this sound library. Further details see text.

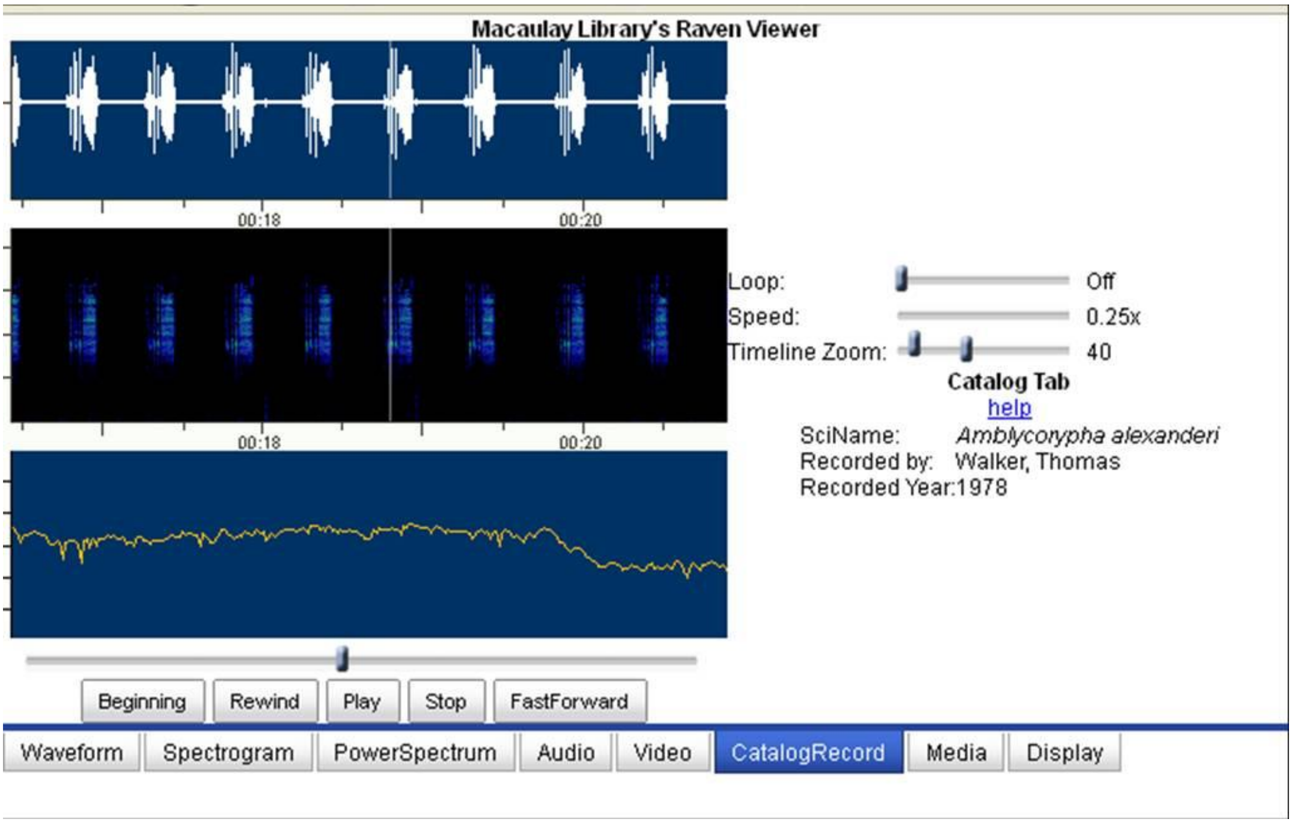

Figure 2

Fig. 2 The SYSTAX database

Screenshot of the new SYSTAX user interface, to be released under www.systax.org. A search for the neotropical tettigoniid genus *Anaulacomera* produces several sound recordings from a voucher specimen of a hitherto undescribed species, documented by pictures. Facetting allows to restrict the search to pictures or sounds exclusively.

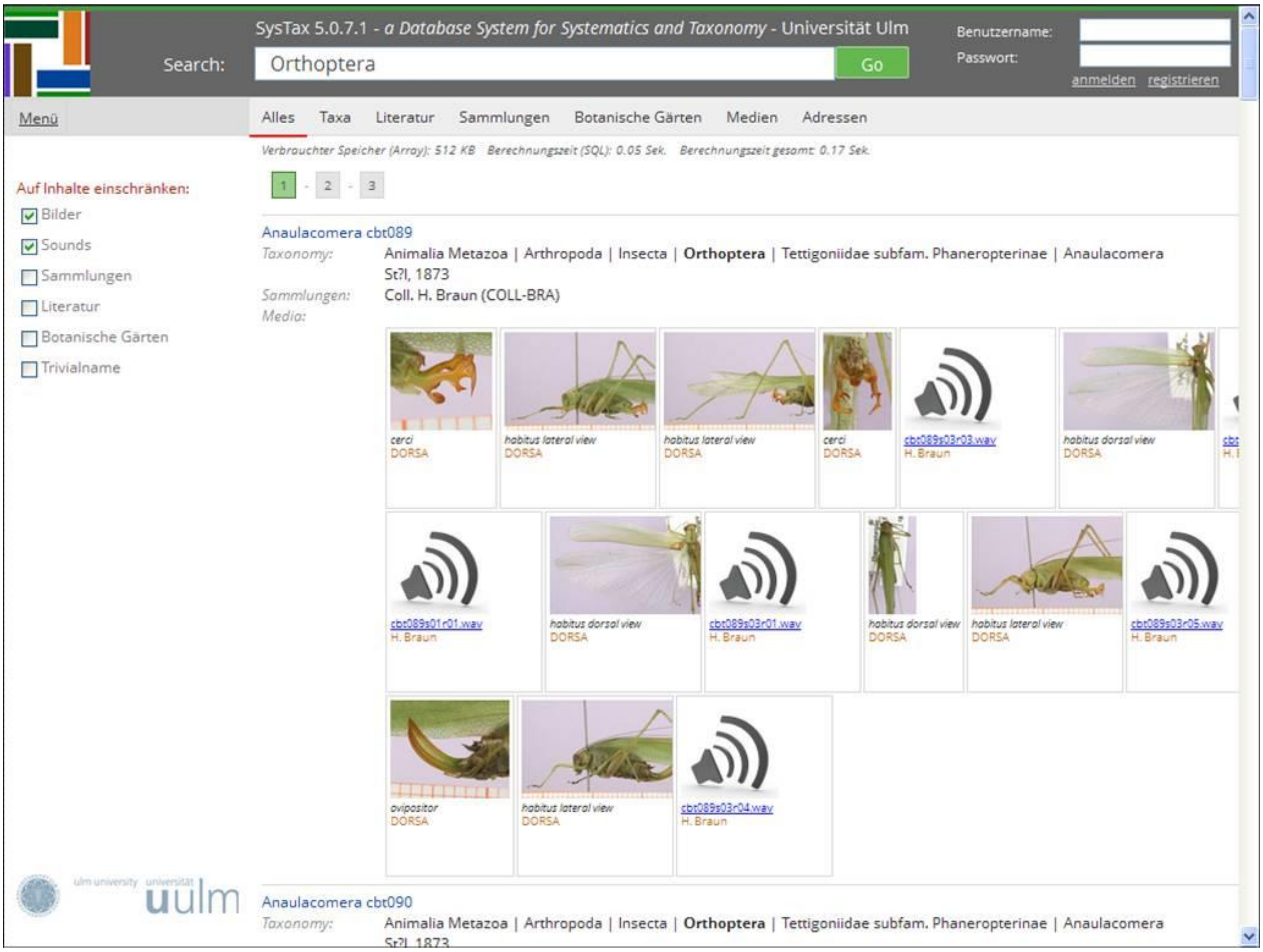

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Figure 3

Fig. 3 Embedding metadata within sound files

Metadata were embedded within wav and mp3 fields directly from the SYSTAX database, using Soundminer software (http://store.soundminer.com/). Metadata are visible within most mp3-players, displaying the species name as ―track name‖, and the recordist as ―artist‖ (courtesy: Sigfrid Ingrisch).

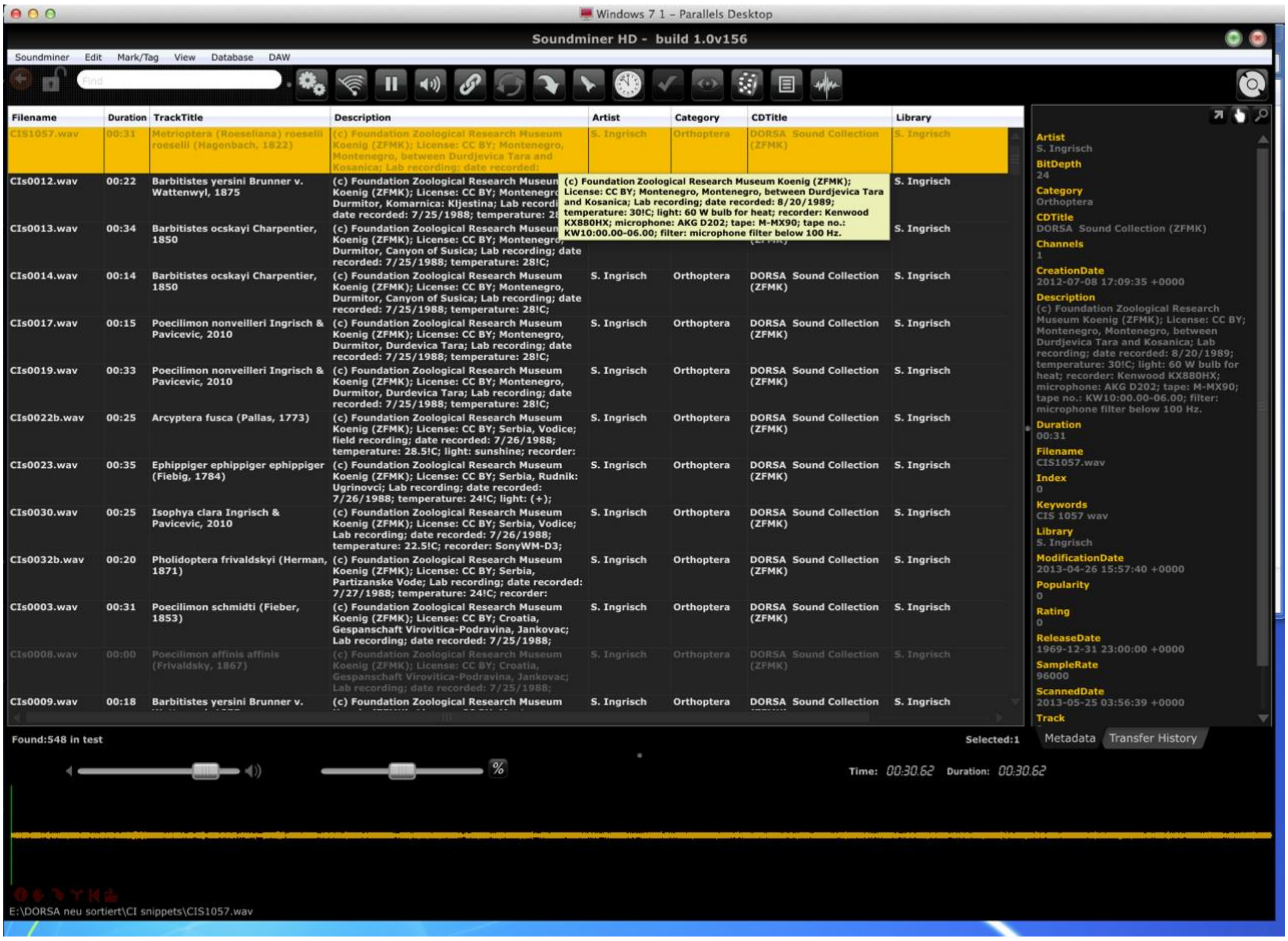

Figure 4

Fig. 4 A data warehouse for sound management

The scheme illustrates elements and workflow for acoustic profiling of Orthoptera. Songs are sampled either by recording individual songsters (Targeted Recordings), or entire acoustic scenes, each of which could contain several Orthoptera songs. Targeted recordings are treated like specimens, with time and locality stamps, and preferably a voucher specimen. All databases listed in Table 1 are designed to store individual recordings. These distributed databases could be federated via ABCD- or Darwin-protocol. Soundscapes require distinct data management of large multimedia files. Orthoptera songs could be extracted manually or semi-automatically as sound snippets, and eventually be identified (ID) manually, or using automatic sound recognition algorithms (ASR). Many snippets can be extracted from each scene, resulting in a 1: many relation between scenes and snippets.