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Bioacoustic time capsules: Using acoustic monitoring to document biodiversity

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ABSTRACT

In the current extinction crisis, emerging technologies can support the urgent need to document biodiversity worldwide. Automated acoustic recorders are increasingly being used to remotely monitor species and soundscapes across the planet, generating a growing and valuable sound collection from present ecosystems. Such a collection can become a benchmark for future ecological research and shed light on our understanding of global change. Here we discuss the challenges and potential of acoustic monitoring to compose *bioacoustic time capsules*, environmental recordings capable to document, for future generations, how the planet's acoustic communities were in the past. For the present, acoustic monitoring can assist in ecological research and increase the chances of a species being detected, described, and hence protected. For the future, the collected time-series of audio recordings will compose *bioacoustic time capsules*, providing singular historical information on the structure and dynamics of past ecosystems and the activity of extinct fauna (*acoustic fossils*). Thus, we claim that acoustic monitoring should be included in biologist's toolbox to optimize the diligent task of documenting and protecting biodiversity.

Human activities are prompting alarming rates of species loss and natural population declines worldwide, pushing biodiversity into a new extinction crisis (Barnosky et al., 2011; Johnson et al., 2017). Such a global process exceeds the capacity of biologists to properly document, understand, and protect the planet's life (Wilson, 2017), and many species may likely undergo extinction even before being described (Costello et al., 2013). Facing this urgent challenge, we do need more "boots on the ground" to document biodiversity (Wilson, 2017), and novel emerging technologies can be invaluable tools for this task.

Automated audio recorders enable systematic and unattended recordings of environmental sounds and have recently opened new opportunities for ecological research and conservation practices (Wrege et al., 2017; Sugai et al., 2018). A myriad of organisms, including crustaceans, arachnids, insects, fish, amphibians, reptiles, birds, and mammals produces species-specific acoustic cues during their daily activity (Bradbury and Vehrencamp, 1998; Gerhardt and Huber, 2002), leaving a highly-informative trace that can be registered and further examined to reveal the presence of species and multiple aspects of their ecology and behavior (Blumstein et al., 2011; Obrist et al., 2010). Thus, the passive acoustic monitoring (PAM) of biological sounds can provide, in a non-invasive manner, long-term and standardized data of the composition and dynamics of animal communities.

Ecological research using PAM is increasingly being employed both in terrestrial and aquatic ecosystems (Linke et al., 2018; Sugai et al., 2018). Among a wide range of applications, PAM has been used to support rapid acoustic inventories on priority conservation areas, to detect the presence of cryptic species, and to unveil changes in species' abundance, phenology and distribution patterns (Laiolo, 2010; Sueur and Farina, 2015). Particularly, PAM recordings can broaden the possibilities to monitor populations and communities over time (Farina et al., 2011; Deichmann et al., 2017) and space (Llusia et al., 2013; Lomolino et al. 2015), improving our capacity to assess large-scale ecological processes.

In addition to its current use, acoustic monitoring may have an important role in future research. PAM and directional recordings reserve valuable information about our current biodiversity and can work as a *bioacoustic time capsules*, i.e., audio records that are capable to document, for future generations, how the planet's acoustic communities were in the past. Once ecosystems' integrity is approaching unsafe boundaries for biodiversity persistence (Newbold et al., 2016), the

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recordings being currently collected worldwide can become a benchmark for upcoming research and perhaps help to understand the magnitude and direction of global change in the future.

Recordings containing sounds of probably extinct species can already be found in biological collections, such as the Ivory-billed woodpecker (*Campephilus principalis*), the Bachman's warbler (*Vermivora bachmanii*), or the Chile Darwin's frog (*Rhinoderma rufum*). Following the paleontological terminology, these recordings resemble trace fossils, i.e. records of past biological activity, like animal's footprints or burrows (Seilacher, 2007). Thus, we can refer them to *acoustic fossils*. Given the current scenario of mass extinction, it is expected that many of the collected audio recordings will likely become evidence of extinct fauna in a near future, adding to the records of *acoustic fossils*.

Beyond the importance of audio recordings to document biodiversity patterns, they can also help to piece together aspects of species' natural history. Paleontologists have tried to reconstruct sounds of extinct species based on their morphological characters and sound production structures, including those produced by crickets (Gu et al., 2012), dinosaurs (Diegert and Williamson, 1998), and hominids (Barney et al., 2012). For instance, the finding of an exceptionally preserved stridulatory apparatus of the 165 million-year-old extinct bush-cricket *Archaboilus musicus* unveiled that the species likely produced radiated songs at 6.4 kHz, and together with paleobotanical reconstructions of the Jurassic forest where this bush-cricket inhabited, suggested a communication system well adapted to long-distance signaling close to the ground (Gu et al., 2012). However, this is rather a rare example, and for most of the extinct species, we probably will never be able to hear their vocalizations, even for those recently extinct but unrecorded, such as the Dodo (*Raphus cucullatus*), the Steller's sea cow (*Hydrodamalis gigas*), or the Madagascan sloth lemurs (*Palaeopropithecus* spp.). Thus, the collection of audio recordings nowadays helps to preserve evidence of our current and ephemeral environment and will possibly have an inestimable value in the future.

To build *bioacoustics time capsules,* audio recordings at any temporal scope must be stored, curated and preserved for the long term. Museums and biological collections can assist in such purpose as they preserve types, specimens, and other biological material that are used as a baseline to investigate changes in biodiversity, playing an important role in our understanding of nature (Suarez and Tsutsui, 2004; Pyke and Ehrlich, 2010). For instance, directional recordings of animal vocalizations have long been deposited in museums and sound libraries. The British Library provides a section of digitalized biological sounds, with early bird recordings made by Ludwig Koch (1881–1974) and Carl Weismann (1906–1999) since the 1930's. The Macaulay Library, maintained by the Cornell Lab of Ornithology, includes more than 367 thousand audio files, mostly focused on birds, while FonoZoo sound library at the Spanish National Museum of Natural Sciences house recordings of more than one thousand frog species. These sound repositories have supported research in multiple areas, such as taxonomy (Köhler et al., 2017), conservation (Laiolo, 2010), evolution (Goicoechea et al., 2010), and behavior (Guerra et al., 2018).

With the widespread adoption of automated audio recorders by biologists for PAM-based research (Linke et al., 2018; Sugai et al., 2018), the diverse and huge collection of environmental recordings being collected can be important assets for *bioacoustics time capsules.* Yet, to take advantage of such opportunity, present constraints in data preservation and open-access should be overcome. Differently from manual recordings, automated recordings are considerably larger and commonly gathered in time-series, generating enormous amounts of data. Thus, PAM data currently challenge the capacities of sound libraries and audio repositories. To accommodate these datasets as *bioacoustic time capsules*, biological collections should be supplied with cutting-edge digital infrastructure to allow big data management and online deposit of PAM datasets. First steps on this direction have started to be developed, with pioneering platforms specifically designed to deal with passive audio recordings, such as ARBIMON (Aide et al., 2013), REAL (Kasten et al., 2012), and Ecosounds, which can guide forthcoming PAM-oriented public libraries. Additionally, some initiatives to collect long-term audio recordings from environments undergoing human-impacts have been promoted so far and, in some cases, at the interface between science, art, and citizen-science (e.g., Wild Sanctuary, 2018, Fragments of Extinction, Center for Global Soundscapes). For instance, the Wild Sanctuary, led by Bernie Krause, contains over 4500 h of environmental sounds, with a remarkable portion recorded before human-induced habitat alterations.

Besides the aim of having suitable collections for long-term storage of large volume of recordings, the availability of PAM datasets for a future use also requires a more active role from researchers, who are responsible for the data deposit (Riede, 2018). Toledo et al. (2015) have recently emphasized the scant application of this practice among scientists and called for journals to demand authors to provide their recordings along with publications. The worldwide collected audio recordings from PAM are mostly scattered over individual projects, preventing them from being properly safeguarded and shared. This common practice increases the potential risk of loss or damage of valuable audiovisual records, as for what has dramatically happened in recent dates (Dena et al. 2018) and hampers the collective effort of documenting the current biodiversity crisis.

To contribute to the need of registering biodiversity for present and future research, many options of commercial and customized audio recorders developed for PAM are currently available: (i) programmable devices with scheduling functions for terrestrial (e.g. SM4, ~$850, 219 × 186 × 78 mm, 1.3 kg, Wildlife Acoustics®; BAR, ~$600, 110 × 130 × 70 mm, 0.3 kg, Frontier Labs®; SWIFT, ~$300, 119 × 129 × 61 mm, 1.1kg, Cornell Lab of Ornithology, BRP®) and marine environments (e.g., SM4MDEEP, ~$9.000, 1.480 × 165 mm, 32.2 kg, Wildlife Acoustics®), (ii) permanent cellular-based recording stations (ARBIMON Permanent Station, ~$4000, 174 × 116 × 48 mm plus solar panel, 1.2 kg, Sieve Analytics®), (iii) low-cost programmable recorders (AudioMoth, ~$40, 58 × 48 × 18 mm, 80 g, Open Acoustic Devices; Hill et al., 2017), (iv) low-cost non-programmable USB flash drive audio recorders (e.g., UR09, ~$10, 64 × 22 × 10 mm, 14 g, HNSAT, Farina et al., 2014), or (v) open-source customizable devices (AURITA, ~$450, 350 × 230 × 86 mm, with hard case Beason et al., 2018; SOLO, ~$110, Whytock and Christie, 2017).

Moreover, straightforward and best practices guides for field recording provide researchers the fundamentals of acoustics, equipment, and recording methods (Obrist et al., 2010; Llusia et al., 2011; Browning et al., 2017; Gibb et al., 2018). Despite its underlying complexity, analytical solutions to extract and synthesize biological information from passive audio recordings are also growing and moving from manual procedures to automated frameworks employing machine learning algorithms (e.g. Kholghi et al., 2018; Sueur, 2018; Ulloa et al., 2018). These new methods offer options to discriminate singular elements contained in audio recordings, hence decreasing the time devoted in identifying species-specific acoustic signals over long time-series datasets. Paired with big data analysis in ecology (Marvin et al., 2016; Farley et al., 2018), advances toward automated analyses offer new perspectives on the use of PAM within the ecologist's toolbox (Gibb et al., 2018). The growing use of PAM for a variety of taxa, subjects, and locations across the planet offers an excellent framework to build *bioacoustic time capsules*. Thus, we encourage scientists to intensify the use of passive acoustic monitoring with the aim of documenting biodiversity patterns worldwide. Basic information on natural history, species distribution, and ecology is still lacking to effectively protect species and their habitats (Whittaker et al., 2005; Brito, 2010), and acoustic monitoring can help researchers in this diligent task. For the present, PAM can assist in biodiversity inventories, field surveys, and monitoring programs (Laiolo, 2010; Obrist et al., 2010; Sueur and Farina, 2015) and increase the chances of a species being detected, described, and hence protected. For the future, the collected time-series of environmental recordings will compose *bioacoustic time capsules*, providing singular historical information on the structure and dynamics of past ecosystems. In this last perspective, we will all have failed to protect biodiversity if these recordings soon become *acoustic fossils* of extinct species or communities, but at least we would provide future generations historical registers of extinct fauna and how our ecosystems once sounded.

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