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It's time to listen: there is much to be learned from the sounds of tropical ecosystems

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"The universe is your orchestra. Let nothing less be the territory of your new studies." – Raymond Murray Schafer (1969)

KNOWLEDGE THAT CAN BE GAINED FROM ACOUSTIC DATA COLLECTION IN TROPICAL ECOSYSTEMS is low-hanging fruit. There is every reason to record and with every day, there are fewer excuses not to do it. In recent years, the cost of acoustic recorders has decreased substantially (some can be purchased for under $50, e.g., Hill *et al.* 2018) and technology needed to store and analyze acoustic data is continuously improving (e.g., Corrada Bravo *et al.* 2017, Xie *et al.* 2017). Soundscape recordings provide a permanent record of a site at a given time and contain a wealth of invaluable and irreplaceable information. Although challenges remain, failure to collect acoustic data now in tropical ecosystems would represent a failure to future generations of tropical researchers and the citizens that benefit from ecological research. In this commentary, we (1) argue for the need to increase acoustic monitoring in tropical systems; (2) describe the types of research questions and conservation issues that can be addressed with passive acoustic monitoring (PAM) using both short and long-term data in terrestrial and freshwater habitats; and (3) present an initial plan for establishing a global repository of tropical recordings.

In an era of rapid environmental change, remote sensing methods are particularly important for ecology and conservation biology because they produce consistent data streams that can be analyzed over different spatial and temporal scales (Kerr & Ostrovsky 2003, Turner *et al.* 2003, Nagendra *et al.* 2013). Passive acoustic monitoring (PAM) is one way to characterize and evaluate ecosystems remotely using sounds. First developed for use in the marine realm (Tavolga 2012), autonomous recordings can detect a range of sounds produced by natural and

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physical phenomena (Krause 1987). The "soundscape" includes all sounds emanating from any given habitat, which can be classified with respect to their source: geophony (climate and geography), biophony (all wildlife) and anthrophony (human activities; Pijanowski *et al.* 2011). Analysis and monitoring of these various contributions to a soundscape permits rapid assessments of biodiversity as well as the health and stability of an ecosystem (e.g., Blumstein *et al.* 2011, Pijanowski *et al.* 2011, Fuller *et al.* 2015, Bertucci *et al.* 2016, Burivalova *et al.* 2017, Deichmann *et al.* 2017, Staaterman *et al.* 2017).

APPLICATIONS OF ECOACOUSTICS IN THE TROPICS

Many tropical biologists have been startled by the sound of a nearby tree fall, while others have been warned of an oncoming storm by croaking toucans or the presence of a predator by screeching squirrel monkeys; yet many of us have never considered that these sounds are data that can be harnessed to answer questions about tropical ecosystems. Here are a few examples of the types of questions that can be answered using sounds:

POPULATION DYNAMICS AND ACTIVITY PATTERNS.— We know very little about the natural activity fluctuations within tropical forest communities, and perhaps even less in tropical freshwater systems. Thus, it is difficult to precisely assign causal relationships between human activities and changes in biodiversity (Thompson 2003). For example, is the decline in abundance of a hornbill species in an Indonesian forest a part of a naturally-occurring seasonal and super-annual fluctuation pattern, or is the population actually decreasing due to hunting, logging, and habitat loss? If measurements are taken during a 'low' part of an undetected cycle,

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small population numbers could make the impact of an otherwise-sustainable hunting practice appear catastrophic. Alternatively, unsustainable hunting rates could be seen as deceivingly benign if measurements were taken during a peak time. Recording soundscapes regularly to span the natural cycles of animal activity helps us correctly understand these patterns (Bridges *et al.* 2000, Towsey *et al.* 2014, Linke *et al.* In Review), which otherwise would be extremely difficult to decipher using traditional biodiversity monitoring methods.

BROAD SPATIAL SCALES.— Our current methods for comparing biodiversity of multiple habitats (beta diversity) are insufficient. This task is notoriously difficult in tropical forests and streams due to the sheer number of species present and the amount of sampling necessary. The ability to deploy multiple acoustic sensors across landscapes in a short period of time enables simultaneous recording, which allows researchers to make meaningful comparisons and tackle elusive patterns in tropical forest and freshwater fauna (e.g., Bormpoudakis *et al.* 2013, Gasc *et al.* 2013, Rodriguez *et al.* 2014). For instance, PAM can improve our understanding of ecological processes across entire elevational gradients helping us to track the impact of climate change on animal distributions (Campos-Cerqueira *et al.* 2017).

RAPID INVENTORIES AND SPECIES OF CONSERVATION CONCERN.— The presence of rare and cryptic species in tropical habitats are difficult to detect in short trips to the field (Thompson 2003, Plaisance *et al.* 2011), but PAM methods have been successfully used to detect such animals in densely forested habitats, producing results that would otherwise require massive search efforts by field crews. For example, PAM has been used to estimate presence and abundance of African forest elephants (*Loxodonta cyclotis*) inhabiting dense rainforests of

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Central Africa (Wrege *et al.* 2017) as well as cryptic fish in tropical coastal habitats (Staaterman *et al.* 2017) and an endemic and threatened bird in Puerto Rican Mountains (Campos-Cerqueira & Aide 2016). Invasive species such as fish (Rountree & Juanes 2017) and pest insects (Mankin *et al.* 2011) have also been detected using PAM. Likewise, PAM can detect the recovery of species extirpated from a site after natural disaster, disease or other perturbation (Butler *et al.* 2016). The ability for PAM data to be collected rapidly from many places but analyzed later makes it a valuable tool for rapid inventories (Sueur *et al.* 2008, Ribeiro *et al.* 2017), which tend to be costly and difficult to fund.

HUMAN IMPACTS AND SHIFTING BASELINES.— Comparing soundscapes in areas under different management regimes allows for a rapid understanding of the intensity of impact caused by different human activities (e.g., Alvarez-Berríos *et al.* 2016, Burivalova *et al.* 2017, Deichmann *et al.* 2017). Examples include changes in habitat structure (Tonolla *et al.* 2010, Geay *et al.* 2017) or levels of hunting activity in protected areas (Astaras *et al.* 2017). Furthermore, acoustic data collected over the long-term can be used to answer broader questions regarding the effects of environmental change on species abundance, phenology, distribution (Campos-Cerqueira & Aide 2017, Campos-Cerqueira *et al.* 2017) and behavior (Llusia *et al.* 2013, Narins & Meenderink 2014). For example, acoustic monitoring has been used to demonstrate changes in the seasonal onset of birdsong (Buxton *et al.* 2016), which may be indicative of climatic influences on the timing of reproduction. Acoustic “time-capsules” – measurements made in the past or the present – will be critically important for similar observations in the decades to come.

ADVANTAGES OF PASSIVE ACOUSTIC MONITORING

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Using PAM, rather than traditional methods, to monitor and analyze biodiversity will help us do a better job of understanding and conserving tropical terrestrial and freshwater ecosystems. Netting, trapping, distance sampling, visual transects, etc. are labor-intensive, expensive and logistically impractical in many places – often even more so in the tropics than in the temperates. In addition, most observations of animal behavior are influenced by human presence and limited to daylight hours. Crucially, the autonomous nature of acoustic sensors permits continuous collection of PAM data without biases from the "observer effect" (Shonfield & Bayne 2017). PAM can cover broad spatial and temporal scales, including simultaneous and long-term monitoring, which is simply not possible with traditional methods (Linke *et al.* In Press). This can even be done in real-time (e.g. Van Parijs *et al.* 2009, Aide *et al.* 2013), providing researchers and managers with information necessary for immediate decision-making, and make adaptive management more feasible. Finally, collection of big data through PAM creates permanent records that can be re-analyzed when new analytical tools become available, when additional research questions arise, or to compare past to present conditions.

The related technique of camera trapping has greatly improved our capacity to estimate species composition, abundance and density of medium to large-bodied mammals and birds – groups that are difficult to study using traditional methods – in terrestrial (Burton *et al.* 2015) and arboreal habitats (Gregory *et al.* 2014). That said, camera trapping is restricted to this subset of species (but see Hobbs & Brehme 2017) and the detection range is relatively limited. PAM has the additional benefit of having broader detection ranges [e.g., maximum 1km detection radius calculated for primate sounds (Kalan *et al.* 2015); up to many km depending on frequency,

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microphone height and habitat type (Darras *et al.* 2016)] and sampling a wider range of taxonomic groups (Aide *et al.* 2017). We consider camera trapping and acoustic monitoring to be complementary in terms of taxonomic groups and advocate the use of both methods where possible.

CHALLENGES

While PAM holds many advantages over other methods, it would be remiss not to recognize that challenges do exist. For example, as with other methods that result in the collection of big data, PAM faces the challenge of data storage and management. Storing recordings on multiple hard drives is not expensive, but it is not a particularly effective way to encourage their use in analyses by the broader community. Furthermore, extracting meaningful biological information from recordings is complex. Automated detection tools for species-level analyses have advanced significantly over the last decades (e.g., Aide *et al.* 2013, Kalan *et al.* 2015, de Camargo *et al.* 2017). Still, there are limitations to automatic approaches because they require training data to create different classifiers for different species and programming or signal processing expertise to develop automated species identification models, among others. At the soundscape level, many acoustic indices and soundscape analysis methods have been proposed and used for the assessment of biodiversity (e.g., Sueur *et al.* 2008, Pieretti *et al.* 2011, Villanueva-Rivera *et al.* 2011, Gasc *et al.* 2013, Fuller *et al.* 2015, Vega *et al.* 2016, Aide *et al.* 2017, Rankin & Axel 2017), yet there is no consensus to date as to which are most effective, primarily due to the difficulties in generalizing across taxa and ecosystems (Buxton *et al.* 2018). Existing indices can also be sensitive to geophony like rain, wind, and river flow, or can be skewed by certain

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acoustically-dominant species (Staaterman *et al.* 2017, Linke *et al.* In Review). Most also lack measures of uncertainty (e.g., detection probabilities) – an issue likely to be exacerbated in highly diverse tropical habitats. Nevertheless, collection of acoustic data now opens up the possibility of analyzing long time series of sounds in the future as analytical methods become more advanced and standardized – a possibility that can only be realized if we start recording now.

BROADER IMPACTS OF ECOACOUSTICS

In addition to serving as permanent records of ecosystem health and providing data for scientific research, animal sounds can serve as an alluring tool for engaging public audiences. Camera trapping has been successful for many reasons, but chief among them is the charismatic nature of the resulting photographs - who doesn't smile when they see wildlife "selfies" or animals caught in the act of defiling a camera? We argue that sounds can be just as captivating - many of us have seen public audiences become wide-eyed when we play them a unique, previously-unknown animal sound. Ecoacousticians have successfully enlisted the help of citizen scientists to gather data on bats (e.g., *Bat Detective*: www.batdetective.org), birds (e.g., *eBird*: ebird.org) and to record soundscapes on a global scale (*Record the Earth*: www.recordtheearth.org). Italian sound artist David Monacchi's *Fragments of Extinction* project, initiated in 2001, records the world's undisturbed primary equatorial forests to highlight disappearing soundscapes and brings attention and urgency to the ongoing loss of a 'sonic heritage of millions of years of evolution' (Monacchi & Krause 2017). Ecological sound art is an effective medium for science dissemination and immersive experiences of soundscapes can engage listeners at an emotional level. This acts as a

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powerful and accessible tool for inspiring public awareness about the value of ecoacoustics and ecosystem health in general (Monacchi & Krause 2017) and its efficacy in driving behavior changes is another interesting topic for scientific investigation.

A WAY FORWARD

With the increasing popularity of PAM and rapid flurry of analytical tools, it is now necessary to take advantage of obvious opportunities for acoustic data collection, to develop standards for data collection that allow cross-site comparisons, and to create an open repository to store, visualize and share recordings.

COLLECT MORE DATA.— Just as a meteorological station has become a standard and invaluable accessory at biological field stations, there should also be a permanent acoustic recorder. Anyone can put out a recorder, and researchers with long-term field programs are in a particularly good position to conduct passive acoustic monitoring for biodiversity. Long-term research sites typically have metadata related to vegetation composition and structure, faunal richness and abundance, and/or physical landscape variables that can be used together with acoustic data to create and validate population, community, and soundscape monitoring models. Detailed methods for collecting ecoacoustic data and a review of available hardware can be found in WWF's guide to acoustic monitoring (Browning *et al.* 2017); we encourage researchers to consult this report and take advantage of their field sites by beginning to compile invaluable long-term acoustic datasets that will contribute to compiling a global database.

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STANDARDIZED ACOUSTIC DATA COLLECTION.— To build a comprehensive PAM program, one needs to acquire the necessary hardware and software, develop a method for data collection, and determine a plan for storage of acoustic data files and associated metadata. While we understand that every PAM project will have specific requirements to address the research questions of interest, the best way to maximize the utility of any PAM effort is to follow a standard storage and metadata protocol. We strongly encourage researchers to use the data storage and metadata standards proposed by Roch *et al*. (2016). When acoustic data are organized and annotated in a uniform way, it allows other researchers (present-day or future) to utilize the data for additional questions.

A GLOBAL DATABASE.— With global data being increasingly publicly available in the ecological sciences (e.g., TRY, GBIF, GenBank, BOLD, eMammal, etc), only a limited fraction meets the best practices standards defined by Joppa *et al*. (2016). Ideally, data should be freely available at high spatial resolution, up-to-date, user-friendly and assessed for accuracy, thereby increasing our ability to answer broad questions and improve its utility for conservation management. The Macaulay Library (https://www.macaulaylibrary.org/) and xeno-canto (https://www.xeno-canto.org/) are two large databases that house bioacoustic data, but only the latter allows full-soundscape recordings to be uploaded. Existing ecoacoustics databases include ARBIMON (https://arbimon.sieve-analytics.com/home), the Remote Environmental Assessment Laboratory (REAL, http://lib.real.msu.edu/), Ecosounds (http://ecosounds.org), and the Center for Global Soundscapes (https://centerforglobalsoundscapes.org), although only the first allows users to upload their own data. For marine acoustic data, there is support across federal agencies to archive PAM recordings at the National Center for Environmental Information (NCEI);

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terrestrial and freshwater ecologists must follow suit. A free platform for soundscape storage to enable future temporal and spatial comparisons is absolutely necessary to advance tropical ecology and conservation.

CONCLUSION

We are convinced that PAM is a powerful tool that can be used to assess biodiversity over a range of spatial and temporal scales, and can detect rare species, human impacts, and climatic shifts. Just as a plant or animal voucher specimen can provide information on diet, disease, and evolutionary relationships, so too can a sound recording provide information on species occurrence, density, distribution, phenology, inter- and intraspecific communication, and much more. The rapid proliferation of acoustic recorders and analysis algorithms makes this an exciting frontier in tropical ecology, yet we urge scientists to create standards in our approach to data collection, analysis and archiving that will amplify the utility of recordings. What PAM can reveal will be invaluable in future decades as tropical ecosystems continue to change.

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