Conservation Bioacoustics: Listening to the Heartbeat of the Earth

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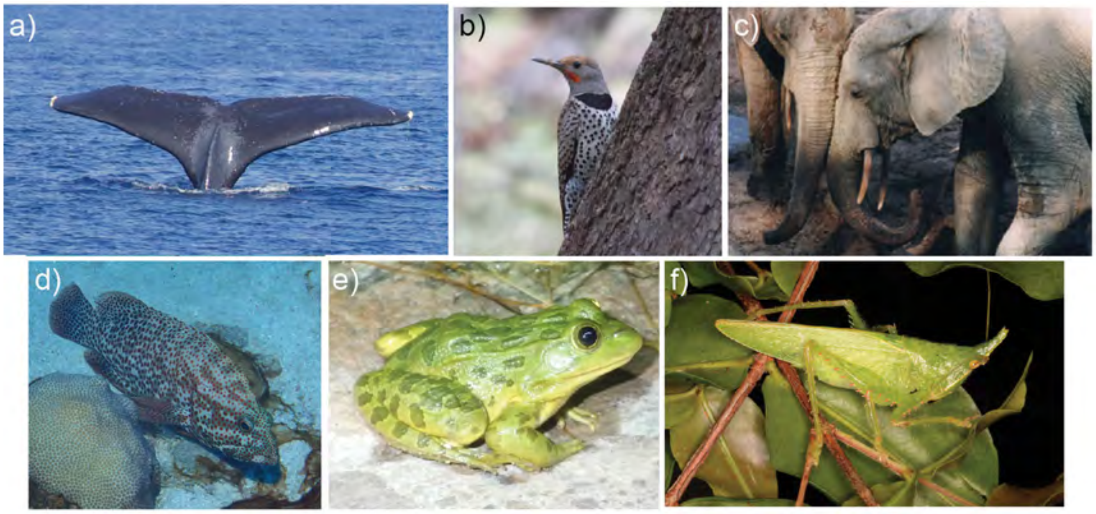
What Is Conservation Bioacoustics?

If you close your eyes and just listen to an outdoor environment, the sounds that you hear provide ever-changing details about the world around you. These sounds of biological (e.g., animal calls), geophysical (e.g., thunder), and human-made (e.g., traffic) origin comprise what is often referred to as the soundscape (examples in *Acoustics Today* include Miksis-Olds et al., 2018; Slabbekoorn, 2018; also see acousticstoday.org/soundscapes).

As popularized by Rachel Carson's *Silent Spring*, the loss of calling frogs in wetlands was an immediate and audible indication that frogs had changed their behavior. This important observation led to a profound realization: the frogs' ecological community and ecosystem integrity were deteriorating (Carson, 1962). Indeed, we can glean a wealth of information from the ever-shifting composition of a soundscape, wherein both silence and sounds reveal the health of an ecosystem. How a soundscape transforms across days, seasons, and years can ultimately inform the conservation of the habitat and the animals calling within.

Just as many indigenous groups have recognized the importance of listening to nature for stewarding natural resources for millennia (Gray et al., 2001), scientists are now developing and implementing technologies that allow the study of sounds from a wide diversity of

Figure 1. *Bioacoustics has been used for conservation of a wide variety of taxa, originating with cetaceans (**a**,* Megaptera novaeangliae; *photo by Ben Gottesman) and birds (**b**,* Colaptes chrysoides; *photo by A. Rice), but has quickly expanded to forest elephants (**c**,* Loxodonta cyclotis; *photo by E. Rowland), groupers vulnerable to overfishing (**d**,* Cephalopholis cruentata; *photo by A. Rice), endangered frogs (**e**,* Lithobates chiricahuensis; *photo by A. Rice), and important ecological indicator species in tropical forests such as katydids (**f**,* Acantheremus major; *photo by M. Ayres).*



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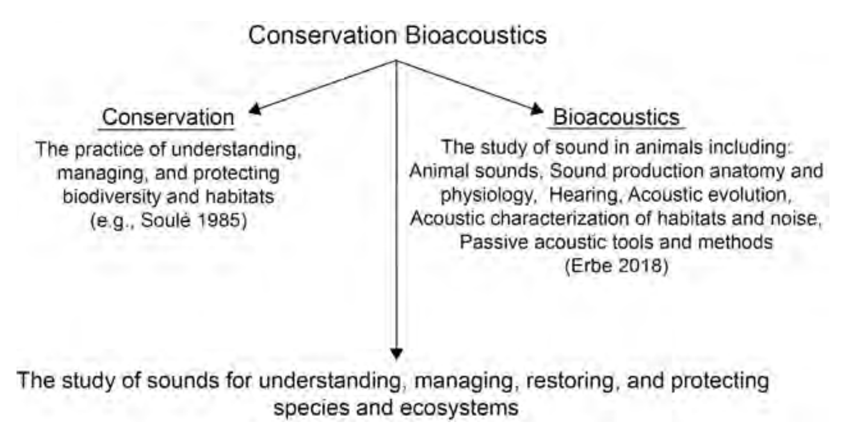


Figure 2. *Flowchart showing the conceptual relationship between the scientific fields of Conservation (e.g., Soulé, 1985) and Bioacoustics (Erbe, 2018) and how the two can be integrated to create the field of Conservation Bioacoustics.*

taxa and ecosystems at the vast spatial and temporal scales necessary to enable effective conservation actions (**Figure 1**). This growing field combines the disciplines of Conservation Biology (Soulé, 1985) with Bioacoustics (Erbe, 2018) to create a new, integrative field of Conservation Bioacoustics (Laiolo, 2010).

Based on Laiolo (2010), we use a working definition of "Conservation Bioacoustics" as applying the study of sounds in nature for understanding, managing, restoring, and protecting species and ecosystems (**Figure 2**). Currently, passive acoustic monitoring (PAM) is a primary application of Conservation Bioacoustics. PAM is enabled through autonomous recording devices, which record sounds within the environment and often focus on monitoring sounds of protected species (Van Parijs et al., 2009; Sugai et al., 2020; also see tinyurl.com/ASA-PAM). The recorders are placed noninvasively in environments, such as being buckled to a tree or suspended on the seafloor, and passively record sound in these environments. This is in contrast to "active acoustics," where devices emit a sound and the reflection pattern is the signal of interest. Because of its noninvasive nature, PAM is especially geared toward studying vulnerable species, where permitting is difficult and minimizing stress on the organism is essential.

What distinguishes Conservation Bioacoustics is its inherent motivation to shape ecological research into fuel for conservation success. For example, acoustic methods have played a key role in the identification and conservation of a unique population of New Zealand blue whales. These methods allowed a research team from Oregon State University, Corvallis, to establish that a group of blue whales were permanent, not seasonal, residents of the South Taranaki Bight in New Zealand (Barlow et al., 2018). This Bight also overlaps with mounting human pressures on natural resources, including petroleum exploration and potential seabed mining, with noise pollution that shrinks the range over which the whales can communicate. Knowledge of this newly documented population has helped activate and inform a social movement in New Zealand to enact the protection of these whales. The researchers developed models forecasting whale presence throughout the Bight (Barlow and Torres, 2021). From there, they can identify prime whale habitats, inform industrial limits, and successfully couple the scientific output to a conservation outcome.

Although the example of New Zealand blue whales represents a promising pathway to conservation success (di Sciara and Gordon, 1997; Tyack, 2001), translating a bioacoustics output to a conservation outcome is not always as intuitive or straightforward. Here, we illustrate a conceptual map documenting our working vision of how Conservation Bioacoustics can help span the research-implementation gap (**Figure 3**).

Translating Bioacoustics into Conservation

Conserving biodiversity is a multidisciplinary and iterative process that entails a variety of stakeholder

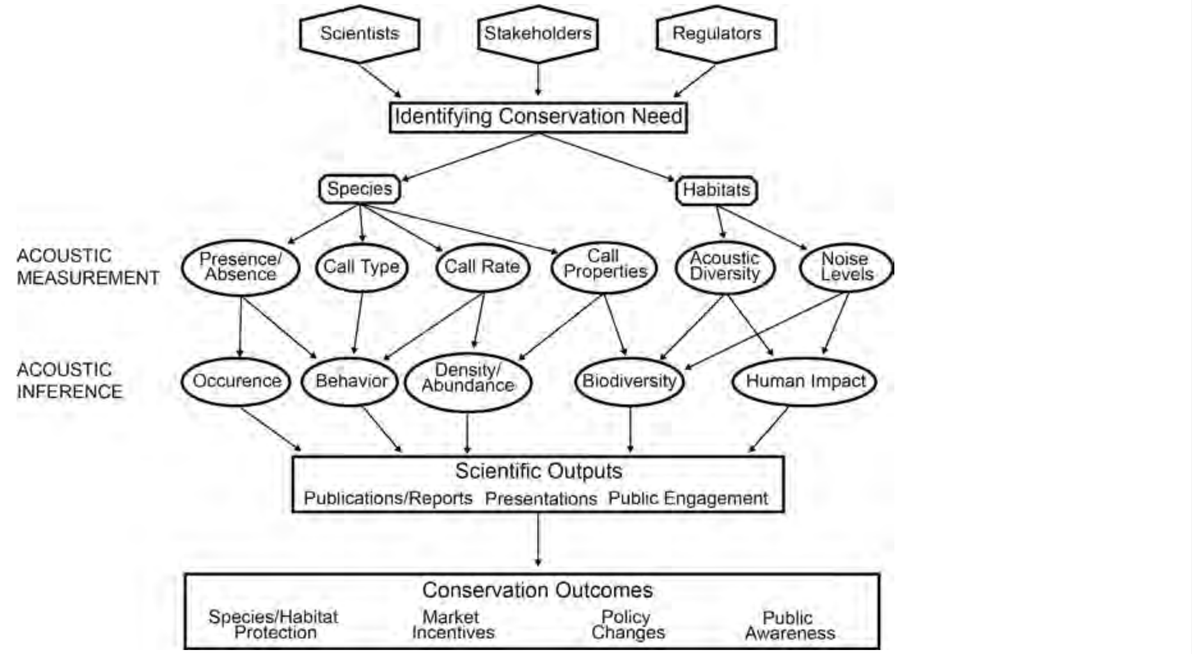


Figure 3. *Flowchart representation of the overall process of Conservation Bioacoustics, leading from constituents identifying conservation needs through to data collection, scientific outputs, and conservation outcomes.*

perspectives spanning biology, economics, environmental engineering, politics, and local communities. To initiate this process, a combination of these stakeholders identify an urgent or emerging conservation challenge. From there, they can define the species and/or habitats that are the conservation targets. Then, they can devise a plan for using acoustic data to shed light on these conservation targets.

Acoustic data can be the source for ecological information that directly aligns with conservation needs. Researchers can analyze acoustic data to learn when a vocally active species is occupying an ecosystem. Acoustic data can also capture the "noise footprints" that humans generate in ecosystems. For example, in forest landscapes, the sounds of gunshots on PAM recordings can demonstrate where and when poachers may be attempting to hunt forest elephants and noise from chainsaws can reveal legal and illegal logging activity (Wrege et al., 2017). In coastal environments, recordings of vessel noise or pile-driving activity can be used to estimate the time that whales are exposed to elevated anthropogenic noise levels and if those noise levels either exceed regulatory thresholds or represent a threat to the recovery of depleted populations (McKenna et al., 2016).

Transforming Outputs to Outcomes

Translating bioacoustics to conservation requires a fundamental understanding of the distinction between outputs and outcomes. Traditionally, the scientific method has data synthesized into a strictly scientific output. Outputs typically take the form of peer-reviewed publications, conference presentations, or materials for public engagement. However, to achieve effective and impactful conservation, these outputs are but a stepping stone to an ultimate conservation outcome. These outcomes can take the form of protective legal measures, revision of management practices, strategic deployment of patrols to reduce illegal activity, financial incentives to conserve species or habitats, or greater public awareness and community stewardship.

Fundamentally, Conservation Bioacoustics is highly interdisciplinary and integrates ecological research, technology, and education; this combination forms three foundational components of a Conservation Bioacoustics framework. Technological advancements and education through training students and practitioners around the world (capacity building) are also key pillars driving the acceleration of conservation research, critical toward moving the field forward and fulfilling the goals of conservation success.

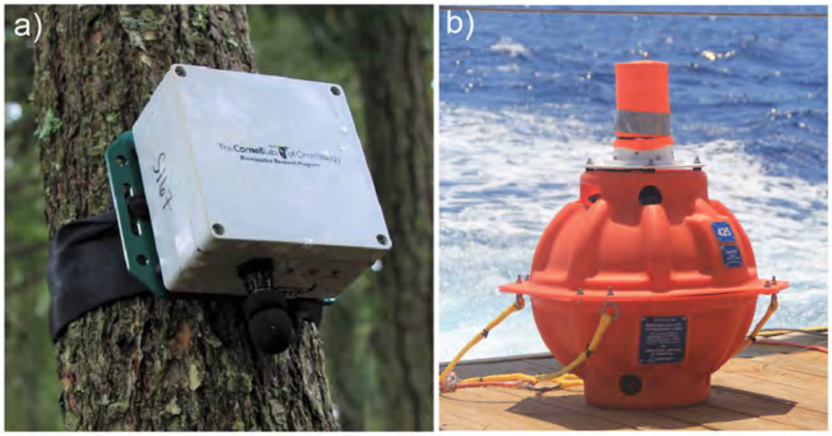
Technological Advancements

Pursuing any scientific inquiry in Conservation Bioacoustics relies on constantly evolving recording technologies. In the early days of bioacoustics, recordings were analog, capturing no more than two hours on media such as tape. These recordings would then be transformed into spectrograms, which are visualizations of the recorded acoustic signals. The analysis to come could be long and tedious. With printouts of spectrograms scattered about, scientists would use rulers to measure the durations and pitches of each signal.

When analog audio transitioned to being digital in the mid-1980s, scientists saw many improvements in how acoustic data were collected, including the capability to record higher quality sound for longer intervals (Pavan et al., 2022). With the digital-recording revolution, increasing battery life, and larger data storage capacity, acoustic data could now be collected at previously unthinkable durations. In this accelerating era of PAM, the equipment could be left recording unattended for days or weeks at a time, with recent feats even managing years (**Figure 4**). Leaving rulers behind, computer-based analysis software such as Cornell's Raven Pro Software (see ravensoundsoftware.com) makes it possible to easily create spectrograms and annotate signals of interest, including relevant acoustic measurements and metadata. Conservation assessments often call for acoustic data that cover multiple seasons across several years to understand the seasonal patterns of important life history events of focal species (such as breeding or migration), and in an era of increasing human influence on the world's ecosystems (the epoch now referred to as the Anthropocene; e.g., Slabbekoorn, 2018), how those temporal patterns might be fluctuating because of climate change.

These technological innovations have expanded the potential for conservation impact by empowering people from across different backgrounds to exercise environmental stewardship via bioacoustics, using tools designed for citizen scientists like BirdNET (see birdnet.cornell.edu) or Haikubox (see haikubox.com) that help nonscientists automatically identify birds through artificial intelligence (AI)-based song recognition. The ability for recording devices to operate longer directly translates to less frequent deployment and recovery of equipment. For example, although remote regions are often the most biodiverse, collecting data in these environments can be costly in both logistical expenses and human effort. Because acoustic devices can record longer, researchers now have the opportunity to pursue in-depth studies in these ecologically significant remote areas. These devices offer greater returns on investment with their ability to collect data in quantities from which ecologically meaningful insights can be derived. With ecosystem monitoring now made accessible to smaller

Figure 4. *Representative recording devices developed at Cornell and used in Conservation Bioacoustics, including a terrestrial "Swift" recorder deployed in a tree (**a**) and a marine "Rockhopper" recorder device (**b, orange sphere**) on the stern of a research vessel awaiting deployment at sea.*



field teams globally, Conservation Bioacoustics could be the catalyst for localized conservation success.

Historically, most Conservation Bioacoustics recordings have been archival, meaning that the data can only be analyzed once the devices (or recording media) are returned to the laboratory. However, with increasing global connectivity (satellite, cellular, and WiFi), newer recording devices can detect signals of interest live from the field, reporting acoustic detections to practitioners and managers in near real time. Real-time detection marks a striking step forward from the field's traditional reliance on archival audio data, where it could take months or even years to access and analyze the data. Advancements like these facilitate data-driven decision making and conservation interventions.

With the exponential growth of acoustic data available to analyze, AI approaches (e.g., machine listening) have transformed the analytical capabilities in the Conservation Bioacoustics workflow (Tuia et al., 2022). Public data repositories of acoustic data (Parsons et al., 2022) have provided validated reference sounds for training and improving the performance of AI models (Kahl et al., 2021). Notably, the BirdNET algorithm, a deep convolutional neural network, can recognize over 6,000 bird species from raw acoustic data (Kahl et al., 2021). BirdNET is just one example among a growing pool of AI models (Tuia et al., 2022). The impact of these emerging AI models will be profound, dramatically increasing the ability to automate and expedite parts of the Conservation Bioacoustics analysis pipeline. The timeline from field recordings to conservation action will be accelerated, generating conservation outcomes at a pace relevant to rapid environmental, ecological, and climatological changes.

Capacity Building and Engagement

To maximize success, conservation practitioners around the world must be empowered with the necessary tools to conduct bioacoustic monitoring in the ecosystems significant to their livelihoods and well-being. Although the importance of crafting university curricula at both the undergraduate and graduate levels cannot be overlooked, we need to look beyond traditional educational institutions. On-the-ground conservation practitioners should have the same access to relevant extensive training as the ones who often feel the effects of biodiversity loss and climate change first.

Despite the valuable insights that the acoustic data provide for conservation solutions, Conservation Bioacoustics remains an elusive skill set for university students, given its rare presence in higher education curricula. Consider, for example, the authors' home institution, Cornell University in Ithaca, New York. Although Conservation Bioacoustics has been a prominent research direction at Cornell for over three decades, a course bridging the field to students had yet to be offered. Where there was a gap, we saw an opportunity. In the fall semester of 2022, we taught Cornell's inaugural "Introduction to Conservation Bioacoustics" course. In a semester, we presented students with the theory and application of bioacoustics and conservation, recording technology, sound propagation, analytical approaches, signal processing, and acoustic detection across diverse taxa and ecosystems. At the end of the semester, students applied their new knowledge by implementing their own Conservation Bioacoustics projects during a Hawai'i-based field course during the winter session.

In the next course iteration, we will record key lectures and interactive laboratories to disseminate them publicly. As an international community, we prioritize supporting access to equipment and expertise in places where the utility of Conservation Bioacoustics runs high but resource investment historically runs low. To help make bioacoustics approaches more accessible, the K. Lisa Yang Center for Conservation Bioacoustics (Yang Center) at Cornell University (see bioacoustics.cornell.edu) has developed in-person and online acoustics workshops as well as a Bioacoustics Training and Mentorship Program that provides equipment and a year of training and mentorship to teams (see birds.cornell.edu/ccb/education). Our initial efforts have focused on Indonesia and Malaysia, where we are about to complete our first annual training and mentoring cycle. The program ends with an in-person symposium, where participants will present their Conservation Bioacoustics projects. The feedback from this first cohort has been positively energizing. Building on the momentum, we are working to expand this program to the Pantanal wetlands of South America and the tropical rainforest regions in Central Africa.

Conservation science has long suffered from "parachute science," the act of scientists conducting research in a country that is not their own without investing in the community or sharing results in the places where the work was conducted. To achieve the greatest impact, capacity building in Conservation Bioacoustics endeavors must follow an entirely different paradigm. Capacity-building efforts are most successful when community members have the skills and resources to conduct their own Conservation Bioacoustics projects.

Where the Field Is Headed

Conservation Impacts from Bioacoustics

Over the last decade, the rapid expansion of Conservation Bioacoustics has risen in parallel with a diversity of bioacoustics-informed conservation outcomes. We have accomplished scales of analyses previously unthinkable of 10 or 20 years ago, fueled by the maturation of technology for longer term and less expensive data collection.

In terrestrial habitats, the initial discovery of infrasonic vocalizations by elephants by Payne et al. (1986) led to the widespread use of PAM for understanding and managing forest elephant populations in Central and Western Africa (Wrege et al., 2017). Extended use of PAM in the Western North Atlantic Ocean has enabled the long-term study of occurrence patterns of North Atlantic right whales, documentation of shifting migration patterns, and new management strategies to promote their conservation, including increasing the size of protected areas and seasonal exclusion zones to minimize the impact of human activities (Davis et al., 2017). Yet, although progress in the field has been substantial, these successes have nevertheless tested the limits of existing systems and, in turn, highlighted emerging challenges.

Technological Challenges

Although it is now possible to collect large quantities of information, data collection is still primarily constrained by storage, power, and the ability to share large quantities of data. Storage continues to become cheaper and larger, but battery technology has not seen comparable advancements in maximizing longevity or minimizing environmental impact. Lower power devices are still being developed, but battery life remains the limiting factor and solar power is not yet practical for many applications. Because many imperiled/exploited species and human activities (e.g., traffic, hunting) are detectable through sound, real-time acoustic detection enables rapid response and intervention of conservation managers (Van Parijs et al., 2009). However, battery life and connectivity remain key issues, particularly in densely forested areas or remote locations.

Expanding Scales of Data Collection

Once long-term data are collected, it still needs to be stored in a way that can be accessed by multiple people, often across a geographically distributed area. Cloud data storage may seem like the best path forward because it makes data sharing more intuitive, but it entails significant costs for long-term storage. And when the funding for a project reaches the end of its cycle, what becomes of the data? Without ongoing project funding, there is often no path for ongoing data storage, which constrains the ability to aggregate cumulative datasets for more comprehensive PAM efforts.

In the United States, one institutional model that has begun to tackle these challenges successfully is the National Center for Environmental Information (NCEI), which is located within the National Oceanic and Atmospheric Administration (NOAA). NCEI has established a large data repository for the long-term storage and public accessibility of passive acoustic data from US government-funded marine PAM projects within US waters (see ncei.noaa.gov/products/passive-acoustic-data) (Wall et al., 2021). However, comparable repositories still need to cover long-term terrestrial passive acoustic data as well as passive acoustic data collected in other regions outside of the United States.

Moreover, machine listening has rapidly changed the prospects for automatically detecting sounds of interest, even with small amounts of initial training data (Tuia et al., 2022). Nevertheless, there are substantial ongoing challenges to automating analysis of bioacoustics data. These challenges include evaluating model performance when detection events are challenging for humans to confirm or refute (faint calls) (e.g., Digby et al., 2013), training effective models when training data are limited (few-shot learning), and deciphering complex soundscapes with many overlapping signals in time and frequency as well as the limited ability to aggregate and exchange training data across research groups while accurately attributing credit to the original data sponsors and collectors.

Translating Bioacoustics Sounds into Population Estimates

How to best translate Conservation Bioacoustics data into policy remains an area for further optimization. Because many regulatory measures are centered around population size or the number of individuals of a particular species, it is desirable to apply bioacoustics for density and abundance estimation (Marques et al., 2013). Inherent to density estimation approaches is knowing a species' detection probability, detection range, and call rate (Marques et al., 2013). However, these parameters are not yet well-established for many marine and terrestrial species deemed a conservation priority.

Bioacoustics and Conservation Outcomes

Finally, for Conservation Bioacoustics to reach full maturity, the connection between Conservation Bioacoustics and conservation action must be enhanced. Additionally, researchers must deliver acoustic insights with sufficient speed and interpretability to facilitate effective management action. Conservation Bioacoustics has seen rapid growth and emerged from a nascent and obscure subdiscipline into an increasingly accepted and promising field with transformative potential for natural resource conservation in both scale and scope. The continued acceleration of technology, examples of successful conservation outcomes through research, the growing number of students and experts, and the increased public awareness of the opportunities and importance of Conservation Bioacoustics all point to the field's continued growth and impact potential in our current crisis of global biodiversity loss.

Acknowledgments

We thank Christopher W. Clark for his vision for using bioacoustics to achieve conservation opportunities and the importance of integrating biology, technology, and education for the success of Conservation Bioacoustics as an emerging field. Further development of the conceptual framework for integrating bioacoustics and conservation came from extensive discussions with Susan Parks and David Luther. We also thank K. Lisa Yang for providing generous support to ensure the continued success of Conservation Bioacoustics for years to come.

References

Barlow, D. R., and Torres, L. G. (2021). Planning ahead: Dynamic models forecast blue whale distribution with applications for spatial management. *Journal of Applied Ecology* 58(11), 2493-2504. https://doi.org/10.1111/1365-2664.13992.

Barlow, D. R., Torres, L. G., Hodge, K. B., Steel, D., et al. (2018). Documentation of a New Zealand blue whale population based on multiple lines of evidence. *Endangered Species Research* 36, 27-40. https://doi.org/10.3354/esr00891.

Carson, R. (1962). *Silent Spring*. Houghton Mifflin, Boston, MA.

Davis, G. E., Baumgartner, M. F., Bonnell, J., Bell, J., et al. (2017). Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific Reports* 7, 13460. https://doi.org/10.1038/s41598-017-13359-3.

Digby, A., Towsey, M., Bell, B. D., and Teal, P. D. (2013). A practical comparison of manual and autonomous methods for acoustic monitoring. *Methods in Ecology and Evolution* 4(7), 675-683. https://doi.org/10.1111/2041-210X.12060.

di Sciara, G. N., and Gordon, J. (1997). Bioacoustics: A tool for the conservation of cetaceans in the Mediterranean Sea. *Marine and Freshwater Behaviour and Physiology* 30(2), 125-146. https://doi.org/10.1080/10236249709379020.

Erbe, C. (2018). Overview of animal bioacoustics. *The Journal of the Acoustical Society of America* 143(3), 1734. https://doi.org/10.1121/1.5035656.

Gray, P. M., Krause, B., Atema, J., Payne, R., Krumhansl, C., and Baptista, L. (2001). The music of nature and the nature of music. *Science* 291(5501), 52-54. https://doi.org/10.1126/science.10.1126/SCIENCE.1056960.

Kahl, S., Wood, C. M., Eibl, M., and Klinck, H. (2021). BirdNET: A deep learning solution for avian diversity monitoring. *Ecological Informatics* 61, 101236. https://doi.org/10.1016/j.ecoinf.2021.101236.

Laiolo, P. (2010). The emerging significance of bioacoustics in animal species conservation. *Biological Conservation* 143(7), 1635-1645. https://doi.org/10.1016/j.biocon.2010.03.025.

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. A., Moretti, D. J., Harris, D., and Tyack, P. L. (2013). Estimating animal population density using passive acoustics. *Biological Reviews* 88(2), 287-309. https://doi.org/10.1111/brv.12001.

McKenna, M. F., Shannon, G., and Fristrup, K. (2016). Characterizing anthropogenic noise to improve understanding and management of impacts to wildlife. *Endangered Species Research* 31, 279-291. https://doi.org/10.3354/esr00760.

Miksis-Olds, J. L., Martin, B. R., and Tyack, P. (2018). Exploring the ocean through soundscapes. *Acoustics Today* 14(1), 26-34.

Parsons, M. J. G., Lin, T.-H., Mooney, T. A., Erbe, C., et al. (2022). Sounding the call for a global library of biological underwater sounds. *Frontiers in Ecology and Evolution* 10, 810156. https://doi.org/10.3389/fevo.2022.810156.

Pavan, G., Budney, G., Klinck, H., Glotin, H., et al. (2022). History of sound recording and analysis equipment. In Erbe, C., and Thomas, J. A. (Eds.), *Exploring Animal Behavior Through Sound: Volume 1: Methods*. Springer Cham, Cham, Switzerland, pp. 1-36. https://doi.org/10.1007/978-3-030-97540-1_1.

Payne, K. B., Langbauer, W. R., and Thomas, E. M. (1986). Infrasonic calls of the Asian elephant (*Elephas maximus*). *Behavioral Ecology and Sociobiology* 18(4), 297-301. https://doi.org/10.1007/BF00300007.

Slabbekoorn, H. (2018). Soundscape ecology of the Anthropocene. *Acoustics Today* 14(1), 42-49.

Soulé, M. (1985). What is conservation biology? *BioScience* 35(11), 727-734. https://doi.org/10.2307/1310054.

Sugai, L. S. M., Desjonquères, C., Silva, T. S. F., and Llusia, D. (2020). A roadmap for survey designs in terrestrial acoustic monitoring. *Remote Sensing in Ecology and Conservation* 6(3), 220-235. https://doi.org/10.1002/rse2.131.

Tuia, D., Kellenberger, B., Beery, S., Costelloe, B. R., et al. (2022). Perspectives in machine learning for wildlife conservation. *Nature Communications* 13(1), 792. https://doi.org/10.1038/s41467-022-27980-y.

Tyack, P. L. (2001). Bioacoustics. In Steele, J. H., *Encyclopedia of Ocean Sciences,* 2nd ed. Academic Press, Oxford, UK. pp. 357-363. https://doi.org/10.1016/B978-012374473-9.00436-7.

Van Parijs, S. M., Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., and Van Opzeeland, I. C. (2009). Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series* 395, 21-36. https://doi.org/10.3354/meps08123.

Wall, C. C., Haver, S. M., Hatch, L. T., Miksis-Olds, J., Bochenek, R., Dziak, R. P., and Gedamke, J. (2021). The next wave of passive acoustic data management: How centralized access can enhance science. *Frontiers in Marine Science* 8, 873. https://doi.org/10.3389/fmars.2021.703682.

Wrege, P. H., Rowland, E. D., Keen, S., and Shiu, Y. (2017). Acoustic monitoring for conservation in tropical forests: examples from forest elephants. *Methods in Ecology and Evolution* 8(10), 1292-1301. https://doi.org/https://doi.org/10.1111/2041-210X.12730.

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