

MINI REVIEW



Bioacoustic monitoring as an early warning system for forest ecosystem disruptions: a tool for proactive conservation

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ABSTRACT

Bioacoustic monitoring is an innovative ecological tool that uses soundscape analysis to evaluate biodiversity and identify disruptions in forest ecosystems. This method provides a non-invasive, cost-effective, and continuous way to track species presence, population changes, and human-related disturbances like illegal logging and poaching. By examining animal calls and environmental sounds, bioacoustic monitoring is an early warning system, enabling conservationists to notice ecological changes before they escalate. This mini-review delves into the principles, applications, and benefits of bioacoustic monitoring, highlighting its importance in proactive forest conservation strategies. It also addresses how advancements in acoustic technology enhance the accuracy and efficiency of conservation efforts, promoting sustainable forest management and the preservation of biodiversity. This approach has significant potential to bolster conservation policies and incorporate community-based monitoring initiatives, ultimately improving global forest sustainability.

KEYWORDS

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Soundscape analysis;
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Introduction

Bioacoustic monitoring is an innovative method used in ecological research to study natural soundscapes and evaluate biodiversity. It involves capturing and analyzing acoustic signals from forests, including vocalizations of animals and ambient environmental noises. By leveraging sound analysis, conservationists can detect early signs of ecological disruption, allowing for timely interventions to protect forest ecosystems [1].

Forests are complex ecosystems that host an incredible diversity of life, making them vital for global biodiversity conservation. However, these ecosystems are increasingly threatened by deforestation, habitat fragmentation, climate change, and human activities such as illegal logging and poaching. Traditional ecological monitoring methods, such as manual field surveys and camera traps, often require significant time and labor, making them less efficient for large-scale and continuous monitoring. On the other hand, bioacoustic monitoring enables real-time tracking of environmental changes, allowing conservationists to detect and mitigate ecological threats before they escalate.

Bioacoustic data can be used to track changes in species composition, detect habitat degradation, and identify the presence of invasive species. This makes bioacoustic monitoring a powerful tool for conservation biology, as it helps researchers understand how environmental factors influence wildlife populations and behaviors. Furthermore, integrating this method with artificial intelligence (AI) and machine learning has allowed scientists to process vast amounts of acoustic data more efficiently, improving biodiversity assessments and forest management practices [2]. Researchers can create more detailed ecological models by combining bioacoustic data with remote sensing technologies, further enhancing conservation strategies.

Principles of Bioacoustic Monitoring

Technological aspects of bioacoustic monitoring

Bioacoustic monitoring relies on specialized recording equipment, including:

Autonomous recording units (ARUs)

Autonomous Recording Units (ARUs) are self-sustaining devices designed to capture environmental sounds over extended periods without human intervention. These units are typically placed in remote or difficult-to-access areas, such as dense forests, to record soundscapes and monitor wildlife activity continuously. They are built to withstand various environmental conditions, such as extreme temperatures, humidity, and rainfall, ensuring reliable data collection. ARUs are widely used in conservation and ecological research because they allow for passive monitoring, reducing the need for frequent human presence, which could disturb wildlife [3].

Handheld recorders

Handheld recorders are portable audio recording devices that researchers use to capture high-quality sound samples in the field. These devices allow researchers to record specific species, document vocal behaviors, and conduct rapid assessments of environmental conditions. Because of their portability and ease of use, handheld recorders are particularly useful for studying rare or cryptic species that automated units may not detect [4]. Researchers can also use these devices to verify and cross-check bioacoustic data collected by other monitoring systems.

Acoustic sensors

Acoustic sensors are specialized devices that detect and capture sound waves from the environment. These sensors can

be installed in fixed locations or used as mobile units to monitor changes in biodiversity and ecosystem conditions over time. Some acoustic sensors are designed to be networked together, forming a large-scale bioacoustic monitoring system that provides real-time data collection across vast areas. These systems are particularly valuable for assessing the impacts of environmental changes, such as deforestation, habitat fragmentation, or climate variability [5]. By continuously gathering sound data, acoustic sensors help researchers track species distributions, identify ecological disruptions, and detect illegal human activities such as logging or poaching.

Soundscape recording and analysis

A soundscape refers to the collective auditory environment of a particular location, encompassing all natural, biological, and human-made sounds. Soundscapes include three main components: biophony (sounds produced by living organisms such as birds, insects, and mammals), geophony (natural environmental sounds like wind, rain, and river flow), and anthrophony (human-generated noises such as traffic, machinery, and construction activities) [6].

The analysis process includes:

Spectrogram analysis: A spectrogram is a visual representation of sound that displays frequency on the vertical axis, time on the horizontal axis, and intensity (loudness) as variations in color or brightness. Spectrogram analysis is an essential tool in bioacoustic research, as it allows scientists to identify specific animal calls, distinguish between different species, and detect patterns in vocal activity over time. By comparing spectrograms from different periods, researchers can track changes in biodiversity, monitor seasonal variations in species behavior, and assess the impact of environmental disturbances. Spectrograms are particularly useful for identifying species with similar vocalizations, as they provide a clear visual differentiation of sound frequencies [7].

Acoustic indices: Acoustic indices are statistical measures used to quantify biodiversity and habitat quality based on sound recordings. Commonly used indices include the Acoustic Complexity Index (ACI), which measures the complexity of a soundscape and helps assess species richness; the Bioacoustic Index (BI), which evaluates the overall biological activity within an environment; and the Normalized Difference Soundscape Index (NDSI), which distinguishes between natural and human-made sounds to determine the level of anthropogenic impact [8]. These indices provide objective metrics for monitoring ecosystem health and tracking changes in species diversity over time. They are particularly useful for large-scale studies where manual species identification would be impractical.

Automated call recognition: Automated call recognition is a technology that uses artificial intelligence (AI) and machine learning to identify animal vocalizations by comparing recorded calls with existing sound libraries. This method significantly reduces the time and effort required for manual species identification, making bioacoustic monitoring more efficient. Automated recognition software can analyze large datasets, detect rare or cryptic species, and classify sounds with high accuracy. This technology is particularly valuable for monitoring nocturnal or elusive animals that are difficult to

observe directly. By automating the identification process, researchers can conduct large-scale biodiversity assessments and track changes in species distribution with greater precision [9].

Key acoustic indicators of forest health

Animal calls

Animal calls refer to the vocalizations produced by various species, including birds, amphibians, mammals, and insects. These calls serve multiple ecological functions, such as communication, territory defense, mating signals, and predator warnings. Monitoring animal calls provides insights into species richness, population trends, and behavioral patterns. Changes in vocalization frequency or diversity can indicate environmental stress, habitat degradation, or shifts in ecological balance. For example, a decline in bird song activity in a particular area may suggest a loss of suitable nesting habitats or increased human disturbance [10]. By analyzing animal calls, conservationists can develop targeted strategies to protect vulnerable species and maintain ecosystem stability.

Environmental sounds

Environmental sounds include non-biological natural noises such as wind, rainfall, river flow, and ocean waves. These sounds play a crucial role in shaping habitat conditions and influencing animal behavior. For instance, the intensity of rainfall can affect amphibian breeding activities, while changes in river flow patterns may alter fish migration routes. Environmental sounds also contribute to soundscape analysis by providing context for interpreting biological and anthropogenic noises. Monitoring these sounds helps researchers understand climate variations, ecosystem dynamics, and the overall health of a habitat. Unusual changes in environmental sounds may indicate ecological disturbances, such as droughts, floods, or habitat destruction.

Anthropogenic noises

Anthropogenic noises are sounds generated by human activities, including deforestation, industrial operations, transportation, and urban development. These noises can have significant ecological consequences, as they interfere with animal communication, disrupt natural behaviors, and contribute to habitat degradation [11]. For example, excessive traffic noise can mask bird songs, making it difficult for birds to communicate and find mates. In forested areas, the presence of chainsaw sounds may indicate illegal logging, while gunshot sounds can signal poaching activities. Identifying and tracking anthropogenic noises allows conservationists to monitor human impacts on ecosystems and implement measures to reduce noise pollution and protect wildlife habitats.

Applications in Forest Ecosystems

Case studies of effective bioacoustic monitoring

Several real-world applications highlight the efficacy of bioacoustic monitoring in forest conservation:

Amazon rainforest

The Amazon Rainforest, the world's largest tropical rainforest, spans multiple South American countries, with the majority located in Brazil. It is home to an incredibly diverse range of

plant and animal species, many of which are found nowhere else on Earth. Due to rapid deforestation and habitat destruction, scientists use bioacoustic monitoring to study changes in biodiversity. By recording and analyzing bird calls, researchers can assess species composition, track population declines, and measure the impact of environmental disturbances [12]. Long-term bioacoustic data from the Amazon has been crucial in revealing the effects of deforestation on bird populations, providing evidence to support conservation policies and reforestation efforts.

Southeast Asia

Southeast Asia is a biodiversity hotspot, encompassing countries such as Indonesia, Malaysia, Thailand, and the Philippines. The region is known for its rich amphibian diversity, with many species being highly sensitive to environmental changes. Bioacoustic monitoring has been used to detect declines in frog populations by recording their vocalizations. Since amphibians rely on specific humidity and temperature conditions for survival, their calls serve as bioindicators of climate change and habitat degradation [13]. Studies in Indonesia and Malaysia have shown that shifts in frog call frequencies and intensities correlate with changes in environmental conditions, making bioacoustic monitoring an effective tool for conservation efforts in this region.

African savannahs

The African savannahs are vast grassland ecosystems found in regions such as Kenya, Tanzania, and South Africa. These landscapes support large herbivores like elephants, giraffes, and zebras, as well as apex predators like lions and cheetahs. Bioacoustic monitoring in African savannahs is often used to study elephant vocalizations, particularly infrasound communication, which consists of low-frequency sounds that travel long distances. By recording and analyzing these vocalizations, researchers can track elephant movement patterns, detect signs of stress, and identify potential threats such as poaching or habitat encroachment [14]. This technology has helped conservationists develop better strategies for elephant protection and human-wildlife conflict mitigation.

Species presence and biodiversity assessment

Species presence refers to the occurrence or detection of a particular species within a given area. In bioacoustic monitoring, species presence is determined by identifying specific vocalizations recorded in an environment. Detecting species presence through sound analysis is particularly useful for elusive or nocturnal animals that are difficult to observe visually. Researchers use bioacoustic recordings to confirm the existence of species in a habitat, track their distribution, and assess population health. This data helps guide conservation planning by identifying key areas that require protection or restoration [15].

Biodiversity assessment is the process of measuring and evaluating the variety of species present in an ecosystem. Bioacoustic monitoring plays a significant role in biodiversity assessments by capturing vocalizations from multiple species and analyzing patterns of species richness and abundance. By monitoring soundscapes over time, researchers can detect changes in biodiversity due to environmental disturbances such

as habitat destruction, climate change, or invasive species. Biodiversity assessments help conservationists prioritize areas for protection and develop strategies for ecosystem management.

Advantages of Bioacoustic Monitoring

Bioacoustic monitoring offers a range of advantages over traditional methods:

Cost-effectiveness

Cost-effectiveness in bioacoustic monitoring refers to the ability to collect valuable ecological data at a lower cost compared to traditional survey methods. Deploying autonomous recording units (ARUs) in multiple locations allows researchers to gather extensive data without the need for frequent field visits [16]. This reduces travel expenses, equipment costs, and labor requirements. Additionally, AI-powered software can automate species identification, further minimizing human effort. The ability to continuously collect data over long periods makes bioacoustic monitoring an economical choice for large-scale biodiversity studies.

Non-invasiveness

Non-invasiveness means that bioacoustic monitoring does not physically disturb wildlife or alter their natural behaviors. Traditional wildlife monitoring methods, such as capturing and tagging animals, can cause stress and impact their normal activities. In contrast, bioacoustic monitoring allows researchers to study species in their natural habitats without direct human interference. By passively recording sounds, scientists can observe animal behaviors, communication patterns, and habitat interactions without affecting the ecosystem. This ethical and minimally intrusive approach makes bioacoustic monitoring ideal for conservation studies [17].

Scalability and continuous monitoring

Scalability refers to the ability of bioacoustic monitoring systems to be expanded and adapted for different ecological studies. Whether monitoring a small reserve or an entire rainforest, bioacoustic systems can be deployed at various scales to suit different research needs. Continuous monitoring is the process of collecting data over extended periods without interruptions. Unlike traditional wildlife surveys, which provide only snapshots of an ecosystem at specific times, bioacoustic monitoring allows for 24/7 data collection [18]. This is particularly important for studying seasonal patterns, migration events, and long-term biodiversity trends.

Conclusions

Bioacoustic monitoring represents a transformative approach to forest conservation, offering real-time insights into ecosystem health and enabling proactive conservation strategies. Its ability to function as an early warning system enhances biodiversity management and habitat protection. Future research should explore integrating bioacoustic techniques with climate models and remote sensing for a more comprehensive understanding of ecosystem dynamics. Expanding bioacoustic initiatives to community-driven conservation programs can further amplify their impact, ensuring long-term forest sustainability. Additionally, collaborations between researchers, policymakers, and local communities can help scale up bioacoustic monitoring for global conservation efforts.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. Kotera MM, Phillott AD. Calls for conservation: a review of bioacoustics monitoring with case studies from India. *Asian j environ ecol.* 2022;19(4):142-150. <https://doi.org/10.9734/AJEE/2022/v19i4425>
2. Kumar B, Ghosh O. An overview of ai applications in wildlife conservation. *AI and Machine Learning Techniques for Wildlife Conservation.* 2025:19-48. <https://doi.org/10.4018/979-8-3693-6935-7.ch002>
3. Shonfield J, Bayne E. Autonomous recording units in avian ecological research: current use and future applications. *Avian Conserv Ecol.* 2017;12(1). <https://doi.org/10.5751/ACE-00974-120114>
4. Whytock RC, Christie J. Solo: an open source, customizable and inexpensive audio recorder for bioacoustic research. *Methods Ecol Evol.* 2017;8(3):308-312. <https://doi.org/10.1111/2041-210X.12678>
5. Sessler GM. Acoustic sensors. *Sens Actuators A: Phys.* 1991;26(1-3): 323-330. [https://doi.org/10.1016/0924-4247\(91\)87011-Q](https://doi.org/10.1016/0924-4247(91)87011-Q)
6. Baquero MP, Parcerisas C, Seger KD, Perazio C, Acosta NB, Mesa F, et al. Comparison of two soundscapes. *Oceanography.* 2021;34(4):62-65.
7. Brodie S, Towsey M, Allen-Ankins S, Roe P, Schwarzkopf L. Using a novel visualization tool for rapid survey of long-duration acoustic recordings for ecological studies of frog chorusing. *Front ecol evol.* 2022;9:761147. <https://doi.org/10.3389/fevo.2021.761147>
8. Alcocer I, Lima H, Sugai LS, Llusia D. Acoustic indices as proxies for biodiversity: a meta-analysis. *Biol Rev.* 2022;97(6):2209-2236. <https://doi.org/10.1111/brv.12890>
9. Aide TM, Corrada-Bravo C, Campos-Cerqueira M, Milan C, Vega G, Alvarez R. Real-time bioacoustics monitoring and automated species identification. *PeerJ.* 2013;1:e103. <https://doi.org/10.7717/peerj.103>
10. Teixeira D, Maron M, van Rensburg BJ. Bioacoustic monitoring of animal vocal behavior for conservation. *Conserv Sci Pract.* 2019;1(8):e72. <https://doi.org/10.1111/csp2.72>
11. Sordello R, Ratel O, Flamerie De Lachapelle F, Leger C, Dambry A, Vanpeene S. Evidence of the impact of noise pollution on biodiversity: A systematic map. *Environ Evid.* 2020;9:1-27. <https://doi.org/10.1186/s13750-020-00202-y>
12. Rappaport DI, Swain A, Fagan WF, Dubayah R, Morton DC. Animal soundscapes reveal key markers of Amazon forest degradation from fire and logging. *Proc Natl Acad Sci.* 2022;119(18): e2102878119. <https://doi.org/10.1073/pnas.2102878119>
13. Justin DY, CoboCuan A, Márquez R, Sheridan JA, Grafe TU, Farina A, et al. Novel acoustic snapshot of a sarawak forest. *J Ecoacoust..* 2021;5(1):1. <https://doi.org/10.35995/jea5010001>
14. Lamb OD, Shore MJ, Lees JM, Lee SJ, Hensman SM. Assessing raspberry shake and boom sensors for recording African elephant acoustic vocalizations. *Front conserv sci.* 2021;1:630967. <https://doi.org/10.3389/fcosc.2020.630967>
15. Changapur MW, Seema S. Bioacoustics Monitoring to improve conservation efforts for endangered species. In 2023 7th International Conference on Computation System and Information Technology for Sustainable Solutions (CSITSS) 2023:1-7. *IEEE.* <https://doi.org/10.1109/CSITSS60515.2023.10334168>
16. Fiss CJ, Lapp S, Cohen JB, Parker HA, Larkin JT, Larkin JL, et al. Performance of unmarked abundance models with data from machine-learning classification of passive acoustic recordings. *Ecosphere.* 2024;15(8):e4954. <https://doi.org/10.1002/ecs2.4954>
17. Zemanova MA. Towards more compassionate wildlife research through the 3Rs principles: Moving from invasive to non-invasive methods. *Wildl Biol.* 2020;2020(1):1-7. <https://doi.org/10.2981/wlb.00607>
18. Sethi SS, Jones NS, Fulcher BD, Picalini L, Clink DJ, Klinck H, et al. Characterizing soundscapes across diverse ecosystems using a universal acoustic feature set. *Proc Natl Acad Sci.* 2020;117(29): 17049-17055. <https://doi.org/10.1073/pnas.2004702117>