# Terrestrial Passive Acoustic Monitoring: Review and Perspectives

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# Terrestrial Passive Acoustic Monitoring: Review and Perspectives

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*Passive acoustic monitoring (PAM) is quickly gaining ground in ecological research, following global trends toward automated data collection and big data. Using unattended sound recording, PAM provides tools for long-term and cost-effective biodiversity monitoring. Still, the extent of the potential of this emerging method in terrestrial ecology is unknown. To quantify its application and guide future studies, we conducted a systematic review of terrestrial PAM, covering 460 articles published in 122 journals (1992–2018). During this period, PAM-related studies showed above a fifteenfold rise in publication and covered three developing phases: establishment, expansion, and consolidation. Overall, the research was mostly focused on bats (50%), occurred in northern temperate regions (65%), addressed activity patterns (25%), recorded at night (37%), used nonprogrammable recorders (61%), and performed manual acoustic analysis (58%), although their applications continue to diversify. The future agenda should include addressing the development of standardized procedures, automated analysis, and global initiatives to expand PAM to multiple taxa and regions.*

*Keywords: audio recorders, auditory monitoring, automated data collection, bioacoustics, ecoacoustics, faunal survey, soundscapes*

**Wildlife monitoring has undergone a remarkable** transformation in the twenty-first century, with the development and introduction of technologies that greatly expand the possibilities for biodiversity assessment and ecological research (e.g., remote sensing, camera trapping, DNA barcoding; Pimm et al. 2015). These methods have allowed us to better track the effects of a rapidly changing environment on biodiversity, including the impacts of habitat loss, species introductions, and climate change (Llusia et al. 2013, Schmeller et al. 2017). Among these cutting-edge technologies, automated audio recorders have recently revolutionized traditional faunal survey methods based on auditory detection (Obrist et al. 2010, Blumstein et al. 2011).

Terrestrial environments are typically replete with sounds from multiple sources, particularly from animals (McGregor 2005). Animal sounds are highly informative. In addition to their use as characteristics for species identification, they also convey cues about abundance, position, body size, and motivation of emitters (Bradbury and Vehrencamp 1998, Wilkins et al. 2013). Additionally sounds can propagate in multiple directions, through physical obstacles, and over relatively long distances; therefore, vocal animals are generally more easily detectable by hearing than by seeing (Rosenthal and Ryan 2000, Heinicke et al. 2015). For this reason, auditory surveys have become the basis for many biodiversity assessment programs, such as the North American Amphibian Monitoring Program (Weir and Mossman 2005) and several terrestrial bird survey initiatives (Rosenstock et al. 2002).

In addition to these properties, sounds can be reliably recorded by analog or digital devices. Historically, the development of portable tape recorders enabled researchers to record animal sounds in the field, providing new opportunities for faunal surveys (Parker 1991, Vielliard 1993, Haselmayer and Quinn 2000). A subsequent milestone was the release of digital audio recorders, which supplied researchers with affordable and smaller devices, maintaining high fidelity to analog signals and optimizing auditory surveys (Obrist et al. 2010). More recently, early autonomous recorders provided additional innovations by allowing unattended recording over long periods, with longer battery life and programmable recording schedules (Sueur et al. 2012, Digby et al. 2013). These advances translate into several advantages for species surveys, including broader temporal and spatial sampling, reduced observer bias, and long-term storage of field recordings, which can later be digitally analyzed and checked for dubious vocalizations. Therefore, passive acoustic monitoring (PAM) now stands as a powerful

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tool for biodiversity monitoring, supporting a variety of ecological, behavioral, and conservation applications (Farina and Gage 2017, Wrege et al. 2017, Linke et al. 2018).

Wildlife surveys based on passive acoustics have been widely applied in marine environments to detect species presence, estimate population dynamics, measure home ranges, and determine activity patterns and movement routes (Mellinger et al. 2007). Similarly, this technique offers ample possibilities for faunal surveys in terrestrial environments, because acoustic sensors allow noninvasive data collection for a wide range of animals emitting detectable acoustic signals (Browning et al. 2017). Moreover, PAM can increase the temporal and spatial coverage of monitoring programs while providing favorable cost–benefit trade-offs for wildlife surveys in relation to traditional survey methods (Ribeiro et al. 2017, Wrege et al. 2017). Nevertheless, the use of PAM in terrestrial-monitoring programs is still relatively incipient when compared with its use for marine fauna, and it has only recently gathered significant attention (Servick 2014). By understanding the current trends, limitations, and challenges of terrestrial PAM, we can better guide future applications and the progress of this emergent method in ecological research.

In the present article, we provide a comprehensive review and synthesis of the use of passive acoustic monitoring for terrestrial wildlife survey. First, we characterize the historical evolution and expansion of PAM-based studies across research topics, focal organisms, geographical locations, and methodological procedures. Second, we synthesize current applications, trends, key shortfalls, and future challenges, drawing attention to the potential of PAM to support of global initiatives and citizen science projects, through the adoption of standardized procedures and coordinated monitoring of multiple taxa and regions using common monitoring stations.

## Reviewing the literature of terrestrial passive acoustic monitoring

We conducted a systematic review of passive acoustic monitoring on terrestrial ecosystems using complementary literature searches in the Thomson Reuters Web of Science (WoS) platform, spanning all years on record (1900–2018). The first search was performed on 24 August 2017, with the following keywords: *(((sound* OR acoustic* OR call* OR song* OR sing* OR vocal*) AND (monito* OR passive OR record* OR survey OR sampl* OR automat* OR activit*)) AND (wildlife OR biodiversit* OR animal* OR soundscape* OR ecoacoustic* OR vertebrate* OR mammal* OR bird* OR avian* OR anura* OR amphibia* OR frog* OR toad* OR insect* OR artropod* OR orthoptera OR cricket* OR cicada*))*. A second search was performed on 9 September 2017, using *((call* OR acoustic*) AND (survey OR activit*))*. To update our database, the two previous literature searches were repeated on 27 September 2018. These searches were restricted to 13 WoS subject areas: biology, biodiversity conservation, environmental sciences, remote sensing, ecology, entomology, acoustic, behavioral sciences, zoology, ornithology, and evolutionary biology. In addition, to include potentially meaningful articles absent from the reviews in WoS, complementary searches were performed using Google Scholar on 15 September 2017 and 27 September 2018, using the keyword combination *((wildlife acoustic) AND (passive acoustic monitoring))*.

The literature search procedure resulted in more than 10,000 articles. From this initial list, we excluded those unrelated to this review (false positives)—that is, articles that did not employ PAM to survey biological aspects of terrestrial fauna, such as underwater environments (for a review, see Mellinger et al. 2007); environmental sound pressure level assessments (see Lynch et al. 2011, Shannon et al. 2016); and the use of acoustic lures, playbacks, and call–broadcast surveys without joint use of passive acoustics (see McGregor 2000, Suraci et al. 2017). Articles aimed at estimating species density and movement by acoustic location systems using microphone arrays were also excluded, because several comprehensive reviews have been published on these methods (see Marques et al. 2013, Stevenson et al. 2015, Measey et al. 2017). This filtering finally led to a final data set of 460 selected articles (see the supplemental information).

From each article found in this literature search, we extracted key information to characterize PAM-based research: publication year, monitoring year, journal of publication, research topic, monitored taxa, geographical coordinates of the recorded sites, recording settings (type of recorder and daily recording period), and acoustic analysis applied to derive biological information from the passive recordings (table 1).

## Overview of passive acoustic monitoring in terrestrial ecosystems

Studies using PAM in terrestrial ecosystems started in the 1990s and have exponentially increased in the last decades, at an average rate of 2.8 articles per year in the 1990s (from 0 to 11 per year), 10.8 in the 2000s (from 3 to 19 per year), and 42.5 in the 2010s (from 28 to 62 per year; figure 1a). Noticeably, the number of articles increased more than fifteenfold during this period, with the peak in 2017 (i.e., the last complete year spanned by this review). The actual monitoring reported in these articles has a similar pattern to the publication trend, with a 3–4-year lag between monitoring and publication; the peak was in 2012, and 50% of the recordings were made after 2008 (figure 1b). This prominent rise in PAM-based research has mostly resulted from the increased availability of automated audio recorders, whose use has risen from 2 to 48 articles per year since their commercial release in 2007. So far, this type of recorder represents 39% of all published articles, whereas nonprogrammable audio recorders represent 61% (figure 1a).

Overall, we could delimit three general developing phases of terrestrial PAM: *establishment*, during which the first studies using ad hoc acoustic methods to assist faunal inventories and investigate species activity and habitat use were published (before 2000); *expansion*, which is represented by

*Table 1. Description of items compiled in this review and used to characterize publication and research trends in passive acoustic monitoring in terrestrial ecosystems from 1992–2018.*

| Items | Classes | Categories | Description |
|---|---|---|---|
| Publication | Publication year | | |
| | Journal of publication | | |
| Data collection | Monitoring year | | Years when the acoustic monitoring was conducted |
| | Study sites | | Geographical coordinates of the sites at which the acoustic monitoring was conducted |
| Research area | Research topics | Activity patterns | Studies assessing seasonal and diel activity levels of populations and communities |
| | | Behavior | Studies focused on aspects of animal behavioral biology |
| | | Community Ecology | Studies addressing the determinants of species diversity, community structure, and assembly |
| | | Conservation Biology | Studies concerned with the conservation of species, habitats, and ecosystems |
| | | Ecoacoustics | Investigations of soundscape patterns and dynamics |
| | | Habitat use | Studies addressing species preference and selection over distinct environmental conditions |
| | | Signal processing | Automated methods for detecting and classifying species in acoustic recordings |
| | | Species assessment | Faunal inventories and surveys aiming to document biodiversity |
| | | Species distribution/Occupancy | Estimates of distribution patterns of species over multiple scales; imperfect species detectability |
| | | Survey technique | Protocols, data collection procedures, or comparisons with other survey methods |
| | | Urban Ecology | Ecological studies that include urban context |
| | Monitored taxa | Bats | |
| | | Nonflying mammals | |
| | | Birds | |
| | | Anurans | |
| | | Invertebrates | |
| | | Soundscapes | Environmental sounds as a whole that emerge from the landscape |
| Recording settings | Recording system | Automated recorder | Audio recorders with scheduled recording options |
| | | Nonprogrammable recorder | |
| | Recording period | Continuous | Recordings obtained continuously across the day |
| | | Dawn | Recordings obtained exclusively at dawn |
| | | Morning | |
| | | Afternoon | |
| | | Dusk | |
| | | Night | |
| Acoustic analysis | | Manual | Extraction of biological information mostly relied on human effort (e.g., manual measurement of acoustic parameters, visual or aural inspection of spectrograms) |
| | | Semiautomated | Combination of manual and automated methods |
| | | Automated | Extraction of biological information mostly relied on computing effort (e.g., built-in software recognizers, ad hoc discriminant function analyses) |
| | | Acoustic indices | Estimation of α or β acoustics-based ecological indices (which is a particular automated method) |

a visible increase in the number of studies focusing on the same earlier topics, followed by an initial diversification of research areas (conservation biology, community ecology, and ecoacoustics, between 2000–2010); and *consolidation*, which is the exponential growth of studies covering multiple research topics and reaching the highest publication rates in recent years (after 2010; figure 2).

Presently, studies using terrestrial PAM cover a wide range of research areas, studied organisms, surveyed locations, and methodological approaches. The 460 articles

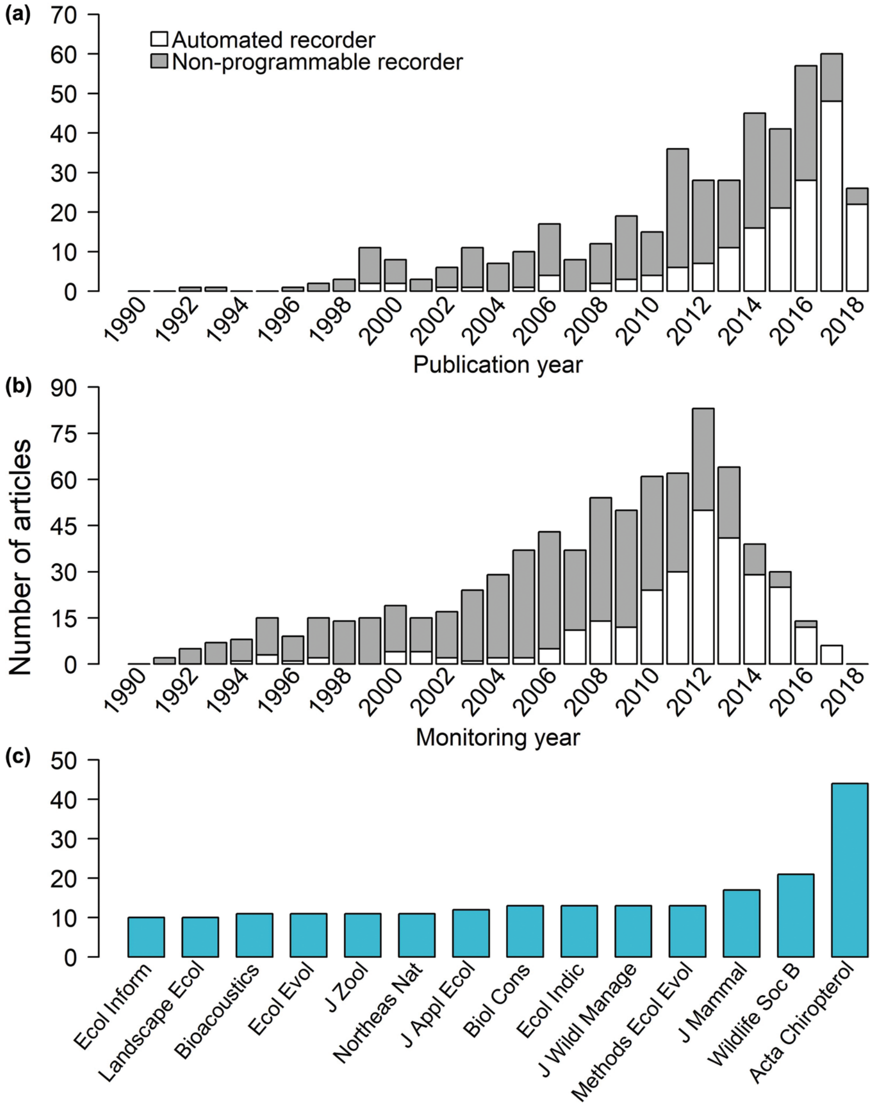


***Figure 1. The publication rates of studies using passive acoustic monitoring in terrestrial ecosystems (1992–2018) across (a) years, (b) monitoring periods, and (c) journals. Only journals with the most number of articles are shown. In the upper panels (a) and (b), the colors represent the recording system employed: automated audio recorders (white) and nonprogrammable recorders (gray).***

identified in our search were published in 122 journals, with 14 journals concentrating 46% (210) of all of the articles (figure 1c). Across these journals, the main research subjects were divided among taxonomy-oriented studies, applied ecology and conservation biology, and methodological studies. Among the research topics investigated so far, reports on species activity patterns were the most frequent (25%), followed by habitat use (16%), survey technique (15%), and species assessment (9%; figure 2).

Terrestrial PAM has become as useful as other well-established survey techniques (e.g., camera traps) to assess and monitor species, either as a standalone method or as a complementary approach (Browning et al. 2017). For example, Llusia and colleagues (2013) used anuran phenological patterns to estimate thermal tolerances of calling behavior, with further implications for the assessment of climate change impacts. Cryptic, rare, and endangered species, such as koalas (Ellis et al. 2011) and elephants (Wrege et al. 2017), have been monitored to reveal behavioral and ecological aspects. Applied conservation programs have also benefited from PAM, through monitoring of hunting activities (Astaras et al. 2017), studies of species responses to anthropogenic impacts (Gil et al. 2014), and multitaxa assessments (Deichmann et al. 2017). Together, these successful applications reinforce the ample potential of passive acoustics for practical applications in terrestrial ecosystems, contributing to the toolbox of conservation practitioners and researchers (Ribeiro et al. 2017).

**Monitored taxa.** Over the focal organisms investigated with terrestrial PAM, bats were, by far, the biological group most studied (50% of the articles; figure 3a). Likewise, the journal with the most articles on terrestrial PAM is fully devoted to this group (9%, *Acta Chiropterologica*; figure 1c). However, most of the articles within this taxon were based on nonprogrammable audio recorders (89%), with automated devices only recently appearing (figure 3b). The trajectory of PAM applications for bat surveys clearly exemplifies the three distinct developing phases of PAM for terrestrial application: first, focusing on methodological issues regarding the use of ultrasound detectors and early applications for species assessment (Rachwald 1992, Kuenzi and Morrison 1998), followed by an increase in applications and diversification of investigated topics, and, finally, consolidating as a robust method to support a variety of goals including species inventory, population/community assessment, and species conservation (Russo and Jones 2003, Froidevaux et al. 2014).

After bats, birds were the most researched terrestrial group (20%), followed by anurans (12%), nonflying mammals (6%), and invertebrates (5%). Automated recording systems were more frequently used than nonprogrammable ones for all of these groups, except invertebrates (figure 3a). Pioneer contributions between 1990 and 2000 mostly reported the efficiency of acoustic methods, discussed the optimization of sampling procedures (e.g., Mohr and Dorcas 1999, Bridges

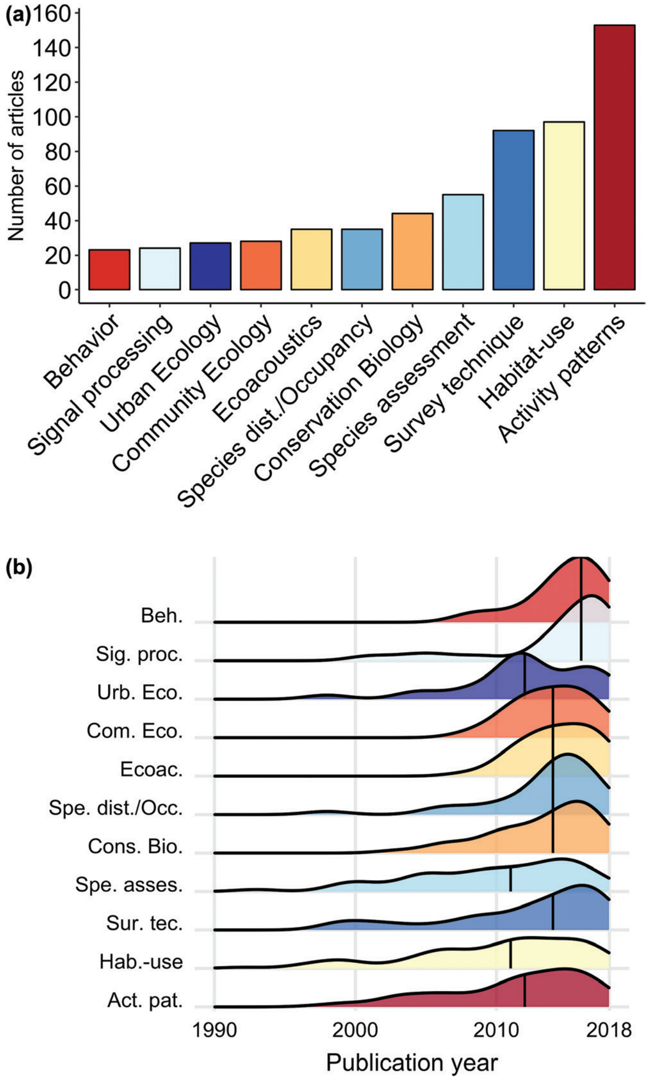


*Figure 2. The research topics of studies using passive acoustic monitoring in terrestrial ecosystems (1992–2018): (a) number of published articles per topic, and (b) density plots of articles over time. Vertical black lines represent the median number of published articles for each topic.*

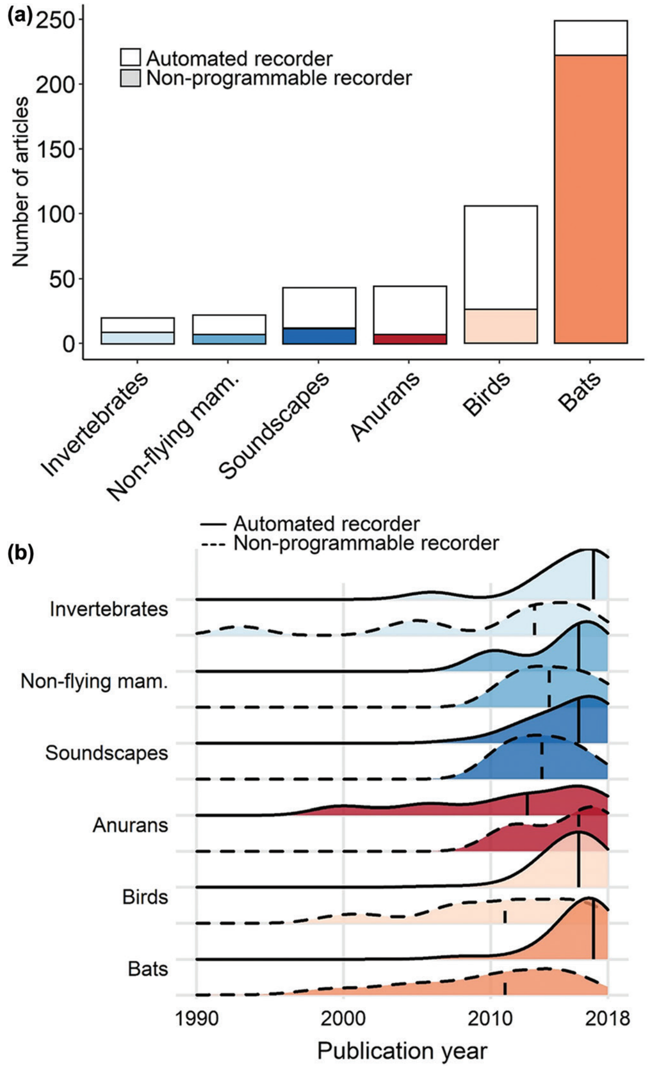


*Figure 3. The taxa studied in articles using passive acoustic monitoring in terrestrial ecosystems (1992–2018): (a) the number of published articles per focal organism and (b) density plots of the articles over time. The colors and line types represent the recording system employed: automated audio recorders (the white boxes and solid lines), and nonprogrammable recorders (the color boxes and dashed lines). The vertical black lines represent the median number of published articles for each taxon.*

and Dorcas 2000), and addressed general activity patterns, such as for tropical cricket assemblages (Riede 1993) and birds (Evans and Mellinger 1999).

Soundscapes (i.e., environmental sounds as a whole that emerge from the landscape) were examined in 7% of the studies. This recent approach has been fostered by the challenge of extracting biological information from the large volumes of acoustic data obtained through PAM, using acoustic indices to synthesize patterns made by vocal organisms, irrespective of species identity (Sueur et al. 2008). Consequently, a new research area was created, first formalized as *soundscape ecology* and posteriorly as *ecoacoustics* (Pijanowski et al. 2011, Sueur and Farina 2015). Soundscape dynamics have shown promise to represent overall animal activity patterns, and this new research program has been garnering increasing significance in ecological research (Servick 2014, Gasc et al. 2015, Farina and Gage 2017).

**Geographical distribution.** PAM-based studies have been mostly concentrated in the northern temperate zone (65%), primarily in North America and Europe, whereas a markedly smaller number of studies occurred in tropical (25%) and southern temperate zones (10%). To our knowledge, large areas of the globe still have no recorded sites with this technique to date, with regions of Asia, western Oceania,

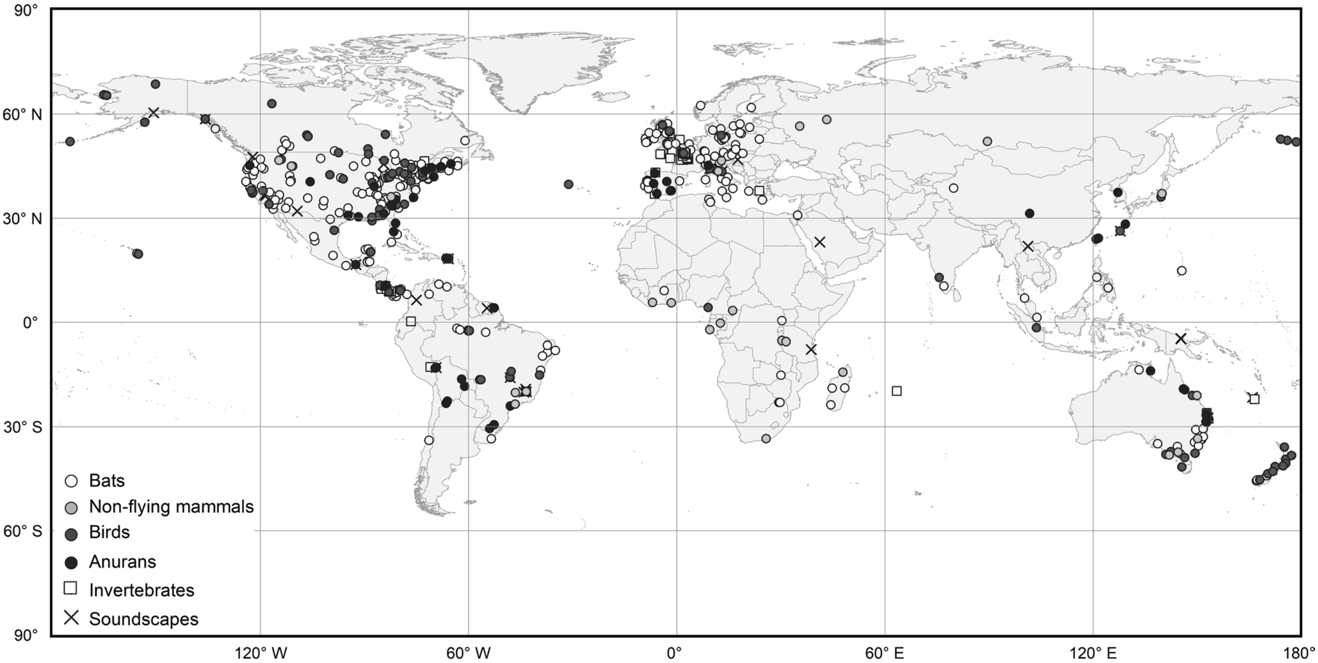


*Figure 4. The geographic distribution of the study sites in articles using passive acoustic monitoring in terrestrial ecosystems (1992–2018) included in this review. The colors represent the focal taxa of each article.*

northern Africa, and southern South America standing as the main gaps (figure 4). Passive recordings of bats, birds, and anurans were more widely distributed than other biological groups. PAM of nonflying mammals was concentrated on a few focal taxa, such as elephants in Africa, whereas invertebrate and soundscape studies likely reflect the geographical location of the main research groups in Europe and the United States.

**Recording periods.** Although 19% of the studies using PAM recorded audio samples throughout the entire day, the majority of studies recorded only during specific periods (figure 5a). Among these, sampling effort was mostly concentrated at night (37%) and dusk (32%), when nonprogrammable recorders were primarily used (72% and 74%, respectively). This temporal asymmetry was due to the larger contribution of studies focusing on nocturnal species—namely, bats and anurans (figure 5b). The recordings at dawn represented 21% of the recording periods and were conducted with both types of recorders in a similar proportion (56% with nonprogrammable). Morning and afternoon were the least frequent recording periods (figure 5a), with a higher proportion of automated recorders being used (68% and 74%, respectively).

As was expected, researchers generally prioritized acoustic monitoring on periods coinciding with the highest activity levels of the species of interest (figure 5b). Therefore, bats and anurans were investigated at more restricted daily periods, mainly at night (43% and 51%) and dusk (38% and 30%, respectively), whereas birds and soundscapes were investigated over wider periods and mainly at dawn (34% and 37%). During the morning and afternoon, recordings were collected only in studies focused in nonflying mammals, birds, invertebrates, and soundscapes (figure 5b).

**Acoustic analysis.** The main procedure used to extract biological information from PAM recordings has been manual analysis, which mostly relies on human effort (e.g., manual measurement of acoustic parameters, visual or aural inspection of spectrograms) and corresponded to 58% of the studies (figure 6a). Fully automated analyses were applied in only 19% of the studies, with relatively more frequent use for bat signals (32% of the articles within the group), because several software packages contain built-in classification algorithms and libraries for automated recognition of bat species (e.g., Analook and Batsound). For other biological groups, fully automated methods are still being developed and tested (e.g., Digby et al. 2013, Astaras et al. 2017, Ulloa et al. 2018), and there are still relatively few alternatives to manual or semiautomated PAM data analysis (Kasten et al. 2012, Llusia et al. 2013).

Semiautomated procedures (i.e., combining both manual and automated analyses) were applied in 15% of the studies, with more applications than fully automated procedures for anurans, birds, and nonflying mammals (figure 6). Acoustic indices (10.5%) were applied mostly for soundscape studies, which, by definition, rely exclusively on the automated extraction of these indices to represent overall patterns of acoustic communities. Interestingly, acoustic indices were

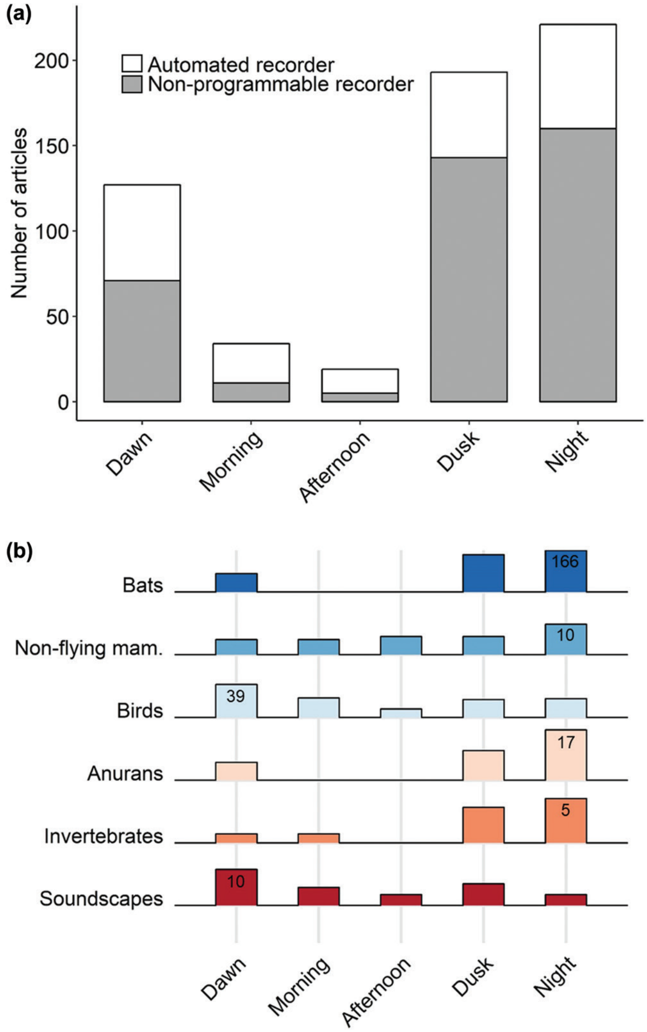


*Figure 5. The daily recording periods applied in studies using passive acoustic monitoring in terrestrial ecosystems (1992–2018): (a) the number of published articles per period (excluding those performed throughout the entire day) and (b) the number of articles per period for each taxon. In the upper panel (a), the colors represent the recording system employed: automated audio recorders (white) and nonprogrammable recorders (gray).*

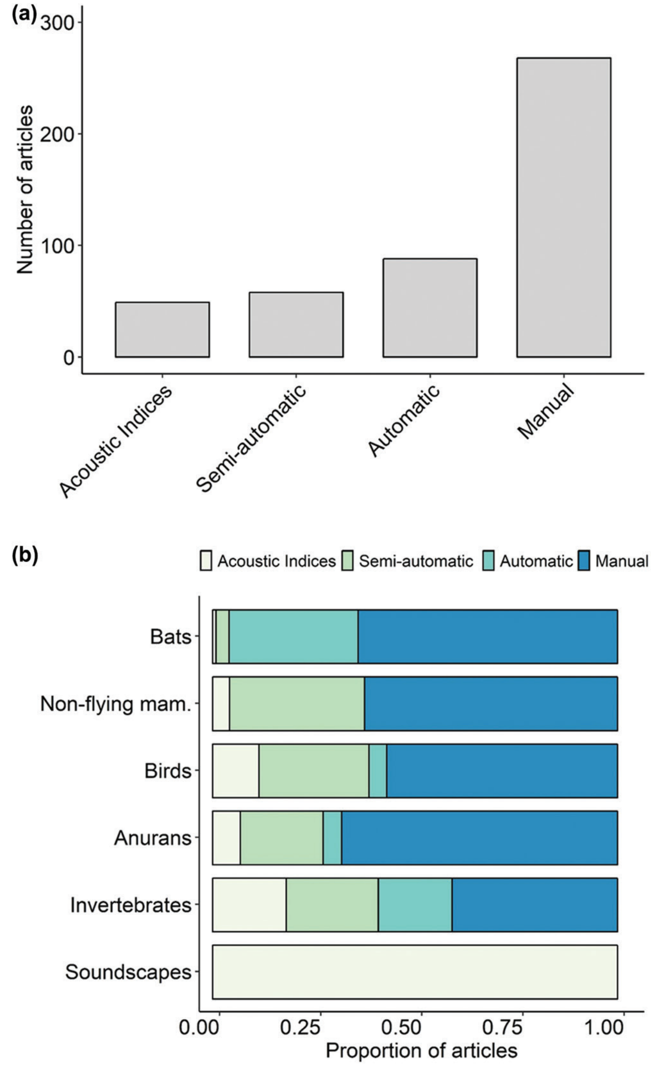


*Figure 6. The analysis approach applied to acoustic data in studies using passive acoustic monitoring in terrestrial ecosystems (1992–2018): (a) the number of published articles per type of acoustic analysis and (b) the proportion of articles per type for each taxon.*

also used as proxies for species diversity by a few studies (figure 6).

## Challenges and future directions for terrestrial PAM

We identified three main challenges for a further expansion of PAM-based research in terrestrial ecosystems. These shortfalls, which can likely be extended to the application of PAM in other environments, are nonstandardized monitoring procedures, time-consuming acoustic analysis, and limited data curation and data sharing resources.

Research focused on methodological approaches and the limitations of PAM only substantially appeared during the consolidation phase identified in this review (2010–2018), although some custom passive audio recorders capable of monitoring the vocal activity of terrestrial fauna were proposed early in the literature (Peterson and Dorcas 1994). Examples of methodological developments include studies providing field recording protocols (Obrist et al. 2010), designing methods for estimating the detection space of PAM stations (Llusia et al. 2011), comparing detection accuracy in relation to human observers (Digby et al. 2013, Wimmer et al. 2013) and to other survey techniques (Horton et al. 2015, Enari et al. 2017), and evaluations of changes in detectability given different recording schedules (La and Nudds 2016, Madalozzo et al. 2017). In addition, recent efforts to promote ecoacoustics as a new discipline have also generated contributions to PAM through both semiotic and theoretical unifying proposals (Farina 2014, Sueur and Farina 2015, Farina and Gage 2017). However, despite these efforts, further formalization of general methods for designing and employing PAM programs remain a challenging objective for future research. Such a methodological framework should include, for instance, generalized procedures to estimate species detectability, protocols for determining adequate recording schedules and sampling efforts, and guidelines to optimize the set of audio settings and autonomy in PAM stations. These accomplishments would benefit forthcoming studies by guiding decision-making in PAM planning and standardizing sampling protocols (Brandes 2008, Roch et al. 2016).

A critical challenge in PAM studies is still the analysis and handling of very large amounts of acoustic data, especially for programs spanning wide temporal or spatial extents (Browning et al. 2017). As the data volumes resulting from PAM programs often approach the scale of big data, automation of essential procedures such as species detection and recognition are desirable. There are currently several research areas devoted to developing automated methods to meet this pressing demand (e.g., signal processing and pattern recognition; Xie et al. 2017, Ulloa et al. 2018). However, current solutions often require professional experience and time-consuming supervision. An open avenue is the development of analytical solutions that are transferable among multiple species and acoustic conditions, thus facilitating management and data mining of PAM recordings for wildlife monitoring. Although fully automated solutions are progressing, PAM users and researchers should consider the best balance between research goals, measurement accuracy, and time allocated to analysis of the time series of recordings, with semiautomated procedures currently being the preferred solution (Kasten et al. 2012, Llusia et al. 2013).

The challenge of extracting biological information is larger for noisy and complex environments. Manual scanning may be valuable when automated procedures show poor performance, such as recordings containing overlapping vocalizations or a low signal-to-noise ratio (Hugel 2012, Browning et al. 2017). Still, manual approaches are labor intensive and can be unattainable for large amounts of recordings. These challenges have favored the development and use of acoustic diversity indices to characterize overall acoustic communities, although their biological meaning is arguable (Servick 2014). Acoustic indices are more reliable in representing general patterns of species vocal activity instead of diversity (Gasc et al. 2017) and offer singular opportunities to track global change impacts on biodiversity (Krause and Farina 2016, Sueur and Farina 2015). More research focused on identifying and understanding the facets of biodiversity provided by acoustic indices are highly encouraged, because the acoustic component expressed by these indices can be related to other biodiversity aspects, such as phylogenetic and functional diversity (Gasc et al. 2015).

Another necessary step forward for increasing the applicability of PAM is the development and improvement of widely available sound repositories for curation, management, and sharing of temporal acoustic data sets, facilitating the access and preservation of these sizeable data sets. Existing public sound libraries and repositories are mostly focused on storing conventional manual audio recordings (i.e., directional recordings), and their infrastructure is often not suitable for transferring and storing the raw time series of recordings produced by PAM. To fill this gap, new repository initiatives have been appearing for managing PAM data, such as ARBIMON (Aide et al. 2013), Pumilio (Villanueva-Rivera and Pijanowski 2012), and REAL (Kasten et al. 2012). Ideally, researchers should archive audio recordings in sound repositories, similar to what is done for museum specimens and DNA sequences, although this practice is still not ubiquitous (Toledo et al. 2015). Because bandwidth and storage capabilities have been increasing exponentially, we expect the rapid proliferation of acoustic repositories in the next decade, with new opportunities for collective efforts on managing and analyzing terrestrial PAM data.

## Integrating PAM to global monitoring networks

Methods to capture multiple taxa information over broad spatial and temporal scales have been a central issue for improving global biodiversity monitoring in the face of human-driven changes (Schmeller et al. 2017). Worldwide long-term ecological research and monitoring networks have often been supported by methods that enable coordinated, standardized, and scalable projects (Pimm et al. 2015). In this context, we strongly advocate the use of PAM as a suitable and standardized method for measuring essential biodiversity variables using sensor networks (Kissling et al. 2017), thus increasing our ability to monitor and preserve global biological diversity.

PAM stations can easily be added to existing monitoring sites and can provide data from vocal animals. Affordable commercial or custom-built recorders have become increasingly available, making acoustic monitoring more accessible (e.g., Mennill et al. 2012, Farina et al. 2014, Whytock and Christie 2017). Moreover, individual research teams should pool resources and combine efforts to overcome logistical limitations and financial costs, benefiting collectively from extended data collection and improved knowledge of species natural history, site selection, and signal identification. Coordinated PAM stations may also inspire the development of more customizable or accessible recording systems adaptable for different research purposes.

Such advances could favor the implementation of PAM in remote and currently unmonitored areas, meeting the urgent need for tracking unprotected areas at risk (Watson et al. 2016), located mostly in the same regions in which spatial gaps in acoustic monitoring have been identified by our review. PAM is suitable for surveying threatened fauna and monitoring their responses to environmental change, contributing to the development of wildlife protection strategies under the current global biodiversity crisis. In addition, a wide variety of taxa can be simultaneously monitored with audio recordings. Therefore, worldwide efforts to commit to a set of standardized procedures can be facilitated by the availability of programmable recording schedules that allow the recording of multiple species in PAM (e.g., static ultrasonic detectors for monitoring high-frequency animal sounds as bats and orthopteran species; Newson et al. 2017).

The increasing role of citizen science in providing large-scale ecological data also has a large potential to support the widespread adoption of PAM. The French national acoustic biodiversity monitoring gathers acoustic data from orthopteran communities over a large extent of France, using passive audio recorders that have been supervised by volunteers since 2006 (see Jeliazkov et al. 2016). In another citizen-based program, a long-term integrated system of audiovisual recordings from Japan provides live streaming from remote areas to online users; participants can identify bird species and discuss their identification through social media, improving the efficiency of bird inventories (Saito et al. 2015). Ritts and colleagues (2016) worked with First Nations in Canada to deploy automated sound sensors and interpret sounds along a potential shipping corridor and to determine its impacts on the population. Even before the expansion of passive acoustics, the volunteer-based wildlife acoustic survey proposed by the North American Amphibian Monitoring Program had already demonstrated the synergistic potential between citizen since and acoustic monitoring (Cosentino et al. 2014).

## Conclusions

Our review traces the emergence and progress of terrestrial PAM, a burgeoning toolbox for animal surveys. The use of PAM in terrestrial ecology has been growing exponentially since the 1990s, reaching widespread adoption and a wide range of applications, with unprecedented publication rates. Bats have been the most researched group until now, mainly supported by nonprogrammable audio recorders. Nevertheless, new technologies for the automated recording of animal sounds have fostered the consolidation of this emerging method, especially since the 2010s, expanding applications to a large variety of ecological and conservation studies focused on several terrestrial organisms and surpassing the use of nonprogrammable recorders. The development of innovative analytic tools for automated signal detection and the computation of acoustic diversity indices have opened new avenues for PAM applications in community ecology and other scientific areas. However, our review also unveiled important gaps in terms of both geographical coverage and temporal design of PAM programs. Monitored areas have been mostly concentrated in a few regions of the northern temperate zone, whereas recording efforts mainly focused at dusk and night, because of the larger contribution of studies on nocturnal species.

The main barriers for the expansion of terrestrial PAM remain in establishing baselines for standardizing acoustic sampling, and in developing efficient solutions for automated signal analysis of long-term acoustic data sets. Another step forward is the improvement of PAM-oriented sound repositories for data management and sharing. Global monitoring and citizen science initiatives can find in PAM flexible options to coordinate multitaxa assessments over varying ecological conditions, providing new procedures for data collection over large spatial and temporal extents.

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## Supplemental material

Supplementary data are available at *BIOSCI* online.

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