Received: 29 November 2018 | Revised: 4 May 2019 | Accepted: 20 May 2019

DOI: 10.1111/fwb.13356

SPECIAL ISSUE

Freshwater Biology WILEY

Passive acoustic monitoring as a potential tool to survey animal and ecosystem processes in freshwater environments

Camille Desjonquères[1,2,3] | Toby Gifford[4] | Simon Linke[5]

[1]Molecular and Behavioural Ecology Group, Department of Biological sciences, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin, USA

[2]Institut de Systématique, Evolution, Biodiversité (ISYEB), Muséum National d'Histoire Naturelle, CNRS, EPHE, Sorbonne Université, Paris, France

[3]Neuro-PSI, UMR 9197, Université Paris-Sud, CNRS, Université Paris-Saclay, Orsay, France

[4]SensiLab, Monash University, Caulfield, Victoria, Australia

[5]Australian Rivers Institute, Griffith University, Nathan, Queensland, Australia

Correspondence

Camille Desjonquères, Department of Biological Sciences, University of Wisconsin-Milwaukee, 3209 N Maryland Ave, Milwaukee, WI, U.S.A.
Email: cdesjonqu@gmail.com

Funding information

Fondation Fyssen; ARC DECRA, Grant/Award Number: DE130100565

Abstract

1. Biodiversity in freshwater habitats is decreasing faster than in any other type of environment, mostly as a result of human activities. Monitoring these losses can help guide mitigation efforts. In most studies, sampling strategies predominantly rely on collecting animal and vegetal specimens. Although these techniques produce valuable data, they are invasive, time-consuming and typically permit only limited spatial and temporal replication. There is need for the development of complementary methods.
2. As observed in other ecosystems, freshwater environments host animals that emit sounds, either to communicate or as a by-product of their activity. The main freshwater soniferous groups are amphibians, fish, and macroinvertebrates (mainly Coleoptera and Hemiptera, but also some Decapoda, Odonata, and Trichoptera). Biophysical processes such as flow or sediment transport also produce sounds, as well as human activities within aquatic ecosystems.
3. Such animals and processes can be recorded, remotely and autonomously, and provide information on local diversity and ecosystem health. Passive acoustic monitoring (PAM) is an emerging method already deployed in terrestrial environments that uses sounds to survey environments. Key advantages of PAM are its non-invasive nature, as well as its ability to record autonomously and over long timescales. All these research topics are the main aims of ecoacoustics, a new scientific discipline investigating the ecological role of sounds.
4. In this paper, we review the sources of sounds present in freshwater environments. We then underline areas of research in which PAM may be helpful emphasising the role of PAM for the development of ecoacoustics. Finally, we present methods used to record and analyse sounds in those environments.
5. Passive acoustics represents a potentially revolutionary development in freshwater ecology, enabling continuous monitoring of dynamic bio-physical processes to inform conservation practitioners and managers.

KEYWORDS

anthropogenic noise, biodiversity monitoring, ecoacoustics, soundscape, underwater sounds

1 | INTRODUCTION

Freshwater environments host a large number of endemic species, some of which are highly threatened (Céréghino, Biggs, Oertli, & Declerck, 2008; Keith, Persat, Feunteun, & Allardi, 2011). Those environments are undergoing tremendous threats stemming from anthropological activities such as drainage, pollution (agricultural fertilisation or industrial waste), cattle, or dam construction (Dudgeon et al., 2006; Wood, Greenwood, & Agnew, 2003). These activities result in direct loss, fragmentation (Wood et al., 2003) and quality alteration of habitats (e.g. pollution or desiccation), such that species have declined at a much higher rate in freshwater systems (83%) than in all ecosystems (60%) between 1970 and 2014 (WWF, 2018).

To evaluate and predict the impact of these threats on freshwater environments, their effects need to be monitored. Monitoring an environment consists of measuring adequate variables to extract relevant knowledge on ecological condition. In freshwater environments, these variables can be structural variables such as flow discharge, sediment type, or biological communities or functional variables such as ecosystem processes and species interactions (Sandin & Solimini, 2009).

The use of passive acoustic monitoring (PAM) as a non-invasive ecoacoustic method to sample and monitor ecosystems is gaining traction globally (Blumstein et al., 2011; Furnas & Callas, 2015; Felisberto et al., 2015; Heinicke et al., 2015; Gibb, Browning, Glover-Kapfer, & Jones, 2018; 2010). This method consists of recording and analysing the sounds emanating from an environment, in either air or water, to extract information about presence of particular species (e.g. Kottege, Jurdak, Kroon, & Jones, 2015; Ulloa et al., 2016) or about ecosystem conditions and dynamics (Fuller, Axel, Tucker, & Gage, 2015; Pieretti, Farina, & Morri, 2011; Sueur, Pavoine, Hamerlynck, & Duvail, 2008). Passive acoustic monitoring can be very accurate and cost-effective for various applications in ecology such as detecting rare, invasive, or threatened species (Campos-Cerqueira & Aide, 2016; Gasc, Anso, Sueur, Jourdan, & Desutter-Grandcolas, 2018), contrasting differences in structure and condition of ecosystems (Duarte et al., 2015; Gasc, Sueur, Pavoine, Pellens, & Grandcolas, 2013), and continuously monitoring environments (Aide et al., 2013). Passive acoustic monitoring has particularly strong potential in low visibility environments such as dense forests or underwater, because sound propagation is not as strongly impacted by obstacles as other sensing methods such as netting or visual detection. Passive acoustic monitoring has so far been used in terrestrial habitats such as tropical and temperate forests (Depraetere et al., 2012; Malavasi & Farina, 2013; Rodriguez et al., 2014), urban areas (Pieretti & Farina, 2013), and plains (Mullet, Gage, Morton, & Huettmann, 2015); and in marine habitats such as open ocean (Parks, Miksis-Olds, & Denes, 2014; Ruppé et al., 2015), coral reefs (Bertucci, Parmentier, Berten, Brooker, & Lecchini, 2015), and coastal waters (Felisberto et al., 2015; McWilliam & Hawkins, 2013). Although there is a wealth of studies on bioacoustics of freshwater animals, mainly looking at behaviour (e.g. Colleye & Parmentier, 2012; Jansson, 1979), or sound production mechanisms (e.g. Fine & Parmentier, 2015; Jansson, 1972), so far, PAM has rarely been used in freshwater environments (Anderson, Rountree, & Juanes, 2008; Desjonquères et al., 2015; Straight, Freeman, & Freeman, 2014).

Although it has rarely been applied to date, PAM of freshwater environments has the potential to circumvent issues with traditional sampling techniques. Passive acoustic monitoring mainly requires the installation of a hydrophone and an audio recorder to record sounds produced underwater and at air/water interface (such as a calling frog). Passive acoustic monitoring is a non-invasive technique that neither modifies the environment, nor disturbs animal behaviour. With the advent of autonomous and weather resistant recorders, long-term PAM can be undertaken with reasonable efforts and costs (Blumstein et al., 2011; Linke, Gifford, et al., 2018).

Passive acoustic monitoring offers advantages in freshwater environments for three main reasons. The methods currently used to monitor populations are primarily netting and electro-fishing—two invasive methods that: (1) can impact the health of captured individuals or at least provoke fright responses (Clément & Cunjak, 2010; Ensign, Temple, & Neves, 2002); (2) do not allow continuous monitoring (Arrington & Winemiller, 2003); (3) require extensive time and labour for deployment and maintenance. Passive acoustic monitoring is not affected by these issues, and is therefore an attractive complement to existing methods.

To foster the development of PAM techniques for freshwater environments we: (1) review the current knowledge on underwater sounds in freshwater environments; (2) demonstrate the potential for PAM to be applied to various fields of freshwater biology and ecology; and (3) illustrate current methods for PAM in freshwater environments. This article does not aim to comprehensively cover the extensive literature on a well-established discipline, but rather to inform the freshwater biology community of the possibilities offered by PAM of freshwater environments.

2 | WHAT CAN BE ACOUSTICALLY MONITORED IN FRESHWATER ENVIRONMENTS?

2.1 | Biological composition and interactions

Freshwater environments harbour a stunning diversity of sounds (Figure 1a,b) (Desjonquères et al., 2015; Gottesman et al., 2018; Linke, Gifford, et al., 2018). At least four animal groups produce detectable sounds underwater in aquatic environments: amphibians, fish, insects, and crustaceans (Aiken, 1985; Favaro, Tirelli, Gamba, & Pessani, 2011; Fine & Parmentier, 2015; Gerhardt & Huber, 2002). These animals emit sounds with a variety of mechanisms including constricted expulsion of air in amphibians (Gerhardt & Huber, 2002) and insect larvae (Aiken, 1985; Balduf, 1935), contraction of swim bladder muscles in fish (Fine &

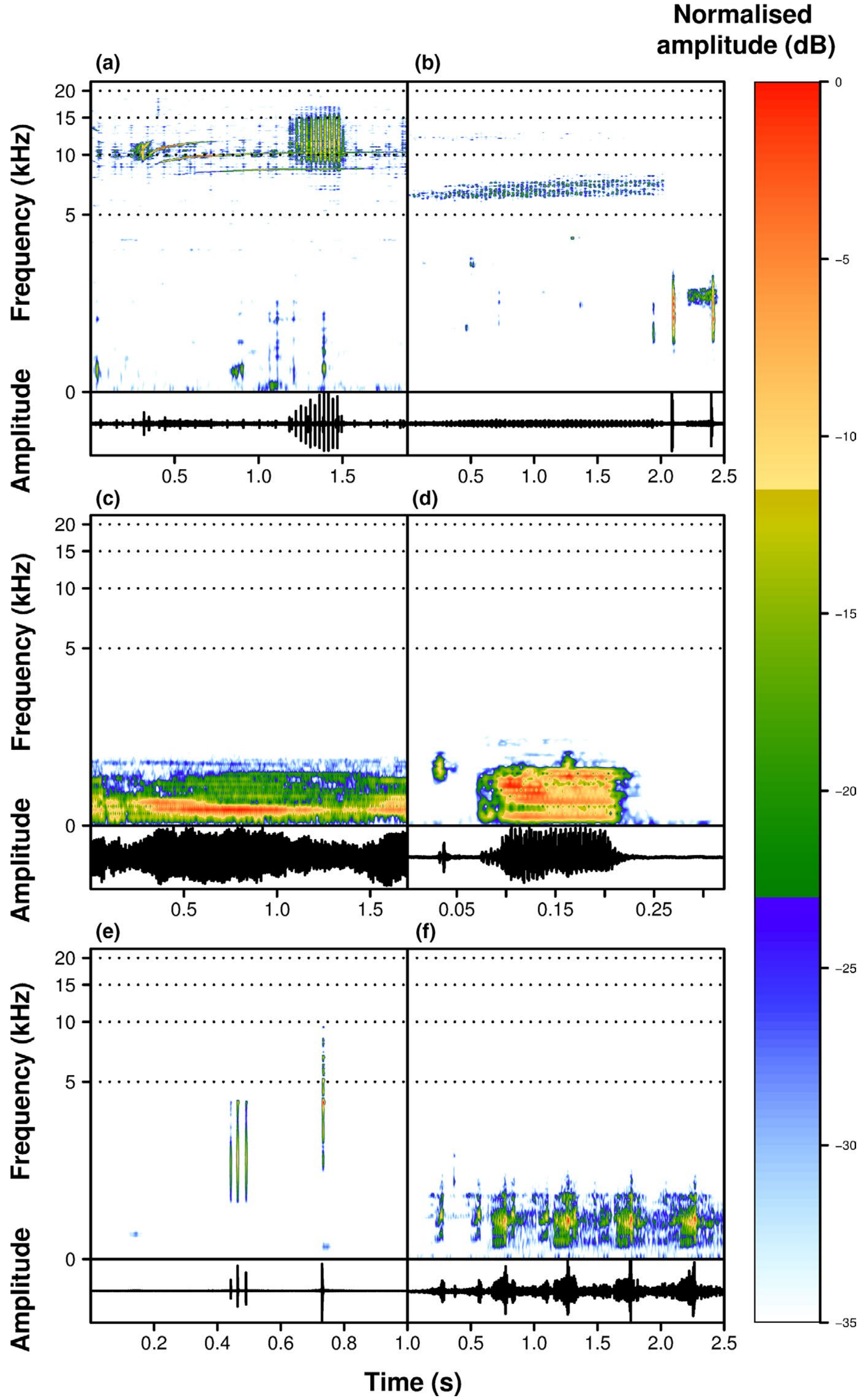

FIGURE 1 Spectrograms and oscillograms of sound productions and environmental recordings in freshwater (Fourier window length: 1,024 samples, frame overlap: 80%, window type: Hanning). (a) Environmental recording in a secondary channel of the river Rhône (France). (b) Environmental recording in a waterhole in Talaroo (Australia). (c) Water beetle (*Acilius sulcatus*). (d) Spangled grunter (*Leiopotherapon unicolor*). (e) Red swamp crayfish (*Procambarus clarkii*). (f) Painted frog (*Discoglossus pictus*)

Parmentier, 2015), and stridulation in many aquatic insects (Aiken, 1985), some fishes (mainly catfish: Mohajer, Ghahramani, & Fine, 2015), and potentially crustaceans (Favaro et al., 2011). Sounds emitted by aquatic animals differ in their temporal and frequency structures (Figure 1c–f). Sound frequencies vary from about 50 Hz for some fishes (Lugli, Yan, & Fine, 2003) up to 100,000 Hz for a family of caddisflies (Silver & Halls, 1980). These sounds are mainly produced during mating behaviour (Aiken, 1985), territorial disputes (Jansson & Vuoristo, 1979) or distress conditions (Aiken, 1985). Some of the sounds described are likely to be involved in species recognition during mating and are therefore expected to be species-specific (Jansson, 1989; Pedroso, Barber, Svensson, Fonseca, & Amorim, 2013). Species-specific sounds can be used to survey various aspects of population dynamics, for example in the context of an endangered species (Dutilleux & Curé, 2018). However, numerous species-specific sounds remain unrecorded and undescribed, particularly those of aquatic insects, fish, and crustaceans (Desjonquères, 2016).

Freshwater ecosystem monitoring usually involves the characterisation of macro-invertebrate and fish communities (Bailey, Linke, & Yates, 2014). The use of PAM for community-level monitoring could complement, or when appropriate, replace classical methods such as specimen collection or visual identification.

2.2 | Physico-chemical processes

2.2.1 | Water chemistry: gas exchanges

A key part of water chemistry is the concentration and composition of gases dissolved in it. Gas content can be influenced by several factors, including primary productivity, water turbulence and nature of the sediments (Brönmark & Hansson, 2017). At the water/air interface, sound pressure has been demonstrated to accurately represent re-aeration (Morse et al., 2007). Re-aeration measures the amount of gas (usually oxygen) integrated by a flowing water body due to water turbulence; re-aeration is an important parameter used to calculate whole-stream metabolism.

Underwater sounds can yield information about gas exchanges linked to primary production and organic matter decomposition. In marine environments, O_2 production of seagrass meadows can be estimated using the variation in propagation of emitted signals (Felisberto et al., 2015). Given the high price of efficient O_2 sensors, using acoustic alternatives could significantly reduce the cost of measurement and provide a more comprehensive picture of environment (including other relevant sounds). In freshwater environments, it was recently reported that the emission of gases during plant respiration or photosynthesis and organic matter decomposition produce whistling and ticking sounds (Linke, Gifford, et al., 2018). Moreover, anaerobic organic matter decomposition mainly produces methane, which, when expelled, also produces ticking sounds (Linke, Gifford, et al., 2018; C.D. personal observations). Using these sounds could facilitate monitoring primordial ecosystem processes such as plant respiration, organic matter decomposition, and primary production.

Water chemistry is likely to be related to sound emission. Indeed, if the water is unsaturated in oxygen, oxygen emitted during photosynthesis will diffuse in the water. In saturated waters, oxygen will not be able to diffuse and bubbles should form, potentially emitting specific whistling and ticking sounds. By contrast, eutrophied environments with sediments rich in organic matter will also have highly active ticking and whistling sounds due to anoxic organic decomposition producing methane bubbles. We suggest that testing for the specificity of these sounds provides an interesting avenue for a new application to probe water chemistry with acoustics.

2.2.2 | Physical habitat and hydrological processes

Sounds emitted by hydrological processes such as sediment transport and flow turbulence have specific acoustic signatures. These unique underwater soundscapes can be detected with hydrophone measurements both with laboratory experiments and large-scale measurements in the field (Tonolla, Lorang, Heutschi, Gotschalk, & Tockner, 2011; Tonolla, Lorang, Heutschi, & Tockner, 2009). They provide measures of habitat characteristics across spatially continuous and heterogeneous environments of riverine floodplains. Sounds generated by physical structures reflect important hydraulic (i.e. turbulence levels) and geomorphic (i.e. bedload mobility) dynamic processes. Using such sounds, Tonolla, Acuña, Lorang, Heutschi, and Tockner (2010) were able to classify riverine habitats characterised by different hydromorphological features according to the amplitude contained in nine frequency bands. Underwater acoustic monitoring was also used for rapid assessment of bedload transport (Geay et al., 2017) and hydropeaking events (Lumsdon et al., 2018). Acoustics enables instantaneous and continuous monitoring of sediment transport dynamics. Passive acoustic monitoring in freshwater habitats could therefore help further unravel spatio-temporal hydrological and geomorphological dynamics and thanks to such sounds, extract real-time information about extreme weather conditions such as ice forming and melting, or dramatic changes in water flow due to floods or droughts.

3 | STUDY AREAS FOR PAM: FRESHWATER ECOACOUSTICS

Ecoacoustics is a recently formalised scientific discipline defined as “a theoretical and applied discipline that studies sound along a broad range of spatial and temporal scales in order to tackle biodiversity and other ecological questions” (Farina & Gage, 2017; Sueur & Farina, 2015). Here, we present four promising areas of application for acoustic monitoring in freshwater systems: (1) spatial ecology; (2) community ecology; (3) environmental change; and (4) noise pollution.

3.1 | Spatial ecology: species distribution, abundance, and biodiversity

Applying PAM techniques to species detection allows for automatic recording, detection, and localisation of single species (Risch et al., 2014). Using a network of acoustic sensors may further reveal the spatial distribution of species within the environment, either roughly with regularly spaced hydrophones (Desjonquères, Rybak, Ulloa, et al., 2018) or precisely using an array of hydrophones and comparing differences in intensity and time of arrival (Hulgard, Moss, Jakobsen, & Surlykke, 2016; Malinka, Gillespie, Macaulay, Joy, & Sparling, 2018; Morrissey, Ward, DiMarzio, Jarvis, & Moretti, 2006).

Using acoustic indices allows for overall diversity assessment at different sites and for contrasting diversity at different locations (Gasc, Sueur, Pavoine, et al., 2013; Parks et al., 2014). This is particularly interesting in freshwater environments where most of the time other non-invasive methods such as visual detection are hindered by cloudy water and vegetation. Acoustic detection also seems especially apt for rare species because it can be deployed continuously for long periods with little effort, maximising the chance of positive detection of infrequent events.

Quantifying spatial heterogeneity in freshwater environments may facilitate detection of favourable habitats for certain species. Sounds emitted by flow turbulence and sediment transport could be likely to act as important cues for several aquatic organisms (including fish and adult stage aquatic insects) for habitat selection: Radford, Stanley, Simpson, and Jeffs (2011) revealed that marine fish larvae use the sounds of coral reefs to locate adequate habitats. Additionally, some aquatic organisms have been shown to use acoustic cues in their environment for spatial orientation and positioning within and among suitable habitats (Slabbekoorn & Bouton, 2008).

3.2 | Community ecology: species interactions

Single sounds are ephemeral phenomena produced at a specific point in space and time, and with characteristic frequency content. Each sound emitted by a specific organism, occupies a specific position (or positions) within the acoustic space—termed an acoustic niche (Krause, 1993). As acoustic space is shared between different individuals, species, and environmental sounds, sounds may overlap potentially resulting in masking. Inter- and intra-specific competition for the acoustic space might therefore occur (Krause, 1987). Similar to the concept of the Hutchinsonian niche (Hutchinson, 1957), this competition is thought to result in the partitioning of the resource—here acoustic space (Krause, 1987). This hypothesis is called the acoustic niche hypothesis (ANH, Krause, 1993). According to this hypothesis, acoustic populations in the same acoustic community (same environment) are expected to diverge acoustically to avoid the cost of masking. A competing hypothesis states that animals sharing the same acoustic space—and thus the same habitat—should have converging calls due to the similarity of the propagation constraints. This hypothesis is called the acoustic adaptation hypothesis (AAH, Morton, 1975).

Both the AAH and ANH are currently debated and have received contrasting support at the community level (e.g. support for AAH: Tobias, Planque, Cram, & Seddon, 2014; support for ANH: Stanley, Walter, Venkatraman, & Wilkinson, 2016; Villanueva-Rivera, 2014). Desjonquères, Rybak, Castella, Llusia, and Sueur (2018) found that in acoustic communities of secondary channels of the Rhône river, most sound types had frequency characteristics corresponding to the best propagating sounds, potentially corroborating the AAH in freshwater environments. Community structure and species interactions such as food webs are central subjects in freshwater ecology (Atkinson, Capps, Rugenski, & Vanni, 2017). Passive acoustic monitoring may make it possible to survey those relationships for example by detecting alarm calls of prey species or change in acoustic activity of a prey at the approach of a predator (ter Hofstede, 2018). Moreover, PAM allows collection of long-term recordings, providing the statistical power required to reveal acoustic competitive interactions potentially linking to the ANH (Krause, 1993).

3.3 | Assessment of response to environmental change

Environmental change such as global warming or pollution can have profound consequences for freshwater environments (Strayer & Dudgeon, 2010). Biodiversity in freshwater environments is declining faster than in many other threatened environments (Dudgeon et al., 2006; Mantyka-Pringle, Martin, Moffatt, Linke, & Rhodes, 2014). Such changes are particularly noticeable in the soundscape (Pavan, 2017) and thus acoustic monitoring is particularly suited to surveying environments regularly with automated recorders. Such regular surveys can produce time series revealing the short-term effects of global changes (Krause & Farina, 2016). Global warming is particularly alarming for ectotherm species and threatened species. Not only does presence/absence reveal potential response to changes in spatial range, activity rates can also be indicative of suboptimal conditions. Indeed, many call parameters of ectotherms are affected by temperature (Sanborn, 2005). For instance, (Llusia, Márquez, Beltrán, Moreira, & do Amaral, 2013) showed that chorus attendance in frog species is partly determined by temperature. Moreover, in the goby *Padogobius martensi*, pulse rate is strongly influenced by water temperature and the emission of sounds is limited to a specific range of temperatures (Torricelli, Lugli, & Pavan, 1990). Another advantage of PAM is its continuity. For example, population or phenology shifts in response to global change could be assessed more efficiently using long-term continuous PAM, rather than yearly snapshots.

3.4 | Responses to noise pollution

Human activities generate noises that can have tremendous impact on living organisms (Halfwerk & Slabbekoorn, 2015). This aspect of soundscape conservation has been gaining traction in recent years (Pavan, 2017). Aquatic environments are particularly vulnerable due to the relatively low attenuation of sounds in water (Parks et al., 2014; Tyack & Janik, 2013). Freshwater environments are subjected to noise coming from sediment extraction, motorised boats, recreational activities, and construction (Bolgan et al., 2016). Noise pollution can result in injuries such as hearing loss, internal bleeding, or even death (Popper & Hastings, 2009; Popper & Hawkins, 2019; Popper et al., 2005), mask communication signals (Fletcher, 2007), or affect population sizes and density (Laiolo, 2010). Monitoring demographic and behavioural responses of species to invasive noises would help inform mitigation measures.

The recently published meta-analysis by Cox, Brennan, Gerwing, Dudas, and Juanes (2018) revealed adverse effects of noise on fish, ranging from behavioural changes in foraging efficiency, reproductive success or predation risks to physiological effects such as increased hearing thresholds or high levels of stress hormones.

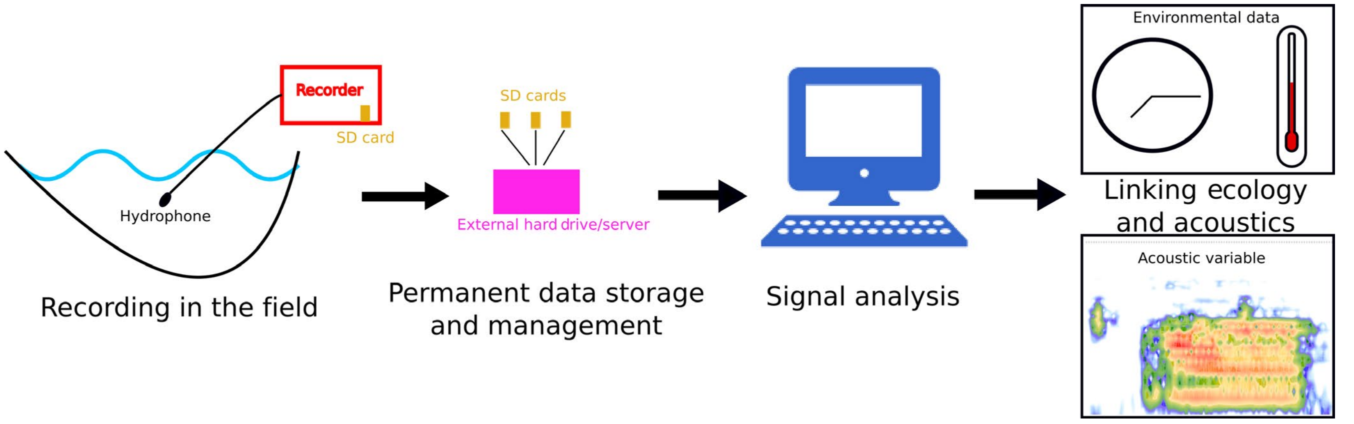

FIGURE 2 Passive acoustic monitoring workflow. From left to right: sounds are recorded underwater using a recorder and a hydrophone. The sound then needs to be stored in permanent storage hardware. The recordings can then be analysed with acoustic indices or automatic detection. Finally sounds and acoustic attributes are linked

However, it seems that fish from noisy environments are less susceptible to noise (Harding et al., 2018). Desjonquères, Rybak, Ulloa, et al. (2018) found evidence using PAM that artificial noise increases the acoustic activity of an aquatic insect as well as delaying the activity cycle. However, such studies for freshwater environments are still rarely undertaken.

Measurements of the extent of anthropogenic noise in freshwater environments are still scarce (Bolgan et al., 2016). Predictive models of noise propagation are powerful tools for estimating the spread of noise impacted areas. Such models have been developed in marine environments (Farcas, Thompson, & Merchant, 2016); however, they show limitations in shallow environments and would therefore require some adjustments to be applied to freshwater environments. Passive acoustic monitoring allows mapping of the extent and intensity of noise disturbances underwater and could be used to validate or update such propagation models.

4 | HOW TO UNDERTAKE PAM IN FRESHWATER

Passive acoustic monitoring requires several steps, including recording, storing, and analysing sounds as well as linking sounds to environmental variables (Figure 2). In this section, we discuss practically how PAM can be applied to freshwater environments. We describe: (1) recording methods and the practical considerations for sampling designs; (2) data storage; (3) signal analysis; and (4) analyses to link ecology and acoustics.

4.1 | Recording and sampling design

4.1.1 | Recording units

To record underwater sound emanating from freshwater environments, one simply needs a hydrophone connected to a recorder. The sensitivity of the hydrophone should be tuned to the species or ecological communities of interest. Hydrophones vary in overall sensitivity and sensitivity at different frequencies: some are specifically dedicated to high or low frequency ranges (Merchant et al., 2015). A diversity of recorders, both proprietary and open-source, are emerging, allowing for continuous automatic recording (Acevedo, Corrada-Bravo, Corrada-Bravo, Villanueva-Rivera, & Aide, 2009; Digby, Towsey, Bell, & Teal, 2013; Whytock & Christie, 2017). These can range from high quality, sophisticated commercial units by manufacturers such as Wildlife Acoustics (Maynard, U.S.A.) or Frontier Labs (Brisbane, Australia), to affordable open source recorders for $50 (Hill et al., 2018). Some can even be accessed wirelessly to download data (Sethi, Ewers, Jones, Orme, & Picinali, 2017). Some of these recorders are designed to resist rough natural conditions such as extremely low or high temperatures, strong precipitation, or animal nibbling.

Although these recorders have been mainly designed for terrestrial and marine environments, they are generally transferable to freshwater environments. In relatively small environments, such as pools, ponds, and streams, recorders can be installed on the bank (Figure 3). For bigger environments such as lakes, installing a recorder on an anchored floater (Kuehne, Padgham, & Olden, 2013) or fully submerged is the most convenient options. High-flow environments might be challenging to monitor, as high amplitude sounds of flow turbulence and sediment transport—although extremely informative for hydrological processes assessment (Tonolla et al., 2010)—can mask valuable signals for acoustic community and population assessments. One solution designed by Tonolla et al. (2011) was for the hardware to move with the river flow. For this study, hydrophones attached to floaters recorded the flow turbulence along a river transect. This setup also allows recording of transects of a river that are difficult to access.

4.1.2 | Temporal and spatial resolution

Acoustic structure and function in freshwater environments are spatially and temporally heterogeneous. Animals communicate at specific times and in particular microhabitats (Bradbury & Vehrencamp, 1998; Endler, 1992). Perhaps one of the most famous examples of

FIGURE 3 Pictures of typical recording set-ups. (a) Automatic recorders and hydrophones set up in a pond in Vidauban (France). (b) Automatic recorder set-up in a secondary channel of the river Rhône (France)

temporal heterogeneity—the dawn chorus—comprises different species of birds, each calling during a specific time frame (Dabelsteen & Mathevon, 2002). Such sound production patterns are not exceptional: many species have very specific calling schedules. For example, several aquatic insects have both diurnal and annual cycles of activity (Desjonquères, Rybak, Ulloa, et al., 2018; Jansson, 1974). These temporal patterns have also been detected at the acoustic community level in terrestrial (Lellouch, Pavoine, Jiguet, Glotin, & Sueur, 2014; Rodriguez et al., 2014) as well as in aquatic environments (Linke, Decker, Gifford, & Desjonquères, 2018; Ruppé et al., 2015). Acoustic diversity not only varies diurnally but also seasonally (Amoser & Ladich, 2010; Gage & Axel, 2014; Jansson, 1974; Risch et al., 2014). It is therefore crucial to choose a recording schedule appropriate to the ecological question being addressed. In this special issue, Linke, Decker, et al. (2018) reveal that in order to capture most acoustic diversity in a freshwater pool, it is more efficient on average to sample short recordings at many times of the day and over several days than longer recordings at fewer times and days.

Spatial heterogeneity and sound propagation also play an essential role in acoustic monitoring designs. It has already been demonstrated in terrestrial environments that heterogeneous landscapes result in uneven distribution of sounds (Gómez, Isaza, & Daza, 2018; Mullet, 2017; Tucker, Gage, Williamson, & Fuller, 2014). The main practical challenge to consider when spatially designing a sampling protocol is the distance at which sounds can be detected from their source or active space. Active space varies according to the characteristics of sounds, the microphone or hydrophone sensitivity and the attributes of the environment being monitored (Darras, Pütz, Fahrurrozi, & Tscharntke, 2016). Sounds have different active space depending on how acoustic parameters are attenuated along their propagation. Attenuation can be a result of spreading loss (because sound travels in three dimensions), excess energetic dissipation (due to part of the acoustic energy being lost as heat along its propagation) or reflection and refraction off obstacles. Reflection and refraction of sounds as well as differences in propagation speed of various frequencies may result in distortion of the sound. The diversity of species' acoustic traits and environmental parameters results in a diversity of active spaces. Active spaces should therefore be assessed separately in acoustically different species or groups of species emitting similar sounds (Alves, Amorim, & Fonseca, 2016).

Assessments in shallow freshwater environments such as ponds and rivers can be challenging due to the complexity of sound propagation in shallow waters. In such environments, some frequencies might be attenuated at relatively short distances (few decimetres; Aiken, 1982). Shallow water environments act as a high pass filter and there is a relationship between the depth of an environment and the cut off frequency of that filter: the deeper the environment, the lower the cut-off frequency (Forrest, Miller, & Zagar, 1993). Freshwater environments can also contain dense vegetation covers and heterogenous bottom surfaces containing soft, sandy or rocky sediments. All these elements can potentially affect the propagation of sound. There is therefore a need to quantify their effects on sound propagation, to facilitate modelling in various environments and, in turn, to help monitor freshwater environments more efficiently. Passive acoustic monitoring should therefore be planned according to information about spatio-temporal heterogeneity and efficiency of propagation in the targeted environment.

4.2 | Permanently storing and archiving data

As for any data collection, once the data are collected, it is extremely important to store and archive them properly to avoid loss. Meta-data associated to the recordings should also be readily accessible and properly stored. For PAM, this step is particularly challenging due to the amount of data potentially collected. Various software packages are available to help with metadata associated with the recordings (e.g. Roch et al., 2013). An increasing number of sound archives are becoming publicly available resources to store sounds and share them. The most extensive and well known of them is the Macaulay Library hosted at Cornell University. These sound archives are also valuable tools to share species specific sounds; however, too few freshwater sounds are available in existing archives (Linke, Gifford, et al., 2018; Rountree, Bolgan, & Juanes, 2018).

4.3 | Signal analysis

Passive acoustic monitoring allows the collection of terabytes of data with little effort. These raw data then require processing. Two main routes for automatic signal processing are currently under development. This section provides an overview of those two routes as well as some strategic references to get started on the subject.

4.3.1 | Recognition of individual sound events and signals

Signal recognition uses elaborate techniques such as template matching or machine learning to extract and classify signals from raw environmental recordings. There is a suite of methods available; either supervised—when the signals of interest are known; or unsupervised—when the algorithms are not optimised with a prior database (Ulloa, Aubin, Llusia, Bouveyron, & Sueur, 2018). Detection methods vary from relatively simple methods based on estimates of amplitude level of a species-specific frequency band (e.g. Desjonquères, Rybak, Ulloa, et al., 2018; Dutilleux & Curé, 2018) to more refined pattern recognition via cross-correlation (Ulloa et al., 2016) as well as more complex methods using machine learning (e.g. Morfi & Stowell, 2018; Xie, Towsey, Zhang, & Roe, 2016; Zhang, Towsey, Zhang, & Roe, 2017). Automatic detection and classification methods usually first involve feature extraction and then classification of these features (Sharan & Moir, 2016). These methods have mainly been developed for bird vocalisations (Priyadarshani, Marsland, & Castro, 2018) but are increasingly applied to other taxa (Ganchev, Potamitis, & Fakotakis, 2007; Himawan, Towsey, Law, & Roe, ; Risch et al., 2014; Xie et al., 2016).

These analysis tools are implemented in a variety of software. The newest detection methods are usually initially developed as custom made scripts in coding environments such as Matlab (Mathworks), R (R Core Team, 2015) or Python (Python Software Foundation). Some coding environments also have entire packages dedicated to sound detection such as XBAT, Osprey, or Triton in Matlab as well as monitoR in R. Automatic tools can also be implemented in sound analysis software such as Raven (Cornell Lab of Ornithology).

The success of the detection of sounds in environments can be hindered by the presence of noise and other masking sounds such as other species calling simultaneously (Priyadarshani et al., 2018). These methods are essential for the development of real time monitoring (Aide et al., 2013). Freshwater applications include automatic detection of an invasive fish (Kottege et al., 2015), detection of spawning events (Straight et al., 2014) and monitoring of endangered species (Dutilleux & Curé, 2018).

4.3.2 | Acoustic indices

Given the current biodiversity crisis, estimating species diversity and contrasting species communities is paramount to inform decision making in conservation biology. A diversity of species produces sounds. This acoustic diversity can be used to extract information on species richness (Buxton, Agnihotri, Robin, Goel, & Balakrishnan, 2018; Pieretti et al., 2011; Pijanowski, Farina, Gage, Dumyahn, & Krause, 2011; Sueur, Pavoine, et al., 2008); however, the relationships between acoustic and species diversity are not always straightforward (Linke, Decker, et al., 2018). Soundscape composition can be quantified using acoustic indices. As with classic diversity indices such as species richness or evenness, acoustic diversity indices are mathematical functions designed to examine different aspects of sounds and represent some characteristics of the biodiversity (Sueur, Farina, Gasc, Pieretti, & Pavoine, 2014).

A wide variety of indices have been developed in the last decade, each tuned to detect specific attributes of the soundscape (Gage, Towsey, & Kasten, 2017; Sueur et al., 2014). Two main types of acoustic indices can be distinguished, similarly to ecological indices: α and β indices. Alpha indices quantify some attributes of one soundscape, while β indices allow the comparison between soundscapes. Acoustic indices can measure overall amplitude of a recording (*M*, Depraetere et al., 2012), diversity of frequency with the spectral entropy index (H_f; Sueur, Pavoine, et al., 2008), or the acoustic diversity index (Villanueva-Rivera, Pijanowski, Doucette, & Pekin, 2011) or acoustic complexity index (Pieretti et al., 2011). These indices have been applied to various terrestrial and marine environments (Buscaino et al., 2016; Fuller et al., 2015; Gasc Sueur, Jiguet et al., 2013) and to detect variation in biodiversity patterns relating to different levels of urbanisation (Kuehne et al., 2013) or different ecosystems (Depraetere et al., 2012). Most of these indices are built into free access R packages such as *seewave* (Sueur, Aubin, & Simonis, 2008) or *soundecology* (Villanueva-Rivera, Pijanowski, & Villanueva-Rivera, 2018). Two main avenues of application can be distinguished for acoustic indices: (1) estimation of biodiversity, and (2) contrasting spatio-temporal variations.

Although the accuracy of acoustic indices for measuring species diversity has been demonstrated in some environments (Buxton et al., 2018; Pieretti et al., 2011; Sueur, Pavoine, et al., 2008), they appear to need adjustment in freshwater ponds due to the low signal-to-noise ratios (Desjonquères et al., 2015), as with marine environments (Parks et al., 2014). To overcome this issue, audio filtering techniques could potentially help reduce noise or enhance signals of interest. Another suggested avenue of research on acoustic diversity methods recommends combination of several acoustic indices that reveal complementary aspects of the soundscape, either using false colour spectrogram (Indraswari et al., 2018; Towsey, Wimmer, Williamson, & Roe, 2014) or neural networks (Gómez et al., 2018). Yet another option suggests bringing together automatic detection of single sound events and classification of basic elements of the soundscape or sound types to identify acoustic diversity in soundscape recordings. These new methods, currently emerging, might be less sensitive to environmental noise (Eldridge, Casey, Moscoso, & Peck, 2016; Phillips, Towsey, & Roe, 2018; Ulloa et al., 2018) and would be interesting to apply in freshwater environments.

Acoustic indices can also be used to detect and contrast acoustic communities sampled in different habitat types or at different times (Buscaino et al., 2016; Gasc, Sueur, Pavoine, et al., 2013; Retamosa Izaguirre, Ramírez-Alán, & De la O Castro, 2018; Rodriguez et al., 2014). Acoustic indices have also been applied in freshwater streams with some success; for example, Linke, Decker, et al. (2018) were able to detect onset and end of major acoustic events such as fish and insect choruses in freshwater environments. Acoustic indices allow discrimination of different temporal or ecological conditions in freshwater environments. The use of acoustic indices has to be calibrated to each setting—for example bird responses to restoration efforts in forests have been best characterised using Acoustic Entropy by Ng, Butler, and Woods (2018), whereas on floodplains, M and ACI were the only indices that were able to quantify increased activity (Linke & Deretic, 2018).

4.4 | Linking ecology and acoustics

Once acoustic recordings have been analysed, an important remaining step is to relate extracted acoustic attributes to environmental data. This requires statistical analyses such as linear models (Fuller et al., 2015), random forest (Buxton et al., 2018) or neural networks (Gómez et al., 2018). Acoustic datasets can be challenging to analyse as they are usually time series, i.e. repeated measurements at the same location but different time. Although this challenge constitutes one of PAM's biggest strengths as it allows studying environments continuously, it can also be problematic for statistical analysis due to the non-independence of data points. Non-independence of data points, if it is not accounted for, may result in spurious significance (Forstmeier, Wagenmakers, & Parker, 2016). This potential for spurious significance is rarely accounted for in ecoacoustic studies. However, there are several ways to account for it or mitigate the risk; for example, in Desjonquères, Rybak, Ulloa, et al. (2018), the use of functional linear models allow to take the temporal variation into account with a sum of sine and cosine functions. Another option if one is not interested in the temporal variation is to average the acoustic data over several hours or days (Bertucci, Parmentier, Lecellier, Hawkins, & Lecchini, 2016; Desjonquères, Rybak, Castella, et al., 2018). Finally, linear models can also include another variable that varies over time and thus can account for the temporal variation such as temperature or using correlational data rather than hypothesis testing (Bohnenstiehl, Lillis, & Eggleston, 2016).

5 | CONCLUSION

This article discusses the potential applications of PAM in freshwater environments for freshwater biology and ecology. Passive acoustic monitoring could be used to monitor key species and ecosytem processes. More specifically, it could potentially be applied to the localisation of rare, invasive or threatened species, or allow the identification of eutrophication environments with the sounds of respiration. This review highlights several areas in which further developments are needed before PAM can be operationalised in freshwater environments. It is, in particular, essential to describe underwater sounds, to develop robust detection methods and assess spatio-temporal variations. Nevertheless, PAM already offers benefits to freshwater monitoring by allowing for low cost, noninvasive and continuous surveys. This review, as part of the special issue *"Acoustic methods in freshwater systems: A new frontier in continuous system monitoring"*, highlights the broad interest of PAM for freshwater ecologists. Overall, PAM appears as a promising tool to continuously monitor and mitigate current freshwater environmental crises.

ACKNOWLEDGMENTS

S.L. was supported by ARC DECRA DE130100565. C.D. was supported by a Fyssen post-doctoral fellowship. We thank Jérôme Sueur and Fanny Rybak for their valuable discussions and input on the manuscript.

ORCID

Camille Desjonquères https://orcid.org/0000-0002-6150-3264

Toby Gifford https://orcid.org/0000-0002-9902-3362

Simon Linke https://orcid.org/0000-0002-1797-3947

REFERENCES

Acevedo, M. A., Corrada-Bravo, C. J., Corrada-Bravo, H., Villanueva-Rivera, L. J., & Aide, T. M. (2009). Automated classification of bird and amphibian calls using machine learning: A comparison of methods. *Ecological Informatics*, *4*, 206–214. https://doi.org/10.1016/j.ecoinf.2009.06.005

Aide, T. M., Corrada-Bravo, C., Campos-Cerqueira, M., Milan, C., Vega, G., & Alvarez, R. (2013). Real-time bioacoustics monitoring and automated species identification. *PeerJ*, *1*, e103. https://doi.org/10.7717/peerj.103

Aiken, R. B. (1982). Shallow-water propagation of frequencies in aquatic insect sounds. *Canadian Journal of Zoology*, *60*, 3459–3461. https://doi.org/10.1139/z82-436

Aiken, R. B. (1985). Sound production by aquatic insects. *Biological Reviews*, *60*, 163–211.

Alves, D., Amorim, M. C. P., & Fonseca, P. J. (2016). Assessing acoustic communication active space in the Lusitanian toadfish. *Journal of Experimental Biology*, *219*, 1122–1129.

Amoser, S., & Ladich, F. (2010). Year-round variability of ambient noise in temperate freshwater habitats and its implications for fishes. *Aquatic Sciences*, *72*, 371–378. https://doi.org/10.1007/s00027-010-0136-9

Anderson, K. A., Rountree, R. A., & Juanes, F. (2008). Soniferous fishes in the Hudson River. *Transactions of the American Fisheries Society*, *137*, 616–626. https://doi.org/10.1577/t05-220.1

Arrington, D. A., & Winemiller, K. O. (2003). Diel changeover in sandbank fish assemblages in a neotropical floodplain river. *Journal of Fish Biology*, *63*, 442–459. https://doi.org/10.1046/j.1095-8649.2003.00167.x

Atkinson, C. L., Capps, K. A., Rugenski, A. T., & Vanni, M. J. (2017). Consumer-driven nutrient dynamics in freshwater ecosystems: From individuals to ecosystems. *Biological Reviews*, *92*, 2003–2023. https://doi.org/10.1111/brv.12318

Bailey, R. C., Linke, S., & Yates, A. G. (2014). Bioassessment of freshwater ecosystems using the reference condition approach: Comparing established and new methods with common data sets. *Freshwater Science*, *33*(4), 1204–1211.

Balduf, W. V. (1935). *The bionomics of entomophagous Coleoptera*. Buffalo Grove, IL: John S Swift Co., Inc.

Bertucci, F., Parmentier, E., Berten, L., Brooker, R. M., & Lecchini, D. (2015). Temporal and spatial comparisons of underwater sound signatures of different reef habitats in Moorea Island, French Polynesia. *PLoS ONE*, *10*, e0135733. https://doi.org/10.1371/journal.pone.0135733

Bertucci, F., Parmentier, E., Lecellier, G., Hawkins, A. D., & Lecchini, D. (2016). Acoustic indices provide information on the status of coral reefs: An example from Moorea Island in the South Pacific. *Scientific Reports*, *6*, 33326. https://doi.org/10.1038/srep33326

Blumstein, D. T., Mennill, D. J., Clemins, P., Girod, L., Yao, K., Patricelli, G., … Kirschel, A. N. G. (2011). Acoustic monitoring in terrestrial environments using microphone arrays: Applications, technological considerations and prospectus: Acoustic monitoring. *Journal of Applied Ecology*, *48*, 758–767. https://doi.org/10.1111/j.1365-2664.2011.01993.x

Bohnenstiehl, D. R., Lillis, A., & Eggleston, D. B. (2016). The curious acoustic behavior of estuarine snapping shrimp: Temporal patterns of snapping shrimp sound in sub-tidal oyster reef habitat. *PLoS ONE*, *11*, e0143691.

Bolgan, M., Chorazyczewska, E., Winfield, I. J., Codarin, A., O'Brien, J., & Gammell, M. (2016). First observations of anthropogenic underwater noise in a large multi-use lake. *Journal of Limnology*, *75*, 644–651.

Bradbury, J. W., & Vehrencamp, S. L. (1998). *Animal communication*. Sunderland, MA: Sinauer Associates.

Brönmark, C., & Hansson, L.-A. (2017). *The biology of lakes and ponds*. Oxford, UK: Oxford University Press.

Buscaino, G., Ceraulo, M., Pieretti, N., Corrias, V., Farina, A., Filiciotto, F., … Mazzol, S. (2016). Temporal patterns in the soundscape of the shallow waters of a Mediterranean marine protected area. *Scientific Reports*, *6*, 34230.

Buxton, R. T., Agnihotri, S., Robin, V. V., Goel, A., & Balakrishnan, R. (2018). Acoustic indices as rapid indicators of avian diversity in different land-use types in an Indian biodiversity hotspot. *Journal of Ecoacoustics*, *2*, GWPZVD. https://doi.org/10.22261/jea.gwpzvd

Campos-Cerqueira, M., & Aide, T. M. (2016). Improving distribution data of threatened species by combining acoustic monitoring and occupancy modelling. *Methods in Ecology and Evolution*, *7*, 1340–1348. https://doi.org/10.1111/2041-210x.12599

Céréghino, R., Biggs, J., Oertli, B., & Declerck, S. (2008). The ecology of European ponds: Defining the characteristics of a neglected freshwater habitat. *Hydrobiologia*, *597*, 1–6. https://doi.org/10.1007/s10750-007-9225-8

Clément, M., & Cunjak, R. A. (2010). Physical injuries in juvenile Atlantic Salmon, slimy sculpin, and blacknose dace attributable to electrofishing. *North American Journal of Fisheries Management*, *30*, 840–850.

Colleye, O., & Parmentier, E. (2012). Overview on the diversity of sounds produced by clownfishes (Pomacentridae): Importance of acoustic signals in their peculiar way of life. *PLoS ONE*, *7*, e49179. https://doi.org/10.1371/journal.pone.0049179

Cox, K., Brennan, L. P., Gerwing, T. G., Dudas, S. E., & Juanes, F. (2018). Sound the alarm: A meta-analysis on the effect of aquatic noise on fish behavior and physiology. *Global Change Biology*, *24*, 3105–3116. https://doi.org/10.1111/gcb.14106

Dabelsteen, T., & Mathevon, N. (2002). Why do songbirds sing intensively at dawn? A test of the acoustic transmission hypothesis. *Acta Ethologica*, *4*, 65–72. https://doi.org/10.1007/s10211-001-0056-8

Darras, K., Pütz, P., Fahrurrozi, Rembold. K., & Tscharntke, T. (2016). Measuring sound detection spaces for acoustic animal sampling and monitoring. *Biological Conservation*, *201*, 29–37. https://doi.org/10.1016/j.biocon.2016.06.021

Depraetere, M., Pavoine, S., Jiguet, F., Gasc, A., Duvail, S., & Sueur, J. (2012). Monitoring animal diversity using acoustic indices: Implementation in a temperate woodland. *Ecological Indicators*, *13*, 46–54. https://doi.org/10.1016/j.ecolind.2011.05.006

Desjonquères, C. (2016). *Acoustic diversity and ecology of freshwater environments: Exploration in temperate environments*. Paris, France: Museum National D'histoire Naturelle-MNHN.

Desjonquères, C., Rybak, F., Castella, E., Llusia, D., & Sueur, J. (2018). Acoustic communities reflects lateral hydrological connectivity in riverine floodplain similarly to macroinvertebrate communities. *Scientific Reports*, *8*(1), 14387. https://doi.org/10.1038/s41598-018-31798-4

Desjonquères, C., Rybak, F., Depraetere, M., Gasc, A., Le Viol, I., Pavoine, S., & Sueur, J. (2015). First description of underwater acoustic diversity in three temperate ponds. *PeerJ*, *3*, e1393. https://doi.org/10.7717/peerj.1393

Desjonquères, C., Rybak, F., Ulloa, J. S., Kempf, A., Bar, Hen. A., & Sueur, J. (2018). Monitoring the acoustic activity of an aquatic insect population in relation to temperature, vegetation and noise. *Freshwater Biology*. https://doi.org/10.1111/fwb.13171

Digby, A., Towsey, M., Bell, B. D., & Teal, P. D. (2013). A practical comparison of manual and autonomous methods for acoustic monitoring. *Methods in Ecology and Evolution*, *4*, 675–683.

Duarte, M. H. L., Sousa-Lima, R. S., Young, R. J., Farina, A., Vasconcelos, M., Rodrigues, M., & Pieretti, N. (2015). The impact of noise from open-cast mining on Atlantic forest biophony. *Biological Conservation*, *191*, 623–631. https://doi.org/10.1016/j.biocon.2015.08.006

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D. J., Lévêque, C., … Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, *81*, 163–182. https://doi.org/10.1017/s1464793105006950

Dutilleux, G., & Curé, C. (2018). Automated acoustic monitoring of endangered common spadefoot toad populations reveals patterns of vocal activity. *Freshwater Biology*. https://doi.org/10.1111/fwb.13111

Eldridge, A., Casey, M., Moscoso, P., & Peck, M. (2016). A new method for ecoacoustics? Toward the extraction and evaluation of ecologically-meaningful soundscape components using sparse coding methods. *PeerJ*, *4*, e2108. https://doi.org/10.7717/peerj.2108

Endler, J. A. (1992). Signals, signal conditions, and the direction of evolution. *The American Naturalist*, *139*, S125–S153.

Ensign, W. E., Temple, A. J., & Neves, R. J. (2002). Effects of fright bias on sampling efficiency of stream fish assemblages. *Journal of Freshwater Ecology*, *17*, 127–139.

Farcas, A., Thompson, P. M., & Merchant, N. D. (2016). Underwater noise modelling for environmental impact assessment. *Environmental Impact Assessment Review*, *57*, 114–122. https://doi.org/10.1016/j.eiar.2015.11.012

Farina, A., & Gage, S. H. (2017). *Ecoacoustics: The ecological role of sounds*. Hoboken, NJ: John Wiley & Sons.

Favaro, L., Tirelli, T., Gamba, M., & Pessani, D. (2011). Sound production in the red swamp crayfish *Procambarus clarkii* (Decapoda: Cambaridae). *Zoologischer Anzeiger - A Journal of Comparative Zoology*, *250*, 143–150. https://doi.org/10.1016/j.jcz.2011.01.002

Felisberto, P., Jesus, S. M., Zabel, F., Santos, R., Silva, J., Gobert, S., … Borges, A. V. (2015). Acoustic monitoring of O_2 production of a seagrass meadow. *Journal of Experimental Marine Biology and Ecology*, *464*, 75–87. https://doi.org/10.1016/j.jembe.2014.12.013

Fine, M. L., & Parmentier, E. (2015). Mechanisms of fish sound production. In F. Ladich (Ed.), *Sound communication in fishes* (pp. 77–126). Vienna, Austria: Springer Vienna.

Fletcher, N. (2007). Animal bioacoustics. In T. D. Rossing (Ed.), *Springer handbook of acoustics* (pp. 785–804). New York, NY: Springer.

Forrest, T. G., Miller, G. L., & Zagar, J. R. (1993). Sound propagation in shallow water: Implications for acoustic communication by aquatic animals. *The International Journal of Animal Sound and its Recording*, *4*, 259–270.

Forstmeier, W., Wagenmakers, E.-J., & Parker, T. H. (2016). Detecting and avoiding likely false-positive findings – A practical guide. *Biological Reviews*, *92*(4), 1941–1968. https://doi.org/10.1111/brv.12315

Fuller, S., Axel, A. C., Tucker, D., & Gage, S. H. (2015). Connecting soundscape to landscape: Which acoustic index best describes landscape configuration? *Ecological Indicators*, *58*, 207–215. https://doi.org/10.1016/j.ecolind.2015.05.057

Furnas, B. J., & Callas, R. L. (2015). Using automated recorders and occupancy models to monitor common forest birds across a large geographic region: Automated Recorders Monitoring Common Birds. *The Journal of Wildlife Management*, *79*, 325–337. https://doi.org/10.1002/jwmg.821

Gage, S. H., & Axel, A. C. (2014). Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. *Ecological Informatics*, *21*, 100–109. https://doi.org/10.1016/j.ecoinf.2013.11.004

Gage, S. H., Towsey, M., & Kasten, E. P. (2017). Analytical methods in ecoacoustics. In A. Farina & S. H. Gage (Eds.), *Ecoacoustics: The ecological role of sounds* (pp. 273–296). Oxford, UK: Wiley.

Ganchev, T., Potamitis, I., & Fakotakis, N. (2007). Acoustic monitoring of singing insects. *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP 2007, Honolulu, Hawaii, USA*, pp. IV–721.

Gasc, A., Anso, J., Sueur, J., Jourdan, H., & Desutter-Grandcolas, L. (2018). Cricket calling communities as an indicator of the invasive ant *Wasmannia auropunctata* in an insular biodiversity hotspot. *Biological Invasions*, *20*, 1099–1111. https://doi.org/10.1007/s10530-017-1612-0

Gasc, A., Sueur, J., Jiguet, F., Devictor, V., Grandcolas, P., Burrow, C., … Pavoine, S. (2013). Assessing biodiversity with sound: Do acoustic diversity indices reflect phylogenetic and functional diversities of bird communities? *Ecological Indicators*, *25*, 279–287. https://doi.org/10.1016/j.ecolind.2012.10.009

Gasc, A., Sueur, J., Pavoine, S., Pellens, R., & Grandcolas, P. (2013). Biodiversity sampling using a global acoustic approach: Contrasting sites with microendemics in New Caledonia. *PLoS ONE*, *8*, e65311. https://doi.org/10.1371/journal.pone.0065311

Geay, T., Belleudy, P., Gervaise, C., Habersack, H., Aigner, J., Kreisler, A., … Laronne, J. B. (2017). Passive acoustic monitoring of bed load discharge in a large gravel bed river. *Journal of Geophysical Research: Earth Surface*, *122*, 528–545.

Gerhardt, H. C., & Huber, F. (2002). *Acoustic communication in insects and anurans: Common problems and diverse solutions*. Chicago, IL: University of Chicago Press.

Gibb, R., Browning, E., Glover-Kapfer, P., & Jones, K. E. (2018). Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. *Methods in Ecology and Evolution*, *10*(2), 169–185. https://doi.org/10.1111/2041-210x.13101

Gómez, W. E., Isaza, C. V., & Daza, J. M. (2018). Identifying disturbed habitats: A new method from acoustic indices. *Ecological Informatics*, *45*, 16–25. https://doi.org/10.1016/j.ecoinf.2018.03.001

Gottesman, B. L., Francomano, D., Zhao, Z., Bellisario, K., Ghadiri, M., Broadhead, T., … Pijanowski, B. C. (2018). Acoustic monitoring reveals diversity and surprising dynamics in tropical freshwater soundscapes. *Freshwater Biology*, https://doi.org/10.1111/fwb.13096

Halfwerk, W., & Slabbekoorn, H. (2015). Pollution going multimodal: The complex impact of the human-altered sensory environment on animal perception and performance. *Biology Letters*, *11*, 20141051. https://doi.org/10.1098/rsbl.2014.1051

Harding, H. R., Gordon, T. A. C., Hsuan, R. E., Mackaness, A. C. E., Radford, A. N., & Simpson, S. D. (2018). Fish in habitats with higher motorboat disturbance show reduced sensitivity to motorboat noise. *Biology Letters*, *14*, 20180441.

Heinicke, S., Kalan, A. K., Wagner, O. J. J., Mundry, R., Lukashevich, H., & Kühl, H. S. (2015). Assessing the performance of a semi-automated acoustic monitoring system for primates. *Methods in Ecology and Evolution*, *6*, 753–763. https://doi.org/10.1111/2041-210x.12384

Hill, A. P., Prince, P., Piña, Covarrubias. E., Doncaster, C. P., Snaddon, J. L., & Rogers, A. (2018). AudioMoth: Evaluation of a smart open acoustic device for monitoring biodiversity and the environment. *Methods in Ecology and Evolution*, *9*, 1199–1211. https://doi.org/10.1111/2041-210x.12955

Himawan, I., Towsey, M., Law, B., & Roe, P. (2018). Deep learning techniques for koala activity detection. In Proceedings Interspeech 2018 (pp. 2107 – 2111). https://doi.org/10.21437/Interspeech.2018-1143

Hulgard, K., Moss, C. F., Jakobsen, L., & Surlykke, A. (2016). Big brown bats (*Eptesicus fuscus*) emit intense search calls and fly in stereotyped flight paths as they forage in the wild. *The Journal of Experimental Biology*, *219*, 334–340. https://doi.org/10.1242/jeb.128983

Hutchinson, G. E. (1957). Concluding remarks. *Cold Spring Harbor Symposia on Quantitative Biology*, *22*, 415–427. https://doi.org/10.1101/sqb.1957.022.01.039

Indraswari, K., Bower, D. S., Tucker, D., Schwarzkopf, L., Towsey, M., & Roe, P. (2018). Assessing the value of acoustic indices to distinguish species and quantify activity: A case study using frogs. *Freshwater Biology*. https://doi.org/10.1111/fwb.13222

Jansson, A. (1972). Mechanisms of sound production and morphology of the stridulatory apparatus in the genus *Cenocorixa* (Hemiptera, Corixidae). *Annales Zoologici Fennic*, *9*, 120–129.

Jansson, A. (1974). Annual periodicity of male stridulation in the genus *Cenocorixa* (Hemiptera, Corixidae). *Freshwater Biology*, *4*, 93–98. https://doi.org/10.1111/j.1365-2427.1974.tb00941.x

Jansson, A. (1979). Experimental hybridization of *Sigara striata* and *S. dorsalis* (Heteroptera, Corixidae). *Annales Zoologici Fennici.*, 105–114.

Jansson, A. (1989). Stridulation of Micronectinae (Heteroptera, Corixidae). *Annales Entomologici Fennici*, *55*(4), 161–175.

Jansson, A., & Vuoristo, T. (1979). Significance of stridulation in larval Hydropsychidae (Trichoptera). *Behaviour*, *71*, 167–186.

Keith, P., Persat, H., Feunteun, E., & Allardi, J. (2011). *Les poissons d'eau douce de France*. France: Biotope éditions.

Kottege, N., Jurdak, R., Kroon, F., & Jones, D. (2015). Automated detection of broadband clicks of freshwater fish using spectro-temporal features. *The Journal of the Acoustical Society of America*, *137*, 2502–2511.

Krause, B. (1987). Bioacoustics, habitat ambience in ecological balance. *Whole Earth Review*, *57*, 14–18.

Krause, B. L. (1993). The niche hypothesis: A virtual symphony of animal sounds, the origins of musical expression and the health of habitats. *The Soundscape Newsletter*, *6*, 6–10.

Krause, B., & Farina, A. (2016). Using ecoacoustic methods to survey the impacts of climate change on biodiversity. *Biological Conservation*, *195*, 245–254. https://doi.org/10.1016/j.biocon.2016.01.013

Kuehne, L. M., Padgham, B. L., & Olden, J. D. (2013). The soundscapes of lakes across an urbanization gradient. *PLoS ONE*, *8*, e55661.

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

Lellouch, L., Pavoine, S., Jiguet, F., Glotin, H., & Sueur, J. (2014). Monitoring temporal change of bird communities with dissimilarity acoustic indices. *Methods in Ecology and Evolution*, *5*, 495–505. https://doi.org/10.1111/2041-210x.12178

Linke, S., Decker, E., Gifford, T., & Desjonquères, C. (2018). Diurnal variation in freshwater ecoacoustics: Implications for site-level sampling design. *Freshwater Biology*. https://doi.org/10.1111/fwb.13227

Linke, S., & Deretic, J.-A. (2018). Ecoacoustics can detect ecosystem responses to environmental water allocations. *Freshwater Biology*.

Linke, S., Gifford, T., Desjonquères, C., Tonolla, D., Aubin, T., Barclay, L., … Sueur, J. (2018). Freshwater ecoacoustics as a tool for continuous ecosystem monitoring. *Frontiers in Ecology and the Environment*, *16*, 231–238. https://doi.org/10.1002/fee.1779

Llusia, D., Márquez, R., Beltrán, J. F., Moreira, C., & do Amaral, J. P. (2013). Environmental and social determinants of anuran lekking behavior: Intraspecific variation in populations at thermal extremes. *Behavioral Ecology and Sociobiology*, *67*, 493–511. https://doi.org/10.1007/s00265-012-1469-2

Lugli, M., Yan, H. Y., & Fine, M. L. (2003). Acoustic communication in two freshwater gobies: The relationship between ambient noise, hearing thresholds and sound spectrum. *Journal of Comparative Physiology A*, *189*, 309–320.

Lumsdon, A. E., Artamonov, I., Bruno, M. C., Righetti, M., Tockner, K., Tonolla, D., & Zarfl, C. (2018). Soundpeaking - Hydropeaking induced changes in river soundscapes. *River Research and Applications*, *34*(1), 3–12. https://doi.org/10.1002/rra.3229

Malavasi, R., & Farina, A. (2013). Neighbours' talk: Interspecific choruses among songbirds. *Bioacoustics*, *22*, 33–48. https://doi.org/10.1080/09524622.2012.710395

Malinka, C., Gillespie, D., Macaulay, J., Joy, R., & Sparling, C. (2018). First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, *590*, 247–266. https://doi.org/10.3354/meps12467

Mantyka-Pringle, C. S., Martin, T. G., Moffatt, D. B., Linke, S., & Rhodes, J. R. (2014). Understanding and predicting the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish. *Journal of Applied Ecology*, *51*, 572–581. https://doi.org/10.1111/1365-2664.12236

McWilliam, J. N., & Hawkins, A. D. (2013). A comparison of inshore marine soundscapes. *Journal of Experimental Marine Biology and Ecology*, *446*, 166–176. https://doi.org/10.1016/j.jembe.2013.05.012

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E. (2015). Measuring acoustic habitats. *Methods in Ecology and Evolution*, *6*(3), 257–265. https://doi.org/10.1111/2041-210x.12330

Mohajer, Y., Ghahramani, Z., & Fine, M. (2015). Pectoral sound generation in the blue catfish *Ictalurus furcatus*. *Journal of Comparative Physiology. A, Neuroethology, Sensory, Neural, and Behavioral Physiology*, *201*(3), 305–315. https://doi.org/10.1007/s00359-014-0970-7

Morfi, V., & Stowell, D. (2018). Deep learning for audio event detection and tagging on low-resource datasets. *Applied Sciences*, *8*, 1397. https://doi.org/10.3390/app8081397

Morrissey, R. P., Ward, J., DiMarzio, N., Jarvis, S., & Moretti, D. J. (2006). Passive acoustic detection and localization of sperm whales (*Physeter macrocephalus*) in the tongue of the ocean. *Applied Acoustics*, *67*, 1091–1105. https://doi.org/10.1016/j.apacoust.2006.05.014

Morse, N., Bowden, W. B., Hackman, A., Pruden, C., Steiner, E., & Berger, E. (2007). Using sound pressure to estimate reaeration in streams. *Journal of the North American Benthological Society*, *26*, 28–37.

Morton, E. S. (1975). Ecological sources of selection on avian sounds. *The American Naturalist*, *109*, 17–34.

Mullet, T. C. (2017). Connecting soundscapes to landscapes: Modeling the spatial distribution of sound. In *Ecoacoustics: The ecological role of sounds* (p. 211). Oxford, UK: John Wiley & Sons.

Mullet, T. C., Gage, S. H., Morton, J. M., & Huettmann, F. (2015). Temporal and spatial variation of a winter soundscape in south-central Alaska. *Landscape Ecology*, *31*(5), 1117–1137. https://doi.org/10.1007/s10980-015-0323-0

Ng, M.-L., Butler, N., & Woods, N. (2018). Soundscapes as a surrogate measure of vegetation condition for biodiversity values: A pilot study. *Ecological Indicators*, *93*, 1070–1080. https://doi.org/10.1016/j.ecolind.2018.06.003

Obrist, M. K., Pavan, G., Sueur, J., Riede, K., Llusia, D., & Márquez, R. (2010). Bioacoustics approaches in biodiversity inventories. *Abc Taxa*, *8*, 68–99.

Parks, S. E., Miksis-Olds, J. L., & Denes, S. L. (2014). Assessing marine ecosystem acoustic diversity across ocean basins. *Ecological Informatics*, *21*, 81–88. https://doi.org/10.1016/j.ecoinf.2013.11.003

Pavan, G. (2017). Fundamentals of soundscape conservation. In A. Farina & S. H. Gage (Eds.), *Ecoacoustics: The ecological role of sounds* (pp. 235–258). Oxford, UK: Wiley-Blackwell.

Pedroso, S. S., Barber, I., Svensson, O., Fonseca, P. J., & Amorim, M. C. P. (2013). Courtship sounds advertise species identity and male quality in sympatric *Pomatoschistus* spp. gobies. *PLoS ONE*, *8*, e64620.

Phillips, Y. F., Towsey, M., & Roe, P. (2018). Revealing the ecological content of long-duration audio-recordings of the environment through clustering and visualisation. *PLoS ONE*, *13*, e0193345. https://doi.org/10.1371/journal.pone.0193345

Pieretti, N., & Farina, A. (2013). Application of a recently introduced index for acoustic complexity to an avian soundscape with traffic noise. *The Journal of the Acoustical Society of America*, *134*, 891–900. https://doi.org/10.1121/1.4807812

Pieretti, N., Farina, A., & Morri, D. (2011). A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI). *Ecological Indicators*, *11*, 868–873. https://doi.org/10.1016/j.ecolind.2010.11.005

Pijanowski, B. C., Farina, A., Gage, S. H., Dumyahn, S. L., & Krause, B. L. (2011). What is soundscape ecology? An introduction and overview of an emerging new science. *Landscape Ecology*, *26*, 1213–1232. https://doi.org/10.1007/s10980-011-9600-8

Popper, A. N., & Hastings, M. C. (2009). The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology*, *75*, 455–489. https://doi.org/10.1111/j.1095-8649.2009.02319.x

Popper, A. N., & Hawkins, A. D. (2019). An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. *Journal of Fish Biology*, *94*, 692-713.

Popper, A. N., Smith, M. E., Cott, P. A., Hanna, B. W., MacGillivray, A. O., Austin, M. E., & Mann, D. A. (2005). Effects of exposure to seismic airgun use on hearing of three fish species. *The Journal of the Acoustical Society of America*, *117*, 3958. https://doi.org/10.1121/1.1904386

Priyadarshani, N., Marsland, S., & Castro, I. (2018). Automated birdsong recognition in complex acoustic environments: A review. *Journal of Avian Biology*, *49*, jav-01447. https://doi.org/10.1111/jav.01447

R Core Team. (2015). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Radford, C. A., Stanley, J. A., Simpson, S. D., & Jeffs, A. G. (2011). Juvenile coral reef fish use sound to locate habitats. *Coral Reefs*, *30*, 295–305. https://doi.org/10.1007/s00338-010-0710-6

Retamosa Izaguirre, M. I., Ramírez-Alán, O., & De la O Castro, J. (2018). Acoustic indices applied to biodiversity monitoring in a Costa Rica dry tropical forest. *Journal of Ecoacoustics*, *2*, TNW2NP. https://doi.org/10.22261/jea.tnw2np

Risch, D., Castellote, M., Clark, C. W., Davis, G. E., Dugan, P. J., Hodge, L. E., … Van Parijs, S. M. (2014). Seasonal migrations of North Atlantic minke whales: Novel insights from large-scale passive acoustic monitoring networks. *Movement Ecology*, *2*(1), 24.

Roch, M. A., Baumann-Pickering, S., Hwang, D., Batchelor, H., Berchok, C. L., Cholewiak, D., … Van Parijs, S. M. (2013). Tethys: A workbench for bioacoustic measurements and environmental data. *The Journal of the Acoustical Society of America*, *134*, 4176. https://doi.org/10.1121/1.4831309

Rodriguez, A., Gasc, A., Pavoine, S., Grandcolas, P., Gaucher, P., & Sueur, J. (2014). Temporal and spatial variability of animal sound within a neotropical forest. *Ecological Informatics*, *21*, 133–143. https://doi.org/10.1016/j.ecoinf.2013.12.006

Rountree, R. A., Bolgan, M., & Juanes, F. (2018). How can we understand freshwater soundscapes without fish sound descriptions? *Fisheries*, *44*(3), 137–143. https://doi.org/10.1002/fsh.10190

Ruppé, L., Clément, G., Herrel, A., Ballesta, L., Décamps, T., Kéver, L., & Parmentier, E. (2015). Environmental constraints drive the partitioning of the soundscape in fishes. *Proceedings of the National Academy of Sciences of the United States of America*, *112*, 6092–6097. https://doi.org/10.1073/pnas.1424667112

Sanborn, A. (2005). Acoustic signals and temperature. In S. Drosopoulos & M. F. Claridge (Eds.), *Insect sounds and communication* (pp. 111–125). Contemporary Topics in Entomology. Boca Raton, FL: CRC Press

Sandin, L., & Solimini, A. G. (2009). Freshwater ecosystem structure-function relationships: From theory to application. *Freshwater Biology*, *54*, 2017–2024. https://doi.org/10.1111/j.1365-2427.2009.02313.x

Sethi, S. S., Ewers, R. M., Jones, N. S., Orme, D., & Picinali, L. (2017). Robust, real-time and autonomous monitoring of ecosystems with an open, low-cost, networked device. *bioRxiv*, 236075

Sharan, R. V., & Moir, T. J. (2016). An overview of applications and advancements in automatic sound recognition. *Neurocomputing*, *200*, 22–34. https://doi.org/10.1016/j.neucom.2016.03.020

Silver, S. C., & Halls, J. A. (1980). Recording the sounds of hydropsychid larvae—A cautionary tale. *Journal of Comparative Physiology*, *140*, 159–161.

Slabbekoorn, H., & Bouton, N. (2008). Soundscape orientation: A new field in need of sound investigation. *Animal Behaviour*, *76*, e5–e8.

Stanley, C. Q., Walter, M. H., Venkatraman, M. X., & Wilkinson, G. S. (2016). Insect noise avoidance in the dawn chorus of Neotropical birds. *Animal Behaviour*, *112*, 255–265. https://doi.org/10.1016/j.anbehav.2015.12.003

Straight, C. A., Freeman, B. J., & Freeman, M. C. (2014). Passive acoustic monitoring to detect spawning in large-bodied catostomids. *Transactions of the American Fisheries Society*, *143*, 595–605.

Strayer, D. L., & Dudgeon, D. (2010). Freshwater biodiversity conservation: Recent progress and future challenges. *Journal of the North American Benthological Society*, *29*, 344–358. https://doi.org/10.1899/08-171.1

Sueur, J., Aubin, T., & Simonis, C. (2008). Seewave: A free modular tool for sound analysis and synthesis. *Bioacoustics*, *18*, 213–226.

Sueur, J., & Farina, A. (2015). Ecoacoustics: The ecological investigation and interpretation of environmental sound. *Biosemiotics*, *8*, 493–502. https://doi.org/10.1007/s12304-015-9248-x

Sueur, J., Farina, A., Gasc, A., Pieretti, N., & Pavoine, S. (2014). Acoustic indices for biodiversity assessment and landscape investigation. *Acta Acustica United with Acustica*, *100*, 772–781. https://doi.org/10.3813/aaa.918757

Sueur, J., Pavoine, S., Hamerlynck, O., & Duvail, S. (2008). Rapid acoustic survey for biodiversity appraisal. *PLoS ONE*, *3*, e4065.

ter Hofstede, H. M. (2018). Effects of predator cues on prey signalling behaviour: Bats and Katydids in the neotropical forest. Animal Behavior society meeting, Milwaukee, WI, 2018.

Tobias, J. A., Planque, R., Cram, D. L., & Seddon, N. (2014). Species interactions and the structure of complex communication networks. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 1020–1025. https://doi.org/10.1073/pnas.1314337111

Tonolla, D., Acuña, V., Lorang, M. S., Heutschi, K., & Tockner, K. (2010). A field-based investigation to examine underwater soundscapes of five common river habitats. *Hydrological Processes*, *24*, 3146–3156. https://doi.org/10.1002/hyp.7730

Tonolla, D., Lorang, M. S., Heutschi, K., Gotschalk, C. C., & Tockner, K. (2011). Characterization of spatial heterogeneity in underwater soundscapes at the river segment scale. *Limnology and Oceanography*, *56*, 2319–2333. https://doi.org/10.4319/lo.2011.56.6.2319

Tonolla, D., Lorang, M. S., Heutschi, K., & Tockner, K. (2009). A flume experiment to examine underwater sound generation by flowing water. *Aquatic Sciences*, *71*, 449–462. https://doi.org/10.1007/s00027-009-0111-5

Torricelli, P., Lugli, M., & Pavan, G. (1990). Analysis of sounds produced by male *Padogobius martensi* (Pisces, Gobiidae) and factors affecting their structural properties. *Bioacoustics*, *2*, 261–275.

Towsey, M., Wimmer, J., Williamson, I., & Roe, P. (2014). The use of acoustic indices to determine avian species richness in audio-recordings of the environment. *Ecological Informatics*, *21*, 110–119. https://doi.org/10.1016/j.ecoinf.2013.11.007

Tucker, D., Gage, S. H., Williamson, I., & Fuller, S. (2014). Linking ecological condition and the soundscape in fragmented Australian forests. *Landscape Ecology*, *29*, 745–758. https://doi.org/10.1007/s10980-014-0015-1

Tyack, P. L., & Janik, V. M. (2013). Effects of noise on acoustic signal production in marine mammals. In H. Brumm (Ed.), *Animal communication and noise* (pp. 251–271). Berlin Heidelberg: Springer.

Ulloa, J. S., Aubin, T., Llusia, D., Bouveyron, C., & Sueur, J. (2018). Estimating animal acoustic diversity in tropical environments using unsupervised multiresolution analysis. *Ecological Indicators*, *90*, 346–355. https://doi.org/10.1016/j.ecolind.2018.03.026

Ulloa, J. S., Gasc, A., Gaucher, P., Aubin, T., Réjou-Méchain, M., & Sueur, J. (2016). Screening large audio datasets to determine the time and space distribution of Screaming Piha birds in a tropical forest. *Ecological Informatics*, *31*, 91–99. https://doi.org/10.1016/j.ecoinf.2015.11.012

Villanueva-Rivera, L. J. (2014). *Eleutherodactylus* frogs show frequency but no temporal partitioning: Implications for the acoustic niche hypothesis. *PeerJ*, *2*, e496. https://doi.org/10.7717/peerj.496

Villanueva-Rivera, L. J., Pijanowski, B. C., Doucette, J., & Pekin, B. (2011). A primer of acoustic analysis for landscape ecologists. *Landscape Ecology*, *26*, 1233–1246. https://doi.org/10.1007/s10980-011-9636-9

Villanueva-Rivera, L. J., Pijanowski, B. C., & Villanueva-Rivera, M. L. J. (2018). Package 'soundecology'.

Whytock, R. C., & Christie, J. (2017). Solo: An open source, customizable and inexpensive audio recorder for bioacoustic research. *Methods in Ecology and Evolution*, *8*, 308–312. https://doi.org/10.1111/2041-210x.12678

Wood, P. J., Greenwood, M. T., & Agnew, M. D. (2003). Pond biodiversity and habitat loss in the UK. *Area*, *35*, 206–216.

WWF (2018). *Living planet report 2018: Aiming higher*. Gland, Switzerland: WWF international.

Xie, J., Towsey, M., Zhang, J., & Roe, P. (2016). Adaptive frequency scaled wavelet packet decomposition for frog call classification. *Ecological Informatics*, *32*, 134–144. https://doi.org/10.1016/j.ecoinf.2016.01.007

Zhang, L., Towsey, M., Zhang, J., & Roe, P. (2017). Using non-negative matrix factorisation to facilitate efficient bird species richness surveys. *Ecological Indicators*, *80*, 297–302. https://doi.org/10.1016/j.ecolind.2017.05.017

How to cite this article: Desjonquères C, Gifford T, Linke S. Passive acoustic monitoring as a potential tool to survey animal and ecosystem processes in freshwater environments. *Freshw Biol*. 2019;00:1–13. https://doi.org/10.1111/fwb.13356