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INTRODUCTION

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Six steps towards operationalising freshwater ecoacoustic monitoring

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Abstract

1. Applications in bioacoustics and its sister discipline ecoacoustics have increased exponentially over the last decade. However, despite knowledge about aquatic bioacoustics dating back to the times of Aristotle and a vast amount of background literature to draw upon, freshwater applications of ecoacoustics have been lagging to date.
2. In this special issue, we present nine studies that deal with underwater acoustics, plus three acoustic studies on water-dependent birds and frogs. Topics include automatic detection of freshwater organisms by their calls, quantifying habitat change by analysing entire soundscapes, and detecting change in behaviour when organisms are exposed to noise.
3. We identify six major challenges and review progress through this special issue. Challenges include characterisation of sounds, accessibility of archived sounds as well as improving automated analysis methods. Study design considerations include characterisation analysis challenges of spatial and temporal variation. The final key challenge is the so far largely understudied link between ecological condition and underwater sound.
4. We hope that this special issue will raise awareness about underwater soundscapes as a survey tool. With a diverse array of field and analysis tools, this issue can act as a manual for future monitoring applications that will hopefully foster further advances in the field.

KEYWORDS
ecoacoustics, ecological monitoring, freshwater, passive acoustics, underwater sounds

Bioacoustics—the study of sounds produced by or affecting living organisms—and its sister discipline ecoacoustics—the study of environmental sounds as ecosystem attributes potentially revealing ecological patterns and processes—have grown in importance as non-invasive and continuous approaches to ecological monitoring. While underused in freshwater settings, this special issue aims to demonstrate that it is especially useful in the aquatic sciences. One of the reasons for the accelerated declines in freshwater biodiversity is that species are simply harder to detect, which can impede monitoring and management. While citizen scientists can easily detect changes in endangered bird populations, even specialists often have trouble accurately characterising freshwater assemblages (Arrington & Winemiller, 2003; Ebner et al., 2008). A key advantage of acoustic monitoring methods is the ability to record 24/7, thus accounting for temporal variation in ecological assessments (Linke, Gifford, et al., 2020). Another important issue in freshwater systems is the invasive nature of most sampling techniques (e.g. netting, electrofishing), which leads to changes in observability—some fish are attracted to the disturbance, others flee. Acoustic methods avoid this problem. This special issue examines the monitoring potential of ecoacoustic techniques in a freshwater setting.

An exponential increase in application of acoustic techniques has recently occurred in mainly terrestrial realms (Figure 1), although not yet in aquatic environments: only seven of the 46 papers published on ecoacoustics are in aquatic settings (two in freshwater and five in marine environments). Acoustics has been used to monitor the presence of rare and endangered species (Willacy, Mahony & Newell, 2015), population trajectories (Marques et al., 2013), but also the impact of anthropogenic activities on ecosystems (Fuller, Axel, Tucker & Gage, 2015; Ng, Butler & Woods, 2018; Popper & Hawkins, 2019). Thanks to advances in technology, such as cheap autonomous recorders (Hill et al., 2018) and dedicated (sometimes free) software packages (Sueur, Aubin & Simonis, 2008), as well as an increase in computational power to automate call detection, acoustic monitoring is now accessible to a much wider audience of researchers and practitioners compared to only a few years ago.

Bioacoustic research in freshwater systems carries a long tradition; Aristotle identified the two common mechanisms of sound production by fish (stridulation and drumming, see Figure 2) in his *Historia Animalium* (340BCE). While a current Google Scholar search is proof of continuing engagement in this area of research with >2,750 scientific publications for the term "freshwater + bioacoustics" (8 August 2018), applications for monitoring individuals, populations and ecosystems are more sparse in freshwater settings. Freshwater bioacoustics to date has focussed less on ecological context, but mainly dealt with mechanistic descriptions of sound reception and sound production, as well as behavioural studies about communications (see Fine & Parmentier, 2015; Ladich, 2015 for overviews of the respective fields). A third group of studies has mainly researched the effect of noise on underwater organisms (Amoser & Ladich, 2010; Bolgan et al., 2016; see Popper & Hawkins, 2019 for a recent review).

This emerging field has great potential for the study of freshwater environments but is currently underdeveloped. In this introduction to the special issue, we describe six key steps that need to be undertaken to boost utility of freshwater acoustic approaches in ecological monitoring and assessment:

1. Characterising sounds and linking occurrences to organisms and ecosystem processes
2. Improving automatic detection and analysis methods
3. Making data and science accessible
4. Quantifying spatial heterogeneity and modelling spatial sound propagation
5. Considering multi-scale temporal variation
6. Deriving links between ecological condition and sounds

Here, we highlight recent key progress towards these six steps and as well as the contribution of this special issue towards operationalising freshwater ecoacoustic monitoring.

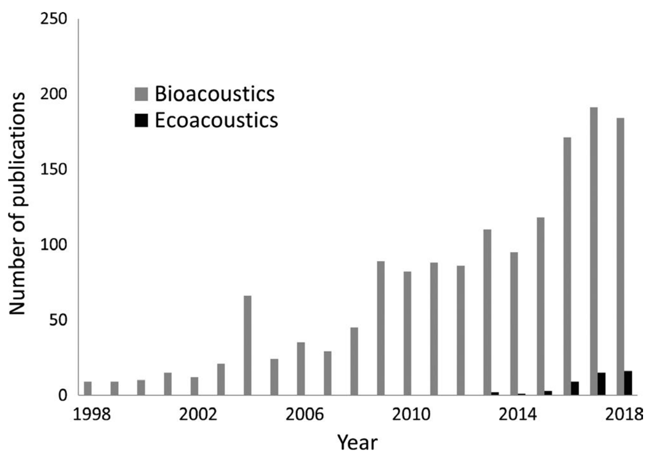

FIGURE 1 Increase in bioacoustic and ecoacoustic studies in the last 2 decades. (Search for "bioacoustics" and "ecoacoustics" respectively)

FIGURE 2 Sonifery in fish as described by Aristotle in 340 BCE (*Historia Animalium*, Book IV, Chapter 4, Translated by D'Arcy Wentworth Thompson): "No mollusc or crustacean can produce any natural voice or sound. Fishes can produce no voice, for they have no lungs, nor windpipe and pharynx; but they emit certain inarticulate sounds and squeaks, which is what is called their 'voice', as the lyra or gurnard, and the sciaena (for these fishes make a grunting kind of noise) and the caprus or boar-fish in the river Achelous, and the chalcis and the cuckoo-fish; for the chalcis makes a sort piping sound, and the cuckoo-fish makes a sound greatly like the cry of the cuckoo, and is nicknamed from the circumstance. The apparent voice in all these fishes is a sound caused in some cases by a rubbing motion of their gills, which by the way are prickly, or in other cases by internal parts about their bellies; for they all have air or wind inside them, by rubbing and moving which they produce the sounds." Portrait of Aristotle. Louvre, Paris. Image by Eric Gaba, Wikimedia, CC2.5-SA [Colour figure can be viewed at wileyonlinelibrary.com]

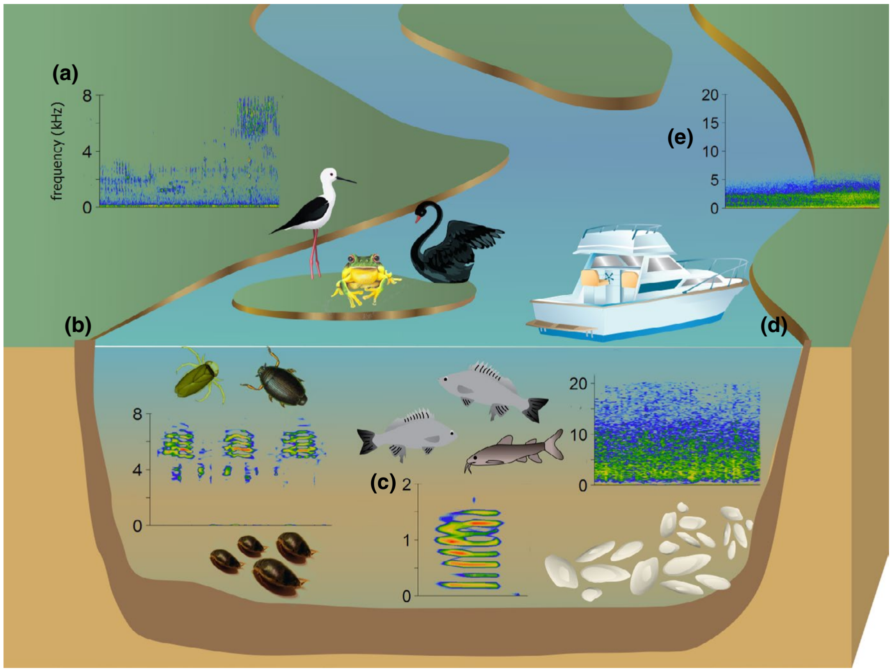

FIGURE 3 Ecoacoustics can detect and monitor: (a) water-dependent birds and amphibians (Dema et al., 2020; Dutilleux & Curé, 2020; Indraswari et al., 2020; Linke & Deretic, 2020); (b) activity of aquatic insects and other invertebrates (Desjonquères, Rybak, et al., 2020; Gottesman et al., 2020; Linke, Decker, et al., 2020); (c) communication between fish (Grabowski et al., 2020; Hanache et al., 2020; Higgs & Humphrey, 2020; Linke, Decker, et al., 2020; Roca et al., 2020; Rountree & Juanes, 2020); (d) biophysical processes such as sediment transport and gas exchange (Gottesman et al., 2020; Linke, Decker, et al., 2020); (e) anthropogenic disturbance, for example boat and engine noises (Desjonquères, Rybak, et al., 2020; Higgs & Humphrey, 2020) [Colour figure can be viewed at wileyonlinelibrary.com]

1 | CHARACTERISING SOUNDS AND LINKING OCCURRENCES TO ORGANISMS AND ECOSYSTEM PROCESSES

In freshwater environments, four main groups are known to produce sounds: amphibians, crustaceans, fish, and insects (for a detailed discussion, see Desjonquères, Gifford & Linke, 2020, also see Figure 3). Unlike terrestrial bioacoustics, where the organisms emitting sounds are often clearly visible, underwater acoustics is often not accompanied by visual surveys. Incidental observations are also unlikely as specialised equipment (i.e. a hydrophone) is used for the detections. While ecoacoustic analysis using indices or spectrograms is still feasible (Gottesman et al., 2020; Linke, Decker, Gifford & Desjonquères, 2020), even when not all sounds are resolved, interpretation can sometimes be difficult. We, therefore, concur with Rountree, Bolgan and Juanes (2019): in many cases, it is imperative to know and catalogue the source of the sounds. Example applications that cannot work without detailed characterisations are monitoring endangered species or tracking invasion front by soniferous species such as tilapia or brown bullhead catfish.

In the special issue, contributions to the field range from multi-taxon descriptions to detailed characterisations aiming to develop automatic detection algorithms. Channelling the groundbreaking multi-taxon characterisation by Desjonquères et al. (2015), the study by Gottesman et al. (2020) catalogued soundtypes, but did not attempt to link them to organisms. The authors, however, noted that most sounds could probably be attributed to aquatic insects as soniferous families of coleoptera, hemiptera, and trichoptera were documented at the site. A similar approach was taken by Linke, Decker, et al. (2020), who catalogued >8,000 instances of 42 sound types, that they catalogued into sounds emitted by fish, hemiptera (true bugs), and coleopteran (beetles). While they could not link the sounds to species, they had reference recordings of some of the families at their site in Australia's tropical savanna and were thus able to at least to link them to the family level. The fish reference recordings were established by underwater video, a strategy advocated for all underwater habitats (Rountree et al., 2019) and recently tested in the marine realm by Mouy, Rountree, Juanes and Dosso (2018). The paper by Linke, Decker, et al. (2020) also highlights the need to identify other sources and levels of sound, such as gas exchange (in their case methane bubbling from the sediment) and river flow.

2 | IMPROVING AUTOMATIC DETECTION AND ANALYSIS METHODS

While identifying and cataloguing sounds is crucial, a second obstacle is processing of sounds. Most freshwater studies still use manual annotation—i.e. a researcher listening to the sound files and manually classifying and annotation sound events. For example, Linke, Decker, et al. (2020) annotated 8,097 individual sound events—a feat that took many months—while Gottesman et al. (2020) sorted through 2,121 individual sound files of varying length. Other papers in the special issue extend terrestrial efforts to catalogue single-species sounds for taxonomic distinction or development of automatic detection algorithms. This can be simplified by properly cataloguing sounds and building automatic detection algorithms.

In this special issue, for example, calls by four species of piranha were documented by Rountree and Juanes (2020), who also characterised vocalisations and their variation. This information can be used to build automatic classification algorithms, as can the characterisations by Grabowski, Young, and Cott (2020), who analysed spawning calls by soniferous burbot in northern Canada. Automatic detection algorithms are now widespread in terrestrial and marine systems, where they have been used for birds (Potamitis, Ntalampiras, Jahn & Riede, 2014) as well as terrestrial (Zeppelzauer, Hensman & Stoeger, 2015) and marine animals (Širović, 2016).

In this issue, we present only the second study ever to develop an automated detection algorithm for a freshwater organism. While the first paper by Straight, Freeman, and Freeman (2014) classified spawning noises emitted by two different species of Catastomidae, in this issue Dutilleux and Curé (2020) present an automated detection algorithm for the underwater vocalisations of the spadefoot toad (*Pelobates fuscus*) based on the temporal patterning of acoustic energy in a target frequency band. They find it feasible to monitor presence of this species with largely automated acoustic methods. As a consequence of their continuous monitoring, they present a substantially richer picture of temporal dynamics and variation in the *P. fuscus* breeding season.

Approaching automatic detection from a completely different angle, two further studies describe detection of water-dependent terrestrial birds and anurans using acoustic indices, bridging the gap between single-species bioacoustics and ecoacoustic approaches. To detect the highly endangered white-bellied heron (*Ardea insignis*) in Bhutan, Dema et al. (2020) employed a deep learning algorithm that selected a combination of acoustic indices. A similar, but even easier approach was chosen to classify calls by three frog species in Northern Australia (Indraswari et al., 2020)—three easily calculated indices were combined to distinguish calls of two hyliids and a myobatrachid anuran. While it was not the core objective of the temporal study by Linke, Decker, et al. (2020), filtered acoustic indices were found to be able to detect nocturnal insect choruses, diurnal variation of creek flow, and early morning fish choruses. These studies show that acoustic indices as simple detectors can work for dominant sound events.

3 | MAKING DATA AND SCIENCE ACCESSIBLE

Despite an excellent baseline of published research and a flurry of new activity as documented in this issue, the lack of available reference calls is a key obstacle to operationalising acoustic monitoring. Unlike the international bird bioacoustics community, freshwater acousticians have so far hardly contributed sound samples to any of the international sound archives. While the Cornell Lab of Ornithology's Macaulay Library has some fish sounds (982, which represents 0.25% of all calls), these are mainly marine and from the 60s and 70s. As a matter of fact, since we started working on a first draft of Linke et al. (2020) in 2016, not a single fish call has been added. This lack of reference material greatly increases the difficulty for researchers new to the field, as the emitter of an underwater sound is not obvious. We do not know what drives differences in scientific communities to publish their acoustic data—this is not just restricted to the freshwater field as non-avian calls are grossly under-represented in all major archives. We, therefore, call on the international community to submit their documented and validated calls to the Macaulay Library, the Berlin Animal Sound Archive, the Paris Sonothèque or other central bioacoustics repositories. An alternative approach would be mandatory submission on acceptance of a journal paper, similar to the common practice in the genetics community.

4 | MEASURING SPATIAL HETEROGENEITY AND MODELLING SOUND PROPAGATION

Quantifying spatial heterogeneity as a potential source of error in ecological assessments is a standard procedure that has seen surprisingly little application in ecoacoustics, apart from a multi-site study on grasslands in Greece (Bormpoudakis, Sueur, & Pantis, 2013). This is surprising, as spatial replication will increase statistical rigour. We suspect that this lack of spatial replication to date has been influenced by two factors. First, recorders and fieldwork expenses can be high. However, this is no different to other traditional techniques. We, therefore, suspect that a second factor is more important: the volume of data and the demands on computational systems. This can be overcome by two techniques described in this special issue. Linke, Decker, et al. (2020) demonstrate that small subsamples are adequate to characterise soundscapes (see below), whereas two other studies introduce modern data visualisation techniques to freshwater monitoring (Dema et al., 2020; Indraswari et al., 2020).

In this special issue, only one publication directly deals with spatial heterogeneity in activity. Using a regularly spaced array of hydrophones, Desjonquères, Rybak, et al. (2020) reveal that acoustic activity of the same species of aquatic hempitera is significantly higher in open water than in vegetated areas. This is a large gap in research as spatial distribution of any ecological feature is a key part of any environmental system. Not restricted to underwater applications, we encourage the ecoacoustics community to research spatial heterogeneity and its effect on the variability on acoustic assessments, similar to the activities of the bioassessment community 20–30 years ago (Nichols, Robinson & Norris, 2006).

5 | CONSIDERING MULTI-SCALE TEMPORAL VARIATION

In contrast to standard biomonitoring applications, which are more focussed on spatial replication, increased temporal resolution is a key strength of ecoacoustic approaches. As papers in this special issue demonstrate, acoustic monitoring is able to resolve both human-induced and natural variation over longer timescales (Linke & Deretic, 2020). However, short-term acoustic variation, stemming from diurnal or lunar cycles needs to be considered in study design. Examples of this variation are the nightly insect choruses (hemiptera and coleoptera) that both Gottesman et al. (2020) and Linke et al. (2020) describe in their contributions. Both studies also described a diurnal shift in acoustic communities, but also a longer-term cycle, which Gottesman et al. (2020) attribute to a rain event but Linke et al. (2020) consider to be linked to decreased insect activity in bright moonlight.

If all calls are to be characterised, a 24-hr sampling regime is recommended (Linke et al., accepted); however, detecting change will probably only require a subsample of the overall soundscape. This was demonstrated by Linke and Deretic (2020), who recorded terrestrial sounds to determine wetland health. In their study, restricting the recordings to periods of high activity of their indicator species actually reduced statistical noise. A similar pattern was found by both Higgs and Humphrey (2020) and Grabowski, Young and Cott (2020), whose target species of fish were more active overnight. Again, scheduling will be dependent on the objective of the monitoring programme.

6 | LINKS BETWEEN SOUND AND ECOLOGICAL CONDITION

Of course, the final goal in all ecological assessment schemes is to establish a link between the surrogate measure—in this case sound—and ecological condition. This has been successfully demonstrated in terrestrial settings (Fuller et al., 2015; Ng et al., 2018), but has proved more difficult in a freshwater context. Only 20% of fish are soniferous (Luczkovich, Mann & Rountree, 2008), so declines in call richness cannot be conclusively linked to a decline in fish richness—indeed, species richness could increase if non-soniferous taxa displace their soniferous counterparts. In the case of macroinvertebrates, traditionally employed in condition assessments, some of the most tolerant taxa are the loudest.

In this special issue, authors take three approaches to directly link sound to ecological condition. First, changes in sound can indicate a change in the community (Linke & Deretic, 2020). While none of the studies in this special issue investigated underwater sounds in response to ecological restoration, this study from Australia (Linke & Deretic, 2020) used water-dependent birds and frogs to monitor the ecological outcomes of environmental water allocations. Using single-call analysis, they detected recovery by water-dependent taxa, but no effect on a non-water-dependent control group. After removal of outliers and focus on the dawn chorus, acoustic indices also indicated a response to the restoration action, albeit weaker than the manually processed call analysis.

Second, ecoacoustics can determine direct effects of noise on aquatic organisms. In the special issue, responses by both fish and invertebrates to anthropogenic noise were described. Both environmental factors such as temperature and vegetation covers, as well as anthropogenic noise were related to the acoustic activity of a species of aquatic hemiptera (Desjonquères, Rybak, et al., 2020). Instead of using sound only as a proxy of disturbance, their study demonstrates that sonic activity can be a bioindicator of changed environmental condition. Two other studies did not describe noise as a proxy, but as a direct effect. Both Hanache et al. (2020) and Roca, Magnan and Proulx (2020) described changed feeding behaviour of two fish species in relation to ambient noise. The former study in particular discussed farther reaching consequences of noise pollution—noise can modify predator behaviour and therefore change the entire food web. The effect of noise on aquatic organisms will have to be quantified on a case-by-case basis though, as Higgs and Humphrey (2020) did not find any effects on the round goby (*Neogobius melanostomus*).

The last—and extremely powerful application for passive acoustics is detection of invasive species. In this special issue, Higgs and Humphrey (2020) describe application of passive acoustics to monitor the invasive round goby. Building autodetection algorithms for invasives would be a logical next step for early detection of invasive species like Tilapia or the Brown Bullhead Catfish.

IMPACT OF THE SPECIAL ISSUE

As marine and terrestrial ecoacoustic monitoring is leaping from strength to strength, we hope that this special issue will give a significant boost to the field of freshwater ecoacoustics. We hope that both scientists and practitioners will use this special issue both as a compendium and an inspiration to operationalise ecoacoustic analysis in freshwater ecosystem. In this issue, we provide a compendium to get users started with principles of underwater acoustics and applied analysis methods (Desjonquères, Gifford, et al., 2020). The issue then follows on to demonstrate applications, both underwater and for water-dependent ecosystems. Case studies include monitoring native populations and ecosystems as well as invasives—using both analysis of single calls and whole soundscape analysis. We hope that these studies can be used as templates for future applications and kickstart a new era in innovative monitoring of freshwater systems.

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