Freshwater Ecoacoustics—A New Addition to the Limnologists' Methods Toolkit

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Glossary

Automatic call recognizer An application that uses various techniques (often machine learning or artificial intelligence) to automatically find acoustic events.
Autonomous Recording Unit A self-contained audio recording device that is deployed in marine or terrestrial environments for bioacoustical monitoring.
Bioacoustics The branch of acoustics concerned with sounds produced by or affecting living organisms, especially as relating to communication.
Ecoacoustics An interdisciplinary science that investigates natural and anthropogenic sounds and their relationship with the environment over a wide range of study scales, both spatial and temporal, including populations, communities, and landscapes. Ecoacoustics operates in all types of terrestrial and aquatic (freshwater and marine) ecosystems extending the scope of acoustics and bioacoustics.
Hydrophone A microphone designed to be used underwater for recording or listening to underwater sound. Most hydrophones are based on a piezoelectric transducer that generates an electric potential when subjected to a pressure change, such as a sound wave.
Passive acoustic monitoring (PAM) Is used to measure and monitor sounds emitted by organisms or ecosystems. It differs from active acoustic monitoring which often manifests itself by sonar emissions from research vessels.
Soundscape The acoustic environment as perceived by humans.

Introduction to aquatic bioacoustics and ecoacoustics

Environmental changes—both natural and human-induced—can be very difficult to monitor. Often remote locations can be only reached infrequently so changes in the environment that occur between sampling events can be hard to detect. Ability to detect change is also exacerbated in freshwater systems, for which specialized equipment and expertise are often needed. Freshwater species are about three times more likely to be endangered by extinction than terrestrial taxa, making it crucial to properly monitor these species (Almond et al., 2020). Bioacoustics and its sister discipline ecoacoustics are emerging non-invasive and real-time monitoring techniques that have been used to survey rare and endangered species' population trajectories and the impact of human activities on ecosystems (Sueur and Farina, 2015; Farina and Gage, 2017). Bioacoustics is analogous to biology—i.e., studying single species and the sounds they produce, including production mechanisms. Ecoacoustics is an interdisciplinary science that investigates natural and anthropogenic sounds and their relationship with the environment over a wide range of study scales, both spatial and temporal, including populations, communities, and landscapes.

Problem 1: Risks to fish health and habitat integrity. Classic techniques like netting and electrofishing can cause injury or even death in fish. This is inappropriate for sensitive or threatened species.

Problem 2: Bias. While all sampling methods are biased to varying degrees, a key source of bias is the act of sampling itself. It often causes fright responses of the target fish, making detection difficult.

Problem 3: Temporal variation. Usually single survey events are used to estimate ecosystem health and monitor population. This can only deliver a snapshot of the population at a single sampling time.

Fig. 1 Three key problems with traditional monitoring that ecoacoustics solves.

Ecoacoustics addresses three problems with more traditional sampling methods (Fig. 1). Apart from mitigating sampling-induced risk of damage to species and ecosystems as well as certain sampling biases, acoustic monitoring is able to autonomously detect continuous environmental change in an ecosystem. This is a major improvement on classic sampling techniques which often only entail annual or quarterly sampling.

In terrestrial systems, acoustic monitoring has been used to monitor wildlife populations for many decades. Historically, tape recorders were used to capture the sounds of nature by researchers like Aldo Leopold and Rachel Carson who used acoustics in behavioral and ecological studies. Sounds have been used to survey birds and amphibians since the 1960s, formalized in the Breeding Bird Survey of North America (Peterjohn and Sauer, 1999). These surveys were then manually processed by listening to the recordings to tally call types and frequencies. These manual survey processing techniques that resulted in studies optimizing call detection continued until the 21st century. The first auto-detection algorithms were developed between 1996 and 2005 with increased and accessible computational power as research computing moved from centralized clusters to home computers and laptops. Automatic processing revolutionized both bioacoustics and ecoacoustics as much larger data volumes could be processed.

Ecoacoustics is an emerging discipline studying the ecological relevance of environmental sounds (Sueur and Farina, 2015; Farina and Gage, 2017). It studies sounds at ecologically relevant scales including the individual, population, community and landscape (or soundscape). An acoustic population is composed of the songs of one species. An acoustic community is made up of different species producing sounds. Finally, a soundscape not only includes the acoustic community (biophony) but also geological sounds (geophony) such as wind or rain and anthropogenic noises (anthropophony) such as airplane or car sounds (Pijanowski et al., 2011). In this chapter, we discuss the history of bioacoustics in freshwater systems, as used to study both fish and invertebrates. We then describe abiotic sounds and introduce the holistic field of ecoacoustics. After a short primer on analysis techniques, we cover current challenges and recent frontiers in the field, before closing with a discussion of ecoacoustics as an engagement tool.

History of bioacoustics in inland waters

While even experienced freshwater ecologists are often unaware of the diversity in underwater sounds, the field of bioacoustics has a long tradition. In his Historia Animalium, Aristotle described the two key methods of sound production in fish in close to correct anatomical detail (Aristotle, 1910). Aristotle mentioned both stridulation ("rubbing motion of the gills"), as well as the use of the swim bladder ("an organ with air inside it") as sound producing mechanisms. In the 17th century, Izaak Walton noted that fish could hear and in the middle of 19th century sound production in fishes was also mentioned in communications to Charles Darwin by Fritz Mueller (https://www.darwinproject.ac.uk/fritz-m-ller). Mueller described sound production in 10 families, both by stridulation and vibration of the swimbladder. Ralph W. Tower—a professor at Brown University—in 1908 described the sound production mechanism of three drumfishes, as well as the sea-robin and toadfish in a groundbreaking and anatomically detailed study, paving the way towards an expanding field of research and on-ground applications (Tower, 1908).

The abundance of reference calls for fish is still greatly lagging behind reference calls for birds or anurans, despite a large effort by two researchers in the 1970s, Marie Fish and William Mowbray (Fish and Mowbray, 1970). The entire archive was digitized and is currently still shaping the backbone of the fish section within the Cornell's Macaulay Library sound archive. That said, the library still only harbors ~900 fish calls, as opposed to ~1.2 million bird calls, although this is hard to quantify as the taxonomic backbone for 'Actinopterygii' has recently disappeared from the library. Currently, a major drive to catalogue fish sounds is underway—on the aptly named 'FishSounds' platform (https://fishsounds.net/).

The science of behavioral aspects of fish sound and communication was driven forward by academics in North America and Europe including Arthur Popper, Michael Fine, Friedrich Ladich and Eric Parmentier, among many others (Ladich and Fine, 2006; Fine and Parmentier, 2015). In the early 2000s, a group of researchers led by Rodney Rountree and Joseph Luczkovich led the charge to drive an expansion of the field of applied ecoacoustics, especially of fish (Luczkovich et al., 2008). In recent years, researchers in the freshwater realm started to document calls, but also began to use acoustic data in behavioral and general ecological studies. For example a research group led by Rodney Rountree started cataloguing the sounds of six piranha species in the Amazon

(Rountree and Juanes, 2020) and a few Canadian studies looked at behavioral aspects of burbot (*Lota lota*) under arctic winter ice using acoustics (Grabowski et al., 2020). The science of building automatic recognizers and other processing options has also greatly progressed, starting with an automatic signal processing workflow for river redhorse (*Moxostoma carinatum*) spawning by a group of American researchers from the University of Georgia (Straight et al., 2014).

Fish bioacoustics

Fish have one of the highest diversities of vocal organs of any animal group, with many sounds made by the swim bladder—a gas filled organ that is mainly used to regulate buoyancy in the water column (Fig. 2). Similar to a plastic air balloon or a drum skin, the

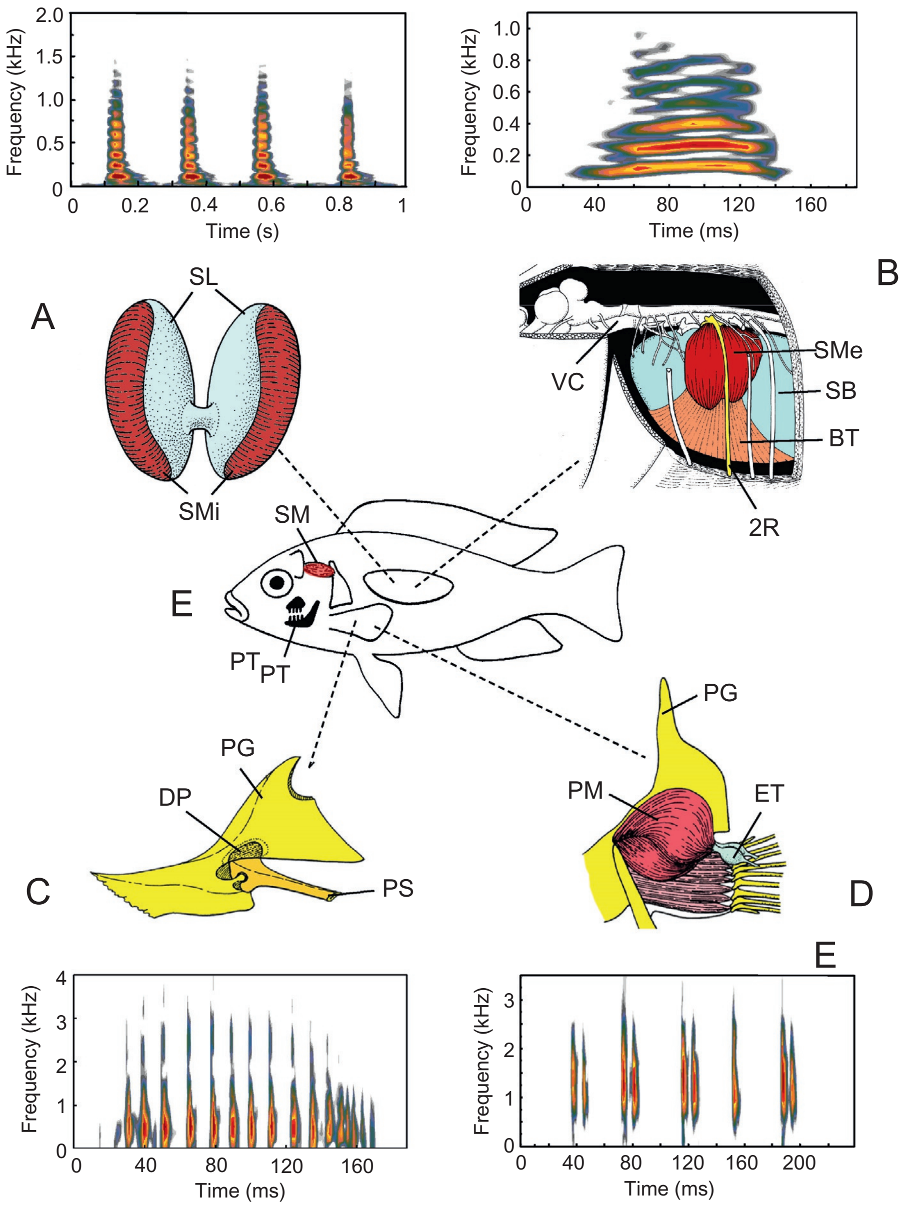

Fig. 2 Diversity of sound generating mechanisms in fishes and sonagrams of sounds produced by these mechanisms. (A) Intrinsic sonic muscles (SMi) attached to both swim bladder lobes (SL) in the Lusitanian toadfish *Halobatrachus didactylus*, (B) extrinsic sonic muscles (SMe) originating at the second rib (2R) and inserting on a broad tendon (BT) ventrally of the swim bladder in the black piranha *Serrasalmus rhombeus*, (C) in the stridulatory mechanism in catfish a ridged dorsal process (DP) of the pectoral spine (PS) rubs in a groove of the shoulder girdle (SG), (D) enhanced pectoral fin tendons (ETs) are plucked similar to guitar strings in the croaking gourami *Trichopsis vittata*, (E) Pharyngeal teeth (PT) stridulation in damselfish, sunfish, among others, and pectoral girdle vibration in sculpins by a sonic muscle (SM) originating at the skull and inserting at the dorsal part of the pectoral girdle. 2R: second rib, BT: broad tendon, DP: dorsal process of pectoral spine, ET: enhanced tendons, PG: pectoral girdle, PM: pectoral adductor muscle, PT: pharyngeal teeth, PS: pectoral spine, SL: swim bladder lobes, SM: sonic muscle, VC: vertebral column. All sonagrams show sounds produced in agonistic contexts. With permission from Ladich (2014).

vibrations of the swim bladder produce harmonic sounds, allowing it to be used as a resonator in sound production (Ladich, 2014). Sound production using the swim bladder includes a variety of mechanisms—hinting at convergent evolution—with the common feature being the perfect resonator of the swim bladder itself (Ladich and Fine, 2006). Some fish—toadfishes (Family: Batrachoididae) for example—have intrinsic muscles that trigger the vibration of the swim bladder to produce sound. Other taxonomic groups trigger the vibrations in the swim bladder by external muscles (Ladich, 2014). These muscles can be either directly attached to the swim bladder—for example in the family Terapontidae, a common family of freshwater grunters in Australia. The second mechanism, observed in Piranhas is an indirect connection via tendons or bony plates (Rountree and Juanes, 2020).

Not all sound production mechanisms involve the swim bladder. Catfish (multiple families in the order Siluriformes) rub a spine against the pectoral girdle—located under the pectoral fin—to produce a sound by stridulation (Ladich, 2014). The nature of this sound means that catfish can be heard above water as the production mechanism is not associated with the airfilled resonator that collapses above water. Other sound producing mechanisms around the pectoral fin are tendon vibration—often compared to plucking a guitar string, as well as vibration of the entire pectoral girdle in sculpins (Superfamily: Cottidae). Last, stridulation sounds can also be produced by grinding pharyngeal teeth, a second mechanism of piranha sound production, but also observed in damselfish (Family: Pomacentridae) and sunfish (Family: Molidae) (Fig. 2; Ladich, 2014).

Invertebrate bioacoustics

Aquatic invertebrates—especially insects—are one of the major components of the freshwater orchestra (Linke et al., 2018; Desjonquères et al., 2020). A wide diversity of insects and a few freshwater crustaceans are known to produce sounds underwater. This includes four orders of insects—Coleoptera, Heteroptera, Odonata and Trichoptera (Desjonquères et al., 2015). Sound production has been reported in one family of Asian Odonata larvae, one family of Trichoptera larvae, and two Coleoptera larvae species. Sound production in larvae is relatively anecdotal in contrast with sound production in Coleoptera and Heteroptera adults. Six families of Coleoptera and seven families of Heteroptera are known or suspected to produce sounds (Aiken, 1985).

Most insects and Crustaceans stridulate: they rub a tough ridge—the scraper—against a finely striated surface—the file. Most people are familiar with crickets producing sounds by rubbing their hind legs against their elytras; in the case of aquatic insects, a variety of body parts are involved. Most Corixidae produce sounds by rubbing a striated area of their front legs on the ridge of their head (Aiken, 1985). Other body parts involved in insect sound production include the abdomen, wings, various leg segments, and genitalia (in *Micronecta* sp. for example). Although stridulation is the most common mechanism of sound production in insects, some species produce sounds in other ways including muscle contraction (e.g., in a lesser diving beetle, *Acilius sulcatus*), or air expulsion (e.g., in the larvae of the great silver water beetle *Hydrophilus piceus* or the diving beetle *Cybister confusus*).

Aquatic invertebrates produce sounds for reasons similar to their terrestrial counterparts: sex, fear and food. Many insect signals are associated with reproduction. For example males produce signals to attract females and repel male competitors. Such is the case with water boatman males, *Palmacorixa nana*, which produce courtship signals to attract females. Females are attracted to the densest aggregations of calling males while males avoid those dense aggregations where they experience more antagonistic interactions. Some insect larvae and adults such as *Hygrobia* beetles produce antipredator squeaks when handled. *Hygrobia* beetles were even sold as 'squeakers' in London's Covent Garden Market (Aiken, 1985). Finally, some caddisflies in the family Hydropsychidae emit ultrasounds when fighting for their retreat and feeding territory (Vuoristo and Jansson, 1979).

Although invertebrates are one of the major components of the underwater orchestra, they remain a neglected focus of freshwater bioacoustic and ecoacoustic studies. A recent review of the literature highlights that they represent the focus of only a quarter of the freshwater acoustic studies while they are estimated to constitute almost 90% of the sound producers(Greenhalgh et al., 2020). This neglect is likely the source of our limited knowledge about the mechanisms and functions of sounds produced by invertebrates.

The sound of physico-chemical processes

Various physico-chemical processes produce sounds including flow turbulence, sediment transport and gas emissions (Linke et al., 2018). First, similar to wind in terrestrial environments, the water current in rivers and streams is an important source of sounds. Some may consider it as noise concealing animal sounds. Yet flow sounds can be rich and informative. These sounds result from flow turbulence and sediment transport and are thus indicative of geomorphological characteristics of the study locations (Tonolla et al., 2011; Lumsdon et al., 2018). Such sounds have enabled researchers to classify different river segments and habitat types, differentiate rivers with and without hydropeaking, and quantify water reaeration.

Another important component of freshwater soundscape comes from gas emitted by ecological processes such as organic matter decomposition, plant respiration and photosynthesis. Anaerobic decomposition of organic matter by micro-organisms may create methane pockets in the sediment that when released produce diverse bubbling sounds in standing water environments such as ponds and lakes (Linke et al., 2018). These decomposition sounds often co-occur with the sound of photosynthesis. Aquatic plants and algae release oxygen bubbles when photosynthesizing. These bubbles may produce ticking and whistling sounds when expelled in specific conditions (Freeman et al., 2018). Recent soundscape research shows that soundscape daily variation was related to oxygen daily variation, suggesting that such sounds may constitute important drivers of the soundscape (van der Lee et al., 2020).

Researchers are starting to uncover sounds related to physico-chemical processes. But this area requires extended research to better understand these sounds. Do different plant species produce different sounds? Do environmental conditions influence these sounds? Monitoring these sounds is likely to provide valuable insights towards the understanding of dynamics of ecological processes in freshwater environments.

Anthropogenic noises

In addition to being a tool for monitoring and assessment of natural components of ecosystem health, the soundscape can also assess the amount of anthropogenic noise present. As vocalizations have a communicative role for many soniferous animals, the incursion of human-induced noise can interfere with the normal functioning of an ecosystem. As with other aspects of freshwater ecoacoustics, knowledge regarding the impact of noise on freshwater ecosystems is sparse compared to terrestrial and marine environments, for which there is an abundance of evidence that noise has often deleterious effects.

In freshwater environments, anthropogenic noise comes from various sources including transport (boats but also cars on nearby roads and bridges), recreation (water parks), extraction (gravel pits) and construction activities. These noises can be present in a wide range of environments, including lakes, rivers and ponds. For example, in Irish lakes surveyed by Marta Bolgan and her colleagues, anthropogenic noise reaches sound pressure levels as high as 135 dB re 1 μPa (Bolgan et al., 2016).

Freshwater taxa suggested to be negatively impacted by noise include various species of fishes, invertebrates, and river dolphins (Celi et al., 2013; Popper and Hawkins, 2019). Mechanisms of disruption include interference with the communicative functions of animal calls; behavioral change in response to sound, for example provoking fear responses; physical damage to hearing mechanisms in the case of loud sounds such as pile driving, and possibly interference in echolocation function. Recent research has also investigated the effect of noise on feeding behavior of freshwater fish and has showed that immediate effects of noise include less efficient prey capture (Purser and Radford, 2011). Noise could thus impose disruptions on the whole trophic chain.

For suitable conservation policies to be developed, much more work needs to be done to assess and quantify the impact of noise on freshwater environments. Whilst there is widespread recognition of 'noise pollution' as a policy issue in marine environments (although virtually no binding regulations to address it), there has been little corresponding governmental attention in freshwater environments.

Ecoacoustics—Theory and analysis methods

Until recently, the study of animal sounds has focused on single species in controlled experimental settings. Lately, researchers are starting to adopt a more integrative approach to understand the importance of environmental factors in influencing acoustic behaviors (Short et al., 2020). For example, the presence of noise, other species, or rain may result in variation in acoustic behavior. Concurrently, recording the sound emanating from the environment has become technically easier with the advent of autonomous recorders. Ecoacoustics has resulted from these two paradigm shifts (Sugai et al., 2019).

The ecoacoustic understanding of acoustic communities is currently based on two main theories: the acoustic niche hypothesis and the acoustic adaptation hypothesis (Krause, 1993). According to the acoustic niche hypothesis, each species occupies a specific acoustic niche and this pattern is driven by the cost of overlapping with other species. Species sharing the same vocalizing environment, timing and frequency band, are thus expected to diverge in at least one of those dimensions (time, space or frequency; Krause, 1993). The acoustic adaptation hypothesis posits that animals vocalizing should optimize their signal such that it propagates well in their environment. Thus, animals vocalizing in the same habitat should acoustically converge towards optimal propagation. These two hypotheses are expected to result in two different patterns of signal co-existence (Morton, 1975). This question of constraints in acoustic community assemblage has generated much interest and tests for these hypotheses reveal conflicting evidence. Novel theoretical development suggests that the two predicted patterns (divergence or convergence) may result from a variety of other ecological and historical processes and should thus be interpreted with care just as any other ecological community pattern.

Ecoacoustics relies heavily on data collected by autonomous recorders over several days, months and sometimes even years. Data volumes are usually too large to be processed manually by listening. For example, the Australian Acoustic Observatory—an Australian-wide passive acoustic monitoring scheme—will collect recordings equivalent to a duration of 2000 years of recordings over 5 years (Roe et al., 2021). Ecoacousticians thus need to use automatic or semi-automatic analysis methods. There are two main approaches: acoustic indices and signal classification.

Acoustic indices are mathematical functions allowing quantification of certain characteristics of the spectrogram thought to be related to some aspect of bio- or acoustic diversity (Sueur et al., 2014). They are cost-effective tools to characterize the variation in animal sound production in recordings. There are more than 60 acoustic indices available. They have been applied successfully to detect acoustic and biological diversity; to distinguish soundscapes in different environmental conditions including different time (Linke et al., 2020a), different habitats (Fuller et al., 2015) and land management types; or to estimate population abundance (Borker et al., 2014). The efficiency of acoustic indices as indicators of biological diversity is under a lot of scrutiny. In aquatic environments, this scrutiny has different stakes. Most acoustic indices were developed with bird songs in mind and thus may not be the best tools to characterize acoustic diversity in freshwater environments composed mostly of rhythmic, non-tonal sounds from insects and fish. Yet, acoustic indices allow us to detect spatio-temporal differences in freshwater environments (Linke et al., 2020a).

Another approach to automatically process recordings is the use of automatic signal detection and classification. This approach usually relies on machine learning techniques to detect and classify acoustic signals. These methods can require a labelled training dataset in the case of supervised learning or be based on clustering methods that do not require labelled data (Ulloa et al., 2018). Such approaches are particularly efficient to detect specific signals emitted by single species. Machine learning techniques can also be used similarly to acoustic indices to classify different types of sound recordings and detect acoustic anomalies in a dataset (Sethi et al., 2020).

Recent developments in applied freshwater ecoacoustics

Automatic processing

Driven by a thriving research community and easier access to both computational resources and reference calls, recent years saw exponential growth in the development of automatic processing in ecoacoustic applications. Automatic call recognizers are a key technique for automatic processing. The term 'call recognizer' is an umbrella term for a number of auto-detection techniques, ranging from hand-coded custom algorithms to even 'point-and-click' windows in applications like Kaleidoscope (Wildlife Acoustics, 2019) or Raven (Cornell Bioacoustics Research Program, 2011). Many applied studies in ecoacoustics currently choose an intermediate path in which algorithms are implemented in a larger statistical or mathematical framework, such as Matlab, R or Python libraries (for example Katz et al., 2016).

An example of a hybrid approach is a recent study in which our lab developed call recognizers for eight frog species (within the genera *Litoria*, *Limnodynastes*, *Crinia and Neobatrachus*) to monitor environmental water allocations. We used an algorithm 'binary point matching' delivered via the R package monitoR (Katz et al., 2016). The algorithm develops a template by transforming a spectrogram into a binary representation. It then searches for a matching pattern in the dataset the operator wants to find the sound in. The core algorithm is coded in R and the user can optimize three parameters:

- The call template, which is the actual call that is used to develop the recognizer.
- The amplification—if the call is too quiet this can lead to a lack of detections, if it is too loud it can confuse the algorithm.
- The threshold, which triggers a detection.

For the frog study, we optimized these three parameters, which was the manual part building the recognizer. This is just one potential avenue; recent developments have also increasingly used AI and machine learning techniques that automatically classify all acoustic events.

In freshwater science, the first automatic recognizer was a simple pattern matching algorithm to analyze and monitor spawning noises in river redhorse in Georgia (Straight et al., 2014). Lately, underwater recordings from the endangered spadefoot toad (*Pelobates fuscus*) have been used to develop a call recognizer and give insight into the anuran species' ecology, especially in regard to the breeding season (Dutilleux and Curé, 2020). With improvements in technology, we predict that further call recognizers will follow soon, as clear call characterizations have recently been published for a range of fish taxa, for example piranhas and burbot (Grabowski et al., 2020; Rountree and Juanes, 2020).

Ecoacoustic analysis

Ecoacoustics usually researches the ecology of acoustic signals as organisms interact with each other, as well as their environment. Ecoacoustics has been developed by and for ecological practitioners. Summary indices are often used to simplify complex acoustic data, including the amplitude of the signal (M)—which is analogous to species abundance, or an acoustic complexity index (ACI), analogous to species richness, as well as an entropy index (H) which is analogous to Shannon's diversity index (Sueur et al., 2014). These acoustic indices have been used extensively in terrestrial applications, including studies monitoring ecological responses to environmental water allocations (Linke and Deretic, 2020).

Acoustic indices have been deemed good surrogates for acoustic events in underwater environments. Utility of different indices seems to be varying—depending on the signal and the system. The first study in freshwater systems (Desjonquères et al., 2015) found that the acoustic richness index (which is a combined index of acoustic entropy and overall sound pressure) best described 48 sounds in 3 ponds. In a similar study in British ponds, a whole suite of indices, including M, H and ACI were found significant in representing sound types (Greenhalgh et al., 2021). A study in waterholes from Australia (Linke et al., 2020a) found that ACI, filtered by frequencies can be related to a suite of signals, including a nocturnal insect chorus, diurnal variation in creek flow, as well as fish choruses that mainly occurred in the mornings. In flowing waters, Decker et al. (2020) combined these indices to describe acoustic variation in 12 Queensland rivers.

A new visual analysis method involves the use of false-color spectrograms, which are constructed from multiple acoustic indices (Fig. 3; Linke et al., 2020a). While summary indices could depict insect choruses, flow and fish calls, false-color spectrograms are also able to detect variation within these events. The nocturnal hemipteran choruses for example display complex interaction patterns between multiple species of hemiptera, but also rise and fall in diurnal creek flow (Fig. 3).

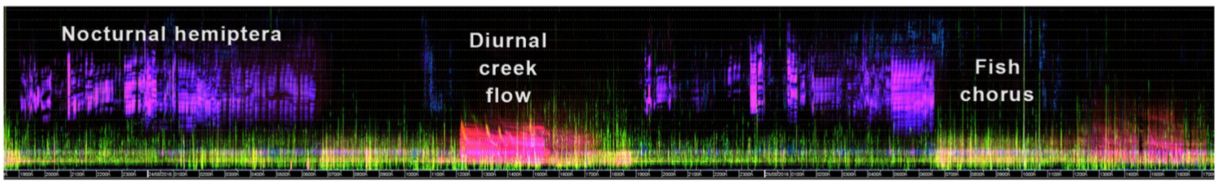

Fig. 3 False-color spectrogram of the diel variation in the Einasleigh River, Northern Australia described by Linke, Decker et al. (2020).

Linking sound to environmental condition

A limited number of studies have drawn links between frog and bird sounds and ecosystem condition in terrestrial and wetland settings (Linke and Deretic, 2020). However, a change in soundscapes does not automatically indicate the direction of change in an ecosystem. Soundscapes in degraded ecosystems for example, can become richer as ecological condition worsens, e.g., when pollution tolerant 'noisy' taxa start dominating the soundscape. Similarly, invasive species can increase soundscape complexity, while impeding ecological function. Previously, studies have investigated the response of bird and frog communities to disturbances (Fuller et al., 2015). This concept has even been extended to water-dependent terrestrial ecological communities in the United States and the Murray-Darling Basin. For example, in Australia, summary acoustic indices were utilized to track recovery of ecological communities in response to environmental water delivery as a restoration measure (Linke and Deretic, 2020). If we assume that an increased gradient of landscape complexity and good ecological condition will harbor higher species richness, it follows that the acoustic signal is enhanced by diverse complex communities.

The difference between aquatic and terrestrial applications of ecoacoustics is that only 20% of fish species and not all invertebrates are soniferous. Shifts in sonic activity will likely depend on the group of fishes. For example, an increase of the more pollution-tolerant Ariid catfish taxa will add to soundscape complexity, whereas displacement of more sensitive Terapontidae can reduce sonic activity. Therefore, an improvement in water quality is not directly related to an increase in sonic activity. Macroinvertebrates are important indicators of river health, but not all invertebrates produce sounds. While some sensitive taxa, e.g., caddisfly larvae, can be soniferous, the main classes of sound-producing organisms are aquatic hemiptera and beetles that have higher tolerances to warm water, low dissolved oxygen and mild organic pollution (Fig. 4). That said, dominance of very tolerant taxa e.g., chironomids and oligochaetes, will lead to a quieter soundscape. Thus, the most diverse soundscapes may be found at intermediate environmental conditions.

So far, few studies have linked acoustic measures to ecological condition in freshwater systems. A geomorphic link was established when comparing the sounds of pristine streams to streams that were impacted by sedimentation—mainly caused by grazing (Tonolla et al., 2011). Through the increased sediment input, gravel beds turned into sand beds and consecutively, the soundscapes were a lot quieter. Recently, a study from Holland related dissolved oxygen levels to underwater soundscapes. The change in soundscape was expressed not only by the proximate cause (i.e., roughness of the riverbed) but there was also a relation between sonic activity and dissolved oxygen (van der Lee et al., 2020). Listening to the invertebrate community, therefore demonstrated a first hint towards the validity of our theory of intermediate disturbance.

Knowledge gaps

Automated analysis of freshwater recordings is complicated by our general lack of knowledge regarding inland water soundscapes. Compared with terrestrial and marine environments, there has been relatively little history of freshwater acoustic analysis. In order to advance the field to the point of practical widespread application for conservation, a concerted global effort in recording, cataloguing, analyzing and sharing freshwater soundscapes is needed.

Over the last 5 years or so, automated analysis of data by computer algorithms has been revolutionized by a technique known as deep learning—a type of machine learning that leverages the increasing power of highly parallel computer graphics cards. Deep learning has been successfully applied to finding structure in complex data in a number of application domains, both supervised (with the help of human annotations) and unsupervised (without annotations). Deep learning has been recently applied in ecoacoustics for unsupervised learning in terrestrial and marine environments (Sethi et al., 2020), and supervised learning in freshwater environments (Guyot et al., 2021). The possibility of further using unsupervised automated analysis techniques in freshwater ecoacoustics is tantalizing, as it would facilitate a step-change in the volume of data analysis feasible.

Ecoacoustic monitoring generates high volumes of data. The logistical benefits of passive acoustic monitoring—namely the relative ease of long-term remote multi-site observation—tends to result in datasets much larger than typically encountered in ecology, sometimes of the order of PetaBytes. The storage and processing of such large datasets is a key challenge in ecoacoustic work

Fig. 4 Pollution tolerant taxa are responsible for key changes in aquatic soundscapes.

in any environment. Typically, studies will employ temporal sampling regimes (for example recording 1 min of every 10 min) and impose audio quality constraints by recording at low sample rates (for example 16,000 samples per second) to reduce data capture volumes. There is a trade-off, however, as such sampling regimes may miss rare but important events, the serial correlation patterns in acoustic indices are not generally known which confounds statistical inference, and high frequency sounds may be missed (Linke et al., 2020b).

The importance of spatial replication is increasingly being recognized in ecoacoustics generally. However, freshwater environments place greater demands in this regard, particularly in comparison to marine ecoacoustics. A foundational tenet of marine ecoacoustics is that sound travels far underwater, however this is not generally true in freshwater, particularly in shallow environments. On the contrary, sound there can be attenuated much more sharply than in terrestrial environments (Karaconstantis et al., 2020). Consequently, freshwater ecoacoustics can demand higher spatial replication and concomitant data storage and recording equipment requirements.

Because of the difficulties associated with data storage (Barclay et al., 2018), processing audio data in situ (i.e., at the recording site) is an attractive alternative where feasible. Running machine learning algorithms in real-time is sometimes possible, obviating the need to store all of the recorded audio. Instead, storing much smaller volumes of meta-data for species detection events and counts (for example) may be sufficient. Alternatively, processing may act as a filter to store audio only for periods of time deemed interesting. Algorithms for creating detection events and/or marking periods of time as interesting may include specialized species recognizers or more general anomaly detection approaches. Despite the steady increase in computational power of low-cost edge devices, processing on site remains challenging, as the machine learning algorithms typically employed push the capacity of these devices and add to the difficulty of providing power to long-term remote recording setups.

The sparsity of catalogued reference calls is a key obstacle to the practical application of freshwater ecoacoustic studies. In contrast to the rich catalogues of bird calls, freshwater acoustics has seen little representation in the leading international sound archives. The Cornell Lab of Ornithology's Macaulay Library does have some fish sounds (982, which represents 0.25% of the library, Linke et al., 2020b), however these are mainly from marine environments. This lack of reference material is challenging for researchers entering the field, as the emitter of an underwater sound is not obvious. In order for the field of freshwater ecoacoustics to advance, the international community should submit their documented and validated calls to the Macaulay Library, the Berlin Animal Sound Archive, the Paris sonothèque or other central bioacoustics repositories.

Ecoacoustics as a communications and engagement tool

The integrated nature of ecoacoustics calls for greater collaboration with other disciplines, including electronics, remote sensing, data science, humanities, and social sciences (Sueur and Farina, 2015). Collaborations between scientists and artists have become increasingly popular as environmental research calls for more effective methods to engage communities in the scientific process and its outcomes. Many of these collaborations can be categorized broadly as science communication, where artists are engaged to translate resulting data for accessible public dissemination. However, there is evident value in interdisciplinary research that brings together creative and scientific knowledge and perspectives to inform field work methods, analysis and outcomes. Freshwater ecoacoustics has benefited from various art science collaborations that have contributed to advancing the discipline and engaging communities in the process.

The rapid advancements of accessible and affordable digital technologies have resulted in numerous pathways for communities to directly engage with the emerging field of freshwater ecoacoustics. Creative projects, mobile applications and interactive experiences that engage communities in river soundscapes have the capacity to encourage environmental stewardship and inspire freshwater conservation (Gilmurray, 2017). Hydrophones capturing rich and immersive underwater soundscapes have been used in the context of creative work since the 1970s, with composers including Maggi Payne, Jana Winderen, Douglas Quin, Chris Watson, David Monacchi and Ros Bandt, all renowned for their creative projects that draw listeners beneath the surface of rivers, lakes and oceans. The resulting creative experiences have been a catalyst for communities to engage with freshwater ecoacoustics and facilitate local citizen science initiatives.

These interdisciplinary efforts have also strengthened engagement from those in the arts and humanities to promote the emerging discipline of freshwater ecoacoustics. Composer Rob Mackay has developed many creative projects and community engagement initiatives around hydrophones with recent examples including 'Red River: Listening to a Polluted River' (https://redriverpoetry.com/). This 18-month research project was funded by the United Kingdom Arts and Humanities Research Council and led by Dr. John Wedgwood Clarke. This project has included soundscapes, poetry, community events, workshops and showcases at conferences including COP26 in Glasgow. Another example is 'The Secret Sound of Ponds' presented at the Science Gallery Detroit, which is a collaboration between Benjamin Gottesman, David Rothenberg and Camille Desjonquères (https://detroit.sciencegallery.com/depth-exhibits/the-secret-sound-of-ponds). This project features an immersive sonic sculpture installation that was accompanied by a hydrophone building and recording workshop, freshwater soundscape data collection in the Detroit River and a live performance designed to connect people to the hidden life of freshwater environments through sound. The subsequent increased engagement in freshwater ecoacoustics has prompted students engaging in interdisciplinary pathways including science students creating podcasts with aquatic soundscapes and emerging sound artists such as David de la Haye who are using sound to raise awareness and cultural value of freshwater habitats.

Listening to rivers with hydrophones can help local communities understand freshwater biodiversity in accessible and engaging ways (Barclay et al., 2018). For example, the project 'River Listening' has developed new approaches for citizen science engagement with freshwater ecoacoustics that have inspired various communities to engage with hydrophone recording (Barclay et al., 2018). The project developed noninvasive recording techniques with accessible hydrophone kits and participatory workshops to engage local communities in the process and outcomes. Preliminary work in community engagement with freshwater ecoacoustics explored the possibilities of hydrophone recording through interactive workshops, recording expeditions, and art installations designed to draw attention to the sounds beneath the surface of rivers. The workshops explored methods for using acoustics to understand aquatic biodiversity and involved extensive experimentation with recording techniques, new technologies, and community collaborations to compare aquatic soundscapes and the most effective methods for recording in freshwater ecosystems. The resulting database of hydrophone recordings have informed the scientific research and a diversity of community events and creative projects disseminated the outcomes worldwide.

Various endeavors have been established within River Listening to encourage ongoing community engagement outside of scheduled workshops. These efforts include a customized digital platform, virtual sound maps with live streaming hydrophones, and a mobile application that allows communities to record, upload, and compare sounds in a global database (Barclay et al., 2020). These digital outcomes underpin the major creative projects and facilitate the collection of recordings for scientific monitoring. The central tools for public engagement around River Listening have been creative outcomes, including site-specific performances and installations that have toured internationally. The most effective tool for public engagement has been the River Listening Sound Walks, which require audiences to visit their river to experience the work. The sound walks involve a custom built mobile application that transforms the listener's phone into a sonic compass to guide them along the riverbank and explore the cultural and biological diversity of the river through sound (Barclay et al., 2018). The installation triggers geo-located soundscapes that are accompanied by images and text identifying the sounds that are drawn from a local database of hydrophone recordings.

Perhaps most importantly, the community engagement processes surrounding River Listening have acted as a catalyst to amplify First Nations voices and facilitate opportunities for Indigenous knowledge holders to take a leadership role in the projects. The River Listening project has had the great privilege of learning from Indigenous leaders such as Lyndon Davis, Brendan Kennedy and Anne Poelina in Australia (https://www.riverlistening.com/). In 2017, the Whanganui River in Aotearoa (New Zealand) was the first river in the world to be granted personhood and recognized as a living being. Anne Poelina has been leading the conservation and protection of the Mardoowarra (Fitzroy River) in Western Australia and has advocated for the river to be recognized as a living ancestral being. Poelina argues that healthy rivers are culturally located and there are Indigenous ways of knowing, being and doing based on nonlinear time, a located temporality, which connects people, rivers and place (Martuwarra et al., 2021). She believes that healing river ecosystems is a cultural endeavor and that listening, hearing and voicing rivers is a first, Indigenous step. Poelina, along with many First Nations leaders in Australia and beyond, believe that water management requires Indigenous-led restorative research and practices to ensure Indigenous values are recognized (Martuwarra et al., 2021).

Listening to rivers provides unique methods for bridging traditional knowledge systems, emerging science and creative practice when working directly with communities in freshwater management. The methods of engaging with freshwater ecoacoustics in the field can embrace Indigenous leadership and traditional knowledge, and the ongoing monitoring of acoustic sensors can be managed by local communities. The interdisciplinary pathways that continue to emerge in the field of freshwater ecoacoustics indicate that interdisciplinary collaborations are vital in engaging communities in listening to rivers and inspiring freshwater conservation.

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