COLUMN
PERSPECTIVE

How Can We Understand Freshwater Soundscapes Without Fish Sound Descriptions?

Rodney A. Rountree | The Fish Listener, East Falmouth, MA 02536. Email: rrountree@fishecology.org

Marta Bolgan | Laboratoire de Morphologie Fonctionnelle et Evolutive, Institut de Chimie Bât. B6C, Université de Liège, Liège, Belgium

Francis Juanes | Biology Department, University of Victoria, Victoria, BC

Photo credit:
Rodney A. Rountree

DOI: 10.1002/fsh.10190

The ecological importance of the freshwater soundscape is just beginning to be recognized by society. Scientists are beginning to apply Passive Acoustic Monitoring (PAM) methods that are well established in marine systems to freshwater systems to map spatial and temporal patterns of behaviors associated with fish sounds as well as noise impacts on them. Unfortunately, these efforts are greatly hampered by a critical lack of data on the sources of sounds that make up the soundscape of freshwater habitats. A review of the literature finds that only 87 freshwater species have been reported to produce sounds in North America and Europe over the last 200 years, accounting for 5% of the known freshwater fish diversity. The problem is exacerbated by the general failure of researchers to report the detailed statistical descriptions of fish sound characteristics that are necessary to develop PAM programs. We suggest that publishers and editors should do more to encourage reporting of statistical properties of fish sounds. In addition, we call for research, academic, and government agencies to develop regional libraries of fish sounds to aid in PAM and anthropogenic noise impact studies.

Aquatic animals can be more challenging to study than their terrestrial counterparts for various reasons, such as accessibility, lack of visibility, and cost. Many fish produce distinctive voluntary and incidental sounds during specific activities, such as feeding, predator avoidance, territory defense, agonistic interactions, courtship, and spawning (Ladich and Fine 2006). Examples of known and unknown fish sounds recorded in North America are provided in Supplementary file S1 available in the online version of this article. Scientists have learned to take advantage of this phenomenon to remotely locate and monitor fish activity by listening for the sounds fish make in order to produce spatial and temporal maps of the species and behavior (Rountree et al. 2006; Luczkovich et al. 2008). Surveys using this technique are referred to as Passive Acoustic Monitoring (PAM), which involves using one or more hydrophones to passively record underwater sounds, and should not be confused with hydroacoustics, acoustic telemetry, or other forms of active bioacoustics (Rountree et al. 2006). Today PAM has become a relatively popular tool used in a broad range of applications in behavior, fisheries, conservation, invasive species, and anthropogentic noise impacts studies (see reviews in Fish and Mowbray 1970; Rountree et al. 2006; Cotter 2008; Gannon 2008; Luczkovich et al. 2008; Mann et al. 2008; Farina 2014). However, it has received less attention in freshwater habitats (Anderson et al. 2008; Rountree and Juanes 2016; Linke et al. 2018; Rountree et al. in press). Despite the limited attention, freshwater habitats have been shown to have a high diversity of unidentified biological sounds; in fact, most sounds recorded in freshwater are of unknown origin (e.g., Anderson et al. 2008; Rountree et al., in press).

The goal of this perspective paper is to inspire other scientists, funding agencies, and reviewers of funding proposals and papers to place more importance on descriptive studies of fish sounds in temperate freshwater habitats and for the scientific community to build catalogs of such fish sounds that can be used for PAM and other purposes. The need is especially important in temperate freshwater systems where few fish sounds have been described even for economically important species. We have been calling for this type of work for decades in both the literature (e.g. Rountree et al. 2002, 2006; Anderson et al. 2008) and professional conferences, but little progress has been made to date because the freshwater fisheries management community has not recognized its importance. Even those working with fish sounds may not fully appreciate how little data there are and how poorly sounds are being described in the literature from a PAM perspective. You cannot use PAM effectively if you do not know the sounds, let alone develop a deep understanding of freshwater soundscapes and anthropogenic impacts on them.

PAM REQUIRES KNOWLEDGE OF SOUNDS

Important advantages of PAM are that it is noninvasive (as opposed to active acoustic and traditional fishery sampling methods), is relatively low cost, and can be conducted remotely and long-term. However, in order to identify a fish species in the wild using PAM, prior knowledge and validation data are required. PAM is dependent on the evidence that sounds recorded in the wild, whether incidental or voluntary, actually belong to a specific species. Evidence for the identity of the species that produces a particular sound is often obtained by comparing the remotely recorded PAM sounds with known sounds recorded either in captivity, or, preferably whenever possible, in the field with *in situ* methodologies (Rountree et al. 2006; Rountree 2008; Mouy et al. 2018). Alternatively, when no other data are available, comparisons of sounds suspected to be a particular species with known sounds from related species can be helpful, though caution is advised since sounds may or may not follow a phylogenetic pattern (e.g., Malavasi et al. 2008; Mélotte et al. 2016). However, when conducting PAM studies in a given location, it is important for researchers to attempt to document unknown sound sources by direct *in situ* or laboratory-based observation or by field auditioning of individuals captured in parallel sampling. Rountree provides an introduction to field auditioning for those unfamiliar with the methodology (available: https://www.researchgate.net/publication/319356495).

The description of a specific fish sound is not always enough for accurate PAM applications in locations or habitats where other organisms might make similar sounds. Therefore, caution is advised when attributing sounds to a species when recording in multispecies locations where sounds of other species are unknown. The problem is particularly acute when investigators attribute a new sound to a species because it occurs in association with the known sound. A classic example of that is the mistaken attribution of an unknown sound to the Northern Searobin *Prionotus carolinus*, because they occurred during playback experiments (Moulton 1956). The same sounds were later mistakenly attributed to the Weakfish *Cynoscion regalis*, due to frequent co-occurrence with known Weakfish sounds with similar frequency range and pulse structure (Fish and Mowbray 1970). However, these sounds were in fact produced by the Striped Cusk-eel *Ophidion marginatum*, for which sounds were first recorded in the laboratory decades later (Mann et al. 1997; Rountree and Bowers-Altman 2002).

Today, one of the most important limitations of PAM is the lack of standardized, open access libraries of fish sounds, and consequent result that most fish sounds recorded in the wild remain unknown (Rountree et al. 2002). The challenge is seen to be even greater when you consider that other freshwater organisms such as turtles (e.g., Giles et al. 2009), amphibians (e.g., Given 2005), aquatic insects (see review in Sueur et al. 2011), crustaceans (e.g., Sandeman and Wilkens 1982), and some mammals (e.g., O'Shea and Poché 2006) also produce underwater sounds and are also poorly documented.

LACK OF FOCUS ON IDENTIFICATION OF FRESHWATER FISH SOUNDS

Perhaps the first documentation of sound production in freshwater fish occurred in 1830 (Thompson 1830) at a time when many scientists assumed fish were both deaf and mute (Galton 1874; Parker 1918). It was more than 3 decades before the subject was specifically addressed in detail in Europe (Moreau 1864, 1876; Dufossé 1874). Fish sounds were first seriously studied in North America by Abbott (1877) who pointed out the importance of sound production in the ecology of freshwater fishes. By the time Bridge (1904) reviewed the phenomenon in 1904, sound production was known in 20 species of North American and European fishes (Supplementary file S2 available in the online version of this article; Figure 1). Since then the number has risen to just 87 species of freshwater and diadromous fishes in 12 orders and 20 families from North America, Europe, and Russia (Supplementary file S2; Table 1), accounting for only about 5% of the 1,213 and 546 known species for North America and Europe (and Russia), respectively (Nelson et al. 2004; Burkhead 2012). At the present rate of examination of freshwater fishes for sound production, it will take hundreds of years to survey all the known species in Europe and North America (Figure 1).

The most frequently studied groups were the Cypriniformes with 28 species in four families, Perciformes with 18 species in five families, Salmoniformes (11 species), and Acipenseriformes with 11 species (Table 1). Two examples highlight how sparse our knowledge is of sound production by temperate freshwater fishes. (1) Only 4 of the 51 species of ictalurid catfishes known in North America have been studied, despite the fact that most are likely soniferous. (2) Only 8 of the 33 known centrarchid species have been examined (Supplementary file S2), excluding even Largemouth Bass *Micropterus salmoides* and Smallmouth Bass *M. dolomieu*, despite their great economic importance. In addition, 13 of the 64 species in North America that have been reported to produce sounds have at least one population considered at risk, but only half of them have been well described (Table 2; Supplementary file S2).

HOW CAN WE UNDERSTAND ANTHROPOGENIC NOISE IMPACTS IF WE DON'T KNOW WHAT ORGANISMS PRODUCE SOUNDS?

Recently, there has been a surge in interest in documenting noise impacts on freshwater ecosystems (Holt and Johnston 2015; Bolgan et al. 2017; Linke et al. 2018), but these are

Table 1. Number of species reported to produce sounds by taxonomic order and family. The percent of the species within each taxonomic group with descriptions of behavior and with at least one statistic of the sound characteristics are also shown. Orders represented by more than one family include totals for the order. Study type: Anecdotal = sound production briefly mentioned, Descriptive = sound production behavior described, Quantitative = detailed description of behavior with at least some quantitative description of sound characteristics. Sound statistics: None = none reported, Low = very limited or graphical description of sound characteristics, High = detailed description of sound characteristics.

Order	Family	Number of species	Percent of all species	Anecdotal	Descriptive	Quantitative	None	Low	High
Acipenseriformes	Acipenseridae	11	13	56	9	27	27	55	18
Petromyzontiformes	Petromyzontidae	1	1	0	100	0	100	0	0
Anguilliformes	Anguillidae	2	2	0	50	50	0	100	0
Clupeiformes	Clupeidae	3	3	0	67	33	33	33	33
Cypriniformes		28	32	35	18	39	54	11	36
	Catostomidae	2	2	0	50	50	50	0	50
	Cobitidae	2	2	88	0	0	100	0	0
	Cyprinidae	23	26	34	13	43	48	13	39
	Nemacheilidae	1	1	0	100	0	100	0	0
Siluriformes		5	6	0	60	40	40	20	40
	Ictaluridae	4	5	0	50	50	25	25	50
	Siluridae	1	1	0	100	0	100	0	0
Salmoniformes	Salmonidae	12	14	0	33	67	33	25	42
Esociformes	Umbridae	1	1	88	0	0	100	0	0
Percopsiformes	Aphredoderidae	1	1	88	0	0	100	0	0
Cyprinodontiformes	Cyprinodontidae	1	1	0	0	100	0	0	100
Scorpaeniformes	Cottidae	5	6	0	0	100	0	40	60
Perciformes		18	20	0	33	67	11	56	33
	Centrarchidae	10	11	0	40	60	20	70	10
	Gobiidae	4	5	0	25	75	0	50	50
	Moronidae	1	1	0	100	0	0	100	0
	Percidae	2	2	0	0	100	0	0	100
	Sciaenidae	1	1	0	0	100	0	0	100
All species				23	27	50	34	32	34

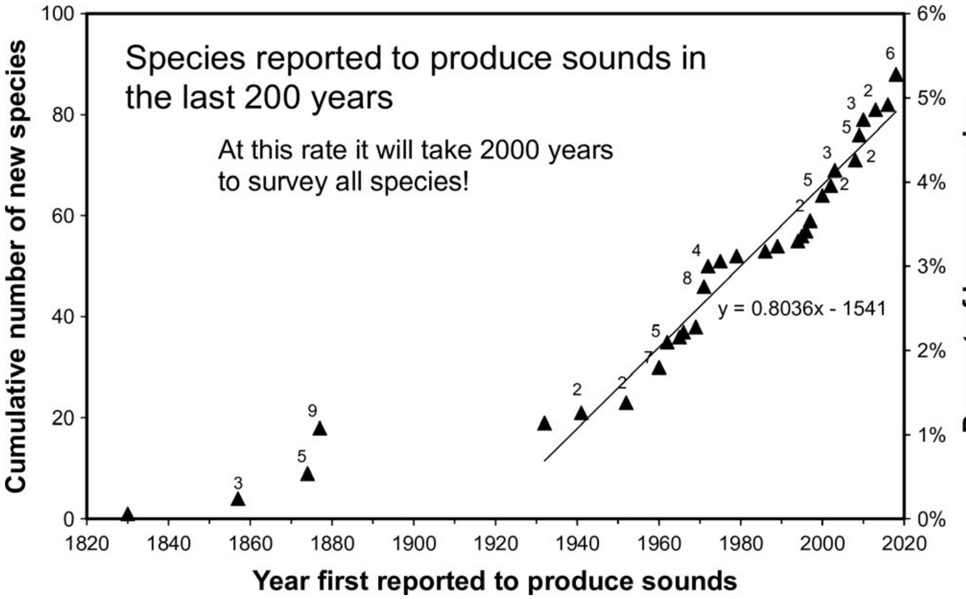

Figure 1. Plot of the cumulative number of new species reported to produce sounds each year over the last 200 years. Years with only a single new species are not labeled, otherwise the number of new species for the year is labeled next to the symbol.

hampered by a lack of information on the sounds produced by freshwater organisms (Rountree et al., in press), as well as the limited data on fish hearing (e.g. Ladich 1999; Mann et al. 2007). Despite the limited study of noise in freshwater habitats, the information that is available suggests a troubling pattern of high exposure to anthropogenic noise from many sources (Wysocki et al. 2007; Amoser and Ladich 2010; Tonolla et al. 2010; Rountree et al., in press). Chronic noise exposure from boating activities and automobile traffic are most widespread. Although such noise impacts are not as acute as those produced by pile-driving or seismic surveys, they are likely to mask the often low-amplitude sounds made by freshwater organisms. Just as importantly, they may significantly alter the soundscape with potential negative impacts on both soniferous and non-soniferous organisms that depend on hearing for orientation, prey detection, and predator avoidance (e.g., Cotter 2008; Fay 2009). Our recent survey of freshwater habitats in a large geographic area of North America finds that the soundscape of ponds, lakes, rivers, and streams are dominated by anthropogenic noise, but contain a high diversity of fish and other biological sounds (Rountree et al. in review). Until more data become available on the biological components of freshwater soundscapes, we recommend that a precautionary approach be adopted by scientists, conservationists, resource managers, and legislators in development of regulations governing anthropogenic noise impacts on freshwater ecosystems.

CRITICAL LACK OF SOUND DESCRIPTIONS

Of special concern is the lack of studies that report detailed statistical data on sound characteristics that are necessary for PAM studies of freshwater soundscapes; few characteristics are measured and sample sizes are limited (Table 1). Of the 87 species reported to produce sounds to date (an additional species was reported to lack sound production), 23% were anecdotal accounts, and 34% failed to report any statistical description of sound characteristics.

Table 2. Freshwater species known to produce sounds and for which at least one population in North America is at risk.

Common name	Species	North American status	Stats	References
Gulf Sturgeon	*Acipenser oxyrinchus desotoi*	Threatened	None	Sulak et al. (2002)
Atlantic Sturgeon	*A. oxyrinchus oxyrinchus*	Endangered	None	Rountree (Pers. Obs.)
Pallid Sturgeon	*Scaphirhynchus albus*	Endangered	Best	Johnston and Phillips (2003)
Shovelnose Sturgeon	*S. platorynchus*	Threatened	Best	Johnston and Phillips (2003)
Alewife	*Alosa pseudoharengus*	Species of concern	Best	Rountree et al. (2018)
Ornate Shiner	*Codoma ornata*	Threatened	Best	Johnston and Vives (2003)
Cutthroat Trout	*Oncorhynchus clarkii*	Some populations threatened or endangered	Graphical	Stober (1969)
Chum Salmon	*O. keta*	Threatened	Limited	Kuznetsov (2009)
Coho Salmon	*O. kisutch*	Some populations threatened or endangered	None	Neproshin (1972)
Sockeye Salmon	*O. nerka*	Endangered	None	Neproshin (1972)
Atlantic Salmon	*Salmo salar*	Endangered	Best	Rountree et al. (2018)
Cuatro Ciénegas Pupfish	*Cyprinodon bifasciatus*	Threatened	Best	Johnson (2000)
Pygmy Sculpin	*Cottus paulus*	Threatened	Good	Kierl and Johnston (2010)

In fact, detailed statistics were reported in only 30 species (Table 1, Supplementary file S2). We do not point out these trends as criticism of past studies, many of which were high quality reports on behavior, physiology, or morphology that simply did not focus on the sounds themselves. Other studies were conducted before the technology to quantitatively describe the acoustic characteristics of underwater sounds became available. However, the consequence is that insufficient data are currently available for effective PAM studies in most freshwater habitats in North America and Europe. Few species have been described in sufficient detail for soundscape studies in habitats where multiple species are present even for the most frequently studied taxa (e.g., 11% in Acipenseriformes to 42% in Salmoniformes).

In total, we found 157 records where at least one parameter was measured and reported for a specific sound in 58 species (External data set 1). Sound duration was the most frequently reported parameter in 43 species (Table 3). Peak (or alternatively fundamental) frequency was reported for 41 species, but only 31 of these included a measure of variance such as standard deviation (SD) or standard error of the mean (SE). Often studies report vague statistics such as "most energy below 800 Hz" or a frequency maximum, without any indication of sample size or variance. We found only 99 records from studies reporting both sound duration and peak/fundamental frequency for at least one sound (many species produce different sounds under different contexts). However, even with these limited data we can see some utility for discrimination of taxonomic groups based on sound characteristics (Figure 2). A plot of sound duration by frequency for sounds labeled by taxonomic order indicates some clustering. Note that each symbol represents one measurement for at least one sound type for one species in at least one study, based on data from 9 orders, 13 families, and 34 species in 25 studies since 1960.

A serious problem faced by all scientists interested in sound production by fishes is the lack of standardized nomenclature for sounds and reliance on the use of onomatopoeic names. One solution is to base sound classification on patterns in acoustic parameters. The clustering of sounds in Figure 2, hints at the potential to use multivariate techniques to identify broad sound types from which a standardized naming system could be developed, but unfortunately, that requires large data sets from many species that are not yet available for freshwater habitats.

Table 3. Percent of all species where at least one study reports the indicated acoustic measurement for at least one sound type. (SE = standard error of the mean).

Sound parameter	Number of species	Percent of species with sound statistics	Percent of all soniferous species
Duration	43	75	49
Duration SE	38	67	43
Frequency limits	40	70	45
Peak frequency	41	72	47
Peak SE	31	54	35
Pulse rate	11	19	13
Pulse rate SE	10	18	11

Failure of scientists to report more detailed descriptions of sound characteristics likely results in part from pressure from reviewers and publishers to limit tabular data. In our own studies, we have experienced pressure from reviewers and publishers to limit statistical descriptions of fish sounds to only the most rudimentary parameters and have been strongly discouraged from reporting detailed tabular statistics. This is unfortunate because basic parameters such as peak frequency and duration are simply not enough to distinguish sounds in field studies where a high diversity of sounds is the norm rather than the exception. Graphical representations of sounds are informative, but do not provide information on variation in structure, and are often based only on the best available examples from laboratory studies, not what is typically observed in field studies. A generally myopic focus on biologically relevant sound characteristics such as fundamental frequency and consequent lack of recognition that other characteristics may be helpful markers of species identity despite their lack of biological relevance also contributes to the problem. Further, most studies are focused on the behavior of individual species and do not consider the potential for their data to be incorporated in PAM studies.

The limited descriptions of acoustic characteristics of sounds found in the literature on temperate freshwater fishes highlights the need for a consensus on what parameters should be reported to be at least minimally useful for PAM. For example, vague reports of frequency ranges should be discouraged, in favor of statistics of the fundamental or peak frequency. We recommend that the frequency structure be described in more detail including measures of frequency quartiles and percentiles and bandwidth quartiles and percentiles, together with estimates of their variances (e.g., standard error of the mean). Although such measures are estimations of the power spectra of the sounds, tabular data, or supplemental data sets, are preferable over graphical presentations in publications as they can

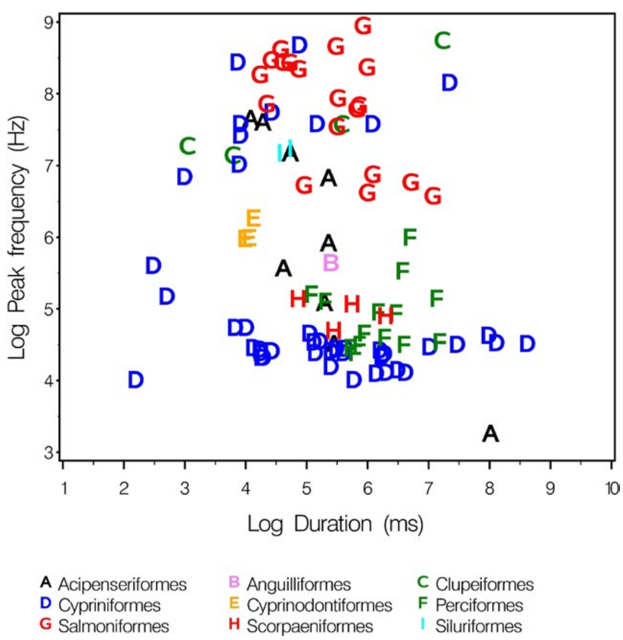

Figure 2. Plot of the sound duration against sound peak frequency for the 99 sounds where both measures were reported. Each letter represents a value reported for one sound type from one species in one study (raw data provided in Supplementary file S2). Number of species = 34, Number of studies = 25.

be more accurately utilized in PAM applications. Otherwise researchers are forced to make "eye-ball" estimates of acoustic parameters for comparison with other sounds in PAM applications. Similarly, detailed information on sound duration characteristics, based on energy content and/or frequency changes, can also be useful. Such measurements are relatively easy to produce in many acoustic programs. More laborious measures of importance include data on pulse rate and pulse structure, which are also more sensitive to data quality and often results in lower sample sizes. Data on variation in these parameters within individual specimens is rarely reported but can be useful in identification of closely related species (Rountree and Juanes 2018). Finally, many studies focus on descriptions of individual sound units (e.g., a knock or grunt) and fail to report if, and how, they are combined into sound trains. For example, the Alewife *Alosa pseudoharengus* produces trains of 1–16 (mean ± Standard error = 5.9 ± 0.6) "coughs" at an average rate of 2.47 (±0.4) sounds/s (Rountree et al. 2018). Data on the temporal structure of sound trains can be useful species markers when the individual sounds are similar among species.

CALL FOR DEVELOPMENT OF REGIONAL SOUND LIBRARIES

In order to further develop PAM applications for use in freshwater habitats we need to establish regional libraries of fish sounds available to everyone (Rountree et al. 2002). Currently scientists interested in conducting research on the soundscape of almost any freshwater or marine habitat are forced to develop their own libraries or at best rely on contacting a network of scientists in hopes of finding someone that has some familiarity with the sounds being recorded. Investigators seeking to develop sound libraries can focus on auditioning fishes from specific habitats or geographic areas or, alternatively, they might focus on specific taxonomic groups of widespread importance (e.g., Ictaluridae). Libraries should include more than just representative samples; whenever possible they should include sufficiently numerous samples to provide data for the development of automated sound detection and classification methodologies applicable to variable recording conditions (different locations, habitats, and suites of species contributing to the soundscape). And of course, libraries should include as much metadata as possible with each recording (date, time, location, water conditions, habitat, recording methods and equipment, photographic and video materials, and data on the sound source such as size, gender, behavior, etc.). We also advocate the inclusion of voucher specimens in institution and museum fish collections to anchor specific sounds to specific species, populations, genders, and maturation stages, particularly in taxa that are undergoing frequent revisions.

Unfortunately, no such library currently exists for freshwater fish sounds, let alone other freshwater organisms. Sound libraries are extremely limited even in the more well-established research on soniferous fishes in marine ecosystems. No systematic effort to establish a library has been conducted since the pioneering work of Marie Fish and William Mowbray on marine fishes more than 5 decades ago (Fish and Mowbray 1970). Even that library was lost until it was rescued from obscurity more than a decade ago (Rountree et al. 2002) and made available through fishbase.com (Froese and Pauly 2018) and The Macaulay Library at the Cornell Lab of Ornithology (https://www.macaulaylibrary.org). The critical need for sound libraries of fishes has been recognized for decades (Rountree et al. 2002, 2006; Luczkovich et al. 2008), but has not advanced since the work of Fish and Mowbray (1970).

CONCLUSIONS

In summary, little is known of biological components of freshwater soundscapes in temperate regions of the world, despite their high diversity and widespread occurrence. Systematic efforts to identify and catalog fish and invertebrate sounds are critically needed to advance PAM for conservation, ecosystem management, and fisheries applications. In addition, authors, reviewers, and publishers are encouraged to publish detailed statistical descriptions of sounds that are necessary for PAM applications, rather than solely providing an example spectrogram and vague description of acoustic characteristics. Finally, quantification of anthropogenic noise impacts on freshwater ecosystems is exceedingly difficult when virtually nothing is known about what organisms produce sound, their behavior, or acoustic interactions, let alone how non-soniferous organisms depend on sound for orientation, predator avoidance, and foraging.

ACKNOWLEDGMENTS

There is no conflict of interest declared in this article.

REFERENCES

Abbott, C. C. 1877. Traces of a voice in fishes. The American Naturalist 11:147–156.

Amoser, S., and F. Ladich. 2010. Year-round variability of ambient noise in temperate-freshwater habitats and its implications for fishes. Aquatic Sciences 72:371–378.

Anderson, K. A., R. A. Rountree, and F. Juanes. 2008. Soniferous fishes in the Hudson River. Transactions of the American Fisheries Society 137:616–626.

Bolgan, M., J. O'Brien, E. Chorazyczewska, I. J. Winfield, P. McCullough, and M. Gammell. 2017. The soundscape of Arctic Charr spawning grounds in lotic and lentic environments: can passive acoustic monitoring be used to detect spawning activities? Bioacoustics 27:57–85.

Bridge, T. W. 1904. Fishes. Pages 141–650 *in* S. F. Harmer, and A. E. Shipley, editors. The Cambridge Natural History. Macmillan and Co., Limited, London.

Burkhead, N. M. 2012. Extinction rates in North American freshwater fishes, 1900–2010. BioScience 62:798–808.

Cotter, A. J. R. 2008. The 'soundscape' of the sea, underwater navigation, and why we should be listening more. Advances in Fisheries Science 50:451–471.

Dufossé, L. 1874. Reserches sur les bruits et les sons expressifs que font entendre les poisons d'Europe et sure les organs producteurs de ces phenomenes acoustiques ainsi que sur les appareils de l'audition de plusieurs des ces animaux. Annales des Sciences Naturelles. Zoologie et Biologie Animale 19:1–53.

Farina, A. 2014. Soundscape ecology: principles, patterns, methods and applications. Springer Science & Business Media, New York.

Fay, R. 2009. Soundscapes and the sense of hearing of fishes. Integrative Zoology 4:26–32.

Fish, M. P., and W. H. Mowbray. 1970. Sounds of Western North Atlantic Fishes. John Hopkins Press, Baltimore, Maryland.

Froese, R., and D. Pauly, editors. 2018. FishBase. World Wide Web electronic publication. Available: www.fishbase.org (April 2018).

Galton, J. C. 1874. The song of fishes. The Popular Science Review 13:336–349.

Gannon, D. P. 2008. Passive acoustic techniques in fisheries science: a review and prospectus. Transactions of the American Fisheries Society 137:638–656.

Giles, J. C., J. A. Davis, R. D. McCauley, and G. Kuchling. 2009. Voice of the turtle: The underwater acoustic repertoire of the long-necked freshwater turtle, *Chelodina oblonga*. Journal of the Acoustical Society of America 126:434–443.

Given, M. F. 2005. Vocalizations and reproductive behavior of male pickerel frogs, *Rana palustris*. Journal of Herpetology 39:223–233.

Holt, D. E., and C. E. Johnston. 2015. Traffic noise masks acoustic signals of freshwater stream fish. Biological Conservation 187:27–33.
Johnson, D. L. 2000. Sound production in *Cyprinodon bifasciatus* (Cyprinodontiformes). Environmental Biology of Fishes 59:341–346.
Johnston, C. E., and C. T. Phillips. 2003. Sound production in sturgeon *Scaphirhynchus albus* and *S. platorynchus* (Acipenseridae). Environmental Biology of Fishes 68(1):59–64.
Johnston, C. E., and S. P. Vives. 2003. Sound production in *Codoma ornata* (Girard) (Cyprinidae). Environmental Biology of Fishes 68(1):81–85.
Kierl, N. C., and C. E. Johnston. 2010. Sound production in the Pygmy Sculpin *Cottus paulus* (Cottidae) during courtship and agonistic behaviors. Journal of Fish Biology 77:1268–1281.
Kuznetsov, M. Y. 2009. Traits of acoustic signalization and generation of sounds by some schooling physostomous fish. Acoustical Physics 55:866–875.
Ladich, F. 1999. Did auditory sensitivity and vocalization evolve independently in otophysan fishes? Brain, Behavior and Evolution 53:288–304.
Ladich, F., and M. L. Fine. 2006. Sound generating mechanisms in fishes: a unique diversity in vertebrates. Pages 3–43 *in* F. Ladich, S. P. Collin, P. Moller and B. G. Kapoor, editors. Communication in Fishes, Vol. 1. Science Publishers, Enfield, New Hampshire.
Linke, S., T. Gifford, C. Desjonquères, D. Tonolla, T. Aubin, L. Barclay, C. Karaconstantis, M. J. Kennard, F. Rybak, and J. Sueur. 2018. Freshwater ecoacoustics as a tool for continuous ecosystem monitoring. Frontiers in Ecology and the Environment 16:231–238.
Luczkovich, J. J., D. A. Mann, and R. A. Rountree. 2008. Passive acoustics as a tool in fisheries: an introduction to the American Fisheries Society symposium. Transactions of the American Fisheries Society 137:533–541.
Malavasi, S., S. Collatuzzo, and P. Torricelli. 2008. Interspecific variation of acoustic signals in Mediterranean gobies (Perciformes, Gobiidae): comparative analysis and evolutionary outlook. Biological Journal of the Linnean Society 93:763–778.
Mann, D. A., A. D., Hawkins, and J. M. Jech. 2008. Active and Passive Acoustics to Locate and Study Fish. Pages 279–309 *in* J. F. Webb, R. R. Fay, and A. N. Popper, editors. Fish Bioacoustics. Springer Handbook of Auditory Research, Vol. 32. Springer, New York.
Mann, D. A., J. D. Bowers-Altman, and R. A. Rountree. 1997. Sounds produced by the Striped Cusk-eel *Ophidion marginatum* (Ophidiidae) during courtship and spawning. Copeia 1997:610–612.
Mann, D. A., P. A. Cott, B. W. Hanna, and A. N. Popper. 2007. Hearing in eight species of northern Canadian freshwater fishes. Journal of Fish Biology 70:109–120.
Mélotte, G., R. Vigouroux, C. Michel, and E. Parmentier. 2016. Interspecific variation of warning calls in piranhas: a comparative analysis. Scientific Reports 6:36127.
Moreau, F.-A. 1864. Sur la voix des poisons. Comptes Rendus de l'Académie des Sciences, Paris 59:436–438.
Moreau, F.-A. 1876. Recherches experimentales sur les fonctions de la vessie natatoire. Annales des Sciences Naturelles, Zoologie 6:1–85.
Moulton, J. M. 1956. Influencing the calling of sea robins (*Prionotus* spp.) with sound. The Biological Bulletin 111:393–398.
Mouy, X., R. Rountree, F. Juanes, and S. E. Dosso. 2018. Cataloging fish sounds in the wild using combined acoustic and video recordings. The Journal of the Acoustical Society of America 143(5):EL333–EL339.
Nelson, J. S., E. J., Crossman, H. Espinosa-Perez, L. T. Findley, C. R. Gilbert, R. N. Lea, and J. D. Williams. 2004. Common and Scientific Names of Fishes from the United States, Canada, and Mexico, 6th edition. American Fisheries Society. Special Publication 29. Bethesda, Maryland.
Neproshin, A. 1972. Some physical characteristic of sound in Pacific salmons. Zoologichesky Zhurnal 51:1025–1030. (in Russian).
O'Shea, T. J., and L. B. Poché Jr. 2006. Aspects of underwater sound communication in Florida manatees (*Trichechus manatus latirostris*). Journal of Mammalogy 87:1061–1071.
Parker, G. H. 1918. A critical survey of the sense of hearing in fishes. Proceedings of the American Philosophical Society 57:69–98.
Rountree, R. A. 2008. Do you hear what I hear? Future technological development – and needs- in passive acoustics underwater observation. Marine Technology Reporter 51(9):40–46.
Rountree, R. A., and J. Bowers-Altman. 2002. Soniferous behavior of the Striped Cusk-eel, *Ophidion marginatum*. Bioacoustics 12:240–242.
Rountree, R. A., R. G. Gilmore, C. A. Goudey, A. D. Hawkins, J. Luczkovich, and D. A. Mann. 2006. Listening to fish: applications of passive acoustics to fisheries science. Fisheries 31:433–446.
Rountree, R. A., and F. Juanes. 2016. Potential of passive acoustic recording for monitoring invasive species: Freshwater Drum invasion of the Hudson River via the New York Canal System. Biological Invasions 19:2075–2088.
Rountree, R. A., and F. Juanes. (2018). Potential for use of passive acoustic monitoring of piranhas in the Pacaya–Samiria National Reserve in Peru. Freshwater Biology. Available: https://doi.org/10.1111/fwb.13185
Rountree, R. A., F. Juanes, and M. Bolgan. (2018). Air movement sound production by Alewife, White Sucker, and four salmonid fishes suggests the phenomenon is widespread among freshwater fishes. PLoS ONE, 13, e0204247.
Rountree, R. A., F. Juanes, and M. Bolgan. In press. Fish farts, burps, moans and groans; a cacophony of murmurs in danger of being lost before they are recognized. Scientific reports.
Rountree, R. A., P. J. Perkins, R. D. Kenney, and K. R. Hinga. 2002. Sounds of Western North Atlantic Fishes: Data rescue. Bioacoustics 12:242–244.
Sandeman, D. C., and L. A. Wilkens. 1982. Sound production by abdominal stridulation in the Australian Murray River crayfish, *Euastacus armatus*. Journal of Experimental Biology 99:469–472.
Stober, Q. J. 1969. Underwater noise spectra, fish sounds and response to low frequencies of Cutthroat Trout (*Salmo clarki*) with reference to orientation and homing in Yellowstone Lake. Transactions of the American Fisheries Society 98:652–663.
Sueur, J., D. Mackie, and J. F. C. Windmill. 2011. So small, so loud: extremely high sound pressure level from a pygmy aquatic insect (Corixidae, Micronectinae). PLoS ONE 6:e21089.
Sulak, K. J., R. E. Edwards, G. W. Hill, and M. T. Randall. 2002. Why do sturgeons jump? Insights from acoustic investigations of the Gulf sturgeon in the Suwannee River, Florida, USA. Journal of Applied Ichthyology 18:617–620.
Thompson, J. 1830. Voice of fishes. Page 147 *in* J. C. Loudon, editor. The Magazine of Natural History and Journal of Zoology, Botany, Mineralogy, Ecology, and Meteorology 3. Longman, Rees, Orme, Brown, and Green, London.
Tonolla, D., V. Acuna, M. S. Lorang, K. Heutschi, and K. Tockner. 2010. A field-based investigation to examine underwater soundscapes of five common river habitats. Hydrological Processes 24: 3146–3156.
Wysocki, L. E., S. Amoser, and F. Ladich. 2007. Diversity in ambient noise in European freshwater habitats: noise levels, spectral profiles, and impact on fishes. Journal of the Acoustical Society of America 121:2559–2566.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article. AFS