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Author for correspondence:
Camille Desjonquères
e-mail: cdesjonqu@gmail.com

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The potential of acoustic monitoring of aquatic insects for freshwater assessment

Camille Desjonquères[1], Simon Linke[2], Jack Greenhalgh[3], Fanny Rybak[4] and Jérôme Sueur[5]

[1]Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, LECA, 38000 Grenoble, France
[2]CSIRO Environment, Dutton Park, Queensland 4102, Australia
[3]Instituto Pirenaico de Ecología, Av. Ntra. Sra. de la Victoria, 22700, Jaca, Huesca, España
[4]Université Paris-Saclay, CNRS, Institut des neuroscience Paris-Saclay, 91400 Saclay, France
[5]Institut Systématique Evolution Biodiversité (ISYEB), Muséum National d'Histoire Naturelle, CNRS, Sorbonne Université, EPHE, Université des Antilles, 57 Rue Cuvier, 75005 Paris, France

CD, 0000-0002-6150-3264

Aquatic insects are a major indicator used to assess ecological condition in freshwater environments. However, current methods to collect and identify aquatic insects require advanced taxonomic expertise and rely on invasive techniques that lack spatio-temporal replication. Passive acoustic monitoring (PAM) is emerging as a non-invasive complementary sampling method allowing broad spatio-temporal and taxonomic coverage. The application of PAM in freshwater ecosystems has already proved useful, revealing unexpected acoustic diversity produced by fishes, amphibians, submerged aquatic plants, and aquatic insects. However, the identity of species producing sounds remains largely unknown. Among them, aquatic insects appear to be the major contributor to freshwater soundscapes. Here, we estimate the potential number of soniferous aquatic insects worldwide using data from the Global Biodiversity Information Facility. We found that four aquatic insect orders produce sounds totalling over 7000 species. This number is probably underestimated owing to poor knowledge of aquatic insects bioacoustics. We then assess the value of sound producing aquatic insects to evaluate ecological condition and find that they might be useful despite having similar responses in pristine and degraded environments in some cases. Both expert and automated identifications will be necessary to build international reference libraries and to conduct acoustic bioassessment in freshwaters.

This article is part of the theme issue 'Towards a toolkit for global insect biodiversity monitoring'.

1. Introduction

Surveying variations in biodiversity over time is an essential aspect of conservation biology, informing subsequent evidenced-based habitat management and conservation efforts [1]. Many conventional biodiversity survey methods have been developed to quantify trends in species distributions, fitness and habitat condition. Conventional survey methods consist of approaches such as sub-sampling a representative area within an ecosystem, using quadrats, line transects, and point counts. Alternatively, sampling a representative number of individuals within a population, with methods such as mark-recapture, allows us to extrapolate trends in biodiversity to larger spatial and temporal scales [2].

These conventional survey methods have provided an accurate inference of ecological condition and change over time. However, many conventional methods used to survey freshwater biodiversity are labour-intensive, expensive, non-selective, and often require killing and preserving specimens for later identification in a laboratory [3,4]. This assessment process thus relies on invasive and destructive sampling methods that usually have low spatio-temporal replication and require specialized taxonomic expertise.

Passive acoustic monitoring (PAM) is emerging as a non-invasive alternative sampling method [5,6]. PAM facilitates the simultaneous deployment of multiple acoustic recorders in different locations for extended periods of time, thus achieving high spatio-temporal resolution [7]. PAM was initially developed in terrestrial and marine environments but has recently been transferred to survey freshwater environments [4,8,9]. This freshwater ecoacoustic research has shown that four animal groups produce sound underwater in freshwater environments: amphibians, crustaceans, fishes and insects. Aquatic insects are insects with at least one life stage bound to water. It is estimated that there are approximately 76 000 species of aquatic insects worldwide [10]. Aquatic insects are probably the most important contributors to freshwater soundscapes globally owing to their high abundance, diversity and propensity to produce sounds underwater [11,12].

Assessing the ecological condition of freshwater environments usually relies on sampling taxonomic groups that are indicative of specific environmental conditions because of variations in their abundance, or presence/absence along an environmental gradient [13]. For example, aquatic plants have been used to classify lake ecosystems and determine ecological condition [14,15]. However, aquatic insects are more extensively used as bioindicators in the assessment of freshwater ecosystems [16,17]. Most species are aquatic as larvae, or both as larvae and adults. Several aquatic insect groups, such as Odonata [13], Ephemeroptera [18], Plecoptera [19] and Coleoptera [20] are used in long-term water quality monitoring programmes via their incorporation in biological indices, such as the Biological Monitoring Working Party index [16] and the Average Score Per Taxon index [17]. These indices assign a numeric value to certain taxa based on their ecological significance.

The adoption of PAM in freshwater environments as a reliable survey method is contingent on generating detailed knowledge of soniferous taxa before meaningful ecological conclusions can be drawn. In particular, knowledge of species-specific sounds produced by aquatic insects indicative of specific environmental conditions is required. To date, very little research has been carried out to describe species-specific aquatic insect sound production in freshwater environments. Sound producing organs, essentially stridulatory organs, have been used to delineate and identify insect species for years, in particular for terrestrial insects (mainly Orthoptera and Hemiptera) [21], but also for aquatic species as illustrated in field guide books [22]. The occurrence of different sound organs used as diagnostic characters suggest the production of species-specific sounds. An increased understanding of these species-specific sounds produced by aquatic insects has the potential to facilitate the automatic monitoring and assessment of freshwater ecosystem condition at high spatial and temporal scales.

In this review, we estimate the potential number of aquatic insect species that can be recorded in freshwater environments worldwide using Global Biodiversity Information Facility data (GBIF; https://www.gbif.org/). With this data, we seek to address the following questions: (i) which aquatic insects are soniferous? (ii) what is the current knowledge on the sounds produced by those aquatic insects in terms of mechanisms and functions? and (iii) are soniferous aquatic insects representative of a sufficient range of environmental tolerance values to infer environmental condition? We then discuss the information soniferous aquatic insects could provide about freshwaters' ecological status. Finally, we highlight specific areas where research could improve and potential challenges that could arise.

2. Review of soniferous aquatic insects

(a) Methodology

We used the GBIF database to estimate the potential number of aquatic insects that produce sounds. For that, we identified the candidate genera using Aiken's extensive review (Aiken [23]), recent publications, and C. Desjonquères, S. Linke 2016, personal unpublished observations. To count the number of species contained in each of these genera, we queried the GBIF database using the 'get_gbifid' and 'gbif_downstream' functions from the 'taxize' package v. 0.9.100 [24,25]. We excluded extinct species with the result of the 'name_lookup' function from the rgbif package v. 3.7.8 [26,27] and eliminated multiple instances of the same species name. We ran all the analysis in R v. 4.3.1 [28].

We conducted a literature search through the species list we obtained from GBIF to identify the number of species that have actually been reported to produce sounds and collected data on the mechanisms, acoustic features, behavioural context, life stages and sex of sound producers in these articles. When a sound production mechanism was reported for one species in a genus, we assumed this species to be present in all the other species of the genus. We inventoried species for which there is a report of observed sound production and set all other species to 'supposed'. We identified the life stage (larvae, adult or both) that can produce sound. We reported description of sex (male, female or both), sound frequency range and behavioural context (mating, defence or preparation for flight).

(b) Results: estimation of the worldwide soniferous aquatic insects

Soniferous aquatic insects are known to belong to four orders: Coleoptera, Hemiptera, Odonata and Trichoptera. Among these orders, 18 families and 105 genera totalling 7024 species could be identified as soniferous species (table 1; electronic supplementary material, S1). Thus 9.2% of aquatic insects probably produce sounds. Most of the species producing sounds are within Coleoptera and Hemiptera (5610 and 1043 species respectively) while sound production in Trichoptera (370 species) is sporadic and in Odonata (three species) is fairly anecdotal (figure 1).

Among these 7024 species, only 97 have been reported to produce sounds in the literature and only 43 (0.6%) have their sounds properly described in terms of frequency range, mechanism, sex, lifestage and behavioural context (table 1; electronic supplementary material, S1). These 97 species are in 13 families and 65% of these species are in Corixidae, Micronectidae and Hydrophilidae (electronic supplementary material, table S1).

3. What is the sensitivity of these species to environmental conditions?

Freshwater aquatic insects have been used as indicators of water quality since the Berlin botanists Kolkwitz and Marsson described tolerance values in the Saprobien system over 100 years ago [90]. They are well catalogued internationally, and while rooted in the

Table 1. Sound production in aquatic insects families. (Detailed description of sound production in aquatic insects with life stage, sex, sound production mechanism, frequency range, behavioural context and references. A typical stridulatory apparatus is made of a file (f) and a scraper (s).)

order	family	life stage	sex	mechanism	frequency range (kHz)	behavioural context	references
Coleoptera	Amphizoidae	adult	?	— f: wing patch — s: elytra	?	?	Arrow [29]
Coleoptera	Dytiscidae	both	both	— f: costal vein, wing patch, protibia, sternum, hind coxa — s: elytra, protarsus, metafemur, hind tibia, hind femur — muscle contraction — axillary sclerites	0.2–10	preparation for flight, defence, mating	Parfitt [30], Reeker [31], Sopp [32], Clainpanain [33], Arrow [29], Mukerji [34], Marku [35], Balfour-Browne [36], Leston *et al.* [37], Smith [38], Larson & Pritchard [39], Greenhalgh *et al.* [40]
Coleoptera	Gyrinidae	adult	both	?	?	?	C. Desjonquères, S. Linke 2016, personal observations
Coleoptera	Haliplidae	adult	?	— f: elytra — s: toothed area on the pleural fold	?	?	Seeger [41], Hammond [42]
Coleoptera	Hydraenidae	adult	male	— f: head — s: pronotum	?	?	Perkins [43]
Coleoptera	Hydrophilidae	both	both	— f: third abdominal segment — s: lower face of the elytron — air expulsion from spiracles	3–10	mating, defence	Balfour-Browne [44], Buhk [45], Procher [46], White [47], Allen [48], Spangler [49], van Tassel, [50], Maillard [51], Britton [52], Maillard & Sellier [53], Meyer-Rochow [54], Ryker [55], Ryker [56], Hammond [42]
Coleoptera	Hygrobiidae	adult	both	— f: margin of elytra — s: tip of the abdomen	?	defence	Aiken [23]
Coleoptera	Noteridae	adult	?	— f: wing patch — s: elytra	?	?	Marku [35]
Hemiptera	Belostomatidae	adult	male	?	?	?	Hungerford [57], Smith [58]
Hemiptera	Corixidae	adult	both	— f: pegs on the fore femur, hind legs — head, opposite femur, hemelytra	1–7.5	mating	Butler [59], Poisson [60], Moore [61], Finke [62], Jansson [63], Jansson [64], Jansson [65], Jansson [66], Aiken [67], Theiss [68], Theiss *et al.* [69]
Hemiptera	Diaprepocoridae	adult	male	— dorsal surface of the sixth abdominal resembling a pair of tongs	?	?	Jaczewski [70]
Hemiptera	Micronectidae	adult	male	— f: right paramere (portion of the male genitalia) — s: ridge of the eighth abdominal segment	6–15	?	Leong [71], King [72], Bailey [73], Jansson [74], Sueur *et al.* [75], Desjonquères *et al.* [8,76]
Hemiptera	Naucoridae	adult	?	?	?	?	Frisch [77]

(*Continued.*)

Table 1. (*Continued.*)

order	family	life stage	sex	mechanism	frequency range (kHz)	behavioural context	references
Hemiptera	Nepidae	adult	?	— f: fore femur — s: fore coxa	?	?	De la Torre-Bueno [78]
Hemiptera	Notonectidae	adult	male	— f: fore coxa, fore femora — s: fore femur, rostrum	8–12	mating	Hale [79], Hutchinson [80,81], Lundblad [82], Brooks [83], Leong [71], Wilcox [84], Wilcox [85]
Hemiptera	Pleidae	adult	?	— f: mesothorax — s: prothorax	?	?	Poisson [86]
Odonata	Epiophlebiidae	larvae	both	— f: tergites of abdominal segments — s: ?	?	defence	Asahina [87], Asahina [88]
Trichoptera	Hydropsychidae	larva	both	— f: underside of the head — s: fore femur	0.2–9	defence	Jansson & Vuoristo [89]

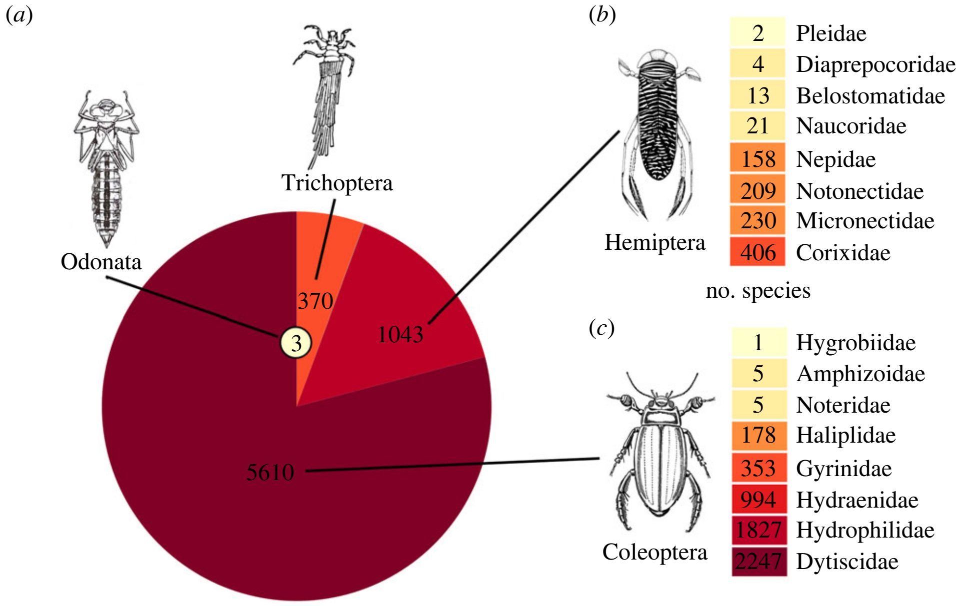

Figure 1. Taxonomic distribution of aquatic insects expected to produce sounds. Global distribution of the total number of potentially soniferous species in the four soniferous aquatic insect orders (*a*), in the eight soniferous Hemiptera families (*b*), and in the eight soniferous Coleoptera families (*c*).

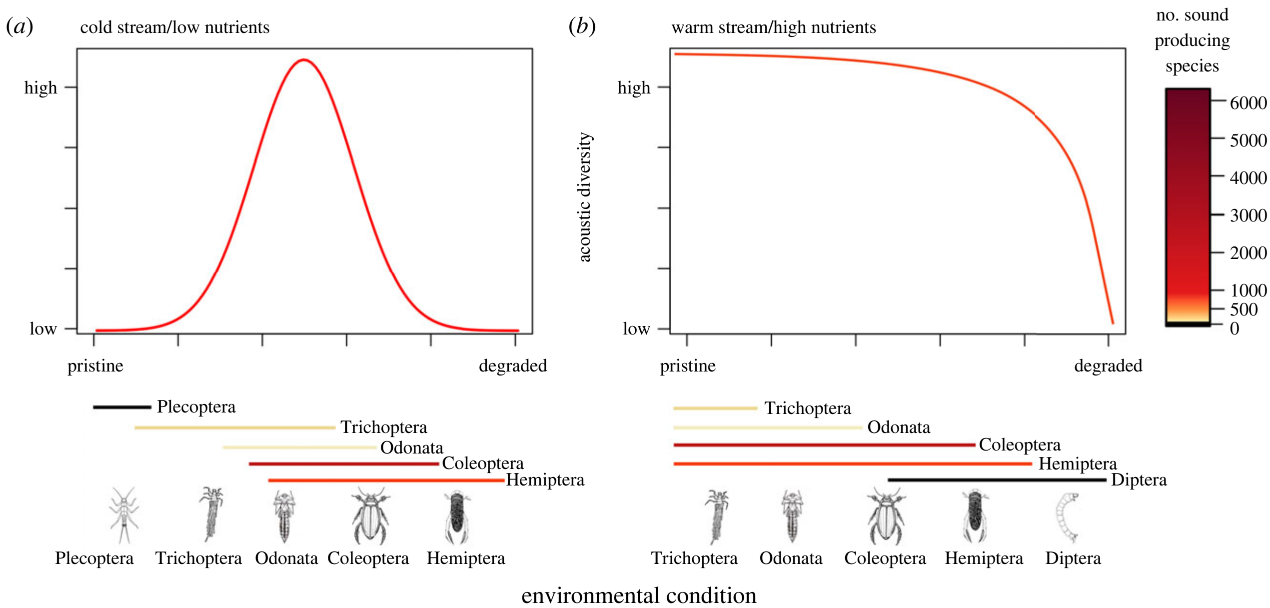

Figure 2. Expected relationship between environmental condition and acoustic diversity in (*a*) cold streams with low nutrient levels (e.g. a temperate stream) (*b*) and warm streams with high nutrient levels (e.g. a tropical stream).

last century [91–93], many of these have recently been updated or adapted to different stressors [94]. While all of these assign tolerance values—measures of the sensitivity to various aspects of water pollution—to species, genera or sometimes higher taxonomic levels, extra research will be needed to overcome a key problem with the distribution of indicator values concerning aquatic insects.

The problem arises from the distribution of the indicator values in relation to the presence of sound production or not in species (as described in [9]). As detailed in the previous section, the two key soniferous groups are Coleoptera and Hemiptera, with some sound production documented in Trichoptera and Odonata. All of these groups have intermediate tolerance values between 2.5 and 7 on a scale of 1 to 10 [3]. Thus they can bear some levels of eutrophication with warm waters and low dissolved oxygen, but not as extreme conditions as classic high tolerance taxa such as Chironomidae with tolerance values up to 9 [91–93].

This opens up two problems. First, while we expect the highest acoustic diversity in the most pristine ecological conditions in terrestrial environments; in many freshwater environments, we predict that the sites with most acoustic activity and richness will be sites at intermediate environmental conditions—typically warm water, medium level nutrient input and low flows. Extremes on either the side of the gradient on the other hand will be quieter or even silent, leading to difficulties in the interpretation of soundscape metrics (figure 2*a*). To illustrate this, imagine a pristine, colder fast flowing stream with high oxygen levels and rocky or gravelly sediment. This type of stream will be dominated by Ephemeroptera, Plecoptera and Trichoptera. Out of these three taxa, only the latter contains one soniferous family. Medium-level disturbances such as nutrient and sediment input or flow regulation can shift the community towards high occurrence of soniferous Hemiptera and Coleoptera [95], which will lead to peak sonifery. A further shift to highly tolerant taxa, such as Annelida, Hirudinea or Chironomidae, will then cause a reduction in soundscape as none of them are soniferous [9].

The second problem is a classic issue in freshwater science—or even all of ecology. Biological assessment attempts to measure a site condition—usually by evaluating a sampled area in light of similar sites that are known to be in good ecological condition. This is known as the 'reference condition approach', used to compare like with like and create valid evaluation metrics (for a detailed comparison of approaches, see [96]). This is necessary to disentangle natural variation from human impacts. For example, our peak soniferous community of Hemiptera and Coleoptera is an indicator of a mildly degraded cold water stream, yet, in a slow flowing, tropical system with intermediate or even high natural nutrient loads, these conditions will be indicator of a pristine condition—as will the Hemiptera and Colepoptera dominated soundscape. The soundscape will decline at higher levels of stress again, when other even hardier taxa take over (figure 2*b*). To overcome this conundrum, we need to match invertebrate communities and their soundscape to environmental gradients and evaluate a soundscape by matching a site to other similar sampling locations—a 'soundscape reference condition approach'.

In terrestrial environments, while estimating species richness or composition with acoustics is still difficult, there are promising studies that demonstrate relationships between species richness/diversity and acoustic indices in avian and anuran communities [97,98]. One of the explanations is simply that most species in these groups are soniferous. Song variation and complexity, as well as temporal heterogeneity add variation that needs to be accounted for. One option to account for temporal heterogeneity is to use long term recordings which if analysed together allow us to smooth this heterogeneity.

In freshwater, Jansson [65,99] attempted to use three *Micronecta* (Hemiptera) species to assess lake condition. The three species have different habitat requirements and thus can be used as bioindicators. However fluctuations in the number of collected individuals limited the efficacy of this technique. A study of the acoustic activity of a Mediterranean *Micronecta* population, estimated by the amplitude in the frequency band of the sound production, suggested that acoustic monitoring could help estimating species density [76]. This would require modelling the relationship between acoustic activity and species density, and sounds highly promising to make this bioassessment method more viable.

Finally, several studies have shown links between acoustic diversity and environmental condition in freshwater environments [11,40,100]. The question remains open as to whether the most extreme conditions (pristine and degraded) with rather silent insect communities can be differentiated with acoustics or not. One possibility is that instead of voluntary insect sounds, plant sounds or by-product insect sounds (e.g resulting from movement or feeding) could dominate these quiet insect communities [4,8,101]. Another possibility would be to use tools complementary to acoustics such as environmental DNA (eDNA) or key indicator species collection to combine with acoustics.

4. Discussion

We show that almost 10% of the aquatic insect species diversity is likely to produce sounds. We also demonstrate an important gap in knowledge about the characteristics of the sounds they produce, the production mechanisms and the behavioural context. These species-specific sounds could be used as indicators of species presence to assess acoustic community composition in freshwater environments. Presence/absence of certain species can be used as an indicator of environmental condition. Our results show that most sound producing species have intermediate tolerance values. Therefore we suggest that acoustic monitoring will be useful to differentiate between intermediate condition environments.

There are major gaps of knowledge concerning the sex of sound producers, behavioural context, and frequency range. This lack of knowledge is probably owing to the difficulty of studying aquatic insects in their environments. Vegetation and turbid water often prevent direct observation and experimentation in the field. Sound production mechanisms appear better studied because most supposed sound production mechanisms are based on museum descriptions on voucher specimens that can be observed ad libitum [23]. Being able to identify sound producing species will require massive effort from researchers and naturalists to inventory the sound production of various species. Indeed, confidently assigning sounds to a species might seem trivial in a terrestrial environment but can be very difficult in the murky waters of a pond. This effort thus requires recording in the field, and, in most cases, to collect, isolate and record individuals in aquariums [40]. One reason that may also explain the limited knowledge on aquatic insect sound production is the absence of a global consortium and libraries as in fish sounds [102] or underwater sounds [103].

Apart from a handful of larger synthesis [4,12,23], behavioural [66,89,104] and ecological [11,40] studies, the study of sound in aquatic insects has received relatively little interest from the freshwater scientific community. It is thus possible that sound production has been overlooked in some genera, families or even orders. Moreover the diversity of aquatic insects might still need taxonomic description in some areas of the world [10]. This would thus suggest that our estimate of the potential number of soniferous aquatic insect species is lower than the real number and there is potential for detecting additional species.

Another research axis will be to assess the link between acoustic diversity and freshwater environment condition. Although several studies reveal promising results for this relationship [11,40,100,101], they are limited to a few sites, habitat category, disturbance types and climatic realm (mostly temperate environments, but see [105] for a PAM study in tropical freshwater). A more comprehensive understanding of the link between environmental condition and sound production is necessary, as well as a better knowledge of sound production and the environmental conditions necessary for sound production in these species. This relies on a wider replication of studies across a variety of environmental conditions and in other parts of the world. Specifically, future studies should take into account various environmental variables (e.g. temperature, vegetation or community composition) and cover a wider geographical range to include tropical and arctic regions.

One major advantage of PAM is the possibility to monitor at high temporal resolution. Yet species signals are quite heterogeneous over time: they have daily and seasonal patterns. Moreover species activity can be highly variable. To assess the community and reliably collect presence data of a representative number of species, it is necessary to record over at least a whole day or week over the period of activity of most aquatic insects [106,107]. This period will vary depending on the climatic realm and habitat type and knowledge about this is highly limited. Thus further studies are necessary to assess the period of highest acoustic richness over a year. Using autonomous recording units is a convenient way to collect data over long periods of time without requiring observers to be present in the field [7].

Despite the lack of information about ecological condition in freshwater environments, aquatic insect sounds could yield valuable information about breeding phenology and distribution. Indeed sound production is associated with critical behaviours (including mating, breeding, defence against predators and territoriality). Thus monitoring the acoustic activity of these insects will yield valuable ecological insight and could help build acoustic species distribution models [108] based on available global freshwater maps [109]. This would be particularly valuable for invasive or threatened species.

Finally application of PAM is strongly contingent on analysis methods. Owing to the massive amount of data collected it is necessary to have automated analysis methods. Single species identification tools based on machine learning are now widely available and only require a decent amount of annotated data for training [110]. This type of application should thus be fairly easily transferable to the few aquatic insect species for which we have clear information about sound production and sufficient training data. Community level analysis is more challenging owing to the lack of reference databases for aquatic insects. Acoustic indices have been applied a few times to freshwater environments but reveal limited efficiency to assess species richness while being more efficient to distinguish between sites [107,111]. One avenue of research that has successfully been applied to other environments with limited knowledge of sound producers such as tropical forests is unsupervised learning [112,113]. This method relying on detection and clustering of sound events allows us to obtain sound type composition of a recording without requiring an annotated database. Applying this type of machine learning application is highly promising for community composition assessment and thus bioassessment. Another option would be combining PAM to other sampling methods such as net sweep or eDNA to compare acoustic activity and community composition.

To conclude, the study of aquatic insect acoustic monitoring for ecological condition assessment is a promising field of research. Several studies have already highlighted this potential [4,8,9,12,114]. Here we quantify the potential number of species that can be detected by sound and relate them to their bioassessment value. We suggest that this field will open new opportunities for the assessment of these highly threatened environments.

Data accessibility. Data and code have been submitted as electronic supplementary material [115] and are available on the github repository: https://github.com/Desjonqu/SoundofAquaticInsects.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

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