Marine Invertebrate Anthropogenic Noise Research – Trends in Methods and Future Directions

Wale, M.A.[1*], Briers, R.A.[1], Diele, K.[1]

[1] Aquatic Noise Research Group, School of Applied Sciences, Edinburgh Napier University, Edinburgh, UK

*** Correspondence:**

Dr Matthew Wale

M.Wale@Napier.ac.uk

Prof Karen Diele

K.Diele@Napier.ac.uk

Abstract

Selecting the correct methods to answer one's chosen question is key to conducting rigorous, evidence-based science. A disciplines' chosen methods are constantly evolving to encompass new insights and developments. Analysing these changes can be a useful tool for identifying knowledge gaps and guiding future studies. Research on the impact of anthropogenic noise on marine invertebrates, a topic with specific methodological challenges, has undergone substantial changes since its beginning in 1982. Using this field as an example, we demonstrate the benefits of such method analysis and resulting framework which has the potential to increase conclusive power and comparability of future studies. We list taxa studied to date, use a range of descriptors to analyse the methods applied, and map changes in experimental design through time. Based upon our analysis,

three research strategies are proposed as a best practice framework for investigating effects of noise on marine invertebrates and delivering policy-relevant information.

Keywords: Marine Noise, Anthropogenic Noise, Marine Invertebrates, Methods, Best Practice, Framework

I. Introduction

When seeking to produce rigorous evidence-based science, it is vital to carefully select methods that deliver robust and repeatable results. The chosen methods employed by a particular discipline evolve over time through the incorporation of new techniques and theory. Through this evolution, the shortcomings identified by previous research are addressed, or new parameters of specific interest are included. By studying how chosen methods and experimental designs have changed over time, knowledge gaps can be identified, and a best practice framework created to facilitate the advancement of future studies in said discipline. Here using marine invertebrate anthropogenic noise research as an example, an area of research that possesses both specific methodological challenges and has seen high advancement in recent years, we demonstrate how such an analysis can be conducted.

Anthropogenic activity in the oceans has been on the rise since the industrial revolution. Growth in shipping, oil and gas exploration, and more recently the installation of renewable energy devices have led to a sharp rise in the oceanic noise floor on a global scale (Hildebrand, 2009; Ross, 2005). Low-frequency sound pressure (20 - 200 Hz) produced by sonar, shipping, and marine construction, travels through water with little energy loss (Caruthers, 1977), propagating over large distances and remaining in the environment for long periods of time. For particle motion, the noise levels in water drop off far quicker than those of sound pressure, however, vibration can persist through the sediment (> 500 m) and create a layer of increased particle motion in the water layer directly above (Hazelwood and Macey, 2021) which may affect benthic organisms. Over the last century, the increased level of anthropogenic activity has led to a 10 – 100-fold increase in oceanic background noise (Tyack, 2008). With rising pH through climate change, the transparency of the ocean to low-frequency noise is increasing (Brewer and Hester, 2009) potentially doubling this rise in background noise by the end of the twenty-first century (Ilyina et al., 2010).

Anthropogenic noise has now been widely recognised as a pollutant in the marine environment. Legislation around the world has been created (e.g., Marine Strategy Framework Directive 2012 Descriptor 11, and IMO MEPC.1/Circ.833) to address the observed rise, and to identify the effects that this noise has on marine organisms. Despite this, the growing reliance on maritime transport (Institute of Shipping Economics and Logistics, 2016), and the push for renewable energy (Marine Board, 2010) will continue to increase the noise levels experienced by marine life in the foreseeable future.

When concerns over the effects of anthropogenic noise in the oceans first arose, the research focus lay solely on marine mammals (Malme and Thomson, 1973; Myrberg, 1978), organisms known to utilise (and produce) sound in their environment for communication and orientation. As the underwater sound research field developed, its scope broadened to include other taxa, with work encompassing fish (e.g., Schwarz and Greer, 1984), marine reptiles (O'Hara and Wilcox, 1990) and invertebrates (e.g., Lagardère, 1982; Pearson et al., 1994).

Interest in the effects of anthropogenic noise on marine invertebrates began at a similar time to that of other taxonomic groups, in the early eighties (Lagardère, 1982). However, it was not until 30 years later that the concern over human generated disturbances significantly sparked research on the effects this noise has on marine invertebrates. Although not considered to be able to hear in the traditional sense, by detecting pressure changes, most marine invertebrates "hear" by the reception of vibratory stimuli where the sound source is not in contact with the animal's body (Budelmann, 1992). Three types of sensory organs have evolved to allow this detection: internal statocyst systems, chordotonal organs, and superficial body receptor systems (Breithaupt and Tautz, 1988, 1990; Breithaupt, 2002). The recent research advances in this field have shown that man-made noise can alter the biology of marine invertebrates in a number of ways, from behaviour (Wale *et* al., 2013a; Mooney *et al*., 2016; Roberts *et al*., 2016, Wale *et al*., 2019; Ruiz-Ruiz *et al*., 2020; Jones *et al*., 2021), to physiology (Wale *et* al., 2013b; Langhammer *et al*., 2016; Solan *et al*., 2016, Wale *et al*., 2019; Slater *et al*., 2020), biochemistry (Stefano *et al*., 2016; Vazzana *et al*., 2016, 2020a,b; Wale *et al*., 2019), and genetics (Peng *et al*., 2016; Zhou *et al*., 2018; Shi *et al*., 2019; Hall *et al*., 2021). The large diversity of invertebrate physiologies, morphologies, and life histories leads to unpredictable responses to anthropogenic noise exposure. For example, noise-induced changes in larval movement speeds and settlement times are often highly variable and species specific (Branscomb and Rittschof, 1984; Pine et al., 2012; Stocks et al., 2012; Wilkens et al., 2012; Jolivet *et al*., 2016). These variations demonstrate the need to study the responses of a large range of species, including their different life stages, to sound.

Despite the current interest in how marine invertebrates react to man-made noise, the full extent of these effects, and the number of species affected, are still poorly understood (Popper *et al*., 2020: Duarte *et al*., 2021). To date, invertebrates still only represent a small proportion of the marine noise literature, as highlighted by an ISI Web of Science search generating 275 results for marine mammals, but only 37 for marine invertebrates in the same search (Basic Search, Topic, Search terms: Marine Mammal [replaced with Invertebrate in the second search] Anthropogenic Noise, 04/03/2021).

Reviews of studies on marine invertebrates and noise have summarised the findings (de Soto, 2016, Carrol *et al*., 2017), and highlighted current limitations (Hawkins *et al*, 2014; Hawkins and Popper, 2017). Most recently di Franco *et al*. (2020) and Ferrier-Pages *et al*. (2020) have reviewed the effects of noise on Mediterranean and coral-reef invertebrates, respectively. Both reviews focus on study findings to identify the possible consequences of noise on these specific environments, while the methods applied, and potential implications thereof were not considered. Typically (see Hawkins, 2014; Hawkins and Popper, 2017; Popper *et al*., 2020) reviews form their conclusions based on the field of aquatic noise research as a whole, including taxa from different orders, and generalizations have been made that are not always representative of the different subfields and their recent advances, such as the increasing inclusion of particle motion measurements in recent years.

Here we present a systematic methodological review focusing on marine invertebrates, identifying and evaluating the approaches taken to date to study the effects of anthropogenic noise on this taxonomic group. Rather than focusing on the results of each study, which have largely been reviewed elsewhere (see, above), here we review the methods used to generate said results. This review aims to (i) identify method trends throughout the history of this field, and based upon this analysis, (ii) develop an actionable best practice framework for the assessment of anthropogenic noise effects in marine invertebrates, considering the identified knowledge gaps. Three research strategies are proposed in a best practice framework that can be followed by those starting in the field of anthropogenic noise research or by established researchers, to help identify the most appropriate methods of study with respect to specific questions. The steps taken in this method analysis for marine invertebrate noise research will also assist researchers from other disciplines to informatively assess their own methods. By generating discipline-specific assessment criteria and best practice frameworks, researchers can help advance their field in a cohesive and comparable direction.

II. Methods

Literature searches were conducted from August 2011 to February 2021 (final search 23 February 2021). Searches were performed in the ISI Web of Science database (Basic Search, Topic) covering all available indexes and utilizing an adapted version of the search terms outlined by Williams *et al*. (2015). An additional set of invertebrate specific search terms were used in combination with the above to reduce the number of irrelevant results (Table 1). This led to a total of 5777 hits (including duplicates), with 273 unique results returned when a second search term was included. All results were manually assessed for relevance (whether they were studies on anthropogenic noise and marine invertebrates) leaving 50 papers. The reference lists of all identified relevant papers were searched for additional applicable studies and these were added to the literature found in the Web of Science search. This process was repeated until no new papers were found. Further to this, Google Scholar searches, personal communication, and citation alerts set up in Google Scholar, Mendeley, and ResearchGate since 2011 lead to a final count of 95 studies. Of these, the majority (78) are peer-reviewed literature, the remaining are technical reports produced for government agencies (4), conference proceedings (10), university published research (1), and industry reports (2).

Each study was assigned a number of descriptors to characterize the method it used. These descriptors comprise three neutral categories focusing on the type and length of sound exposure used, and the field of biology investigated (see II (1) below). In addition to these, six pairs of opposing descriptors (see II (2), e.g., single vs multiple species) focus on specific components of the applied method or experimental design. A seventh descriptor “pair” looking at dose dependency is also included, with the types of dependency further split into three unique categories (P7 below). The seven descriptor pairs have binary outcomes (exceptions to this can occur when a study has conducted multiple different analyses). One of the identified outcomes indicates a method advantage when studying anthropogenic noise impacts on marine invertebrates, and the other indicates a limitation (see examples given below). These outcomes should not however be considered positive or negative judgements on the quality of the research, as many of the “limitations” have their own advantages and practicalities. For example, in the laboratory/field descriptor pair (P4 below), tank-based studies provide a level of control over exposure conditions that would be unattainable in the field, however, a field component would allow a better representation of the noise field experienced in situ and provide potential validation of any laboratory findings. Therefore, including a field component is seen as the advantage in this descriptor pair.

The chosen descriptors are listed below, with descriptions given where necessary. N = Neutral Descriptor, P = Descriptor Pairs.

(1) Neutral Descriptors

N1 - Area of Biology

A single study may often contain multiple descriptors.

- DNA Integrity and Genetics: Studies that measure gene expression through transcriptomics and metabolomics or those that measure changes in DNA integrity.
- Biochemistry: Studies that measure changes in internal chemical processes to investigate the production of stress-related compounds.
- Physiology: Studies that measure changing metabolic responses.
- Morphology and Trauma: Studies that measure changes to morphology, or trauma in tissues and organs.
- Larval Development: Studies that measure differences in development including inter-stage timing, total development time, mortality, and settlement.
- Behaviour: Studies relating to animal behaviour.
- Ecology: Studies relating to species abundance and distribution.

- Fisheries: Studies that use catch rates or other fishery production statistics as a metric for noise effects.

N2 - Exposure Type

Playback of noise recordings e.g., ship noise, through speakers, is a common technique for noise exposure and used both in laboratory and field studies. Exposure to the original noise source is less common in laboratory studies but can occur when the authors are investigating aquarium or aquaculture noise, as well as actively creating sediment vibration in the laboratory (See Roberts *et al*., 2015).

- Laboratory: Exposure to noise in aquarium tanks, both large and small (see below).
- Field: Exposure to noise in the field, or in a semi-field environment (experiments where sea cages or other holding systems are used in the field).
- Playbacks: Exposure to noise either through underwater speakers, in air speakers, shaker tables, or a combination of these, in the laboratory or field.
- Source: Exposure to noise directly from the original noise source.

At least two of the above-listed descriptors are applied to any of the considered studies. In this analysis, the laboratory and field descriptors are considered together, as are the playbacks and source descriptors. These pairs act independently of each other with one pair being the exposure environment and the other being the noise source.

N3 - Exposure Length

Hawkins and Popper (2017) describe an acute noise exposure as occurring “for a brief period, usually from a particular source”. In the present review, a maximum length of 6 h was considered as an acute exposure to accommodate studies where a single exposure to an air gun pass were used.

When classifying the exposure regime used in each study, the following categories were used (a single study may contain more than one of these exposure types):

- Acute: A short-term exposure to noise of less than or equal to 6 h.
- Continuous: A continuous long-term noise exposure of longer than 6 h.
- Repeated: An exposure where animals are exposed to multiple acute noise events, resulting in an exposure period longer than 6h.
- Modelled: Responses modelled from recordings of noise levels and previous data on the hearing thresholds and responses of invertebrates, without recording any responses first-hand. For modelled exposures, no other descriptors were assessed.

(2) Descriptor Pairs

In all pairs (P) the first descriptor is considered the limitation and the second the advantage.

P1 - Particle Motion

This descriptor covers the inclusion of particle motion measurements in a given study. In some instances where the noise stimulus is presented via shaker tables without having measured the exact particle motion the study was ranked as having included particle motion measurements, as the method of exposure can be replicated to produce the same particle motion level. The inclusion of this metric is especially important to calibrate for the unpredictable interference patterns created in laboratory tanks (see descriptor P5).

- No Particle Motion Measurements
- Particle Motion Measurements

P2 - Number of Species

Thoroughly investigating the responses of a single species is common in biological studies, as such it should only be considered a limitation when in combination with limitations highlighted in other descriptor pairs (such as a single species combined with a single area of biology).

- Single Species
- Multiple Species

P3 - Number of Areas of Biology

These areas refer to those identified in descriptor N3.

- Single Area of Biology
- Multiple Areas of Biology

P4 - Laboratory/Field

- Aquarium Only
- Field Aspect: This applies to studies that are wholly based in the field, semi-field, or those with a combined laboratory/field approach.

P5 - Tank Size

The size of exposure tanks applies only to laboratory-based studies and is most relevant to experiments using noise playbacks from speakers. This descriptor focuses specifically on the tank in which the animals are exposed to sound rather than to vials or chambers holding the animals (often important for larval studies) inside an exposure tank. A large tank was defined as a tank in which the animal(s) can be exposed to noise at a distance greater than 1m to the source (Gray *et al*., 2016), or where the noise field produced would have limited reflection and refraction. Unpredictable interference patterns of the particle motion will occur in all tanks, it is, therefore, important to calibrate for this (see descriptor P1).

- Small Tanks: Aquaria where the animal is exposed at a distance closer than 1m to the noise source.
- Large Tanks: Aquaria where the animal can be exposed near the centre of the tank at 1m or more from the noise source.

P6 - Sample Size

Sample size will vary in response to the expected magnitude of the response, the statistical tests chosen to answer the research question, and the type of experiments performed. A smaller sample size, although sometimes necessary, can create large confidence intervals (Ennos, 2000), with variability around the mean decreasing as the sample size increases. Small sample sizes in biochemical and genetic studies are common and should not be considered a limitation. Here, 10 replicates were chosen to represent a relatively large sample size, but we acknowledge that the required sample size to detect a given effect is dependent on the levels of variability inherent in the system.

- Small Sample Size: Less than 10 replicates per treatment
- Large Sample Size: More than or equal to 10 replicates per treatment

P7- Dose Dependency

Evaluating dose-response relationships is required for identifying the minimum dose of a test stimulus needed to elicit a response, as well as the dose at which said stimulus becomes detrimental or toxic (Yoshimura *et al*., 1997). Here both the inclusion of dose dependency within a study, as well as the specific aspect of sound measured for establishing dose dependency are considered. A single study can contain multiple sound aspects.

- No Dose Dependency
- Dose Dependency
    - Frequency
    - Intensity
    - Duration

A full breakdown of all descriptors assigned to each study is presented in the supplementary material.

III. Results

In this review, we identified 95 studies that have been published on marine invertebrate noise exposure (gathered through search criteria detailed above). These studies cover 80 species from seven phyla (Figure 1), with the majority focusing on commercially important crustaceans, bivalves, and cephalopods. To create a better representation of the effects of noise on marine invertebrates, a more diverse range of species, response parameters, exposure lengths and noise sources need to be researched.

(1) Exposure and Area of Biology (N1, N2, N3)

Research on the impact of anthropogenic noise on marine invertebrates has undergone substantial change since its beginning (Figures 3 – 5), most of which has occurred since 2012. Acute noise exposures have dominated the field throughout its history (Figure 2). However, the studies conducted between 2012 and 2021 have increasingly used continuous noise exposures (17% of the literature) and have started to include modelled noise exposures (2% of the literature) (Figure 3C).

One of the most substantial changes is the increase in the use of noise playbacks, which has risen from 38% to 71% of exposures since 2012. Field exposures were abundant prior to 2012 (48% of publications) and, although their frequency has increased of late due to increased research efforts, their relative proportion within the literature has decreased (34%) (Figure 3B).

The field has been dominated by behavioural studies from its outset, and this trend has continued until today. Behavioural studies made up 29% of the literature prior to 2012, with this changing to 45% between 2012 and 2021 (Figure 3A). Studies focusing on physiology and morphology have fallen from 16% and 23% respectively before 2012 to 10%, and 11%, whereas investigations on larval development have risen from 3% to 6% since 2012. The proportion of experiments looking into biochemical responses has risen from 13% to 16% since 2012, ecological experiments have remained constant (3% prior to 2012, 2% after), and the first experiments on the effects of noise on genetics (Peng *et al.*, 2016) conducted in 2016 (Figure 3A). The study of the effects of noise on invertebrate fisheries has decreased in representation falling from 13% to 4% since 2012 (Figure 3A).

(2) Particle Motion (P1)

Particle motion is the component of sound detected by most fish, and all marine invertebrates, yet it is often neglected in bioacoustic studies (see IV below). To truly characterize the sound field experienced by these animals in their natural environment, and to as accurately as possible reproduce it in tank-based experiments, particle motion must be measured along with the sound pressure. Branscomb and Rittschof (1984) were the first to include particle motion in their analysis. Through the use of a shaker table, the authors were able to effectively characterize the particle motion in their experiment. However, for 28 years particle motion measurements were rarely conducted, accounting for only 10% of studies. Since 2012 however, this knowledge gap has increasingly been addressed as evidenced by 29% of studies in this period having now included particle motion measurements (Figure 4A).

(3) Number of Species (P2)

Responses to anthropogenic noise are often species specific. Therefore, to identify shared responses that can be extrapolated to other taxa, multiple species should ideally be investigated in a single study, with an identical experimental set-up. The number of such studies has been consistent throughout the history of the field, accounting for 25% (27% previously) of assessed publications from 2012 to 2021 (Figure 4B). In contrast, when investigating a single species (75% of studies, Figure 4B), there is an opportunity to comprehensively study multiple aspects of biology at the same time (P3 below, Figure 4C).

(4) Number of Areas of Biology (P3)

To obtain a more complete picture of the way anthropogenic noise affects an organism/taxon, responses must be investigated at multiple levels of biological organization. This allows researchers to uncover the links between more visual behavioural responses and the cryptic responses that may be their underlying drivers. It is becoming increasingly common for authors to explore multiple aspects of an animal's biology, with these studies now accounting for 37% of the total literature, and 39% of studies from 2012 to 2021 (Figure 4C).

(5) Laboratory/Field (P4)

When deciding whether to conduct a study in tanks or in the field, a number of factors must be considered. Laboratory-based studies offer a fine degree of control unobtainable in the field, where external factors may influence the exposures, and consequently the final results may be skewed. Conversely, noise exposures presented in a tank will never fully match those experienced in the field and removing animals from their natural environment may artificially influence their responses to stress. Therefore, where viable, the use of field investigations can help validate laboratory results. Although early studies on the responses of marine invertebrates to anthropogenic noise were fully laboratory-based (Branscomb and Rittschof, 1984; Lagardère, 1982; Regnault and Lagardère, 1983), the emphasis quickly switched to studies incorporating a field component (Figure 9). Recently however there has been a resurgence in aquarium only investigations, with a rise from 45% prior to 2012 to 66% between 2012 and 2021 (Figure 5A).

(6) Tank Size (P5)

When dealing with noise playbacks, a small tank will often increase the levels of particle motion, as this is greatest close to the noise source, and therefore potentially expose an animal to noise greater than intended. It is therefore important to use large tanks (where the animal can be exposed ≥1m from the noise source or where the noise field produced would have limited reflection, refraction, or interference, Gray *et al*., 2016), where appropriate, in tank-based experiments that involve noise playbacks (see IV below). For all studies, best practice involves taking particle motion readings at the location where the animal is exposed to noise (Descriptor P1), to give a true representation of the levels they receive. There has been a shift towards large tank studies (> 1 m *sensu* Gray *et al*., 2016), increasing from 11% of the literature before 2012 to 39% after this point (Figure 5B).

(7) Sample Size (P6)

In general, a larger sample size will allow more robust conclusions regarding the effects anthropogenic noise is having on the organisms/taxa in question and should be strived for wherever possible. However, this is not always feasible, especially when working with complex systems, vulnerable species, limited resources, or specific techniques. The majority of studies have endeavoured to use as large a sample size as was practical. The number of studies that used a small sample size has declined from 33% prior to 2012 to 23% after (Figure 5C).

(8) Dose Dependency (P7)

Prior to 2012, dose dependency measurements were included in 38% of studies (19% frequency, 19% intensity) (Figure 6), whereas only 22% of the studies published between 2012 and 2021 (14% frequency, 14% intensity, 1% duration) incorporated such measurements (Figure 6). Within the latter period, those studies addressing dose dependency often addressed multiple components of the noise exposure (Samson *et al*., 2014; Roberts *et al*., 2015;2016a; Mooney *et al*., 2016; Peng *et al*., 2016; Charifi *et al*., 2017).

IV. Discussion

There have been several changes in the methods chosen to investigate the effects of anthropogenic noise on marine invertebrates since the beginning of research in this field, 39 years ago. One of the most substantial changes is the rise in both laboratory-based studies and the use of noise playbacks. Field studies allow animals to be exposed to noise under the most realistic conditions possible, often with the noise coming directly from the source. They also keep the exposure environment accurate to what the animal would experience in a “real world” situation with possible predation, competition, and environmental variables remaining present in the experimental set-up. The rise in laboratory-based studies from 2012 to 2021 is however likely due to the increased level of control garnered from this style of experimentation. As the field progressed there has been a move away from simply focusing on establishing evidence of a response, towards generating a mechanistic understanding of the specific type of organismic reactions exhibited during sound exposure. The use of both noise playbacks and laboratory/aquarium environments gives researchers the opportunity to conduct a range of experiments under controlled conditions, and at relatively low cost compared to field studies. This allows for more in-depth studies and exploration of a wider range of responses. Additionally, laboratory studies are often employed when the alternative field experiment would prove impractical for logistical reasons. Ideally, studies are designed to include both laboratory and field experiments, where the fine-scale control gained in laboratory experiments is coupled with field trials to validate the findings in situ.

As the number of laboratory studies has increased so too has the size of the tanks used for these studies. Increasing awareness of the acoustical properties of aquarium tanks, especially concerning the reflection and interference of sound waves and particle motion that subsequently increases the sound intensity, has caused this move away from the use of small tanks. The use of large tanks is especially prudent when dealing with marine invertebrates, where the particle motion component of underwater sound is most important. Large tanks allow animals to be exposed at an adequate distance from both the noise source and any tank walls, such that the received particle motion is not significantly increased. Similarly, the measurements of said particle motion have increasingly been incorporated into studies in recent years. Formerly it was typically neglected, likely due to the high cost of commercially available particle motion sensors which are often covered under export laws due to their original military applications. As these sensors are becoming more readily available, both through the creation of new sensors, and increased collaboration and equipment sharing, particle motion is increasingly becoming a standard measure when characterizing the exposure. Despite the increase in particle motion measurements for noise exposures, there is still a lack of these measurements for the particle motion produced by the original noise source in situ (e.g., that produced by offshore wind turbines). Such measurements need to be included in all future studies (where possible) to help validate the chosen levels of sound exposures and provide policy relevant information on the effects of noise.

The selection of the response parameters used in the study of anthropogenic noise has changed in line with the increased use of more technical methods. The first studies to investigate the effects of noise on marine invertebrates focused on behavioural responses. This has remained the dominant topic, being a key focus from 2012 to 2021. The field, however, has also expanded to include biochemical and genetic studies, that can identify the underlying drivers behind, and links between, observed responses. In a similar manner to the inclusion of multiple areas of biology, the number of investigations that use multiple species within an individual study has increased. This has allowed more complex questions to be addressed, such as how noise affects communities, and how different species respond to the same noise exposure, uncovering varying levels of susceptibility to said noise.

However, likely because of the higher degree of complexity of the studies, the inclusion of dose dependency measurements has reduced in recent years, with a large number of investigations aimed at identifying the presence of a specific response, rather than the precise level of sound needed to trigger said response. Despite this, dose dependency information is vital for the creation of anthropogenic noise suppression strategies (Pooper *et al*., 2020), and its inclusion in future work should be encouraged.

(1) Research Strategies

Based upon the above analysis of the methods used in marine invertebrate noise studies, a conceptual framework is presented, suggesting three alternative research strategies for optimizing future research on the effects of noise on marine invertebrates (see Figure 7 and text below).

Two of the three strategies give guidelines for either single species (Figure 7 – Research Strategy 1) or multiple species (Figure 7 – Research Strategy 3) experiments with the main focus on behaviour, physiology, larval development, biochemistry, genetics, or morphology and trauma. These studies are likely more laboratory-based or incorporate a laboratory and field design and are ideally fit to the integrative approach advocated below. The third strategy focuses on ecology and fisheries studies (Figure 7 – Research Strategy 2) which are more field based. The three strategies are in line with suggestions of Hebel *et al*. (1997) and Kight and Swaddle (2011) that research should be conducted in a holistic manner, with an integrative approach, to assess the effects of pollutants in the environment. Whilst responses of marine invertebrates to noise in terms of behaviour and physiology are often explored together (Lagardère, 1982; Christian *et al*., 2003; Payne *et al*., 2007; Pine *et al*., 2012; McDonald *et al*., 2014; and Solan *et al*., 2016), biochemical analysis alongside behavioural observation has only been included in a small number of recent studies (Filiciotto *et al*., 2014, 2016, 2018; Celi *et al*., 2015; Stefano *et al*., 2016; and Vazzana *et al*., 2016). A thorough integrative approach has, to date, only been adopted by a small number (see Day *et al*., 2016; 2017; Jolivet *et al*., 2016; Peng *et al*., 2016; Shi *et al*., 2019, Wale *et al*., 2019, and Ruiz-Ruiz *et al*., 2020) that combine response parameters from multiple levels of biological organization. In doing so they have uncovered links between the visually obvious behavioural responses and more cryptic responses to noise exposure.

The framework (below) informs the development of future investigations into the effects of noise on marine invertebrates, helping researchers to identify the most appropriate and informative methods with respect to their specific questions. The framework, presented as a research development flow chart (Figure 7) can be worked through to assess the method options of prospective studies. This flow chart is additionally presented in a sequential key format in the supplementary material.

Given that all studies involving marine invertebrates should include particle motion measurements at the location the experimental animal receives the stimulus (ideally correlating with source measurements taken in the field) so that the noise field experienced (Popper et al., 2001; Nedelec et al., 2016; Hawkins and Popper, 2017) can be accurately characterized and compared across studies, this metric is not specifically mentioned in any of the below strategies.

The proposed framework is customisable and can be complemented with study-specific indicators where appropriate to maximise information gained with respect to a specific question. An example of this is larval culture experiments where a multi-generational broodstock is used, and study-specific indicators dealing with this aspect of the method can be added to the framework.

(a) Research Strategy 1

Number of Species – Single

Main Field of Biology – Behaviour /Physiology /Larval Development /Biochemistry /Genetics /Morphology & Trauma

When studying only one species, in a single experiment, it is beneficial to integrate as many areas of biology as possible (Kight and Swaddle, 2011), for a more comprehensive assessment of how noise affects that species. When the main response parameter investigated is either behavioural or physiological, securing samples for later biochemical and/or genetic analysis will add value. Conversely, when the work focuses on biochemical or genetic responses, then, where possible, changes in behaviour during the noise exposure should be assessed simultaneously or recorded for later analysis.

(b) Research Strategy 2

Main Field of Biology – Ecology/Fisheries

Where possible, studies focusing on ecology or fisheries should simultaneously examine the effects of noise on multiple species to gain information at the population or ecosystem level, if the response parameters allow easy comparability between all species studied. If this is not possible and only a single species can be investigated, complementary samples for later biochemical and/or genetic analysis should be taken whenever possible, or behavioural observations or recordings conducted during the exposure.

(c) Research Strategy 3

Number of Species – Multiple

Main Field of Biology – Behaviour /Physiology /Larval Development /Biochemistry /Genetics /Morphology & Trauma

When investigating the effects of noise on multiple species in an individual study, the parameters tested must be the same or equivalent to allow comparison between species. With multiple species experiments, the identification of species-specific responses in the same experimental/environmental context may only allow a single field of biology to be explored, however, value would be added when including more than one.

(d) Exposure Assessment

Whilst planning any experiments using the research development flow chart (Figure 7) an important question will always relate to whether the study will be performed in the field or the laboratory, and if the latter whether a field component can be included. Both research approaches have their own merits, with a combined approach allowing the fine control of laboratory-based experiments to, where appropriate, generate methods that can be taken into the field where the most realistic environmental and acoustic conditions are present. In laboratory experiments, large tanks should be utilised to reduce an excessive level of particle motion and potential exposure to noise levels greater than intended. All experiments should be conducted with a sample size compatible with the systems, species, resources, and techniques of the study. The sample size should be large enough to allow robust statistical analysis and conclusions about the effects anthropogenic noise is having on the organisms in question. The exposure assessment portion of the research development flowchart covers these questions and should be worked through for all intended research strategies.

V. Conclusions and Future Directions

This review summarized and assessed the methods of studies that have investigated the effects of anthropogenic noise on marine invertebrates from 1982 to 2021. Whilst our assessment revealed a number of “limitations” in the methods or experimental designs applied in said studies, the aim was not to evaluate, *sensu stricto*, the results generated. Instead, by assessing the trends in research methods over time, an accurate picture of marine invertebrate noise research in the past and its evolution to the current state of the art was generated. Our results show that earlier generalizations regarding the current state of the field have underestimated the recent progress made.

Most of the changes in the chosen research approach happened between 2012 and 2021, a period characterised by a 3-fold increase in the number of publications (77% of total published studies on the effects of noise on marine invertebrates) compared to 1982 to 2011. Along with the increasing interest and research effort in the field, a number of new trends have developed in the methods chosen. The majority of these trends move the field away from the identified "limitations" towards the identified "advantages" (Figures 4-6). 39% of papers published between 2012 and 2021 have included particle motion measurements, allowing more accurate characterisation of the noise field experienced by the focal animals and providing a higher degree of precision when reproducing noise in tank-based trials. The use of large tanks for playback experiments in combination with particle motion measurements allows conclusive experiments since noise is represented as accurately as possible in the laboratory.

Of the studies published since 2012, 34% have also included a field component to help validate results in situ. There has however been a renewed trend towards aquarium-only studies, likely due to their larger potential for fine-scale control and ability to act as a starting point in noise investigations. This is especially useful when studying a species for the first time in this context, given the often difficult logistics and high expense of a field study.

Conducting research in a multidisciplinary integrative way, although logistically challenging, allows a more thorough assessment of the effects of anthropogenic noise, and shows not only whether noise affects an organism but potentially how and why these responses occur. There is a developing trend towards studies that focus on a single species in detail, with 39% of papers from 2012 to 2021 assessing the effects of noise on multiple levels of biological organization. Such studies generate a more complete understanding of how noise is affecting individual species, both through changes in visible behaviour and more cryptically through physiological and biochemical investigation (see Day *et al*., 2016, 2017; Filiciotto *et al*., 2016; Jolivet *et al*., 2016; Peng *et al*., 2016; Wale *et al*., 2019;

Ruiz-Ruiz *et al*., 2020). This way of conducting research forms part of two of the three here suggested strategies for conducting experiments on the effects of noise on marine invertebrates. A third strategy focuses on using multiple species in an individual experiment, a strategy which 25% of studies have followed since 2012. For all three strategies, knowing and considering the sound levels in the environment where an organism originates from is important, as the animals' previous exposure, or naivety, to noise may affect the response elicited in noise exposure experiments (Day *et al*., 2020).

The conceptual framework (Figure 7) presented in this review can be used as a guide for future work on marine invertebrates and anthropogenic noise. This formalised way of assessing and identifying the most adequate research methods and experimental design can be adapted not only for other taxa in noise research, but also serve as an outline for methodological analyses in other disciplines where descriptors can be specifically adapted or chosen for that particular field.

Looking to the future, there are a number of recommended directions for the field of marine invertebrate noise research. First and foremost is the inclusion of particle motion measurements in all studies. There is also an urgent need for particle motion measurements of noise sources in the field. These measurements will allow future studies to be accurately calibrated, and past studies to be validated against these values, making their findings more policy relevant. For future studies, it would be desirable to investigate an organism on multiple levels of biological organization to enable a more complete understanding of the effects of noise. Where possible, the use of a complementary laboratory and field approach should be taken, where the fine-scale control of tank-based experiments is coupled with field trials to validate the findings in situ. Additionally, if feasible, dose-response relationships should be explored within the study so that the threshold of a particular response can be identified. Regulators often request dose dependency measurements, for incorporation into legislation to help reduce noise levels in the environment and protect marine biota

(Popper *et* al., 2020; Williams *et al*., 2015b). To improve the translation from research outcomes into policy-making outputs, we advocate the inclusion of this component more frequently in noise-related research.

Given the multiple interactions between man and the marine environment, there is an urgent need to work across disciplines and integrate multiple stressors into studies, investigating any stressor interactions that may occur in the "real world". Long term exposures experiments, looking at both regular and sporadic noise exposure, will help identify any levels of habituation or tolerance that develop, along with identifying effects on growth, reproduction, and multi-generational responses. Similarly, cross-taxa experiments will allow research to be conducted in a holistic manner that assesses noise effects on species interactions, environmental dynamics, and larger ecosystemic effects of anthropogenic noise.

VI. References

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., van der Schaar, M., López-Bejar, M., Morell, M., Zaugg, S., Houégnigan, L., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front. Ecol. Environ. 9, 489–493. doi:10.1890/100124

Andriguetto-Filho, J.M., Ostrensky, A., Pie, M.R., Silva, U. a., Boeger, W. a., 2005. Evaluating the impact of seismic prospecting on artisanal shrimp fisheries. Cont. Shelf Res. 25, 1720–1727. doi:10.1016/j.csr.2005.05.003

Boudreau, M., Courtenay, S.C., Lee, K., 2009. Proceedings of a workshop held 23 January 2007 at the Gulf Fisheries Center Potential Impacts of Seismic Energy on Snow Crab: An Update to the September 2004 Review, in: Can. Tech. Rep. Fish. Aquat. Sci. p. vi - 31.

Branscomb, E.S., Rittschof, D., 1984. An Investigation of Low Frequency Sound Waves as a Means of Inhibiting Barnacle Settlement. J. Exp. Mar. Bio. Ecol. 79, 149–154.

Breithaupt, T., Tautz, J., 1988. Vibration Sensitivity of the Crayfish Statocyst. Naturwissenschaften 75, 310–312.

Breithaupt, T., Tautz, J., 1990. The sensitivity of crayfish mechanoreceptors to hydrodynamic and acoustic stimuli, in: Wiese, K., Krenz, W.-D., Tautz, J, Reichert, H., Mulloney, B. (Eds.), Frontiers in Crustacean Neurobiology. Birkhäuser, Basel, pp. 114–120.

Breithaupt, T., 2002. Sound perception in aquatic crustaceans, in: Wiese, K. (Ed.), The Crustacean Nervous System. Springer, Berlin, pp. 548–559.

Brewer, P.G., Hester, K., 2009. Ocean Acidification and the Increasing Transparency of the Ocean to Low-Frequency Sound. Oceanography 22, 86–93. doi:10.5670/oceanog.2009.99

Budelmann, B.U., 1992. Hearing in Non-arthropod Invertebrates, in: The Evolutionary Biology of Hearing; Webster D.B., Fay, R.R., P.A.N., Ed.; Springer-Verlag: New York, pp. 141–155.

Carroll, A.G., Przeslawski, R., Duncan, A., Gunning, M., Bruce, B., 2017. A Critical Review of the Potential Impacts of Marine Seismic Surveys on Fish & Invertebrates. Mar. Pollut. Bull. 114, 9–24. doi:10.1016/j.marpolbul.2016.11.038

Celi, M., Filiciotto, F., Vazzana, M., Arizza, V., Maccarrone, V., Ceraulo, M., Mazzola, S., Buscaino, G., 2015. Shipping Noise Affecting Immune Responses of European Spiny Lobster (*Palinurus elephas*). Can. J. Zool. 121, 113–121. doi:10.1139/cjz-2014-0219

Charifi, M., Sow, M., Ciret, P., Benomar, S., Massabuau, J.C., 2017. The sense of hearing in the Pacific oyster, *Magallana gigas*. PLoS One 12, 1–19. doi:10.1371/journal.pone.0185353

Christian, J.R., Mathieu, A., Thomson, D.H., 2003. Effect of Seismic Energy on Snow Crab (*Chionoecetes opilio*). Report from LGL Ltd. and Oceans Ltd. for the National Energy Board, File No. CAL, pp.1-00364.

Caruthers, J.W., 1977. Fundamentals of Marine acoustics. Elsevier Scientific Publishing Company, Amsterdam.

Day, R.D., McCauley, R.D., Fitzgibbon, Q.P., Hartmann, K., Semmens, J.M., 2019. Seismic air guns damage rock lobster mechanosensory organs and impair righting reflex. Proc. R. Soc. B Biol. Sci. 286. doi:10.1098/rspb.2019.1424

Day, R.D., McCauley, R.D., Fitzgibbon, Q.P., Hartmann, K., Semmens, J.M., 2017. Exposure to seismic air gun signals causes physiological harm and alters behavior in the scallop *Pecten fumatus*. Proc. Natl. Acad. Sci. U. S. A. 114, E8537–E8546. doi:10.1073/pnas.1700564114

Day, R.D., McCauley, R.D., Fitzgibbon, Q.P., Semmens, J.M., 2016. Seismic air gun exposure during early-stage embryonic development does not negatively affect spiny lobster *Jasus edwardsii* larvae (Decapoda:Palinuridae). Sci. Rep. 6, 22723. doi:10.1038/srep22723

Day, R.D., Fitzgibbon, Q.P., McCauley, R.D., Hartmann, K., Semmens, J.M., 2020. Lobsters With Pre-Existing Damage to Their Mechanosensory Statocyst Organs Do Not Incur Further Damage From Exposure to Seismic Air Gun Signals. Environ. Pollut. 267, 115478. doi:10.1016/j.envpol.2020.115478

de Soto, N.A., 2016. Peer-Reviewed Studies on the Effects of Anthropogenic Noise on Marine Invertebrates: From Scallop Larvae to Giant Squid, in: Popper, A.N., Hawkins, A. (Eds.), The Effects of Noise on Aquatic Life II, Advances in Experimental Medicine and Biology. Springer New York, New York, NY, pp. 17–26. doi:10.1007/978-1-4939-2981-8_3 de Soto, N.A., Delorme, N., Atkins, J., Howard, S., Williams, J., Johnson, M., 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. Sci. Rep. 3, 2831. doi:10.1038/srep02831

De Vincenzi, G., Maccarrone, V., Filiciotto, F., Buscaino, G., Mazzola, S., 2015. Behavioural Responses of the European Spiny Lobster, *Palinurus elephas* (Fabricius, 1787), to Conspecific and Synthetic Sounds. Crustaceana 88, 523–540. doi:10.1163/15685403-00003430

DFO, 2004. Potential Impacts of Seismic Energy on Snow Crab, DFO Canada Science Advisory Secretariat, Habitat Status Report 2004/003.

Di Franco, E., Pierson, P., Di Iorio, L., Calò, A., Cottalorda, J.M., Derijard, B., Di Franco, A., Galvé, A., Guibbolini, M., Lebrun, J. Micheli, F., 2020. Effects of Marine Noise Pollution on Mediterranean Fishes and Invertebrates: A Review. Mar. Pollut. Bull., 159, p.111450. doi:10.1016/j.marpolbul.2020.111450

Di Stefano, V., Maccarrone, V., Buscaino, G., Mazzola, S., Filiciotto, F., 2016. Experimental Procedure for the Evaluation of Behaviour and Biochemical Stress of *Palinurus elephas* exposed to boat noise pollution. IAMC-CNR Capo Granitola.

Doyle, R., Kim, J., Pe, A., Blumstein, D.T., 2020. Are Giant Clams (*Tridacna maxima*) Distractible? A Multi-Modal Study. PeerJ 8. doi:10.7717/peerj.10050

Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., Erbe, C., Gordon, T.A.C., Halpern, B.S., Harding, H.R., Havlik, M.N., Meekan, M., Merchant, N.D., Miksis-Olds, J.L., Parsons, M., Predragovic, M., Radford, A.N., Radford, C.A., Simpson, S.D., Slabbekoorn, H., Staaterman, E., Van Opzeeland, I.C., Winderen, J., Zhang, X., Juanes, F.,

2021. The soundscape of the Anthropocene ocean. Science, 371(6529). doi:10.1126/science.aba4658

Ennos, A.R., 2000. Statistical and Data Handling Skills in Biology. Pearson Education.

Ferrier-Pagès, C., Leal, M.C., Calado, R., Schmid, D.W., Bertucci, F., Lecchini, D. and Allemand, D., 2021. Noise Pollution on Coral Reefs? - A Yet Underestimated Threat to Coral Reef Communities. Mar. Pollut. Bull., 165, p.112129. doi:10.1016/j.marpolbul.2021.112129

Fewtrell, J.L., McCauley, R.D., 2012. Impact of air gun noise on the behaviour of marine fish and squid. Mar. Pollut. Bull. 64, 984–93. doi:10.1016/j.marpolbul.2012.02.009

Fields, D.M., Handegard, N.O., Dalen, J., Eichner, C., Malde, K., Karlsen, Ø., Skiftesvik, A.B., Durif, C.M.F., Browman, H.I., Ratilal, P., 2019. Airgun Blasts Used in Marine Seismic Surveys Have Limited Effects on Mortality, and No Sublethal Effects on Behaviour or Gene Expression, in the Copepod *Calanus finmarchicus*. ICES J. Mar. Sci. 76, 2033–2044. doi:10.1093/icesjms/fsz126

Filiciotto, F., Vazzana, M., Celi, M., Maccarrone, V., Ceraulo, M., Buffa, G., Arizza, V., de Vincenzi, G., Grammauta, R., Mazzola, S., Buscaino, G., 2016. Underwater Noise from Boats: Measurement of its Influence on the Behaviour and Biochemistry of the Common Prawn (*Palaemon serratus*, Pennant 1777). J. Exp. Mar. Bio. Ecol. 478, 24–33. doi:10.1016/j.jembe.2016.01.014

Filiciotto, F., Vazzana, M., Celi, M., Maccarrone, V., Ceraulo, M., Buffa, G., Stefano, V. Di, Mazzola, S., Buscaino, G., 2014. Behavioural and Biochemical Stress Responses of *Palinurus elephas* after Exposure to Boat Noise Pollution in Tanks. Mar. Pollut. Bull. 84, 104–114. doi:10.1016/j.marpolbul.2014.05.029

Fitzgibbon, Q.P., Day, R.D., McCauley, R.D., Simon, C.J., Semmens, J.M., 2017. The impact of seismic air gun exposure on the haemolymph physiology and nutritional condition of spiny lobster, *Jasus edwardsii*. Mar. Pollut. Bull. 125, 146–156. doi:10.1016/j.marpolbul.2017.08.004

Goodall, C., Chapman, C., Neil, D., 1990. The Acoustic Response Threshold of the Norway Lobster, *Nephrops Norvegicus* (L.) in a Free Sound Field, in: Wiese, K., Krenz, W.-D., Tautz, J., Reichert, H., Mulloney, B. (Eds.), Frontiers in Crustacean Neurobiology. Birkhäuser Basel, Basel, pp. 106–113. doi:10.1007/978-3-0348-5689-8_11

Gray, M.D., Rogers, P.H., Popper, A.N., Hawkins, A.D., Fay, R.R., 2016. “Large” Tank Acoustics: How Big Is Big Enough? in: Popper, A.N., Hawkins, A. (Eds.), The Effects of Noise on Aquatic Life II. Springer New York, New York, NY, pp. 363–369. doi:10.1007/978-1-4939-2981-8_43

Guerra, A., González, A.F., Rocha, F., 2004. A review of the records of giant squid in the north-eastern Atlantic and severe injuries in Architeuthis dux stranded after acoustic explorations. ICES Annu. Sci. Conf. 29, 1–17.

Guerra, Á., González, Á.F., Pascual, S., Dawe, E.G., 2011. The giant squid Architeuthis: An emblematic invertebrate that can represent concern for the conservation of marine biodiversity. Biol. Conserv. 144, 1989–1997. doi:10.1016/j.biocon.2011.04.021

Hall, J.R., Lehnert, S.J., Gonzalez, E., Kumar, S., Hanlon, J.M., Morris, C.J., Rise, M.L., 2021. Snow Crab (*Chionoecetes opilio*) Hepatopancreas Transcriptome: Identification and Testing of Candidate Molecular Biomarkers of Seismic Survey Impact. Fish. Res. 234, 105794. doi:10.1016/j.fishres.2020.105794

Harrington, J.J., Mcallister, J., Semmens, J.M., 2010. Assessing the short-term impact of seismic surveys on adult commercial scallops (*Pecten fumatus*) in Bass Strait.

Hawkins, A.D., Pembroke, A.E., Popper, A.N., 2014. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish Biol. Fish. 25, 39–64. doi:10.1007/s11160-014-9369-3

Hawkins, A.D., Popper, A.N., 2017. A Sound Approach to Assessing the Impact of Underwater Noise on Marine Fishes and Invertebrates. ICES J. Mar. Sci. J. du Cons. 74, fsw205. doi:10.1093/icesjms/fsw205

Hazelwood, R., Macey, P., 2021. Noise Waveforms within Seabed Vibrations and Their Associated Evanescent Sound Fields. J. Mar. Sci. Eng. 9. doi:10.3390/jmse9070733

Hebel, D.K., Jones, M.B., Depledge, M.H., 1997. Responses of Crustaceans to Contaminant Exposure: A holistic approach. Estuar. Coast. Shelf Sci. 44, 177–184. doi:10.1006/ecss.1996.0209

Hildebrand, J., 2009. Anthropogenic and Natural Sources of Ambient Noise in the Ocean. Mar. Ecol. Prog. Ser. 395, 5–20. doi:10.3354/meps08353

Heyward, A., Colquhoun, J., Cripps, E., McCorry, D., Stowar, M., Radford, B., Miller, K., Miller, I., Battershill, C., 2018. No Evidence of Damage to the Soft Tissue or Skeletal Integrity of Mesophotic Corals Exposed to a 3D Marine Seismic Survey. Mar. Pollut. Bull. 129, 8–13. doi:10.1016/j.marpolbul.2018.01.057

Hubert, J., Campbell, J., van der Beek, J.G., den Haan, M.F., Verhave, R., Verkade, L.S., Slabbekoorn, H., 2018. Effects of Broadband Sound Exposure on the Interaction Between

Foraging Crab and Shrimp – A Field Study. Environ. Pollut. 243, 1923–1929. doi:10.1016/j.envpol.2018.09.076

Ilyina, T., Zeebe, R.E., Brewer, P.G., 2010. Future Ocean Increasingly Transparent to Low-Frequency Sound Owing to Carbon Dioxide Emissions. Nat. Geosci. 3, 18–22. doi:10.1038/ngeo719

Institute of Shipping Economics and Logistics, 2016. Shipping Statistics and Market Review. ISL Inst. Shipp. Econ. Logist. 60.

Jolivet, A., Tremblay, R., Olivier, F., Gervaise, C., Sonier, R., Genard, B., Chauvaud, L., 2016. Validation of Trophic and Anthropic Underwater Noise as Settlement Trigger in Blue Mussels. Sci. Rep. 6, 33829. doi:10.1038/srep33829

Jones, I.T., Stanley, J.A., Mooney, T.A., 2020. Impulsive pile driving noise elicits alarm responses in squid (*Doryteuthis pealeii*). Mar. Pollut. Bull. 150, 110792. doi:10.1016/j.marpolbul.2019.110792

Jones, I.T., Peyla, J.F., Clark, H., Song, Z., Stanley, J.A., Mooney, T.A., 2021. Changes in Feeding Behavior of Longfin Squid (*Doryteuthis pealeii*) During Laboratory Exposure to Pile Driving Noise. Mar. Environ. Res. 165, 105250. doi:10.1016/j.marenvres.2020.105250

Kaifu, K., Segawa, S., Tsuchiya, K., 2007. Behavioral Responses to Underwater Sound in the Small Benthic Octopus *ocellatus*. J. Mar. Acoust. Soc. Japan 34, 266–273. doi:10.3135/jmasj.34.266

Kastelein, R.A., 2008. Effects of vibrations on the behaviour of cockles (bivalve molluscs). Bioacoustics 17, 74–75. doi:10.1080/09524622.2008.975377

Kight, C.R., Swaddle, J.P., 2011. How and Why Environmental Noise Impacts Animals: An Integrative, Mechanistic Review. Ecol. Lett. 14, 1052–61. doi:10.1111/j.1461-0248.2011.01664.x

Kunc, H.P., Lyons, G.N., Sigwart, J.D., McLaughlin, K.E., Houghton, J.D.R., 2014. Anthropogenic Noise Affects Behavior Across Sensory Modalities. Am. Nat. 184, E93–E100. doi:10.1086/677545

La Bella, G., Cannata, S., Froglia, C., Ratti, S., Rivas, G., 1996. First assessment of effects of air-gun seismic shooting on marine resources in the Central Adriatic Sea. Int. Conf. Heal. Saf. Environ. Oil Gas Explor. Prod. 1, 227–238. doi:10.2523/35782-ms

Lagardère, J.-P., 1982. Effects of Noise on Growth and Reproduction of *Crangon* in Rearing Tanks. Mar. Biol. 71, 177–185.

Langhamer, O., Holand, H., Rosenqvist, G., 2016. Effects of an Offshore Wind Farm (OWF) on the Common Shore Crab *Carcinus maenas*: Tagging Pilot Experiments in the Lillgrund Offshore Wind Farm (Sweden). PLoS One 11. doi:10.1371/journal.pone.0165096

Lecchini, D., Bertucci, F., Gache, C., Khalife, A., Besson, M., Roux, N., Berthe, C., Singh, S., Parmentier, E., Nugues, M.M., Brooker, R.M., Dixson, D.L., Hédouin, L., 2018. Boat Noise Prevents Soundscape-based Habitat Selection by Coral Planulae. Sci. Rep. 8, 1–9. doi:10.1038/s41598-018-27674-w

Lin, C., Zhang, L., Pan, Y., Yang, H., 2017. Influence of Vibration Caused by Sound on Migration of Sea Cucumber *Apostichopus japonicus*. Aquac. Res. 48, 5072–5082. doi:10.1111/are.13324

Lindeboom, H.J., Kouwenhoven, H.J., Bergman, M.J.N., Bouma, S., Brasseur, S., Daan, R., Fijn, R.C., De Haan, D., Dirksen, S., Van Hal, R., Hille Ris Lambers, R., Ter Hofstede, R., Krijgsveld, K.L., Leopold, M., Scheidat, M., 2011. Short-term Ecological Effects of an Offshore Wind Farm in the Dutch Coastal Zone; Acompilation. Environ. Res. Lett. 6. doi:10.1088/1748-9326/6/3/035101

Lossent, J., Lejart, M., Folegot, T., Clorennec, D., Di Iorio, L., Gervaise, C., 2018. Underwater operational noise level emitted by a tidal current turbine and its potential impact on marine fauna. Mar. Pollut. Bull. 131, 323–334. doi:10.1016/j.marpolbul.2018.03.024

Malme, C.I., Thomson, D.H., 1973. Marine Mammals and Noise. San Deigo, Calif. Acad. 9.

Marine Board, 2010. Marine Renewable Energy - Research Challenges and Opportunities for a new Energy Era in Europe.

McCauley, R., Fewtrell, J., Duncan, A., Jenner, C., Jenner, M-N., Penrose, J., Prince, R., Adhitya, A., Murdoch, J., McKabe, K., 2000. Marine seismic surveys: analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid. Australian Petroleum Production and Exploration Association (APPEA) Journal, pp. 692–706

McCauley, R.D., Day, R.D., Swadling, K.M., Fitzgibbon, Q.P., Watson, R.A., Semmens, J.M., 2017. Widely used marine seismic survey air gun operations negatively impact zooplankton. Nat. Ecol. Evol. 1, 1–8. doi:10.1038/s41559-017-0195

McDonald, J.I., Wilkens, S.L., Stanley, J. A, Jeffs, A. G., 2014. Vessel Generator Noise as a Settlement cue for Marine Biofouling Species. Biofouling 1–9. doi:10.1080/08927014.2014.919630

Mooney, T.A., Samson, J.E., Schlunk, A.D., Zacarias, S., 2016. Loudness-dependent Behavioral Responses and Habituation to Sound by the Longfin Squid (*Doryteuthis pealeii*). J. Comp. Physiol. A Neuroethol. Sensory, Neural, Behav. Physiol. 202, 489–501. doi:10.1007/s00359-016-1092-1

Morris, C.J., Cote, D., Martin, B., Kehler, D., 2018. Effects of 2D seismic on the snow crab fishery. Fish. Res. 197, 67–77. doi:10.1016/j.fishres.2017.09.012

Morris, C.J., Cote, D., Martin, S.B., Mullowney, D., 2020. Effects of 3D Seismic Surveying on Snow Crab Fishery. Fish. Res. 232, 0–9. doi:10.1016/j.fishres.2020.105719

Myrberg, A. A., 1978. Ocean Noise and the Behaviour of Marine Mammals. Acad. Press.

Nedelec, S.L., Campbell, J., Radford, A.N., Simpson, S.D., Merchant, N.D., Fisher, D., 2016. Particle Motion: The Missing Link in Underwater Acoustic Ecology. Methods Ecol. Evol. 7, 836–842. doi:10.1111/2041-210X.12544

Nousek-mcgregor, A.E., Tee, F., Mei, L., 2016. Does Noise From Shipping and Boat Traffic Affect Predator Vigilance in the European Common Hermit Crab? in: Popper, A.N., Hawkins, A.D. (Eds.), The Effects of Noise on Aquatic Life II. pp. 767–774. doi:10.1007/978-1-4939-2981-8_94

O'Hara, J., Wilcox, J.R., 1990. Avoidance Responses of Loggerhead Turtles, *Caretta,* to Low Frequency Sound. Copeia 1990, 564–567.

Payne, J.F., Andrews, C.A., Cook, A.L., Christian, J.R., 2007. Pilot Study on the Effects of Seismic Air Gun Noise on Lobster (*Homarus americanus*). Can. Tech. Rep. Fish. Aquat. Sci. 2712 1–46.

Pearson, W.H., Skalski, J.R., Sulkin, S.D., Malme, C.I., 1994. Effects of Seismic Energy Releases on the Survival and Development of Zoeal Larvae of Dungeness Crab (*Cancer magister*) 38, 93–113.

Peng, C., Zhao, X., Liu, S., Shi, W., Han, Y., Guo, C., Jiang, J., Wan, H., Shen, T., Liu, G., 2016. Effects of Anthropogenic Sound on Digging Behavior, Metabolism, Ca2+/Mg2+ ATPase Activity, and Metabolism-related Gene Expression of the Bivalve *Sinonovacula constricta*. Sci. Rep. 6, 24266. doi:10.1038/srep24266

Pieretti, N., Lo Martire, M., Corinaldesi, C., Musco, L., Dell'Anno, A., Danovaro, R., 2020. Anthropogenic Noise and Biological Sounds in a Heavily Industrialized Coastal Area (Gulf of Naples, Mediterranean Sea). Mar. Environ. Res. 159, 105002. doi:10.1016/j.marenvres.2020.105002

Pine, M.K., Jeffs, A.G., Radford, C. a, 2012. Turbine Sound May Influence the Metamorphosis Behaviour of Estuarine Crab Megalopae. PLoS One 7, e51790. doi:10.1371/journal.pone.0051790

Popper, A.N., Salmon, M., Horch, K.W., 2001. Acoustic Detection and Communication by Decapod Crustaceans. J. Comp. Physiol. A Sensory, Neural, Behav. Physiol. 187, 83–89. doi:10.1007/s003590100184

Popper, A.N., Hawkins, A.D., Thomsen, F., 2020. Taking the Animals' Perspective Regarding Anthropogenic Underwater Sound. Trends Ecol. Evol. 1–8. doi:10.1016/j.tree.2020.05.002

Przeslawski, R., Huang, Z., Anderson, J., Carroll, A.G., Edmunds, M., Hurt, L., Williams, S., 2018. Multiple field-based methods to assess the potential impacts of seismic surveys on scallops. Mar. Pollut. Bull. 129, 750–761. doi:10.1016/j.marpolbul.2017.10.066

Regnault, M., Lagardère, J., 1983. Effects of Ambient Noise on the Metabolic Level of *Crangon crangon* (Decapoda, Natantia). Mar. Ecol. Prog. Ser. Oldend. 11, 71–78.

Roberts, L., Cheesman, S., Breithaupt, T., Elliott, M., 2015. Sensitivity of the Mussel *Mytilus edulis* to Substrate-borne Vibration in Relation to Anthropogenically Generated Noise. Mar. Ecol. Prog. Ser. 538, 185–195. doi:10.3354/meps11468

Roberts, L., Cheesman, S., Elliott, M., Breithaupt, T., 2016. Sensitivity of *Pagurus bernhardus* (L.) to Substrate-borne Vibration and Anthropogenic noise. J. Exp. Mar. Bio. Ecol. 474, 185–194. doi:10.1016/j.jembe.2015.09.014

Roberts, L., Laidre, M.E., 2019. Finding a home in the noise: Cross-modal impact of anthropogenic vibration on animal search behaviour. Biol. Open 8. doi:10.1242/bio.041988

Ross, D., 2005. Ship Sources of Ambient Noise. IEEE J. Ocean. Eng. 30, 257–261.

Ruiz-Ruiz, P. A., Hinojosa, I. A., Urzua, A., & Urbina, M. A. (2019, July). Anthropogenic Noise Disrupts Mating Behavior and Metabolic Rate in a Marine Invertebrate. In Proceedings of Meetings on Acoustics 5ENAL (Vol. 37, No. 1, p. 040006). Acoustical Society of America. doi:10.1121/2.0001302

Samson, J.E., Mooney, T.A., Gussekloo, S.W.S., Hanlon, R.T., 2014. Graded Behavioral Responses and Habituation to Sound in the Common Cuttlefish *Sepia officinalis*. J. Exp. Biol. 217, 4347–4355. doi:10.1242/jeb.113365

Schwarz, A.L., Greer, G.L., 1984. Responses of Pacific Herring Clupea *harengus pallasi*, to Some Underwater Sounds. Can. J. Fish. Aquat. Sci. 41, 1183–1192.

Shi, W., Han, Y., Guan, X., Rong, J., Du, X., Zha, S., Tang, Y., Liu, G., 2019. Anthropogenic noise aggravates the toxicity of cadmium on some physiological characteristics of the blood clam *Tegillarca granosa*. Front. Physiol. 10, 1–10. doi:10.3389/fphys.2019.00377

Solan, M., Hauton, C., Godbold, J.A., Wood, C.L., Leighton, T.G., White, P., 2016. Anthropogenic Sources of Underwater Sound can Modify How Sediment-dwelling Invertebrates Mediate Ecosystem Properties. Sci. Rep. 6, 20540. doi:10.1038/srep20540

Sole, M., Lombarte, A., Lopez-Bejar, M., Mao, A., Andre, M., 2010. Imaging techniques to study the effects of low frequency sounds on cephalopods spp. Instrum. Viewp. 102.

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., André, M., 2013. Ultrastructural damage of *Loligo vulgaris* and *Illex coindetii* statocysts after low frequency sound exposure. PLoS One 8, e78825. doi:10.1371/journal.pone.0078825

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., van der Schaar, M., André, M., 2013. Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? Deep Sea Res. Part II Top. Stud. Oceanogr. 95, 160–181. doi:10.1016/j.dsr2.2012.10.006

Solé, M., Lenoir, M., Fontuño, J.M., Durfort, M., Van Der Schaar, M., André, M., 2016. Evidence of Cnidarians sensitivity to sound after exposure to low frequency noise underwater sources. Sci. Rep. 6. doi:10.1038/srep37979

Solé, M., Lenoir, M., Fortuño, J.M., Van Der Schaar, M., André, M., 2018. A critical period of susceptibility to sound in the sensory cells of cephalopod hatchlings. Biol. Open 7, 1–13. doi:10.1242/bio.033860

Solé, M., Sigray, P., Lenoir, M., Van Der Schaar, M., Lalander, E., André, M., 2017. Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma. Sci. Rep. 7, 1–13. doi:10.1038/srep45899

Spiga, I., 2016. Acoustic Response to Playback of Pile-Driving Sounds by Snapping Shrimp, in: Popper, A.N., Hawkins, A.D. (Eds.), The Effects of Noise on Aquatic Life II. pp. 1081–1088. doi:10.1007/978-1-4939-2981-8134

Spiga, I., Caldwell, G.S., Bruintjes, R., 2016. Influence of Pile Driving on the Clearance Rate of the Blue Mussel, *Mytilus edulis* (L.), in: Proceedings of Meetings on Acoustics. doi:10.1121/2.0000277

Staaterman, E.R., Clark, C.W., Gallagher, A.J., Claverie, T., Vries, M.S. de, Patek, S.N., 2012. Acoustic Ecology of the California Mantis Shrimp (*Hemisquilla californiensis*), in: Hawkins, A.D., Popper, A.N. (Eds.), The Effects of Noise on Aquatic Life. pp. 165–168. doi:10.1007/978-1-4419-7311-5_37

Stanley, J.A., Wilkens, S.L., Jeffs, A.G., 2014. Fouling in your own nest: vessel noise increases biofouling. Biofouling 30, 837–844. doi:10.1080/08927014.2014.938062

Slater, M., Fricke, E., Weiss, M., Rebelein, A., Bögner, M., Preece, M., Radford, C., 2020. The Impact of Aquaculture Soundscapes on Whiteleg Shrimp *Litopenaeus vannamei* and Atlantic Salmon *Salmo salar*. Aquac. Environ. Interact. 12, 167–177. doi:10.3354/AEI00355

Stanley, J.A., Wilkens, S., McDonald, J.I., Jeffs, A.G., 2016. Vessel Noise Promotes Hull Fouling. Adv. Exp. Med. Biol. 875, 1097–1104. doi:10.1007/978-1-4939-2981-8_136

Stocks, J.R., Broad, A., Radford, C., Minchinton, T.E., Davis, A.R., 2012. Response of Marine Invertebrate Larvae to Natural and Anthropogenic Sound: a Pilot Study. Open Mar. Biol. J. 6, 57–61. doi:10.2174/1874450801206010057

Tidau, S., Briffa, M., 2019. Anthropogenic noise pollution reverses grouping behaviour in hermit crabs. Anim. Behav. 151, 113–120. doi:10.1016/j.anbehav.2019.03.010

Tidau, S., Briffa, M., 2019. Distracted decision makers: Ship noise and predation risk change shell choice in hermit crabs. Behav. Ecol. 30, 1157–1167. doi:10.1093/beheco/arz064

Tyack, P., 2008. Implications for Marine Mammals of Large-scale Changes in the Marine Acoustic Environment. J. Mammal. 89, 549–558. doi:10.1644/07-MAMM-S-307R.1

Vazzana, M., Celi, M., Maricchiolo, G., Genovese, L., Corrias, V., Quinci, E.M., de Vincenzi, G., Maccarrone, V., Cammilleri, G., Mazzola, S., Buscaino, G., Filiciotto, F., 2016. Are Mussels able to Distinguish Underwater Sounds? Assessment of the Reactions of *Mytilus galloprovincialis* after Exposure to Lab-generated Acoustic Signals. Comp. Biochem. Physiol. -Part A Mol. Integr. Physiol. 201, 61–70. doi:10.1016/j.cbpa.2016.06.029

Vazzana, M., Ceraulo, M., Mauro, M., Papale, E., Dioguardi, M., Mazzola, S., Arizza, V., Chiaramonte, M., Buscaino, G., 2020. Effects of Acoustic Stimulation on Biochemical Parameters in the Digestive Gland of Mediterranean Mussel *Mytilus galloprovincialis* (Lamarck, 1819). J. Acoust. Soc. Am. 147, 2414–2422. doi:10.1121/10.0001034

Vazzana, M., Mauro, M., Ceraulo, M., Dioguardi, M., Papale, E., Mazzola, S., Arizza, V., Beltrame, F., Inguglia, L., Buscaino, G., 2020. Underwater High Frequency Noise: Biological Responses in Sea Urchin *Arbacia lixula* (Linnaeus, 1758). Comp. Biochem. Physiol. -Part A Mol. Integr. Physiol. 242, 110650. doi:10.1016/j.cbpa.2020.110650

Wale, M.A., Briers, R.A., Hartl, M.G.J., Bryson, D., Diele, K., 2019. From DNA to Ecological Performance: Effects of Anthropogenic Noise on a Reef-Building Mussel. Sci. Total Environ. 689, 126–132. doi:10.1016/j.scitotenv.2019.06.380

Wale, M.A., Simpson, S.D., Radford, A.N., 2013a. Noise Negatively Affects Foraging and Antipredator Behaviour in Shore Crabs. Anim. Behav. 86, 111–118. doi:10.1016/j.anbehav.2013.05.001

Wale, M.A., Simpson, S.D., Radford, A.N., 2013b. Size-dependent Physiological Responses of Shore Crabs to Single and Repeated Playback of Ship Noise. Biol. Lett. 9, 20121194. doi:10.1098/rsbl.2012.1194

Walsh, E.P., Arnott, G., Kunc, H.P., 2017. Noise affects resource assessment in an invertebrate. Biol. Lett. 13. doi:10.1098/rsbl.2017.0098

Wilkens, S.L., Stanley, J. A, Jeffs, A. G., 2012. Induction of Settlement in Mussel (*Perna canaliculus*) Larvae by Vessel Noise. Biofouling 28, 65–72. doi:10.1080/08927014.2011.651717

Woodcock, S.H., Johansen, J.L., Steer, M.A., Gaylard, S.G., 2014. Regional Sustainability Planning in the Upper Spencer Gulf Investigating potential impacts of shipping on giant Australian cuttlefish.

Williams, R., Wright, A.J., Ashe, E., Blight, L.K., Bruintjes, R., Canessa, R., Clark, C.W., Cullis-Suzuki, S., Dakin, D.T., Dewey, R.K., Dorocicz, J., Erbe, C., Hammond, P.S., Merchant, N.D., Nowlan, L., Wale, M.A., 2015. Impacts of Anthropogenic Noise on Marine Life: Publication Patterns, New Discoveries, and Future Directions in Research and Management. Ocean Coast. Manag. 115, 17-24. doi: 10.1016/j.ocecoaman.2015.05.021

Yoshimura, I., Wakana, A., Hamada, C., 1997. A Performance Comparison of Maximum Contrast Methods to Detect Dose Dependency. Ther. Innov. Regul. Sci. 31, 423–432. doi:10.1177/009286159703100213

Zhadan, P.M., 2005. Directional sensitivity of the Japanese scallop *Mizuhopecten yessoensis* and Swift scallop *Chlamys swifti* to water-borne vibrations. Russ. J. Mar. Biol. 31, 28–35. doi:10.1007/s11179-005-0040-7

Zhou, W., Huang, X., Xu, X., 2018. Changes of movement behavior and HSP70 gene expression in the hemocytes of the mud crab (*Scylla paramamosain*) in response to acoustic stimulation. Mar. Freshw. Behav. Physiol. 51, 3–14. doi:10.1080/10236244.2018.1439337

Zhou, W., Xu, X., Tu, X., Yougan, C., 2016. Preliminary Exploration for Effects of Sound Stimulus on the Movement Behavior of *Litopenaeus Vannamei*, in: IEEE/OES China Ocean Acoustics Symposium.

Author Contributions

MW and KD conceived the study. MW undertook the bibliometric analysis, literature evaluation, and designed the evaluation methods. KD and RB contributed to the refinement of these methods. MW led the drafting of the manuscript. KD and RB contributed to the manuscript's development.

Funding

This work received funding from Edinburgh Napier University and from the MASTS pooling initiative (The Marine Alliance for Science and Technology for Scotland). MASTS is funded by the Scottish Funding Council and contributing institutions.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Table 1. Terms used in the ISI search. Adapted after Williams *et al.* (2015) with the addition of invertebrate specific terms. Terms enclosed in quotation marks to omit unrelated publications.

	Term 2							
Term 1	Crab	Lobster	Clam	Mussel	Scallop	Squid	Invertebrate	Without Term 2
Airgun Noise	1	-	-	-	-	1	4	144
"Anthropogenic Noise"	24	7	2	5	4	4	167	1506
Marine Anthropogenic Noise Impact	15	9	2	4	3	5	84	499
"Marine Noise"	2	1	1	-	-	-	6	49
"Noise Playbacks"	-	-	-	1	-	-	5	44
"Ocean Noise"	-	2	-	2	-	2	5	351
"Pile Driving" Noise	3	4	-	4	-	2	13	396
"Seismic Survey" Noise	3	6	-	-	1	-	11	619
"Shipping Noise"	1	1	-	-	-	-	6	208
Sonar Anthropogenic Noise	-	-	-	-	-	2	5	154
"Tidal Turbine" Noise	1	-	-	-	-	-	1	35
"Underwater Noise"	9	14	-	10	3	2	52	1229
"Wind Farm" Noise	2	6	-	5	-	1	10	543
					Total (Duplicates not removed)		546	5777
					Total (Duplicates removed)		273	

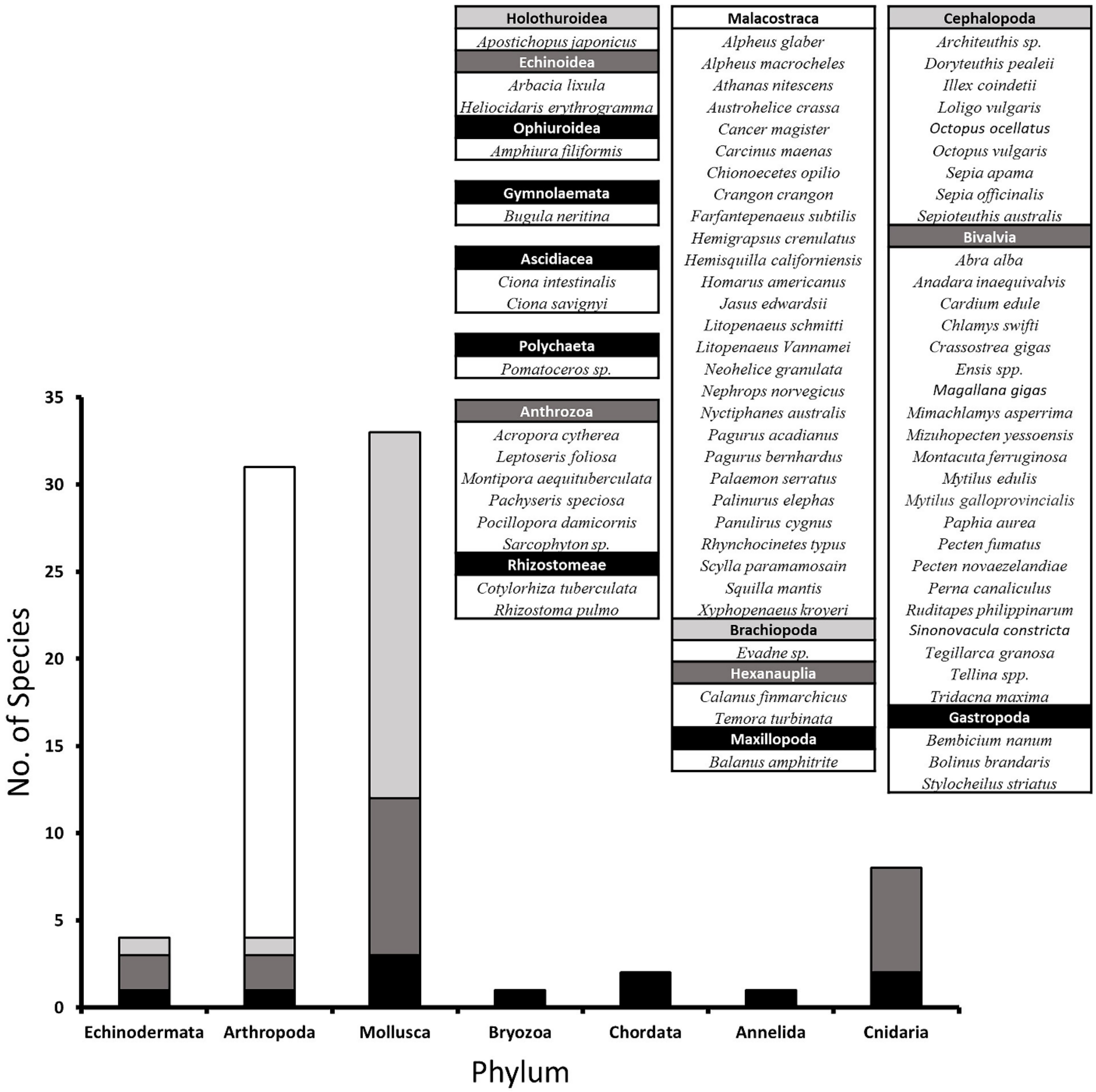

Figure 1. Phyletic distribution of invertebrates studied in anthropogenic noise research. Breakdown of the 65 species currently present in the literature according to taxa. Species cover 14 classes from seven phyla.

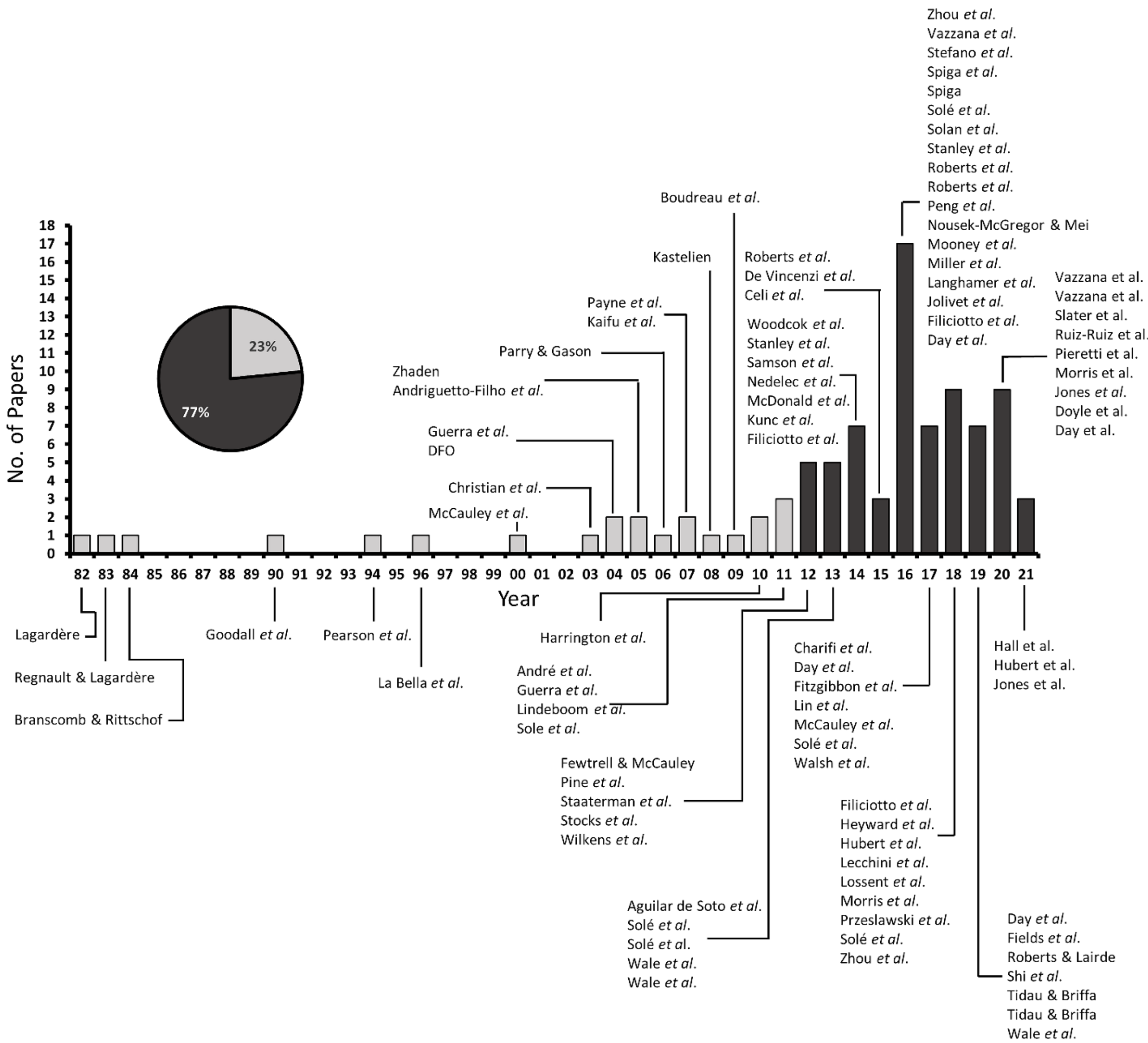

Figure 2. History of marine invertebrate anthropogenic noise studies. The studies are presented according to their occurrence over time (i.e., publication date).

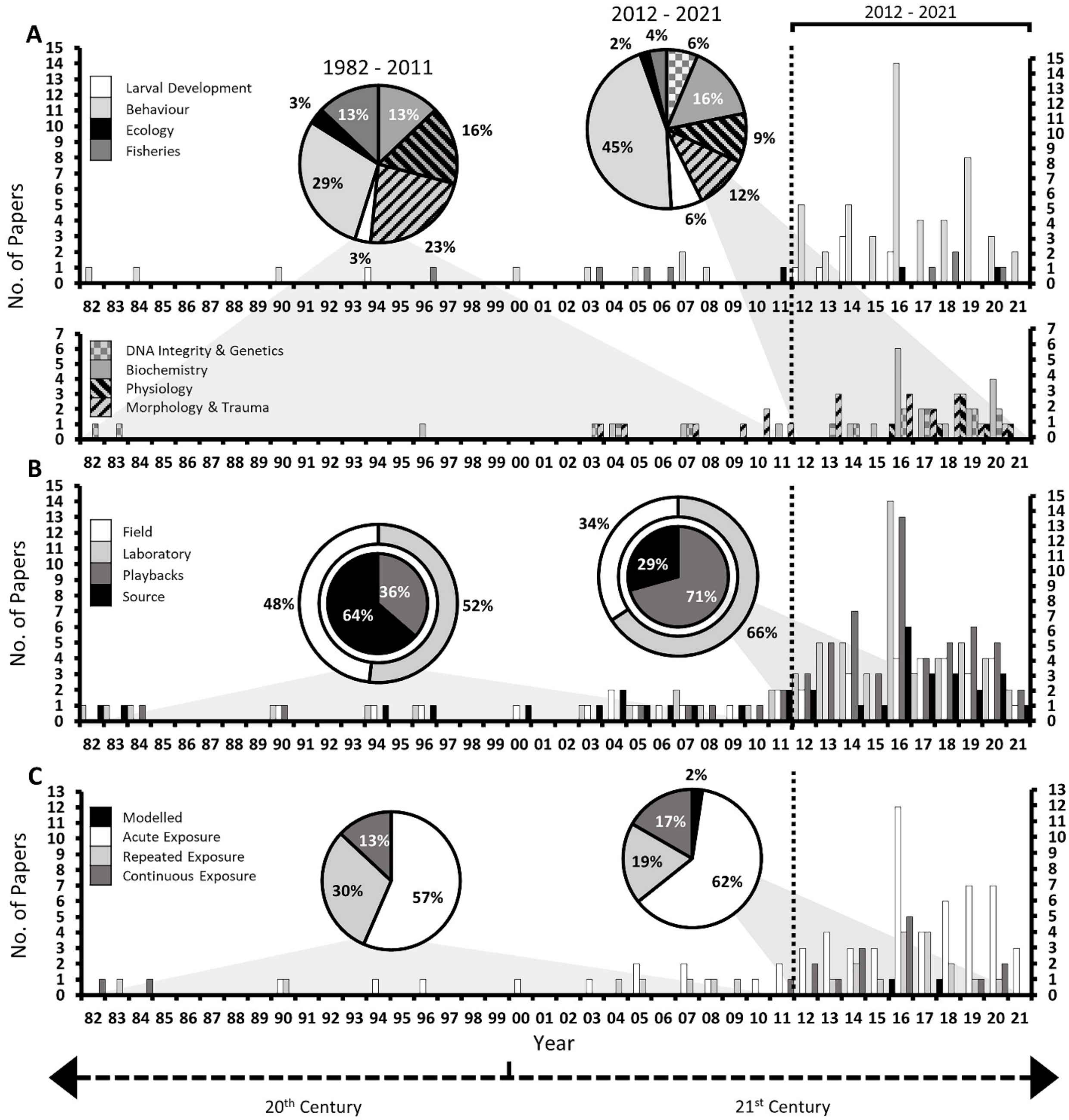

Figure 3. Neutral descriptors (N1, N2, N3). (A) Area of biology, (B) exposure type used, and (C) exposure length, addressed in marine invertebrate noise literature over the 39-year history of the field. Data presented separately for 1982-2011 (n=22) and 2012-2021 (n=73). Information gained from 95 total publications.

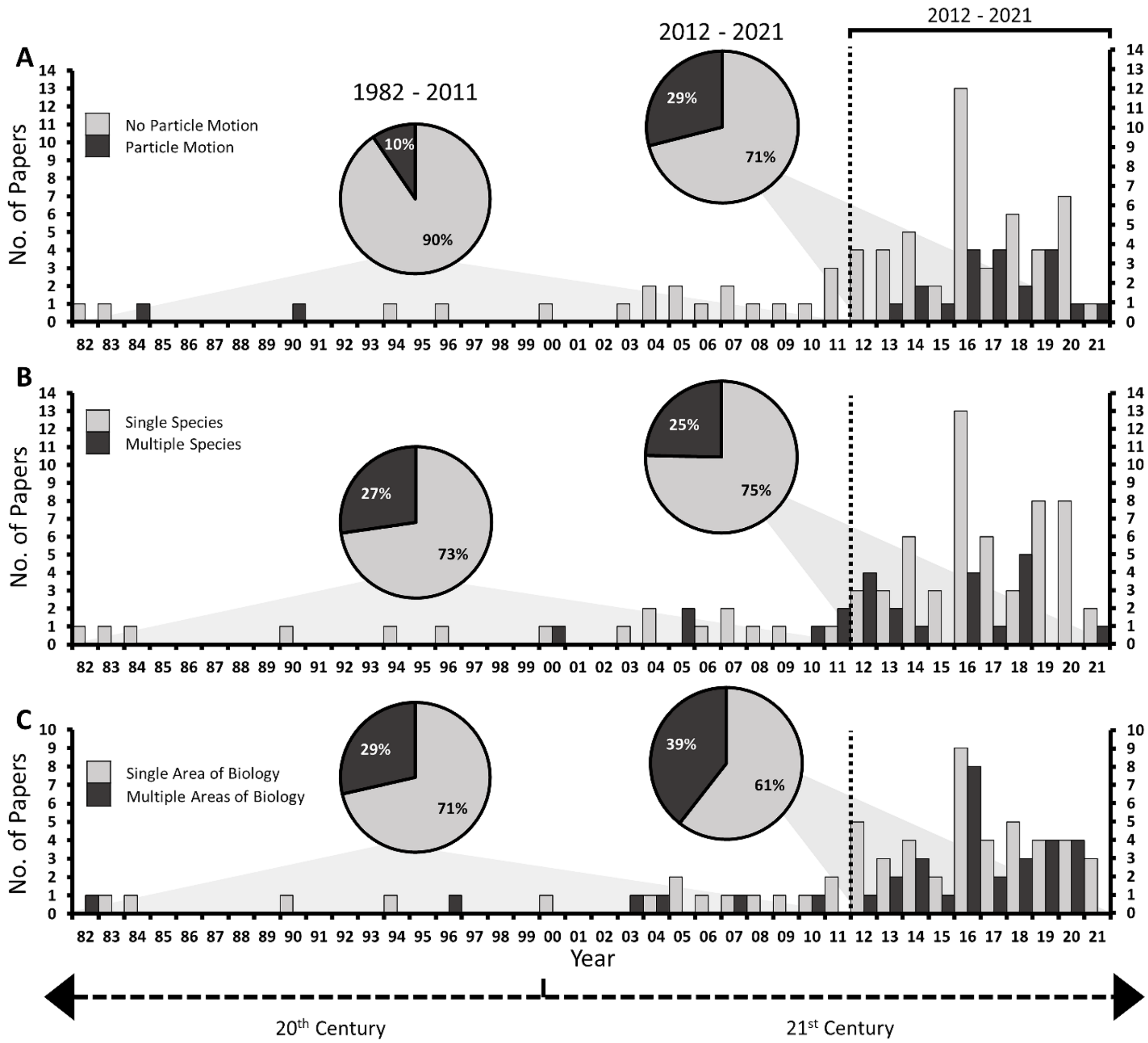

Figure 4. Descriptor pairs (P1, P2, P3). (A) The inclusion of particle motion measurements, (B) number of species studied, and (C) number of areas of biology investigated in marine invertebrate noise literature over the 39-year history of the field. Data presented separately for 1982-2011 (n=22) and 2012-2021 (n=73). Information gained from 95 total publications.

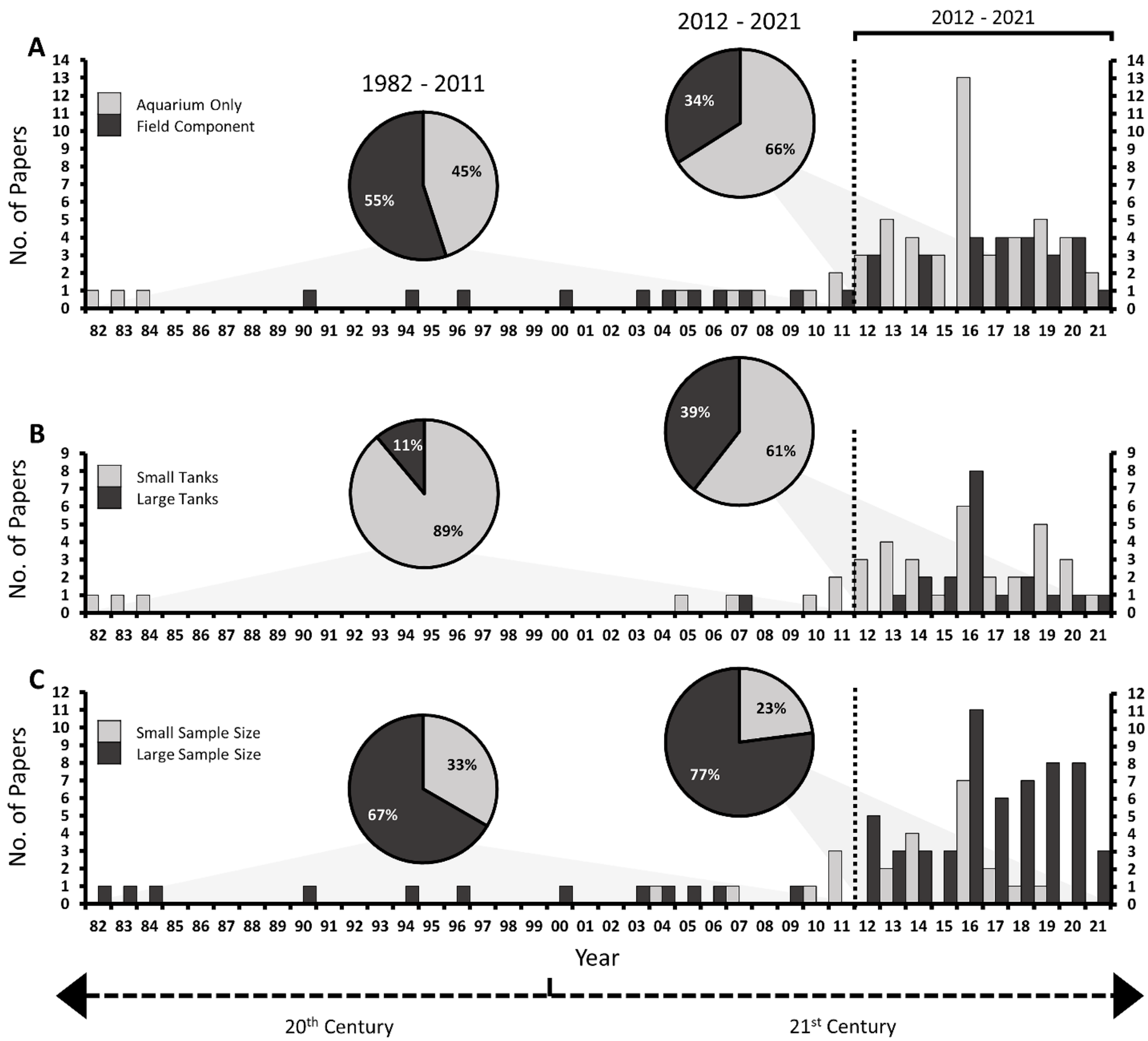

Figure 5. Descriptor pairs (P4, P5, P6). (A) Studies with aquarium only experiments and those with a field component, (B) tank size used in noise exposure, and (C) study sample size in marine invertebrate noise literature over the 39-year history of the field. Data presented separately for 1982-2011 (n=22) and 2012-2021 (n=73). Information gained from 95 total publications.

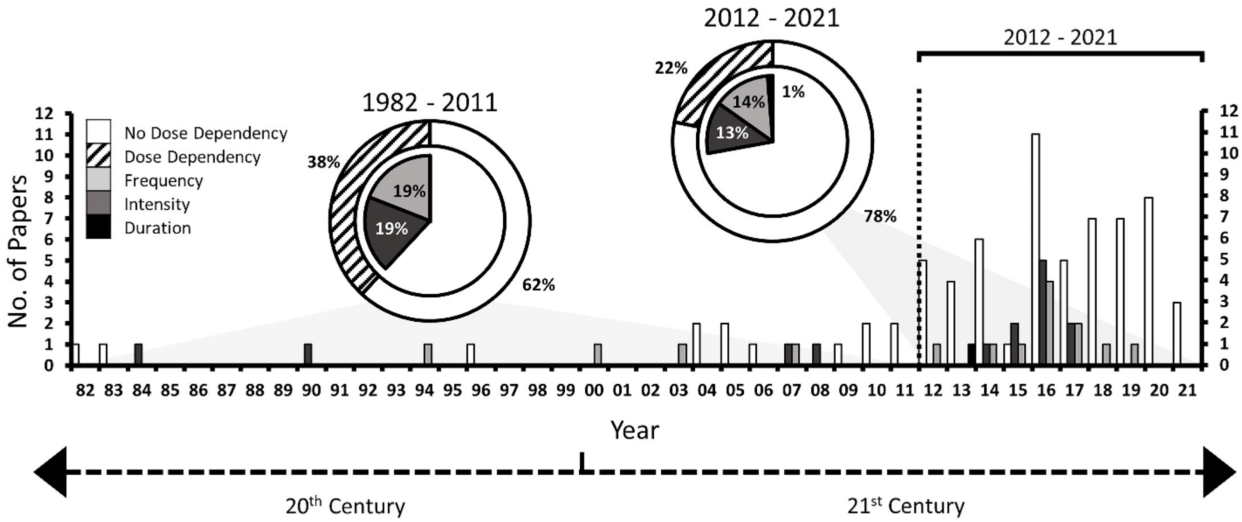

Figure 6. Descriptor pair (P7). The inclusion of dose dependency measurements in marine invertebrate noise literature over the 39-year history of the field. Dose dependency is further split to identify the specific aspect of sound measured. Data presented separately for 1982-2011 (n=22) and 2012-2021 (n=73). Information gained from 95 total publications.

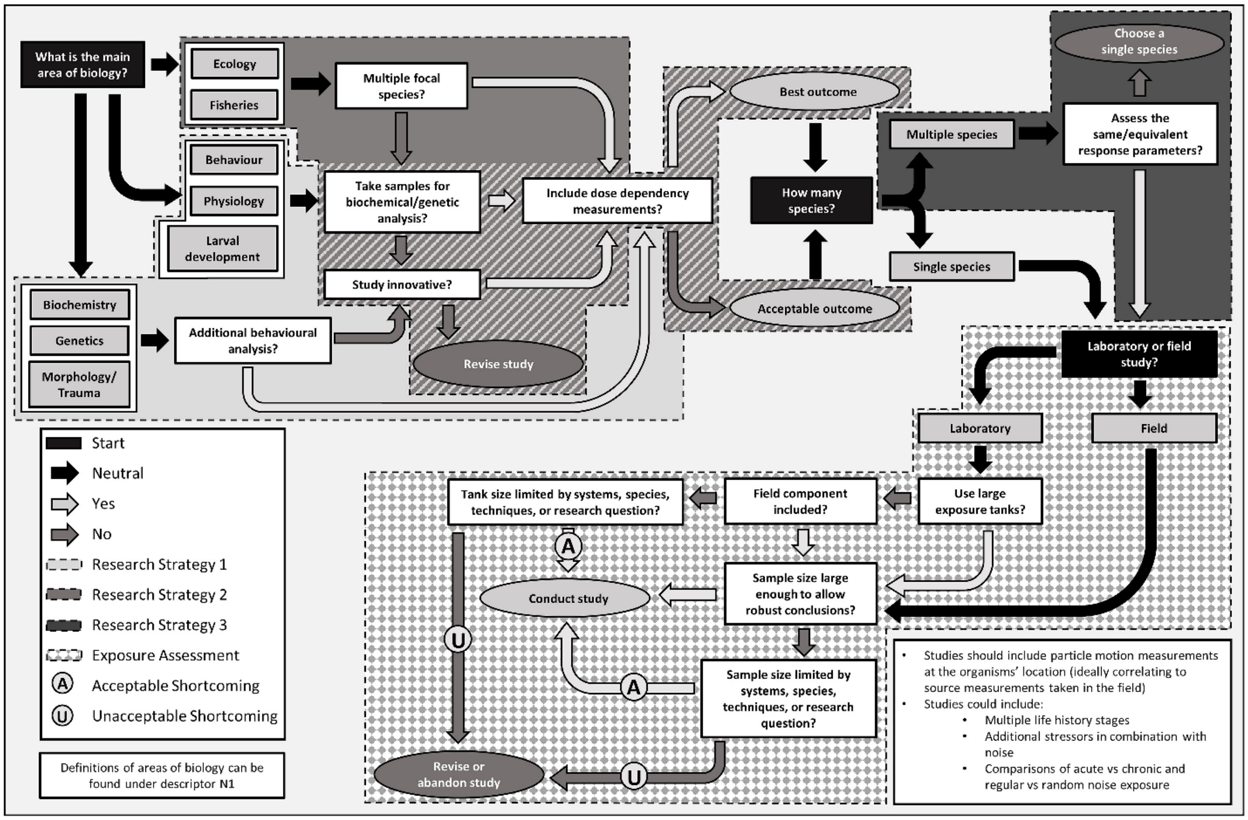

Figure 7. Conceptual research strategy flow chart, to assess methods of prospective studies on the effects of noise on marine invertebrates.