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REVIEWS

Information gaps in understanding the effects of noise on fishes and invertebrates

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Abstract The expansion of shipping and aquatic industrial activities in recent years has led to growing concern about the effects of man-made sounds on aquatic life. Sources include (but are not limited to) pleasure boating, fishing, the shipping of goods, offshore exploration for oil and gas, dredging, construction of bridges, harbors, oil and gas platforms, wind farms and other renewable energy devices, and the use of sonar by commercial and military vessels. There are very substantial gaps in our understanding of the effects of these sounds, especially for fishes and invertebrates. Currently, it is almost impossible to come to clear conclusions on the nature and levels of man-made sound that have potential to cause effects upon these animals. In order to develop a better understanding of effects of man-made sound, this paper identifies the most critical information needs and data gaps on the effects of various sounds on fishes, fisheries, and invertebrates resulting from the use of sound-generating devices. It highlights the major issues and discusses the information currently available on each of the information needs and data gaps. The paper then identifies the critical questions concerning the effects of man-made sounds on aquatic life for which answers are not readily available and articulates the types of information needed to fulfill each of these drivers for information—the key information gaps. Finally, a list of priorities for research and development is presented.

Keywords Behavior · Pile driving · Seismic airguns · Shipping · Fish · Invertebrates

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Introduction

Since the start of the Industrial Age, humans have increasingly exploited aquatic environments. These developments often involve the accidental or deliberate generation of underwater sounds. Today, in the early twenty-first century, these sources of sound have become more diverse and have the potential to add sound to large expanses of the aquatic environment. Some sources result in a chronic increase in low level background noise over extended periods of time, effectively masking sounds of interest to aquatic animals or having other behavioral effects. Other sources, while taking place over shorter periods, are more intense and have the potential to kill or injure aquatic animals as well as alter their behavior (e.g., Slabbekoorn et al. 2010).

Sources of man-made sound in water have been discussed extensively in the literature (e.g., Hawkins et al. 2008; Popper and Hastings 2009; Popper et al. 2014; Popper and Hawkins 2012; Hawkins and Popper 2014; Normandeau 2012). In brief, the sources include (but are not limited to): pleasure boating; fishing, shipping; geophysical surveys for oil and gas; dredging; construction of bridges, harbors, oil and gas platforms, wind farms and other renewable energy devices; and the use of sonar by commercial and military vessels.

There is growing concern about the effects of these man-made sounds on aquatic life. It has been pointed out that there are very substantial gaps in our understanding of effects of these sounds (e.g., Popper and Hastings 2009; Normandeau 2012; Hawkins and Popper 2014; Popper et al. 2014). Much of the information on effects currently comes from "gray literature" reports that have not been peer reviewed, are often anecdotal, and lack detail on experimental design and controls.

Reading the literature on effects of sounds, particularly as it relates to fish, invertebrates, and turtles, it is clear that there are so many information gaps that it is almost impossible to come to clear conclusions on the nature and levels of man-made sound that have potential to cause changes in animal behavior or even physical harm. There is strong interest in developing such sound exposure criteria by investigators, regulators, and industry (e.g., Woodbury and Stadler 2008; Stadler and Woodbury 2009; Popper et al. 2014), but, to date, the criteria proposed have not been based on substantive data. The most comprehensive recent attempt at reviewing the data has drawn only limited conclusions on those sound levels that might affect fish and turtles (Popper et al. 2014). No setting of criteria has even been attempted for aquatic invertebrates since so little is known about effects of man-made sound on these animals.

Because of the substantial lack of knowledge on effects of man-made sounds, and because of limited funding and facilities to undertake appropriate research it is important to consider priorities in terms of the kinds of information required. The purpose of this paper is to identify the major information gaps in what we know about effects, and then set priorities for future work. The origin of this analysis was a public workshop supported by the US Bureau of Ocean Energy Management (BOEM) Environmental Studies Program, held in March 2012 "*to identify the most critical information needs and data gaps*" on the effects of various man-made sound on fishes, fisheries, and invertebrates resulting from the use of sound-generating devices by the energy industry (Normandeau 2012). This review is based on that analysis but encompasses all sound sources and their effects on fishes and invertebrates: it is not limited to sound generated by the energy industry. Many of the examples provided are taken from marine and coastal waters, as there is a paucity of good science for other waters, but the concepts presented most likely apply to freshwater systems as well.

It is not the goal of this paper to present a comprehensive review of the material that resulted in identification of major gaps. Instead, we have been selective in choosing citations to document the gaps. For more comprehensive reviews readers are directed at the aforementioned papers. This review is strongly influenced not only by the extensive work reported in the Normandeau report to BOEM, but also by other meetings that the authors have participated in (and often organized—e.g., Hawkins et al. 2008; Popper and Hawkins 2012, 2015; Popper et al. 2014). While the suggestions made in this review belong to the authors, they have benefitted from discussions with colleagues from around the world. Although they will not be mentioned by name, for fear of missing some, their contributions are gratefully acknowledged.

Goals of this analysis

The goal of Gap Analysis is to define the present state of knowledge, the desired or 'target' state of knowledge, and the gaps between them. This analysis asks:

- Where are we now in our knowledge of the effects of man-made sound on marine and coastal fishes and invertebrates?
- Where do we want to be?
- What must be put in place so that the desired target state can be reached?

This gap analysis sets out to highlight those requirements that are being met and those that are not. It provides a foundation for deciding what is required to achieve a particular outcome.

For each topic considered in this review, an attempt has been made to:

- Define information needs about effects of noise on fishes and invertebrates
- Consider which of those needs are currently being met
- Examine those needs that are not being met and how they might be met
- Suggest research that might have high priority for future funding

Organization of the analysis

Definitions of terms used in this analysis are provided in Text Box 1, and the discussion of information in the analysis is divided into several major topics. Along with each brief discussion, a table, representing the heart of the analysis, is presented for each topic. In the tables, the left-hand column ("Drivers for Information Acquisition") describes the underlying concerns or actions that raise the questions for which answers are not readily available from existing research. The right-hand column ("Information Gaps") articulates the types of information that would be needed to fulfill each driver. There are a number of recurrent themes—questions that arise under more than one topic.

The analysis is followed by a list of priorities for research and development. Priorities on this list have been defined in terms of those that are achievable, have the most relevance, and have the greatest potential to advance our understanding of the impact issues in the reasonable future. The far broader research questions listed in the Gap Analysis itself provide a picture of where, over the next decade, the field should go. Addressing these broader research questions will be the responsibility of many groups around the world.

Topic 1: background levels of sound in the sea

Existing environmental conditions must be considered in those sea areas likely to be affected by developments that generate underwater sound (Knudsen et al. 1948). There are few historical records of levels of sound in the sea. On the rare occasions that systematic measurements of sound in the sea have taken place, it has often been at local sites and the records are often incomplete or unpublished.

A significant number of ambient noise measurements were obtained in deep water during the first half of the twentieth century. Knudsen et al. (1948) showed that at frequencies between 200 Hz and 50 kHz the level of ambient noise is dependent upon sea-state. The underlying physical processes that result in this variation are incompletely understood, but flow noise from surface wind, breaking waves, and bubble formation is thought to be important. Wenz (1962) confirmed that in the frequency region above 100 Hz the ambient noise level depends on weather conditions, with wind and waves creating sound. The level is related to the wind speed and decreases with increasing frequency above approximately 500 Hz. At frequencies around 100 Hz, distant shipping makes a significant contribution to ambient noise levels in almost all the world's oceans.

The data from Wenz (1962), Knudsen et al. (1948) are generally accepted as providing overall indications of the range of sea noise levels and the source of the dominant noise in each frequency range. Cato (1992) has also contributed to our knowledge of biological contributions to the ambient noise. However, their measurements were undertaken at particular times and places and often in relatively deep-water environments. Fewer data have been published for shallow coastal waters and estuarine environments, and hardly any for freshwater environments. Relatively little is known about the range of sounds associated with particular habitats and the contributions made to the soundscape by different biotic and abiotic sources. A consistent approach to measuring and reporting the characteristics of underwater soundscapes is essential to understanding how aquatic biota are affected by sounds, both natural and man-made. McWilliam and Hawkins (2014) have pointed out that soundscape interpretation is still at a developmental stage. Advancing understanding of the spatial dynamics of soundscapes in underwater habitats has the potential for better understanding of ecosystem processes, particularly how spatial patterns of recruitment may have developed and how migratory species may navigate by the detection of acoustic features within the environment (Simpson et al. 2004; Mann et al. 2007; van Parijs et al. 2009; Radford et al. 2010; Bittencourt et al. 2014; Gage and Axel 2014).

Text Box 1 Concepts and terms (in bold) critical for understanding this review

Noise is used colloquially to describe unwanted sound that interferes with detection of other sounds of interest. Noise is also used to describe background levels of sound in the sea, including the naturally occurring and spatially uniform sounds generated by distributed biological sources, weather events, and/or physical phenomena that cannot be assigned to individual sources. In this paper the term ***sound***, rather than noise, is used to refer to identifiable man-made sources, such as ships or oil and gas platforms, or distant man-made sources that cannot be located. Where others have used the term ***ambient noise*** or ***background noise*** to describe naturally occurring sounds from distributed sources then that usage will also be followed

The term ***soundscape*** is used in this review to describe the physical sound field at a particular time and place. The term does not consider the sound field as experienced or perceived by any organism living there

In considering effects of sound (or any stimulus) on organisms, reference is made to ***acute*** or ***chronic*** effects. Acute effects may result in mortal or potentially mortal injury to animals as well as sudden changes in behavior. Death may occur immediately upon exposure to a stimulus, or at some time afterwards due to the actual damage imposed or reduced fitness that leads to predation on the affected animal. Chronic effects refer to long-term changes in the physiology and/or behavior of an animal. These generally do not lead to mortality themselves, but they may result in reduced fitness leading to increased predation, decreased reproductive potential, or other effects. Acute effects are generally the result of very intense (***loud***) sounds. Exposure to the individual sounds is often of short duration. In many instances these sounds are repeated. Acute effects may also arise from large changes in the hydrostatic pressure generated by explosions and other sources. Such adverse effects may also be described as ***barotrauma*** (see Stephenson et al. 2010; Carlson 2012; Halvorsen et al. 2011, 2012a)

Chronic effects result from exposure to both continuous sound and intermittent sound over long time periods, not necessarily at high levels, and may result from increased shipping or other human activities. The sounds resulting in chronic effects are often continuously generated over large areas, where the overall background level of sound in the area is higher than the natural background level

Cumulative effects arise from the temporal repetition and accumulation of effects from a single type of source—for example the repeated strikes of a pile driver. ***In-combination effects***, also described as ***synergistic effects*** or ***aggregate effects***, arise from the accumulation of effects from a number of different types of stressors—for example, from sounds from different sources or from the combined effects of sound exposure, water contamination, and fishing (e.g., Johnson 2012). U.S. National Environmental Policy Act (NEPA) analyses consider both cumulative and in-combination effects, as defined here, as cumulative impacts

There is often uncertainty about the use of "**impact**" and "**effect**." They are often used synonymously, but it is clear that there are subtle differences in meaning by different authors. A more specific usage has been adopted here. "Impact" refers to a causal agent, such as the sound from a seismic operation or the wake from a ship. "Effect" means the resultant response of or on an animal or population

Finally, ***man-made*** is to be seen as synonymous with ***human-made*** and ***anthropogenic*** as used in other literature and is gender-neutral

A review of marine underwater noise Hildebrand (2009) cites the data of Mazzuca (2001), which suggests an overall increase of 16 dB in low frequency noise during the period from 1950 to 2000, corresponding to a doubling of noise power (3 dB increase) in every decade for the past five decades. In some parts of the ocean it is known that man-made sound has been increasing across much of the frequency spectrum (Andrew et al. 2002; McDonald et al. 2008), especially at lower frequencies (<500 Hz) (Frisk 2007). Indeed, at these frequencies, the level of sound above background may serve as an indicator of the degree of industrialization of the ocean. The volume of cargo transported by sea has been doubling approximately every 20 years, and it is likely that this has resulted in an overall increase in sound levels at many locations. Offshore oil and gas exploration and production, as well as renewable energy developments, have also expanded over the same period.

Currently, there are insufficient measurements of aquatic sound levels to understand how they have changed over past decades. There is a total absence of data on sound levels in aquatic ecosystems that pre-date the increase of man-made sound levels in the 1900s. Perhaps more critically there is an absence of long-data sets that indicate changes in sound levels over time. There are few measurements to adequately describe or quantify aquatic noise on a global scale. The long-term variation of sound in aquatic environments is a fundamental knowledge gap. Long time series of sound levels are required at a range of locations including not only those exposed to increasing levels of man-made sound but also areas that are representative of quiet conditions or are dominated by sounds of biological origin (Table 1).

Table 1 Background levels of sound in the sea

Drivers for information acquisition	Information gaps
There is strong interest in describing and characterizing soundscapes in different parts of the ocean, including inshore waters as well as other aquatic environments. How do these vary by locale, season, time of day, weather conditions, etc.? Aquatic soundscapes are the result of:	Definition of those physical quantities and metrics that are most useful for describing aquatic soundscapes. Protocols for underwater soundscape surveys
Ambient sounds generated by physical factors;	Analyses of the contribution to sound levels from natural sources, including biological sources
Biological sounds;	Breakdown of the overall contribution to sound levels from man-made and other sources. Agreement on how measurements of the outputs from different sources should be compared
Man-made sounds; and	Methods for comparing the contribution of different sources to the overall aquatic soundscape, in the form of inventories or budgets
The local sound transmission regime	Scientific programs that monitor trends in soundscapes through the acquisition of long-term data sets with immediate emphasis in areas of future change and/or critical habitat
Ambient noise is site specific, and more data are required on the soundscapes associated with different habitats and ecological niches	A long-term commitment for the establishment of ocean observing stations dedicated to "ecological" sound measurements and for programs to survey different ocean soundscapes
Appropriate methods for the measurement, description and analysis of soundscapes will be critical in the future for identifying trends in level and characteristics of the acoustic environment. There is currently no archive for recordings, no protocol for making such measurements, and few analyses of natural soundscapes performed to specified standards	
Monitoring of soundscapes before, during, and after the new developments, like the construction and operation of wind farms, is needed, but is rarely carried out. Most observations on soundscapes have been incidental to other activities. Results of monitoring that has taken place are not generally made publicly available There is a need for a repository of data on soundscapes and the sharing of such data	
Presentation of noise budgets can be difficult to interpret, depending on the units used to derive them	

Topic 2: sources of man-made sound

Underwater noise needs to be understood and modeled in terms of the spatial and temporal fields generated by different sound sources, both natural and man-made. Together with propagation characteristics, such information enables an inventory to be developed—to contribute to the building of soundscapes for an area. Comprehensive numerical models of the sound field are required, based on knowledge and measurements of the sources and of the propagation environment. Such models can be used to explore the relative significance of different sources, guide design of further measurements, and provide tools for planning mitigation efforts where necessary.

To model sound fields it is necessary to know the distinctive characteristics of individual sources in order to examine their effects upon animals and habitats. There are many different man-made sound sources in aquatic environments, and they can be quite complex in their characteristics (reviewed in Popper and Hawkins 2012, 2015; Popper et al. 2014). Some of these, such as explosions, seismic air guns, and impact pile driving have the potential to add to acute noise exposure since they produce sounds that are impulsive and very intense, particularly close to the source. In contrast, sounds produced by "quieter" sources such as operating wind farms and vessels provide chronic exposure. The sounds continue for long periods of time (perhaps even indefinitely) although they are generally not nearly as loud as impulsive sources.

Explosions

Explosives are used underwater in a wide range of applications including the construction or removal of installations such as offshore oil platforms. Explosions differ in a number of ways from low-amplitude point sources of sound (Weston 1960). During an underwater explosion a spherical shock wave is produced along with a large oscillating gas bubble that radiates sound. The shock pulse has rapid rise time and exponential decay. Near the source, the pressure rise time for high explosives, such as TNT, is nearly instantaneous with an exponential decay after the initial impulse. In contrast, the impulse rise time to peak pressure with explosives such as black powder is around a millisecond (Urick 1983) and the decay of the impulse following peak pressure is slower.

The original shock wave is thought to be the primary cause of harm to aquatic life at a distance from the shot point; the sound generated by the pulsating bubble may also contribute significantly to damage (Cole 1948). Explosions beneath the substrate may generate seismic waves, travelling along the interface, which may be detected by those animals with particle motion detectors, including benthic fishes and invertebrates.

There are several guidelines for the protection of aquatic life during the use of explosives in water (Young 1991; Keevin and Hempen 1997; Wright 1998). Yelverton et al. (1975) looked at the relationship between fish size and their response to underwater blasting although it is not clear whether this relationship is the same for sound as it is for explosions (Casper et al. 2013b). A literature synthesis report on the explosive removal of offshore structures is especially informative on recommended procedures to be followed (CSA 2004).

Seismic airguns

The airgun is the primary sound source used for seismic exploration by the oil and gas industry. Airguns work by producing an air bubble from a compressed air supply (e.g., Mattsson et al. 2012; CSA 2014). The sound impulse generated by a single airgun is omnidirectional, with greatest energy at low frequencies, typically on the order of 20–50 Hz, with declining energy at frequencies above 200 Hz. Arrays consisting of several air guns are towed behind vessels during a seismic survey. The interaction of multiple guns fired simultaneously enhances the primary pulse over the trailing bubble pulses and, through suitable geometric arrangement, results in vertical focusing of the sound energy. During the survey, the array is fired at regular intervals (e.g., every 10–15 s), as the towing vessel moves ahead. The sound pulse is directed downwards to enter the seabed and the reflected sound is detected by long hydrophone arrays streamed behind the vessel (streamers) (Caldwell and Dragoset 2000).

The source level (a measure of the acoustic noise output) of an airgun array is typically estimated from measurements made some distance away and back calculated to a specified distance from the source (typically 1 m). The source level can vary greatly with the design of an array and the number of airguns in the array (Richardson et al. 1995). Most of the energy produced is in the 10–120 Hz bandwidth (Richardson et al. 1995), but higher frequencies do propagate horizontally. Because the array itself is often very large, back calculation from far field measurements is likely to underestimate the source level.

When acoustic energy in the water encounters the bottom, a variety of transmission modes can occur, including both body waves (shear and longitudinal) as well as interface waves such as head waves. The interface waves can generate large vertical and horizontal particle motion components within the substrate at levels that can be detected by fishes and perhaps invertebrates.

Impact pile driving

Impact pile driving is commonly used for the construction of foundations for a large number of structures including offshore wind turbines, harbor walls, bridges, and offshore structures for the oil and gas industry (reviewed in Popper and Hastings 2009). The pile is a long tube, stake, or beam that is driven into the seabed, often by means of a hydraulic hammer. Sound is generated by direct contact of the pile with the water as well as by shear and longitudinal ground-borne pathways within the seabed or through the ground if the pile is on land adjacent to water (e.g., Hazelwood 2012; Hazelwood and Macey 2015). The substrate can contribute via direct propagation or interface (Sholte-like) waves (sometimes called ground-roll). The latter originate at the water sediment interface and have large velocity components that decay rapidly with vertical distance from the interface (Brekhovskikh and Lysanov 2003). Such waves are much more likely to affect bottom-living fishes and invertebrates than those in the water column. Shear waves and interface waves travel slower than compression waves (sounds) and their peak energy is at lower frequencies (Dowding 2000).

Of particular concern are high energy impulsive sounds generated by impact driving of large diameter steel shell piles (Illingworth and Rodkin 2001, 2007; Reyff 2012). The impulsive sounds generated by impact pile driving are characterized by a relatively rapid rise time to a maximal pressure value followed by a decay period that may include a period of diminishing, oscillating maximal and minimal pressures. The bulk of the energy in pile impact impulses is at frequencies below 500 Hz, within the hearing range of most fishes, with much less energy above 1 kHz (Laughlin 2006; Rodkin and Reyff 2008). Moreover, it is possible that the pressure levels at some distance from the driven pile are greater than at locations closer to the pile when sub-surface waves, generated by the pile, re-enter the water column and combine with the water-borne signal (Popper and Hastings 2009).

Dredging

Dredging or mining of materials from the seabed can be conducted by mechanical means or by suction (see National Research Council (2002) for a review of marine dredging). Mechanical dredging involves the use of a grab or bucket to loosen the seabed material and raise it to the sea surface. In contrast, suction dredging involves raising loosened material to the sea surface by way of a pipe and centrifugal pump.

Bucket dredges produce a repetitive sequence of sounds generated by winches, bucket impact with the substrate, bucket closing, and bucket emptying (Dickerson et al. 2001; Robinson et al. 2011). Grab and backhoe dredgers are also characterized by sharp transients from operation of the mechanical parts. Suction dredgers produce a combination of sounds from relatively continuous sources including engine and propeller noise from the operating vessel and pumps and the sound of the drag head moving across the substrate.

De Jong et al. (2011) reported measurements of radiated noise from Dutch dredgers involved in the extension to the Port of Rotterdam. Robinson et al. (2011) carried out an extensive study of the noise generated by a number of trailing suction hopper dredgers during marine aggregate extraction. Source levels of six dredging vessels were estimated and an investigation undertaken into the origin of the radiated noise. Source levels at frequencies below 500 Hz were generally in line with those expected for a cargo ship travelling at modest speed. Levels at frequencies above 1 kHz were elevated by additional noise generated by the aggregate extraction process. The elevated broadband noise was dependent on the aggregate type being extracted with gravel generating higher noise levels than sand. There were significant differences between source level measurements reported by de Jong et al. (2011) and Robinson et al. (2011), especially at high frequencies. Both reports estimate the *dipole* source levels.

Very little research has been carried out on the effects of sound from dredging on fishes and aquatic invertebrates. In general the effects will be chronic rather than acute. Behavioral responses and masking effects are to be expected, with possible negative consequences.

Operating wind farms

Sound generated by a wind farm is reported to be much lower during the operational phase than during construction (Madsen et al. 2006; Thomsen et al. 2006). The greatest source of sound from wind farms comes during construction when pile driving is used to lay foundations (see above). However, whereas construction might affect marine animals for a relatively short period of time, operational sound has the potential to cause chronic effects over much longer periods.

The principal source of sound from an operational wind farm is turbine noise that propagates into the tower and foundations, coupling the sound into the water and seabed (OSPAR 2009). Most of the noise appears to be generated below about 700 Hz and is dominated by narrowband tones (Wahlberg and Westerberg 2005; Madsen et al. 2006). There may also be noise from vessels used to maintain the wind-turbines.

Sound levels within wind farms are not significantly higher than the background noise (Nedwell et al. 2007). The highest level noted by Wahlberg and Westerberg (2005) was for a narrow band tone at approximately 180 Hz. There is also a particle motion component to sounds generated by wind farms, the sound component detected by all fishes, including sharks, and many invertebrates (Sigray and Andersson 2012).

Vessel noise

While a complete understanding of the relative contributions of various sources of sound in the marine environment is lacking, a significant portion of human noise results from the increasing number of large commercial ships operating over wide-ranging geographic areas, which can result in chronic noise exposure. Most vessels, but particularly large ships, produce predominately low frequency sound (i.e., below 1 kHz) from onboard machinery, hydrodynamic flow around the hull, and from propeller cavitation, which is typically the dominant source of noise (Ross 1987, 1993). Radiated vessel noise relates to many factors, including ship size, speed, load, condition, age, and engine type (Arveson and Vendittis 2000; Richardson et al. 1995; National Research Council 2002, 2003). Source levels of vessels can range from <150 dB re: 1 μPa at 1 m to over 190 dB for the largest commercial vessels (Scrimger and Heitmeyer 1991; Richardson et al. 1995; Arveson and Vendittis. 2000; Wales and Heitmeyer 2002; Hildebrand 2009; McKenna et al. 2012). Note that it is not always clear whether authors are reporting estimated source levels or received noise levels.

The number of commercial ships in the ocean has doubled between 1965 and 2003 to nearly 100,000 large commercial vessels, and shipping industry analysts forecast that the amount of cargo shipped will again double or triple by 2025, with an attendant increase in the amount of ambient noise entering the ocean from commercial shipping (National Research Council 2003). There may also have been a substantial increase in sound levels in coastal waters, and in rivers and lakes, as a result of an increase in the number of smaller pleasure and recreational fishing vessels. One of the most serious implications of this increase in shipping noise is the chronic impact it may have in terms of masking sounds of the soundscape, including sounds of biological origin, affecting communication in fishes and invertebrates.

Fishing

Fishing by means of towed fishing gears involves a vessel dragging a net fitted with spreading and bottom contact devices across the seabed. Sound is generated both by the towing vessel and by the fishing gear being dragged across the seabed. Chapman and Hawkins (1969) gave early consideration to the effects of these sounds. The greatest contribution from fishing gears comes particularly from bottom trawls, which are fitted with chains, rollers, and metal bobbins that generate irregular sounds as they come in contact with one another and with the seabed. There are also low frequency (below 100 Hz) sounds from the vibrations of warps or wires connecting the trawl to the ship, the trawl doors or spreading devices, and contact with the seabed. No published information on absolute levels or typical spectra is currently available. In some parts of the ocean fishing vessels operate almost continuously, with possible chronic effects. There have been no recent studies of the impact of noise from fishing vessels, but there has been interest in reducing noise levels from fishery research vessels in order to reduce any impacts upon fish during stock assessment surveys (reviewed by De Robertis et al. 2012).

Sonar

Sonar is widely used by fishing and other vessels. Typical sonars include depth sounders, fish-finding sonars, fishing net control sonars, side-scan sonars, multi-beam sonars, and a variety of sonars for mapping the topography of the seabed. The principles of sonar operation are described by Ainslie (2010). Sonars work at frequencies from 10 to 800 kHz. Although ultrasonic frequencies are attenuated over short distances by absorption, the contribution to ambient noise is significant due to the large numbers of such units.

Sonars are generally operated at frequencies well above the hearing ranges of most fishes and invertebrates, with the exception of some clupeid fishes, including shads and menhaden, which can detect and respond to ultrasonic frequencies (Dunning et al. 1992; Mann et al. 1997).

Some military sonars operate at low frequencies (1 kHz and less), or mid frequencies (1–10 kHz) that do fall within the hearing range of fishes. The signals projected include combinations of swept frequency (FM) and tones pulses. As these sonars operate at large ranges the signals can be very intense. Investigations using low and mid-frequency naval sonars have shown no tissue damage in fishes, although there is the potential for temporary hearing loss in some specimens of some species (Popper et al. 2007; Kane et al. 2010; Halvorsen et al. 2012c).

Table 2 Characterizing man-made sources

Drivers for information acquisition	Information gaps
The nature of the sound field (spectral, temporal, and spatial) generated by various man-made sound sources is crucial to understanding the effects of sound exposure. There are currently few agreed standards for measuring the output of different sound sources. Particle motion, which is an important component of sound detection for fishes and invertebrates, is seldom measured. Particle motion requires vector rather than scalar measurements	Characterization of the sounds generated by different sources, in terms of particle motion as well as sound pressure to agreed standards using appropriate metrics and terminology
There is currently no archive of sound files, recorded to an agreed-upon standard, providing examples of the sounds generated by different sources	Partnership between government and industry to undertake research on the outputs of different sound sources. A specific example is pile driving, for which sediment transmission may be important but the sound fields have not yet been adequately characterized in terms of sound pressure, particle motion, and other characteristics (rise time, degree of kurtosis etc.)
Sounds of differing characteristics (e.g., impulsive vs. continuous; short vs. long term) have different effects upon animals. Those characteristics that are especially damaging to fishes and invertebrates need to be defined, so that impacts might be reduced	Information on the particle motion associated with interface waves and ground roll that may affect fishes and invertebrates, especially from pile driving and seismic sources
The oil and gas industry has conducted some research that describes the outputs of seismic sources. Little research has been done on other potentially damaging sources, including pile driving where substrate borne vibration may be especially important to fishes and invertebrates	Characterization of impulsive sounds. What is it that makes some sources more damaging than others? Is it the peak amplitude, the total energy, the rise-time, the duty-cycle, or all of these features that determines whether tissues are damaged?
Of considerable concern is how the output of sound sources should be measured and the effects of different sound sources on fishes and invertebrates assessed. Sound sources and their outputs must be monitored and analyzed from the perspective of the affected animals if their effects are to be fully understood	Identification of the characteristics of continuous sound most likely to have effects on animals
There is particularly strong interest in describing sounds appropriately in terms of their cumulative and aggregate effects upon aquatic animals (see Topic 5 on Effects)	Determination of whether the effects on fishes and invertebrates are similar or whether different metrics and response characteristics are needed for different groups
What future trends should we expect in the development of sound sources? Are aquatic animals likely to be subjected to larger pile drivers, more extensive seismic surveys and wider swathes of dredging and aggregate abstraction in the future as technology develops?	Preparation of a sound archive, providing examples of sounds generated by different sources, recorded to agreed standards

Other continuous sounds

Vibratory pile driving produces a continuous sound with peak sound pressure levels lower than those observed in impulses generated by impact pile driving. The principle of operation is that counter-rotating, out-of-balance masses rotate in an enclosure attached to the top of the pile. The rotating masses generate a resultant vertical vibratory force that slowly forces the pile into the substrate. Sound signals generated by vibratory pile driving usually consist of a low fundamental frequency characteristic of the speed of rotation of the revolving mass in the vibratory hammer, typically on the order of 30 Hz, and its higher harmonics (e.g., Laughlin 2006).

There is increasing interest in the energy generation by wave and tidal power. Few sound measurements are available for these devices and there have been no scientific studies of their impact on fishes and invertebrates (Table 2).

Topic 3: sound exposure metrics

An issue that arises both in describing soundscapes and examining the sounds produced by particular sources is how best to describe the sounds. A variety of metrics exist for the physical description of underwater sounds (e.g., Ellison and Frankel 2012; Ainslie and De Jong 2015). It is important to consider the utility of these metrics for investigating the effects of sounds upon aquatic animals.

Table 3 Metrics and terminology

Drivers for information acquisition	Information gaps
A wide range of instruments and metrics are used to measure, describe, and analyze underwater sounds. However, currently sounds are only described in terms of sound pressure, whereas many fishes and invertebrates respond to particle motion	Consensus on the adoption of relevant and universally acceptable metrics for sound pressure and particle motion so that sounds may be described appropriately. This will enable proper comparison of the effects of sounds of different types on different taxa
Increasingly, biologists and others without specialist knowledge of acoustics are conducting measurements and applying different metrics to different taxa, often without guidance on the most appropriate metrics	Development of a common terminology for sound measurement and exposure that is useful and understandable to the whole community—from acousticians to biologists to regulators. An authoritative and critical glossary of terms in current use is also required
Much of the literature concerned with the effects of underwater sound uses differing and confusing terminology. There are no widely accepted definitions or terminology applicable to underwater sound for universal use. Even the common term *sound pressure level* is defined in different ways by ANSI and ISO, the two main standards organizations. There is no widely accepted definition of *source level*. The lack of a standard terminology creates ambiguities in the interpretation of data and assessment of effects	

Measurement parameters are not well defined for underwater sounds, especially for impulsive sounds. The Dutch research institute, TNO, recently published a set of standards for measurement and monitoring of underwater sound (see Ainslie 2011). The document is intended to provide an agreed upon terminology and conceptual definitions for use in the measurement procedures for monitoring of underwater noise.

Measurements close to sources are often in the non-linear portion of the sound field especially for pile drivers and explosions and to some degree for seismic sources. It is in these regions that damage to fishes and invertebrates may occur.

Sound can be measured not only in terms of sound pressure but also in terms of acoustic particle motion (Ellison and Frankel 2012; Rogers et al. 2015). As a vector quantity with both magnitude and direction, particle motion is the oscillatory displacement (m), velocity (m/s), or acceleration (m/s^2) of fluid particles in a sound field. Although some fishes are sensitive to sound pressure, most fishes and invertebrates detect particle motion (Popper and Fay 2011). It is therefore especially important to examine the magnitudes of both sound pressure and particle motion generated at different locations by man-made sound sources.

With some sources, including both pile drivers and seismic airguns, it is likely that interface waves, consisting of large particle motions close to the substrate (ground roll), are set up that travel at speeds different from the speed of sound.

Particle motion may be of particular interest in terms of its effects on fishes and invertebrates. Particle motion may act in different directions. While there has been great interest in the last few years in developing vector sensors for navy applications, the technology is not mature and measurements cannot be made routinely. Particle motion is not a standard output from propagation models either. A clear need is to develop easily used and inexpensive instrumentation and methodologies to characterize particle motion from various sound sources, perhaps concurrent with measures of sound pressure at the same locations (Table 3).

Topic 4: sound propagation

As sounds travel away from the source their characteristics change. Examination of the changes accompanying sound propagation is important for interpreting measurements made in the field and requires the application of models to assist in estimating effects upon animals. While there are many models for propagation, most of these have been developed for use in deep water basins (oceans) and either have to be modified or new models developed for sound propagation in shallower waters, including rivers, lakes and harbors. The issue with shallower water is that there is substantial interaction of the sound with the surface and bottom characteristics, and this can result in differential attenuation of sounds at

Table 4 Sound propagation

Drivers for information acquisition	Information gaps
The propagation of sounds through the sea and seabed can greatly influence the sound received by fishes and invertebrates. Propagation models are available for specific oceanic environments (i.e., shallow, deep, ice covered, and temperate waters). However, those models have primarily been developed by industry for their own purposes (e.g., for estimating geological resources) and do not provide the relevant information needed for assessing the exposure to which animals are subjected or predicting biological effects. Researchers and regulators need to be able to estimate the received levels of sound pressure and particle motion to which aquatic animals are exposed in the water column and close to the seabed. Current models have not been designed to do that	Models of sound propagation that are specifically tailored to estimate the exposure to which fishes and invertebrates will be subjected, expressed in terms of sound pressure and particle motion, for animals in the water column, close to the sea surface, or close to the seabed
With respect to the masking of biological sounds, there is concern that impulsive sounds might merge with one another over distances as a result of reverberation and other effects	Characterization of changes in man-made sounds over large distances from the source, particularly factors that render them likely to mask biological sounds
Some sound sources, including seismic airguns and pile drivers, send energy into the seabed, creating substrate vibrations that may affect benthic fishes and invertebrates	Information about propagation of sound and vibration through the seabed by means of interface waves—this is especially relevant to benthic fishes and invertebrates
	Understanding the effects over large ocean basins of multiple or continuous activities that alter the soundscape
	Characterization and modeling of sound propagation in shallower waters

different frequencies, with very little propagation of sound energy at frequencies that are longer in wavelength than the depth of the water (Rogers and Cox 1988). Many estimates made of source levels are based on sound radiation from a point source in deep water. Many man-made sources are deployed in shallow water and the sources themselves are large and distributed (for example the airgun arrays used for seismic surveys). Some of these sources generate seismic and interface waves within the substrate, which must be taken into account especially for fishes and invertebrates living close to or within the substrate. It is important that propagation models take these considerations into account (see Pine et al. 2013) (Table 4).

Topic 5: effects of sound on fishes and invertebrates

There are more than 32,000 known species of fishes (www.fishbase.org) and far more species of aquatic invertebrates. Research into the effects of acoustic exposure has examined only a fraction of fishes or invertebrates. There is an immediate need to identify those species of greatest interest for managers and regulators, to group those species based on common physical or physiological characteristics, and to determine if those common characteristics result in common responses to acoustic exposures (see Popper et al. 2014).

To achieve this goal, three issues will have to be addressed. The first will be to identify the appropriate characteristics for grouping of fishes and invertebrates. The second issue will be to identify appropriate criteria for assessing the effects of sound on species and species groups (e.g., Hawkins and Popper 2014). The third issue is to decide how the appropriate studies should be conducted. Can they be done in the laboratory or do they have to be done in the field? Methods for measuring fish hearing are highly variable, with much of the variability a function of the acoustic environment in which studies have been done (Ladich and Fay 2013) and how the sound fields are produced and calibrated (Rogers et al. 2015). Special steps must be taken to ensure that aquatic animals are exposed to sounds under carefully controlled conditions in order to obtain replicable and reliable data (Table 5).

Topic 6: sound production, sound detection and exposure to man-made sounds—invertebrates

There are almost no data on sound detection by aquatic invertebrates. The few experiments that have been

Table 5 Effects of sound on fishes and invertebrates

Drivers for information acquisition	Information gaps
The great diversity of fishes and invertebrates poses major problems in understanding the effects of sound upon them. It is not just diversity of species within each taxonomic group but also diversity of animal size and life history status within each species. An important question is whether it is possible to identify particular "types" of animals that may serve as models for other species and life history stages	Confirmation of those anatomical features (including the presence of a swim bladder) that indicate the sensitivity of fishes to sound and that can provide, a useful basis upon which to categorize fishes for experimentation
In considering fishes it is important that cartilaginous species (sharks and rays) are considered along with the bony fishes	Investigation of the anatomical features of invertebrates that influence their sensitivity to sound so that representative species can be selected for experimentation
Knowledge of the hearing abilities and behavior of fishes and invertebrates with respect to sound is not just of academic interest. Hearing threshold curves or audiograms are already being used in environmental statements to assess whether animals are potentially affected by man-made sounds. Metrics for impact assessment, and especially those based on weighted frequency responses, require reliable measurements of hearing abilities	Establish well-equipped field sites where the response of animals can be examined under controlled acoustic conditions to extend knowledge of hearing by fishes and invertebrates. Facilities should provide appropriate depths and quiet ambient noise conditions, allowing precise measurement of sound stimuli
The use of physiological methods to measure hearing abilities is less satisfactory than the use of behavioral methods. Physiological methods (e.g., auditory evoked potentials) only measure detectable responses from the ear or lower portions of the brain. They do not fully reflect the ability of the brain of the animal to process and extract information, or whether there will be a behavioral response by the animal	Measures of hearing must be made, wherever possible, using behavioral methods since physiological measures (e.g., auditory evoked potentials) do not give an accurate indication of the detection ability of animals
Information on the masking of biologically important sounds by 'real' sounds—including man-made sounds is critically important	Specially designed tanks can play a role in enabling precisely controlled and measured sound stimuli to be presented to fishes and invertebrates
Currently, despite strong interest in determining how fishes and invertebrates use sound and the soundscape and respond to man-made sound, there are remarkably few experimental data. There are almost no observations obtained from fishes and invertebrates exposed to man-made sounds under controlled or field conditions. Valid audiograms are only available for a handful of species. Many studies have been carried out under inappropriate acoustic conditions where the reliability of acoustic measurements has been open to doubt. There is a lack of facilities in which sound signals can be presented to fishes and invertebrates under carefully controlled conditions. If appropriate acoustic conditions can be provided then it should be possible to investigate further the thresholds or criteria for the occurrence of different effects from exposure to sound, and how they change with different sound types and levels. It should also be possible to determine those source characteristics that cause detrimental effects; e.g., magnitude, rise time, duration, kurtosis, duty-cycle	Resolution of methodological difficulties in presenting measurable sounds to fishes and in determining thresholds to different types of sound
	Development of appropriate instrumentation to accompany these special acoustic conditions
	Experimentation under similar conditions to evaluate injury and physiological damage to aquatic animals including assessment of the relative importance of factors like rise-time and kurtosis, and to assess cumulative effects, recovery from injury and other important aspects of sound exposure

done indicate that only low frequency sounds are detected and that it is the particle motion component of the sound field that is important (e.g., Mooney et al. 2010, 2012; Hughes et al. 2014). There are no data that indicate whether masking occurs in aquatic invertebrates. There are also only a few studies that indicate whether man-made sounds have any impact on invertebrate behavior. A study of the effects of seismic exploration on shrimp, suggests no behavioral effects from sounds with a source level of about 196 dB re 1 μPa rms at 1 m (Andriguetto-Filhoa et al. 2005). There is, however, evidence from laboratory experiments that metamorphosis of the megalopae of crabs is significantly delayed when animals exposed to either tidal turbine or sea-based wind turbine sound, compared to silent control treatments (Pine et al. 2012). In

Table 6 Sound production, sound detection and exposure to man-made sounds—invertebrates

Drivers for information acquisition	Information gaps
Almost nothing is known about the detection of sound and vibration by aquatic invertebrates. Some invertebrates such as snapping shrimp, mantis shrimp and lobsters are known to produce specific sounds, but the role of these sounds remains to be determined. The role of sound in lives of these animals has hardly been explored, and information on the impact of man-made sounds is almost totally lacking. There is a particular lack of controlled exposure experiments on invertebrates. There have been few studies of the potential of sound exposure to cause mortality or sub-lethal injury in marine and coastal invertebrates. The few studies carried out indicate a potential for sub-lethal responses, detected using biochemical, physiological, or histopathological measurements In this state of ignorance there needs to be a focus on examining those species that are of greatest interest, either because of their ecological importance, or their role in supporting commercial fisheries, or because sound is suspected of being important to them. Especially important animals might include Crustaceans (crabs, lobsters, shrimps), Mollusks (scallops, clams) and Cephalopods (squid, octopus), and those organisms making up the zooplankton Having selected priority species, it would be sensible to investigate how well they can detect sounds, and to examine how they use sound in their everyday lives. Do some or all of these invertebrates communicate by means of sound? Is sound important for vital life functions like reproduction, migration, feeding, or choice of habitat? Are the sounds important to invertebrates likely to be suppressed or masked by man-made sounds that alter the soundscape? How does exposure to sound affect invertebrate physiology and their behavior? Are there biomarkers that might indicate effects? What amplitudes of sound and vibration potentially cause effects, and can dose/response curves be developed? The effects of exposure of aquatic invertebrates to man-made sounds has been examined in only a few species, but sufficient work has been done to indicate that there may be tissue injury and other physiological effects from exposure to high level sounds There is a particular lack of knowledge on the behavior of invertebrates in response to sound. Do any invertebrates show substantial behavioral reactions that potentially alter fitness (e.g., reductions in settlement within favorable habitats, altered reproductive behavior)?	Identification of which marine and coastal invertebrates are of most concern with respect to exposure to man-made sound Determination of the importance of sound to invertebrates. This could include cataloguing the sounds they produce; their ability to detect sounds; their vulnerability to masking or suppression of calling following exposure to man-made sounds; whether they engage in acoustic and other activities related to their long-term fitness, e.g. during spawning; whether they use sound cues during their migrations or in selecting suitable habitats Development of better information on the ability of invertebrates to detect sound and vibration, including: whether invertebrates are responsive to sound pressure or particle motion; which sound and vibration receptors are involved and how sensitive they are; whether high level sounds damage these receptors and/or other tissues; whether the receptors regenerate if they are damaged; whether some invertebrates are especially sensitive to substrate vibration; whether invertebrates can distinguish between sources at different distances or sounds from different directions; whether they can distinguish between sounds of differing quality; whether sound detection by invertebrates is masked by man-made sounds or if invertebrates can detect signals in the presence of biological maskers; whether sound exposure can result in hearing loss Research on the effects on aquatic invertebrates of exposure to man-made sounds and substrate vibrations

contrast, mussel larvae showed significantly faster settlement when exposed to the underwater noise produced by a 125-m long steel-hulled passenger and freight ferry (Wilkens et al. 2012). Boudreau et al. (2009) investigated the impact of high-level impulsive sounds on snow crabs, but showed no short or long-term effects of seismic exposure in adult or juvenile snow crabs or on eggs. However, Aguilar de Soto et al. (2013) reported malformations in scallop larvae and developmental delays resulting from exposure to seismic airguns.

Wale et al. (2013) reported that the playback of simulated ship noise under laboratory conditions increases shore crabs' metabolism. Increased metabolism is a sign of stress and could potentially reduce the growth of crabs and have implications for their survival. However, caution is needed when interpreting these results in a real-world context (Table 6).

Table 7 Sound production—fishes

Drivers for information acquisition	Information gaps
Some fishes make sounds that are important in their everyday lives. Commercially important vocal fishes include the families Gadidae (codfishes), Sciaenidae (croakers and drums), and Serranidae (groupers) There is considerable scope for man-made sounds to suppress or mask those sounds with potentially deleterious effects upon vital functions such as spawning	Identification of those fishes engaging in acoustic activities important for their long-term fitness, such as spawning, and finding locations where vocalizing aggregations occur Basic research on the sounds made by fishes, and the role of sound production in their lives, including seasonal, demographic, situational or species differences in calling behavior Research on the vulnerability of fishes to suppression or masking by man-made sounds Ability of fishes to compensate for changing noise conditions by changing their calls Creation of a library of sounds produced by marine and freshwater fishes and invertebrates. Its absence hinders use of passive acoustics as a tool for determining effects of sound on behavior, as well as research on the role of the soundscape in fish ecology To support the library, there is also a need for new tools that use multiple modalities of observation in combination with passive acoustics to identify unknown biological sound sources and document associated behavior. Better software tools are needed to automate measurements of sound characteristics (such as number, duration, and frequency of sounds, etc.) and to identify particular sounds

Topic 7: sound production—fishes

It is still not clear how widespread sound production is amongst fishes, although it is likely to be far more extensive than currently known. The behavior of fish is often suppressed under aquarium conditions unless very special measures are taken to provide a quiet environment, with similar characteristics to the natural environment. Even where particular sound-producing species have been examined, and it is evident that sound is important to the species, it has not always been possible to examine the full range of their acoustical behavior. In those fishes that have been examined closely it is evident that sound is often associated with reproductive behavior. However, spawning behavior of and the role of sounds in the reproductive process have yet to be described for most fishes. It is evident that sound production is found in a wide range of families and species and it appears to have evolved independently in many groups (e.g., Tavolga 1971; Myrberg 1978, 1981; Zelick et al. 1999; Bass and Ladich 2008) (Table 7).

Topic 8: sound detection—fishes

Sound is important to fishes and is also likely to be important to many aquatic invertebrates. Many fishes, and at least some invertebrates, depend on sound to communicate with one another, detect prey and predators, navigate from one place to another, avoid hazards, and generally respond to the world around them.

The presentation of measured sound stimuli to fishes under experimental conditions presents great difficulties. The relationship between sound pressure and particle velocity in the majority of experimental tanks is extremely complex, and there is no reliable way of calculating the relative levels of the two quantities (Parvulescu 1964; Gray et al. 2015, Rogers et al. 2015). Both parameters should be measured, but calibrated particle motion detectors are not widely available and these measurements are rarely done. Audiograms (measures of hearing sensitivity versus frequency) and sound pressure thresholds presented in the literature must be treated with great skepticism unless the sound field has been carefully specified. Relatively few

Table 8 Sound detection—fishes

Drivers for information acquisition	Information gaps
Increased knowledge of the hearing abilities of fishes is required to assist in examining the effects of man-made sound upon them. There is also a need to clarify whether particular species are sensitive to sound pressure and particle motion	Confirmation whether fishes can be divided into categories, based on anatomical features (such as in the ear or relationship between ear and swim bladder) that may represent their relative sensitivity to sound
An immediate question is whether fishes can be sorted into different functional hearing groups, obviating the need to examine every species. What do we need to know to define the main groups?	Information obtained under carefully controlled acoustic conditions on the sensitivity and frequency range for both sound pressure and particle motion in different species and different life stages. Can the hearing characteristics of fish within different anatomical groups be described adequately by generalized weighting functions?
There are severe methodological difficulties to be overcome in conducting experiments on the hearing of fishes. Many experiments are currently being carried out under poor acoustic conditions. The need for appropriate conditions for the presentation and measurement of sounds in terms of both sound pressure and particle motion has already been emphasized. There is also a need to perform experiments on hearing against different levels of background noise to examine any effects from masking. There are distinct differences between the audiograms derived using different methods. In general, those obtained from Auditory Evoked Potentials (AEP) measurements show lower sensitivity but wider bandwidth than those obtained from behavioral techniques. Currently, impact assessments are being conducted using data on the hearing abilities of fishes that has been determined under less than optimal acoustic conditions and which may not be truly representative of their hearing abilities in the natural environment. Better data are required	Data obtained in earlier studies under inappropriate acoustical conditions require more critical reappraisal Studies to determine sensitivity of fishes to substrate vibrations Studies on the ability of fishes to discriminate between sounds of differing quality coming from different directions and distances and how man-made sounds affect these abilities
We know that fishes can discriminate between sounds of differing quality and can determine the direction and distance of sound sources. It also seems likely that some can detect substrate vibrations. The full extent of their hearing capabilities remains to be explored. The discrimination and recognition of sounds may be especially affected in the presence of noise	

experiments on the hearing of fishes have been carried out under appropriate acoustical conditions and the results from many of the measurements made in tanks, and expressed solely in terms of sound pressure, are unreliable (Table 8).

Topic 9: masking

There is always a background level of sound in the sea, and ambient sounds may have an impact upon the lowest sound levels that fishes and other animals can hear. Interference with the detection of one sound (generally called the signal) by another sound is called masking, and the sound that does the masking is generally called the masker (see Fay and Megela Simmons 1999) (Table 9).

Topic 10: effects of sound in terms of injuries and changes in physiology

Death and injury are probably the most easily observed and dramatic end-points in terms of responses to sound for fishes (and invertebrates). There are only the most limited data on mortality in fish. There have been several reports from Caltrans (2001) documenting fish mortality very close to pile driving sources, and there is also confirmation that explosions will kill nearby fish (e.g., Yelverton et al. 1975; Keevin and Hempen 1997; Govoni et al. 2003, 2008; also reviewed in Popper and Hastings 2009). However, death has rarely been documented for exposure to continuous sound sources. There is some evidence from the gray literature that fish larvae and

Table 9 Masking in fishes

Drivers for information acquisition	Information gaps
From experiments on the masking of pure tone signals in the presence of noise it seems likely that man-made sounds will mask detection of the soundscape and/or biologically relevant sounds in some (if not all) species of fish. However, data are available for only a handful of species and additional research is required to examine the masking of those sounds important to fishes (their own calls, and sounds used for navigation, habitat detection, prey and predator detection) by changes in ambient noise. It should be possible to predict the extent of masking by man-made sounds based on improved knowledge of hearing capabilities of fishes and of the types of sound generated by different sources under different conditions	Experimental studies examining the masking of sounds of real importance to fishes, initially focusing on species for which sounds have been shown to play a key functional role
The effects of masking can be of considerable significance. This issue is not currently being given sufficient attention in the preparation of impact assessments, where chronic effects are often ignored. The presence of man-made sound has the potential to inhibit or suppress vocal behavior and to interfere with the detection of important sound cues, and may affect vital life functions. It is important to gain a wider knowledge of the significance of sound in fish behavior so that the population level consequences of masking can be assessed	Development of models predicting the degree of masking of particular sounds by different man-made sounds under varying conditions in the sea
Periodic and intermittent sounds may affect masking if they are merged together as a result of long distance propagation and reverberation. The masking potential of repetitive sounds from seismic surveys and pile driving operations has yet to be assessed	The masking potential of intermittent sounds from seismic surveys and pile driving operations remains to be assessed

juveniles may be damaged by exposure to low frequency naval sonars (Jorgensen et al. 2005) but other investigations of the effects of impulsive pile driving on larvae showed no effect (Bolle et al. 2012). Additionally, exposure of fishes to very high intensity sonars operating at frequencies below 1 kHz and from 2 to 4 kHz showed no mortality (Popper et al. 2007; Halvorsen et al. 2012c).

The greater likelihood is that fishes and invertebrates will be injured by high intensity impulsive sounds with rapid rise times, and that some of these injuries could result in fatalities over the short term or over a longer term if animal fitness is compromised (Halvorsen et al. 2011, 2012a, b; Casper et al. 2012a, b, 2013a, b). If an animal is injured it may be more susceptible to infection because of open wounds or a compromised immune system. Even if the animal is not compromised in some way, it is possible that the damage will result in lowered fitness, reducing the animal's ability to find food or making it more subject to predation (Table 10).

Topic 11: effects of sounds upon behavior

Perhaps the most important concern is how man-made sounds alter the general behavior of fishes and invertebrates. It is likely that fishes and invertebrates will respond behaviorally to man-made sounds at much lower sound levels than would result in physiological effects. Animals are likely to show behavioral responses to sounds at much greater distances from the source than those that will result in physical injury. Changes in behavior could have population level effects as a consequence of keeping animals away from preferred habitats, diverting them from migratory routes (e.g., salmon or American shad), or interfering with reproductive behavior. Issues not only involve the responses of the animals but also whether habituation occurs to repeated exposure.

There have been very few studies on the behavior of wild (unrestrained) fishes in response to sounds (reviewed by Hawkins et al. 2014). Such studies have been confined to only a few species and the data are

Table 10 Effects of sound in terms of injuries and changes in the physiology of fishes

Drivers for information acquisition	Information gaps
Little is known about the magnitude of the effects of man-made sounds on the physiology of fishes. It is not yet clear whether death, injury, or physiological effects only occur when fishes are close to the sound source or whether such effects are also evident at a distance. Instant mortality is often not of great concern since it is seems to occur in only a small fraction of a fish population that is closest to an intense sound source. Rather, there is interest in sub-lethal effects and the potential for delayed mortality	Identification of the full range of injuries or physiological effects that may result from exposure to different sound sources and sound levels
There are a number of ways of assessing physiological effects, including tissue damage (including damage to the auditory tissues), the use of biomarkers (measures of changes in the physiology of the animal and levels of stress hormones like cortisol), and changes in auditory sensitivity, for example Temporary Threshold Shift (TTS). The importance of these measures needs to be critically assessed. Which injuries can be regarded as potentially lethal, and which are unlikely to affect the animal in the long term?	Identification of the most reliable indicators (particular injuries, physiological parameters or biomarkers) of deleterious effects from sounds, which might be incorporated into trauma indices and applied in determining dose/response relationships
There may be some biomarkers that are indicative of a real and lasting change to the physiology of the animal, affecting vital life functions. Other biomarkers may show only transient changes. Effects have been observed from sounds on blood proteins, blood enzymes, blood calcium, food consumption rates, respiration rates, growth rates and the state of the hepatopancreas (liver) in a variety of aquatic animals. Free radical damage has also been observed in relation to sound exposure	Identification of which fishes are more susceptible than others to injury or tissue damage
Is TTS an important indicator of damage? What level of hearing loss and persistence has significant implications for behavior?	Determination of the characteristics of man-made sources that cause injury or detrimental changes in physiology; e.g., magnitude, rise time, duration, duty-cycle
In terms of injury and tissue damage it would appear that some fishes, and especially those possessing gas-filled swim bladders or other cavities, might be more susceptible to damage than others, and that the rate of equilibration with depth is important for these fishes	What is the role of anatomy (e.g., the presence of the swim bladder and other gas spaces) in producing physiological effects and how are these effects affected by depth, size, age, season or other factors?
The development and application of physiological trauma indices for fish, which quantify a qualitative assessment of injuries, ranking the physiological costs of impairment, is important as a means for assessing the injuries to an animal. A slight change in an enzyme or a hormonal response might not be accorded the same status as a change in histopathology of a vital organ	Is Temporary Threshold Shift of importance when considering effects of some or all man-made sounds? If so, how should TTS be determined and what degree and duration of TTS is most likely to alter behavior?
An issue of great importance is the effect of intermittent exposure. Many man-made sounds are repeated, both through repetition of a single source and the recruitment of additional sounds from other sources. Are there cumulative and aggregate effects from these repeated exposures? Is there full recovery of function after damage? Is there is a period of healing if sufficient time passes between sound exposures?	Research on the physiological effects of repeated exposure to sound and resolution of the best metrics for expressing the accumulation of sound energy. Is there a better descriptor than sound exposure level (SEL), which is now expressed in two forms: the single strike SEL or the cumulative SEL?
Assessing the effects of cumulative and aggregate exposure has implications both in terms of dose/response relationships and more broadly in terms of designing mitigation measures	
Comparison of the relative impact of exposure to different duty cycles (patterns of presentation) also has relevance to the metrics used to describe and measure cumulative effects from multiple pulses from the same source	

Table 11 Effects of sounds upon the behavior of fishes

Drivers for information acquisition	Information gaps
The potential impact of man-made sounds extends well beyond the distances at which physical or physiological effects occur. A major concern is whether these sounds affect behavior, in turn affecting vital functions such as reproduction, migrations or choice of habitat. Behavioral impacts may range from small (and inconsequential) awareness of sounds to fishes changing their migratory routes, leaving favored sites for feeding and/or breeding, or failing to detect appropriate high-quality habitat	Detailed data on behavioral responses of free-swimming fish in their natural habitats following exposure to relevant sounds
Experiments on captive fishes, whether in tanks in the laboratory or cages in the sea are unlikely to yield valid results. Fishes show changes in behavior and restrictions in their behavioral repertoire in captivity. Currently we have only poor knowledge of behavioral responses in the wild and how they change with different types and levels of sound. Moreover, impacts from man-made sound on fishes leading to changed behavior must be understood in a species specific, size specific, biological state specific and seasonal context	Dose/response curves for behavioral responses to sound exposure
Different types of sound source may elicit different behavioral reactions or result in onset of behavioral reactions at different sound levels. Responses may vary greatly by species, motivation of animals, and other behavioral and physiological conditions. An important question is whether an observed response results in impaired access to essential habitat for feeding, reproduction, concealment, territoriality, communication, or other life processes	Data to support ranking the significance of different behavioral responses for a given species. The ability to distinguish between inconsequential responses and responses that will affect vital functions is important for defining dose/response relationships for behavior
It is important to consider which aspects of a sound are responsible for a given behavioral response (i.e., exposure level, peak pressure, or frequency content). The effects of chronic exposure over long periods to low level sounds may be as important as exposure to isolated high-level sounds	Examination of the effects of chronic exposure over long periods to low-level sound
It is known that fishes may change their behavioral responses after the repeated presentation of sounds. In some cases their reactions may diminish and they may eventually ignore the sound. The full response may be restored after an interval without sound. There is currently little information on the occurrence of habituation	Examination of the role of habituation in behavioral responses

often contradictory. There is a lack of information not only for immediate effects on fish that are close to a source but also on fish that are more distant (Table 11).

Priorities for research derived from the gap analysis

Many information needs are listed in the Gap Analysis but some issues of higher priority for future research have emerged. New research in these areas would provide better understanding of the effects of sound on fishes and invertebrates. A list of the highest priority research from each topic is presented below.

Describing soundscapes

Information is required on the overall contribution made to sound levels and sound quality in aquatic environments from all sources. These particularly include examining baseline ambient conditions, how they change over time and space, and how they will be affected by additional human activities.

There is a need to develop scientific programs that monitor trends in soundscapes through the acquisition of long-term data sets. It is especially important to begin the monitoring of soundscapes in areas of future change and/or critical habitat. At least 30 global sites or networks are routinely collecting data on ocean noise, but in almost all cases the monitoring stations involved have been established to perform specific functions. A variety of sensor designs and data collection and transmission protocols have been applied. Many other isolated measurements of ocean noise have been made in the course of specific studies for military purposes or for the preparation of environmental statements. However, there is no central repository for these data, nor are there any standards or protocols for data collection.

A long-term commitment is required for the establishment of sound monitoring stations and to programs to survey different underwater soundscapes. Priority locations for observing stations include areas where activities are anticipated in the foreseeable future such as areas for energy development, construction work, including roads and bridges close to freshwater sites, and marine mineral extraction. An important question is how much man-made sound the environment can tolerate without its ecological status being changed.

There is a need for a library of sounds produced by fishes and invertebrates. Lack of such a library hinders use of passive acoustics as a tool for determining effects of sound on behavior and examining masking of communication by man-made sounds.

New tools are required to identify unknown biological sound sources and document associated behaviors. Better software tools are also needed to automate measurements of sound characteristics.

In addition to reporting real-time measurements of underwater sound, monitoring stations should be capable of collecting and storing raw data at sufficient frequency and duration to adequately describe sound levels at various temporal scales. Storage of raw data enables a time series of measurements to be calculated at a later time in different metrics, for either comparing results to other studies or to comply with regulatory thresholds.

Maps of the sound metrics and their statistics collected by long-term studies using passive acoustic monitoring networks may provide useful information for marine spatial planning, site evaluation, and impact assessments. Because soundscapes vary at different locales within the regions of concern, site-specific studies of passive acoustic monitoring should be performed before, during, and after sound-generating activities related to the energy industry (e.g., site evaluations using seismic air guns, construction and operation of a energy production site).

Impacts of particular sound sources

What are the main characteristics of the sound fields generated by human activities; expressed in terms that will enable their effects upon aquatic organisms to be assessed?

Information is required on the characteristics of the sounds generated by different sources. Some sound sources, and in particular pile drivers, where transmission through the substrate may be important, have not yet been adequately characterized in terms of the sound fields and other disturbances that they produce.

In addition, those characteristics of man-made sources that cause detrimental effects on animals need to be defined. Better knowledge of the propagation of sounds (in terms of both sound pressure and particle motion) is required, especially for those sounds relevant to fishes and invertebrates. There is a particular need to investigate the propagation of sound and vibration through the seabed, as this is especially relevant to benthic fishes and invertebrates and for exposure to both pile driving and seismic airguns.

There is a need to describe and fully evaluate the effects of the sound fields (in both the near field and far field) produced by explosions, seismic airguns, pile driving, dredging, wind farm operation, vessel noise, fishing activities, and sonar systems. Some research has already been performed by the oil and gas industry to characterize the sound fields generated by seismic airguns and that work should serve as an example for other industries to follow. Research related to the impacts of vessel noise, fishing, activities, and sonar also needs to be advanced.

Sound fields should be expressed in terms of metrics that may be most useful in describing effects upon marine organisms Ainslie and De Jong (2015). As many fishes and invertebrates are sensitive to particle motion, rather than sound pressure, it is especially important to monitor particle motion along with sound pressure. The development of instrumentation and software for this purpose should receive a high priority.

Studies should provide raw data to allow for different metrics to be applied subsequently, particularly if a standard terminology is later established.

Effects of man-made sounds on marine animals

What effects do man-made sounds have upon fishes and invertebrates?

More information is required on the effects of sound on fishes and invertebrates, especially in terms of changes to their survival and reproductive success. Experiments are required to evaluate the levels of injury and physiological damage that are experienced by aquatic animals as a result of exposure to sound, including assessment of the relative importance of acoustical factors like frequency, rise-time, and duty cycle.

Such studies may be performed under controlled laboratory conditions or under field conditions (e.g., cages, pens) but in either case the experiments must include careful measurements of sound pressure and particle motion received by the animal. There is a need to develop a broader understanding of any injuries and/or physiological effects that result from exposure to different sound sources, sound levels, repetition rates, and number of events. Are there particular injuries, physiological parameters or biomarkers that might provide evidence of deleterious effects from sounds, and which might be incorporated into trauma indices and applied in determining dose/response relationships?

Assessment of effects has to include both cumulative and aggregate effects of sound exposure. The effects of repeated exposure to single and multiple stressors and interactions between multiple stressors (both natural and anthropogenic) must be considered. There is a need to decide which metrics are most appropriate for expressing the accumulation of sound energy. This requires further information on the degree and types of injury caused by sounds of differing characteristics.

Key components of experimental research for advancing our knowledge of effects of man-made sounds on fishes and invertebrates are: (1) laboratory or field experiments with adequate controls; (2) animal subjects representative of the different groups defined by sound detection ability, anatomy, ecological associations, commercial importance, and conservation status; (3) treatment groups exposed to sound stimuli over different temporal scales, and either over different spatial scales from the source or simulated levels and characteristics sufficient to quantify mortality, physiological damage, temporary threshold shift, masking, and behavioral responses; (4) appropriate instrumentation to precisely measure a suite of sound characteristics (e.g., spectral density, sound exposure level (single strike and cumulative), rms sound pressure levels, measures of peakiness, rise time, particle motion, etc.) presented to treatment groups; and (5) processed and raw data should be adequately archived.

More extensive and detailed knowledge of the hearing abilities of fishes and invertebrates is required. Hearing threshold curves (audiograms) are being used in environmental impact assessments and/or in the preparation of weighting curves to assess whether animals are potentially affected by man-made sounds. Much of the current data do not give an accurate indication of the detection ability of the animals since they were obtained either under unsatisfactory acoustic conditions or by means of physiological measurements (Ladich and Fay 2013; Gray et al. 2015; Rogers et al. 2015; Sisneros et al. 2015). Audiograms should be developed using behavioral analysis in carefully designed experiments that can adequately replicate the sound characteristics of man-made sound sources (e.g., pile driving, dredging, seismic airguns, etc.) under "free-field" or "far-field" acoustic conditions. Well-equipped field sites, where the response of animals can be examined under approximate 'free-field' acoustic conditions, are required to extend knowledge of the hearing by fishes and invertebrates. Conditions are required where animals can be examined at appropriate depths, under quiet ambient noise conditions, and where sound stimuli can be precisely measured. Specially designed tanks can also play a role in enabling precisely controlled and measured sound stimuli to be presented to fishes and invertebrates so that their detection abilities can be determined (Rogers et al. 2015; Slabbekoorn 2015). At the same time, there are instances, such as with larval fishes where behavioral methods have not yet always been worked out, and where other approaches, such as auditory brainstem response might provide important data (e.g., Wright et al. 2011).

The susceptibility of animal hearing to masking by man-made sounds especially needs to be investigated (Dooling and Blumenrath 2015). The consequences for fishes and invertebrates of changes to the soundscape need to be assessed in terms of the effects this will have on their ability to detect sounds.

Information on the behavioral responses of fishes and invertebrates to different sound sources is also needed in order to assess the effects of man-made sounds. Information is required on responses over time (for example to repeated exposure) and over long distances. How do animals respond when they encounter a sound? Do they leave an area? Do they return later? Is their fitness impaired? Experiments exploiting new technologies (e.g., active acoustics, tagging) at an appropriate scale and for a variety of sound sources should be encouraged. It is important to note that such studies cannot be carried out in the laboratory or even in large cages, but require detailed observations on the behavior of animals in the natural environment.

More information is required on the effects of man-made sounds on the distribution of fishes and their capture by different fishing gears. There may be different effects on different species, on different fishing grounds and habitat types. Access to fisheries statistics at fine spatial and temporal scales may provide useful insight, but fishery-independent surveys using multiple gear types following before-after-control-impact study design may provide better information on the effects of particular man-made sounds to catch rates and distributions (vertical and horizontal) of fishes and commercially important invertebrates.

Selection of appropriate species for further study must be made carefully. Although endangered and threatened species in areas likely to be affected by various sound sources are of greatest interest, practically-speaking these species are often not readily available for experimentation. In some cases it may be necessary to examine closely related species as surrogates. Species that are representative of the various anatomical and ecological associations should receive high priority for examination. Fishes could be grouped by their swim bladder morphology and life stage (eggs, larvae, juvenile, adult) so that emphasis can be placed on those categories for which sound is likely to be especially important (Popper et al. 2014; Hawkins and Popper 2014). Invertebrates selected for study should represent the major taxonomic groups and those species of greatest commercial and ecological importance should be prioritized such as bivalves (e.g., scallops, clams), cephalopods (e.g., squid), crustaceans (e.g., lobsters, shrimps), echinoderms (e.g., sea urchin), and corals (e.g., coral larvae). Fishes and invertebrates of high commercial importance (top ten in landings or value) should also be considered.

Mitigation of effects

Can mitigation measures reduce sound exposure and reduce and/or eliminate detrimental effects from sound-generating activities?

Although the preceding Gap Analysis did not specifically consider the mitigation of any effects this is an important aspect of environmental impact assessment that requires consideration. There are two kinds of mitigation. The first involves the use of biological information to minimize effects. The second involves changes to the sound source to minimize effects.

To facilitate biological forms of mitigation, information is required on those periods in the lives of marine fishes and invertebrates, or those critical locations, when they might be especially affected by exposure to man-made sound. Specific requirements are to identify critical habitats, migration routes, and reproductive periods so that exposure might be avoided. Such information requires close cooperation with fisheries biologists.

For some sources there may be potentially useful mitigation measures applied to the source itself that might decrease the exposure of fishes and invertebrates to sound. Research is needed to establish the means for reducing unwanted and damaging sound from a range of sound sources. Industry must look closely at making changes to those sources or seeking alternatives to them that will cause less harm. Sound shielding technologies capable of effectively and verifiably reducing harm from existing sources should also be investigated. In considering source mitigation it is important to examine those characteristics of the sounds that might make them especially likely to be harmful to fishes and invertebrates (in terms of level, duration, rise time, duty cycle etc.).

Studies are especially required to examine the efficacy of ramp-up, soft-start and other aversive techniques. Can fishes and invertebrates be induced to move away from an area by using ramp up in order to allow potentially damaging sounds to be produced subsequently?

Passive Acoustic Monitoring (PAM) systems are routinely used to detect marine mammals by registering their natural calls. PAM systems have not yet been developed to detect the presence of fishes and invertebrates, perhaps because there are fewer vocal species and the calls are often much lower in amplitude than those of marine mammals, making it harder to detect fishes and invertebrates. There is a possibility that active acoustic monitoring, by means of sonar, may detect the presence of some fishes and invertebrates without disturbing them. The application of active acoustic monitoring should be further explored.

Where mitigation measures have been implemented to overcome or reduce the effects of exposure to sound, the efficacy of those measures should be monitored and assessed.

Measurement and description of sounds and the conduct of acoustic experiments

It is especially important to describe sounds properly, and conduct experiments under controlled acoustic conditions

Agencies must come to a consensus on the adoption of relevant and universally acceptable metrics that describe sounds appropriately and enable comparison of the effects of sounds of different types on different taxa. This has to be done for both sound pressure and particle motion.

A common terminology needs to be developed for sound measurement and exposure that is useful and understandable to the whole community—from acousticians to biologists to regulators.

Inexpensive instrumentation, which does not require specialist skills, is required for the measurement of underwater sound, both in the laboratory and in the ocean. Measurement of particle motion is a particular priority.

Special acoustic facilities are required that will enable investigators to present sounds to aquatic animals in the laboratory, or in the field, with full specification of the signals presented both in terms of sound pressure and particle motion. Such field sites are required to extend knowledge of the hearing by fishes and invertebrates, as well as their behavioral responses.

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References

Aguilar de Soto NA, 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):1–5

Ainslie M (2010) Principles of sonar performance modelling. Springer, New York

Ainslie M (2011) Standard for measurement and monitoring of underwater noise, Part I. Physical quantities and their units. TNO Report TNO-DVTNO-DV 2011 C235:C235

Ainslie M, De Jong C (2015) Sources of underwater sound and their characterization. In: Popper AN, Hawkins D (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)

Andrew RK, Howe BM, Mercer JA, Dzieciuch MA (2002) Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoust Res Lett Online 3(2):65. doi:10.1121/1.1461915

Andriguetto-Filhoa JM, Ostrenskya A, Pieb MR, Silvac UA, Boeger WA (2005) Evaluating the impact of seismic prospecting on artisanal shrimp fisheries. Cont Shelf Res 25:1720–1727

Arveson PT, Vendittis DJ (2000) Radiated noise characteristics of a modern cargo ship. J Acoust Soc Am 107:118

Bass AH, Ladich F (2008) Vocal-acoustic communication: From neurons to brain. In: Webb JF, Fay RR, Popper AN (eds) Fish bioacoustics. Springer Science + Business Media, LLC, New York, pp 253–278

Bittencourt L, Carvalho RR, Lailson-Brito J, Azevedo AF (2014) Underwater noise pollution in a coastal tropical environment. Mar Pollut Bull 83(1):331–336. doi:10.1016/j.marpolbul.2014.04.026

Bolle LJ, de Jong CA, Bierman SM, van Beek PJ, van Keeken OA, Wessels PW, van Damme CJ, Winter HV, de Haan D, Dekeling RP (2012) Common sole larvae survive high levels of pile-driving sound in controlled exposure experiments. PLoS ONE 7(3):e33052. doi:10.1371/journal.pone.0033052

Boudreau M, Courtenay SC, Lee K (2009) Proceedings of a workshop held 23 January at the Gulf Fisheries Center potential impacts of seismic energy on snow crab: an update to the September review. In: Boudreau M, Courtenay SC, Lee K (eds) Canadian Technical Report of Fisheries and Aquatic Sciences 2836, pp vii–31

Brekhovskikh LM, Lysanov IUP (2003) Fundamentals of ocean acoustics. Springer, New York

Caldwell J, Dragoset W (2000) A brief overview of seismic air-gun arrays. Lead Edge 2000(August):898–902

Caltrans (2001) Pile installation demonstration assessment fisheries impact assessment. San Francisco Oakland Bay bridge East span seismic safety project

Carlson TJ (2012) Barotrauma in fish and barotrauma metrics. Adv Exp Med Biol 730:229–233. doi:10.1007/978-1-4419-7311-5_51

Casper BM, Halvorsen MB, Popper AN (2012a) Are sharks even bothered by a noisy environment? Adv Exp Med Biol 730:93–97. doi:10.1007/978-1-4419-7311-5_20

Casper BM, Popper AN, Matthews F, Carlson TJ, Halvorsen MB (2012b) Recovery of barotrauma injuries in Chinook salmon, Oncorhynchus tshawytscha from exposure to pile driving sound. PLoS ONE 7(6):e39593. doi:10.1371/journal.pone.0039593

Casper BM, Halvorsen MB, Matthews F, Carlson TJ, Popper AN (2013a) Recovery of barotrauma injuries resulting from exposure to pile driving sound in two sizes of hybrid striped bass. PLoS ONE 8(9):e73844. doi:10.1371/journal.pone.0073844

Casper BM, Smith ME, Halvorsen MB, Sun H, Carlson TJ, Popper AN (2013b) Effects of exposure to pile driving sounds on fish inner ear tissues. Comp Biochem Physiol A: Mol Integr Physiol 166(2):352–360. doi:10.1016/j.cbpa.2013.07.008

Cato DH (1992) The biological contribution to the ambient noise in waters near Australia. Acoust Australia 20:76–80

Chapman CJ, Hawkins AD (1969) The importance of sound in fish behaviour in relation to capture by trawls. FAO Fisheries Reports 621(3):717–729

Cole RH (1948) Underwater explosions. Princeton University Press, Princeton NJ

CSA (2004) Explosive removal of offshore structures—information synthesis report. Continental Shefl Associates, OCS Study MMS 2003-070. New Orleans, LA

CSA (2014) Quieting technologies for reducing noise during seismic surveying and pile driving workshop. Summary Report for the US Dept. of the Interior, Bureau of Ocean Energy Management. Contract Number M12PC00008. 68 pp. + apps

De Jong C, Ainslie M, Blacquière G (2011) Standard for measurement and monitoring of underwater noise, part II: procedures for measuring underwater noise in connection with offshore wind farm licensing. Report no TNO-DV:C251

De Robertis A, Wilson CD, Williamson N (2012) Do silent ships see more fish? Comparison of a noise-reduced and a conventional research vessel in Alaska. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life. Advances in experimental medicine and biology, vol 730. Springer Science + Business Media, New York, pp 449–452

Dickerson C, Reine KJ, Clarke DG (2001) Characterization of underwater sounds produced by bucket dredging operations. United States Army Engineer Research and Development Center, Vicksburg

Dooling RJ, Blumenrath SH (2015) Masking experiments in humans and birds using anthropogenic noises. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)

Dowding CH (2000) Construction vibrations. Prentice Hall, Upper Saddle River

Dunning DJ, Ross QE, Geoghegan P, Reichle JJ, Menezes JK, Watson JK (1992) Alewives in a cage avoid high-frequency sound. North Am J Fish Manag 12:407–416

Ellison WT, Frankel AS (2012) A common sense approach to source metrics. Adv Exp Med Biol 730:433–438. doi:10.1007/978-1-4419-7311-5_98

Fay RR, Megela Simmons A (1999) The sense of hearing in fishes and amphibians. In: Fay RR, Popper AN (eds) Comparative hearing: fish and amphibians. Springer, New York, pp 269–318

Frisk GV (2007) Noiseonomics: the relationship between ambient noise levels and global economic trends. In: Paper presented at the Pacific Rim Underwater Acoustics Conference, Vancouver, BC, Canada, 3–5 October 2007

Gage SH, Axel AC (2014) Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. Ecol Inform 21:100–109. doi:10.1016/j.ecoinf.2013.11.004

Govoni JJ, Settle LR, West MA (2003) Trauma to juvenile pinfish and spot inflicted by submarine detonations. J Aquat Animal Health 15:111–119

Govoni JJ, West MA, Settle L, Lynch RT, Greene MD (2008) Effects of underwater explosions on larval fish: implications for a coastal engineering project. J Coastal Res 24:228–233

Gray MD, Rogers PH, Popper AN, Hawkins AD, Fay RR (2015) Large tank acoustics: how big is big enough? In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)

Halvorsen MB, Casper BM, Woodley CM, Carlson TJ, Popper AN (2011) Predicting and mitigating hydroacoustic impacts on fish from pile installations. National Cooperative Highway Research Program Research Results Digest 363 (October 2011)

Halvorsen MB, Casper BM, Matthews F, Carlson TJ, Popper AN (2012a) Effects of exposure to pile-driving sounds on the lake sturgeon, Nile tilapia and hogchoker. Proc Biol Sci R Soc 279(1748):4705–4714. doi:10.1098/rspb.2012.1544

Halvorsen MB, Casper BM, Woodley CM, Carlson TJ, Popper AN (2012b) Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE 7(6):e38968. doi:10.1371/journal.pone.0038968

Halvorsen MB, Zeddies DG, Ellison WT, Chicoine DR, Popper AN (2012c) Effects of mid-frequency active sonar on

hearing in fish. J Acoust Soc Am 131(1):599–607. doi:10.1121/1.3664082
Hawkins AD, Popper AN (2014) Assessing the impacts of underwater sounds on fishes and other forms of marine life. Acoust Today 10(2):30–41
Hawkins A, Popper AN, Wahlberg M (2008) International conference on the effects of noise on aquatic life. Bioacoustics 17:1–350
Hawkins AD, Roberts L, Cheesman S (2014) Responses of freeliving coastal pelagic fish to impulsive sounds. J Acoust Soc Am 135:3101–3116. doi:10.1121/1.4870697
Hazelwood RA (2012) Ground roll waves as a potential influence on fish: measurement and analysis techniques. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life. Advances in experimental medicine and biology, vol 730. Springer Science + Business Media, New York, pp 449–452. doi:10.1007/978-1-4419-7311-5_101
Hazelwood RA, Macey PC (2015) The intrinsic directional information of ground roll waves. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)
Hildebrand JA (2009) Anthropogenic and natural sources of ambient noise in the ocean. Mar Ecol Prog Ser 395:5–20. doi:10.3354/meps08353
Hughes AR, Mann DA, Kimbro DL (2014) Predatory fish sounds can alter crab foraging behaviour and influence bivalve abundance. Proc R Soc B Biol Sci 281(1788):20140715. doi:10.1098/rspb.2014.0715
Illingworth R, Rodkin R (2001) Noise and vibration measurements associated with the pile installation demonstration project for the San Francisco-Oakland Bay Bridge east span. Technical Report of Illingworth & Rodkin Inc., Petaluma
Illingworth R, Rodkin R (2007) Compendium of pile driving sound data. Prepared for the California Department of Transportation, Sacramento, California. September 27, 2007
Johnson CE (2012) Regulatory assessments of the effects of noise: moving from threshold shift and injury to behavior. Adv Exp Med Biol 730:563–565. doi:10.1007/978-1-4419-7311-5_127
Jorgensen R, Olsen K, Falk-Petersen IB, and Kanapthippilai P (2005). Investigations of potential effects of low frequency sonar signals on survival, development and behaviour of fish larvae and juveniles. The Norwegian College of Fishery Science, University of Tromso, Norway. 49 pp
Kane AS, Song J, Halvorsen MB, Miller DL, Salierno JD, Wysocki LE, Zeddies D, Popper AN (2010) Exposure of fish to high-intensity sonar does not induce acute pathology. J Fish Biol 76(7):1825–1840. doi:10.1111/j.1095-8649.2010.02626.x
Keevin TM, Hempen GL (1997) The environmental effects of underwater explosions with methods to mitigate impacts. U.S. Army Corps of Engineers, St. Louis District
Knudsen V, Alford RS, Emling JW (1948) Underwater ambient noise. J Mar Res 7:410–429
Ladich F, Fay RR (2013) Auditory evoked potential audiometry in fish. Rev Fish Biol Fish 23(3):317–364. doi:10.1007/s11160-012-9297-z
Laughlin J (2006) Underwater sound levels associated with pile driving at the Cape Disappointment boat launch facility, wave barrier project. Washington state parks wave barrier project underwater technical report, vol 13
Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack P (2006) Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar Ecol Prog Ser 309:279–295
Mann DA, Lu Z, Popper AN (1997) Ultrasound detection by a teleost fish. Nature 389:381
Mann DA, Casper BM, Boyle KS, Tricas T (2007) On the attraction of larval fishes to reef sounds. Mar Ecol Prog Ser 338:307–310
Mattsson A, Parkes G, Hedgeland D (2012) Svein Vaage broadband air gun study. Adv Exp Med Biol 730:469–471. doi:10.1007/978-1-4419-7311-5_106
Mazzuca LL (2001) Potential effects of low frequency sound (lfs) from commercial vessels on large whales. University of Washington
McDonald MA, Hildebrand JA, Wiggins SM, Ross D (2008) A 50 Year comparison of ambient ocean noise near San Clemente Island: a bathymetrically complex coastal region off Southern California. J Acoust Soc Am 124:1985–1992
McKenna MF, Ross D, Wiggins SM, Hildebrand JA (2012) Underwater radiated noise from modern commercial ships. J Acoust Soc Am 131(1):92–103. doi:10.1121/1.3664100
McWilliam JN, Hawkins AD (2014) A comparison of inshore marine soundscapes. J Exp Mar Biol Ecol 446:166–176
Mooney TA, Hanlon RT, Christensen-Dalsgaard J, Madsen PT, Ketten DR, Nachtigall PE (2010) Sound detection by the longfin squid (Loligo pealeii) studied with auditory evoked potentials: sensitivity to low-frequency particle motion and not pressure. J Exp Biol 213(Pt 21):3748–3759. doi:10.1242/jeb.048348
Mooney TA, Hanlon R, Madsen PT, Christensen-Dalsgaard J, Ketten DR, Nachtigall PE (2012) Potential for sound sensitivity in cephalopods. Adv Exp Med Biol 730:125–128. doi:10.1007/978-1-4419-7311-5_28
Myrberg AA Jr (1978) Ocean noise and the behavior of marine animals: Relationships and implications. In: Fletcher JL, Busnel RG (eds) Effects of noise on wildlife. Academic Press, New York, pp 169–208
Myrberg AA Jr (1981) Sound communication and interception in fishes. In: Tavolga WN, Popper AN, Fay RR (eds) Hearing and sound communication in fishes. Springer, New York, pp 395–426
National Research Council (2002) Effects of trawling and dredging on seafloor habitat. National Academy Press, Washington
National Research Council (2003) Ocean noise and marine mammals. National Academy Press, Washington
Nedwell JR, Parvin SJ, Edwards B, Workman R, Brooker AG, Kynoch JE (2007) Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters. Subacoustech Report No. 544R0738 to COWRIE Ltd
Normandeau (2012) Effects of noise on fish, fisheries, and invertebrates in the US Atlantic and Arctic from energy industry sound-generating activities. A Workshop Report for the US Dept of the Interior, Bureau of Ocean Energy Management

OSPAR (2009) Overview of the impact of anthropogenic underwater sound in the marine environment. Biodiversity Series. OSPAR Commission
Parvulescu A (ed) (1964) Problems of propagation and processing. Marine bio-acoustics. Pergamon Press, Oxford
Pine MK, Jeffs AG, Radford CA (2012) Turbine sound may influence the metamorphosis behaviour of estuarine crab megalopae. PLoS ONE 7(12):e51790. doi:10.1371/journal.pone.0051790
Pine MK, Jeffs AG, Radford CA (2013) The cumulative effect on sound levels from multiple underwater anthropogenic sound sources in shallow coastal waters. J Appl Ecol 51:23–30
Popper AN, Fay RR (2011) Rethinking sound detection by fishes. Hear Res 273:25–36. doi:10.1016/j.heares.2009.12.023
Popper AN, Hastings MC (2009) The effects of anthropogenic sources of sound on fishes. J Fish Biol 75(3):455–489. doi:10.1111/j.1095-8649.2009.02319.x
Popper AN, Hawkins AD (2012) The effects of noise on aquatic life. Advances in experimental medicine and biology, vol 730. Springer Science + Business Media, New York
Popper AN, Hawkins AD (2015) The effects of noise on aquatic life. II. Springer Science + Business Media, New York
Popper AN, Halvorsen MB, Kane AS, Miller DL, Smith ME, Song J, Stein P, Wysocki LE (2007) The effects of high-intensity, low-frequency active sonar on rainbow trout. J Acoust Soc Am 122(1):623–635
Popper AN, Hawkins AD, Fay RR, Mann DA, Bartol S, Carlson TJ, Coombs S, Ellison WT, Gentry RL, Halvorsen MB, Løkkeborg S, Rogers PH, Southall BL, Zeddies DG, Tavolga WN (2014) Sound exposure guidelines for fishes and sea turtles: a technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. ASA S3/SC1.4 TR-2014. Springer and ASA Press, Cham, Switzerland
Radford CA, Stanley JA, Tindle CT, Montgomery JC, Jeffs AG (2010) Localised coastal habitats have distinct underwater sound signatures. Mar Ecol Prog Ser 401:21–29
Reyff J (2012) Underwater sounds from unattenuated and attenuated marine pile driving. Adv Exp Med Biol 730:439–444. doi:10.1007/978-1-4419-7311-5_99
Richardson WJ, Greene CR Jr, Malme CI, Thomson DH (1995) Marine mammals and noise, vol 98. Academic Press, New York
Robinson SP, Theobald PD, Lepper PA, Hayman G, Humphrey VF, Wang LS, Mumford S (2011) Measurement of underwater noise arising from marine aggregate operations. Adv Exp Med Biol 730:465–468. doi:10.1007/978-1-4419-7311-5_105
Rodkin RB, Reyff JA (2008) Underwater sound from marine pile driving. Bioacoustics 17(1–3):138–140
Rogers PH, Cox M (1988) Underwater sound as a biological stimulus. In: Atema J, Fay RR, Popper AN, Tavolga WN (eds) In sensory biology of aquatic animals. Springer-Verlag, New York, pp 131–149
Rogers PH, Hawkins AD, Popper AN, Fay RR, Gray MD (2015) Parvulescu revisited: small tank acoustics for bioacousticians. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)
Ross D (1987) Mechanics of underwater noise. Peninsula Publishing, Los Altos
Ross D (1993) On ocean underwater ambient noise. Acoustics Bulletin 18(1993):5–8
Scrimger P, Heitmeyer RM (1991) Acoustic source-level measurements for a variety of merchant ships. J Acoust Soc Am 89:691
Sigray P, Andersson MH (2012) Underwater particle acceleration induced by a wind turbine in the Baltic Sea. In: The effects of noise on aquatic life. Springer, New York, pp 489–492
Simpson SD, Meekan MG, McCauley RD, Jeffs A (2004) Attraction of settlement stage coral reef !shes to reef noise. Mar Ecol Prog Ser 276:263–268
Sisneros JA, Popper AN, Hawkins AD, Fay RR (2015) Auditory evoked potential audiograms compared to behavioral audiograms in aquatic animals. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)
Slabbekoorn H (2015) Aiming for progress in understanding underwater noise impact on fish: complementary need for indoor and outdoor studies. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)
Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C, Popper AN (2010) A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol Evol 25(7):419–427. doi:10.1016/j.tree.2010.04.005
Stadler JH, Woodbury DP (2009) Assessing the effects to fishes from pile driving: application of new hydroacoustic criteria. Inter-noise 2009 innovations in practical noise control
Stephenson JR, Gingerich AJ, Brown RS, Pflugrath BD, Deng Z, Carlson TJ, Langeslay MJ, Ahmann ML, Johnson RL, Seaburg AG (2010) Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory. Fish Res 106(3):271–278. doi:10.1016/j.fishres.2010.08.006
Tavolga WN (1971) Sound production and detection. In: Hoar WS, Randall DJ (eds) Fish physiology, vol V. Academic Press, New York
Thomsen F, Lüdemann K, Kafemann R, Piper W (2006) Effects of offshore wind farm noise on marine mammals and fish. Biola, Hamburg, Germany on behalf of COWRIE Ltd
Urick RJ (1983) Principles of underwater sound, 3rd edn. McGraw-Hill, New York
van Parijs SM, Clark CW, Sousa-Lima RS, Parks SE, Rankin S, Risch D, van Opzeeland IC (2009) Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. Mar Ecol Prog Ser 395:21–36
Wahlberg M, Westerberg H (2005) Hearing in fish and their reactions to sound from offshore wind farms. Mar Ecol Prog Ser 288:298–309
Wale MA, Simpson SD, Radford AN (2013) 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
Wales SC, Heitmeyer RM (2002) An ensemble source spectra model for merchant ship-radiated noise. J Acoust Soc Am 111:1211

Wenz GM (1962) Acoustic ambient noise in the ocean: spectra and sources. J Acoust Soc Am 34:1936–1956

Weston DE (1960) Underwater explosions as acoustic sources. Proc Phys Soc 76:233

Wilkens SL, Stanley JA, Jeffs AG (2012) Induction of settlement in mussel (*Perna canaliculus*) larvae by vessel noise. Biofoul J Bioadhes Biofilm Res 28:65–72

Woodbury D, Stadler J (2008) A proposed method to assess physical Injury to fishes from underwater sound produced during pile driving. Bioacoustics 17:289–297

Wright, DG, Hopky GE (1998) Guidelines for the use of explosives in or near Canadian fisheries waters. Canadian Technical Report of Fisheries and Aquatic Sciences 2107: iv + 34p

Wright KJ, Higgs DM, Leis JM (2011) Ontogenetic and interspecific variation in hearing ability in marine fish larvae. Mar Ecol Prog Ser 424:1–13. doi:10.3354/meps09004

Yelverton JT, Richmond DR, Hicks W, Saunders H, Fletcher ER (1975) The relationship between fish size and their response to underwater blast. Report DNA 3677T, Director, Defense Nuclear Agency, Washington, DC

Young GA (1991) Concise methods for predicting the effects of underwater explosions on marine life. DTIC Document. Naval Surface Warfare Center, Silver Spring

Zelick R, Mann DA, Popper AN (1999) Acoustic communication in fishes and frogs. Comparative hearing: fish and amphibians. Springer, New York