Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities

Literature Synthesis

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Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities

Draft Literature Synthesis

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ABOUT THE COVER

Cover photos courtesy of Norwegian Meteorological Institute (ship), BOEM (oil platform), and Laszlo Ilyes (school of fish).

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Acronyms and Abbreviations

µPa	microPascal
ADFG	Alaska Department of Fish and Game
AEP	Auditory Evoked Potential
ANSI	American National Standards Institute
BOEM	Bureau of Ocean Energy Management (United States)
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement (since superseded by BOEM) (United States)
CPUE	Catch Per Unit Effort
dB	Decibel
dB_{peak}	Decibels measured in terms of peak sound pressure
dB_{rms}	Decibels measured in terms of root-mean-square pressure
DOSITS	Discovery of Sound in the Sea (DOSITS.ORG)
EEZ	Exclusive Economic Zone
EFH	Essential Fish Habitat
ESA	Endangered Species Act
ESP	Environmental Studies Program
FERC	Federal Energy Regulatory Commission (United States)
FMP	Fishery Management Plan
GLM	General Linear Models
HAPC	Habitat Areas of Particular Concern
Hz	Hertz
IACMST	Inter-Agency Committee on Marine Science and Technology (United Kingdom)
ICES	International Council for Exploration of the Sea
ISO	International Organization for Standardization
kg	kilogram
kHz	kilohertz
km	kilometer
lbs	pounds
LNG	Liquefied Natural Gas
MAFMC	Mid-Atlantic Fishery Management Council
Magnuson-Stevens Act	Magnuson-Stevens Fisheries Conservation and Management Act (United States)
MMPA	Marine Mammal Protection Act (United States)
MMS	Minerals Management Service (precursor to BOEM) (United States)
NEFMC	New England Fishery Management Council
NEPA	National Environmental Policy Act (United States)
nm	Nautical Miles
NMFS	National Marine Fisheries Service (United States)
NOAA	National Oceanographic and Atmospheric Administration (United States)
NPFMC	North Pacific Fishery Management Council
NRC	National Research Council (United States)
OCS	Outer Continental Shelf

OCSLA	Outer Continental Shelf Lands Act (United States)
PAM	Passive Acoustic Monitoring
PCAD model	Population Consequences of Acoustic Disturbance model
PTS	Permanent Threshold Shift
RMS	Root-Mean-Square (in sound measurements)
SAFMC	South Atlantic Fishery Management Council
SEL	Sound Exposure Level
$\mathrm{SEL_{cum}}$	Cummlative Sound Exposure Level
$\mathrm{SEL_{ss}}$	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
µPa	microPascal

1 Background and Overview

1.1 Introduction

The Bureau of Ocean Energy Management (BOEM) Environmental Studies Program is convening a workshop (hereafter referred as the Workshop) *to identify the most critical information needs and data gaps* on the effects of various man-made sound on fish, fisheries, and invertebrates resulting from the use of sound-generating devices by the energy industry**.** To help focus the Workshop and maximize the contributions of the participants this document presents a Literature Synthesis (or Synthesis) that summarizes current knowledge of the topic as of January 2012.

While the focus of this Literature Synthesis and Workshop will be on fish, fisheries, and invertebrates of U.S. Atlantic and Arctic Outer Continental Shelf (OCS), the findings will have a bearing on related activities around the world. Because of limited available data focused on species in the regions of interest, much of the literature reviewed and many of the species discussed are not taken directly from United States sources or locales. However, in most cases, the findings can be extrapolated to, and are fully relevant for, the species, sources, and regions of interest.

The Workshop will consider renewables, including offshore wind development, as well as oil and gas, and all the operations needed to implement these activities and decommission them after their termination. The Workshop will also cover exploration, including the use of devices for monitoring habitats, like boomers and multi-beam sonars, and sand and gravel (mineral) mining (dredging). While BOEM has jurisdiction to issue leases, easements, and rights-of-way for wave and tidal energy developments, the Federal Energy Regulatory Commission (FERC) has the primary regulatory responsibility for these developments. Wave and tidal energy development activities will not, therefore, be given prominence at the Workshop, although this Literature Synthesis is informed by appropriate studies and findings with respect to those developments.

The Workshop itself will serve as the basis for a final report identifying information needs and data gaps. The final document from the Workshop (the Report) will comprise this Literature Synthesis, a Meeting Report, and a Gap Analysis.

This Literature Synthesis summarizes existing recent literature through 2011. It picks up where previous syntheses (e.g., Popper and Hastings 2009) left off and provides an initial identification of information needs and data gaps for the Workshop. This Synthesis is intended to be read by all participants prior to the Workshop and to serve as a jumping off point for all of the presentations. Thus, this Literature Synthesis will enable all speakers and participants at the Workshop to focus on new data and ideas rather than review older material. It is intended that the Workshop itself will go beyond the thinking of earlier groups and take knowledge forward.

Information needs and data gaps identified in this Synthesis are given in italized bullets. For the purpose of this Literature Synthesis, the authors have provided these lists without prioritization. Moreover, the lists in this Synthesis are not complete and are also far too extensive to provide BOEM, any United States or international organization, or the scientific community with guidance on information needs and data gaps. During the Workshop, participants will develop revised lists of information gaps and data needs and help prioritize them to provide the best possible guidance for agencies and researchers. Indeed, it is the expectation of BOEM and the authors that the lists will be modified substantially during the Workshop and that the final lists produced will benefit substantially from the presentations, breakout groups, and discussions at the Workshop.

1.2 Additional Literature Reviews and Syntheses

This Literature Synthesis provides a comprehensive, though by no means complete, listing of the literature on the effects of sound on fish, fisheries, and invertebrates. It includes citations of the most relevant literature, and highlights those studies that are most important for current and future understanding of the topic at hand. Additional literature, and many more citations, can be found in the following sources:

- Popper and Hawkins (2012)—The outcome of a 2010 conference on Effects of noise on aquatic life, including over 150 papers on numerous topics.
- Le Prell et al. (2012)—A set of comprehensive reviews on effects of man-made sound on humans. The principles discussed in this book are highly relevant for all animals, and there are valuable discussions of metrics.
- Bingham (2011)—Proceedings on a 2009 Workshop titled “Status and Applications of Acoustic Mitigation and Monitoring Systems for Marine Mammals” and published by the Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE; the predecessor bureau to BOEM). Much of the material is relevant to fish and invertebrates.
- Small et al. (2011)—A final report of the Chukchi Sea Acoustics Workshop that reviews acoustic monitoring studies in the Alaskan Arctic and determines priority research objectives for monitoring natural and anthropogenic underwater sounds.
- Slabbekoorn et al. (2010)—A paper calling for a better understanding of the ecological impact of anthropogenic sounds.
- Olso and Paris Commission (OSPAR) (2009)—An overview of the impacts of man-made underwater sound in the marine environment by a European environmental commission.
- Popper and Hastings (2009)—A comprehensive and critical review of pile driving and other sources and their effects on fish.
- Webb et al. (2008a)—A book that reviews fish hearing, sound production, and related topics. Reviews cover anatomy and physiology of the auditory system as well as behavior and physiology of hearing and sound communication.
- Boyd et al. (2008)—A review by the European Science Foundation of effects upon marine mammals, which develops a framework for risk assessment.
- Hawkins et al. (2008)—The proceedings of a 2007 conference on the effects of noise on aquatic life.
- Southall et al. (2007)—A comprehensive review of effects of sound on marine mammals. The basic ideas are important for thinking about effects of sounds, with particular emphasis on physiology and physical damage.

- Nowacek et al. (2007)—A review of the effects of sound on marine mammals from a behavioral perspective.
- Wahlberg and Westerberg (2005)—A paper examining potential effects of wind farm sounds on fish.
- Inter-Agency Committee on Marine Science and Technology (IACMST) (2006)—A summary report of a United Kingdom working group on the effects of underwater sound on marine life.
- National Research Council (NRC) (2005)—A review by the National Academies of Science (United States) on effects of sound on marine mammals, but many of the issues raised are highly relevant to fish and invertebrates.
- Popper et al. (2003)—A paper examining what is known about hearing and use of sound by aquatic invertebrates.

1.3 Animals of Interest

A number of different terms are used in this document to refer to the animals of interest, following biological convention. The major groups being dealt with are generally referred to as fish and invertebrates. Fish is a general term that will be used, unless otherwise specified, to refer to members of two taxonomic classes: Osteichthyes (bony fishes) and Chondrichthyes (cartilaginous fishes; also referred to as elasmobranchs). Two groups of jawless vertebrates also regarded as fish, the lampreys (class Agnatha) and hagfishes (class Myxini),[1] are not included in this synthesis due to a paucity of information on hearing or use of sound. A general discussion of fish biology can be found in the text by Helfman et al. (2009).

The Chondrichthyes have cartilaginous skeletons and includes sharks, skates, rays, and chimaeras. As will be discussed, very little is known about hearing, use of sound in behavior, or how man-made sound may affect these animals (Casper et al. 2012). However, since elasmobranchs are critical parts of the marine ecosystem, they are species of considerable interest (Carrier et al. 2004; Hueter et al. 2004).

The Osteichthyes make up the vast majority of species referred to as fishes. These bony fishes include a number of more primitive species (e.g., sturgeon [*Acipenser* sp.], paddlefish, and gars) as well as the teleosts, which are the largest of all vertebrate groups. The teleosts include most of the species one thinks of when referring to fish, including most of the major commercial species such as herring, cod, tuna, and salmon.

By convention in the community of fish biologists, the word “fish” will generally refer to one or more members of a single species. “Fishes” refers to more than one species.

Invertebrates are animals that do not have backbones. Since very little is known about hearing, use of sound, or effects of man-made sound on these species, not much will be discussed about them in this review, other than to point out the few things that are known (Sections 5.2 and 8.1).

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[1] The taxonomic position of the clade Myxini, or hagfishes, is controversial and it is not clear if they are considered true vertebrates or a sister group to the vertebrates. Since these animals are not mentioned further in this survey, we will not consider their vertebrate relationships any further.

At the same time, since many invertebrates, including crustaceans, mollusks, and cephalopods, are of considerable economic importance, questions will be raised about potential effects, and what is needed to assess such effects. Specific invertebrate groups will be discussed at appropriate parts of this Synthesis.

1.4 Definitions

In this section a number of concepts and terms will be defined that are critical for understanding this Synthesis and the output of the Workshop. Moreover, to facilitate understanding of what may be new terms for some readers, a glossary is included in Appendix A to define many of the terms used in this Synthesis. Individuals needing a wider background on the basics of underwater acoustics and marine bioacoustics should look at the website from Discovery of Sound in the Sea (www.dosits.org) or the Aquatic Acoustic Archive (often referred to as A3) (http://aquaticacousticarchive.com).

Data are a collection of observations or measurements. Data can be used to generate reports, graphs, and statistics. When those data are processed to provide outputs, the resultant ***information*** allows decisions to be taken, conclusions to be drawn, or hypotheses and theories to be proposed and tested. In considering ***information needs***, the concern is with information required to support future management decisions or operations by BOEM and by the energy industry. In considering ***data gaps***, the priority is to seek any absence of observations and measurements required to support those information needs. Such data gaps may provide a basis for deciding on future research priorities.

Not all data are of the same quality or collected according to appropriate protocols. Care must be taken in evaluating the value of data from different sources. In the field of underwater sound effects, where information is used to underpin management decisions, it is generally better to seek data and information from peer-reviewed published papers by independent authors and from other primary sources rather than rely on reviews or third party reports.

The term ***noise*** is often used colloquially to describe unwanted sound, or sound that interferes with detection of any other sound that is of interest. However, 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, or physical phenomena like ice ridging, some of which cannot be assigned to individual sources. In this Literature Synthesis the term ***sound***, rather than noise, is used both to refer to identifiable man-made sources, such as individual ships or oil and gas platforms, or to distant man-made sources, which cannot be located or identified. Where others have used the term ***ambient noise*** or ***background noise*** to describe naturally occurring sounds from distributed sources then that usage will be respected and followed.

The term ***soundscape*** is used in this Literature Synthesis 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. The acoustic environment of an animal or population of animals will be referred to as its ***acoustic habitat***.

In considering effects of sound (or any stimulus) on organisms, reference is made to ***acute*** or ***chronic*** effects. Acute effects generally result in mortal or potentially mortal injury to animals. 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 that leads to increased predation, decreased reproductive potential, or other effects. With respect to sound, acute effects are generally the result of very intense (often called ***loud***) sounds. Exposure to the individual sounds is often of short duration, whether the sources are seismic airguns, pile driving, or sonars. 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 be described by the term ***barotrauma*** (see Stephenson et al. 2010; Carlson 2012).

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 (e.g., a harbor, in the vicinity of a shipping lane, around an oil rig, or around an LNG [liquefied natural gas] port), where the overall background level of sound in the area is higher than the natural background level.

In this Synthesis, a distinction is drawn between cumulative effects and in-combination effects. ***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. By contrast, ***in-combination effects***, sometimes 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). National Environmental Policy Act (NEPA) analyses consider both cumulative and in-combination effects, as defined here, under cumulative impacts.

Finally, this Literature Synthesis uses the term ***man-made*** to refer to the activities of concern and the sounds they produce. This term is to be seen as synonymous with ***human-made*** and ***anthropogenic*** as used in other literature and reports.

1.5 Natural Sounds in the Sea

The sea abounds with natural sounds, some of which are produced by physical processes such as wind on the surface, rain, water moving over reefs, and tidal flow (e.g., Bass and Clark 2003). There are also numerous sounds of biological origin produced by marine mammals (Richardson et al. 1995; Tyack 2000; Southall et al. 2007; Erbe 2012), fish (Tavolga 1971; Myrberg 1978, 1980; Hawkins and Myrberg 1983; Popper et al. 2003; Bass and Ladich 2008), and invertebrates (Popper et al. 2003). Such sounds are of great biological significance to the species that make them since they are often used for communication of reproductive state, location, presence of predators or competitors, or for finding other members of the same species. These sounds are also often intercepted where one species hears the sounds of another and may use such information as a warning of the presence of predators or to track down prey (Myrberg 1981).

These sounds of natural origin are important to the animals concerned and throughout this Literature Synthesis emphasis will be placed on the need to gain wider knowledge of sounds of biological origin and to monitor existing levels of natural sound and their trends.

1.6 The Big Questions

BOEM has the authority under the Outer Continental Shelf Lands Act (OCSLA), as amended by the Energy Policy Act of 2005, to issue leases for various energy and minerals mining related activities. Issuance of a lease, whether for exploration or production, is a federal action and as such requires that BOEM adhere to all relevant federal regulations. Of particular relevance among these regulations are the NEPA, the Magnuson-Stevens Fisheries Conservation and Management Act (Magnuson-Stevens Act), and the Endangered Species Act (ESA). Under NEPA, BOEM is required to identify and address environmental impacts associated with their actions. In the formal NEPA process, this impact assessment includes consultation and review by any agencies whose resources of concern could be affected or who have the authority to issues permits governing parts of the project. In the Outer Continental Shelf (OCS), fisheries and threatened or endangered marine species are two of the resources that could be affected by BOEM activities. Among other things, the Magnuson-Stevens Act gives the National Oceanographic and Atmospheric Administration (NOAA) the authority to examine potential impacts to the habitat considered essential to fish and invertebrate species (i.e., Essential Fish Habitat [EFH]) that are federally managed for the purposes of commercial fishing. Changes in the soundscape could be construed as a change in habitat value for some of these species if such a change reduces the ability of these species to perform their normal life functions.

Similarly, NOAA has the authority to evaluate potential impacts, or *taking*, on marine species and their critical habitats that are protected under the ESA. For ESA-protected species, the term *taking* applies to impacts that can range from harassment that causes individuals to vacate an area to physical damage including mortality. Relative to exposure to anthropogenic noise, NOAA guidelines define two levels of harassment for marine mammals: Level A harassment with the potential to injure a marine mammal in the wild (180 dB_{rms} re 1 µPa) and Level B harassment with the potential to disturb a marine mammal in the wild by causing disruption to behavioral patterns such as migration, breeding, feeding, and sheltering (160 dB_{rms} re 1 µPa for impulse noise such as pile driving and 120 dB_{rms} re 1 µPa for continuous noise such as vessel thrusters). Similar guidelines have not yet been established for other ESA marine species, but effects of noise must still be considered during the NEPA process. This Literature Synthesis is geared towards identifying the knowledge gaps that remain so that BOEM can conduct thorough and scientifically based assessments of impacts on fish, fisheries, and invertebrates.

Under the OCSLA, BOEM was given the mandate to conduct scientific research to address impact issues associated with the offshore oil and gas leasing and minerals mining programs. Under the Energy Policy Act of 2005, this mandate was extended to offshore renewable energy development and alternate use of existing structures. The Environmental Studies Program (ESP) was established in 1973 with three general goals:

- Establish the information needed for assessment and management of environmental impacts on the human, marine, and coastal environments of the OCS and the potentially affected coastal areas.

- Predict impacts on the marine biota that may result from chronic, low-level pollution or large spills associated with OCS production, or impacts on the marine biota that may result from drilling fluids and cuttings discharges, pipeline emplacement, or onshore facilities.
- Monitor human, marine, and coastal environments to provide time series and data trend information for identification of significant changes in the quality and productivity of these environments, and to identify the causes of these changes.

Information developed under the ESP is used to address the ESA, Marine Mammals Protection Act (MMPA), Clean Air Act, Magnusen-Stevens Act, and the Clean Water Act, among others, in order to ensure that BOEM meets its long-term goals of environmentally sound development of the Nation's energy and mineral resources of the OCS. Alteration to the soundscape in the OCS is one of the questions being addressed under this program.

The issues relating to the effects of underwater sound are extensive and complex. Humans gain many benefits from activities that generate sound, whether it is the transport of goods, availability of energy, fishing for food, or defense provided by navies. It is not the intention of those pursuing these activities to produce sounds that could have an adverse impact, but sound is often the inevitable result of their activities. The benefits of those activities must be balanced against the adverse effects they may be having on the animals that share the seas with us.

Initial Questions in Relation to the Generation of Underwater Sound by Man, and Its Effects

These questions provide a basic background on the soundscape, and inform understanding of more specific issues as discussed later in this Literature Synthesis.

- *What are the levels and characteristics of sound in different parts of the ocean? Are levels of sound in the sea, and variations in levels, changing as a result of human activities? If so, how are they changing? Which developments, natural and man-made, are having the largest effect on ocean sound levels and characteristics? What are the main man-made sound sources? Is man-made sound affecting the long-term background level of sound in the oceans?*
- *Does the sound made by man in the sea harm marine fish and invertebrates? Do man-made sounds have a significant and detrimental effect upon the fitness of fish and invertebrates, affecting their welfare and/or their survival? What are the chief sound-related risks to these animals?*
- *Is there evidence that intense sound can have acute impacts on fish and invertebrates or that lower levels of continuous sound may lead to chronic effects?*
- *If man-made sounds do affect fish and invertebrates adversely, then what can and should be done about it? How might the levels of man-made sounds be reduced or their impact mitigated? Can these sounds be reduced in level, or replaced by alternative sources or methodologies? Can adjustments to the timing of these activities limit their impacts?*
- *Which energy industry sound-generating activities are most damaging to fish and invertebrates?*

- *What research should receive priority in answering the above questions and is feasible to conduct?*

Man-made sound-producing activities, alone or in combination, become biologically significant when they affect the ability of an individual animal to survive and reproduce. Such effects on individuals can then cascade into population-level consequences and affect the stability of an ecosystem. In NEPA analysis, impacts generally must result in population-level effects to be considered significant. Impacts to species protected under the ESA are treated differently; in this case, effects on individuals can be considered significant. A major unanswered question in many circumstances will be whether there is a significant impact of sound exposure on the fitness of individuals within populations that jeopardizes the viability of those populations. This is the ‘so what?’ question:

- *Does a response to man-made sound by an individual fish or invertebrate, or even by large numbers of these animals, really matter?*

2 Decision-Making Framework

Geographical expansion of the energy industry will similarly expand the potential impacts of exploration and production activities on fish and invertebrates, and also upon the fisheries for those animals. Environmental impact assessments of proposed activities will be necessary as part of the permitting process. These assessments will involve evaluation of the effects of sound sources in causing physical injury, behavioral disturbance, and population level impacts upon marine animals. Information needs and data gaps will inevitably be identified.

Two main strands of information[2] are required to assess adverse effects of sound at a particular locale. First, knowledge is required on the species of fish and invertebrates present and the nature and importance of the fisheries upon them in the given area. The identified species may then be screened and evaluated for particular vulnerabilities or for any protection they may receive under the Magnuson-Stevens Act, ESA, and NEPA. That knowledge will in turn lead to evaluation of the likely responses of those animals to sound and consideration of the effects upon them from their exposure to sound.

Second, knowledge is required on the proposed sound-generating activities, the associated sound sources, their characteristics, and the circumstances of their deployment, including time of year. Together with knowledge of the propagation conditions, the degree of exposure of animals to the sounds can be estimated and expressed in metrics (magnitude, duration, and timing) that properly reflect any detrimental effects.

These two strands of information are then brought together in an assessment of any adverse effects. Given the inherent uncertainty of attempting to evaluate the impact of man-made sounds on fishes and invertebrates, one useful approach is to conduct a risk assessment. Risk analysis systematically evaluates and organizes data, information, assumptions, and uncertainties to help

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[2] The current NOAA Cetacean & Sound Mapping initiative follows this approach. While targeted upon whales rather than fish, the methodology of this United States Exclusive Economic Zone (EEZ)-wide study embodies two-strand information gathering (species distribution and sound mapping) followed by subsequent synthesis. For more information, see the website http://www.st.nmfs.noaa.gov/cetsound/.

understand and predict the relationships between environmental stressors and their ecological effects. The likelihood that an adverse effect upon biological receptors may occur as a result of exposure to potentially harmful sounds is evaluated, and a conclusion is reached about the severity of the effects. Risk assessment can be used to construct what-if scenarios to evaluate new and existing technologies for effective prevention, control, or mitigation of impacts, and to provide a scientific basis for risk-reduction strategies (EPA 1998; Suter 2007; Defra 2011).

When different responses occur at different levels of exposure (i.e., where there is a dose/response relationship), a variety of methods can be used to provide a quantitative estimate of risk, often with associated confidence intervals. However, such relationships are not always evident. The inherent variability in a receiver's response and limited understanding of the ecosystem, its components, and their functional interdependencies may result in a complex or poorly understood dose/response relationship. If that is the case, then ecological risk must be assessed in a more general way. Semi-quantitative methods involving scoring systems or qualitative ranking schemes may be developed to provide a qualitative level of risk.

Risk assessment can be used to identify vulnerable species and flag areas and times of the year where there is high risk of a population level effect upon particular species. Regulatory decisions can then be taken. Figure 2–1 illustrates the steps that may be followed and shows the wide range of information that is required to assess adverse effects and then perform a risk analysis to inform the eventual regulatory outcome.

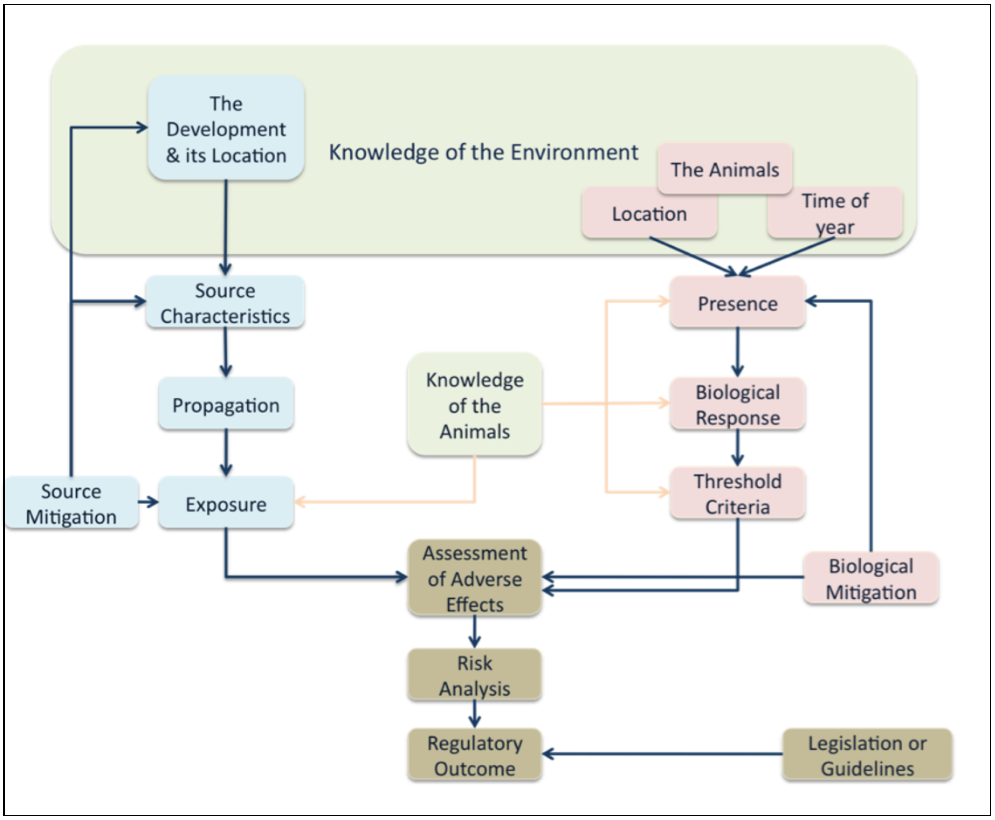

Figure 2–1. The decision-making process to assess adverse effects and perform a risk analysis to inform the regulatory outcome.

There are four main steps to the risk assessment itself:

- Formulating the problem
- Carrying out an assessment of the risk
- Identifying and appraising the management options available
- Addressing the risk with the chosen risk management strategy

A mass of information is required to perform a risk assessment for fish and invertebrates in the context of noise in the marine environment so that management decisions can be made.

Questions for the Main Information Requirements

- *Which are the key species and fisheries likely to be affected in the areas under consideration? Does the distribution and behavior of the key species change at different times of the year? Is there sufficient information on the distribution of the animals and their use of key habitats? Are there times of the year when the animals are more vulnerable? When and where do the main fisheries take place?*
- *What are the current conditions in the area of interest, especially with respect to sound levels? Is the area of interest an acoustically pristine environment where the only sounds are from natural sources? What other stressors might already affect the area (e.g., chemical, electromagnetic)? Is the area likely to be subject to climatic or other changes in the future?*
- *What are the main energy-related developments taking place in the area? Which sound sources will be deployed—distinguishing between primary sources (i.e., airguns, pile drivers, dredgers) and secondary sources (i.e., support vessels, multi beam sonars)?*
- *How can sound exposure best be assessed? What metrics should be used?*
- *What is known about the effects upon the species of interest at different levels of sound exposure*[3]*(e.g., intensity, duration)? Can dose response relationships be derived for different effects?*
- *What are the risks to individuals and populations from sound exposure? Can population level effects be determined from the data available? If not, what additional data are needed? Can cumulative or in-combination effects be integrated into the risk assessment?*
- *Is it possible to mitigate risk by changing the timing of sound-generating activities, reducing their spatial extent (e.g., reducing the area of a seismic survey) in relation to what is known of the biology of key species or by employing other mitigation measures to reduce the received sound levels?*

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[3] Here, sound exposure is used in a general sense to describe the dose of sound received by an animal in terms of both its level and its duration. A number of metrics are in use, which will be described in Section 6.

3 Identification of Priority Habitats, Species, and Fisheries

3.1 Introduction

Considering the scale of development planned in the Atlantic and Arctic Oceans by the energy industry, which are the habitats, species, and fisheries most likely to be affected? And which are the key habitats, species, and fisheries that warrant priority treatment? This section identifies the habitats, species and fisheries that need to be prioritized as those most likely to be exposed to sound-generating activities by the energy industry. Two main regions of interest are covered: the Arctic Outer Continental Shelf (OCS) Region, and the Atlantic OCS Region. Each of these has its own physical and biological characteristics, along with a host of species and fisheries that are both ecologically and economically important. These characteristics are discussed below by category and region.

3.2 Habitat and Ecosystem Characteristics

3.2.1 Arctic OCS Region

General Description

The Arctic OCS region is adjacent to the state of Alaska and includes United States waters of the Chukchi Sea and the Beaufort Sea (Figure 3–1). The Arctic OCS has three planning areas designated by BOEM: Beaufort Sea, Chukchi Sea, and Hope Basin (see Figure 3–1). As described in the Fishery Management Plan (FMP) for Fish Resources of the Arctic Management Area (NPFMC 2009a), both of these are dominated by the clockwise, wind-driven Beaufort Gyre, which carries water and ice and leads to westerly and south-westerly currents along the Alaska coast. The Chukchi Sea has an area of about 595,000 km^2 and depths ranging from 30 to 3,000 m, with the majority of the shelf being a shallow depth of 30 to 60 m. Ice cover dominates the Chukchi Sea for most of the year, with complete cover generally observed from early December to mid-May. Even in the height of summer, the Chukchi Sea remains about 20% covered in ice. At 476,000 km^2 in area, the Beaufort Sea is slightly smaller than the Chukchi Sea. The average depth is just over 1,000 m and the maximum depth is 4,683 m. Ice coverage is greater in the Beaufort Sea than in the Chukchi Sea, with only a narrow pass opening in the Beaufort Sea during August and September near its shores.

The breakup and formation of sea ice are variable and dynamic processes that cause gouging in the sea floor and generate ambient noise. In the Beaufort Sea, sea ice motion is correlated with noise under the ice at 10, 32, and 1000 Hz, with low frequencies dominating during autumn and multiple frequencies dominating during summer when ice flow is high (Lewis and Denner 1988). The final report for the Chukchi Sea Acoustics Workshop held on February 9 and 10, 2009, in Anchorage, Alaska, reviews acoustic monitoring studies and underwater noise in the Alaskan Arctic and creates objectives for monitoring natural and anthropogenic noise (Small et al. 2011). There is also evidence to suggest that changes in ambient noise in Arctic waters may be generated by climate change (Lewis and Denner 1988; Small et al. 2011). Increased numbers of predatory sea mammals may be present in the future.

Figure 3–1. U.S. Arctic Outer Continental Shelf (OCS) region showing the Bureau of Ocean Energy Management Planning Area boundaries, the U.S. Exclusive Economic Zone (EEZ) boundary, approximate areas of potential claims of the U.S. OCS, and the Eastern Special Area that lies beyond 200 nautical miles (nm) (370.4 kilometers [km]) and less than 200 nm (370.4 km) from Russia but with U.S. EEZ jurisdiction granted by the Soviet Union in 1990 (International Boundaries Research Unit 2011).

Sea ice in the Arctic affects distribution and movement of animals, and melting ice promotes primary productivity during the spring and summer months. Productivity is low during the long winters with low light penetration. Nutrients flow into the Chukchi Sea from the Pacific Ocean and Bering Sea, fuelling phytoplankton production during the open water season (Codispoti et al. 1991; Carmack et al. 2006).

Essential Fish Habitat in the Arctic OCS

The Magnuson-Stevens Act defines Essential Fish Habitat (EFH) as those waters necessary for fish to breed, spawn, feed, or grow to maturity. EFH areas in the Arctic OCS have been described for Arctic and saffron cod (*Boreogadus saida* and *Eleginus gracilis, respectively*; adult and late juvenile stages), and snow crab (*Chinoecetes opilio*; adult, late juvenile and egg stages) (Table 3–1). These three species are targeted in fisheries elsewhere and are the only species considered to exist in sufficient biomass to support a commercial fishery in the Arctic Management Area. In addition, a host of other key species with potential for commercial harvest, should conditions change, were analyzed in the Environmental Assessment for the Arctic FMP and Amendment 29 to the FMP (NPFMC 2009b; see Table 3–1).

Table 3–1

Essential Fish Habitat and ecologically important species with potential fishery importance in the Arctic Outer Continental Shelf Region.

Common Name	Scientific Name
Alaska plaice	*Limanda aspera*
Arctic cod*	*Boreogadus saida*
Blue king crab	*Paralithodes platypus*
Capelin	*Mallotus villosus*
Flathead/Bering flounder	*Pleuronectes quadrituberculatus*
Rainbow smelt	*Osmerus mordax*
Saffron cod*	*Eleginus gracilis*
Snow crab*	*Chionoecetes opilio*
Starry flounder	*Platichthys stellatus*
Yellowfin sole	*Pleuronectes asper*

* EFH has been designated for this species in the Arctic OCS.

The Arctic FMP outlines procedures for establishment of Habitat Areas of Particular Concern (HAPCs) to protect areas that are sensitive to human impacts, ecologically important, and/or rare habitat types. These help in focusing and implementing conservation priorities and are defined by the Regional Fishery Management Councils (NPFMC 2010). Currently no HAPCs have been established in the Arctic Management Area.

3.2.2 Atlantic OCS Region

General Description

The Atlantic OCS region is divided into four planning areas: North Atlantic, Mid-Atlantic, South Atlantic, and Straits of Florida (Figure 3–2). In the North and Mid-Atlantic regions, the shelf extent generally coincides with the 100-m isobaths. A dominant feature of the North-Atlantic is Georges Bank, a broad, shallow platform approximately 67,000 km^2 in area that leads to complex current structure and high biomass production. The North and Mid-Atlantic areas are separated by the Georges Bank Basin in the north and the Baltimore Canyon Trough in the south.

The South Atlantic Region is dominated by three physical features: the Florida-Hatteras Shelf and Blake Plateau, and the Florida-Hatteras Slope between them. The Straits of Florida connects the Atlantic Ocean to the Gulf of Mexico and its physiography is influenced by reef structure and sediment along with the Florida Current (part of the Gulf Stream). A detailed summary of the characteristics of the Atlantic OCS is found in the Programmatic Environmental Impact Statement for Alternative Energy Development and Production and Alternate Use of Facilities on the Outer Continental Shelf (Chapter 4 in MMS 2007).

Essential Fish Habitat in the Atlantic OCS

The Atlantic OCS region provides habitat that supports a wealth of species including commercially and recreationally important fish and shellfish and endangered and threatened species. Regional Fishery Management Councils are required to describe, identify, conserve and enhance areas designated as EFH (NEFMC 1998). In addition, the councils must minimize adverse effects of fishing on EFH. These actions taken by the councils are to be informed by recommendations from National Marine Fisheries Service (NMFS).

EFH descriptions currently exist for 28 species in the New England region, 14 species in the Mid-Atlantic region, 73 species in the South Atlantic, and an additional 23 highly migratory species (sharks, tunas and billfish) (Table 3–2). Many HAPCs exist for certain habitat, species or life stages in the Atlantic OCS: from river mouths in Downeast Maine[4] (Hancock and Washington counties) for spawning Atlantic salmon (*Salmo salar*), to juvenile Atlantic cod (*Gadus morhua*) habitat on the Northern edge of Georges Bank and the Oculina Bank HAPC off Florida (Figures 3–3 to 3–5). Table B–1 in Appendix B lists HAPCs for the Atlantic OCS.

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[4] A region in Maine that encompasses the rural communities of Hancock and Washington counties.

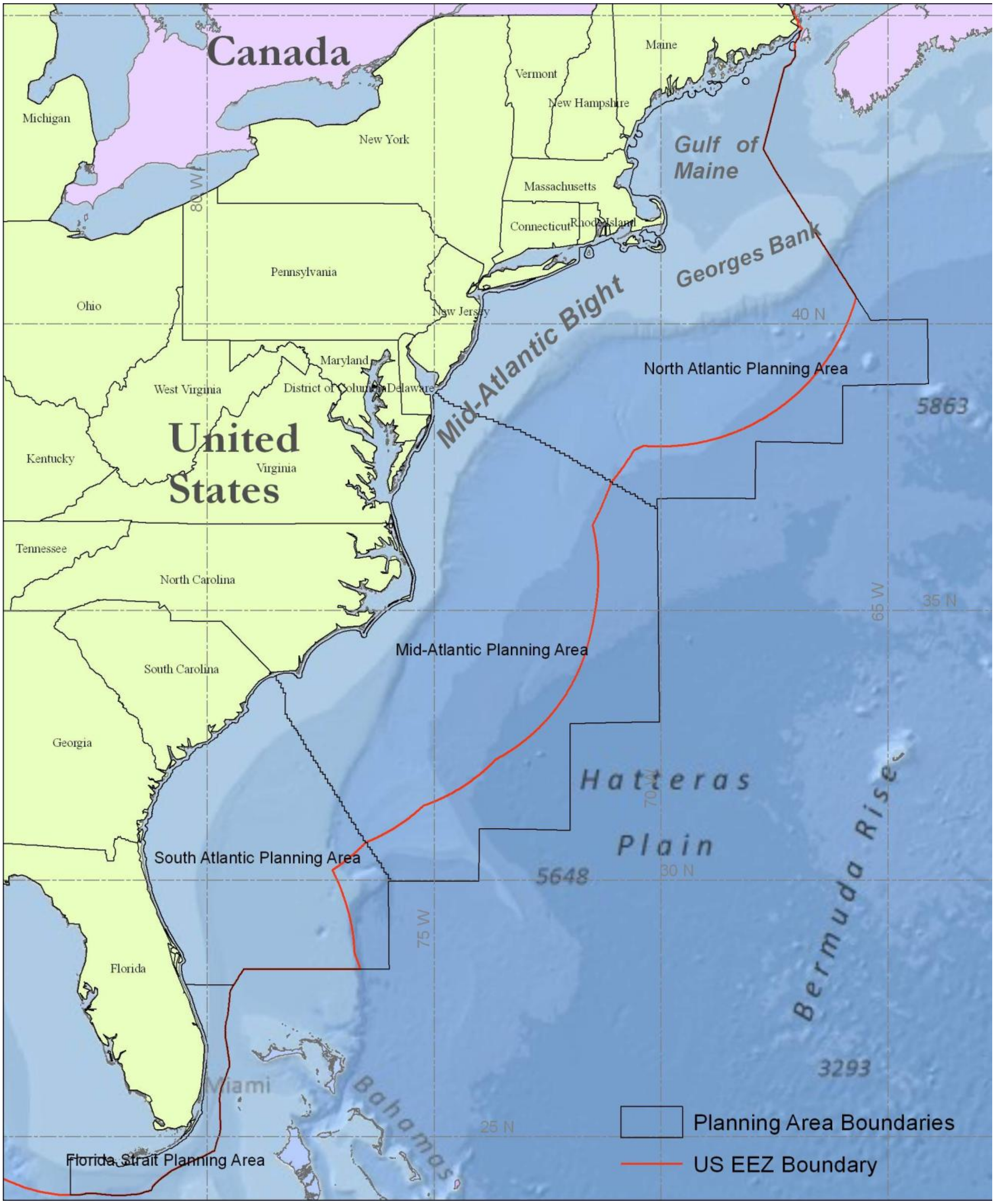

Figure 3–2. U.S. Atlantic Outer Continental Shelf region showing the Bureau of Ocean Energy Management Planning Area boundaries and the U.S. Exclusive Economic Zone (EEZ) boundary.

Table 3–2

Species for which Essential Fish Habitat (EFH) has been defined in the Atlantic OCS by the National Marine Fisheries Service.

Common Name	**Scientific Name**	**Common Name**	**Scientific Name**
New England Species			
American plaice	*Hippoglossoides platessoides*	Pollock	*Pollachius virens*
Atlantic cod	*Gadus morhua*	Red hake	*Urophycis chuss*
Atlantic halibut	*Hippoglossus hippoglossus*	Redfish	*Sebastes* spp.
Atlantic herring	*Clupea harengus*	Rosette skate	*Leucoraja garmani*
Atlantic salmon	*Salmo salar*	Silver hake	*Merluccius bilinearis*
Atlantic sea scallops	*Placopecten magellanicus*	Smooth skate	*Malacoraja senta*
Barndoor skate	*Dipturus laevis*	Thorny skate	*Amblyraja radiate*
Clearnose skate	*Raja eglanteria*	White hake	*Urophycis tenuis*
Deep-sea red crab	*Chaceon quinquedens*	Whiting	*Merluccius* spp.
Haddock	*Melanogrammus aeglefinus*	Windowpane flounder	*Scophthalmus aquosus*
Little skate	*Leucoraja erinacea*	Winter flounder	*Pseudopleuronectes americanus*
Monkfish	*Lophius americanus*	Winter skate	*Leucoraja ocellata*
Ocean pout	*Zoarces americanus*	Witch flounder	*Glyptocephalus cynoglossus*
Offshore hake	*Merluccius albidus*	Yellowtail flounder	*Limanda ferruginea*
Mid-Atlantic Species			
Atlantic mackerel	*Scomber scombrus*	Ocean quahog	*Arctica islandica*
Black sea	*Centropristis striata*	Scup	*Stenotomus chrysops*
Bluefish	*Pomatomus saltatrix*	Spiny dogfish	*Squalus acanthias*
Butterfish	*Peprilus triacanthus*	Summer flounder	*Paralichthys dentatus*
Tilefish	*Lopholatilus chamaeleonticeps*	Illex squid	*Illex illecebrosus*
Surfclam	*Spisula solidissima*	Loligo squid	*Loligo pealeii*
Monkfish	*Lophius americanus*		
South Atlantic Species			
Almaco jack	*Seriola rivoliana*	Misty grouper	*Hyporthodus mystacinus*
Atlantic spadefish	*Chaetodipterus faber*	Mutton snapper	*Lutjanus analis*
Banded rudderfish	*Seriola zonata*	Nassau grouper	*Epinephelus striatus*
Bank sea bass	*Centropristes ocyurus*	Ocean triggerfish	*Canthidermis sufflamen*
Black grouper	*Mycteroperca bonaci*	Pink shrimp	*Farfanteoenaeus duorarum*
Black margate	*Anisostremus surinamensis*	Queen snapper	*Etelis oculatus*
Black sea bass	*Centropristes striata*	Queen triggerfish	*Balistes vetula*
Black snapper	*Apsilus dentatus*	Red drum	*Sciaenops ocellatus*
Blackfin snapper	*Lutjanus buccanella*	Red grouper	*Epinephelus morio*
Blue striped grunt	*Haemulon sciurus*	Red hind	*Epinephelus guttatus*
Bluefish	*Pomatomus saltatrix*	Red porgy	*Pagrus pagrus*
Blueline tilefish	*Caulolatilus microps*	Red snapper	*Lutjanus campechanus*
Brown shrimp	*Farfantepenaeus aztecus*	Rock hind	*Epinephelus adscensionis*

Common Name	**Scientific Name**	**Common Name**	**Scientific Name**
Cobia	*Rachycentron canadum*	Rock sea bass	*Centropristis philadellphica*
Coney	*Cephalopholis fulva*	Sailfish	*Istiophorus platypterus*
Cubera snapper	*Lutjanus cyanopterus*	Saucereye porgy	*Calamus calamus*
Dog snapper	*Lutjanus jocu*	Scamp	*Mycteroperca phenax*
Dolphinfish	*Coryphaena hippurus*	Schoolmaster	*Lutjanus apodus*
French grunt	*Haemulon flavolineatum*	Scup	*Stenotomus chrysops*
Gag grouper	*Mycteroperca microlepis*	Sheepshead	*Archosargus probabtocephalus*
Golden crab	*Chaceon fenneri*	Silk snapper	*Lutjanus vivanus*
Golden tilefish	*Lopholatilus chamaeleonticeps*	Snowy grouper	*Hypothodus niveatus*
Spanish mackerel	*Scomberomorus maculatus*	Speckled hind	*Epinephelus drummondhayi*
Goliath grouper	*Epinephelus itajara*	Spiny lobster	*Panulirus argus*
Gray snapper	*Lutjanus griseus*	Tiger grouper	*Mycteroperca tigris*
Gray triggerfish	*Balistes capriscus*	Tomtate	*Haemulon aurolineatum*
Graysby	*Cephalopholis cruentata*	Vermilion snapper	*Rhomboplites aurorubens*
Greater amberjack	*Seriola dumerili*	Wahoo	*Acanthocybium solandri*
Hogfish	*Lachnolaimus maximus*	Warsaw grouper	*Hyporthodus nigritus*
Jolthead porgy	*Calamus bajonado*	Weakfish	*Cynoscion rgalis*
King mackerel	*Scomberomorus cavalla*	White grunt	*Haemulon plumierii*
Knobbed porgy	*Calamus nodosus*	White shrimp	*Litopenaeus setiferus*
Lane snapper	*Lutjanus synagris*	Whitebone porgy	*Calamus leucosteus*
Lesser amberjack	*Seriola fasciata*	Wreckfish	*Polyprion americanus*
Little tunny	*Euthynnus alleteratus*	Yellowmouth grouper	*Mycteroperca interstitialis*
Mahogany snapper	*Lutjanus mahogoni*	Yellowtail snapper	*Ocyurus chrysurus*
Margate	*Haemulon album*		
Highly Migratory Species and Billfish			
Albacore tuna	*Thunnus alalunga*	Longfin mako	*Isurus paucus*
Atlantic angel shark	*Squatina dumeril*	Porbeagle	*Lamna nasus*
Atlantic bigeye tuna	*Thunnus obesus*	Sand tiger shark	*Odontaspis Taurus*
Atlantic bluefin tuna	*Thunnus thynnus*	Sandbar shark	*Carcharinus plumbeus*
Atlantic sharpnose	*Rhizoprionodon terraenovae*	Scalloped hammerhead	*Sphyrna lewini*
Atlantic skipjack	*Katsuwonus pelamis*	Shortfin mako	*Isurus oxyrhinchus*
Atlantic swordfish	*Xiphias gladius*	Silky shark	*Carcharhinus falciformis*
Atlantic yellowfin tuna	*Thunnus albacores*	Thresher shark	*Alopias vulpinus*
Basking shark	*Cetorhinus maximus*	Tiger shark	*Galeocerdo cuvier*
Blue marlin	*Makaira nigricans*	White marlin	*Tetrpturus albidus*
Blue shark	*Prionace glauca*	White shark	*Carcharodon carcharias*
Dusky shark	*Carcharhinus obscurus*		

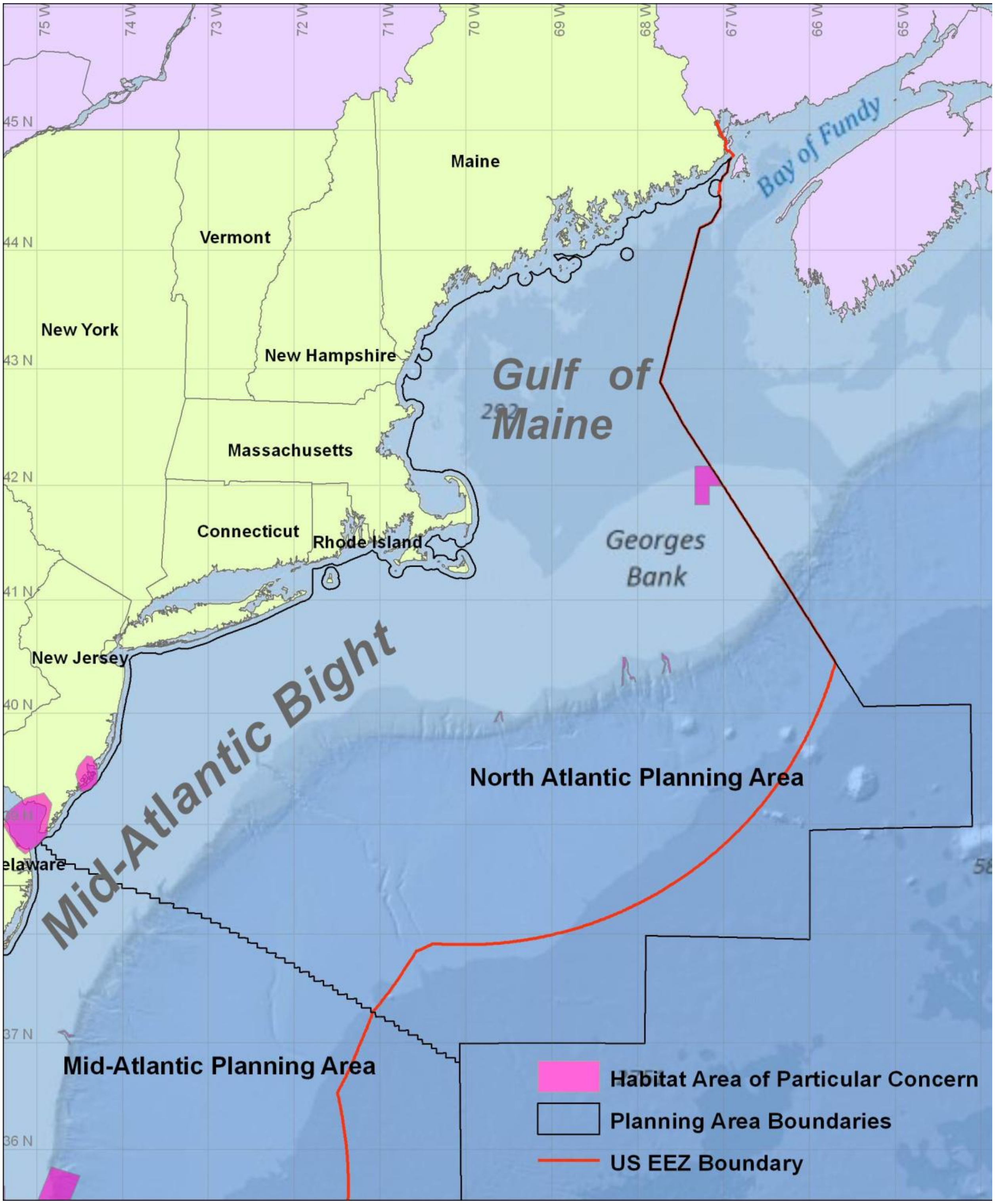

Figure 3–3. U.S. Atlantic Outer Continental Shelf region showing the Habitat Areas of Particular Concern within the Bureau of Ocean Energy Management North Atlantic Planning Area.

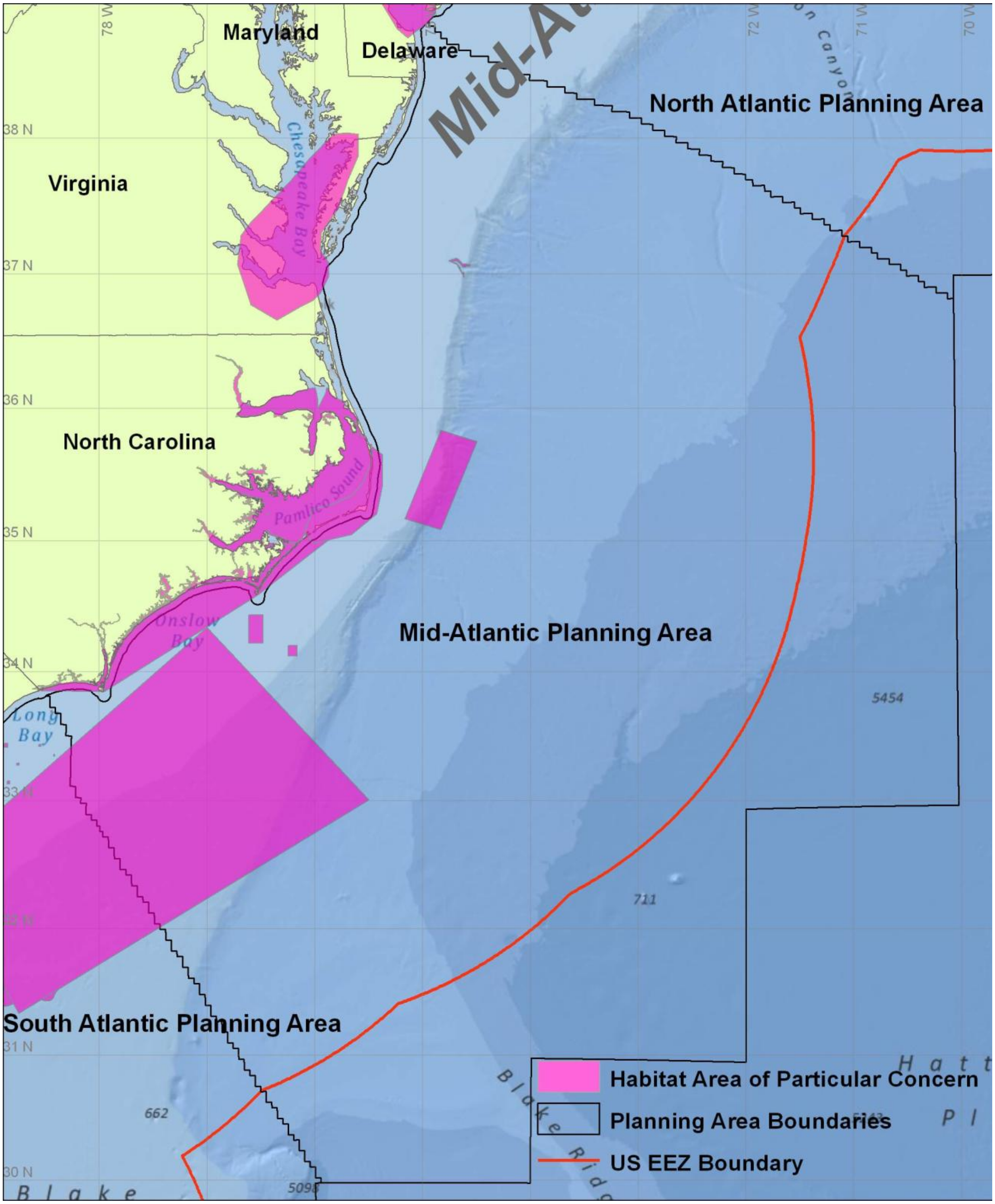

Figure 3–4. U.S. Atlantic Outer Continental Shelf region showing the Habitat Areas of Particular Concern within the Bureau of Ocean Energy Management Mid-Atlantic Planning Area.

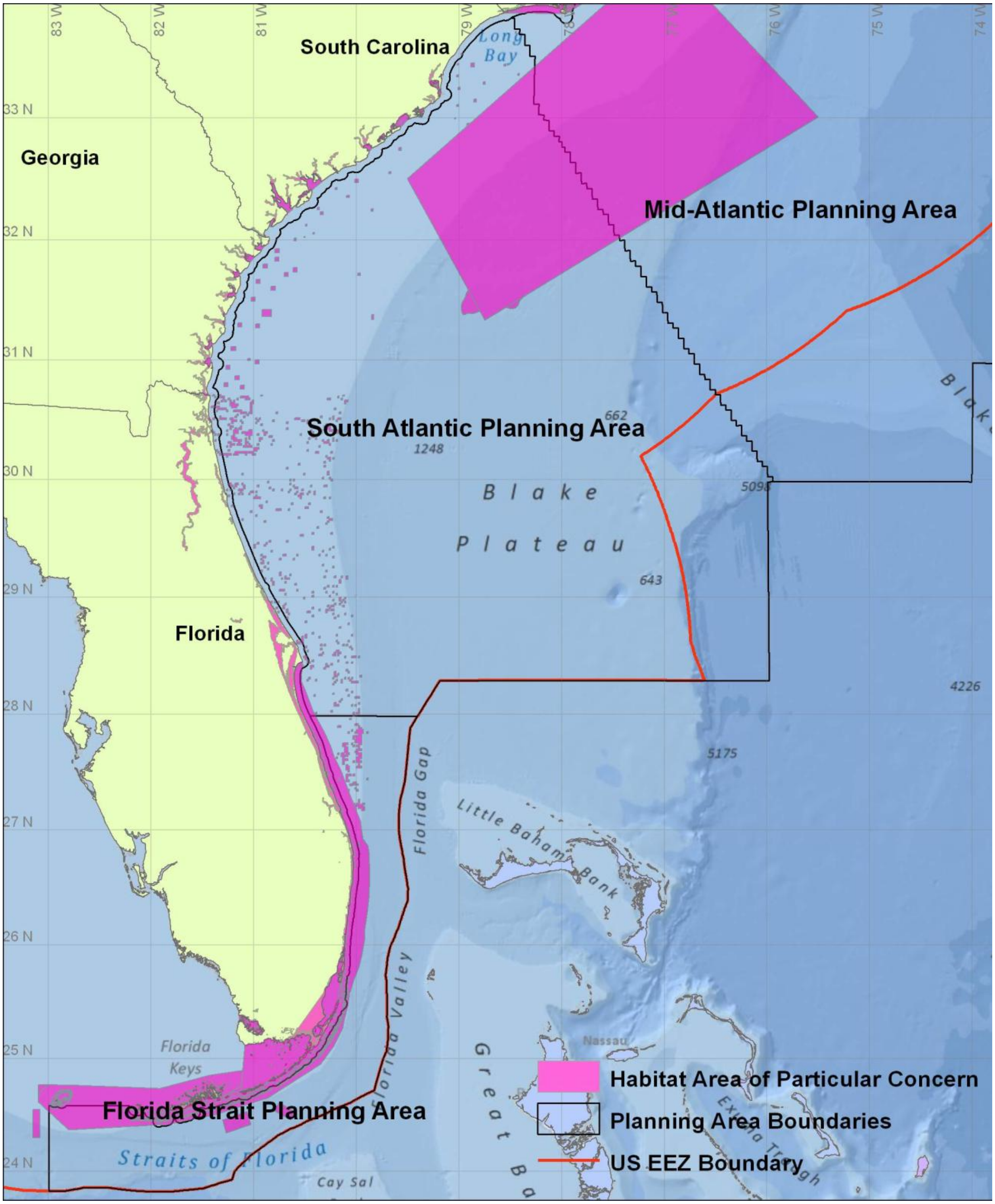

Figure 3–5. U.S. Atlantic Outer Continental Shelf region showing the Habitat Areas of Particular Concern within the Bureau of Ocean Energy Management South Atlantic Planning Area.

3.3 Fisheries

3.3.1 Fisheries in the Arctic OCS Region

The low productivity and difficulty of access in the Arctic contribute to a relatively short list of biological resources that are commercially exploitable. Table 3–3 lists species designated as target and ecosystem component species in the Arctic Fishery Management Plan (NPFMC 2009a), as well as a few other key species and families of fish and invertebrates. The Arctic Fishery Management Plan initially prohibits commercial fishing in the Arctic waters of the Chukchi and Beaufort Seas until sufficient information is gathered to support sustainable fisheries management.

Table 3–3

Major fish and invertebrate taxa of commercial and ecological importance found in the Arctic Outer Continental Shelf region.

Common Name	**Scientific Name**
Fishes	
Arctic cod	*Boreogadus saida*
Pacific herring	*Clupea pallasi*
Saffron cod	*Eleginus gracilis*
Pacific cod	*Gadus macrocephalus*
Arctic staghorn sculpin	*Gymnocanthus tricuspis*
Bering flounder	*Hippoglossoides robustus*
Yellowfin sole	*Limanda aspera*
Canadian eelpout	*Lycodes polaris*
Marbled eelpout	*Lycodes raridens*
Capelin	*Mallotus villosus*
Warty sculpin	*Myoxocephalus verrucosus*
Rainbow smelt	*Osmerus mordax*
Starry flounder	*Platichthys stellatus*
Alaska plaice	*Pleuronectes quadrituberculatus*
Greenland turbot	*Reinhardtius hippoglossoides*
Walleye pollock	*Theragra chalcogramma*
Snailfishes	Liparidae
Pricklebacks (shannies)	Stichaeidae
other sculpins	Cottidae
other eelpouts	Zoarcidae
Invertebrates	
Snow crab	*Chionoecetes opilio*
Circumboreal toad crab	*Hyas coarctatus*
Notched brittlestar	*Ophiura sarsi*
Red king crab	*Paralithodes camtschaticus*
Blue king crab	*Paralithodes platypus*

Subsistence fishing in the Arctic OCS is economically and culturally important for many Alaskans, and is federally managed by the U.S. Fish and Wildlife Service[5] and managed in state waters by the Alaska Department of Fish and Game (ADFG).[6] The ADFG defines subsistence fishing as "the taking of, fishing for, or possession of fish, shellfish, or other fisheries resources by a resident of the state for subsistence uses with gill net, seine, fish wheel, long line, or other means defined by the Board of Fisheries." Subsistence use is typically defined by noncommercial, customary, and traditional uses (e.g., personal or family consumption as food, fuel, clothing, tools, and nonedible products). According to the ADFG Community Subsistence Information System,[7] the 2007 harvest by subsistence fishing in the State Arctic region was estimated at 163,182 pounds (lbs) (74,018 kilograms [kg]) of salmonids, 5,463 lbs (2,478 kg) of saffron cod, 690 lbs (313 kg) of Arctic cod, and 87 lbs (39 kg) of king crab (*Paralithodes* spp.). The species fished for subsistence purposes listed in the Arctic Fishery Management Plan includes Pacific herring (*Clupea pallasii*), Dolly Varden (*Salvelinus malma malma*), anadromous whitefishes (*Coregonus* spp.), Arctic and saffron cod, and sculpins (Cottidae). King and snow crabs are fished for subsistence purposes in the southeastern Chukchi Sea.

Currently very little fishing occurs in the Arctic OCS. The small commercial fisheries that exist are generally restricted to state waters, and subsistence and recreational fisheries are also conducted close to shore. Sound from energy-related activities in nearby Federal waters could propagate to state waters. Shifting ice, warming temperatures, and migrating stocks could lead to more productive and/or accessible fishery resources in the Arctic OCS. These changes would have the potential to allow fisheries to develop. For this reason, the North Pacific Fishery Management Council (NPFMC) has adopted an FMP to be proactive in regulating natural resource harvest in the Arctic before an unregulated fishery and the potential for resource overexploitation develops.

3.3.2 Fisheries in the Atlantic OCS Region

There is a great difference between the inaccessible resources and low productivity of the Arctic OCS region and the abundant historical fisheries in the Atlantic OCS region. The wide range of environments and species has led to fisheries that span the entire coast from Maine to Florida. Table 3–4 lists the many primary species of commercial importance in the Atlantic OCS and their scientific names.

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[5] For information on federal management of subsistence fishing in the Arctic OCS, see http://alaska.fws.gov/asm/index.cfml.

[6] For information on state management of subsistence fishing in the Arctic OCS, see http://www.adfg.alaska.gov/.

[7] See http://www.adfg.alaska.gov/sb/CSIS/index.cfm?ADFG=main.home.

Table 3–4

Common and scientific names of major commercial species of fish and invertebrates in the Atlantic Outer Continental Shelf region.

Common Name	Scientific Name	Common Name	Scientific Name
Alewife	*Alosa pseudoharengus*	Pollock	*Pollachius virens*
Amberjack	*Seriola* spp.	Pompano, African	*Alectis ciliaris*
Amberjack, greater	*Seriola dumerili*	Pompano, Florida	*Trachinotus carolinus*
Amberjack, lesser	*Seriola fasciata*	Porgy, jolthead	*Calamus bajonado*
Bass, striped	*Morone saxatilis*	Porgy, knobbed	*Calamus nodosus*
Bluefish	*Pomatomus saltatrix*	Porgy, red	*Pagrus pagrus*
Butterfish	*Peprilus triacanthus*	Pout, ocean	*Zoarces americanus*
Clam, arc, blood	*Anadara olivaris*	Redfish, Acadian	*Sebastes fasciatus*
Clam, Atlantic jackknife	*Ensis directus*	Salmon, Atlantic	*Salmo salar*
Clam, Atlantic surf	*Spisula solidissima*	Scallop, bay	*Argopecten irradians*
Clam, northern quahog	*Mercenaria mercenaria*	Scallop, sea	*Placopecten magellanicus*
Clam, ocean quahog	*Arctica islandica*	Scamp	*Mycteroperca phenax*
Clam, quahog	*Mercenaria campechiensis*	Scup	*Stenotomus chrysops*
Clam, softshell	*Mya arenaria*	Scups or porgies	Sparidae spp.
Clams or bivalves	*Bivalvia* spp.	Sea bass, black	*Centropristis striata*
Cobia	*Rachycentron canadum*	Sea bass, rock	*Centropristis philadelphica*
Cod, Atlantic	*Gadus morhua*	Seatrout, sand	*Cynoscion arenarius*
Crab, Atlantic horseshoe	*Limulus polyphemus*	Seatrout, spotted	*Cynoscion nebulosus*
Crab, Atlantic rock	*Cancer irroratus*	Shad, American	*Alosa sapidissima*
Crab, blue	*Callinectes sapidus*	Shad, gizzard	*Dorosoma cepedianum*
Crab, florida stone	*Menippe mercenaria*	Shad, hickory	*Alosa mediocris*
Crab, golden deepsea	*Chaceon fenneri*	Shark, Atlantic sharpnose	*Rhizoprionodon terraenovae*
Crab, green	*Carcinus maenas*	Shark, blacknose	*Carcharhinus acronotus*
Crab, jonah	*Cancer borealis*	Shark, blacktip	*Carcharhinus limbatus*
Crab, spider	*Libinia emarginata*	Shark, blue	*Prionace glauca*
Crabs	*Cancer* spp.	Shark, bonnethead	*Sphyrna tiburo*
Croaker, Atlantic	*Micropogonias undulatus*	Shark, bull	*Carcharhinus leucas*
Dogfish, smooth	*Mustelis canis*	Shark, common thresher	*Alopias vulpinus*
Dogfish, spiny	*Squalus acanthias*	Shark, dusky	*Carcharhinus obscurus*
Dolphinfish	*Coryphaena hippurus*	Shark, finetooth	*Carcharhinus isodon*
Drum, black	*Pogonias cromis*	Shark, great hammerhead	*Sphyrna mokarran*
Drum, freshwater	*Aplodinotus grunniens*	Shark, lemon	*Negaprion brevirostris*
Drum, red	*Sciaenops ocellatus*	Shark, makos	*Isurus* spp.
Eel, American	*Anguilla rostrata*	Shark, porbeagle	*Lamna nasus*
Flounder, fourspot	*Paralichthys oblongus*	Shark, sand tiger	*Odontaspis taurus*
Flounder, southern	*Paralichthys lethostigma*	Shark, sandbar	*Carcharhinus plumbeus*

Common Name	Scientific Name	Common Name	Scientific Name
Flounder, summer	*Paralichthys dentatus*	Shark, scalloped hammerhead	*Sphyrna lewini*
Flounder, windowpane	*Scophthalmus aquosus*	Shark, silky	*Carcharhinus falciformis*
Flounder, winter	*Pseudopleuronectes americanus*	Shark, smooth hammerhead	*Sphyrna zygaena*
Flounder, witch	*Glyptocephalus cynoglossus*	Shark, spinner	*Carcharhinus brevipinna*
Flounder, yellowtail	*Limanda ferruginea*	Shark, tiger	*Galeocerdo cuvier*
Flounder,American plaice	*Hippoglossoides platessoides*	Sharks	*Chrondrichthys*
Gag	*Mycteroperca microlepis*	Shrimp, brown	*Farfantepenaeus aztecus*
Goosefish (monkfish)	*Lophius americanus*	Shrimp, dendrobranchiata	*Dendrobranchiata* spp.
Grouper, black	*Mycteroperca bonaci*	Shrimp, marine, other	Caridea
Grouper, red	*Epinephelus morio*	Shrimp, pink	*Farfantepenaeus duorarum*
Grouper, snowy	*Hypothodus niveatus*	Shrimp, rock	*Sicyorzia brevirostris*
Grouper, yellowedge	*Hyporthodus flavolimbatus*	Shrimp, royal red	*Pleoticus robustus*
Grouper, yellowfin	*Epinephelus cyanopodus*	Shrimp, white	*Litopenaeus setiferus*
Groupers	*Serranidae* spp.	Skate, barndoor	*Dipturus laevis*
Haddock	*Melanogrammus aeglefinus*	Skate, little	*Leucoraja erinacea*
Hagfish	*Myxine glutinosa*	Snapper, blackfin	*Lutjanus buccanella*
Hake, Atlantic, red/white	*Urophycis* spp.	Snapper, cubera	*Lutjanus cyanopterus*
Hake, offshore silver	*Merluccius albidus*	Snapper, gray	*Lutjanus griseus*
Hake, red	*Urophycis chuss*	Snapper, lane	*Lutjanus synagris*
Hake, silver	*Merluccius bilinearis*	Snapper, mutton	*Lutjanus analis*
Hake, white	*Urophycis tenuis*	Snapper, red	*Lutjanus campechanus*
Halibut, Atlantic	*Hippoglossus hippoglossus*	Snapper, silk	*Lutjanus vivanus*
Herring, Atlantic	*Clupea harengus*	Snapper, vermilion	*Rhomboplites aurorubens*
Herring, Atlantic thread	*Opisthonema oglinum*	Snapper, yellowtail	*Ocyurus chrysurus*
Herring, blueback	*Alosa aestivalis*	Snappers	*Lutjaninae* spp.
Herrings	*Clupea* spp.	Spot	*Leiostomus xanthurus*
Hind, red	*Epinephelus guttatus*	Squid, longfin	*Loligo pealei*
Hind, rock	*Epinephelus adscensionis*	Squid, northern shortfin	*Ilex Illex illecebrosus*
Hogfish	*Lachnolaimus maximus*	Squids	Squid spp.
Tilefish, blueline	*Caulolatilus microps*	Swordfish	*Xiphias gladius*
Lobster, American	*Homarus americanus*	Tautog	*Tautoga onitis*
Lobster, Caribbean spiny	*Panulirus argus*	Tilefish, golden	*Lopholatilus chamaeleonticeps*
Lobster, slipper	*Scyllarides aequinoctialis*	Tilefish, sand	*Malacanthus plumieri*
Mackerel, Atlantic	*Scomber scombrus*	Tilefishes	*Malacanthidae spp.*
Mackerel, chub	*Scomber colias*	Triggerfish, gray	*Balistes capriscus*
Mackerel, king	*Scomberomorus cavalla*	Tuna, albacore	*Thunnus alalunga*
Mackerel, king and	*Scomberomorus* spp.	Tuna, bigeye	*Thunnus obesus*

Common Name	Scientific Name	Common Name	Scientific Name
cero			
Mackerel, Spanish	*Scomberomorus maculatus*	Tuna, blackfin	*Thunnus atlanticus*
Mako, shortfin	*Isurus oxyrinchus*	Tuna, bluefin	*Thunnus thynnus*
Menhaden	*Brevoortia tyrannus*	Tuna, skipjack	*Katsuwonus pelamis*
Mullet, striped (liza)	*Mugil cephalus*	Tuna, yellowfin	*Thunnus albacares*
Mullet, white	*Mugil curema*	Tunas	*Thunnus* spp.
Mullets	*Mugil* spp.	Tunny, little	*Euthynnus alletteratus*
Oyster, eastern	*Crassostrea virginica*	Wahoo	*Acanthocybium solandri*
Oyster, European flat	*Ostrea edulis*	Weakfish	*Cynoscion regalis*
		Wolffish, Atlantic	*Anarhichas lupus*

The fisheries and species of the Atlantic OCS provide a significant amount of revenue to the United States. Some species are available in great quantities and sold for low prices (i.e., menhaden; Table 3–5; Table B–2 in Appendix B), and others are harvested sparingly and fetch high prices (i.e., Atlantic sea scallops; Table 3–6; Table B–3 in Appendix B). Most often it is somewhere in between. A majority of fisheries in federal waters of the Atlantic OCS are managed by Regional Fishery Management Councils: New England Fishery Management Council (NEFMC), the Mid-Atlantic Fishery Management Council (MAFMC), and the South Atlantic Fishery Management Council (SAFMC). Other stocks and species are managed by states, multi-state commissions, international fishery organizations, or a combination of bodies. Table B–4 in Appendix B lists the status of the fishery for the managed stocks in the Atlantic OCS region.

Table 3–5

Landings* of species of commercial importance in the Atlantic OCS region in 2010, sorted by volume. All species are included that make up greater than 1% of the whole. See Table B–2 in Appendix B for list of species that make up greater than 0.1% of the whole.

Common Name	**Scientific Name**	**Metric Tons (thousands)**	**Pounds (millions)**	**Percentage of Atlantic OCS fisheries landings**
Menhaden	*Brevoortia tyrannus*	229.6	506.25	35.61%
Crab, blue	*Callinectes sapidus*	70.8	156.04	10.97%
Herring, Atlantic	*Clupea harengus*	65.2	143.73	10.11%
Lobster, American	*Homarus americanus*	52.7	116.25	8.18%
Scallop, sea	*Placopecten magellanicus*	25.9	57.05	4.01%
Clam, Atlantic surf	*Spisula solidissima*	17.0	37.47	2.64%
Squid, northern shortfin	*Ilex Illex illecebrosus*	15.8	34.88	2.45%
Clam, ocean quahog	*Arctica islandica*	14.4	31.70	2.23%
Mackerel, Atlantic	*Scomber scombrus*	9.9	21.77	1.53%
Haddock	*Melanogrammus aeglefinus*	9.8	21.63	1.52%
Hake, silver	*Merluccius bilinearis*	8.1	17.81	1.25%
Cod, Atlantic	*Gadus morhua*	8.0	17.72	1.25%
Croaker, Atlantic	*Micropogonias undulatus*	7.3	16.17	1.14%
Goosefish (monkfish)	*Lophius americanus*	7.3	16.08	1.13%
Squid, longfin	*Loligo pealei*	6.7	14.81	1.04%

*Data from http://www.st.nmfs.noaa.gov/st1/commercial/. See http://www.st.nmfs.noaa.gov/st1/commercial/landings/caveat.html for caveats related to NMFS commercial landings data.

Table 3–6

Landings* of most commercially important species in the Atlantic OCS region in 2010, sorted by value in U.S. dollars. All species are included that make up greater than 1% of the whole See Table B–3 in Appendix B for list of species that make up greater than 0.1% of the whole.

Common Name	**Scientific Name**	**$USD Value ($million)**	**Average price/lb (price per kg) ($USD)**	**Percentage of Atlantic OCS Fisheries Value**
Scallop, sea	*Placopecten magellanicus*	450.97	7.91 (17.40)	28.56%
Lobster, American	*Homarus americanus*	399.48	3.44 (7.57)	25.30%
Crab, blue	*Callinectes sapidus*	158.67	1.02 (2.24)	10.05%
Menhaden	*Brevoortia tyrannus*	41.11	0.08 (0.18)	2.60%
Clam, northern quahog	*Mercenaria mercenaria*	33.57	7.79 (17.14)	2.13%
Flounder, summer	*Paralichthys dentatus*	28.63	2.18 (4.80)	1.81%
Cod, Atlantic	*Gadus morhua*	28.14	1.59 (3.50)	1.78%
Shrimp, white	*Litopenaeus setiferus*	27.28	2.15 (4.73)	1.73%
Clam, Atlantic surf	*Spisula solidissima*	25.95	0.69 (1.52)	1.64%
Oyster, eastern	*Crassostrea virginica*	24.49	10.76 (23.67)	1.55%
Haddock	*Melanogrammus aeglefinus*	21.72	1.00 (2.20)	1.38%
Herring, Atlantic	*Clupea harengus*	21.08	0.15 (0.33)	1.33%
Clam, ocean quahog	*Arctica islandica*	20.01	0.63 (1.39)	1.27%
Clam, softshell	*Mya arenaria*	19.97	5.94 (13.07)	1.26%
Goosefish (monkfish)	*Lophius americanus*	19.23	1.20 (2.64)	1.22%
Bass, striped	*Morone saxatilis*	16.86	2.27 (4.99)	1.07%
Squid, longfin	*Loligo pealei*	15.76	1.06 (2.33)	1.00%

*Data from http://www.st.nmfs.noaa.gov/st1/commercial/. See http://www.st.nmfs.noaa.gov/st1/commercial/landings/caveat.html for caveats related to NMFS commercial landings data.

3.4 Species of Importance

3.4.1 Arctic OCS Region

There are no fish species protected under the ESA in the Arctic OCS region. Little is known about the populations of fish in this portion of the Chukchi and Beaufort seas due to inaccessibility of the area. None of the species observed in this area have been seen in enormous numbers, and no known species are indigenous only to the area described in Figure 3–2.

Canada lists the northern wolffish (*Anarhichas denticulatus*) and blackline prickleback (*Acantholumpenus mackayi*) as species of special concern that may inhabit this area. Background information on the species characteristics, distribution, and life history of Arctic fishes and invertebrates can be found from several web resources: Arctic Ocean Diversity (www.arcodiv.org), FishBase (www.fishbase.org), and Fisheries and Oceans Canada (http://www.dfo-mpo.gc.ca/Science/publications/uww-msm/index-eng.asp). A review of the knowledge of the species found in the Arctic OCS is provided in NPFMC (2009b).

3.4.2 Atlantic OCS Region

Several species on the Atlantic Outer Continental Shelf are listed as endangered, threatened, candidates for listing, or species of concern. Atlantic salmon, four populations of Atlantic sturgeon (*Acipenser oxyrinchus oxyrincus*), and shortnose sturgeon (*Acipenser brevirostrum*) are the only currently endangered species found in the Atlantic OCS. All three species are anadromous, living much of their adult lives in the ocean but returning to rivers to spawn. Other species have been proposed for endangered status and not deemed candidates or are currently candidates for listing and the status determination has not been made yet. These species along with species that NMFS does not have enough information to make a determination on are all identified as species of concern. Table 3–7 gives all fish species identified by the NMFS Office of Protected Resources as endangered, threatened, or species of concern in the Atlantic OCS region. Box 1 contains the definitions provided on the NMFS Office of Protected Resources website to explain the difference between designation titles.

The life histories of the economically and ecologically important species have been described in detail by Gabriel (1992) for demersal fishes between Cape Hatteras and Nova Scotia, Robin (1999) for fishes of US Atlantic waters, Bowman et al. (2000) for diets of northwest Atlantic fishes and squid, Collette and Klein-MacPhee (2002) for fishes in the Gulf of Maine, and Love and Chase (2007) for marine diversity of Mid- and South Atlantic bights. Life history and habitat information of EFH-managed species in the North Atlantic and Mid-Atlantic regions are provided in EFH source documents and the EFH Mapper.[8]

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[8] EFH source documents are available at this website: http://www.nefsc.noaa.gov/nefsc/habitat/efh/. Additional information, including an interactive EFH mapper, for other managed species can be found here: http://sharpfin.nmfs.noaa.gov/website/EFH_Mapper/map.aspx.

Table 3–7

Endangered, threatened, and species of concern (fish) in the Atlantic Outer Continental Shelf region (NMFS 2011).[9]

Common Name	**Scientific Name**	**Range**	**Status; Date listed**
Alewife	*Alosa pseudoharengus*	Atlantic: Newfoundland to North Carolina	Species of concern; 2006 and candidate Species
American eel	*Anguilla rostrata*	Atlantic Ocean: Greenland to Brazil	Under status review; 2011
Atlantic Bluefin tuna	*Thunnus thynnus*	Atlantic Ocean and adjacent seas	Species of concern; 2010
Atlantic halibut	*Hippoglossus hippoglossus*	Atlantic: Labrador to southern New England	Species of concern; 2004
Atlantic salmon	*Salmo salar*	Atlantic: Gulf of Maine (other populations in streams and rivers in Maine outside the range of the listed Gulf of Maine DPS); anadromous	Endangered; 2000
Atlantic sturgeon	*Acipenser oxyrinchus oxyrinchus*	North America, Atlantic coastal waters; anadromous	Endangered (New York Bight, Chesapeake Bay, Carolina, and South Atlantic DPS), Threatened (Gulf of Maine DPS); 2012
Atlantic wolffish	*Anarhichas lupus*	Atlantic: Georges Bank and western Gulf of Maine	Species of concern; 2004
Barndoor skate	*Dipturus laevis*	Atlantic: Newfoundland, Canada to Cape Hatteras, North Carolina.	Former species of concern; 2007
Blueback herring	*Alosa aestivalis*	Atlantic: Cape Breton, Nova Scotia, to St. John's River, Florida	Species of concern; 2006 and Candidate Species
Cusk	*Brosme brosme*	Atlantic: Gulf of Maine	Species of concern; 2004 and candidate Species
Dusky shark	*Carcharhinus obscurus*	Western Atlantic	Species of concern; 1997
Nassau grouper	*Epinephelus striatus*	Atlantic: North Carolina southward to Gulf of Mexico	Species of concern; 1991
Night shark	*Carcharinus signatus*	Western Atlantic: Gulf of Mexico, South Atlantic and Caribbean	Species of concern; 1997
Porbeagle	*Lamna nasus*	Atlantic: Newfoundland, Canada to New Jersey	Species of concern; 2006
Rainbow smelt	*Osmerus mordax*	Atlantic: Labrador to New Jersey; anadromous	Species of concern; 2004
Sand tiger shark	*Carcharias taurus*	Atlantic; Gulf of Mexico	Species of concern; 1997

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[9] See http://www.nmfs.noaa.gov/pr/species/fish/.

Common Name	Scientific Name	Range	Status; Date listed
Scalloped hammerhead	*Sphyrna lewini*	Western Atlantic	Candidate species; 2011
Shortnose sturgeon	*Acipenser brevirostrum*	Western Atlantic: New Brunswick to Florida; anadromous	Endangered; 1967
Smalltooth sawfish	*Pristis perotteti*	Atlantic: New York to Brazil	Endangered, U.S. distinct population segment; 2003
Speckled hind	*Epinephelus drummondhayi*	Atlantic: North Carolina to Gulf of Mexico	Species of concern; 1997
Striped croaker	*Bairdiella sanctaeluciae*	Western Atlantic: Florida	Species of concern; 1991
Thorny skate	*Amblyraja radiata*	Atlantic: West Greenland to New York	Species of concern; 2004
Warsaw grouper	*Epinephelus nigritus*	Atlantic: Massachusetts southward to Gulf of Mexico	Species of concern; 1997

Box 1: NOAA Definitions of Designation Titles

***Endangered**: Defined under the ESA as "any species which is in danger of extinction throughout all or a significant portion of its range."*

***Threatened:** Defined under the ESA as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range."*

***Candidate Species**: any species that is undergoing a status review that NMFS has announced in a Federal Register notice. Thus, any species being considered by the Secretary (of the Department of Commerce or Interior) for listing under the ESA as an endangered or a threatened species, but not yet the subject of a proposed rule (see 50 CFR 424.02). NMFS' candidate species also qualify as species of concern. "Candidate species" specifically refers to--*

- *species that are the subject of a petition to list and for which we have determined that listing may be warranted, pursuant to section 4(b)(3)(A), and*
- *species that are not the subject of a petition but for which we have announced the initiation of a status review in the Federal Register.*

***Proposed species**: Those candidate species that were found to warrant listing as either threatened or endangered and were officially proposed as such in a Federal Register notice after the completion of a status review and consideration of other protective conservation measures. Public comment is always sought on a proposal to list species under the ESA. NMFS generally has one year after a species is proposed for listing under the ESA to make a final determination whether to list a species as threatened or endangered.*

***Species of Concern**: species about which NMFS has some concerns regarding status and threats, but for which insufficient information is available to indicate a need to list the species under the ESA. This may include species for which NMFS has determined, following a biological status review, that listing under the ESA is "not warranted," pursuant to ESA section 4(b)(3)(B)(i), but for which significant concerns or uncertainties remain regarding their status and/or threats. Species can qualify as both "species of concern" and "candidate species."*

3.5 Priorities

Examples of fishes in the Atlantic OCS that might be regarded as priority species in terms of risks from exposure to high level sounds are:

- Clupeids (herrings), such as Atlantic menhaden (*Brevoortia tyrannus*) and Atlantic herring (*Clupea harengus*), for their commercial importance based on value and volume of landings
- Fishes, such as Atlantic cod, haddock (*Melanogrammus aeglefinus*), snapper (Lutjanidae), and grouper (Epinephelinae), that use sound to communicate or locate prey and are overfished[10] or are close to being overfished
- Fishes, such as elasmobranch and sturgeon, whose populations are reduced and that are slow-growing, late maturing species with low fecundity
- For invertebrates, noise impacts on the commercially valuable decapods, such as American lobster (*Homarus americanus*), blue crab (*Callinectes sapidus*), and white shrimp (*Litopenaeus setiferus*), Atlantic sea scallop (*Placopecten magellanicus*), and squid (Teuthida), should be evaluated

Both fish species for which EFH has been designated in the Arctic OCS are related to Atlantic cod (Arctic cod and saffron cod), and may use sound to communicate. Global warming has the potential to alter the noise environment in the Arctic because reductions in ice cover would increase the access by vessels, as recognized by fisheries managers in the Arctic. These two species should therefore be considered priority species. Priority should also be placed on evaluating any noise impacts on king and snow crabs given their economic value in Alaskan waters, value for subsistence purposes in the Chukchi Sea, and that climate change could lead to favorable conditions for developing a crab fishery in nearby Arctic waters.

4 Naturally Occurring Sounds in the Sea

4.1 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. In particular, the existing levels of sound in these areas should be investigated, together with information on any trends in those overall levels of sound.

There are few historical records of levels of sound in the sea. Systematic measurement of sound in the sea has rarely taken place, and when it has it has often been at local sites and the records are often incomplete or unpublished. Several studies have indicated that over the past few decades the contribution to ambient noise from ships in busy shipping lanes has increased by as much as 12 dB (Andrew et al. 2002; Hildebrand 2009; Cato 2012; Stocker and Reuterdahl 2012).

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[10] Overfished: When the size of a fish stock is smaller than the sustainable target set by the National Marine Fisheries Service. Overfishing: When a fish stock is being fished at a fishing mortality rate that exceeds the overfishing threshold set by the National Marine Fisheries Service. (Source: http://www.nmfs.noaa.gov/pr/glossary.htm)

A significant number of ambient noise measurements were obtained in deep water during the first half of the 20th century. Knudsen et al. (1948) made an especially important contribution by showing 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) extended our knowledge of sound levels in the sea.[11] He 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, falling with a slope of between 5 and 6 dB per octave (doubling of frequency; see glossary in Appendix A). At frequencies around 100 Hz, distant shipping makes a significant contribution to ambient noise levels in almost all the world's oceans. In the mid-frequency range (around 10 kHz) sediment transport noise may be a significant noise source especially where strong currents and turbulence exist due to wave action or tidal flow. Mellen (1952) showed that at frequencies from 50 kHz upwards, molecular motion of water (thermal noise) contributes to the noise level at an increasing rate.

Ambient noise from 1 to 10 Hz is mainly comprised of turbulent pressure fluctuations from surface waves and the motion of water at the boundaries. This ambient noise depends on both wind strength and water currents, especially in shallow water (e.g., below 100 m). Turbulent pressure changes are not generally acoustic in nature and do not propagate as sound waves. However, hydrophones[12] (underwater microphones) are as sensitive to these pressure changes as propagating sound waves, and measurements represent a combination of both. Low frequency propagated sound does exist at low frequencies and can be measured where turbulent noise does not dominate. Wenz (1962) conjectured that this very low frequency noise includes sound from distant seismic disturbances, earthquakes, and explosions.

At frequencies between 10 and 100 Hz, distant man-made sounds begin to dominate the sound spectrum, with the greatest contribution between 20 and 80 Hz. Sound in this region of the spectrum is not attributable to one specific source but a collection of sources at a distance from the receiver, with distant shipping traffic as the greatest contributor. This is also the region of the spectrum where vocalizations from large whales may dominate background sound levels at certain times of the year, generating higher levels than man-made sound in some regions.

The data from Wenz (1962) and Knudsen et al. (1948) are generally accepted as providing overall indication of the range of sea noise levels and the source of the dominant noise in each frequency range. However, their measurements were undertaken over 50 years ago and in relatively deep water environments. Fewer data have been published for shallow coastal waters and estuarine environments. A recent review of underwater noise by 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

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[11] Additional information on ambient noise and other related topics are available at the DOSITS.org web site, specifically for noise: http://dosits.org/science/soundsinthesea/commonsounds/.

[12] For information on hydrophones, see this website: http://dosits.org/science/soundmeasurement/measure/.

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,[13] 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.

In deep water, low frequency sounds generated by seismic airguns and other sources can travel long distances. Sound from seismic surveys off Nova Scotia, western Africa, and northeast of Brazil has been recorded on a hydrophone array moored along the Mid-Atlantic Ridge over 3,000 km away (Nieukirk et al. 2004).

An especially important information need in considering the impact of man-made sound in a given area is therefore the prevailing level of sound in that area from all sources. A description of the ocean background sound level and its characteristics is required. Then it is necessary to determine where that sound is coming from and the contribution from different sources, both natural and man-made.

Sound levels at one locale will most likely be different from other (and even nearby) locales. Thus, extrapolation is not possible at a detailed level, but it may be possible to make broad generalizations of the kind(s) of sounds and likely acoustic environment for particular areas (e.g., if there is a shipping lane in an area, the mix of sounds may have particular characteristics; if wind farm construction is underway, the mix of sounds will be different).

Many energy developments, and especially wind farms, take place in relatively shallow water compared to those examined by Wenz (1962) and others (e.g., less than 100 m). In coastal waters, in addition to other sources of ambient noise (which includes distant shipping traffic), local shipping traffic, pleasure craft, oil and gas platforms, other mechanical installations, and local marine life may all add to the level of sound. Coastal sound levels may therefore be significantly higher than those in the deep ocean.

It may be argued that since coastal waters are already noisy reduces the impact that any additional man-made sounds may have since fish and invertebrates in the area may have adapted to these sounds. However, it is important to consider whether further developments, in deep water or coastal areas, may have detrimental environmental impacts and affect fish and invertebrates adversely.

Given knowledge of the spatial and temporal complexity and variability of all sound sources, the relative contribution from man-made sources can be distinguished from that of natural sources. Sound inventories (sometimes called sound budgets)[14] can be produced—showing the quantitative contributions from different sources at different locations and at different times (Miller et al. 2008). And these inventories can be projected forward into the future as the oceans become more developed.

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[13] For specific data, see: http://www.marisec.org/shippingfacts/worldtrade/volume-world-trade-sea.php.

[14] See a description of sound budgets at this website: http://www.dosits.org/science/advancedtopics/noisebudget/.

To prepare sound inventories, the different sources of underwater sound are examined and characterized and their contributions modeled. Defining the position and main characteristics of the contributing sources (in particular man-made ones) relies on ‘accurate’ modeling of sound propagation from the source to the measurement location based on ‘representative’ modeling of oceanographic features affecting sound propagation such as wind speed, wave heights, sound velocity profiles, water depth, ocean bottom characteristics, etc.

Currently, there are insufficient measurements of ocean sound levels to understand how they have changed over the past decades, nor are there enough measurements to adequately describe or quantify ocean noise on a global scale. The long-term variation of sound in the ocean is a fundamental knowledge gap: is there a trend in the sound level over time? Trends, if they exist, are likely to depend on the particular frequency bands of interest and the locations in the ocean. At frequencies below 1 kHz where the sound level is usually dominated by man-made sources, such as shipping, seismic surveys, and marine construction, any trend may be related to changes in these activities. To what extent does the ambient sound level in the deep ocean reflect the level of activity in international trade carried by merchant ships? In any sea basin what is the likely effect upon the levels of sound of conducting a series of seismic surveys, or constructing a number of wind farms?

Essential Questions Relating to Background Conditions and How They Might Change

- *What physical quantities and metrics are most useful for describing ocean soundscapes?*
- *What are the levels and characteristics of natural and man-made ocean sound in the areas of interest?*
- *What is the contribution to sound levels in the area from natural sources, including biological sources?*
- *What is the contribution to sound levels in the area from man-made sources?*
- *What would sound levels be like in the absence of man-made sources?*
- *What are the likely future trends in sound levels from man-made sources in the areas of interest?*

To answer these questions, measurements 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.

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.[15] This is reflected by a disparity of sensor designs and of data collection and transmission protocols. 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. Is there a need for a Global Ocean Acoustical Observing System that might define standards and protocols for sensors and for the analysis, storage, and distribution of data

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[15] Some of these sites are given, and can be listened to at http://www.listentothedeep.com/acoustics/index.html.

across a global research community? What additional measurements might be included (such as wind speed and wave height) to make sense of the measurements and aid prediction?

Is there a need to routinely monitor ocean sound? In the European community, the Marine Strategy Framework Directive of 2008[16] now requires member states to define qualitative descriptors for determining good environmental status[17] and to monitor these over time. One of the descriptors is underwater energy, which includes underwater sound (Descriptor 11). The Directive is stimulating the development of ocean observing stations to monitor sound levels and how they change with time, with the overall aim of determining any departure from good environmental status.

4.2 Conserving Acoustic Environments with Special Characteristics

Are there soundscapes in the areas of concern that have special natural characteristics and are likely to change through exposure to man-made sound? Such areas might include biogenic and other reefs or areas where sound-producing fish and invertebrates are gathered. And should some of these areas be conserved or protected because of their particular acoustic characteristics?

Particular soundscapes may be characterized by their ambient sound characteristics and by the particular sound sources, including biological sound producers, which live there. Some animals, such as the larvae of coral reef fishes and crabs, may seek out particular habitats in which to settle on the basis of their noise characteristics (e.g., Jeffs et al. 2003; Tolimieri et al. 2004; Stanley et al. 2012). Animals may use other acoustic features of the marine environment for navigation, to facilitate foraging, and to seek shelter from predators. Some soundscapes, and their associated habitats, animal communities, and ecosystems, may be vulnerable to change and might be damaged by the imposition of man-made noise.

Should certain soundscapes be chosen for closer study and the adoption of conservation measures? This might be done on the grounds that they are:

- Rare or unusual
- Representative of soundscapes that are disappearing
- Likely to change for natural (climatic) reasons
- Areas containing species at risk
- Significant acoustic habitats dominated by biological sounds or containing particular acoustical features important to animals
- Indicative of high biodiversity
- Used for key activities like spawning

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[16] See this website for the Directives: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF.

[17] For more information on good environmental status, see this website: http://ec.europa.eu/environment/water/marine/ges.htm.

- Likely to facilitate examination of conditions before and after exposure to man-made sounds
- Of particular interest to the general public
- Representative of sounds that are particularly unusual

If so, we need to make concerted efforts to identify these soundscapes and their associated acoustic habitats before extensive noise-making activities begin.

This aspect of ocean noise has hardly been explored. There are isolated measurements of noise from different areas and at different times of year—sufficient to show that some acoustical features are special and may be under threat (e.g., Cato 1992). There have been few attempts to classify soundscapes or to define acoustic habitats for particular species.

Setting out to describe different soundscapes and the sounds that contribute to their particular characteristics in a particular ocean basin can fill this information need. Special attention might be paid to describing soundscapes dominated by particular natural features, like the breakup of ice, or which are especially quiet and therefore likely to change through the imposition of man-made noise. Or to soundscapes dominated by biological sounds—where there may be an opportunity to define acoustical habitats for key species and subsequently to examine the impact of additional noise upon these.

5 Biological Sources of Sound in the Areas of Interest

5.1 Invertebrates

At some locations in the ocean a substantial contribution to sound levels comes from invertebrate sources (e.g., snapping shrimp [*Alpheidae* sp.]; Au and Banks 1998). The significance of these sounds is poorly understood for many species and it is not known if the sounds serve a function in the lives of the animals or whether they are purely incidental. The role of these sounds in communication between individuals has hardly been explored. The characteristics of the acoustic habitats these animals inhabit or seek out have rarely been defined.

Many invertebrates, and especially those with hard body parts, can generate sounds. Anyone who has placed a hydrophone close to the seabed will be aware of the many clicks, snaps, and rustles generated by aquatic animals. Some of these sound producers have been identified but many have not. Some of the sounds may be purely incidental but others may be communication sounds that have significance for the animals emitting them.

Amongst the crustacean sound producers are barnacles (Fish 1954; Busnel and Dziedzic 1962), decapods like the spiny lobsters (Palinuridae; Dijkgraaf 1955; Moulton 1957; Latha et al. 2005; Buscaino et al. 2011), prawns (Dendrobranchiata; Dumortier 1963), snapping shrimps (Johnson et al. 1947; Fish 1954; Hazlett and Winn 1962; Au and Banks 1998), the mantis shrimps (Stomatopoda; Hazlett and Winn 1962; Dumortier 1963; Staaterman et al. 2012) and crabs (Dumortier 1963). Amongst the mollusks, populations of the common mussel *Mytilus* give rise to a crackling sound, while squid emit a popping sound (Iversen et al.1963). Sea urchins (Echinoidea) can produce a sustained frying sound (Fish 1954).

Some of the invertebrates that produce sounds have no clearly defined vocal organs, and the sounds they generate may well be incidental. However, a number of crustaceans make sounds that are species-specific and involve particular sound-producing mechanisms. The spiny lobsters have a pair of stridulating organs, each comprising a series of fine parallel ridges lining a surface on the base of the second antenna (Moulton 1957). Californian spiny lobsters (*Panulirus interruptus*) produce pulsatile rasps when interacting with potential predators (Patek et al. 2009). Frictional vibrations, similar to rubber materials sliding against hard surfaces, produce the rasp. The rasps from field recordings typically have a distinct narrow peak below 500 Hz and another broader peak around 1.5 to 2 kHz. Other decapods, like the ocypodid (ghost crabs) and pagurid (hermit) crabs, stridulate (scrape hard parts of the body together) (Guinot-Dumortier and Dumortier 1960; Field et al. 1987), while astacid crayfish squeak with their abdomen (Sandeman and Wilkens 1982). The California mantis shrimp (*Hemisquilla californiensis*) produces a rumble (Patek and Caldwell 2006) when physically handled or approached by a stick. Recently, Staaterman et al. (2012) demonstrated that the sounds produced by California mantis shrimp in the sea are very variable; different individuals produce rumbles that differ in dominant frequency and number of rumbles per bout. The rumble may play a role in establishing territories and/or attracting potential mates.

King crabs produce impulsive sounds during feeding that appear to stimulate movement by other individual crabs, including approach behavior (Tolstoganova 2002). King crabs also produce discomfort sounds when environmental conditions are manipulated.

The sharp, explosive click or snap produced by the various species of snapping shrimp is generated by a plunger mechanism on the enlarged claw (Johnson et al. 1947). The sound is caused by the collapse of a cavitation bubble, which is formed when the shrimp snaps its claw shut (Lohse et al. 2001). The bubble emits not only a sound but also a flash of light—indicating extreme temperatures and pressures inside the bubbles before they burst. It is suggested that the shrimp uses its cavitation bubble to damage, stun, or kill its prey. The high incidence of sound production by these shrimp suggests that the sounds may also serve other functions—perhaps facilitating social interactions. The combined snapping within a large population of snapping shrimp may generate a continuous crackle or frying sound that often interferes with sonar apparatus and with passive listening for ships and other sound sources. Reported source peak-to-peak sound pressure levels for snapping shrimp are 183 to 189 dB re 1 μPa at 1 m over a frequency range of 2 to 200 kHz (Au and Banks 1998). Versluis et al. (2000) report source levels of 210 dB re 1 μPa at 1 m.

The prevalence of sounds from aquatic invertebrates, and especially crustaceans, suggests that sounds are important for communication between individuals and that conspecifics are capable of detecting them. As the sounds may fulfill important functions for the animals of interest, there must be concern that man-made sounds may interfere with their detection, through the process of masking (see Section 10.6).

Questions on Critical Information Needs for Invertebrates

- *What is the best way to monitor and catalogue the sounds made by invertebrates and characterize sounds from key marine species?*

- *What information might allow prediction of seasonal, demographic, situational, or species differences in calling behavior?*
- *How vulnerable are different calls to masking or suppression by man-made sound sources?*
- *Which invertebrates might be engaging in acoustic and other activities related to their long-term fitness, such as spawning, and where do concentrations of them occur?*

5.2 Fishes

Since there are so many species of fish (>32,100 known to date),[18] it is still not clear how widespread sound production is, 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 and appropriate 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 particular, the spawning behavior of many sound-producing species has yet to be described, and the role of such sounds in the reproductive process is not known. Nevertheless, 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).

Sound plays an important role in the lives of many fishes, and many species are themselves vocal. Over 800 species of fish from 109 families are known to make sounds and this is likely to be a substantial underestimate (Kaatz 2002). Of these, over 150 species are found in the northwest Atlantic (Fish and Mowbray 1970). Amongst the vocal fishes are some of the most abundant and important commercial fish species, including Atlantic cod, haddock (Gadidae), and drum fishes (family Sciaenidae). Aristotle reported hearing sounds from fish (see Volume IV, Chapter 9 in *Historia Animalium*),[19] and Pliny the Elder discussed fish ears and hearing around 2000 years ago (cited in Popper and Dooling 2004). Fish (1954) and Fish and Mowbray (1970) summarized the earliest work in this field, and this was updated by Moulton (1963) and Tavolga (1965, 1971), both of whom traced a history of the field that is now known as Marine Bioacoustics (Tavolga 1964, 1967). Myrberg (1981), Zelick et al. (1999), and Bass and Ladich (2008) have produced more recent reviews. Fishes produce sounds when they are feeding, mating, or fighting and they also make noises associated with swimming. They use a wide range of mechanisms for sound production, including scraping structures against one another, vibrating muscles, and a variety of other methods (Tavolga 1971; Zelick et al. 1999; Bass and Ladich 2008).

Behavioral studies have indicated that fishes discriminate between calls produced by different species by means of the pulse interval and pulse number, rather than the frequency (Winn 1964, 1972; Myrberg and Spires 1972). Within a family of fish, such as the cod family, the sounds of different species often differ in their temporal characteristics (Brawn 1961; Hawkins and Rasmussen 1978; Midling et al. 2002). It has been suggested that fish sounds encode information

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[18] For an up-to-date count see www.fishbase.org.

[19] The English translation can be found here: http://etext.virginia.edu/etcbin/toccer-new2?id=AriHian.xml&images=images/modeng&data=/texts/english/modeng/parsed&tag=public&part=4&division=div2

through temporal patterning since, with few exceptions; they show weak frequency modulation and are made up of brief low frequency pulses (e.g., Myrberg and Spires 1972; Bass and Ladich 2008). This is consistent with the belief that fishes are specialized in extracting information in the time domain (Fay 1980). However, it is important to remember that changes in the temporal structure are also accompanied by changes in frequency related to the sound pulse repetition rate. Recent studies (reviewed by Bass and Ladich 2008) have examined the relevant features of the calls to conspecifics and have confirmed the importance of the temporal characteristics of fish calls.

Fishes produce species-specific sounds (Hawkins and Rasmussen 1978; Myrberg and Riggio 1985; Lobel 1998) and individual-specific sounds (Wood et al. 2002). The sounds are often loud and may dominate sea noise. Fishes of the drum family Sciaenidae may interfere with military operations that involve passive listening (Fish and Mowbray 1970; Ramcharitar et al. 2006). Other species, like the damselfishes (Pomacentridae), which live on coral reefs, or the gobies (Gobidae) produce weak sounds that are barely detectable by man but have important biological meaning for the species (Tavolga 1956; Mann and Lobel 1997).

Sounds produced by spawning fishes, such as cod, haddock, and sciaenids, are sufficiently loud and characteristic for them to be used by humans to locate spawning concentrations, and, more importantly, for females to find males (Mok and Gilmore 1983; Ramcharitar et al. 2006; Luczkovitch et al. 2008). There is still a lack of detailed knowledge of the location and characteristics of spawning sites of many species and it is not known whether many fish species return to the same sites each year, or whether site choice is more variable. It is currently difficult to assess whether spawning sites need special protection from activities such as fishing or high levels of man-made noise.

Currently, although the characteristics of the sounds, spawning locations, and sound levels are known for a small number of species, there is a lack of information on the characteristics of the sounds made by many fishes, their functions, the distances over which the sounds travel, or the effects of ambient sound (both natural and man-made) on their propagation. It is not known whether fish can compensate for high background sound levels by changing the characteristics of their calls (known as the Lombard Effect as found in many terrestrial vertebrates; Brumm and Zollinger 2011). However, it is known that some of the more common commercial species communicate by means of sound. There is a need to identify significant aggregations of sound producing fish and consider whether they need protection, before further deterioration takes place in noise levels in the sea. There is also a need to identify concentrations of fish that might be engaging in acoustic and other activities related to their long-term fitness—such as spawning grounds.

As with invertebrates, an effort should be made to sample and describe sounds made by key marine species of fish. In the first instance, more recordings and observations on a wider range of species are needed. Some of these studies might be carried out on captive fish, under appropriate conditions, to allow sound producing behavior to be examined in detail. However, studies are also required in the wild, where fishes are more likely to show their full range of behavior, and where behavior may vary in different contexts. Particular families that would benefit from closer study would include members of the cod family, grunts, drums, herring, shad, and menhaden.

It is also important to examine the fishes' use of sounds to define the particular characteristics of their sounds that are of interest to them and examine the effects of changes in their acoustic habitats. Many fishes engage in communal sound producing, giving rise to choruses. It is most important to examine the impact upon fish choruses and fish communication of man-made sounds, whether this is through masking the detection and recognition of sounds or through induced changes in behavior (see Section 10).

Information should be also gathered that might allow prediction of efficacy of detection, such as seasonal, demographic, situational, or species differences in calling behavior. Vulnerability of different calls to masking by different sources should be examined (see Sections 10.3 and 10.6).

Questions on Critical Information Needs for Fish

- *What sounds do fishes make and what is the role of sound production, including descriptions of the sounds from key marine species?*
- *What information might allow prediction of efficacy of detection, including seasonal, demographic, situational, or species differences in calling behavior?*
- *How vulnerable are different calls to masking or suppression by man-made sound sources?*
- *Which fishes might be engaging in acoustic and other activities related to their long-term fitness, such as spawning, and where do aggregations of them occur?*
- *Do fishes have the ability to compensate for changing background sound conditions? If so, how?*

6 Sources of Man-Made Sound

To adequately describe sound fields in the areas of interest requires quantitative descriptions of the kinds of sources of sound that exist, their frequency spectrum, waveform, level, and variation in both space and time. Such measurements can span a broad frequency range.

Underwater noise also needs to be understood and modeled in terms of the spatial and temporal fields generated by different sound sources, both natural and anthropogenic. Together with the propagation characteristics, such information enables us to provide an inventory—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.

Many fishes (including sharks) and invertebrates are insensitive to sound pressure but sensitive to particle motion and perhaps also to motion of the substrate. One major issue is the extent to which particular sources generate particle motion that may be detected or affect fishes and invertebrates and at what distances from the source. It is important in modeling sound fields to consider the particle motions generated as the pressure component (e.g., Sigray and Andersson 2012). This is generally not done and is a major information need.

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. As discussed in Section 6.1, there are many different man-made sound sources in the sea, and they can be quite complex in their design and characteristics. It is also important to understand the potential changes in sound characteristics when there are multiple sources of the same or different types occurring at the same time in the same area.

6.1 Different Man-Made Sound Sources and their Characteristics

6.1.1 Explosions

Explosives are used underwater in a wide range of applications including the construction or removal of installations such as offshore oil platforms. A literature synthesis report was produced for BOEM on the explosive removal of offshore structures (Continental Shelf Associates 2004). Structure removal typically involves the use of explosives to sever platform legs several feet below the seafloor and in OCS waters it is carried out according to regulatory requirements set by BOEM. For example, observers must monitor areas around the site before, during, and after the detonation of explosives.

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. Considerable heat is liberated. Many explosives require prior detonation. At detonation a physical shock front rapidly compresses the explosive material and advances significantly faster than the sonic velocity of the material. As this front passes through the explosive, it triggers the release of chemical energy and thus realizes a self-sustaining wave that builds up to a stable limiting rate of propagation that is characteristic of the detonating material. This self-sustaining wave, known as a detonation wave, differs from the shock wave. A short distance beyond the explosive blast, generally taken to be three to ten diameters of the explosive’s charge, thermal and direct detonation effects from the explosion can be ignored; the main sources of impact outside this distance are the shock wave and the sounds generated by the expanding gaseous reaction products.

The pressure wave of underwater explosive detonations is composed of a shock or primary pulse followed by a series of bubble pulses. 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. This rise time affects the frequency content in the signature of the explosion, with longer rise times lacking the highest frequencies. There are hundreds of commercially available explosives and many variations in the chemical mixtures of particular types of explosives. Each of them will differ with respect to features like rise time.

In water, explosions from single charges have been extensively studied and are described by Cole (1948) and Urick (1983). In some instances explosive charges are fired successively, rather than in a single detonation, to minimize damage. Shaped charges are commonly used in underwater structure removal to focus the blast energy toward the surface of the component to be severed.

There are several guidelines for the protection of aquatic life during the use of explosives in water (Young 1991; Keevin and Hempen 1997; Wright and Hopky 1998). Yelverton et al. (1975) looked at the relationship between fish size and their response to underwater blasting. The literature synthesis report for BOEM on the explosive removal of offshore structures is especially informative on procedures to be followed in OCS waters (see Continental Shelf Associates 2004).

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.

The sounds generated by underwater explosions may travel great distances. Explosions with energy yields equivalent to less than 40 kg of TNT can be detected at hydrophones in the deep-sound channel at distances up to 16,000 km (Prior et al. 2011).

6.1.2 Seismic Airguns

The airgun is the basic sound source used for seismic exploration by the oil and gas industry for surveys of subsea structures and for general geological exploration. Airguns work by producing an air bubble from a compressed air supply (e.g., Mattsson et al. 2012).[20] The air bubble initially rapidly expands creating an impulsive signal with a slower rise time to peak pressure than in explosions. The bubble then oscillates with decreasing diameter until it vents to the surface. The oscillating bubble creates a series of smaller pulses that follow the primary pulse created by the initial formation of the bubble. The sound impulse generated by a single airgun is omnidirectional, with peak energy at low frequencies typically on the order of 20 to 50 Hz with declining energy at frequencies above 200 Hz. Arrays consisting of several air guns, usually of different sizes, are commonly 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 to 15 seconds), 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).

There are two types of seismic survey: 2D and 3D. With 2D surveys, a single streamer and one or more airguns is deployed. Single airgun sources are used occasionally for shallow water geotechnical work (aimed at detecting surficial and shallow sub-bottom features rather than deep hydrocarbon deposits), though small arrays of a few guns are usually preferred for better pulse shaping and focusing. Such surveys are used to provide initial images of an area and to indicate the presence of oil and gas. In contrast, 3D surveys, while more complicated and time-

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[20] Images and a further discussion of air guns can be found at http://www.dosits.org/technology/observingtheseafloor/airgun/.

consuming, employ multiple streamers of hydrophones, often spanning a width of many tens of meters, to give a three-dimensional image of the seabed. The airguns typically cover an area of tens of square meters, towed a distance of several hundred meters behind the survey vessel. These signals are processed to produce a three-dimensional image of the seabed. The spacing of adjacent survey lines is generally much wider in 2D (sometimes kilometers) than in 3D (usually a few hundred meters) as the latter requires overlap of adjacent swaths of sea bottom imaging.

The main impulse generated beneath the airgun is the sum of the direct pulse and a very strong reflected pulse from the sea surface. Considerable sound energy is also projected horizontally from the airguns. The source level of an airgun measured in the far field and back calculated to a point source is on the order of a theoretical peak source level of 260 dB re 1 µPa at 1m but can vary greatly with the design of an array and the airguns in the array (Richardson et al. 1995). However, airgun arrays are not point sources but are distributed sources. As such the exposure of animals very near the array is more likely to be more closely related to the acoustic output of a single airgun than the whole array (Duncan and McCauley 2000). Most of the energy produced is in the 10 to 120 Hz bandwidth (Richardson et al. 1995), but higher frequencies do propagate horizontally.

Because of their common use for seismic surveys there is a great deal of information about the mechanics of airguns, their deployment and operation, and the characteristics of the acoustic signals they generate (e.g., Dragoset 2000; Laws 2012; Mattsson et al. 2012).

When acoustic energy in the water encounters the ocean 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 seabed at levels that can be detected by fish and perhaps some invertebrates.

6.1.3 Impact Pile Driving

Impact pile driving is commonly used for the construction of foundations for a large number of structures including offshore wind turbines 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 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). The substrate can contribute via direct propagation or interface (Sholte-like) waves. The latter originate at the water sediment interface and have large vertical velocity components that decay rapidly with vertical distance from the interface (Berkhovski and Lysanov 1982). Such waves are much more likely to affect bottom-living fish than those in the water column. Shear waves and interface waves travel slower than sound waves in the bottom 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 & 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. See Popper and Hastings (2009) for an extensive review of the literature on the biological impact of impulsive sound on fish.

Impulses from impact driving of large diameter steel shell pile, such as the 2.44 m (8 ft) steel pile may have peak pressures on the order of over 210 dB re 1 µPa, generally measured about 10 m from the source (Illingworth & Rodkin 2001, 2007; Laughlin 2006; Rodkin and Reyff 2008; Ainslie et al. 2012). However, the actual peak levels vary substantially and depend on numerous factors such as pile diameter, hammer size, substrate, etc. 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).

6.1.4 Dredging

Dredging or mining of materials from the seabed can be conducted by mechanical means or by suction (see NRC 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. A bucket dredger has a continual chain of buckets that scrape the seabed, raise the material to the surface, and empty the material into the hold of a barge or self-propelled ship. A grab dredger has a large mechanical grab that is lowered to the seabed to pick up material, lift it, and deposit it into a barge. A backhoe dredger is a mechanical excavator equipped with a half-open bucket on the end of an hydraulic arm. In contrast, suction dredging involves raising loosened material to the sea surface by way of a pipe and centrifugal pump. Firm material may require prior loosening through the use of water jets or by a cutter. Suction dredging is most effective for the abstraction of relatively fine materials like sand and gravel. As large quantities of water are removed there is a need to remove the excess water at the surface.

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. 2012). 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.

Sound production during excavation is strongly influenced by soil properties—to excavate hard, cohesive and consolidated soils, the dredger must apply greater force to dislodge or entrain the material. Sometimes it is necessary to break up the substrate using explosives or hammering before dredging is possible. Underwater sounds due to the use of explosives and rock breaking by mechanical action can be considerably stronger than those of routine dredging activities (CEDA 2011).

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 (a measure of the acoustic noise output) 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.

Very little research has been carried out on the effects of sound from dredging on marine life and information is sparse. Behavioral reactions and masking effects are to be expected, with possible negative consequences.

6.1.5 Operating Wind Farms

Sound generated by a wind farm is considered 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 Section 6.1.3). However, whereas construction might affect marine animals for a relatively short period of time, operational sound has the potential to cause disturbance over much longer periods.

The principal sources of sound from an operational wind farm are the turbine noise and maintenance vessel noise (OSPAR 2009). Noise from the turbines is thought to originate in the nacelle machinery, primarily in the gearbox, and to propagate into the tower and foundations that couple the sound into the water and seabed. Most of the noise appears to be generated below about 700Hz and is dominated by narrowband tones (Wahlberg and Westerberg 2005; Madsen et al. 2006).

Sound pressure levels within wind farms are not significantly higher than the background noise (Nedwell et al. 2007a). The highest level noted by Wahlberg and Westerberg (2005) was 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 and sharks (Sigray and Andersson 2012).

6.1.6 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 and increasingly larger commercial ships operating over wide-ranging geographic areas. 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 (Richardson et al. 1995; Arvenson and Vendittis 2000; NRC 2003). Source levels of vessels can range from < 150 dB re: 1 µPa to over 190 dB for the largest commercial vessels (Richardson et al. 1995; Arvenson and Vendittis 2000; Hildebrand 2009).

Low frequency sounds from ships can travel hundreds of kilometers and can increase ambient noise levels in large areas of the ocean, interfering with sound communication in species using the same frequency range over relatively large areas (see Southall 2005, 2012). Tens of thousands of large commercial vessels are typically under way at any point in time, concentrated in high-traffic and port areas and presenting an effectively continuous noise source in certain ocean areas.

Background sounds have steadily increased as shipping and other anthropogenic uses of the oceans and inland waters have increased. For instance, in much of the northern hemisphere, shipping noise is the dominant source of underwater noise below 300 Hz (Ross 1987, 1993); vessel operations have increased over time and as a result have increased low-frequency ambient noise levels in some areas (see Curtis et al. 1999; Andrew et al. 2002; McDonald et al. 2006).

The number of commercial ships has doubled between 1965 and 2003 to nearly 100,000 large commercial ships, 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 (NRC 2003). One of the most serious implications of this increase in shipping noise is the impact it may have in terms of masking sounds of the soundscape, including sounds of biological origin, affecting communication between fish.

An Ocean Observing System for large-scale monitoring and mapping of noise throughout the Stellwagen Bank National Marine Sanctuary is currently monitoring noise from small and medium sized vessels and other sources and evaluating the impact upon marine mammals and fish like the haddock.[21]

A report produced by the International Council for Exploration of the Sea (Mitson 1995) describes the criteria for radiated noise levels that must be achieved by research vessels, specifically those used in fisheries acoustics. The report provides a target source level and spectrum that has been cited by a number of other researchers as criteria for a vessel to be regarded as quiet.

There also may have been a substantial increase in sound levels in coastal waters as a result of an increase in the number of smaller pleasure and recreational fishing vessels. However, these vessels are not associated with the energy industry, and as they tend to operate close to shore or in harbors the sound levels are unlikely to have a substantial effect upon offshore waters.

6.1.7 Fishing

Fishing by means of towed fishing gears involves a vessel dragging a net fitted with spreading and bottom contact devices across the seabed. There is potential for damage to the structure of the seabed and also to vulnerable organisms living on or close to the seabed. These issues are discussed in a report from the NRC (2002).

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 warps or cables 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

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[21] See http://www.onr.navy.mil/reports/FY10/npclark.pdf.

spectra is currently available.

It is evident that many fish will detect these sounds from fishing gears. However, the role played by the distributed sounds from a fishing gear in terms of herding or directing the movements of fish is poorly understood (Wardle 1983).

There has long been interest in how the noise radiated by fishing vessels affects fish (e.g., De Robertis et al. 2012). There has been particular concern over the reactions of pelagic fish to research vessels conducting abundance surveys. Through the International Council for Exploration of the Sea (ICES), low-frequency sound (1 to 1000 Hz) limits for the underwater noise radiated by research vessels were recommended to minimize vessel avoidance (ICES 1995). Noise-reduced research vessels conforming to these recommendations are substantially quieter than their conventionally designed (i.e., not noise-reduced) counterparts over a broad frequency range (Mitson and Knudsen 2003). However, Ona et al. (2007) showed that contrary to expectations, herring showed a stronger behavioral reaction when approached by the *G. O. Sars*, a noise-quieted vessel, compared to the *Johan Hjort*, a conventional vessel, with much of the reaction occurring after vessel passage (see also De Robertis et al. 2012). De Robertis et al. (2008) analyzed depth distributions of walleye pollock (*Theragra chalcogramma*) detected by both conventional (*Miller Freeman*) and noise-quieted (*Oscar Dyson*) vessels and found that in daytime surveys, similar acoustic abundances were observed from both vessels. However, a different depth distribution pattern was observed from the two vessels. In both cases the noise-quieted vessels were larger than the conventional vessels they replaced. An ICES Study Group is currently reporting on these and other similar observations.

6.1.8 Sonar

Sonar is widely used by fishing and other vessels, including ships used for the siting of renewable energy developments. Typical sonars include echo 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. These sonars work at frequencies from 20 to 300 kHz with source levels up to 220 dB re 1 µPa at 1 m. Many of them direct their energy downwards, but there is significant energy travelling horizontally either from the side lobes of the transducer or by scatter off the seabed. Some sonars are trained horizontally on to fish schools. 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; Nestler et al. 1992; Ross et al. 1995; Mann et al. 1997) (see Section 8.2).

6.1.9 Other Continuous Sounds

Vibratory pile driving produces a continuous sound with peak pressures 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).

6.2 The Relevant Stimuli

Sound can be measured not only in terms of sound pressure but also in terms of acoustic particle motion (see glossary in Appendix A) (see also Rogers and Cox 1988; Ellison and Frankel 2012). 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, all fishes and invertebrates detect particle motion. 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 seabed (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 their effects on benthic fishes and invertebrates. These particle motions may act in different directions. While there has been great interest in the last few years in developing vector sensors for navy applications, particle motion is not a standard output from propagation models. 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.

6.3 Characterization of Man-Made Sound Sources

Questions in Relation to the Characterization of Man-Made Sound Sources

- *How can the contributions to the mix of sound in different sea basins from different sources be compared? What is the best way to draw up meaningful sound inventories? How does man-made sound affect long-term background sound levels in the oceans?*
- *Which sound sources have been adequately characterized in terms of the sound fields they produce? What is already known? Information is required on the characteristics of the full range of man-made sources and their modification as a result of propagation so that risk to animals can be assessed, mitigation objectives achieved, and the requirements for impact assessment met.*
- *What is the nature of the sound field (spectral, temporal, and spatial) generated by various industry sound sources, in terms of particle motion as well as sound pressure? There is a need for more information about propagation through the seabed by means of interface waves—this is especially relevant to benthic fish and invertebrates. What is known about ground roll?*
- *Are better propagation models required for specific oceanic environments (i.e., shallow, deep, ice covered, and temperate waters)? Seismic propagation models used by the industry concentrate on determining bottom characteristics, whereas researchers/ regulators need to know the received levels of sound pressure and particle motion to which marine animals are exposed in the water column and close to the seabed.*

- *What are the overall variations in background sound levels (ambient noise) created by man-made sources that must be incorporated into propagation models? Which background sounds are important when considering the masking by that noise of sounds of interest to animals?*
- *What is the role of reverberation in the propagation of signals, especially in ice-covered areas and other confined-space environments where it may exacerbate the potential for masking?*
- *How well do sounds from human activities under BOEM's purview mask biologically-important signals for fishes and invertebrates? In particular, can the masking effect of prolonged signal noise sources such as vibroseis, ship noise, dredging, and fixed platforms for oil and gas extraction be quantified? How can knowledge of the masking potential of different types of sound be improved?*
- *What are the diel and seasonal variations in propagation and which regions may have major effects, particularly in relation to what is known about the behavior of fishes and invertebrates, many of which show diel and seasonal changes in behavior?*
- *How do sounds propagate in regions where fishes and invertebrates might be able to avoid them?*
- *What are the characteristics of man-made sound sources in the marine environment, including amplitude and other characteristics (e.g., bandwidth, kurtosis [Henderson and Hamernik 2012], particle motion, impulse, sound exposure level). How might the characteristics of these sounds change with propagation over larger distances from the source?*
- *What are the appropriate standards for measuring man-made sounds that may have an impact on fishes and invertebrates, particularly for particle motion?*[22]

7 Sound Exposure Metrics

A variety of metrics exist for the physical description of underwater sounds (e.g., Ellison and Frankel 2012). It is important to consider the utility of these metrics for investigating the effects of sounds upon aquatic animals.

7.1 Acoustic Measures and Terminology

Measurement parameters are not well defined for underwater sounds, especially for impulsive sounds. The Dutch standards institute, TNO, has recently published a set of standards for measurement and monitoring of underwater sound (see TNO 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, including that associated with wind farm construction.

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[22] A working group is currently being established by ISO to develop standards for a variety of sound sources, including natural, biological, and anthropogenic sounds. Some ANSI standards are also currently available.

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. There is a requirement for the following:

- Instrumentation that can operate in the near field, without damage, and used to measure particle motion as well as sound pressure
- Sound source characterization in the near field
- Identification of the transition point from the near field to the far field where the sound is wholly coherent
- Information on particle motion amplitudes generated by anthropogenic sources especially close to the water surface or close to the seabed where the physics of the adjacent media must be taken into account
- Information on the particle motions associated with interface waves and ground roll that may affect fish and invertebrates, especially from pile driving and seismic sources
- Measurement and analysis techniques applicable to complex environments such as streams, lakes and shallow water.
- Investigation of the acoustics of small open tanks of various characteristics
- Development of special wave tubes and other containers where fish and invertebrates can be maintained and the characteristics of presented sound stimuli fully described
- Development of field sites for acoustic and animal testing that are acoustically comparable to ocean settings and thoroughly characterized and under substantial experimental control
- Simple instrumentation for measuring acoustic particle motion; perhaps a set of equipment that can measure all the relevant parameters that may affect fish (particle motion, sound pressure, SEL, root-mean-square [rms], sound pressure level [SPL], etc.)

7.2 Measurements Applicable to Fishes and Invertebrates

There is a particular need to consider which sound metrics are most appropriate for predicting the effects of sound exposure on fishes and invertebrates (e.g., Ellison and Frankel 2012). Some sounds are more damaging than others, and for determining the effects of different sounds it is important to describe the sounds in terms of those features that relate to the damage caused. It may be appropriate to develop metrics based on the functional hearing groups of fishes (e.g., fishes with swim bladders mechanically linked to the ears, fishes with swim bladders not linked to the ears, and fishes without swim bladders). Metrics for fishes with swim bladders mechanically linked to the ears will likely be referenced to sound pressure, while those without swim bladders will likely be referenced to particle motion. It is possible that metrics for fishes with swim bladders that are not linked to the ears might be best characterized in terms of acoustic pressure and acoustic particle motion, but to a different extent in each species, perhaps depending upon the position of the swim bladder relative to the ears (Popper and Fay 2011).

Weighting functions need to be defined and refined for a number of fishes or fish categories, as has been done for marine mammals (Southall et al. 2007; Southall 2012). Weighting functions are intended to reflect the degree of response of the animal to a range of frequencies and to exclude frequencies that the animal cannot detect. A weighting curve evaluates the importance of different sound frequencies to the fish. Currently, any weighting functions utilized are based on fish and invertebrate hearing sensitivity curves (plotting the lowest sound levels detectable at different frequencies) over the animals' bandwidth of hearing (this is known as an audiogram; see glossary in Appendix A). Many audiograms have been obtained under far from satisfactory acoustic conditions, often using auditory evoked potential (AEP) techniques. Indeed, most measures to date do not distinguish between sensitivity to sound pressure and particle motion. Moreover, the AEP approachs does not give actual measures of hearing sensitivity and bandwidth (frequency range of hearing) since it only registers responses to sound at the ear or in some cases in the initial points of sound analysis in the brainstem of the central nervous system. The only true measures of hearing capabilities are those using behavioral techniques, where the animal demonstrates that it heard the sound through some behavioral response.

Although audiograms, properly obtained, can be used to estimate how well particular sounds might be detected under given conditions they do not provide an indication of the responses that might be elicited or the damage that might be done to the auditory system by particular sounds.

7.3 Noise Exposure Criteria

Studies are needed to document and quantify any impacts upon fishes and invertebrates by noise of differing characteristics as well as on the injury caused by noise of equivalent energy by differing temporal and frequency characteristics.

Questions in Relation to the Impacts of Differing Characteristics of Noise

- *What are the characteristics of impulsive noise that make 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? Which characteristics of continuous noise are most damaging?*
- *How can we best specify the sound fields generated by particular sources (e.g., sonar, pile driving) in terms of their effects upon fishes and invertebrates?*
- *How do we measure and take account of substrate vibration that may affect fishes and invertebrates close to the seabed?*
- *How should we deal with cumulative effects from multiple pulses from the same sources and deal with recovery and the inter pulse interval?*
- *How do cummulative effects accumulate over time? Do successive presentations increase damage? Is there is a period of healing if sufficient time passes between sound exposures?*
- *What metric is the most appropriate metric to help in understanding the accumulation of sound energy? Is there a better descriptor than sound exposure level (SEL) that is now expressed in two forms: the single strike SEL or the cumulative SEL?*
- *How do we consider in-combination effects from different sources and activities?*

8 Effects of Man-Made Sounds: An Overview

A good understanding of the impacts of man-made sound on marine life is essential to rational decision making and is an important goal. There are a wide range of potential impacts on fishes and invertebrates (and other aquatic animals as well), ranging from death (mortality) to behavioral responses. There is no set pattern to when one or another potential impact will occur, and this may vary depending on many things, from the source acoustics to the distance of the animal from the source (and consequent sound level and spectrum), as well as the state and motivation of the animal.

Figure 8–1 suggests this kind of relationship, and makes the point that the potential impacts are overlapping. Thus, close to a sound, where it is of highest intensity, the impact on an animal may include death, physiological effects, temporary hearing shift, masking, and behavioral responses. As the animal gets further from the source, the number of potential types of impact decrease. At greatest distance from the source where the signal is still audible, the only responses may be behavioral. And, indeed, even within any one class of impact, there may be different responses depending on the sound level of the man-made sound, what the animal is doing at the time that the sound is detected, the experience of the animal with that type of sound, and any number of other factors.

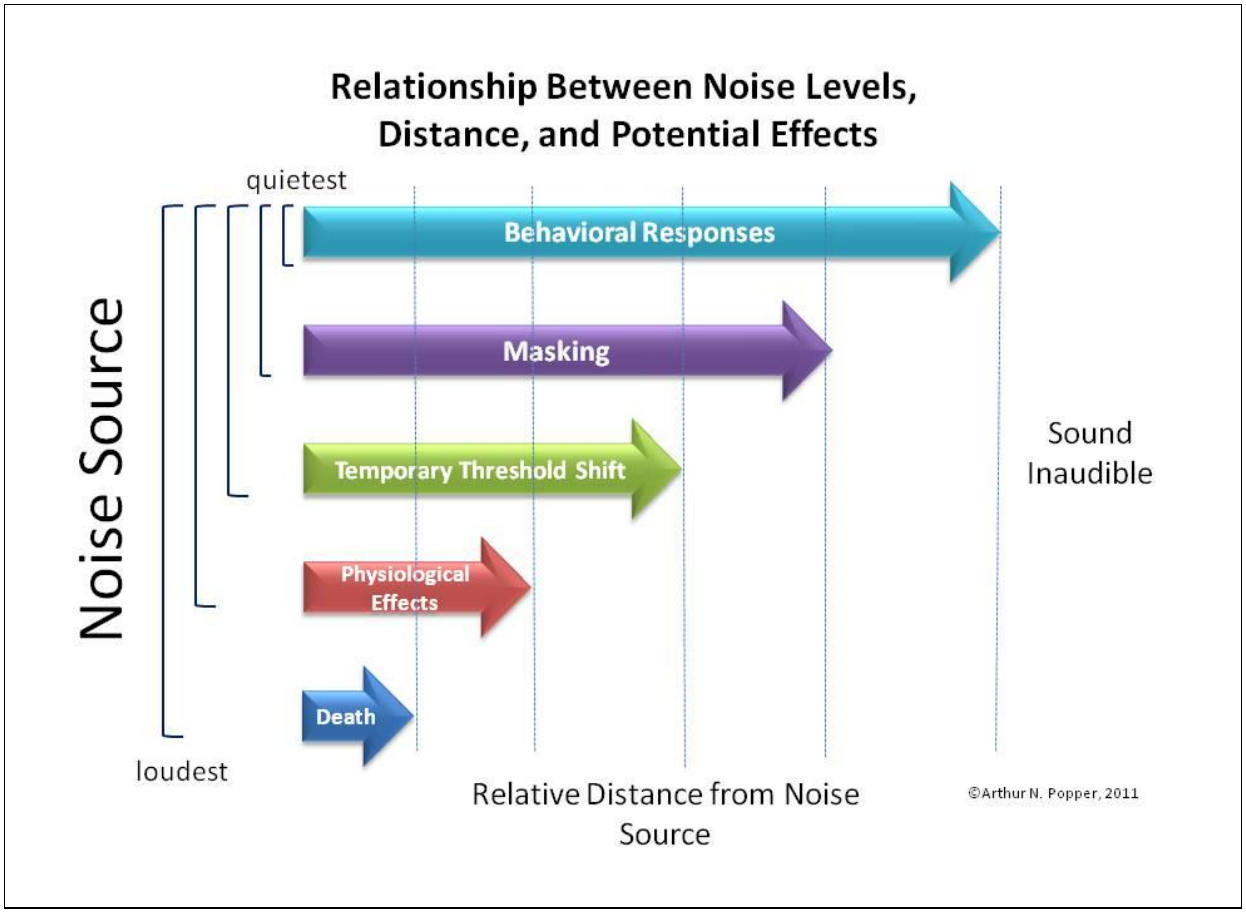

Figure 8–1. Relationship between noise levels and potential effects on animals (see text for discussion).

In other words, there may be numerous consequences of exposure to man-made sounds that range from no response at all to immediate death. And, in understanding the impact of man-made sounds on animals, it is critical to take all of these factors into consideration.

Of particular importance is the issue of when fish will respond to a sound, assuming it is detected. Indeed, even if there is detection of a sound, there are still questions as to whether animals will respond to that sound and whether the response is significant. In effect, one can consider several levels of detection (R. Dooling, pers. comm.).

- Detection—the sound is just audible about the background noise (the masker—whether this be normal ambient and/or man-made). The relationship between signal and noise (signal-to-noise ratio; SNR) is lowest, meaning that the signal is minimally greater than the noise.
- Discrimination—the sound is sufficiently loud above background (a sufficiently high SNR) that the animal can discriminate between two different sounds (e.g., sounds of conspecifics versus predators).
- Recognition—the animal can actually determine what the sound is (that is, the animal can understand the context of the sound).
- Comfortable Communication—animals can communicate, fully understand signals, and use sounds normally.

Thus, even if an animal detects a sound, it may not be able to decide whether the sound is important or not, and even if that is possible, the animal may not be able to determine if it should respond. And, above all else, whether an animal may respond or not may very much depend on the motivational state of the animal. If an animal is feeding or spawning it may not pay as much attention to an external source as it would if it were at rest.

And, finally, one must take into consideration whether animals will habituate to a sound. In other words, if an animal encounters a sound multiple times and learns that the sound has no immediate consequence, it may raise the threshold for when it will respond to that sound.

As discussed earlier, natural soundscapes have changed as a result of anthropogenic sound-generating activities in the ocean. This may in turn have changed acoustic habitats and may be having an adverse impact upon invertebrates and fishes.

We need to examine what is known about the abilities of fishes and invertebrates to detect sound. How well can they hear, and how important is sound to them in their everyday behavior, or for vital activities such as spawning and reproduction?

Key Questions for the Effects of Man-Made Sounds on Species

- *Can we identify thresholds for the occurrence of different effects for different species and be in a position to predict how increasing anthropogenic sound will increase the effects?*
- *What is the nature of such effects and how do they change with different sound types and different sound levels?*

- *Is it possible to develop a broad understanding of physiological effects that are applicable to different sound sources?*
- *What are the characteristics of man-made sources that cause detrimental effects; e.g., magnitude, rise time, duration, duty-cycle (see Section 6)?*
- *What is the role of anatomy (e.g., the presence of the swim bladder and other gas spaces in fishes) producing physiological effects and do animals without air spaces show such effects?*

The ultimate goal should be to understand the population consequences of acoustic exposure. Modeling tools are needed to understand population risks from exposure.

Questions for Modeling Tools

- *What are the cumulative and in-combination effects of repeated exposure to sounds from different sources?*
- *What is the role of habituation, masking, and recovery?*

A major unanswered question is whether there is a significant impact on the fitness of individuals within populations that jeopardizes the viability of those populations. The National Research Council (NRC) addressed this question in its 2003 report on marine mammals and ocean noise (see NRC 2003), but the principles apply equally to all forms of marine life.

There is increasing recognition that sub lethal impacts (e.g., communication masking and significant behavioral responses) from chronic exposure to sounds are perhaps amongst the most important considerations for populations of animals, particularly as they interact with other stressors such as fishing, habitat loss, entanglement, and pollution.

9 Hearing and Sound Detection

Sound is important to fish and other aquatic organisms. 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. In this section, we present a background on sound detection in invertebrates and fishes that is sufficient for understanding the kind(s) of questions that must be asked if we are to better understand the effects of man-made sound on these organisms. There are a number of very broad general questions to ask (listed here) and then there are also more specific questions that deal with various groups of animals (listed in subsequent sections).

Broad Questions on Hearing and Sound Detection

- *Do we know enough about the hearing abilities of fishes and invertebrates?*
- *How can increased knowledge of their hearing abilities assist us in reducing the effects of man-made noise?*

- *How do marine organisms derive information from their acoustic environment? Many fish and invertebrates detect particle motion and they may be especially interested in determining the direction of sources in the horizontal and vertical planes.*

Our basic knowledge of the way in which marine organisms detect sound and then respond to different sound stimuli is rudimentary for many invertebrates and fishes.

The idea that animals may use something analogous to acoustic daylight (Buckingham et al. 1992) to gain an image of their surroundings is gaining momentum, but it is difficult to demonstrate empirically in fishes, though it is well known for mammals (Bregman 1990). The properties of sound in water and the low levels of light penetration below the surface in many circumstances mean that for some species sound may have replaced light as the principal source of environmental information.

One of the fundamental problems in most studies of effects of noise on fishes and invertebrates, and indeed on basic studies of hearing and general bioacoustics, is that the sound field in which studies are done is often very complex and unlike the sound field that an animal would encounter in a normal aquatic environment. The problems arise from the numerous perturbations in the sound field that results from wall and air interfaces surrounding test tanks, no matter how large the tanks might be (see Parvulescu 1964 for a classic discussion of this issue; see also Akamatsu et al. 2002). As a result, much of the data on responses, behavior, and physiology from otherwise well-designed studies, leave open questions as to the actual nature of the sound field to which the animals were exposed, and the stimuli to which they responded.

The extent to which the introduction of higher background sound levels masks the ability of marine animals to detect and interpret sound signals from their environment is largely unknown, as is their reaction to man-made sounds. The better the knowledge one has of hearing and auditory behavior in a species, the better one can define its acoustic habitat. It is evident that for many species such detailed knowledge is not yet available. Further, for some species, these data are unlikely to be available in the foreseeable future. Many of the most valuable studies of the hearing abilities of aquatic animals have been carried out in the free field or at specialized facilities designed to provide appropriate acoustic conditions. Thus, studies have been carried out in very specialized tanks (Hawkins and MacLennan 1976; Popper et al. 2007; Halvorsen et al. 2011, 2012) or in mid-water in the sea (e.g., Hawkins and Chapman 1975) where free field conditions exist and sound fields can be mapped. Thus, a prerequisite for studies intended to resolve the issues raised in this report is that they be done under appropriate acoustic conditions, where both sound pressure and particle motion can be monitored.

Experimental facilities are required and should have the following characteristics:

- The characteristics of underwater sounds should be readily controllable, and the magnitudes, direction and spatial characteristics of particle motion and sound pressure should be capable of being manipulated and measured.
- Underwater sounds of high amplitude can be generated.
- Quiet ambient noise conditions can be obtained and different background noise conditions simulated and manipulated.

9.1 Invertebrates

Although there is evidence that a range of invertebrates are sensitive to low frequency sounds it is not yet clear whether any of them are sensitive to sound pressure, or whether they show the same level of sensitivity to sounds as other aquatic organisms like fishes. Moreover, there has been very little work on the significance of hearing for invertebrates: whether these animals communicate with one another by means of sound, or whether they use sound detection to avoid predators or capture prey.

Marine invertebrates are extremely abundant and important to aquatic ecosystems, but our knowledge of their hearing capabilities is relatively poor. We do not know how well many of them can detect sounds. Offutt (1970) claimed to have measured hearing in American lobster to pure tones from 10 to 150 Hz. The animal was especially sensitive to frequencies within the range of 18 to 75 Hz. More recently, Pye and Watson (2004) reported that immature lobsters of both sexes detected sounds in the range 20 to 1,000 Hz, while sexually mature lobsters were said to exhibit two distinct peaks in their acoustic sensitivity at 20 to 300 Hz and 1000 to 5000 Hz.

Although there is a lack of experimental evidence, Pumphrey (1950), Frings and Frings (1967), and others have suggested that many aquatic invertebrates can detect sounds. The sound receptors may be many and varied, but two classes of organ have been suggested as likely candidates. One includes the wide range of statocyst or otocyst organs found in aquatic animals; the second includes the water flow detectors found in marine invertebrates.

Statocysts are found in a wide range of aquatic invertebrates (Janse 1980; Laverack 1981). In these organs, sensory hairs are attached to a mass of sand or calcareous material. Statocysts are undoubtedly stimulated by gravity and by linear accelerations and in many cases serve an equilibrium function (Schöne 1975). However, they are remarkably similar to the otolith organs in fish (though not evolutionarily homologous) and may also serve to detect the particle motions associated with sound or vibration. Essentially, it is suggested that the tissues of the animal move back and forth as a sound passes through, but the dense statolith lags behind, stimulating the sensory cilia. Cohen (1955) has reported that the statocyst in the lobster is especially sensitive to vibrations of the substratum.

Lovell et al. (2005, 2006) reported that the prawn *Palaemon serratus* is capable of detecting low frequency sounds from 100 up to 3,000 Hz. However, there is to date no behavioral evidence of prawns responding to sounds.

Squid, cuttlefish (Sepiida), and the octopus (Octopoda) have complex statocysts (Nixon and Young 2003). Again, because they resemble the otolith organs of fish, it has been suggested that they may also detect sounds (Budelmann 1992). It has also been suggested that the paired statocysts are functionally similar to the vertebrate vestibular system (Williamson 2009). They may detect both linear and angular accelerations, giving the animal information on its spatial orientation and rotational movements. The statocysts may also be involved in hearing. Early reports suggested that squid were attracted to 600 Hz tones (Maniwa 1976) and that common cuttlefish (*Sepia officinalis*) gave startle responses to 180 Hz stimuli (Dijkgraaf 1963). Behavioral conditioning experiments have confirmed that European squid (*Loligo vulgaris*), common octopus (*Octopus vulgaris*) and common cuttlefish can detect particle acceleration stimuli within the range of 1 to 100 Hz, perhaps by using the statocyst organ as an accelerometer (Packard et al. 1990; Kaifu et al. 2008).

Hu et al. (2009) suggested that Bigfish reef squid (*Sepiotheutis lessoniana*) could detect sound pressures using their statocyst organs, but their evidence was weak. More recently Mooney et al. (2010) obtained electrical responses from the statocyst organs of the longfin inshore squid (*Loligo pealeii*) at frequencies between 30 and 500 Hz with lowest evoked potential thresholds between 100 and 200 Hz. The range of responses suggested that the statocyst acted as an accelerometer. It was suggested that squid might detect acoustic particle motion stimuli from predators and prey as well as low-frequency environmental sound signatures that may aid navigation (see also Mooney et al. 2012).

There are some differences between fish otolith organs and invertebrate statocysts. The chitinous sensory hairs in crabs are very much larger than the sensory cilia within fish otolith organs (by at least one order of magnitude), and the attachment and anatomical positioning of the hairs is rather different. Moreover, although decapod statocysts may contain a number of sand grains, these do not resemble the massive calcified otoliths found in most fish ears. It is likely that statocysts are less sensitive than otolith organs to the small particle accelerations associated with propagated sound waves.

Various flow detectors are found in invertebrates. They include sensory cilia, either naked or embedded within a gelatinous cupula, projecting into the water or situated in pits on the body surface, as well as a great variety of other hair-like and fan-like projections from the cuticle, articulated at the base and connected to the dendrites of sensory cells. Most of these are considered to be receivers of water-borne vibration because they are highly sensitive to mechanical deformation and in close contact with the surrounding water. Experiments with decapod crustaceans and other invertebrates have shown a wide range of cuticular hair organs that are sensitive to oscillatory motion of the water (Laverack 1981; Popper et al. 2001).

Many cephalopods have lines of ciliated cells on their head and arms. In the common cuttlefish and the squid *Lolliguncula*, electrophysiological recordings by Budelmann and Bleckmann (1988) have identified these epidermal lines as an invertebrate analogue to the mechanoreceptive lateral lines of fish and aquatic amphibians and thus as another example of convergent evolution between a sophisticated cephalopod and vertebrate sensory system. Stimulation of the epidermal lines with local water displacements generated by a vibrating sphere causes receptor potentials that have many features that are known from lateral line microphonic potentials.

It is likely that the receptors found in invertebrates will be most sensitive to low frequencies (below 100 Hz) and that they are especially stimulated in the close vicinity of a sound source (within the so-called near field, see Section 2) (Mooney et al. 2010, 2012). Whether they respond to low amplitude sounds, at higher frequencies, from distant sources, must remain in doubt in the absence of clear experimental evidence. The thresholds that have been detected for these detectors are much lower than those observed from the otolith organs of fishes and seem to fall short of the sensitivity necessary in a true auditory receptor. No physical structures have yet been discovered in aquatic invertebrates that are stimulated by sound pressure. We must conclude that many invertebrates are sensitive to local water movements and to low frequency particle accelerations generated by sources in their close vicinity. Some invertebrates, including crustaceans, may be especially sensitive to substratum vibrations. A number of aquatic decapod crustaceans produce sounds, and Popper et al. (2001) concluded that many are able to detect substratum vibration at sensitivities sufficient to tell of the proximity of mates, competitors, or predators. However, whether these invertebrates respond to propagated sound waves at a distance from the source remains uncertain.

There is a particular lack of knowledge on the response of plankton and the smaller nekton (free-swimming organisms showing movements that are largely independent of currents and waves) to sounds. Such organisms are present in large numbers in the sea and form important components of marine food chains. Any adverse effects upon the plankton will have effects upon the animals that graze upon them. Shipping routes and oil and gas developments are moving into waters of high biological production, where their impact upon plankton and nekton should be examined.

Questions for Hearing in Invertebrates

- *Which invertebrates can detect sounds? How well can they detect sounds, and over what range of frequencies?*
- *Which organs detect sounds (which are the receptors)?*
- *Are invertebrates responsive to sound pressure or particle motion?*
- *Do high level sounds damage these receptors and/or other tissues?*
- *Can the receptors regenerate if they are damaged?*
- *Are some invertebrates especially sensitive to substrate vibration?*
- *Can invertebrates distinguish between sources at different distances or from different directions?*
- *Can they distinguish between sounds of differing quality?*
- *Does hearing loss occur as a result of exposure to sound?*

9.2 Fishes

The presentation of measured sound stimuli to fish under experimental conditions presents great difficulties. The relationship between sound pressure and particle velocity in an experimental tank is extremely complex, and there is no reliable way of calculating the relative levels of the two quantities (Parvulescu 1964). Both parameters should be measured, but calibrated particle motion detectors are not widely available and this measurement is 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 experiments on the hearing of fish 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.

Because of these difficulties, we have provided audiograms only for a few species of fishes, like the Atlantic cod (Chapman and Hawkins 1973), dab (*Limanda limanda*), plaice (*Pleuronectes platessa*) (Chapman and Sand 1974), Atlantic salmon (Hawkins and Johnstone 1978), goldfish

(*Carassius auratus*), and several elasmobranch species (Casper and Mann 2009), which have had their hearing abilities examined under appropriate acoustic conditions. We are still largely ignorant of the abilities of most fish species to detect sound.

Figure 9–1 provides audiograms, expressed in terms of particle displacement, for two species of flatfish, and for the Atlantic salmon. The flatfishes do not have a swim bladder or other gas bubble that would increase hearing bandwidth and provide sensitivity to sound pressure. All studies on flatfishes, to date, demonstrate that they have a relatively narrow bandwidth of hearing (up to perhaps 300 to 500 Hz), and their sensitivity to sounds at any particular frequency is likely to be poorer than fishes that have a swim bladder (Chapman and Sand 1974; Casper and Mann 2009).

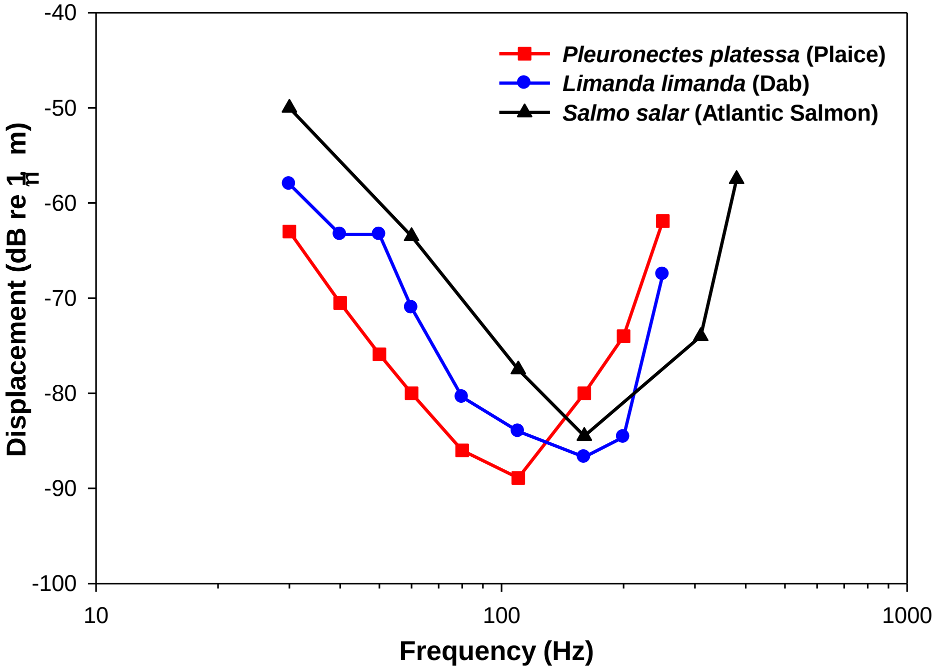

Figure 9–1. Audiograms for plaice (Chapman and Sand 1974), dab (Chapman and Sand 1974), and Atlantic salmon (Hawkins and Johnstone 1978). Acoustic thresholds for all three species were obtained by cardiac conditioning to pure tones against a natural sea noise background.

Some fishes have adaptations that give them sensitivity to sound pressure as well as particle motion. These adaptations are gas bubbles near the ear or swim bladder that functionally affect the ear. One such species is the Atlantic cod, shown in Figure 9–2. At low frequencies (below 110 Hz), hearing in the Atlantic cod is dominated by particle motion, but at higher frequencies the cod is sensitive to sound pressure. Not all species with swim bladders are sensitive to sound pressure. For example, there is substantial evidence that Atlantic salmon, shown in Figure 9–1, is sensitive to particle motion over the whole of its frequency range, even at the infrasonic frequencies below 50 Hz (Hawkins and Johnstone 1978; Knudsen et al. 1992, 1994, 1997).

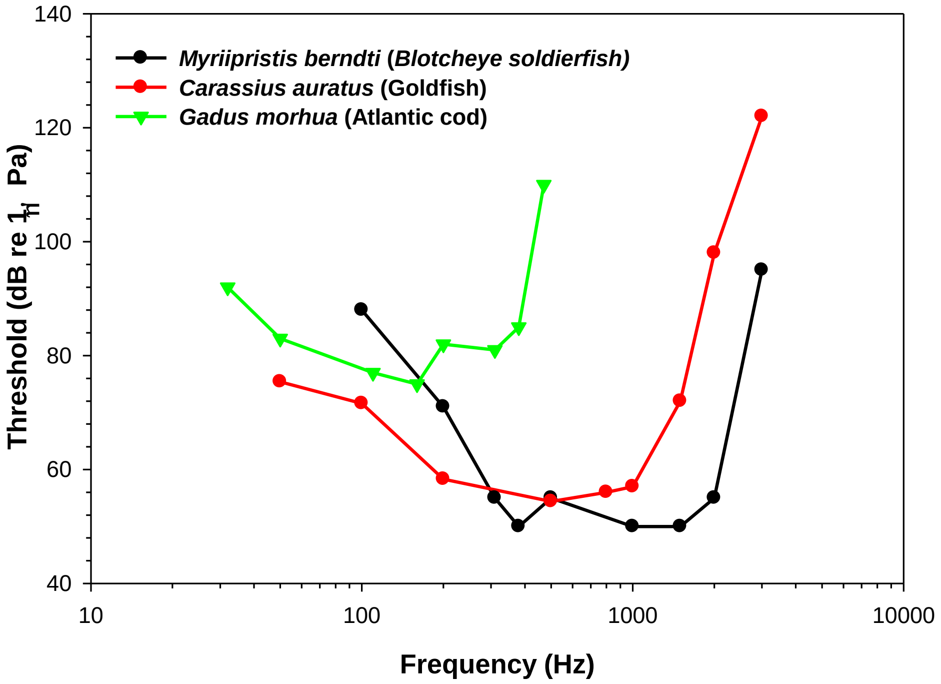

Figure 9–2. Audiogram for blotcheye soldier fish (Coombs and Popper 1979), goldfish (Jacobs and Tavolga 1967), and Atlantic cod (Chapman and Hawkins 1973) . The thresholds for Atlantic cod were obtained by cardiac conditioning to pure tones against a natural sea noise background. Thresholds for the soldier fish and goldfish were obtained using an operant conditioning paradigm in a small tank in a sound shielded room.

Some fishes have special structures mechanically linking the swim bladder, which is located in the abdominal cavity just below the spinal column and kidney, to the ear (e.g., Weberian ossicles in goldfish, catfishes (Siluriformes), and relatives, few of whom are marine) (Weber 1820; Popper et al. 2003; Popper and Fay 2011). In other cases, the swim bladder has extensions that come close to, or may actually contact, portions of the inner ear (e.g., Popper et al. 2003; see Braun and Grande 2008 for review).

In species having a gas bubble or swim bladder, the bubble changes volume in response to fluctuating sound pressures. This produces particle motion at the ears that, in turn, has the potential to cause the sensory epithelium to move relative to the otolith. Fishes with mechanical connections between the swim bladder (or other gas bubble) and ear generally have lower thresholds and wider hearing bandwidths than species without such adaptations. This is because the particle motion is generated much closer to the ear than in species without such connections. The actual level of the signal when it reaches the ear is sufficient to move the otolith and result in sound detection.

Fishes with these kinds of connections include some of the squirrelfishes (Holocentridae) (Coombs and Popper 1979), drums, and croakers (Sciaenidae) (reviewed in Ramcharitar et al. 2006). In addition, there is evidence that similar connections may occur in many deep-sea fishes, including lantern fishes (myctophids) that may use sound, rather than light, to communicate and find mates (Popper 1980; Buran et al. 2005; Deng et al. 2011). Indeed, there is evidence that mechanical connections between the swim bladder (or other gas bubble) and the inner ear has evolved independently many times in fishes, and there is substantial evidence that such enhancements, as the Weberian ossicles, increase the hearing bandwidth and sensitivity of such fishes (e.g., Coombs and Popper 1979; Fay and Popper 1999; Popper et al. 2003; Ladich and Popper 2004).

The clupeiform fishes (herrings, shads, sardines, anchovies, and menhaden) have a unique and complex linkage between gas-filled spaces in the head and one region of the ear, the utricle (all other species that have specialized connections have them with another ear region, the saccule) (O'Connell 1955; Popper and Platt 1979). Enger (1967) obtained a tentative audiogram for Atlantic herring (*Clupea harengus*) in a small tank indicating that the fish was sensitive to pure tones over the range 30 to 1,000 Hz, falling off steeply above 2 kHz (Figure 9–3). AEP studies on the spotlined sardine (*Sardinops melanostictus*) in a shallow tank showed a rather narrower and much less sensitive audiogram (Akamatsu et al. 2003). Other studies suggested that some clupeid fishes, including shads and menhaden, can detect ultrasound (sound with frequencies higher than 100 kHz) (Dunning et al. 1992; Nestler et al. 1992; Ross et al. 1995).

Actual hearing sensitivity was determined for the American shad (*Alosa sapidissima*) by Mann et al. (1997) (Figure 9–3). American shad showed relatively poor sensitivity to frequencies below 1 kHz (although the authors acknowledged that the thresholds may have been masked by noise) but found sensitivity to high level sounds at ultrasonic frequencies, to over 180 kHz (see Figure 9–3). Similarly, it has been shown that the menhaden *Brevoortia* is capable of detecting sound frequencies from 40 kHz to at least 80 kHz (Mann et al. 2001). In contrast, Pacific herring (*Clupea pallasii*) in a shallow tank with immersed sound projectors showed AEP responses up to 5 kHz but never to ultrasonic frequencies (Mann et al. 2005). Responses at frequencies up to several kHz were found in other species of Clupeinae; the bay anchovy (*Anchoa mitchilli*), scaled sardine (*Harengula jaguana*), and the Spanish sardine (*Sardinella aurita*) detected sounds at frequencies up to about 4 kHz (Mann et al. 2001). It seems that within the Clupeidae, only members of the subfamily Alosinae, which include the shads and menhaden, detect ultrasound.

In some of the earlier literature, a distinction was made between hearing generalists and hearing specialists. Some fish like the Atlantic cod do not fit neatly within either category and many of those fishes that are sensitive to particle motion may be specialists of a different kind. This classification has recently been rejected since it does not take into account fishes like the Atlantic cod, and because of the realization that there is likely to be a gradation in the extent that fish use particle motion and pressure in sound detection (Popper and Fay 2011).

Most audiograms do not provide results for frequencies below 20 to 30 Hz because of the difficulty in obtaining sound projectors that produce undistorted sounds at very low frequencies. Sand and Karlsen (1986), working with a specially designed tank, have shown that Atlantic cod are able to detect low frequency linear accelerations, or infrasound, extending below 1 Hz. The threshold values measured as particle acceleration decline (i.e., sensitivity increases) at frequencies below 10 Hz, reaching the lowest value at 0.1 Hz. The authors put forward the hypothesis that fish may utilize information about the infrasound pattern in the sea for orientation during migration, although behavioral responses have only been shown when the source is within a few body lengths of the fish. There is also a possibility that infrasound is being detected by the lateral line as well as the inner ear.

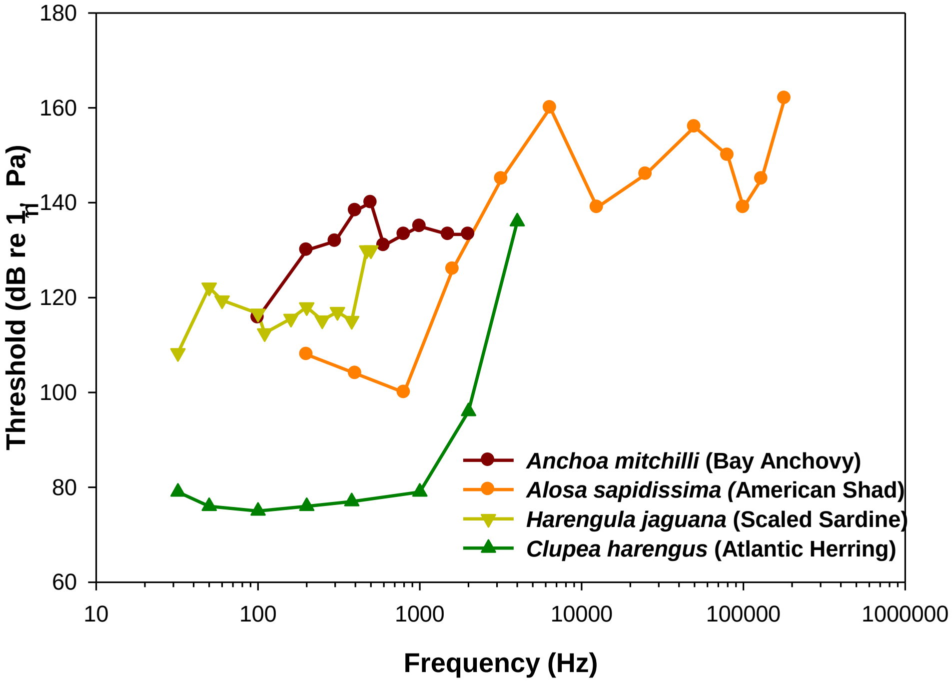

Figure 9–3. Audiograms for clupeid fishes. Thresholds for the Atlantic herring (Enger 1967) were determined by monitoring microphonic potentials in the laboratory. Thresholds for American shad (Mann et al. 1997) were obtained using classical conditioning of heart-rate in a quiet tank, whereas thresholds for bay anchovy and scaled sardine (Mann et al. 2001) were obtained using AEP methods, also in a quiet tank.

Knudsen et al. (1992, 1994, 1997) later examined juvenile Atlantic salmon and several species of Pacific salmon and concluded that, close to the source, frequencies in the infrasound range (5 to 10 Hz) were the most efficient for evoking both awareness reactions and avoidance responses. Similar avoidance responses to infrasound were also shown by downstream migrating European eels (*Anguilla Anguilla*) (Sand et al. 2000). More recently, Sand et al. (2008) have suggested that near-field particle motions generated by the moving hull of a ship are mainly in the infrasonic range, and infrasound is particularly potent in evoking directional avoidance responses. Large vessels, in particular, may generate especially extensive particle motion fields.

Within their relatively restricted frequency range some fish are quite sensitive to sounds. Indeed, in the sea the Atlantic cod is often not limited by its absolute sensitivity but by its inability to detect sounds against the background of natural ambient sea noise. Only under the quietest sea conditions do Atlantic cod show absolute thresholds (see glossary in Appendix A) (Chapman and Hawkins 1973). Any increase in the level of ambient sea noise, either naturally as a result of an increase in wind and waves or precipitation, or from the passage of a ship, results in an increase in the auditory threshold (a decline in sensitivity). The ability of some fish to detect biologically important signals (e.g., sounds from a predator or the sounds made by conspecifics) will be affected not just by variations in natural ambient noise but will also be masked by any extraneous sounds that raise the level of background noise. It should be noted that many of the differences in sensitivity seen in the audiograms of different species might result from variable noise levels prevailing under experimental conditions.

The hearing abilities of many of the extant species (and entire taxa) of fishes remain completely uninvestigated. Priority species for examination include the herring (to be repeated), the mackerel, skates and rays, and jawless fishes like the lamprey.[23] Behavioral audiograms are required for these species under natural and varied noise conditions. Information is especially lacking on the hearing abilities of larval fishes and on the changes that may take place with growth and age. The information requirements are considered below under a number of headings.

9.3 Anatomy and Mechanics of Sound Detectors in Fish

There is extraordinary diversity in the structure of the ears of fishes, especially for the regions of the ear most associated with sound detection—the saccule, lagena, and utricle (Weber 1820;[24] Retzius 1881; Popper et al. 2003; Popper and Schilt 2008). This diversity is well documented in an anatomical study by Retzius (1881), which shows that the size and shapes of these end organs (called otolith organs) varies widely between species. This variation extends to the internal structures of the end organs including the sensory epithelia and the otoliths themselves (Popper and Schilt 2008).

Of considerable interest is how the inner ear functions in sound detection. The excitation of the sensory hair cells on the otolithic end organs is related to relative motion between the epithelia and the very dense overlying otoliths. There are few recent experimental data to show the nature of this movement, though a number of studies, some using models, suggest that the motions are relatively complex, with different patterns related to the frequency and direction of the incident sound (reviewed by Sand and Bleckmann 2008; Rogers and Zeddies 2008). Factors that certainly affect otolith movement include the pathway by which the sound gets to the ear—directly as particle motion or indirectly as particle motion generated by sound pressure acting on the swim bladder.

There are still numerous questions to be asked about the ears of fishes and how they respond to sound. It is very likely that the answers will be complicated by the extraordinary interspecific variation in ear structure (see Retzius 1881; Popper and Schilt 2008) since it is likely that this variation reflects, at least to some degree, different response patterns in different species. However, it is also possible that the differences are not significant in terms of hearing by fishes since it is possible that the variation reflects different experiments or evolutionary approaches to sound processing by the ear and each leads to the same ultimate result. Still, without far more

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[23] There is no evidence to suggest whether lamprey and hagfish can hear or not. Both groups have ears that resemble the ears of other vertebrates (e.g., Popper and Hoxter 1987), but there are sufficient differences in structure that need substantial testing before it is even clear if these species hear sounds and then use sounds to glean information about their environment.

[24] Images from Weber can be seen at http://popperlab.umd.edu/background/index.htm.

data on aspects of ear function such as the movement patterns of the otoliths, the importance of the membrane between the sensory epithelium and the otolith, the role of ciliary bundles on the hair cells of different lengths, and numerous other questions, it will not be possible to fully understand the biomechanics of fish ears.

These questions are not critical for understanding the effects of man-made sounds. What is much more important is the degree of damage that might be done to the auditory system by man-made sounds (considered in Section 10).

9.4 Additional Questions on Fish Hearing: Fish Functional Hearing Groups

Understanding effects of sounds on fishes is crucial to evaluating the impact of sound-generating activities by the energy industry. Thus, in addition the important general questions mentioned above, there is also a wide range of additional questions on fish hearing and use of sound that need to be considered, though not all have the same importance, nor do all give the same broad amount of information.

One of the critical issues to consider is the importance of the diversity in the morphology, hearing physiology, and behavior of fishes. However, further study of even a small portion of the 32,000 known species of fish, or even a substantial portion of those in the areas of interest, is unlikely in the foreseeable future. Thus, it will be important to ask whether sufficient data can be obtained from a smaller number of species that represent various characteristics found in fishes and used to make highly informed decisions about other species. A number of species have already shown great promise as experimental subjects in hearing and sound exposure experiments, but they do not represent a wide and diverse enough range of fishes. Thus, to obtain the kind(s) of data needed, it is probably best to attempt to delineate the main morphological characteristics of fishes from a range of different habitats.

Specifically, data are needed for both physostomous and physoclistous species (see glossary in Appendix A), species living at different depths, species that have different relationships between gas bubbles and the inner ear, and species with and without swim bladders. Sharks and rays must be included in future studies.

Questions for Hearing by Fishes

- *Can fishes be sorted into different functional hearing groups? And, if so, what are the main groups?*
- *Can the hearing characteristics of fish within these groups be described adequately by generalized weighting functions?*
- *What data are needed to generate these weighting functions?*
- *Are the weighting functions for hearing the same as those for injury?*

9.5 Additional Questions on Fish Hearing: Hearing Characteristics of Fishes

Once fishes have been selected for studies, it is imperative to have far more extensive data on hearing capabilities. However, as discussed earlier, data must be obtained in highly defined and understood sound fields, and it may be best to do such studies under free field conditions where boundaries do not alter the sound (e.g., Parvulescu 1964, 1967). And, most importantly, the data needed should represent actual hearing capabilities of fish rather than the kinds of data obtained with AEP where data only reflect what goes on in the ear and ignore the critical processing of sound that goes on in the brain of any animal before the animal makes a response to indicate that it heard, or did not hear, a sound. Thus, such behavioral audiograms are required for a wider range of animals, obtained under quiet conditions, where the ratio of particle motion to sound pressure can be varied and measured.

Additional Questions about Hearing by Fishes

- *What is the frequency range over which pressure and particle motion is detected by different species?*
- *What are the behaviorally determined thresholds to sound pressure and particle velocity?*
- *What are the AEP thresholds to sound pressure and particle velocity?*
- *How do AEP thresholds differ from behaviorally determined thresholds?*
- *What are the thresholds and audiograms for different life stages?*
- *What are the thresholds to biologically relevant sound stimuli?*
- *How sensitive are fish to substrate vibrations?*
- *What is the degree of masking of biologically relevant signals by sea noise and anthropogenic sounds?*
- *What is the extent to which directional sensitivity reduces the effects of masking?*
- *How do fish discriminate between sounds of differing amplitude and frequency?*
- *What is their directional sensitivity to sounds?*

9.6 Sound Source Perception: Auditory Scene Analysis

Sound is a very critical source of environmental information for most vertebrates (e.g., Fay and Popper 2000). While sound is often thought of in terms of communication (e.g., speech), perhaps the most important use of sound is to learn about the surrounding environment. Indeed, humans and all other vertebrates have auditory systems that listen to the acoustic scene and can, from this, learn a great deal about the environment and things in it (Bregman 1990; Bass and Ladich 2008). Whereas the visual scene is restricted by the field of view of the eyes and light level, the acoustic scene provides a three-dimensional, long distance sense that works under most all environmental conditions. It is therefore likely that hearing evolved for detection of the acoustic scene (Fay and Popper 2000), and that fish use sound to learn about their general environment, the presence of predators and prey, as well as for acoustic communication in many species.

Sound is important for fish survival, and anything that significantly impedes the ability of fish to detect a biologically relevant sound could lessen survival.

A fundamental concern with respect to man-made sound, therefore, is whether it interferes with the ability of fishes to detect the acoustic scene, and signals of significance to the animal. Such interference can lead to an inability to find mates, food, or detect the presence of predators until it is too late, and survival of individuals and/or populations are therefore at stake.

In essence, the interference with detection of the acoustic scene is a consequence of noise interfering with the ability of a fish to hear a biologically relevant sound. This is generally referred to as acoustic masking, and it can be thought of in terms of the well-known cocktail party effect whereby an individual in a room can hear the person they are speaking with, but the ability to understand the sounds decreases as background noise at the cocktail party increases—generally as a result of other speakers or the presence of music (see Section 10.6).

Since man-made sound has the potential to interfere with hearing in fish, it is necessary to better understand its effects on behavior.

Questions in Relation to the Effects of Sound on Fish Behavior

- *Do fishes use sound other than for communication and sound production (e.g., for navigation or finding prey)? Do they make use of the acoustic scene?*
- *How does fish behavior change in the presence of maskers that interfere with detection of the acoustic scene, and particularly those produced by man-made sounds?*
- *Do intermittent sounds, such as those produced by seismic exploration or pile driving, interfere with fish behavior and with the acoustic scene?*
- *Do sharks use the acoustic scene and, if so, how and can this be masked?*

10 Effects of Sound on Fish and Invertebrates

This section considers effects of man-made sound on fishes and invertebrates. Since almost nothing is known about effects of man-made sound on invertebrates, only a very limited number of studies can be considered here. There are even fewer data on the effects of man-made sound on elasmobranch fishes, but, as pointed out by Casper et al. (2012), at least some extrapolation may be possible for these cartilaginous fishes from knowing about the bony fishes. Since sharks and rays are a critical part of the ecosystem throughout the oceans of the world, it will be of great importance to understand effects of man-made sounds on at least some of these species.

10.1 Effects of Sounds on Invertebrates

One question that is very hard to deal with is the potential effect of man-made sounds on invertebrates. There are almost no data on hearing by invertebrates, and the few suggestions of hearing indicates that it is for low frequencies and only to the particle motion component of the sound field (e.g., Mooney et al. 2010, 2012). There are no data that indicate whether masking occurs in invertebrates or to suggest whether man-made sounds would have any impact on invertebrate behavior. The one available study, on 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-Filho et al. 2005).

There are also no substantive data on whether high sound levels from pile driving would have physiological effects on invertebrates. The only potentially relevant data are from a study on the effects of seismic exploration on snow crabs on the east coast of Canada (Boudreau et al. 2009). The preponderance of evidence from this study showed no short or long term effects of seismic exposure in adult or juvenile animals or on eggs.

Studies by (1982) and Regnault and Lagardere (1983) demonstrated the effects of ambient noise (20 to 1,000 Hz) on the growth, reproduction, and metabolic level of shrimp. Results showed increased metabolic rates and decreased food uptake from exposure to noise leading to delayed growth and decreased reproduction in association with typical laboratory noise conditions compared to acoustically isolated tanks.

See Section 10.12.1 for a discussion of potential effects of seismic airguns on invertebrates.

Some Critical Questions in Relation to the Effects of Sounds on Invertebrates

- *Which of the key invertebrate species in the regions of interest detect and use sound in behavior?*
- *How might man-made sound alter the behavior of these invertebrates?*
- *What are potential physiological effects of man-made sound on invertebrates, including those that may not hear sounds?*

10.2 Effects of Sounds on Sharks and Rays

There have been no studies concerning how man-made sounds might affect elasmobranchs, either behaviorally or physiologically. However, these species have well-developed ears and there is substantial evidence that they are able to detect and respond to sound, and that sound plays a major role in their lives (reviewed in Myrberg 1978, 1990, 2001; Casper and Mann 2009; Casper et al. 2012). Studies of hearing show that elasmobranchs detect sounds from below 50 Hz to over 500 Hz even though they have no swim bladder or other gas bubble associated with the ear. Since they have no internal gas chambers, the likelihood of physiological effects from other than the most intense sounds is substantially lower than for fishes with gas bubbles, but there are likely to be behavioral effects associated with masking and, perhaps at high chronic sound levels, Temporary Threshold Shift (TTS).

Some Critical Questions on the Effects of Sound on Sharks and Rays

- *How do elasmobranchs respond to the presence of man-made sound at different levels?*
- *Is behavior altered when the acoustic scene is masked?*
- *Do high intensity sounds have any physiological effects on elasmobranchs?*

10.3 Fish Behavior in the Presence of Man-Made Noise

Perhaps the most important concern is how man-made sounds alter the general behavior of fishes. It is likely that fishes will respond behaviorally to man-made sounds at lower sound levels than would result in physiological effects. Thus, fish will show behavioral responses to sounds at much greater distances from the source than those which will result in physical injury. Changes in behavior could have a population level effect such as keeping fish from migratory routes (e.g., salmon or American shad). Issues not only involve detection but also questions of habituation and how fish, in general, respond to a fright stimulus.

There are very few studies on the behavior of wild (unrestrained) fishes, and these have been only on a few species and the data are often contradictory. This includes not only immediate effects on fish that are close to the source but also effects on fish that are further from the source.

Several studies have demonstrated that man-made sounds may affect the behavior of at least a few species of fish. Engås et al. (1996) and Engås and Løkkeborg (2002) examined movement of fish during and after a seismic airgun study although they were not able to actually observe the behavior of fish per se. Instead, they measured catch rate of haddock and Atlantic cod as an indicator of fish behavior. These investigators found that there was a significant decline in catch rate of haddock and Atlantic cod that lasted for several days after termination of airgun use. Catch rate subsequently returned to normal. The conclusion reached by the investigators was that the decline in catch rate resulted from the fish moving away from the fishing site as a result of the airgun sounds.

More recent work (Slotte et al. 2004) showed parallel results for several additional pelagic species including blue whiting (*Micromesistius poutassou*) and Norwegian spring-spawning herring. Slotte et al. used sonar to observe the behavior of fish schools. They reported that fishes in the area of the airguns appeared to swim to greater depths after airgun exposure. Moreover, the abundance of animals 30 to 50 km away from the ensonification increased, suggesting that migrating fish would not enter the zone of seismic activity. It should be pointed out that the results of these studies have been disputed by Gausland (2003) who, in a non-peer-reviewed study, suggested that catch decline was from factors other than exposure to airguns and that the data were not statistically different than the normal variation in catch rates over several seasons.

Most recently, Løkkeborg et al. (2012) have reported similar experiments to those described above, and obtained data that could be interpreted to suggest that some sounds actually result in an increase in fish catch.

In similar studies, Skalski et al. (1992) showed a 52% decrease in rockfish (*Sebastes* sp.) catch when the area of catch was exposed to a single airgun emission at 186 to 191 dB re 1 μPa (mean peak level) (see also Pearson et al. 1987, 1992). They also demonstrated that fishes would show a startle response to sounds as low as 160 dB, but this level of sound did not appear to elicit a decline in catch.

Wardle et al. (2001) used underwater video and an acoustic tracking system to examine the behavior of fish on a reef in response to emissions from a single seismic airgun, They observed startle responses and some changes in the movement patterns of fish. Startle responses have been observed in several fish species exposed to airgun sounds (Hassel et al. 2004; Pearson et al. 1992; Santulli et al. 1999)

In an evaluation of the behavior of free-swimming fishes to noise from seismic airguns, fish movement (e.g., swimming direction or speed) was observed in the Mackenzie River (Northwest Territories, Canada) using sonar. Fishes did not exhibit a noticeable response even when sound exposure levels (single discharge) were on the order of 175 dB re 1 µPa^2·s and peak levels of over 200 dB re 1 µPa (Jorgenson and Gyselman 2009; Cott et al. 2012).

Culik et al. (2001) and Gearin et al. (2000) studied how noise may affect fish behavior by looking at the effects of mid-frequency sound produced by acoustic devices designed to deter marine mammals from gillnet fisheries. Gearin et al. (2000) studied responses of adult sockeye salmon (*Oncorhynchus nerka*) and sturgeon to pinger sounds. They found that fish did not exhibit any reaction or behavior change to the onset of the sounds of pingers that produced broadband energy with peaks at 2 kHz or 20 kHz. This demonstrated that the alarm was either inaudible to the salmon and sturgeon or that neither species was disturbed by the mid-frequency sound (Gearin et al. 2000). Based on hearing threshold data (see Figure 9–2), it is highly likely that the salmonids did not hear the sounds.

Culik et al. (2001) did a very limited number of experiments to determine catch rate of Atlantic herring in the presence of pingers producing sounds that overlapped the frequency range of hearing of this species (2.7 kHz to over 160 kHz).[25] They found no change in catch rate in gill nets with or without the higher frequency (> 20 kHz) sounds present, although there was an *increase* in catch rate with the signals from 2.7 to 19 kHz (a different source than the higher frequency source). The results could mean that the fish did not pay attention to the higher frequency sound, or that they did not hear it, but that lower frequency sounds may be attractive to fish. At the same time, it should be noted that there were no behavioral observations on the fish, and so how the fish actually responded when they detected the sound is not known.

Questions in Relation to the Effects of Sound on Fish Behavior

- *Are migratory patterns, pathways, and schedules altered?*
- *Is feeding and/or reproductive behavior disrupted?*
- *Is access impaired to essential habitat for feeding, reproduction, concealment, territoriality, communication, or other life processes?*
- *Is there masking of sounds involved in courtship, predator avoidance, prey capture, navigation, etc.?*
- *Is there inhibition of vocal behavior?*
- *Can man-made sources keep fish from feeding and/or reproductive sites, thereby affecting population survival?*

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[25] Two different devices were used: one with a range of 2.7 to 19 kHz and another with a range of 20 to 160 kHz.

- *Will fish approaching migratory routes or feeding/reproductive sites wait for some time and then continue on when sounds stop (or is there a gap in sound production), thereby not being affected in the long term?*
- *Do fishes habituate to man-made sounds so that behavior is not altered?*
- *Is it possible to predict the levels of man-made sounds that will alter behavior based on knowing ambient and man-made sound levels and hearing thresholds, and predicting detection of such sounds?*
- *What is the behavior of fish schools in the presence of sound sources?*
- *Are measures associated with only a limited time of day for use of sound sources suitable ways of mitigation for broad behavioral effects?*
- *What are the long-term effects of low but detectable, man-made sound sources on physiology and resultant stress (see Section 10.9)?*

A number of questions relating to the masking of sounds are presented in Section 10.6.

Some changes in behavior may have major effects upon fish populations, reducing their feeding rate and growth rate, preventing their reaching spawning areas at the appropriate time, or interfering with reproductive success. Changes in behavior may also affect fisheries by impairing the ability of fishers to catch fish (see Section 10.5).

It is not likely that a single threshold for onset of a behavioral response will be found because behavior is so varied between and within species, including between fishes of different ages and sizes, and the motivation of the fish exposed to man-made sound sources will also vary. Existing data on behavioral responses for many species do not provide clear dose/response curves. Instead, studies should focus on how animals respond to intense sounds in the short and long term and whether commercially important species show major behavioral changes during or after exposure to sound.

A wide range of issues must be considered when planning studies of behavioral responses to sound. Most importantly, the behavioral responses of wild animals to sound will vary widely by factors including, but not limited to, species, size and age class within a species, animal motivation, and the environment. Thus, analysis of behavior becomes very complex.

One of the fundamental truths about behavioral effects is that experiments on animals held in tanks and even large enclosures are highly likely to yield equivocal results. Captive animals do not show the wide range of behavior observed in wild animals; they tend to behave differently when enclosed than when they are unrestricted, even when the enclosure is very large (Sarà et al. 2007; Mueller-Blenkle et al. 2010; Thomsen et al. 2012). They may also be damaged during capture, or their behavior may be affected by the circumstances under which they were reared. Accordingly, to understand the behavior of animals in response to sounds, the responses must be seen in the context of changes to the natural behavior, which varies from species to species, with age, and with habitat.

Studying behavior in the field is generally very difficult and expensive, and the results are often difficult to interpret (e.g., compare Engås et al. 1996 with Løkkeborg et al. 2012). The observations are often made indirectly with sonar or other techniques that cannot discriminate between species or examine details of individual behavior. While some equipment may provide more detailed data (e.g., video or the Dual-Frequency Identification Sonar DIDSON, a high definition imaging sonar that obtains near-video quality images), their range is often too small to show the response of fish over large bodies of water.

Those fish showing more extensive movements will require the development of more sophisticated tracking and sonar techniques. The overall aim must be to study the natural behavior patterns of fishes—to undertake long-term studies of the animals in their natural habitat aimed at describing their normal activities. Then, the response of these animals to sounds can be examined in their proper context, and in terms of their impact upon the lives of the animals. Before, during, and after studies may have particular relevance for examining the effect of new developments in the aquatic environment (for example, in evaluating the impact of installing offshore wind turbines or wet renewables).

For behavior studies, carefully controlled tests of the relationship between responsiveness and sound level—a dose/response curve—are often lacking. In addition to investigating the context of responsiveness to sound, including the state of the animal, it is important to investigate others factors, including social behavior, which might affect the response.

A particularly critical issue is how sound exposure affects behavior and ultimately survival. Since behavior is species-specific, it will be difficult to generalize from one species to another. For example, the behavioral effects of sound exposure on a schooling pelagic species, such as herring, might be entirely different than on a territorial coral reef species, such as damselfish. Pelagic species may avoid sound exposure by swimming away from the source (although, there is currently no evidence for this for any species). In the case of the highly territorial damselfish, the sound exposure is likely to result in the fish retreating into its territory, even if that results in extended sound exposure. Just as extrapolation from species to species is not appropriate, extrapolation from population to population is problematic. Behavioral effects will be specific to the species and the habitat, and even time of year. For instance, a study on the impact of seismic surveys on cod off of Nova Scotia will not necessarily be informative on the response of Atlantic cod in the North Sea to seismic surveys. Fish of different sizes (ages) within a single species may show differences in behavior.

Other Questions on the Effects of Sound on Behavior and Survival

- *Which aspects of the sound source are responsible for behavioral response (i.e., exposure level, peak pressure, frequency content, etc.)?*
- *What behavioral responses occur when animals are exposed to sound sources?*
- *Do sounds displace animals from favored habitats? Are the responses species-specific or do they depend on the prevailing environmental conditions?*
- *Do long-term industrial operations have an impact on animal residency? If so, which species are affected and to what extent?*

- *What is the impact of masking on animal behavior?*
- *Do animals habituate to repeated sound exposure, so that they no longer respond?*
- *Which species might be representative of other species and worthy of study in the area of concern?*

10.4 Effects on Populations

Ultimately, it is often the effects upon populations of animals that will determine the outcome of a risk assessment. The Population Consequences of Acoustic Disturbance model (PCAD model) defines a rationale for developing assessments of the significance of sub-lethal effects and for identifying the most important gaps in our knowledge (NRC 2005). The greatest problem is to attempt to define the functional relationships between behavioral or physiological responses to sound and the subsequent effects upon populations. It will, however, be a long time before all the information is acquired to run such models.

There are also important caveats when one looks at potential population level impacts. Stock assessments often have large inherent statistical variability and uncertainty making it difficult to detect true changes in the population. Further developments of methodologies for assessing stocks, perhaps using a combination of visual and acoustic techniques, are required. In addition, natural variability might confound any observation of man-made impacts on populations.

10.5 Effects on Fish Catches

As discussed in Section 10.3, there is evidence that man-made sound could have an impact on fish catches. Indeed, catch statistics may provide insight on behavior in response to man-made noise at relatively low cost. During seismic surveys in the Barents Sea, commercial trawl and longline catches of Atlantic cod and haddock have been shown to fall by as much as 50% to 80% (Engås et al. 1996; Løkkeborg and Soldal 1993). Reductions in Catch Per Unit Effort (CPUE) were observed for both types of fishing gear. Catch reductions of similar magnitude (52 %) have also been demonstrated in the hook-and-line fishery for rockfish on the California coast (Skalski et al. 1992). In contrast, catches by other methods (gill nets) have shown an increase during exposure to seismic sound (Løkkeborg et al. 2012). It is evident that both gear- and species-specific effects may occur. The effectiveness of different fishing gear depends on different patterns of fish behavior. Fish catches may fall because of behavioral changes affecting the vulnerability of fish to capture, not just because fish have left an area.

There are very few studies of the effects of seismic sounds on catches of invertebrates. Christian et al. (2003) examined changes in CPUE for snow crab caught in traps and before, during, and after exposure to an array of airguns. It was concluded that there was no detectable response in terms of the trap CPUE.

The value of catch statistics in terms of investigating short-term effects is unknown, but there may be potential for using catch statistics for examining long-term effects on stocks, species, etc. To maximize the potential gain of understanding of long-term effects through catch statistics, statistical models such as General Linear Models (GLM) have been proposed because they take into account the appropriate environmental variables inherent in the system. It may also be necessary to consider catches from a range of fishing gear for the reasons discussed above. There has been concern about how the noise or natural variability in the system may be greater than any seismic impact, which points to a critical need for baseline information in any area. There is a need to understand the overall acoustic environment (soundscape) and its natural variability. Without this knowledge it becomes impossible to provide an accurate context of potential sound impacts because there is a lack of knowledge of the variability the fish encounters on a daily and seasonal basis. Changes in commercial catches are not necessarily a good indicator of population changes because so many different variables can affect them including ocean climate, regulatory measures applied to the fishery, discarding of fish, and misreporting by fishers. Catch statistics need to be interpreted in terms of changes to the entire ecosystem (biological and acoustic). This requires a team of people with different expertise in catch statistics, acoustics, sound propagation, and behavior.

10.6 Effects in Terms of Masking

There is always a background level of sound in the sea, and these normal background (ambient) sounds will have an impact upon the lowest sound levels that an animal (fish) 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. Masking essentially refers to an increase in the threshold for detection or discrimination of one sound in the presence of another. In effect, the masker interferes with the detection of the signal by increasing the threshold for its detection. The degree of masking is the amount that the threshold of hearing for the signal is raised by the presence of the masker (see Fay and Megela-Simmons 1999 for a complete review of masking in fish).

There are several levels of masking, as discussed in Section 7, that depend on the level of the masker and the sound of biological relevance to the receiving animal. We can also think of masking as Energetic or Informational, both of which can have an impact on the behavior of the listener:

- **Energetic masking** occurs when the signal is not detected in the presence of a masker. An example of energetic masking would take place in a train station where the sound from an oncoming train makes it impossible to hear the sounds from the station announcer. In this case, the masking sound from the train raises the threshold of detection for the signal to a point where it is not even detected by the listener.
- **Informational masking** is where the signal is detectable by the listener, but the presence of the masker makes it hard to understand the signal (Clark et al. 2009; Dooling et al. 2009), with the difficulty in understanding the signal dependent on the relative levels of signal and masker (see Section 7).

The same masker can result in either informational or energetic masking, depending on the sound level of the masker. In terms of a man-made source, if the source is sufficiently far from a fish, hearing may not be interfered with at all. If the fish is closer to the man-made source (or the source gets louder), the fish may first show informational masking where it cannot make out the content of a signal, even if the fish knows the signal is present, although the degree of interference with signal content will depend on the levels of the masker and the sound of interest. Finally, a very loud man-made sound might cause energetic masking and the signal is no longer detected. Communication gets more difficult as background sounds increase for all vertebrates that have been studied, including fish and amphibians (see discussion in Fay and Megela-Simmons 1999), birds (e.g., Dooling et al. 2009), and marine mammals (e.g., Clark et al. 2009).

The bottom line is that to be detected, and to potentially elicit a behavioral change, the sound of interest must be detectable within the background noise. In general, this means that the sound of interest has to be higher in level than ambient noise (or perhaps at a substantially different frequency) for it to be detectable (e.g., Fay and Megela-Simmons 1999).

There are important caveats as to whether one sound will mask another. For most vertebrates the greatest amount of masking occurs when the masker is of a similar frequency range to the signal (see Clark et al. 2009 and Dooling et al. 2009 for summaries of this topic). Thus, a 500-Hz signal is most heavily masked by a 500-Hz sound or by a signal that is on either side of 500 Hz. Much less masking of the 500-Hz signal will occur if the masker is 1,000 Hz and even less if the masker is 2,000 Hz. In other words, the bandwidth of the masker, and the energy it has in the same frequency range as the signal of interest, is critical in determining the amount of masking that will occur.

For example, if a sound relevant to a fish is at 600 Hz and the threshold in a totally quiet environment for that frequency is 10 dB, the presence of a 20-dB masker at the same frequency would result in the hearing threshold of the fish being raised to 30 dB or higher. However, if the masker is at 1,500 Hz at the same sound level, there may only be a few dB increase in the hearing threshold for the signal. The degree of masking depends on the frequency difference between the stimulus and masker and their relative levels.

Investigations of hearing in many vertebrate groups, including fishes, have demonstrated that to detect a signal when it is being masked by ambient noise, the signal has to be a certain level above ambient (Fay 1988). In other words, the likelihood of a fish detecting a signal depends on its ability to separate the signal from background noise (the difference in level between the masker and the signal is often referred to as the signal-to-noise ratio).

Realistic masking experiments are required using natural sounds of interest to fish. The maskers to be used should include sound from anthropogenic sources, including both continuous sound and interrupted sound in different temporal patterns and at different amplitudes. A better understanding is needed of the effects of masking by anthropogenic sources in different fishes. Experiments should also be done to evaluate the longer-term consequences of masking for fish behavior and survival.

Masking Questions

- *How does masking affect communication in sound producing fishes (and invertebrates), and are there population level consequences from masking?*
- *Are models of masking from other systems, such as birds, applicable to predict the level of masking and detection of anthropogenic sources in fishes?*
- *At what levels above detection thresholds (masked thresholds) do fishes show responses to man-made sources?*

- *How is the detectability of temporal and other patterns that allow fishes to identify and act upon sounds affected by increased levels of both natural and man-made sound?*
- *How are discrimination and recognition of sounds affected in the presence of noise?*
- *How do periodic and intermittent sounds affect masking?*
- *What are the biologically relevant sounds, other than communication sounds, that might be masked?*

10.7 Auditory Threshold Shift

Effects on hearing are generally classified as permanent or temporary. Permanent Threshold Shift (PTS) is a permanent loss of hearing and may be a consequence of the death of the sensory hair cells of the auditory epithelia of the ear. To date, there is no evidence that PTS resulting from intense sound occurs in fish, and it is considered unlikely since fish are able to repair or replace sensory hair cells that have been lost or damaged (e.g., Lombarte et al. 1993; Smith et al. 2006). Temporary Threshold Shift (TTS) is a transient reduction in hearing sensitivity caused by exposure to intense sound.

TTS and masking are temporary hearing impairments of variable duration and magnitude. After termination of a sound causing TTS, normal hearing ability returns over a period that may range from minutes to days, depending on many factors, including the intensity and duration of exposure (e.g., Popper and Clarke 1976; Scholick and Yan 2001, 2002; Amoser et al. 2004; Smith et al. 2004a, 2004b, 2006; Popper et al. 2005, 2007). TTS itself is not considered to be an injury (Richardson et al. 1995; Smith et al. 2006; Southall et al. 2007), although during a period of TTS, animals may be at some risk to survival in terms of communication, detecting predators or prey, and assessing their environment. The effects and significance of various levels of TTS on free-living fishes have not been examined.

TTS has been demonstrated in a range of fish species (e.g., Popper and Clarke 1976; Scholick and Yan 2001, 2002; Amoser et al. 2004; Smith et al. 2004a, 2004b, 2006; Popper et al. 2005, 2007) to a diverse array of sounds. However, in all cases TTS was only found after multiple exposures to very intense sounds (e.g., well over 190 dB re 1 µPa rms) or long-term exposure (e.g., tens of minutes or hours) to somewhat less intense sounds. Even when one signal source caused TTS in some fish or some species, it did not occur in other specimens or other species (e.g., Popper et al. 2005, 2007; Hastings et al. 2008; Hastings and Miksis-Olds 2012). In most cases, normal hearing returns within a few hours to several days. There is also evidence that, given the same type and duration of sound exposure, a much louder sound will be required to produce TTS in fish that do not hear well (e.g., striped bass [*Morone saxatilis*], sturgeon, and flatfish) compared to fish that do hear well (e.g., catfish and goldfish) (Smith et al. 2004a, 2004b).

Current thinking is that since TTS arises from prolonged exposure to sound (though this is not always so), it is not likely to be of great significance for fish that pass by a source (or where the source moves past the fish—e.g., Popper et al. 2007) since the duration of exposure would be very short. Far greater concern is that when there is chronic noise exposure—where fish are in an area where there is a long-term increase in sound level, there may be masking, and in addition the ability of fish to hear may also be impaired (e.g., Scholick and Yan 2001, 2002; Smith et al. 2004a, b, 2006).

While data are limited, it appears that long-term exposure to moderate increases in man-made sound may not have any impact on hearing capabilities in fishes that do not have specializations that enhance their hearing capabilities (e.g., Wysocki et al. 2007).

Questions on TTS Resulting from Sound Exposure

- *Is TTS an important consideration in examining the effects of man-made sounds? What level of hearing loss has significant implications for behavior?*
- *How long does TTS persist after exposure and what is the level of the shift?*
- *What is the best way to measure, present, and interpret TTS? What are the most appropriate metrics?*
- *Do measures of TTS obtained from behavioral experiments differ from those obtained by AEP methods?*
- *How relevant is the intermittency of exposure on hearing loss and recovery (e.g., stops between pile drives)*
- *Are there cumulative and in-combination effects?*
- *Is there full recovery of function after damage (by species)?*
- *Is there ever permanent hair cell loss or PTS after sound exposure?*
- *What is the morphology of TTS (tip link damage, hair cell loss, etc.)?*
- *Does the equivalent of TTS occur in invertebrates that hear?*

Questions on Damage to Sensory Hair Cells from High Sound Levels

- *What is the extent of hair cell loss from various levels and types of sound, and which end organs are affected?*
- *Is there damage or death of the hair cells?*
- *How long does it take for hair cells to die and recover after exposure?*
- *Does a loss of hair cells correlate with hearing loss (i.e., TTS)?*
- *What percentage of hair cell loss is necessary to generate TTS?*
- *What is the time line of recovery from TTS in relation to hair cell regeneration?*
- *Does damage result from sound pressure or particle motion?*
- *What is the trade-off between time and level for damage?*

10.8 Effects on the Lateral Line

The lateral line is a series of sensory hair cells[26] along the body of the fish that detects low frequency sounds and water motion and informs the fish of objects and other animals in its immediate vicinity (Coombs and Montgomery 1999; Sand and Bleckmann 2008; Webb et al. 2008b). The lateral line is critical in schooling behavior, including in feeding for many (Montgomery and Coombs 1996). Thus, short- or long-term damage to the lateral line could have an impact on fish fitness and survival.

There has been only one study on the effects of high intensity man-made sounds on the lateral line and this showed no damage (Hastings et al. 1996). However, this was to pure tones, which are unlike most man-made sounds, and so the relevance to sounds of concern is not direct. In addition, a study by Denton and Gray (1989) suggested that very strong water motions near the lateral line can damage the cupula that overlies the hair cells, and this could result in loss of lateral line function. However, this study used a mechanical and not an acoustic stimulus and it is therefore not clear if the results have any relevance to effects of man-made sounds.

At the same time, since the lateral line is so critical to fishes, and since it is a mechanosensory system that is based on sensory hair cells, there is the potential that man-made sounds might affect it. Investigations of lateral line responses to man-made sounds are thus an imperative.

Some Questions on the Effects of High Sound Levels on the Lateral Line

- *Are there any effects on the lateral line from exposure to man-made sound?*
- *Does the equivalent to TTS occur in the lateral line? And, if so, what is the nature of the damage and recovery?*
- *Are there hydrodynamic effects from wakes and pressure gradients?*
- *If there is damage, do the hair cells and cupulae regenerate and does function return? What is the time line of recovery and regeneration?*
- *Is there full recovery of function after damage?*

10.9 Effects in Terms of Stress and Arousal

Animals may show no overt sign of responding to an environmental stimulus like a chemical contaminant or an increase in noise but may nonetheless show physiological changes (e.g., Slabbekoorn et al. 2010; Kight and Swaddle 2011). They may, for example, show changes in heart rate or breathing rhythm, or the levels of particular hormones in the bloodstream and tissues may change. This response is often termed stress. There is a need for consistency and clarity in describing stress. Stress is often a normal part of life, integral to stimulating and maintaining healthy neuroendocrine responses and immune system activity (homeostasis). Predicting when stress becomes excessive or damaging to the animal remains difficult. Moreover the very acts of capture, handling, and the taking of samples from an animal may induce the stress response that is being monitored.

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[26] These are very similar to the sensory hair cells found in the ears of fishes and all other vertebrates and are considered to be evolutionarily very closely related in genetics, form, and function (Coffin et al. 2004).

Whether the stress response is beneficial or deleterious depends on the magnitude and duration of the response and the condition of the animal exposed to the stressor. Prolonged exposure to stress may result in immune system suppression, reproductive failure, accelerated aging, damage to DNA, and slowed growth (Kight and Swaddle 2011). Various biomarkers may provide indicators of the cascade of effects leading from behavioral changes to alterations in reproduction and survival.

Interpreting single measurements of endocrine responses to a stressor requires a good understanding of the natural variation in hormones associated with the stress response. In free-ranging animals, where blood is difficult or impossible to sample, it may be necessary to examine other tissues such as scales or tissue samples. Although levels of stress hormones such as cortisol in the bloodstream provide relevant information, accumulation in other tissues may provide superior measures of chronic stress because they provide integrated measures of the magnitude and duration of physiological stress responses.

It is clear that fish may experience acute effects to noise, but it is much less certain that it results in long-term chronic effects (e.g., reviewed in Slabbekoorn et al. 2010). It is the chronic effects, though, that may be more significant. The term allostatic load is applied to the physiological consequences of chronic exposure to fluctuating or heightened neural or neuroendocrine response that results from repeated or chronic stress. Normally, the body's stress response, essential for managing acute threats, is essential for adaptation, maintenance of homeostasis, and survival. However, repeated responses may damage the body in the long term (creating the allostatic load). The effects can be measured as chemical imbalances in the autonomic nervous system, central nervous system, neuroendocrine, and immune systems as well as changes in growth rate, perturbations in diurnal rhythms, and changes in behavior. These changes may introduce risks to individual fitness including loss in reproductive capacity. It is important to distinguish between normal or tolerable variations in response to environmental stress from those changes that will have consequences for survival and reproduction. At present, critical examination of these long-term changes in fish as a result of noise exposure is lacking.

Questions for Information Requirements on the Effects of Stress

- *Can appropriate assays for stress be applied without causing stress?*
- *What levels and kinds of noise cause stress in fish, (level, duration, etc.)?*
- *What are the effects (chronic, acute) of stress on fish (level, duration, etc.)?*
- *What are the effects of stress upon fitness and survival?*

10.10 Effects in Terms of Death or Injury

Death and injury are probably the most easily observed and dramatic end-points in terms of responses to sound for fishes (and invertebrates). Strandings are far more likely to be observed for marine mammals, and so are not considered here. There is 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 documentation that explosions will kill nearby fish (e.g., Yelverton et al. 1975; Keevin et al. 1997; Govoni et al. 2003, 2008; also reviewed in Popper and Hastings 2009). However, death has not been documented for exposure to other sound sources including seismic airguns, dredging, vessel noise, etc. Investigations of exposure of fish to very high intensity sonars below 1 kHz and from 2 to 4 kHz showed no mortality (Popper et al. 2007; Halvorsen et al. 2012). It is highly likely that immediate mortality will only occur in response to certain sound sources, perhaps those with the most rapid rise times. Additional information is needed to understand if immediate death is a substantial issue for fish exposed to the sounds used in energy-related work.

Questions for Information Requirements on Sound-Induced Death or Injury

- *Which types and levels of sound may result in mortality?*
- *What physiological effects are the actual causes of mortality?*
- *Which levels of pressure and particle motion cause mortality?*
- *Is there evidence of any latent or indirect (delayed) mortality?*
- *Are fish eggs and larvae more susceptible to death or injury than adults?*

Since the swim bladder and other gas-filled spaces are likely structures to be damaged, or cause damage to nearby structures, there are a number of specific questions related to potential effects of man-made sounds on these structures.

Questions on the Potential Effects of Sound on the Swim Bladder and Other Tissues

- *What are the effects of depth and volume of the swim bladder on the degree of injury to fish from exposure to intense sounds?*
- *What are the effects of sounds with different rise times on the swim bladder and other organs?*
- *How do the responses of physostomous fishes compare with those of physoclistous fishes?*
- *Are there other responses, such as the development of gas bubbles in the blood and other body tissues?*

10.11 Damage to Non-Auditory Tissues

The greater likelihood is that fishes and invertebrates will be injured by high intensity sounds, and that some of these injuries could result in fatalities over the short term or over a longer term if animal fitness is compromised. If an animal is injured it may be more susceptible to infection because of open wounds or compromised immune systems than uninjured animals. In addition, 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.

The actual nature of injuries from exposure to intense sounds is not well understood. With fish injured by explosives the most commonly injured organ is the gas-filled swim bladder (Yelverton et al. 1975; Keevin and Hempen 1997; Keevin et al. 1997). The swim bladder is a gas-filled sac that functions as a hydrostatic organ allowing the fish to control its buoyancy. When pressures oscillate rapidly as they do when an explosive shock wave passes through the fish, the swim bladder will expand and contract rapidly to the point of rupturing. There is evidence that damage to proximate organs, particularly the kidneys (which lie just dorsal to the swim bladder in most species), can occur (Keevin and Hempen 1997).

Investigations using intense low and mid-frequency sonars have shown no tissue damage (Popper et al. 2007; Kane et al. 2010; Halvorsen et al. 2012), and similar results have been found for at least several species of fish after exposure to seismic airguns in a river (Popper et al. 2005; Song et al. 2008).

In contrast, investigations of salmon exposure to barotrauma have demonstrated a wide range of effects (Stephenson et al. 2010). An abbreviated set of these effects were encountered when exposing several different species to high intensity simulated pile driving signals (Halvorsen et al. 2011; Casper et al. pers. comm.; Halvorsen et al. pers. comm.). These effects ranged from a small amount of hemorrhage at the base of fins to severe bleeding of various internal organs near the swim bladder and actual damage to the swim bladder itself. Halvorsen et al. (2011) (see Section 10.12.2) show that there is a clear correlation between the magnitude of the injury and the intensity of the sound exposure. Significantly, Casper et al. (pers. comm.) have demonstrated that fish will recover from many of the less severe injuries, suggesting that a single or small injury is not tantamount to mortality.

Questions about Injury to Non-Auditory Tissues

- *Are there effects upon the tissues and organs of animals, other than the ear (for example to gas volumes or the blood vascular system) from sounds of different levels, spectral characteristics, and/or rise times?*
- *What are the differences in injuries between physostomous and physoclistous fish, and between fish with and without swim bladders?*
- *Are these injuries lethal immediately or over time or is there recovery from injury?*
- *Is it possible to discriminate between injuries that are potentially lethal from those that are not likely to be lethal?*
- *What are the implications for survival during the recovery process? Is fitness compromised?*
- *How long are the recovery periods when fitness is lowered?*

10.12 Effects of Specific Sources

10.12.1 Airguns

Christian et al. (2003) concluded that there were no obvious effects from seismic signals on crab behavior and no significant effects on the health of adult crabs. They recommended that future studies should concentrate on egg and larval stages, which might be more vulnerable. Pearson et al. (1994) had previously found no effects of seismic signals upon crab larvae for exposures as close as 1 m from the array, nor for mean sound pressure as high as 231 dB re 1 μPa. It was concluded that any reduction in zoeal survival as a result of sound exposure was low.

Payne et al. (2007) examined the effects of seismic sounds upon American lobsters. Exposure of lobster to very high as well as low sound levels had no effects in terms of immediate or delayed mortality or damage to mechano sensory systems associated with animal equilibrium and posture. However sub-lethal effects were observed with respect to feeding and serum biochemistry with effects sometimes being observed weeks to months after exposure. A histochemical change was also noted in the hepatopancreata of animals exposed four months previously, which may have been be linked to organ stress.

Andriguetto-Filho et al. (2005) measured bottom trawl catches from a non-selective commercial shrimp fishery comprising the Southern white shrimp (*Litopenaeus schmitti*), the Southern brown shrimp (*Farfantepenaeus subtilis*), and the Atlantic seabob (*Xyphopenaeus kroyeri*) (Decapoda: Penaeidae), before and after the use of an array of four synchronized airguns, with a peak pressure of 196 dB re 1 µPa at 1 m. No significant deleterious impact of seismic prospecting was observed for the studied species.

André et al. (2011) suggested, based on studies of caged animals, that low frequency sounds can induce acoustic trauma in cephalopods including permanent and substantial alterations of the sensory hair cells of the statocysts, the structures responsible for the animals' sense of balance and position. The authors concluded that the relatively low levels and short exposure applied in their study can induce severe acoustic trauma in cephalopods, but this work needs to be repeated with additional controls.

Studies that have examined the behavior of caged fish have concluded that exposure to airguns does not cause immediate fish mortality nor obvious short-term deleterious effects (Boeger et al. 2006). Some fish have shown changes in swimming behavior and orientation, including startle reactions (Wardle et al. 2001). These startle reactions are brief and transient, and the response may habituate with repeated presentation of the same sound. Sound can however result in more pronounced responses including changes in swimming behavior, schooling, and distribution (Pearson et al. 1992). The horizontal and vertical distributions of both pelagic and ground fish have changed during and after airgun operations (Engås et al. 1996; Engås and Løkkeborg 2002; Slotte et al. 2004; also see Section 10.3).

Reductions in catches of fish have been observed in commercial line and trawl fisheries both during and after seismic surveys (Skalski et al. 1992; Løkkeborg and Soldal 1993; Engås et al. 1993, 1996), and these were reviewed in Section 10.3.

McCauley et al. (2003) determined the effects of exposure to an airgun on the sensory hair cells of fish ears. They found that exposure to multiple shots over several hours produced damage to the sensory epithelia of the saccule, the major auditory end organ of the ear, in a group of caged pink snapper (*Pagrus auratus*). Evidence for damage showed up as early as 18 hours post-exposure and was very extensive when fish were examined 58 days post-exposure as compared to controls.

Popper et al. (2005) investigated the effects of exposure to an airgun array on the hearing of three fish species in the Mackenzie River Delta: northern pike (*Esox lucius*), broad whitefish (*Coregonus nasus*), and lake chub (*Couesius plumbeus*) (see also Cott et al. 2012). Fish were placed in cages in shallow water and exposed to five or 20 airgun shots, while controls were placed in the same cage but without airgun exposure. Hearing in both exposed and control fish were then tested using an AEP response. Threshold shifts were found in exposed fish compared with controls in the northern pike and lake chub, with recovery within 18 hours of exposure, while there was no threshold shift in the broad whitefish. It was concluded that these three species were not likely to be substantially affected by exposure to an airgun array in seismic surveys conducted in rivers as the fish would be exposed to only a few shots.

There has been particular concern over the impact of seismic airguns on the eggs and larvae of fish because of their small size and physical fragility. However, there are very few data on the effects of noise on fish eggs and larvae. Kostyuchenko (1973) and Booman et al. (1996) found indications of seismic effect on fish eggs when exposed to an airgun shot at a close distance. Saetre and Ona (1996) observed effects of seismic signals on fish larvae. Dalen and Knutsen (1987) concluded that so few eggs and fry were present within the very small danger zone around the airgun that the damage caused will have no negative consequences for fish stocks. They calculated that the mortality caused by airguns might amount to an average of 0.0012% a day. In comparison to the natural mortality rate of 5% to 15% a day, the effects of seismic-induced damage would be insignificant.

10.12.2 Pile Driving

There are no substantive data on whether the high sound levels from pile driving or any man-made sound would have physiological effects on invertebrates. The only potentially relevant data are from a study on the effects of seismic exploration on snow crabs on the east coast of Canada (Boudreau et al. 2009). The preponderance of evidence from this study showed no short- or long-term effects of seismic exposure in adult or juvenile animals, or on eggs.

The lack of any gas bubbles (such as the fish swim bladder) that would be set in motion by high intensity sounds may suggest that there would be little or no impact on invertebrates (although, like fish, if the invertebrates are very close to the source, the shock wave might have an impact on survival).

The literature on effect of pile driving has been reviewed recently (Popper and Hastings 2009). Pile driving is a critical issue since it is being encountered more widely and in deeper waters as a result of construction of wind farms, all of which require driving one or more piles to support each wind turbine.

Until recently, the bulk of the data on pile driving has come from a series of studies of caged fish in which animals were exposed to actual pile driving operations and the fish then evaluated for effects on physiological systems (e.g., Abbott et al. 2005; Caltrans 2010a, 2010b; also reviewed in Popper and Hastings 2009). The results of these studies have been equivocal due to the extreme difficulties doing field studies. It is often not possible for the investigators to control the sound source (e.g., onset, number of strikes, sound level). Moreover, there is a concern that since virtually all of these studies were done on salmonids, the fish may not have been given time to acclimate and fill their swim bladders with air before being lowered to depth. Thus, the swim bladder may not have been full of gas, and this might substantially decrease the likelihood of effects occurring (Stephenson et al. 2010; Halvorsen et al. 2011).

Most recently, Halvorsen et al. (2011) reported on a study that examined the effects of exposure of Chinook salmon (*Oncorhynchus tshawytscha*) in a laboratory-based tank that is able to duplicate very high intensity pile driving sounds under acoustic conditions similar to those a fish would encounter if it were outside the acoustic near field of the sound source. Animals were fully acclimated and had full swim bladders before testing. The investigators found that there was a close link between the extent of physiological damage and the intensity of the sound source. There were virtually no physiological effects to sounds below an $\mathrm{SEL_{cum}}$ of 210 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$, and at this level the only effects were minor hemorrhaging that the investigators predicted would not have even a minor effect on fish fitness. At an $\mathrm{SEL_{cum}}$ that was a bit higher (but with sounds given over the same time period), internal injuries started to show up, and when the level reached 219 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ there were massive internal injuries that would likely result in death.

The investigators have subsequently extended the study to examine recovery and found that Chinook salmon would have recovered after a number of days even when the $\mathrm{SEL_{cum}}$ was as high as 213 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ (Casper et al. pers. comm.). Studies with additional species have shown that while there is some variation in timing of the onset of physiological effects, this is always at $\mathrm{SEL_{cum}}$ of greater than 203 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$. In flatfish species without a swim bladder, there was no effect with an $\mathrm{SEL_{cum}}$ as high as 216 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$.

10.12.3 Vessels

Chan et al. (2010) designed a playback experiment to test the effect of vessel noise on predation risk assessment. They found that in response to playback of boat noise Caribbean hermit crabs (*Coenobita clypeatus*) allowed a simulated predator to approach closer to the crabs before they hid. They concluded that anthropogenic sounds distracted prey and made them more vulnerable to predation. This is an important finding, as it suggests that quite subtle responses to sound by an animal may affect its survival. These experiments also point to the importance of examining particular and significant behavior patterns, rather than simply describing changes in movements or simple startle reactions.

Vessel noise produces sounds in the general hearing range of fishes (Amoser et al. 2004). Continuous exposure (30 minutes) to boat noise has been shown to increase cortisol levels (stress response) in fishes (Wysocki et al. 2006). TTS has been associated with long-term, continuous exposure (2 hours), and masked hearing thresholds have also been recorded for fishes exposed to noise from small boats and ferries (Scholik and Yan 2001; Vasconcelos et al. 2007). Additionally, vessels (i.e., trawlers, ferries, small boats) can change fish behavior (e.g., induce avoidance, alter swimming speed and direction, and alter schooling behavior) (Engås et al. 1995; Engås et al. 1998; Sarà et al. 2007). The sounds produced by motor-driven ships cause herring to dive and swim away from the vessel (Mitson and Knudsen 2003). Paradoxically, research vessels specially designed to reduce noise can result in an even greater behavioral reaction (Ona et al. 2007). Sand et al. (2008) pointed out that passing ships produce high levels of infrasonic and low frequency noise (>10 to 1000 Hz) and that infrasonic frequencies may be responsible for the observed avoidance reactions.

11 Current Exposure Criteria

Beyond knowing the potential effects of sound on organisms, it is also critical for BOEM, and other agencies, to gain knowledge of the levels of sounds that may be of potential harm to animals, as well as levels that are likely of no consequence. Developing such criteria or thresholds for harm is not possible until there are sufficient data about the effects of sounds, but once such knowledge is available, such criteria could be of immense value. Importantly, developing criteria is not limited to fish, or to sounds. There are regulatory criteria for many man-made stimuli. There are also extensive sets of regulations and criteria to protect humans from exposure to sounds that could be detrimental (see Rabinowitz 2012 regarding United States regulatory information) and an extensive body of literature on the overall effects of noise on humans (see papers in Le Prell et al. 2012).

In considering effects of noise on fish, there are two approaches of importance. One is the development of criteria for behavioral effects—changes in behavior that are perceived as being potentially harmful to fish and fish populations in the long term. The behavior may involve animals moving from feeding sites, changing migration routes, not hearing potential predators, and other effects likely to be detrimental. The second is effects on physiology and the onset of some kind(s) of physiological responses (e.g., external or internal bleeding) that has the potential of harming individual animals and populations. The criteria for behavior and physiology are likely to be very different. Developing these criteria is particularly difficult since there may have to be different criteria for species that differ in behavior and/or physiology and within a single species depending on animal size (see Popper et al. 2006; Carlson et al. 2007; Popper and Hastings 2009; Halvorsen et al. 2011).

In developing criteria for physiological effects on fish, the critical factors to define are those sound conditions that result in onset of physiological effects (Stadler and Woodbury 2009; Popper and Hastings 2009; Woodbury and Stadler 2008; Halvorsen et al. 2011). This is a point that is much easier to ascertain and quantify than some other point after onset, such as the amount of damage that results in 50% of fish dying or some other such statistical value (e.g., Yelverton et al. 1975).

At the same time, the problem is more complex than simply looking for onset of physiological effects. It may be necessary to focus on the onset of those physiological effects that are likely to be detrimental to animals (e.g., lower fitness). Just as a small scratch on the skin of a human has little likelihood of any impact on fitness (even without benefit of band-aid and disinfectant), a small hemorrhage on the skin of a fish or shark may have no bearing on fitness.

As documented in a recent pile driving study (Halvorsen et al. 2011) there are wide ranges of physiological effects ranging from very minor bleeding externally to massive internal hemorrhaging. Many of these effects do not appear to have any impact on fish survival, and there may be complete recovery from them (Casper et al. pers. comm.).

11.1 Current Criteria for Onset of Physiological Effects

The only current criteria in use for onset of physiological effects on fish are interim criteria developed on the United States west coast by the Fisheries Hydroacoustics Working Group[27] (see reviews in Stadler and Woodbury 2009; Woodbury and Stadler 2009).[28] The interim criteria are:

- Peak SPL: 206 decibels dB re 1 µPa
- SEL_{cum}: 187 dB re 1µPa^2·s for fishes above 2 grams (0.07 ounces).
- SEL_{cum}: 183 dB re 1µPa^2·s for fishes below 2 grams (0.07 ounces).

While these criteria are being used today (see Caltrans 2009), it should be noted that they are based on very limited experimental data, and they were significantly criticized even before they were announced (e.g., Hastings and Popper 2005; Popper et al. 2006; Carlson et al. 2007; Popper and Hastings 2009) because they did not rely on best available science and were based on incomplete studies of the effects of pile driving.

More recently, controlled studies on the effects of simulated pile driving on Chinook salmon (Halvorsen et al. 2011) and other species demonstrated that onset of physiological response occurs at least 16 dB above the levels being used in the current interim criteria, and are probably over 23 dB higher (SEL_{cum}). Unlike current criteria, these data are based on exposure of fish to controlled sound, with similar temporal periods for exposure at different sound levels. One of the significant issues to consider from pile driving or exposure to any relatively long-duration, intense, man-made sound is whether there is a recovery from accumulation if there is some period of time between sound exposure. In other words, if a fish is accumulating an effect over time and there is then a long period of quiet, does the accumulated effect restart at zero? The only relevant data are from studies of exposure to seismic airguns where it was shown that there was complete recovery from TTS in several species within 18 hours of exposure (Popper et al. 2005). As part of the current interim criteria for pile driving, a quiet period of 12 hours is considered to be sufficient for full recovery and the restarting of accumulation (Stadler and Woodbury 2009).

While there are fewer data for eggs and larvae from pile driving, a recent study examined effects on flatfish larvae at life stages including a very short period when these fish have a swim bladder (the swim bladder is lost after the larval stage in flatfish). Using a device similar to the one used by Halvorsen et al. (2011), Bolle et al. (2011) found no damage to different larval stages even at sound levels as high as an SEL_{cum} of 206 dB re 1 µPa^2·s.

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[27] A history of the Fisheries Hydroacoustics Working Group can be found at http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm.

[28] The actual agreement discussed in this paper can be found at http://www.dot.ca.gov/hq/env/bio/files/fhwgcriteria_agree.pdf.

11.2 Behavioral Criteria

The problem in setting behavioral criteria is that there are almost no data on those sound levels that result in behavioral effects other than startle responses. Moreover, such levels are likely to vary depending on numerous factors. These include whether the animal detects the sound (determined by its hearing threshold and whether the sound is masked by ambient noise; see Section 10.6), the motivation of the animal to respond, the different ways in which different species respond to a fright stimulus, and even perhaps on species and size (age) of a particular species. The NMFS (see Caltrans 2009) in their regulation of impact of sound on fishes states that behavioral impact starts at a level of 150 dB in the form of startle responses, but tracing the origin of this suggestion has not proved possible (e.g., Hastings 2008). However, there are almost no behavioral studies that provide guidance, and in even those few cases where data are available, the work was generally done with fishes in cages or other enclosures, where in many cases it was impossible to know if the stimulus was the measured sound pressure or actually particle motion arising in complex tank acoustics (Parvulescu 1964). Moreover, animals in such circumstances do not behave normally and so it is impossible to extrapolate from any caged behaviors to wild animals.

Nedwell et al. (2006) have argued that strong avoidance responses by fish start at about 90 dB above the hearing thresholds of fish. Mild reactions in a minority of individuals may occur at levels between 0 and 50 dB above the hearing threshold, and stronger reactions may occur in a majority of individuals at levels between 50 and 90 dB above the hearing threshold. These figures are largely derived from data available from the application of a fish avoidance system at a nuclear power station, supplemented by observations from the testing of a fish guidance system in shallow raceways (Nedwell et al. 2007b). There are some additional field data from wild fish under different conditions to support these assumptions, but few tests have been done at sound levels sufficiently intense to determine how fish respond at 90 dB above their hearing threshold. Exposure was also for a short time and the effects of habituation were not addressed. Nedwell et al. (2007b) suggested that the best available methodology for evaluating behavioral effects such as avoidance lies in observations made under actual open water conditions, where the movement of individuals is not inhibited by the experimental conditions. Such observations might be made, for instance, during offshore piling or seismic surveys.

In proposing criteria for several types of sound sources, only the cases where data are available on received sound levels have been considered. When received sound level data are not available, as is the case for many studies, no criteria can be discussed.

Many of the questions to be asked about behavior have been discussed at other points in this document.

Questions about Behavior

- *At what sound levels do wild fish start to show behavioral reactions to man-made sounds? How does this vary by species, motivation, and other behavioral and physiological conditions?*

- *At what sound levels do fish start to show substantial behavioral reactions that potentially alter fitness (e.g., change migration routes, move fish from feeding sites, alter reproductive behavior)?*
- *Do different types of sound sources (e.g., seismic versus air gun) elicit different kind(s) of behavioral reactions or result in onset of behavioral reactions at different sound levels?*
- *How is fish behavior altered in the presence of masking sounds? How loud does a masker need to be to impact fish acoustic behavior?*
- *Are there differences in behavioral responses of sound by fish of different ages and sex within a single species?*
- *How does fish behavior change when there is a maintained increase in the sound level in an environment?*

12 Noise Regulation

It may in some circumstances be necessary to introduce regulation designed to reduce the impact of sound on marine life (e.g., Johnson, 2012; Lewandowski et al. 2012; Tasker 2012). Such action can be expensive and place penalties upon development. Regulation must therefore rely on robust scientific justification. Moreover the results of such understanding need to be effectively communicated to the public so as to foster rational discussion and public support.

An initial important question is whether all proposed noise-making activities are necessary. For example, are some seismic surveys simply repeating observations made in earlier surveys? How best can duplication be avoided or prevented? Should noise-making activities be rationed or their incidence regulated?

Understanding the cumulative and in-combination effects of repeated exposure to sounds from different sources is important in considering noise regulation.

Legislation is moving rapidly to embrace maritime spatial planning and it may be necessary in the future to set standards for underwater sound production, perhaps on a precautionary basis. In Europe, the Marine Strategy Framework Directive is already proposing to monitor and set limits on anthropogenic sound. But currently there is insufficient information to build any rationale for the spatial management of sound-making activities to reduce their impacts on sensitive species or habitats. The development of sound inventories may enable administrations to refine their knowledge of the noise being generated and help them to define the threshold values that managers may need to set legally binding conditions on the generation of sound in the ocean.

13 Mitigation

There are two kinds of mitigation. One involves changes to the sound source to minimize effects. The other involves the use of biological information to minimize effects.

13.1 Physical Mitigation

Simply minimizing the noise associated with human activities is often possible, logical, and beneficial. For example, efforts are currently underway within the International Maritime Organization to engage the international shipping industry in implementing vessel-quieting technologies.

Questions Related to Physical Methods of Mitigation

- *Are there ways of avoiding the use of high level noise-making sources or replacing them by other less damaging sources? What are the characteristics of sounds that make them especially damaging to marine life? Can sources be redesigned to make them less damaging?*
- *Are there technological alternatives to airguns for oil and gas exploration? Can alternative sound sources be developed, such as marine vibrators (vibroseis)?*
- *What can be done to existing sound sources to reduce unwanted sound? What research and development might result in quieter sources?*

13.2 Biological Mitigation

Knowledge is required of the numbers and distribution of fish and invertebrates in an area that will be exposed to man-made sound. If there are vulnerable marine organisms in an area, then one way of avoiding adverse effects upon them is to avoid sound production when they are there. This is the basis of the Passive Acoustic Monitoring (PAM) systems that are used for observing marine mammals (e.g., Mann et al. 2008).

Passive listening to detect the presence of vulnerable species may be especially important for mitigation. Recent developments in the use of passive and active acoustic monitoring technologies around offshore industrial applications were reviewed in an interactive forum convened in November 2009 by the BOEMRE.[29]

However, PAM systems are currently designed for marine mammal detection.

Questions on Passive Acoustic Monitoring Systems

- *Can PAM or other similar monitoring systems detect sound-producing fish?*
- *Is the use of sonar and fish capture techniques more appropriate for monitoring the presence of vulnerable fish and shellfish in an area?*
- *Can fish and invertebrates be induced to move away from an area, without subjecting them to stress or injury, in order to allow sounds to be broadcast?*

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[29] For examples, see www.acousticmonitoring.org.

A common procedure for avoiding damage to marine mammals is the use of ramp-up procedures, where the sound levels of the sources (airguns or pile drivers) are gradually raised so that animals have a chance to avoid them by moving away. Evaluating whether the ramp-up procedure is effective in removing fishes or invertebrates from an area prior to airgun operation is important because it is often the only form of operational mitigation applied. It is uncertain whether ramp-up is effective, given that some fishes and invertebrates may occupy home ranges and may be reluctant to move, or may be disadvantaged by doing so, while others can move only slowly—if they can move at all.

Planning the timing of operations may be critical in ensuring effective mitigation of noise making activities. Indeed, this is likely to be the most effective form of mitigation.

Questions on Biological Mitigation

- *Can the efficacy and consequences of ramp-up procedures be evaluated, as well as signals that produce an aversive alarm response, compared to controls?*
- *How do fishes and invertebrates respond to ramp-up or soft-start procedures? Do they vacate the area where detrimental effects may occur? What are their swimming capabilities? How long should the ramp-up last to avoid detrimental impact?*
- *Can spawning seasons or times of the day or night when fish and invertebrates are more or less likely to be affected by sound be defined?*
- *Is there enough information on the biology of the fishes and invertebrates that may be affected adversely by sound exposure?*

14 Coordination

Current scientific knowledge must be applied consistently in supporting conservation management decisions, and the basis for those decisions must be transparent.

There is an increasing need for integrated and relevant research and data synthesis and coordination.

Access to central libraries of recorded and identified sounds can be of great help. Sharing experience in this context is essential as, in some cases, an unknown sound at a given site in a given context may have already been recorded and identified by others.

Automatic detectors and classifiers can be used for streamline analysis of data. Databases and libraries should be regularly updated on a central system in order to avoid the duplication of efforts. In this framework, the importance of the work of the Detection-Classification-Localization Working Group must be emphasized. This group is exchanging information that advances understanding of acoustic methods to detect, classify, locate, track, count, and monitor animals in their natural environment. Currently the emphasis is entirely upon marine mammals.

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Appendix A: Glossary

Absolute threshold – the minimum level at which an acoustic signal (e.g., a pure tone) is detectable by the listener, in a specified fraction of trials (conventionally 50%). The term implies quiet listening conditions: that is, it represents the irreducible absolute threshold. In the presence of a masking sound or noise, the term 'masked threshold' is more appropriate.

Acoustic intensity – The work done per unit area and per unit time by a sound wave on the medium as it propagates. The units of acoustic energy flux are Joules per square meter per second (J/m^2-s) or watts per square meter (W/m^2). The acoustic energy flux is also called the acoustic intensity.

Acoustic threshold – See Threshold.

Active acoustic space - In animal communication the acoustic active space is the area over which a sound from a real-life source remains above detection threshold

Ambient noise – Background noise in the environment, some of which comes from identifiable sources but some of which does not. Some authors limit the term ambient noise to the noise background that has no distinguishable sources

Arterial air embolism – Blockage of an artery created by the entrance of air into the circulation as a result of trauma. Death can occur if an embolus of air obstructs the brain or heart circulation.

Audiogram – The measurement of hearing sensitivity (or lowest sound level detectable – see Threshold) at a number of different frequencies in the hearing bandwidth of an organism.

Auditory Evoked Potential (AEP) – A physiological method for determining hearing bandwidth and sensitivity of animals without training. Electrodes (wires) are placed on the head of the animal to record electrical signals (emitted by the ear and central nervous system) in response to sounds. These signals are low in level and are averaged to raise them above the background electrical noise. It is not possible to determine auditory thresholds for fishes which are comparable to behavioral thresholds using this method but it is possible to gain an idea of the frequency range and to compare the effects of various treatments, such as exposure to high levels of sound.

Bandwidth – The range of frequencies over which a sound is produced or received. The difference between the upper and lower limits of any frequency band.

Continuous sound – a sound for which the mean square sound pressure is approximately independent of averaging time.

Critical band – one of a number of contiguous bands of frequency into which the audio-frequency range may be notionally divided, such that sounds in different frequency bands are heard independently of one another, without mutual interference. An auditory critical band can be defined for various measures of sound perception that involve frequency.

Critical ratio – The difference between signal sound pressure level (SPL) and noise spectral density level at which the signal is just heard above the noise

Cumulative pressure squared – The time-integrated value of the square of the sound pressure over a certain time period.

Decibel (dB) – A logarithmic scale most commonly for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the decibel value is defined as 10 $\log_{10,}$(actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is 20$\log_{10}$(actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., dB re 1 µPa). A difference of 20 dB corresponds to a factor of 10 in sound pressure.

Ensonification – The words, insonify and ensonify, are often used as synonyms but, in fact, they have subtle but different meanings. Sonify is a verb that simply means, “to add sound.” It is traditionally used when sound is added for an effect, either to interpret scientific data (e.g., a Geiger Counter) or to enhance an experience (such as to sonify a video game). When “en” is used as a prefix to a verb to form another verb, then it means “so as to cover thoroughly” as in enwrap. In contrast, the prefix, “in,” means “within” or “into.” Examples of “in” added to a verb to form another verb are inlay and input. Likewise insonify means “to add sound into.”

With regards to exposure to sound, emission refers to sound from the source and immission refers to sound received by a person or animal. If we are intentionally putting sound into an animal (or other target) to determine its effects on behavior, annoyance, hearing, etc., then we are insonifying that animal or target. But if sound is being emitted into a region, for example from a fog horn, then it is ensonifying as far its emission will travel and it may not insonify anything.

Fall time – The amount of time it takes to go from the peak pressure to either zero pressure or the minimum pressure in an impulsive sound wave.

Far field – A region far enough away from a source that the sound pressure behaves in a predictable way, and the particle velocity is related to only the fluid properties and exists only because of the propagating sound wave (see Near field).

Frequency spectrum – See Spectrum.

Gas bladder – See Swim bladder.

Hertz – The units of frequency where 1 Hertz = 1 cycle per second. The abbreviation for Hertz is Hz.

Impulse – See Impulse sound.

Impact sound – Transient sound produced when two objects strike each other and release a large amount of mechanical energy. Impact sound has very short duration but relatively high peak sound pressure.

Impulse or impulsive sound – Transient sound produced by a rapid release of energy, usually electrical or chemical such as circuit breakers or explosives. Impulse sound has very short duration and high peak pressure relative to a continuous sound of comparable mean level

Impulse length – Impulse length can be specified in many ways; an often used definition is the time between the accumulation of 5% and 95% of the total acoustic energy of a single impulse event..

Impulse width – The time required to go from a minimum or zero pressure to the peak pressure and then back to the minimum or zero again.

Infrasound – Sound at frequencies below the hearing range of humans. These sounds have frequencies below about 20 Hz.

Insonification – Irradiation with sound energy. See ensonification for complete differentiation between insonification and ensonification.

Kurtosis – A statistical measure of the peakedness in a signal or other random variable. In terms of an impulsive signal, kurtosis gives an indication of how the signal changes over the duration of the signal. Signals with a high kurtosis tend to have a single peak near the beginning and a long tail of lower energy, whereas signals with very low kurtosis would have a uniform distribution of energy. (See Henderson and Hamernik 2012 for a discussion of kurtosis as it relates to hearing.)

Lagena – One of the three otolithic end organ of the inner ear of fishes. The precise role of the lagena is not defined, but it is likely that it is involved in sound detection in many species. The lagena is also found in all terrestrial vertebrates other than mammals, where it may have evolved into the mammalian cochlea.

Lateral line – A series of sensors along the body and head of fishes that detects water motion. The lateral line uses sensory hair cells (identical to those in the ear) for detection. The cells are located in neuromasts that lie either in canals (e.g., along the side and head of the fish) or freely on the surface in a widely distributed pattern.

Near field – A region close to a sound source that has either irregular sound pressure or exponentially increasing sound pressure towards the source, and a high level of acoustic particle velocity because of kinetic energy added directly to the fluid by motion of the source. This additional kinetic energy does not propagate with the sound wave. The extent of the near field depends on the wavelength of the sound and/or the size of the source.

Octave – A doubling of frequency. One octave above 440 Hz is 880 Hz, whereas one octave below 440 Hz is 220 Hz. Thus, the ratios of frequencies in different octaves is 2:1.

Otolith – Dense calcareous structures found in the otolithic end organs (saccule, lagena, utricle) of the ears of fishes. They are located next to sensory hair cells of the ear and are involved in stimulation of the ear for detection of sound or head motion.

Particle acceleration – a time derivative of particle velocity.

Particle velocity – The time rate of change of the displacement of fluid particles created by the forces exerted on the fluid by acoustic pressure in the presence of a sound wave. The units of velocity are meters per second (m/s).

Population Consequences of Acoustic Disturbance Model (PCAD model) – Model that defines a rationale for developing assessments of the significance of sub-lethal effects and for identifying the most important gaps in our knowledge.

Peak amplitude – The maximum deviation between the sound pressure and the ambient hydrostatic pressure. Sometimes described and measured as half peak to peak.

Peak pressure – The highest pressure above or below ambient that is associated with a sound wave.

Peak overpressures – Overpressure is the pressure above the ambient level that occurs in an impulse sound such as an explosion. The peak overpressure is the highest pressure above ambient.

Permanent threshold shift (PTS) – A permanent loss of hearing caused by some kind of acoustic or other trauma. PTS results from irreversible damage to the sensory hair cells of the ear, and thus a permanent loss of hearing. A threshold shift that shows no recovery with time after the apparent cause has been removed.

Plane-traveling wave – A plane wave is an idealized sound wave that propagates in a single direction along its longitudinal axis. Theoretically the sound pressure is the same over an infinite plane that is perpendicular to the direction of propagation.

Physoclists – See Physostomes.

Physostomes – Fish species in which the swim bladder is connected to the oesophagus by a thin tube. Air to fill the swim bladder is swallowed by the fish and is directed to the swim bladder. Air removal from the swim bladder is by expulsion through this tube to the esophagus. Physoclistous fishes have no such connection. Instead, they add gas to the swim bladder using a highly specialized gas secreting system called the rete mirabile, which lies in the wall of the swim bladder and extracts gas from the blood using a counter-current system, much like that found in the kidney, to remove wastes from the blood. Removal of gas from the swim bladder occurs by reabsorption into the blood.

Pulse – A transient sound wave having finite time duration. A pulse may consist of one too many sinusoidal cycles at a single frequency, or it may contain many frequencies and have an irregular waveform.

Resonance frequency – The frequency at which a system or structure will have maximum motion when excited by sound or an oscillatory force.

Rise time – The interval of time required for a signal to go from zero, or its lowest value, to its maximum value.

Saccule – One of the three otolithic end organs of the inner ear. It is generally thought that the saccule is involved in sound detection in fishes, although it also has roles in determining body position relative to gravity, its primary role in terrestrial vertebrates.

Shock wave – A propagating sound wave that contains a discontinuity in pressure, density, or particle velocity.

Sound attenuation – Reduction of the level of sound pressure. Sound attenuation occurs naturally as a wave travels in a fluid or solid through dissipative processes (e.g., friction) that convert mechanical energy into thermal energy and chemical energy.

Sound energy metric – A value that characterizes a sound by some measure of its energy content.

Sound exposure – The integral over all time of the square of the sound pressure of a transient waveform.

Sound exposure level (SEL) – The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.

Sound exposure spectral density – The relative energy in each narrow band of frequency that results from the Fast Fourier Transform (FFT, a mathematical operation that is used to express data recorded in the time domain as a function of frequency) of a transient waveform. It is a measure of the frequency distribution of a transient signal.

Sound pressure level (SPL) – The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 µPa for water and biological tissues, and 20 µPa for air and other gases. Sound pressure is The force per unit area exerted by a sound wave above and below the ambient or static equilibrium pressure is called the acoustic pressure or sound pressure. The units of pressure are pounds per square inch (psi) or, in the SI system of units, Pascals (Pa). In underwater acoustics the standard reference is one-millionth of a Pascal, called a micro-Pascal (1 µPa). The conventional definition of sound pressure level is in terms of root mean square pressure.

Source level – characterizes the sound power radiated by an underwater sound source expressed in decibels. Often expressed as the SPL at a standard reference distance from a point monopole, placed in a lossless uniform medium and extending to infinity in all directions.

Spectrum – A graphical display of the contribution of each frequency component contained in a sound.

Swim bladder – A gas (generally air) filled chamber found in the abdominal cavity of many species of bony fish, but not in cartilaginous fishes. The swim bladder serves in buoyancy control. In many species the swim bladder may also serve as a radiating device for sound production and/or as a pressure receiving structure that enhances hearing bandwidth and sensitivity.

Temporary threshold shift (TTS) – A threshold shift that shows a recovery with the passage of time after the apparent cause has been removed. Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory hair cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.

Threshold – The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined percent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50% of the time. Auditory thresholds are the lowest sound levels detected by an animal at the 50% level.

Total energy dose – The total cumulative energy received by an organism or object over time in a sound field.

Transient sound – a sound of finite duration for which the sound exposure becomes independent of integration time when the integration time exceeds that duration.

Utricle – One of the three otolithic end organs of the inner ear of fish (the others are the saccule and lagena). The utricle is probably involved in determining head position relative to gravity as well as in sound detection. It is the primary sound detection region in the Clupeiform fishes (herrings, shads, sardines, anchovies, and relatives). A utricle is found in all vertebrates, including humans.

Waveguide – A device for guiding the propagation of waves, such as an air duct.

Weberian ossicles – A series of bones found in the otophysan fishes (goldfish, catfish, and relatives) that connect the swim bladder to the inner ear. It is generally thought that the Weberian ossicles act to couple the motions of the swim bladder walls in response to pressure signals to the inner ear. Thus, the ossicles are functionally analogous to the mammalian middle ear bones as acoustic coupling devices.

Appendix B: Supplemental Tables for Section 3

Appendix Table B–1

Summary of the Habitat Areas of Particular Concern (HAPC) designated* in the Atlantic OCS as shown in Figures 3–3 to 3–5.

Site Name	Species	Number of HAPCs	Average Area Coverage (km^2)	Cumulative Area Coverage (km^2)
10 Fathom Ledge	Dolphin Wahoo	1	432	432
Atlantic Cod	Atlantic Cod	1	1,125	1,125
Big Rock	Dolphin Wahoo	1	103	103
Biscayne Bay		46	19	879
Biscayne National Park		1	880	880
Card Sound	Spiny Lobster	1	82	82
Charleston Bump Complex	Dolphin Wahoo	1	82,204	82,204
Coastal Inlets	Penaeid Shrimp	40	708	28,337
Continuous Seagrass	Snapper Grouper complex	1	2,278	2,278
Discontinuous Seagrass	Snapper Grouper complex	2	303	605
Dry Tortugas National Park		1	318	318
Florida Bay	Spiny Lobster	1	2,820	2,820
Florida Keys National Marine Sanctuary		534	22	11,673
Gray's Reef National Marine Sanctuary		1	79	79
Hardbottom	Spiny Lobster	81	<1	15
Hoyt Hills	Snapper Grouper complex	1	1,720	1,720
Islamorada Hump	Dolphin Wahoo	1	198	198
Lydonia Canyon	Tilefish	2	39	77
Mangroves	Snapper Grouper complex	2874	<1	400
Marathon Hump	Dolphin Wahoo	1	406	406
Norfolk Canyon	Tilefish	1	58	58
Oceanographer Canyon	Tilefish	1	144	144
Patch Reef	Spiny Lobster	1565	<1	45
Perm Sec Nursery Areas	Penaeid Shrimp	48	4	212
Permanent Secondary Nursery Areas	Penaeid Shrimp	48	4	212
Phragmatopoma (worm reefs)		112	58	6,464
Platform Margin Reef	Spiny Lobster	754	1	388
Primary Nursery Areas	Penaeid Shrimp	767	1	471
SEAMAP Hard Bottom	Snapper Grouper complex	42	62	2,601
SEAMAP Nearshore Hard Bottom		42	62	2,601

Site Name	Species	Number of HAPCs	Average Area Coverage (km^2)	Cumulative Area Coverage (km^2)
SEAMAP Offshore Hard Bottom		452	11	4,747
SS Nursery Areas	Snapper Grouper complex	63	4	279
Sandbar Shark	Sandbar Shark	5	4,029	20,147
Special Management Zones	Snapper Grouper complex	51	10	521
Special Secondary Nursery Areas	Snapper Grouper complex	63	4	279
The Point	Dolphin Wahoo	1	3,805	3,805
The Point/Amberjack Lump	Dolphin Wahoo	1	10	10
The Wall off the Florida Keys	Dolphin Wahoo	1	48	48
Tortugas Marine Reserves		2	9	17
Veatch Canyon	Tilefish	1	45	45
Yellowmouth Grouper Spawning	Snapper Grouper complex	2	432	432

* 21 October 2010, http://sharpfin.nmfs.noaa.gov/HAPC/EFHI/dd/hapc.zip

Appendix Table B–2

2010 landings* of species of commercial importance in the Atlantic OCS region, sorted by volume. All species are included that make up greater than 0.1% of the whole.

Species	Metric Tons (thousands)	Pounds (millions)	Percentage of Atlantic OCS Fisheries Landings
Menhaden	229.6	506.25	35.61%
Crab, blue	70.8	156.04	10.97%
Herring, Atlantic	65.2	143.73	10.11%
Lobster, American	52.7	116.25	8.18%
Scallop, sea	25.9	57.05	4.01%
Clam, Atlantic surf	17.0	37.47	2.64%
Squid, northern shortfin	15.8	34.88	2.45%
Clam, ocean quahog	14.4	31.70	2.23%
Mackerel, Atlantic	9.9	21.77	1.53%
Haddock	9.8	21.63	1.52%
Hake, silver	8.1	17.81	1.25%
Cod, Atlantic	8.0	17.72	1.25%
Croaker, Atlantic	7.3	16.17	1.14%
Goosefish (monkfish)	7.3	16.08	1.13%
Squid, longfin	6.7	14.81	1.04%
Shrimp, marine, other	6.2	13.68	0.96%
Flounder, summer	6.0	13.16	0.93%
Shrimp, white	5.8	12.68	0.89%
Dogfish, spiny	5.7	12.67	0.89%
Pollock	5.2	11.37	0.80%
Crab, jonah	4.9	10.72	0.75%
Scup	4.7	10.39	0.73%
Skate, little	4.2	9.27	0.65%
Bass, striped	3.4	7.42	0.52%
Bluefish	3.3	7.26	0.51%
Clams or bivalves	3.2	6.99	0.49%
Shrimp, brown	3.1	6.77	0.48%
Mackerel, Spanish	2.0	4.51	0.32%
Clam, northern quahog	2.0	4.31	0.30%
Mackerel, king and cero	1.9	4.25	0.30%
Hake, white	1.8	3.98	0.28%
Dogfish, smooth	1.7	3.84	0.27%
Redfish, Acadian	1.6	3.63	0.26%
Flounder, winter	1.6	3.50	0.25%
Crabs	1.6	3.46	0.24%
Mullet, striped (liza)	1.6	3.43	0.24%
Swordfish	1.5	3.38	0.24%
Clam, softshell	1.5	3.36	0.24%
Flounder, Atlantic, plaice	1.4	3.11	0.22%

Species	Metric Tons (thousands)	Pounds (millions)	Percentage of Atlantic OCS Fisheries Landings
Flounder, yellowtail	1.3	2.91	0.20%
Crab, Atlantic rock	1.1	2.43	0.17%
Tilefish, golden	1.1	2.40	0.17%
Oyster, eastern	1.0	2.28	0.16%
Spot	1.0	2.20	0.16%
Sea bass, black	0.9	2.09	0.15%
Shad, gizzard	0.9	2.01	0.14%
Flounder, southern	0.8	1.69	0.12%
Flounder, witch	0.8	1.67	0.12%
Tuna, yellowfin	0.6	1.42	0.10%
Hake, red	0.6	1.36	0.10%

*Data from http://www.st.nmfs.noaa.gov/st1/commercial/. See http://www.st.nmfs.noaa.gov/st1/commercial/landings/caveat.html for caveats related to NMFS commercial landings data.

Appendix Table B–3

2010 landings* of species of commercial importance in the Atlantic OCS region, sorted by volume. All species are included that make up greater than 0.1% of the whole.

Species	$USD Value (million)	Average Price/lb (price per kg) ($USD)	Percentage of Atlantic OCS Fisheries Value
Scallop, sea	450.97	7.91 (17.40)	28.56%
Lobster, American	399.48	3.44 (7.57)	25.30%
Crab, blue	158.67	1.02 (2.24)	10.05%
Menhaden	41.11	0.08 (0.18)	2.60%
Clam, northern quahog	33.57	7.79 (17.14)	2.13%
Flounder, summer	28.63	2.18 (4.80)	1.81%
Cod, Atlantic	28.14	1.59 (3.50)	1.78%
Shrimp, white	27.28	2.15 (4.73)	1.73%
Clam, Atlantic surf	25.95	0.69 (1.52)	1.64%
Oyster, eastern	24.49	10.76 (23.67)	1.55%
Haddock	21.72	1.00 (2.20)	1.38%
Herring, Atlantic	21.08	0.15 (0.33)	1.33%
Clam, ocean quahog	20.01	0.63 ((1.39)	1.27%
Clam, softshell	19.97	5.94 (13.07)	1.26%
Goosefish (monkfish)	19.23	1.20 (2.64)	1.22%
Bass, striped	16.86	2.27 (4.99)	1.07%
Squid, longfin	15.76	1.06 (2.33)	1.00%
Shrimp, brown	11.91	1.76 (3.87)	0.75%
Swordfish	11.33	3.35 (7.37)	0.72%
Squid, northern shortfin	11.29	0.32 (0.70)	0.71%
Hake, silver	11.04	0.62 (1.36)	0.70%
Croaker, Atlantic	10.14	0.63 (1.39)	0.64%
Pollock	9.53	0.84 (1.85)	0.60%
Tuna, Bluefin	9.22	7.04 (15.49)	0.58%
Shrimp, marine, other	7.95	0.58 (1.28)	0.50%
Mackerel, king and cero	7.57	1.78 (3.92)	0.48%
Flounder, winter	6.96	1.99 (4.38)	0.44%
Scup	6.91	0.67 (1.47)	0.44%
Tilefish, golden	6.19	2.57 (5.65)	0.39%
Sea bass, black	6.04	2.90 (6.38)	0.38%
Bloodworms	5.87	11.03 (24.27)	0.37%
Crab, Jonah	5.58	0.52 (1.14)	0.35%
Clams or bivalves	5.29	0.76 (1.67)	0.33%
Flounder, American, plaice	4.50	1.44 (3.17)	0.28%
Mackerel, Atlantic	4.40	0.20 (0.44)	0.28%
Flounder, yellowtail	4.19	1.44 (3.17)	0.27%
Hake, white	4.12	1.03 (2.27)	0.26%
Flounder, witch	3.77	2.26 (4.97)	0.24%
Flounder, southern	3.70	2.19 (4.82)	0.23%
Tuna, yellowfin	3.62	2.55 (5.61)	0.23%

Species	$USD Value (million)	Average Price/lb (price per kg) ($USD)	Percentage of Atlantic OCS Fisheries Value
Mackerel, Spanish	3.49	0.77 (1.69)	0.22%
Tuna, bigeye	3.37	3.99 (8.78)	0.21%
Clam, quahog	3.32	6.98 (15.36)	0.21%
Crabs	3.27	0.95 (2.09)	0.21%
Bluefish	3.13	0.43 (0.95)	0.20%
Lobster, Caribbean spiny	2.82	5.88 (12.94)	0.18%
Snapper, vermilion	2.76	2.96 (6.51)	0.17%
Dogfish, spiny	2.59	0.20 (0.44)	0.16%
Eel, American	2.46	2.89 (6.36)	0.16%
Skate, barndoor	2.33	2.81 (6.18)	0.15%
Redfish, Acadian	1.96	0.54 (1.19)	0.12%
Gag	1.79	3.76 (8.27)	0.11%
Spot	1.76	0.80 (1.76)	0.11%
Mullet, striped (liza)	1.71	0.50 (1.10)	0.11%
Shrimp, rock	1.61	1.45 (3.19)	0.10%
Dogfish, smooth	1.58	0.41 (0.90)	0.10%
Shrimp, dendrobranchiata	1.55	4.71 (10.36)	0.10%
Scallop, bay	1.53	11.96 (26.31)	0.10%

*Data from http://www.st.nmfs.noaa.gov/st1/commercial/. See http://www.st.nmfs.noaa.gov/st1/commercial/landings/caveat.html for caveats related to NMFS commercial landings data

Appendix Table B–4

Fishery management plan, stock, jurisdiction, and status information for primary Atlantic OCS Region stocks. From 2010 Status of U.S. Fisheries Report to Congress.[30]

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Atlantic Herring	Atlantic herring - Northwestern Atlantic Coast	NEFMC	No[1]	No[1]	No
Atlantic Sea Scallop	Sea scallop - Northwestern Atlantic Coast	NEFMC	No	No	No
Deep-Sea Red Crab	Red deepsea crab - Northwestern Atlantic	NEFMC	No[2]	Unknown	Unknown
Northeast Multispecies	Acadian redfish - Gulf of Maine / Georges Bank	NEFMC	No	No - Rebuilding	No
	American plaice - Gulf of Maine / Georges Bank	NEFMC	No	No - Rebuilding	No
	Atlantic cod - Georges Bank	NEFMC	Yes	Yes	N/A
	Atlantic cod - Gulf of Maine	NEFMC	Yes	No - Rebuilding	No
	Atlantic halibut - Northwestern Atlantic Coast	NEFMC	No	Yes	N/A
	Haddock - Georges Bank	NEFMC	No	No	No
	Haddock - Gulf of Maine	NEFMC	No	No - Rebuilding	No
	Ocean pout - Northwestern Atlantic Coast	NEFMC	No	Yes	N/A
	Offshore hake - Northwestern Atlantic Coast	NEFMC	Undefined	No	Unknown
	Pollock - Gulf of Maine / Georges Bank	NEFMC	No	Rebuilt	No

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[30] The report is available at http://www.nmfs.noaa.gov/sfa/statusoffisheries/SOSmain.htm.

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Northeast Multispecies	Red hake - Gulf of Maine / Northern Georges Bank	NEFMC	Unknown	No	No
	Red hake - Southern Georges Bank / Mid-Atlantic	NEFMC	Undefined	No	Unknown
	Silver hake - Gulf of Maine / Northern Georges Bank	NEFMC	No	No	No
	White hake - Gulf of Maine / Georges Bank	NEFMC	Yes	Yes	N/A
	Windowpane - Gulf of Maine / Georges Bank	NEFMC	Yes	Yes	N/A
	Windowpane - Southern New England / Mid-Atlantic	NEFMC	Yes	No - Rebuilding	No
	Winter flounder - Georges Bank	NEFMC	Yes	Yes	N/A
	Winter flounder - Gulf of Maine	NEFMC	Unknown[3]	Unknown[3]	Unknown
	Winter flounder - Southern New England / Mid-Atlantic	NEFMC	Yes	Yes	N/A
	Witch flounder - Northwestern Atlantic Coast	NEFMC	Yes	Yes	N/A
	Yellowtail flounder - Cape Cod / Gulf of Maine	NEFMC	Yes	Yes	N/A
	Yellowtail flounder - Georges Bank	NEFMC	No	Yes	N/A
	Yellowtail flounder - Southern New England / Mid-Atlantic	NEFMC	Yes	Yes	N/A

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Northeast Skate Complex	Barndoor skate - Georges Bank / Southern New England	NEFMC	No	No - Rebuilding	No
	Clearnose skate - Southern New England / Mid-Atlantic	NEFMC	No	No	No
	Little skate - Georges Bank / Southern New England	NEFMC	No	No	No
	Rosette skate - Southern New England / Mid-Atlantic	NEFMC	No	No	No
	Smooth skate - Gulf of Maine	NEFMC	No	Yes	N/A
	Thorny skate - Gulf of Maine	NEFMC	No	Yes	N/A
	Winter skate - Georges Bank / Southern New England	NEFMC	No	No	No
Monkfish	Monkfish - Gulf of Maine / Northern Georges Bank	NEFMC / MAFMC	No	No	No
	Monkfish - Southern Georges Bank / Mid-Atlantic	NEFMC / MAFMC	No	No	No
Spiny Dogfish	Spiny dogfish - Atlantic Coast	NEFMC / MAFMC	No	No	No
Atlantic Mackerel, Squid and Butterfish	Atlantic mackerel - Gulf of Maine / Cape Hatteras	MAFMC	No[4]	No[4]	No
	Butterfish - Gulf of Maine / Cape Hatteras	MAFMC	No	Yes[5]	N/A
	Longfin inshore squid - Georges Bank / Cape Hatteras	MAFMC	No	No	No

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Atlantic Mackerel, Squid and Butterfish	Northern shortfin squid - Northwestern Atlantic Coast	MAFMC	No	Unknown	Unknown
Atlantic Surfclam and Ocean Quahog	Atlantic surfclam - Mid-Atlantic Coast	MAFMC	No	No	No
	Ocean quahog - Atlantic Coast	MAFMC	No	No	No
Bluefish	Bluefish - Atlantic Coast	MAFMC	No	No	No
Summer Flounder, Scup and Black Sea Bass	Black sea bass - Mid-Atlantic Coast	MAFMC	No	No	No
	Scup - Atlantic Coast	MAFMC	No	No	No
	Summer flounder - Mid-Atlantic Coast	MAFMC	No	No - Rebuilding	No
Tilefish	Tilefish - Mid-Atlantic Coast	MAFMC	No	No - Rebuilding[6]	No
Shrimp Fishery of the South Atlantic Region	Brown rock shrimp - Southern Atlantic Coast	SAFMC	No	No	No
	Brown shrimp - Southern Atlantic Coast	SAFMC	No	No	No
	Pink shrimp - Southern Atlantic Coast	SAFMC	No	Yes[7]	N/A
	White shrimp - Southern Atlantic Coast	SAFMC	No	No	No
Snapper Grouper Fishery of the South Atlantic Region	Black grouper - Southern Atlantic Coast	SAFMC	No	No	No
	Black sea bass - Southern Atlantic Coast	SAFMC	Yes	Yes	N/A
	Gag - Southern Atlantic Coast	SAFMC	Yes	No	Yes

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Snapper Grouper Fishery of the South Atlantic Region	Gray triggerfish - Southern Atlantic Coast	SAFMC	No	Unknown	Unknown
	Greater amberjack - Southern Atlantic Coast	SAFMC	No	No	No
	Hogfish - Southern Atlantic Coast	SAFMC	Unknown	Unknown	Unknown
	Red grouper - Southern Atlantic Coast	SAFMC	Yes	Yes	N/A
	Red porgy - Southern Atlantic Coast	SAFMC	No	Yes	N/A
	Red snapper - Southern Atlantic Coast	SAFMC	Yes	Yes	N/A
	Scamp - Southern Atlantic Coast	SAFMC	No	Unknown	Unknown
	Snowy grouper - Southern Atlantic Coast	SAFMC	Yes	Yes	N/A
	Speckled hind - Southern Atlantic Coast	SAFMC	Yes	Unknown	Unknown
	Tilefish - Southern Atlantic Coast	SAFMC	Yes	No	No
	Vermilion snapper - Southern Atlantic Coast	SAFMC	Yes	No	No
	Warsaw grouper - Southern Atlantic Coast	SAFMC	Yes	Unknown	Unknown
	White grunt - Southern Atlantic Coast	SAFMC	No	Unknown	Unknown
	Wreckfish - Southern Atlantic Coast	SAFMC	No	Unknown[8]	Unknown

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Coastal Migratory Pelagic Resources of the Gulf of Mexico and South Atlantic	Cobia - Gulf of Mexico	SAFMC / GMFMC	No	No	No
	King mackerel - Gulf of Mexico	SAFMC / GMFMC	No	No	No
	King mackerel - Southern Atlantic Coast	SAFMC / GMFMC	No	No	No
	Little tunny - Gulf of Mexico	SAFMC / GMFMC	No	Undefined	Unknown
	Spanish mackerel - Gulf of Mexico	SAFMC / GMFMC	No	No	No
	Spanish mackerel - Southern Atlantic Coast	SAFMC / GMFMC	No	No	No
Dolphin and Wahoo Fishery of the Atlantic / Coastal Migratory Pelagic Resources of the Gulf of Mexico and South Atlantic	Dolphinfish - Southern Atlantic Coast / Gulf of Mexico	SAFMC / GMFMC	No	No	No
Snapper Grouper Fishery of the South Atlantic Region / Reef Fish Resources of the Gulf of Mexico	Goliath grouper - Southern Atlantic Coast / Gulf of Mexico	SAFMC / GMFMC	No	Unknown	Unknown
	Yellowtail snapper - Southern Atlantic Coast / Gulf of Mexico	SAFMC / GMFMC	No	No	No
Spiny Lobster in the Gulf of Mexico and South Atlantic	Caribbean spiny lobster - Southern Atlantic Coast / Gulf of Mexico	SAFMC / GMFMC	No	Unknown	Unknown

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
Red Drum Fishery of the Gulf of Mexico	Red drum - Gulf of Mexico	GMFMC	No	Undefined	Unknown
Consolidated Atlantic Highly Migratory Species	Albacore - North Atlantic	HMS	Yes	Yes	N/A
	Atlantic Large Coastal Shark Complex[9]	HMS	Unknown	Unknown	Unknown
	Atlantic sharpnose shark - Atlantic[10]	HMS	No	No	No
	Atlantic Small Coastal Shark Complex[11]	HMS	No	No	No
	Bigeye tuna – Atlantic	HMS	No	No - Rebuilding	No
	Blacknose shark - Atlantic[10]	HMS	Yes	Yes	N/A
	Blacktip shark - Gulf of Mexico[12]	HMS	No	No	No
	Blacktip shark - South Atlantic[12]	HMS	Unknown	Unknown	Unknown
	Blue marlin - North Atlantic	HMS	Yes	Yes	N/A
	Blue shark - Atlantic[13]	HMS	No	No	No
	Bluefin tuna - Western Atlantic	HMS	Yes	Yes	N/A
	Bonnethead - Atlantic[10]	HMS	No	No	No
	Dusky shark - Atlantic	HMS	Yes	Yes	N/A
	Finetooth shark - Atlantic[10]	HMS	No	No	No
	Porbeagle - Atlantic[13]	HMS	No	Yes	N/A
	Sailfish - Western Atlantic	HMS	Yes	No - Rebuilding	N/A
	Sandbar shark - Atlantic[12]	HMS	Yes	Yes	N/A
	Shortfin mako - Atlantic[13]	HMS	Yes	No	Yes
	Swordfish - North Atlantic	HMS	No	No	N/A

Fishery Management Plan	Stock	Jurisdiction	Overfishing? (Is Fishing Mortality above Threshold?)	Overfished? (Is Biomass below Threshold?)	Approaching Overfished Condition?
	White marlin - North Atlantic	HMS	Yes	Yes	N/A
	Yellowfin tuna - Western Atlantic	HMS	No	No	Yes

[1.] Although this stock is currently listed as not subject to overfishing and not overfished, the most recent stock assessment conducted for Atlantic herring (2010) could not determine the overfishing or overfished status. Stock status is based on a stock assessment conducted in 2009 (TRAC).

[2.] Although the red crab stock is currently listed as not subject to overfishing and unknown for overfished, the most recent assessment (2006) could not provide conclusions about overfishing and overfished status. The status of this stock is based on an earlier assessment and status will remain unchanged in this report until the stock is assessed again.

[3.] Due to the large degree of uncertainty in the GARM III assessment, the status of winter flounder - Gulf of Maine has been changed to unknown. However, it is likely that the stock is overfished and overfishing is occuring, based on calculated reference points.

[4.] Although this stock is currently listed as not subject to overfishing and not overfished, the most recent stock assessment conducted for Atlantic mackerel (2010) could not determine the overfishing or overfished status. Stock status is based on the assessment conducted in 2005.

[5.] Although the butterfish stock is listed as overfished, the most recent assessment (2009) was unable to provide conclusions about overfished status. Though the butterfish population appears to be declining over time, the underlying causes for population decline are unknown. Despite considerable uncertainty in the recent assessment, no evidence suggests the status of the butterfish stock has improved since the previous assessment (2003). The status of the butterfish stock will remain as overfished in this report until biological reference points can be determined in a future assessment.

[6.] Although the most recent B/Bmsy = 1.04, this stock has not been declared rebuilt. SARC 48 (2009) notes the following: "*The biomass estimates for recent years from the ASPIC model are likely over-optimistic because trends in commercial VTR CPUE declined recently in a manner consistent with the passage of the strong 1999 cohort through the population (an interpretation further supported by the length frequency data). The current assessment model (ASPIC) does not account for those factors. Much of the confidence interval around the 2008 biomass estimate falls below the updated BMSY listed above. Based on these considerations there is no convincing evidence that the stock has rebuilt to levels above BTARGET.*" The rebuilt status will be re-evaluated when the stock is assessed next.

[7.] The Shrimp Review Advisory Panel concluded that the apparent decline in pink shrimp abundance does not appear to be due to overfishing. Based on both the SEAMAP data, and the effort and landings data from the North Carolina and eastern Florida pink shrimp fishery, the Shrimp Review Panel recommended that no management actions are necessary at this time. The Shrimp Review Panel concludes that the pink shrimp stocks in some areas along the Southeast coast are depleted due to factors other than fishing such as environmental and climatic factors. Since shrimp are essentially an "annual crop", it would not be appropriate to develop a rebuilding plan for this stock.

[8.] Although the overfished determination is not known, landings are at extremely low levels and there are only two participants in the fishery.

[9.] In addition to Sandbar Shark, Gulf of Mexico Blacktip Shark, and Atlantic Blacktip Shark (which are assessed individually), the Large Coastal Shark Complex also consists of additional stocks including Spinner Shark, Silky Shark, Bull Shark, Tiger Shark, Lemon Shark, Nurse Shark, Scalloped Hammerhead Shark, Great Hammerhead Shark, and Smooth Hammerhead Shark. In addition, several LCS species cannot be retained in commercial or recreational fisheries, including Bignose Shark, Galapagos Shark, Night Shark, Caribbean Reef Shark, Narrowtooth Shark, Sand Tiger Shark, Bigeye Sand Tiger Shark, Whale Shark, Basking Shark, White

[10.] This stock is part of the Small Coastal Shark Complex, but is assessed separately.

[11.] In addition to Finetooth Shark, Atlantic Sharpnose Shark, Blacknose Shark, and Bonnethead Shark (which are assessed individually), the Small Coastal Shark Complex also consists of: Atlantic Angel Shark, Caribbean Sharpnose Shark, and Smalltail Shark; these 3 species cannot be retained in recreational or commercial fisheries.

[12.] This stock is part of the Large Coastal Shark Complex, but is assessed separately.

[13.] This stock is part of the Pelagic Shark Complex, but is assessed separately.