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

Workshop Report

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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BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement (since superseded by BOEM) (United States)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
MSFCMA	Magnuson-Stevens Fisheries Conservation and Management Act (United States) or Magnuson-Stevens Act
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
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift

1 INTRODUCTION

1.1 Background

As authorized by the Outer Continental Shelf Lands Act (OCSLA), and amended by the Energy Policy Act of 2005, the Bureau of Ocean Energy Management (BOEM) is responsible for oversight of various activities on the OCS, including oil and gas exploration and production; sand and gravel resource assessment and mining; future offshore wind site assessment, turbine installation, and operation; and other renewable energy projects. The OCSLA and supporting regulations, in addition to other environmental statutes (Magnuson-Stevens Fishery Conservation and Management Act [MSFCMA], Endangered Species Act [ESA], and National Environmental Policy Act [NEPA]) to which BOEM must adhere, require that information suitable to assessing impacts to marine resources (including fishes, fisheries, and invertebrates, among other species) from these activities be collected. Fishes and invertebrates of particular interest for impact analysis include those species that are commercially or recreationally important, are threatened or endangered, or are keystone (for example, important prey) species.

Sound from man-made sources has been increasing in the world's oceans. BOEM regulates activities, all of which include one or more sources that introduce sound into the marine environment. Geological and geophysical exploration, pile driving, drilling, dredging, and vessel traffic all have this potential. BOEM is responsible for evaluating the effects of these noise sources on biota. While advances continue to be made in understanding the effects of man-made sound on marine mammals (Southall et al. 2007), the sheer taxonomic and environmental diversity of fishes and invertebrates has made the task of understanding the effects on these species a much more onerous task than for marine mammals (Popper and Hawkins 2012). Much remains to be learned about the hearing or sound-producing capabilities of fishes and invertebrates, let alone how they respond to, and are potentially affected by, man-made sounds.

In order to further their understanding of the issues surrounding the analysis of the effects of man-made sounds on fishes, fisheries and invertebrates, BOEM funded a three-phase project that consisted of: a synthesis of available literature on the subject; a Workshop of experts convened to discuss the state of knowledge (http://www.boemsoundworkshop.com/); and an analysis of the information that is needed to improve BOEM's understanding of the issues ("Gap Analysis"). The Literature Synthesis was prepared in advance of the Workshop and is appended to this report (Appendix E). The Workshop was convened in March 2012; discussions are summarized in this report (Section 2) and presentations are appended (Appendix B). The Gap Analysis is an integral part of this report (Section 3). It includes a full "wish" list of questions and data needs; many of these extend well beyond what is needed to conduct a thorough impact analysis but may be invaluable in helping BOEM and others understand the extend of outstanding issues and also direct research priorities for years to come on a national and international scale. These issues were winnowed down to the priorities representing attainable data needs that will allow significant improvements in understanding impacts from man-made sound in the near future which can then be included in future BOEM environmental analyses (NEPA, ESA, MSFMCA). Anticipating the implementation of one or more of their mandated missions in the U.S. Arctic and the U.S. Atlantic OCS, this project was focused by BOEM on those geographic areas.

1.2 Purpose of the Workshop

BOEM's Environmental Studies Program conceived of and funded the Workshop. The Workshop offered a means to identify the most critical information needs and data gaps on the effects of various man-made sounds produced by sound-generating devices used by the energy and offshore minerals industries upon fishes, fisheries, and invertebrates. It was intended to aid in decision-making for future studies. The information provided by the workshop will be used by BOEM to direct future research, assist with NEPA and other environmental analyses, develop monitoring and mitigation measures in lease stipulations and provide information to lessees. The Workshop included experts in: (a) the sound-producing technologies and activities; (b) physiology, behavior, and hearing of fishes and invertebrates; and (c) environmental regulation. A first step was to bring all participants to a common level of understanding on the issues of concern. The goal in bringing together technical experts from each of these fields was to stimulate a cross-fertilization of knowledge and ideas about the issues and animals of concern and then to use this to enhance the identification of data needs by the entire group.

1.3 Literature Synthesis Overview

In advance of the Workshop, the organizers compiled a synthesis of available literature on natural and man-made sounds in the marine environment; hearing, sound detection, and sound-production in fishes and invertebrates; and effects of sound on these organisms. The goal of this synthesis was three-fold:

- To provide a tool to Workshop participants to bring them to a common level of understanding of the "state of the science";
- To provide a preliminary assessment of information gaps; and,
- To aid in organization of the breakout discussion groups at the Workshop.

An important, and very basic, finding of the Literature Synthesis was that there is a wide, often confusing, array of terminology in use to describe similar features (e.g., noise versus sound) or metrics. This can make it very difficult to compare results reported by different scientists. Where it was possible to do so, the Literature Synthesis attempted to present information using common terminology. Promoting standard terminology is certainly not BOEM's responsibility but in pointing out the inherent difficulties in interpretation, BOEM can encourage improvements in the science.

A number of general questions were posed at the beginning of the Literature Synthesis. These honed in on why man-made sounds in the marine environment are potentially an issue and were used to structure the document. To summarize, the Literature Synthesis initially asked these questions:

- How well can we characterize the existing sounds, both natural and man-made, in the marine environment? Is the sound environment changing? Which man-made sources have the greatest effect?
- Do man-made sounds harm marine fishes and invertebrates? If so, how is that harm manifested?

- Do some levels of sound elicit acute impacts? Can lower levels of continuous sound cause chronic effects?
- Is a response to man-made sound by individual or groups of fishes or invertebrates ecologically significant (and, therefore, of regulatory interest)?
- Can we identify which species or habitats are of greatest concern considering such factors as status of the population (e.g., protection under the ESA; poor status in terms of fisheries), importance to commercial or recreational fisheries; ecological importance?
- Are there mitigating measures available (e.g., technological solutions; sensitivity to critical biological factors)?

Within the areas encompassed by this study, dozens of fish and invertebrate species are harvested commercially and two dozen species are protected under the ESA. These species and the associated fisheries are discussed in the Literature Synthesis. While sound is known to be important in the general behavior of many fish and invertebrates (e.g., codfishes, snappers, groupers), the use of sound is simply not known for most species, and, in particular, for the invertebrates. However, status of the species (whether ESA or overfished), value of the fishery, and presence of important habitats in areas where sound-producing activities under BOEM's purview are expected to occur are important factors in determining the species of concern.

As with many other types of impacts, the environment to which an organism has become acclimated has a big influence on the magnitude of the effect from a new man-made source. In compiling the Literature Synthesis, it was clear that humans have had a substantial influence on levels of sound in the sea but that the levels, as well as natural sound levels, vary greatly from one place to another. This variability has significance in the ability to predict the response of an organism tested in the laboratory or in an environment with background noise that differs from a project area. The Literature Synthesis also reviewed the types of sounds produced by invertebrates and fishes. It was concluded that sounds produced by aquatic invertebrates, particularly crustaceans, are important for communication. Many fish species have been documented as producing sounds that appear to have specific functions (e.g., sounds produced by spawning fishes are often distinctive) although it is not known whether a majority of species vocalize. Hearing ability in fishes can be inferred, to some degree, from anatomy however. The proximity and/or connection between a swim bladder (or other air chamber) and the ear provides a reliable indicator of species that hear relatively well compared to other species without such a connection.

The activities that BOEM regulates have the potential to introduce additional sound into the marine environment in several ways: seismic exploration, sonar, impact and vibratory pile driving, explosives to remove infrastructure, dredging to extract minerals, and increased vessel traffic. The Literature Synthesis has characterized these sources and, to the extent possible, the range of sounds that they generate. An understanding of how man-made sounds overlap with hearing capabilities is critical to evaluating potential impacts and to establishing any regulatory criteria for noise exposure.

All of these discussions build up to the fundamental question driving this project - what are the effects of man-made sounds on fishes, fisheries, and invertebrates? Clearly, there is no simple answer to that. The effects can range from physical to physiological to behavioral. The available research has generally involved a very limited number of species in very specific situations, mostly in the laboratory and less frequently in a field environment. The results of this research is provocative in that there are many indications that fishes and invertebrates do indeed react to man-made sound sources under some circumstances, though not necessarily under all. The question that BOEM faces is whether these reactions are of a magnitude that could affect the stability of a population or affect fisheries.

Summarizing over 300 journal articles and government reports on these subjects, the Literature Synthesis can be used as a guidance reference for impact analyses for specific projects in the future.

2. THE WORKSHOP

The Workshop on the Effects of Noise on Fish, Fisheries, and Invertebrates was held 20-22 March 2012 at the Town and Country Resort in San Diego California. More than 150 people participated in the three-day Workshop (see participant list in Appendix D), including representatives from Federal and State agencies, academia, NGOS, consultants, and public interest groups to meet the goals described in Section 1.2.

2.1 Overview of Meeting

The Workshop was divided into four major areas that included a series of presentations and breakout discussion groups designed as building blocks to address the key questions posed by BOEM at the onset of this project. Speakers, invited experts in their fields (Appendix C), were asked to focus on an overview of fairly broad topics with a charge to identify key areas they felt required additional research. The breakout groups were designed to flesh out specific areas that emerged during preparation of the Literature Synthesis as being particularly relevant to BOEM's needs. The complete agenda is provided in Appendix A.

Plenary Sessions One (Introduction and Overview) and Two (Priority Habitats, Species, and Fisheries) were designed to set the stage, defining why BOEM needs information on the effects of noise and how it will be used (Session One) and which fish and invertebrate resources are of concern (Session Two). Characterizing the sounds likely to emanate from BOEM activities was the subject of Plenary Session Three (Sources and Sound Exposure). Session Three was followed by three concurrent breakout sessions discussing: characterization of sources and how best to determine exposure; mitigation through technology; and noise measurements and metrics. During Plenary Session Four (Effects of Sound on Fishes and Invertebrates), papers describing how fishes and invertebrates detect and use sound as well as how man-made sounds affect these species were presented. Concurrent breakout sessions on this topic discussed: how to determine the effects of exposure to sound on catches; behavior of wild fishes and invertebrates relative to sound exposure; and defining injury, physiological damage, and stresses from sound exposure.

During Session Five (Conclusions), rapporteurs from each breakout session presented the major findings from their discussions. Dr. Hawkins summarized the research issues and data needs that emerged from the technical presentations during the Workshop. Combined with the Literature

Synthesis, the plenary presentations and the rapporteurs' summaries formed the basis of the Gap Analysis.

2.2 Annotated Agenda

Presentations from the plenary sessions and discussions from the breakout groups are summarized in this section. The themes and concepts presented at the workshop were also discussed in the Literature Synthesis and the reader is referred to Appendix E for additional discussion and references supporting statements in these summaries.

2.2.1 Session One: Introduction and Overview

Session One Chair: Ms. Ann Pembroke, Normandeau Associates, Inc.
Session One Rapporteur: Dr. Jennifer Miksis-Olds, Penn State University

Introduction to the Workshop, Purpose and Goals (presentation: Appendix B, p. 1)
Ms. Ann Pembroke, Normandeau Associates, Inc.

Ms. Pembroke described the overall goals of the Workshop which would be discussed during four sessions:

Session One: Introduction and Overview: Establish an understanding of the policies and procedures BOEM must follow to implements its missions, and summarize the current understanding of the science as described in the Literature Synthesis.

Session Two: Priority Habitats, Species and Fisheries: Define the organisms of concern to regulators, managers, and the fisheries and conservation communities.

Session Three: Sources and Sound Exposure: Define the soundscape and sounds emanating from various activities, followed by breakout groups to discuss the characterization of sources, reductions of sound emissions, and cumulative effects.

Session Four: Effects of Sound on Fishes and Invertebrates: Discuss which organisms can hear, how they hear, which make sounds, and how the organisms are affected by man-made sounds. Breakout groups would discuss the implications in terms of behavioral responses of organisms, sound-related injuries, and effects upon fishing.

Session One focused on three questions relative to the science needs, policies, and mitigation approaches of BOEM:

1) Why does BOEM need information on the effects of man-made underwater sound on fishes, fisheries, and invertebrates?
2) What is a significant impact of man-made sound under NEPA? Under ESA? Under the MSFCMA?
3) What authority does BOEM have to require mitigation for impacts of man-made sound?

To address these questions, Session One included three presentations:

- BOEM Introduction and Overview;
- Impact Statements and Regulatory Requirements for Offshore Developments; and
- The State of the Science - Introduction to the Literature Synthesis.

BOEM Introduction and Overview (presentation: Appendix B, p. 2)
Dr. Alan Thornhill, Bureau of Ocean Energy Management (BOEM)

Dr. Thornhill presented an introduction and overview of BOEM including its mission, structure, program goals, and process flow. BOEM is interested in gaining more knowledge on the effects of man-made sound on fishes, fisheries, and invertebrates because they are responsible for regulating industry activities such as exploration, construction, development, operations, maintenance, and decommissioning that all produce noise. BOEM needs to understand the potential impacts of man-made sound from these activities on various animals and ecosystems.

BOEM's mission is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.

The framework for how BOEM assesses annual information needs and how that information is then applied to program discussion was described (Figures 1 and 2). The level of current information and identification of the need for more information on a particular topic begins in the Environmental Studies Program (ESP) and proceeds through risk analysis stages governed by all applicable laws, including, but not limited to, the National Environmental Policy Act (NEPA), Marine Mammal Protection Act (MMPA), and the Endangered Species Act (ESA). NEPA is an overarching mandate and requires consideration of all Acts at the same time. The NEPA process provides information that is used to make appropriate decisions.

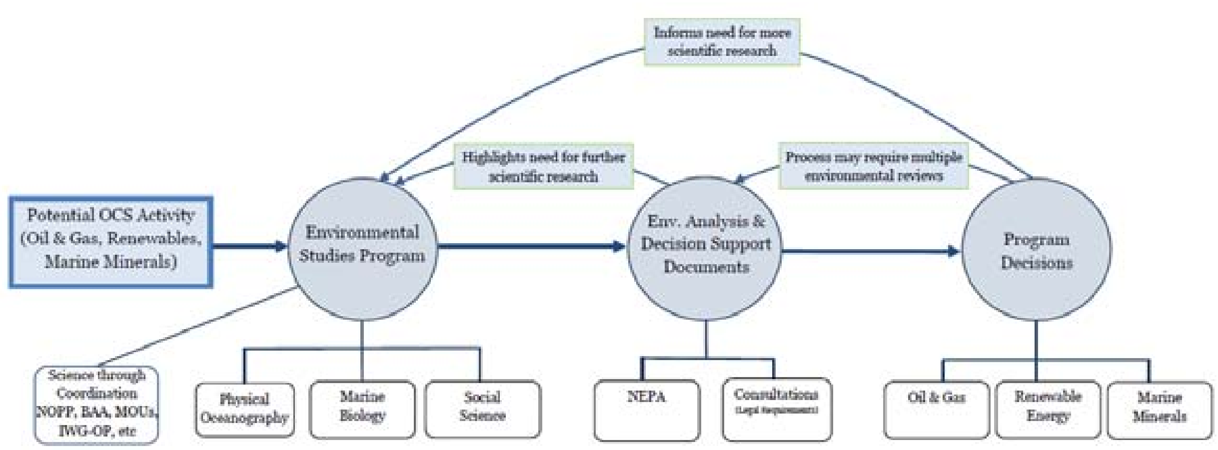

Figure 1. BOEM applied science and informed decisions framework.

The Environmental Studies Program (ESP) is tasked with: 1) establishing the information needed for assessment and management of environmental impacts; 2) predicting impacts on marine biota; and 3) monitoring human, marine, and coastal environments. To accomplish these goals, study priorities are determined by: 1) mission relevance; 2) scientific merit; 3) technical feasibility; 4) timing; 5) applicability to mission; and 6) affordability. Programs of study are then launched to direct adaptive management efforts in a specified area.

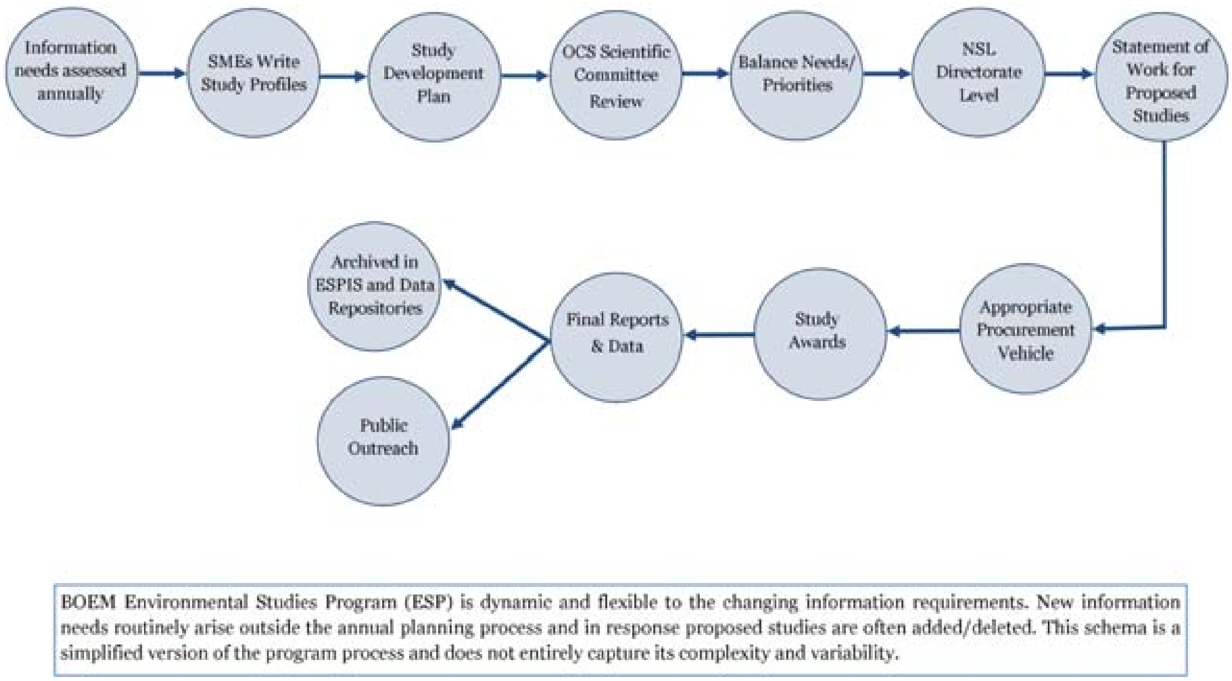

Figure 2. Environmental Studies Program (ESP) process flow. The workshop feeds into the first flow circle as noted in the figure.

Dr. Thornhill pointed out that this Workshop was convened to:

- identify information needs and gaps related to the impacts of man-made sound;
- identify the feasibility of studies to fill the information needs and gaps; and
- develop priorities for addressing identified needs and gaps.

Results from the Environmental Studies Program will be used to direct future research, conduct NEPA analysis; inform BOEM models; and, develop mitigation actions, stipulations, and issue Notice to Lessees (NTLs) to minimize impacts to fishes and fisheries.

Impact Statements and Regulatory Requirements for Offshore Developments (presentation: Appendix B, p. 7)
Ms. Kimberly Skrupky, Bureau of Ocean Energy Management

Ms. Skrupky presented the BOEM strategy to address man-made noise and the related effects on the environment. Activities that are regulated by BOEM and BSEE include geological/geophysical sources, as well as construction, drilling, production and decommissioning, wind and wave energy activities, and marine minerals dredging in federal waters. The development of management strategies for environmental protection, as it relates to BOEM's mission, was identified as ongoing and adaptive, whereby effectiveness must be evaluated through monitoring, re-analysis, and using new information for improvements. Noise is produced in several ways in BOEM's three program areas. Geological and geophysical surveys require the use of several sound-producing devices such as air guns, boomers, sparkers, chirpers, sub-bottom profilers, depth sounders, and side-scan sonar. During construction, drilling, production, and decommissioning, noise is produced by pile driving, routine operations on rigs and platforms, vessels, dynamic positioning systems, explosives, dredging, and ice breaking. BOEM uses several measures to monitor or provide mitigation for species of concern (primarily marine mammals and sea turtles) during sound-producing activities. These measures include use of dedicated observers on the vessels (with a plan to halt work if necessary), monitoring of exclusion zones, passive acoustic monitoring, sound source verification, ramp-up, shut-down, and time-of-year closures. Effective mitigation measures for fishes are generally lacking, however.

State of the Science – Introduction to the Literature Synthesis (presentation: Appendix B, p. 9)
Dr. Arthur N. Popper, University of Maryland
Dr. Anthony Hawkins, Loughine Limited

Dr. Popper and Dr. Hawkins summarized the BOEM Literature Synthesis. Two regions of focus had been identified: the U.S. Atlantic Outer Continental Shelf (OCS) and the Arctic OCS. The Atlantic was selected as a targeted interest area due to the importance of fishing, continued dredging projects, development of new renewable energy projects, and oil and gas exploration activities that may be under consideration in the future. The Arctic OCS was selected because it is a relatively new region of interest that is considered comparatively pristine, with few shipping routes and relatively small fisheries. The Arctic OCS is of special interest because of the challenges related to foreseen/potential oil and gas development in the region.

It is anticipated that these two OCS regions will see an increase in BOEM-regulated activities, so new and updated data are needed as ocean use changes. The Literature Synthesis (Appendix E) highlights these planning areas and the important fisheries. The Synthesis identifies what is known about fish and invertebrate resources and fisheries within the Atlantic and Arctic OCS and what types of data are needed in order to understand more about the impacts of man-made sound on these resources and uses. Currently it is known that: 1) energy developments generate substantial sound; 2) many marine fishes and invertebrates can detect sound and use sound in their everyday lives; and 3) there is the potential for the sounds produced during energy development to adversely affect species and habitats, and to thereby indirectly affect fisheries. How do we bridge the knowledge gaps?

The Literature Synthesis focused on four broad questions:

- Are levels of sound in the sea changing as a result of human activities?
- Do man-made sounds have detrimental effects upon fishes and invertebrates?

- Which sound-generating activities are most damaging to fishes and invertebrates?
- How might effects be reduced or mitigated?

Discussion of Presentations of Session One

The discussion raised some important questions and areas of concern related to both mitigation and communication. First, there was a question on how much authority BOEM has to require mitigation. BOEM can impose mitigation requirements if they are feasible, effective, and necessary. Often the effectiveness of mitigation methodologies is questioned and so it is important to assess whether mitigation actually works. Mitigation based on unproven strategies is often proposed, but decisions should be should be based on their actual effectiveness. BOEM has initiated research on mitigation measures.

A second question centered on the need to bridge the gap between science and regulation. Researchers need to communicate with BOEM and other regulators to help advance management and regulation. Opportunities for interaction include public comment on NEPA documents and environmental impact statements, workshops, and one-to-one conversations.

Session One Summary

In summary, the session considered the drivers and rationale for BOEM's interest in the effects of man-made sound on marine life and described how the BOEM process worked and applied the results of scientific studies in decision-making. The importance of evaluating mitigation proposals was also underlined. It was noted that BOEM's sister agency, Bureau of Safety and Environmental Enforcement, was tasked with developing and enforcing safety and environmental regulations.

The Workshop sessions had been designed to address these over-arching questions. In addressing the larger picture, it was noted that no single answer would fit all sound sources, species, or energy or mineral projects. Two data gaps already identified were the need to consider the effects on animals of particle motion as well as sound pressure, and the need to relate observed responses to the environmental context in which they occurred.

2.2.2 Session Two: Priority Habitats, Species, and Fisheries

Session Two Chair: Dr. Christopher Glass, University of New Hampshire
Session Two Rapporteur: Dr. Joseph Luczkovich, East Carolina University

The focus of Session Two was to identify the species, fisheries, and habitat in the Arctic Ocean and the South and North Atlantic Ocean that may be impacted by noise. There were six questions to be addressed for each of these three ocean regions:

1. Are there species (or life stages of species) or habitats that are particularly vulnerable to man-made sounds?
2. Are there areas within the OCS that should be protected from increased noise?

3. Are there seasonal aspects to the need for protection?
4. Can risk be mitigated? How?
5. Do we know enough to make recommendations on the protection of species and habitats? If not, what do we need to learn?
6. Do fisheries themselves need protection from the effects of man-made sounds?

Protected Species/Habitats (presentation: Appendix B, p. 12)
Dr. Craig Johnson, National Oceanic and Atmospheric Administration

Atlantic salmon (*Salmo salar*), shortnose sturgeon (*Acipenser brevirostrum*), four subpopulations of Atlantic sturgeon (*A. oxyrhincus*), and the smalltooth sawfish (*Pristis pectinata*) are currently listed as endangered by NMFS in the Atlantic. The Gulf of Maine subpopulation of Atlantic sturgeon, elkhorn coral (*Acropora palmata)* in state waters and staghorn coral (*A. cervicornis*) in state waters are listed as threatened in the Atlantic. Critical habitat has been identified for smalltooth sawfish and NOAA is expecting to identify critical habitat for Atlantic sturgeon in the next several years. In the Arctic Region, NMFS has not listed or proposed for listing any marine, anadromous, or catadromous fishes or invertebrates as endangered or threatened.

Offshore energy development activities are associated with several physical, chemical, and biotic stressors that pose potential risks to endangered and threatened fishes and invertebrates. Activities of concern include seismic surveys, underwater detonations, vessel traffic, pile driving, coastal dredging, oil spills, chemical contamination, and potential introduction of non-native species. Dr. Johnson cited research showing evidence of hearing in sturgeon and salmon. Coral and fish larvae have been documented as using sound for orientation and larvae of coral reef fishes can be affected by sound.

NOAA scientists use a risk assessment model that starts with the measured sound levels then tries to assess potential damage to all species in the area. NOAA risk analysis starts with the species of concern (listed as endangered or threatened under ESA or overfished species with management plans), then moves to proposed project, and then considers damages from sounds and other factors that may alter Essential Fish Habitat (EFH) or Habitat Areas of Particular Concern (HAPC). The most difficult information to determine for this analysis is the overlap between the activity and the protected resource. Two types of risks must be assessed: increases in mortality and reductions in reproductive success. When looking at effects on individuals, if it can be determined that there is no effect on the population, the analysis is concluded. Exposure to multiple stressors limits the ability to understand the effects of sound exposure on protected species.

Arctic Fisheries and Habitat (presentation: Appendix B, p. 15)
Dr. Steve MacLean, North Pacific Fishery Management Council

Although there is currently no commercial fishing in the Arctic and the North Pacific Fishery Management Council (NPFMC) prepared a Fishery Management Plan (FMP) for this area. Recognizing that developing environmental issues (e.g., climate change) and human stressors (international fisheries; oil and gas exploration and development; US Coast Guard operation; US

Navy operations; and the US Arctic Policy) are likely to affect the fisheries resources in the Arctic, the NPFMC saw the need for an FMP to establish a policy and process for orderly fishery development and to address potential future issues proactively.

Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*), and snow crab (*Chinoecetes opilio*) are the species with fisheries potential that have the highest biomass in the Chukchi and Beaufort Seas. Bering flounder (*Hippoglossoides robustus*), Pacific herring (*Clupea pallasi*), and warty sculpin (*Myoxocephalus verrucosus*) are also abundant. Subsistence fisheries focus on pink and chum salmon (*Oncorhynchus gorbuscha* and *O. keta*). Populations of species of commercial and subsistence fishery interest in the Arctic are probably not distinct from those in the Bering Sea and North Pacific.

The Arctic Management Area, encompassing waters north of the Bering Strait along the maritime borders between the US and Russia and the US and Canada, is receiving heightened interest from the Council because of climate warming, the limited scientific information available, and the desire to manage this area on an ecosystem basis. Climate change (warmer temperatures) has the potential to reduce sea ice and shift fisheries to the north. It is predicted that Arctic cod, haddock (*Melanogrammus aeglefinus*), herring (clupeid), and capelin (*Mallotus villosus*) populations will shift to the east causing a shift in productive fishing grounds. Walleye pollock (*Theragra chalcogramma*), currently focused in the Bering Sea, is one of the largest fishery in the world but increases in sea temperature may be shifting the population northward, potentially into areas of interest for oil and gas development.

Current research is directed to developing a better understanding of the Arctic environment overall. The Council feels there is insufficient information yet to define the baseline for the system. In addition to considering commercial fisheries, the interactions between fish stocks and marine mammals and sea birds are critical. There is some information that suggests an HAPC for skate eggs should be considered.

South Atlantic Fisheries and Habitat (presentation: Appendix B, p. 18)
Ms. Jaclyn Daly, NOAA and Mr. Roger Pugliese, South Atlantic Management Council

There are many fish and invertebrate species in this region that are considered overfished by the Southeast Fishery Management Council (SAFMC); the habitats of federally-managed species are protected under the Essential Fish Habitat (EFH) regulations of the MSFCMA. Overfished species include but are not limited to: snapper-grouper complex, clupeids, and multiple species of drum, tuna, mackerel, and billfish. Invertebrates that have fishery management plans and are potentially sound-sensitive include deep-water corals (zoanthatria), squid (teuthida), golden crab (*Chaceon fenneri*), spiny lobster (*Panulirus argus*), and brown (*Farfantepenaeus aztecus*), pink (*F. duorarum*), rock (*Sicyorzia brevirostris*), royal red (*Pleoticus robustus*), and white shrimp (*Litopenaeus setiferus*). A comprehensive list of species can be found in Chapter 3 of the Literature Synthesis.

Through the development of Fisheries Management Plans and EFH designations, the SAFMC has also identified Habitat Areas of Particular Concern (a subset of EFH), Marine Protected Areas, and Special Management Zones from Cape Hatteras NC to Cape Canaveral FL. These habitats are designed to afford protective space to commercially and recreationally important fisheries; the effects on managed species from elevated noise levels and bottom disturbing activities in these protected areas should be assessed.

North Atlantic Fisheries and Habitat (presentation: Appendix B, p. 24)
Dr. Kevin Friedland, NOAA

A number of species managed by the New England or Mid-Atlantic Fishery Management Council (American lobster [*Homarus americanus*], American plaice [*Hippoglossoides platessoides*], Atlantic cod [*Gadus morhua*], Atlantic halibut [*Hippoglossus hippoglossus*], butterfish [*Peprilus triacanthus*], goosefish [*Lophius americanus*], haddock, ocean pout [*Zoarces americanus*], scup [*Stenotomus chrysops*], thorny skate [*Amblyraja radiata*], white hake [*Urophycis tenuis*], windowpane flounder [*Scophthalmus aquosus*], winter flounder [*Pseudopleuronectes americanus*], and yellowtail flounder [*Limanda ferruginea*]) are considered overfished, at least regionally. The status of an additional 14 species is unknown however. Habitat for many of these species is widespread in this region. Although general distributions are well-known, specific areas that have important life history functions (e.g., spawning areas) are less well understood. HAPC has been designated for one species – the sandbar shark (*Carcharhinus plumbeus*).

Cold water (or deepwater) corals do not form the massive reefs that tropical corals do. Distribution of deepwater corals is primarily on the shelf break, but these species also occur in deeper portions of the Gulf of Maine.

Dr. Friedland noted that in addition to the direct effects of fishing, these populations may also be affected by changes in temperature patterns, shifts in the plankton and forage fish populations, and habitat impacts of fishing.

Session Two Summary

The panelists were clear that endangered or threatened species are an important consideration under any NEPA analysis. Effects from underwater sound on these species or their habitats (including food resources) could result in mitigation requirements, including restrictions developed during ESA or EFH consultations or permitting negotiations. Federally managed species that are in low stock abundance (whether by overfishing or by other stressors) or are under a fishery management plan (stock rebuilding) should also be given priority review. Drs. Lusczkovich and Glass recommend that these species be categorized based on their ability to produce or detect sound. Sound producing or sound sensitive (i.e., those with swim bladders) species should be given a higher research priority than species with neither characteristic. Further, certain habitats should receive priority consideration, in particular coral reefs because of evidence that fish and invertebrate larvae associated with these reefs use sounds from the reefs to navigate. Sound-sensitivity of other types of habitats has not documented at this point. An example of a sound-sensitive habitat might be areas where soniferous fishes congregate (e.g., cod spawning areas in Massachusetts Bay).

There is much that remains to be learned. While there are clearly seasonal changes in the spatial distribution of soniferous or sound-sensitive species (spawning, seasonal migrations), these areas cannot always be designated precisely. The risks to these species from sound-producing activities have not yet been clearly defined; the need and ability to mitigate these risks is not well understood. Presentations in Session Four certainly suggest that consideration of effects on the fisheries themselves will be important.

2.2.3 Session Three: Sources and Sound Exposure

Session Three Chair: Dr. Roberto Racca, JASCO Applied Sciences (Canada)
Session Three Rapporteur: Dr. James H. Miller, University of Rhode Island

Session Three focused on the quantitative description of underwater sound from natural and man-made sources. Standardizing how researchers describe and measure sound is essential for successful regulation, mitigation, and monitoring of underwater noise that can potentially affect fishes, fisheries, and invertebrates, as well as for analysis of potential effects on animals. The presentations within this session focused on providing a better understanding of characteristics of sources and sound exposure, and on identifying information needs and data gaps by focusing on three questions:

1. What are the levels and characteristics of natural and man-made ocean sound in the areas of interest?
2. What are the likely future trends in sound levels from man-made sources in those areas?
3. Which man-made sources are likely to have the strongest adverse effects on animals?

To address these questions, Session Three included six presentations as follows.

Measurements, Metrics, and Terminology (presentation: Appendix B, p. 33)
Dr. Michael Ainslie, TNO(The Netherlands)

Dr. Ainslie reviewed the fundamental properties of underwater sound (see Appendix A for the specific metrics and their definitions from this presentation) and pointed out the need for having precise terminology that is applied internationally. Ambiguity and discrepancies were identified in describing sounds, generally, selecting examples of relevance to fishes such as the interim criteria for injury to fishes from pile driving activities set out by the Fisheries Hydroacoustic Working Group (FHWG 2008). Some of the ambiguities in describing sounds stemmed from differences between the American National Standards Institute (ANSI 1994) and the International Organization for Standardization (ISO 2007) definitions of sound pressure level. In addition, different ways of measuring and describing sounds have been adopted by different researchers. The need for international terminology standard for underwater sound will be considered at an inaugural meeting at Woods Hole Oceanographic Institution on 11-13 June 2012 (ISO TC 43, SC 3).

Sea Noise (presentation: Appendix B, p. 37)
Dr. Robert McCauley and Dr. Christine Erbe, Curtin University (Australia)

Dr. McCauley described the marine acoustic environment consisting of natural and man-made sounds (marine soundscapes) and the relationship between animals and their environment mediated through sound (acoustic ecology). The definition of "noise" depends on the context, but was generally defined as a signal that interferes with detection of a signal of biological interest to an organism. Sounds from animals appear to substantially contribute to the variability of ambient noise, often in cyclic patterns. Because marine soundscapes depend on the local environment, the spatial variability makes prediction of ambient noise for the world's oceans and regional environments difficult. A consistent approach to measuring and reporting characteristics (e.g., spectral density) of soundscapes are essential to understanding acoustic ecology and assessing potential noise impacts on organisms, a point that paralleled comments made by Dr. Ainslie in the previous presentation. Long-term, publically available data sets collected from ocean observatories will be important in the future to better characterize marine soundscapes. An important question remains as to how much noise is "too much," and what criteria should be used in regulation. Specific data gaps and information needs are highlighted in the Data Gap Analysis.

Seismic Sources (presentation: Appendix B, p. 42)
Mr. Mike Jenkerson, ExxonMobil Exploration Co.

Mr. Jenkerson provided an overview of the output of air gun arrays characterized by historical and current studies. The importance of calibration, measurements, and modeling was emphasized for characterizing the sound field produced by seismic sources used in oil and gas exploration. The important point was made that near field measurements could be 20 dB lower than the back-calculated far field measurements after accounting for transmission loss because at close ranges the sound field is dominated by single air guns rather than the entire air gun array. The presentation focused on improving current airgun modeling by increasing the model frequency range to 25+ kHz, testing accuracy of modeling at higher frequencies with calibration data, and improving particle velocity measurements. Marine vibroseis, using a frequency modulated sweep rather than an impulse, was described as a potentially valuable alternative to airguns because it produces a lower spectral density, particularly at higher frequencies. Marine vibroseis transducers are currently being evaluated by joint-industry research that includes geophysical and environmental testing of prototype transducers and conducting particle velocity measurements.

Pile Driving (presentation: Appendix B, p. 45)
Mr. James Reyff, Illingworth & Rodkin, Inc.

The methods for measuring the intensity and impact of underwater sound generated by pile driving activities were presented. Assessment of impact on organisms can vary based on the metric used for describing the sounds. Standardization of the metrics would help with assessing the impact of pile driving on fishes and invertebrates. Furthermore, there is disagreement among researchers on the current criteria (FHWG 2008) being used in regulation of sound produced from pile driving (See talk by Ainslie who raised the same issue; see talk by Halvorsen who presented research that contradicts the FHWG criteria levels).

Pile types and driving methods were discussed, and the equipment used for different construction applications was identified. Cast or steel shell piles are of greatest interest because they are used for deep water construction and/or for larger projects. These require the biggest hammers for impact driving. The largest piles driven (e.g. 350 ft length) use large hydraulic impact hammers, which use over 1700 kJ of energy during driving events. Methods for minimizing the impact of sound produced from pile driving were discussed, including: air bubble curtains (confined and unconfined), dewatered casings, and dewatered cofferdams.

Wind Farms (presentation: Appendix B, p. 52)
Dr. Jeremy Nedwell, Subacoustech Ltd. (United Kingdom)

The sounds created by wind farms were described. The largest issue facing the wind power industry in the UK is the environmental effects of noise, particularly during the pile driving phase of construction.

Impact driving is used during the construction of wind platforms, with 4-m diameter piles as the current industry standard, although piles up to 12 m in diameter are being considered for future projects. Studies of sound production have only been reported for piles up to 6.5 m in diameter, so the issues with driving very large piles cannot be addressed with current information.

Currently in the UK operational noise must be measured when the wind turbines begin power generation. To determine the impacts, the pre-existing conditions of the soundscape must be known. Typically wind farms are situated in shallow (<50 m) coastal waters where there are numerous other sources of noise including oil platforms and coastal shipping, flow and surf noise, pingers, and oil-gas exploration. In these areas, shipping noise is considered to be the most important biological concern.

Comparing noise levels at short distances from the turbines (14-28 m) to standard coastal noise allows the estimation of the contribution of operating wing turbines to the total sound in the water. The unweighted SPL was estimated to be 128 dB when extrapolated back to 1 m from the source. However, it is difficult to determine the effects of this noise level because of a lack of specific criteria for comparison.

Dr. Nedwell suggested that similar criteria for assessing noise effects upon humans should be applied to fishes. Values for sound pressure weighted to the response of the animal were especially useful.

For wind farms, short-term effects resulting from the construction phase are likely (vessel traffic, pile driving, dredging, trenching). The cumulative effect over the full time scale of the operational phase of wind turbines must be considered, as operational noise may result in habitat exclusion for sensitive species. However, even allowing for long operational time, estimates of habitat loss caused by operation are dwarfed by the sources deployed during installation, especially impact pile driving.

In summary, the noise generated during the operational phase of wind farms is unlikely to be a problem. However, the noise during the construction phase has already become a concern. Ways of minimizing the impact of noise generation during construction should be examined. To accomplish this, research should focus on simultaneous measurements of sound generation and related biological responses.

Other Anthropogenic Sources of Interest (presentation: Appendix B, p. 55)
Dr. Michael Ainslie, TNO (The Netherlands)

The properties of other sound sources were presented, with focus on two sources: ships and explosions. Ships are persistent sound sources that raise background levels, whereas explosions are short in duration but higher in intensity. Other anthropogenic sources of sound include echo sounders, search sonars (fisheries, military, and coastguard), acoustic deterrents, transponders and communication systems, scientific instruments, minesweeping equipment, and acoustic cameras.

Measurements reported by Wales and Heitmeyer (2002) found no correlation between vessel source level at cruising speed or type of vessel. Based on this result, monopole source level could be parameterized entirely as a function of frequency. However, other work has identified differences in broadband radiated noise level between different vessel types and traveling at different speeds.

The energy released from an explosion depends on the charge mass, and is distributed into the water in two phases: shock wave (>200 Hz) is approximately one megajoule (1 MJ), and bubble pulse (<200 Hz). Because of its low frequency, the contribution from the bubble pulse typically does not travel far in shallow water.

It was concluded that shipping contributes persistent low intensity background noise and can be characterized by source level (monopole, dipole, or radiated noise level). Explosions are only occasional noise sources, but are very high intensity and are characterized by energy, peak pressure and duration. The largest contributors to the free-field sound energy (Ainslie and Dekeling, 2011) in the Dutch North Sea, averaged over a year, are probably air guns and shipping (both estimated in the range 1 MJ to 10 MJ), followed by pile driving and explosions (both less than 1 MJ). Worldwide, shipping, airguns, and explosions are estimated to contribute on the order of 100 MJ to 1000 MJ.

Session Three Breakout Group A: Characterizing Sources and Determining Exposure
Chair: Dr. James H. Miller, University of Rhode Island
Rapporteur: Dr. Roger Gentry, E & P Sound and Marine Life Joint Industry Programme

The goal of this breakout group was to clearly identify information gaps with respect to characterizing sources and determining exposures. To guide discussion, the Chair framed the following questions:

1. Can we make meaningful sound inventories? How does man-made sound affect long-term background sound levels in the oceans?
2. 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? How does this change with distance from the source?

3. Which man-made sounds are most important when considering the masking of sounds of importance to animals?
4. How might the characteristics of these man-made sounds change with propagation over larger distances from the source?
5. What are the appropriate standards for measuring man-made sounds that may have an impact on fishes and invertebrates, particularly for particle motion?

Five major areas of concern related to information gaps were identified: 1) terminology and communication; 2) standards; 3) available data; 4) tools available to the research community; and 5) funding. Specific needs within each of these topics were discussed, and are summarized below.

Regarding terminology and communication, the research community needs to develop guidelines for a common terminology. Agreement is needed on how to report data collection methods, instruments used to measure sources, and methods used to calibrate them. An agreed way to measure background noise is needed. Researchers need regulators to specify the types of data they need, and the length of time (months, years) over which they are to be made. The field needs more sophisticated researchers who are adept at both acoustics and biology (an education problem). Biologists generally face a wider spectrum of problems to solve (hearing in many different species) than do acousticians.

The community needs published standards concerning the measurement of background noise, and differences in existing standards identified by the American National Standards Institute (ANSI) and the International Organization for Standardization (ISO) should be resolved. Existing standards must be updated using currently available data. Some of the standards that acousticians use (for instrument calibration, etc.) are only available in Matlab and not in the software most often used by biologists (e.g. Raven).

In regards to data that should be available to researchers, noise measurements are needed in different parts of the oceans for better global representation since trends are found by comparing local budgets against global averages. Data are needed on the elastic properties of the seabed to improve propagation models. Regulators and researchers need access to data that are owned and controlled by industry. Descriptive biological data are needed on hearing abilities in many species of fishes and invertebrates, as a full assessment of noise effects is impossible without this information. Operations should be guided by the biological needs of the area; therefore data are needed on the species that inhabit an area before operations in that area begin.

Tools that must be available to the research community include standard reference sound files for the output of different kinds of acoustic sources, and out-of-plane reverberation models that exist but that are not currently accessible.

The community needs funds to conduct basic research (e.g. measuring sound fields, animal sounds, animal hearing). Industry should provide funds to make noise recordings over biologically-relevant periods of time (often years) instead of just during operations, to enable researchers to collect metadata for validating models or other analytical applications.

Session Three Breakout Group B: Noise Mitigation for Different Sources: Can Outputs be Reduced? Are There Quieter Alternatives?
Chair: Dr. Roberto Racca, JASCO Applied Sciences (Canada)
Rapporteur: Mr. James Reyff, Illingworth & Rodkin, Inc.

The goal of this breakout group was to identify ways to mitigate the effects of sound sources and identify quieter alternatives. The questions posed to the discussion group were:

1. Are there ways of avoiding the use of high level sources or replacing them by other less damaging sources?
    a. What characteristics of sounds make them especially damaging to marine life?
    b. Can sources be redesigned to make them less damaging?
2. Are there technological alternatives to airguns for oil and gas exploration? Can alternative sound sources be developed?
3. What can be done to existing sound sources to reduce unwanted sound? What research and development might result in quieter sources?

The most important noise sources to mitigate were identified as airguns and other geotechnical sources, pile driving, ships, and non-pile driving construction (e.g. dredging). These sources were discussed in detail to determine the appropriate steps necessary to reduce their impact.

Airguns were identified as generating unnecessary and ecologically noxious energy output. Industry is exploring new methods to quieten noise from seismic surveys including the use of vibrators/electro-acoustic sources (which are much lower in amplitude) and underground detonations. Other advancements include enhanced airgun technologies and better optimization of array configuration. These designs are intended to reduce the output of higher frequency sound and provide improved focusing of lower frequency sound. There was brief discussion of the use of autonomous underwater vehicles (AUV) or other deep-deployed sources to reduce insonification of the water column. There is a need to ensure that proper operational procedures aimed at reducing noise are implemented (e.g., not using hull mounted geotechnical sources until on site). There was also discussion on ramp-up or soft-start procedures, with a concern about the lack of guidance to suggest appropriate ramp-up or slow start procedures. It is not even clear if these procedures work for fishes or invertebrates.

Discussion on pile driving first focused on alternative installation methods, such as using vibratory hammers. The problem with vibratory hammers is that they cannot install foundation piles to standardized engineering specifications, and produce a more continuous noise disturbance compared to impact driving. Another alternative to impact driving is hydraulic/pushing methods, but those are not likely to be feasible offshore. Changes in pile material (concrete or metal) and pile tip design may help reduce noise, and it was noted that concrete piles produce lower noise than similar size steel piles. Bubble curtains can be used to reduce noise, although challenges arise in strong currents or deep water. Encapsulated air bubbles and air bubble mats were discussed, and identified as potentially feasible but costly.

There was a brief discussion on mitigating noise from shipping using enhanced propeller designs. It appears that technology for reducing ship noise is developing, and that especially noisy older ships cause much of the problem.

Session Three Breakout Group C: Noise Measurements & Metrics that are Especially Relevant to Determining Sound Exposure: Including Cumulative and Aggregate Effects
Chair: Dr. Brandon Southall, Southall Environmental Associates, Inc.
Rapporteur: Dr. John H. Stadler, NOAA/NMFS, Northwest Region, Habitat Conservation Division

This breakout group began with general discussion centered on three initial questions:

1. What is the difference between acute and chronic exposures?
2. Is it essential to differentiate sources that are near to the receiver from those that are far from the receiver.
3. How can the toxicological concepts of antagonism and synergism be incorporated into dose-response curves?

The group reached a consensus that while the line between acute and chronic exposure is clearly defined in toxicology in terms of duration of exposure, it is not well defined in acoustics. Agreement was reached that injury is most likely to occur in animals that are near a source (with distance related to source level), while sources that are far from the animals are more likely to result in masking and behavioral responses. There was much discussion as to whether sounds from concurrent but different sources counteract one another (antagonism) to reduce the overall effect on an organism or whether they act synergistically to amplify the effects on the organisms.

The remainder of the discussion was spent addressing the six questions posed to the Breakout Group.

1. Is there suitable instrumentation to operate in the near field (non-linear portion of the sound field) to measure particle motion as well as sound pressure?

- Is particle motion important?

Before the group answered the question on instrumentation, it asked the question "is particle motion important?" The consensus was that it is clearly an important factor and needs to be taken into account when assessing the risk to fishes and invertebrates from underwater sounds. This was based, in large part, on the concept that all fishes, and very likely most aquatic invertebrates, are sensitive to particle motion. Particle motion is usually considered to be most relevant in the near-field, where it is not proportional to pressure, but may, in fact, also be important in what is typically considered to be the far field. Examples of this are the responses of fishes to acoustic surveys despite being hundreds of meters from the sound source. Particle motion is not considered in any of the current acoustic criteria for fishes, even though it is now recognized as being fundamental to hearing.

- There needs to be a clear definition of near field and far field.

Currently, there appears to be much confusion over where the near field transitions to the far field and there is a misconception that near field energy stops at the transition region. This "transition point" will vary, depending on the source of the sound, the frequencies, and the environment. For instance, the near field from a seismic airgun array can extend for tens of meters from the source due to the low frequency components of the source. Another example is pile driving, where the vibration of the pile induces vibrations in the surrounding sediments, resulting in sound emissions from substrate at substantial distance from the pile driving operation. This expanded source can produce significant particle motion at considerable distances from the pile.

It as also pointed out that the "dichotomy" between particle motion and pressure may be arbitrary because it ignores the continuum of conditions that exist in moving away from the sound source, much the way the old approach of classifying fishes as hearing generalists or specialists ignored the continuum in hearing abilities and mechanisms. As we begin to reliably and systematically measure particle motion, this distinction will become less important.

- There is a clear need for the development of reliable, easy to use, particle motion instrumentation and analysis software.

Although there are several types of instruments available to measure particle motion, the technology is not mature and the available instruments have various drawbacks. The group recognized the need for the development of readily available, easy to use instrumentation and software to systematically and reliably record, analyze, and report particle motion measurements for a variety of sound sources. In addition, there is a strong need for standardization of how particle motion is measured and reported and standardized protocols for calibrating the instruments similar to those for hydrophones.

2. How can measurements be reliably obtained in complex environments, including water tanks, and at the sea surface and substrate boundaries?

- Studies in small tanks have known limitations.

It was generally agreed that accurate measurements of the sound signal are not possible in tanks due to the complex nature of the sound field. Measurements of sound pressure can vary considerably even over very short distances. Thus, it is often best to conduct acoustic studies in the field, and that is the direction of current research.

Limited studies on effects of sound on organisms can be done in tanks but are better suited to investigating injury or other physical damage than to examining the effects of sound on behavior. Tanks for such studies must be designed to allow full calibration of the pressure and particle motion components of sound field to which animals are exposed. The design and applicability of tank studies will depend, in large part, on understanding the stimulus presented, the scale of the tank, and the boundary conditions in it.

- Generating signals of the appropriate intensity (e.g., pile driving) is difficult, if not impossible, in tanks.

This is a considerable obstacle in designing tank studies to look at the effects of the high intensity sounds. Actual sound sources (e.g., a pile driver) cannot be brought into the laboratory so they must be simulated through other methods such as playback of recording through underwater speakers. Equipment necessary to generate these sounds is not generally available. An additional problem with conducting studies on high intensity sounds in tanks is that standard tanks can fail or be severely damaged by these sounds. The limited equipment that is designed to both generate and withstand these sounds is complex (e.g., the HICI-FT) and can be expensive and difficult to obtain and operate. Field studies, on the other hand, can use actual sound sources, such as air guns or pile drivers, without the constraints of the laboratory. However, it is often not possible for the investigator to control the characteristics of these sounds (e.g., frequency of presentation, amplitude), making it difficult to quantify effects of such sounds, or to establish dose/response curves. In these cases, lab-based tanks, if properly designed, have value.

- Improvements in experimental tank design and acoustic signal generation equipment are necessary to advance the ability to conduct acoustic experiments in the laboratory setting.

3. 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?

- Full time-series recordings need to be preserved for additional analysis.

There was very wide consensus on this point. The group felt that it is vital that when sound data from monitored activities are recorded they be archived in a manner that allows for later analysis. This would provide the opportunity to verify the metrics that were reported as well as to extract additional metrics, including those that are developed or recognized as being important after a study has been conducted. For example, there is a growing library of hydroacoustic monitoring data from pile driving, but sound exposure level, the currently-recognized metric for gauging injury to fishes, was not reported in the earlier efforts. Re-analysis of these earlier data could extract the SEL data and increase their relevance. There is currently no mechanism or standards for archiving these data, and no central repository for storing them.

- The relevant acoustic metric will vary across exposure scenarios.

The group recognized that the relevant metrics can vary, depending on the types of effects that are expected from the exposure to underwater sounds, and the purpose of the recording effort. For instance, the metrics for describing acute exposure to impulsive sounds when close to the sound source (e.g., those that can cause physical injury) will be different from those used to gauge chronic exposure to continuous sounds when far from the source (e.g., those that can cause masking and disrupt behavior). The group identified metrics that are considered important in four scenarios:

  - Injury from acute exposure to impulsive sounds close to the source
  - Injury from acute exposure to non-impulsive sounds close to the source
  - Masking or behavioral disruption from acute exposure to impulsive sounds near the source
  - Chronic exposure to non-impulsive sounds distant from the source.

Some of the metrics were considered essential, must-have metrics, while others were considered optional, or useful to collect if possible. The metrics for these four scenarios are shown in Table 1.

Table 1. Metrics identified by the breakout group that are essential (E), optional (O), or not applicable (N/A) for four exposure scenarios. Metrics that were not discussed under a given scenario are left blank.

Metric	Acute close intermittent injury	Acute close non-impulsive injury	Acute near masking or behavior impulse	Chronic distant non-impulsive
Peak	E	E	E**	
SEL	E	E		
RMS	N/A*	E	E	E
Rise time	E		E	
Measure of peakiness (e.g., kurtosis, crest factor, impulse)	O			
Time-integrated (e.g., 1/3rd Octave band, frequency spectrum, etc)		O	O	E
A measure of S/N ratio that accounts for detectability by species		E		

* this appears to be a vestige of out-of-date regulatory requirements
** only at distance for repetitive impulsive sounds

- Standardization of acoustic metrics and reporting methods are needed.

The group recognized that acoustic metrics are not uniformly reported, and can represent various measures. For instance, peak pressure is used to describe peak-to-peak pressure change, zero to positive peak, zero to negative peak, or the maximum variation from zero (maximum absolute value). While all of these metrics may be useful, the lack of a convention for distinguishing between them can create problems when trying to interpret data. Similar issues can be identified for other metrics. For time-averaged metrics, such as rms, SEL, the averaging window should be specified. There are no conventions for reporting these. While there are several standard definitions of acoustic terminology (e.g., ANSI, ISO), they are not consistent with each other, increasing the chances for misinterpretation.

- The acoustic space around an organism undergoes natural expansion and contraction.

This is important when considering the effects of man-made sound on masking and behavior. Most of the sounds produced by fishes are relatively weak, especially compared to man-made sounds. The spawning sounds of fishes can be weak to reduce the likelihood of interception by competitors or predators. The distance at which these sounds are audible to the intended receiver is inversely proportional to background sound levels. At close range, intermittent man-made sounds have a low probability of masking biological sounds, but at far distances, repetitive impulsive sounds such as seismic airguns can merge into a near-continuous sound through reverberation and cause masking.

4. How should we deal with cumulative effects from multiple pulses from the same sources?

5. What metric is the most appropriate to help in understanding the accumulation of sound energy?

These two questions overlapped and much of the discussion centered on the term "cumulative effects."

- The definition of the term "cumulative effects" varies with context and user.

In an acoustic context, "cumulative effects" can refer to the accumulation of sound energy from a single source (e.g., a pile driver) or a combination of sources (e.g., multiple pile drivers or pile drivers and dredging). In addition, U.S. statutes define this term in various ways (e.g., NEPA and the ESA). Discussion clearly showed the need for terminology that avoids this contextual issue. One suggestion was to use the term "aggregate effects" to refer to the accumulation of sound energy from exposure to multiple sound sources and "cumulative effects" when referring to the accumulation of sound from repeated exposure to a single source. However, no consensus was reached indicating that this issue requires further consideration.

- The most widely used metric to describe the accumulation of sound energy from multiple exposures to a sound source is the "cumulative sound exposure level" (SEL_{cum}).

The advantage of using SEL over other metrics is that it provides a mechanism for summing the energy over multiple exposures. The Federal Highway Administration, in coordination with the California, Oregon, and Washington Departments of Transportation, established a Fisheries Hydroacoustic Working Group (FHWG) to improve and coordinate information on fishery impacts caused by in-water pile driving. Additional members of the FHWG include NOAA Fisheries (Southwest and Northwest), U.S. Fish and Wildlife Service, California Department of Fish and Game, and the U.S. Army Corps of Engineers which are also supported by a panel of hydroacoustic and fisheries experts. The FHWG uses SEL_{cum} to describe the cumulative effects to fishes from exposure to multiple pile strikes. The FHWG has established dual criteria for the onset of injury to fishes of different sizes from exposure to pile driving although the group pointed out limitations because these criteria were based on single exposure studies.

- Monitoring for dead or injured fishes would improve our understanding of the magnitude of the effects of exposure to these sounds as well as provide some verification that current criteria are appropriate.

Regulatory agencies can require visual monitoring and reporting of dead, injured, or distressed fishes, but may not have the authority to require more intensive surveys (such as tow nets) for affected fishes. Some agencies make the decision to do these surveys on their own when carrying out a project, but do not usually have the facilities to conduct these surveys. There are also problems associated with more intensive surveys, including, but not limited to the ability to collect affected fishes in areas where they are dispersed by currents (i.e., a dead fish may float to the surface a considerable distance from where it was affected), the limited ability to collect those that sink to the bottom, and the inability to associate the observed effects (e.g., types of injury) to a received sound level in fishes that are collected.

6. How do effects from different sources and activities accumulate in biological organisms?

While discussion did not conclude by specifically addressing this question, initial discussion at the beginning of the breakout session regarding antagonistic and synergistic effects provided a partial answer.

2.2.4 Session Four: Effects of Sound of Fishes and Invertebrates

Session Four Chair: Dr. Rob McCauley, Curtin University (Australia)
Session Four Rapporteur: Dr. Thomas Carlson, Battelle Pacific Northwest National Laboratory

Session Four was intended to provide BOEM with background of current knowledge, information needs, and data gaps on the fishes and invertebrates that could be affected by sound and their potential physiological and behavioral effects from exposure to all of the BOEM-regulated sound sources. Presentations and discussion with Session Four were guided by the following questions:

1. Which invertebrates and fishes might be engaging in acoustic and other activities related to their long-term fitness, such as spawning, and where do concentrations of them occur?
2. What is the best way to monitor and catalogue the sounds made by invertebrates and fishes and characterize the sounds from key marine species?
3. How vulnerable are different calls to masking or suppression by man-made sound sources?
4. Do fishes have the ability to compensate for changing background noise conditions? If so, how?
5. What is the nature of the physiological effects of exposure to man-made sounds?
6. What are the characteristics of man-made sources that cause detrimental effects?
7. Can man-made sound cause a significant impact on the fitness of individuals within populations that jeopardizes the viability of those populations?
8. Do we know enough about the hearing abilities of fishes and invertebrates?

To address these questions, Session Four included eleven presentations.

Introduction
Ms. Ann Pembroke, Normandeau Associates, Inc.

Ms. Pembroke provided a recap of the prior sessions and set the stage for Session Four.

Diversity of Fishes (presentation: Appendix B, p. 60)
Dr. Brandon Casper, University of Maryland

Dr. Casper provided an overview of the diversity of fishes, contrasting not only their anatomical differences but also their differences in life history and ecology. It is difficult to generalize about the exposure of fishes to sound or their response to sound because of the wide range of habitats they occupy, the wide range of sound exposures they might experience, and the diversity fishes exhibit in physiological adaptations to those environments and in their ability to detect and utilize sound.

There are advantages in distinguishing between effects upon hearing and barotrauma. Impacts to fishes in either category can have effects on their ability to survive and, in the case of barotrauma lead to mortality directly related to the physical injuries sustained during exposure to sound.

There are key anatomical features that might aid categorization of fishes into groups for which some level of generalization about response to sound may be possible. Anatomical features that could aid grouping fish species to assist with generalization of response to sound are skeleton, fat content, reproductive maturity, size, presence of a swim bladder and swim bladder morphology. Grouping of fishes by their sensitivity (generally affected by the relationship of the gas bladder to the ear) and ecological association may also be useful (Figure 3). The potential importance of communication using sound in the life of fishes is now appreciated. It is possible that man-made sound could mask or otherwise interfere with fish communication. The consequences of interruption in communication between fishes are essentially unknown.

		Ecological Associations					
		Large Pelagic	**Small Pelagic**	**Demersal**	**Reef**	**Shallow/Estuary**	**In River**
Fish Categories Arranged by Sensitivity to Sound	**gas bladder connected to ear**		Herring Sprat Shad	Weakfish Deep-sea cod	Squirrel-fish	Catfish Carp Goldfish	Dace Minnow
	gas bladder close to ear			Cod Haddock Saithe	Red Snapper		
	gas bladder distant from ear	Dorado	Horse Mackerel	Spot	Wrasse	Sand-smelt	Salmon Eel
	no gas bladder	Sharks	Mackerel	Plaice Sole		Flounder	
	fish eggs and larvae	Dorado larvae	Herring Larvae	Cod larvae	Red Snapper larvae	Catfish larvae	Salmon eggs

Figure 3. An example of grouping fishes by sensitivity of seismic sound and ecological association prepared at the Halifax workshop on the effects of sound on fish behavior (Source: CEF Consultants Ltd. 2011)

Invertebrates (presentation: Appendix B, p. 62)
Dr. Michel André, University of Catalonia (Spain)

Marine invertebrates are extremely abundant and important to a variety of ecosystems. While there is evidence of sound production and sound detection in some invertebrates, such as snapping shrimp, cephalopods, and some bivalves, the role of sound in the ecology of marine invertebrates is largely unknown. Some invertebrates (e.g., cephalopods) possess statocysts, which consists of sensory hairs attached to a mass of sand or calcareous material, which may assist in detection of sound and vibration. However, the effect of man-made sound on invertebrates is known only from a limited number of studies (See Sections 5.1 and 9.1 in the

Literature Synthesis for additional information). While this presentation did not elaborate on the diversity of invertebrates and their sound production and detection capabilities, Dr. André presented evidence from a case study (André et al. 2011) that suggested that statocyst epithelia of selected cephalopod species can be injured from controlled exposure of low frequency (50-400 Hz) sound.

Injury and Effects on Fish Physiology (presentation: Appendix B, p. 65)
Dr. Michele Halvorsen, Battelle Pacific Northwest National Laboratory

Dr. Halvorsen considered the concepts important to understanding and assessing injury and effects on fish physiology from sound exposure. Sound exposure can affect fishes through barotrauma, injury to inner ear sensory tissues, reduction in hearing sensitivity, and masking. Most impacts, except the most severe exposures, do not result in immediate mortality but may lead to delayed mortality if injuries affect vital functions or indirect mortality where reduction in fitness leads to increased susceptibility to predation.

In general there is too little information to develop a dose-response function for exposure to man-made sound for most species of fish. The exception is for exposure of juvenile salmonids to impulsive pile driving sound. Dr. Halvorsen presented a case study that showed exposure to simulated pile driving sound. The onset of physiological effects only occurred at substantially higher cumulative SELs than those specified in the interim FHWG criteria currently used for regulating sound exposure from pile driving.

Fishes at higher hydrostatic pressures (at greater depths) may be less susceptible to injury from barotrauma associated with pile driving and seismic exploration, than that those at lower hydrostatic pressures (in shallow water or close to the surface). There are a wide range of data needs regarding the response of fishes to sound exposure, These include, but are not limited to, improved understanding of the physiological cost and behavioral impacts of sublethal physical injuries including damage to inner ear sensory tissue, consideration of a broader range of species, exploration of other injury measurement approaches such as bioassays, and assessment of cumulative response to intermittent exposure.

Injury and Effects on Invertebrates (presentation: Appendix B, p. 67)
Dr. Jerry Payne, Department of Fisheries and Oceans (Canada)

Dr. Payne provided an overview of approaches to assessing the effects of sound on invertebrates. This is an area of concern for fishers as well as scientists. In addition to the direct use of certain invertebrate species, the reliance of vertebrates on invertebrates as food and the possible impact on fish stocks resulting from any decrease in food availability is an issue with fishers.

At present very little is known about the response to invertebrates to sound exposure and it is not possible to specify levels of sound exposure that are safe for invertebrates. There are few, if any, data suggesting that exposure to seismic airguns produce immediate mortality for invertebrates. A more important issue for invertebrates is likely to be the induction of sub-lethal effects that may impact life functions without causing death. Assessment of the occurrence and severity of sub-lethal injury to invertebrates is difficult, but experimental approaches developed for assessment of the response of invertebrates from exposure to chemicals have proven helpful. Identification of response variables is underway and includes consideration of metrics and measures for behavior, physiological functions such as growth, reproduction, and many others.

To improve our capability to assess the effects of sound on invertebrates, Dr. Payne advocated the use of laboratory or small-scale mesocosm studies to examine commercially important invertebrates (e.g., lobster, crab, shrimp, scallop, and squid) using behavioral and pathological parameters (e.g., biochemical, physiological, and histopathological endpoints). These laboratory studies should focus on deriving dose-response relationships, including those for chronic sound exposure, for both commercially important species as well as keystone zooplankton species such as *Calanus*. Researchers were recommended to provide guidance to agencies and industry on the extent to which field studies could be useful for assessing effects on animal behavior. Some field studies can provide an opportunity to obtain biomarker data. Basic studies are encouraged to investigate issues of subtle but possibly important effects of noise on animal behavior.

Importance of Sounds for Animals - Sound Production and Sound Detection: Changes in Behavior (presentation: Appendix B, p. 74)
Dr. David Mann, University of South Florida

Dr. Mann played audio recordings and presented spectrograms of a number of different sounds produced by various fish and invertebrate species. Invertebrates, such as snapping shrimp, make some of the loudest naturally occurring sounds in the oceans. Sounds are also made by spiny lobster, but octopus and squid are not known to make sounds.

Many species of fishes make sounds that may accompany behavior such as spawning. It has been suggested that passive acoustic observation of sound-producing (soniferous) fishes using either fixed-location recorders or recorders deployed aboard silent platforms such as gliders may provide a means for estimating their distribution and observing their behavior.

Many species of fish make sounds that are unique and that permit identification of them based on sound alone. Fishes are believed to communicate using sound. The sounds generated by individual fish are not particularly loud with most having source levels on the order of 120 dB re 1 µPa [at 1 m] with the loudest on the order of 160 dB re 1 µPa. Given typical levels of ambient sound in the sea this means that effective communication distances are probably on the order of meters.

Research is needed to improve knowledge of sound produced by invertebrates. Some progress has been made in developing a library of fish sounds, but much more is needed to develop accessible catalogue of identified sounds from fishes and invertebrates. Work is also needed to determine the impacts to fish populations from man-made sound that may mask fish communication or limit its range.

The Auditory Scene, Communication, and Effects of Masking (presentation: Appendix B, p. 79)
Dr. Richard R. Fay, Marine Biological Laboratory

Dr. Fay provided an overview of the auditory scene in the context of animal communication and masking communication from man-made sounds. Masking is defined as the reduction in the detectability of a signal of interest due to the presence of another sound, which is usually noise. For a sound of interest to be detected by an animal, the energy in the sound must be greater than the background noise level in the frequency-selective channels in the animals hearing system.

While much is known about white noise masking of a single-frequency tone in fishes, almost nothing is known about masking of specific signals by noise with particular spectra. In addition, essentially nothing is known about the consequences of masking in the lives of fishes.

Auditory scene analysis is the process by which the auditory system organizes sound into individual, perceptually segregated streams according to their likely sources. Experiments with goldfish (*Carassius auratus*) have shown that they are capable of auditory scene analysis. It is believed that other fishes may also be capable of a primitive form of auditory scene analysis.

Man-made sound may affect auditory scene analysis by preventing or hindering the proper perception of sounds from separate sources, making segregation of such sound from all of the sounds impinging upon the animal difficult or impossible. It is known that auditory scene analysis requires a signal that has a sufficient signal to noise ratio to be segregated from the general noise arriving at the fish. Nothing is known about the consequences of a fish not being able to perform auditory scene analysis in terms of effects on behavior and survival.

Behavior of Pelagic Fish in Response to Anthropogenic Sources (presentation: Appendix B, p. 82)
Dr. John Dalen, Institute of Marine Research (Norway)

Dr. Dalen presented several case studies that highlighted assessments of behavior of selected pelagic species (e.g., herring, mackerel, blue whiting, sand eel, mesopelagic species, salmon, and trout) in response to sound sources that included pile driving hammers, explosives, low frequency military sonars, and seismic exploration sparkers and airguns.

Assessments of the behavior of fishes to man-made sources should be conducted on free swimming fish because caged fish do not exhibit normal behavior. However, observations of the behavior of free swimming fish is very challenging for many reasons and must be conducted in a way that recognizes that behavioral responses of fish to man-made sounds are likely to be species specific, size specific, and biological state specific within particular spatial and temporal contexts.

Fishes avoid fishing trawls but it is not clear if the response is to the trawl or to noise generated by the fishing vessel. Observations of the response of pelagic fishes to seismic sources show that the responses are species specific, with herring showing changes in direction of movement but not in speed of movement.

Responses of Fish to Ship Noise (presentation: Appendix B, p. 87)
Dr. Alex De Robertis, NOAA/NMFS Alaska Fisheries Science Center

Ships generate high levels of low frequency sound that can propagate long distances. It is known that fishes respond to the approach of a vessel. Based on observations of fish avoidance of vessels, including fishery research vessels, the International Council for the Exploration of the Sea (ICES) recommended that a special effort be made to make research vessels quieter (e.g., research vessel noise shall not be exceed 30 dB above hearing threshold of herring and cod at distances > 20 m) at low frequencies based on their audiograms. Noise from vessels can be substantially reduced by making various modifications to operations such as slow rotating propellers.

However, results from several studies have demonstrated that the stimuli that actually elicited reactions were unclear. Indeed, behavioral reactions differed by diel period, location, and physiological state of the fish. Moreover, results suggest that the ICES criteria of 30 dB above threshold may be overly simplistic.

While it has been demonstrated that research vessel noise can be reduced, whether it is worth doing so has been questioned. Current conjecture is that the response of fishes to vessels, both noise-reduced and conventional, is probably due to response to both particle motion and pressure. In controlled experiments, individual fish responded more strongly to sounds that were lower in frequency, had a more sudden onset, were loud, had similarities to sounds made by predators, and had a larger contribution from particle motion. Information needs for response of fishes to vessel noise include a better understanding of the responses, the contribution of particle motion to behavior, and linkages between perception of sound and behavioral response by fishes.

Effects of Noise on Catches (presentation: Appendix B, p. 90)
Dr. Svein Løkkeborg, Institute of Marine Research (Norway)

Dr. Løkkeborg reviewed several studies on the effects of noise on catches. Exposure to impulsive sound for airguns was found to decrease catch rates of cod and haddock in trawling and longline gear by as much as 80%. These species were also observed to move away from the trackline of the seismic vessels. In another field study, gillnet catches of Greenland halibut (*Reinhardtius hippoglossoides*) and redfish (*Sebastes* sp.) increased at exposure to airgun sounds, while longline catches of Greenland halibut and haddock decreased. The proposed explanation was that gillnets catch more fish when fish are actively swimming while longlines only catch fish that are actively feeding. The response of halibut and redfish was to swim more actively in response to airgun sounds while longline catches decreased because the halibut and haddock feeding rate was reduced in response to the sounds. It was observed in the catch data that haddock probably moved away from the sound source and reduced their feeding rate when the airguns were firing.

In studies that investigate the effect of noise, such as seismic air-guns, on fish abundance, the catch rate of fish depends upon the type of fishing gear, the characteristics of the fishing ground, the hearing ability and swimming capability of exposed fish, the habitat preference and site fidelity of fish, the nature of the fright/avoidance response of the various species, and the characteristics of the sound source. The behavioral responses to air guns include increased swimming, decreased feeding motivation, displacement from fishing grounds, decreased longline and trawl catches and increased gillnet catches, if fishing is occurring in the ensonified area. Differences in behaviors as observed in catch data showed that there are species specific differences in the response to air-gun sounds. The data also showed that extrapolation between species, fishing gear, and habitats should be avoided when considering the likely effect of a noise producing activity.

Assessing Effects of Noise on Catches: Statistical Approaches (presentation: Appendix B, p. 94)
Dr. Steven Murawski, University of South Florida

Dr. Murawski reviewed the statistical approaches of assessing effects of sound on catches. Fish catch data are different in their statistical properties from data acquired using a designed sampling project. Data are often skewed and zero inflated, which often requires data transformations. In particular, catch data are biased to high density areas and by regulations that direct fishing effort to particular areas.

Commercial fishing effort is uncontrolled in space and time, and fishing is done using non-standardized gear. While catch data can be obtained at little expense, and the amount of data can be large, it is obtained by effort that is unstructured and lacking any of the features of a statistical sampling design. In general, catches are not proportional to abundance because of the ratcheting up of effort when fish abundance declines.

Often it is very difficult to obtain any practical degree of spatial resolution for fish distribution because of the nature of the fishing effort. It is common for trawlers to tow over distances of several nautical miles before hauling their catch, making it impossible to determine the distribution of fish, either by species, size class, age group, or abundance, in the catch. Most of the common commercial fishing gears have this characteristic to one extent or another.

Because catch data have poor spatial and temporal resolution, high variability, and other undesirable statistical properties, they are of limited utility in understanding the response of fishes to sound. New developments in sampling technologies, such as data storage tags or large-scale acoustic waveguide sensing, in designed experiments should be used to improve our understanding of fish behavior in response to sound sources of interest.

Session Four Breakout Group A: Effects of Exposure to Sound on Catches
Chair: Dr. Alex De Robertis, NOAA/NMFS Alaska Fisheries Science Center
Rapporteur: Dr. John Dalen, Institute of Marine Research (Norway)

Discussion among Workshop participants provided more insight into the utility of catch statistics to studying the effects of sound exposure to fishes and study of the effects of sound on catches. The focus of discussion was guided by these questions:

1. Can catch statistics provide insight into the behavior of fishes and invertebrates in response to man-made noise at relatively low cost.
2. What are the pitfalls in using catch statistics to investigate the impact of sounds?

3. Are there particular precautions that can be taken to avoid confusion between the impact of sounds and other factors affecting catches?

While BOEM's primary interest for ESA species will be noise impacts on individuals and their populations, a priority for assessing noise effects on non-ESA species will be whether noise affects the fisheries, including catch. Generally, analysis of catch data will be most useful when combined with sound exposure metrics. The phase of projects, type of sound sources and effects should be taken into consideration because impacts will be different during construction, operation and decommissioning phases. Fishery-independent surveys may be useful for evaluating effects of construction or acute exposure activities while fishery-dependent catch data may be more valuable at assessing operational impacts. Historic catch data can capture the natural variability that is important for detecting impacts from particular sources. Fishery-dependent catch data may be very useful for exploring long-term trends. Aggregated catch statistics can be also be useful in marine spatial planning to avoid overlap or conflicts between the fishing and energy industries (e.g. driftnet fishery catch statistics used to plan activities within Cook Inlet, Alaska).

While there were Norwegian examples of using low and high resolution of catch data from governmental agencies and fishermen (private logbooks on special agreements) to study the effects of sound on fish behavior, in the US, high resolution catch data is available, but access is limited. Fine-scale catch and effort data based on satellite-tracking data collected by the vessel monitoring system (VMS) does exist, but gaining access to the data is problematic due to the propriety nature of catch and effort data, particularly when small-scale data could reveal the identity of individual fishers and their catch (income). Establishment of good relationships with the fishing industry is important to gain buy-in to share catch information. However, there are regional and cultural differences in relationships between the fishing industry, regulatory agencies and/or the energy industry. Fishery management sectors for example may differ in cooperation, access, and potentially quality of use of catch data for exploring impacts of sounds. For example, pollock fishers in Alaska have voluntarily put recorders on their echo sounders and shared those data with NMFS. Participants agreed that it was important to pursue formal process with NMFS and fishing industry for improving access to catch data.

Pitfalls in using catch statistics to investigate the impact of sounds were discussed and identified. Sources other than sound can influence catch statistics: area closures, quotas, bycatch rules, Marine Protected Areas, and other regulations may influence the interpretation of differences in catch statistics. Moreover, it is difficult to distinguish a particular sound source of impact from others (e.g. vessel noise, trawl noise) when analyzing catch data. Surveys of abundance may require consideration of multiple factors, but catch statistics can be used in a straight-forward way to assess the level of economic activity before, during, and after a sound-generating activity. The recreational fishery may be more vocal over impacts because a majority of development may be near the coast where recreational fishing is more prevalent. Catch statistics may be limited for species that are recreationally or ecologically important.

Also, behavioral effects will be important in interpreting changes in catch statistics (e.g. interpreting and understanding changes in catchability and local movements). A number of Norwegian studies (see Section 6.1.7 of Appendix E, the Literature Synthesis, for further discussion) demonstrate different impacts for different fishing gear types based on their capture mechanism and fish behavior.

Particle motion has been argued to be the primary acoustic parameter to which fishes and some invertebrates respond, especially at close range. For example, seismic and pile driving, may have harmful effects at close ranges, while at far ranges behavioral impacts may have different effects on catch rates for different gear types. Scaling impacts is a challenge, as specific projects primarily look at lethal/harmful effects, but have not looked at cumulative effects and are not focused on sub-lethal effects. Studies of catches can be combined with specific experiments to interpret the mechanisms underlying changes in catches.

Session Four Breakout Group B: What Do We Need to Know About Behavior of Wild Fishes and Invertebrates in Relation to Sound Exposure

Chair: Dr. Rob McCauley, Curtin University (Australia)
Rapporteur: Dr. Michel André, University of Catalonia (Spain)

Discussions from Session Four Breakout Group 4B attempted to describe what we need to know about behavior of wild fishes and invertebrates with reference to sound exposure by addressing a number of questions:

1. At what sound levels do wild fishes and invertebrates start to show behavioral reactions to man-made sounds? How does this vary by species, motivation, and other behavioral and physiological conditions?
2. At what sound levels do fishes start to show substantial behavioral reactions that potentially alter fitness (e.g., change migration routes, move fishes from feeding sites, alter reproductive behavior)?
3. 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?
4. How is fish behavior altered in the presence of masking sounds? How loud does a masker need to be to impact fish acoustic behavior?
5. Is there masking of sounds involved in key behaviors or inhibition of vocal behavior?
6. Does habituation to sounds occur and what is its significance?
7. Does chronic exposure to low level man-made sound sources have physiological effects?
8. Can species be grouped in terms of their response to sound? What species would be representative for future research?
9. Are there differences in behavioral responses to sound by fish of different ages and sex within a single species?
10. Can fishes 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?
11. Do operational procedures such as ramping-up provide sufficient mitigation?

There is a need to predict the response of fishes and invertebrates over varying spatial and temporal scales to noise-generating activities in order to identify any potential for disruption to economic enterprises such as commercial fisheries, recreational fisheries, and eco tourism. Insight into biological responses may help identify ways to reduce degradation of the environment, population-level consequences, and impacts on subsistence fisheries. Additionally, it is necessary to comply with various legal mandates (e.g., ESA and MSFCMA) because of the potential for impacts on endangered or managed species. Currently regulators must often make decisions in the absence of baseline information indicating that there is a need to have more complete baseline data on soundscapes, habitat, and species biology. Management agencies should establish regulations based on science, and therefore increased certainty in the predicted responses of organisms to noise is necessary.

Because many fishes and invertebrates are prey species, there is the potential for noise to impact important ecological interactions. A priority list of species that may be particularly susceptible to noise should be established, as there are many species that are ecologically, commercially and recreationally important. Different species in the same environment may respond to noise differently. The current knowledge of individual species responses may not allow inferences on noise sensitivity of other species, so there is a need for more species-specific understanding of anatomical, physiological, and behavioral responses to sound. The identification of species groups that respond similarly to sound may be useful. Identification of responses to noise throughout all life stages and at small scales is important; therefore laboratory experiments may help fill knowledge gaps when field measurements are impractical. The identification of both acute and chronic responses of fishes and invertebrates to sound is necessary. The construction of ocean observatories to help fill current knowledge gaps and provide baseline and long-term information was suggested. These discussions generated many questions that led to identifying specific information needs, priority areas, and funding recommendations to be included later in the data gap analysis.

Session Four Breakout Group C: Injury, Physiological Damage, and Stresses as a Result of Sound Exposure

Chair: Dr. Michele Halvorsen, Battelle Pacific Northwest National Laboratory
Rapporteur: Dr. Jerry Payne, Department of Fisheries and Oceans (Canada)

Discussion was focused on the injury, physiological damage, and stress resulting from sound exposure. Discussions focused on addressing ten questions:

1. Is Temporary Threshold Shift (TTS) an important consideration in examining the effects of man-made sounds in fishes or invertebrates? What level of hearing loss has significant implications for behavior?
2. What is the best way to measure, present, and interpret TTS?
3. What is the morphology of TTS in fishes?
4. Are there any effects on the lateral line from exposure to man-made sounds?
5. Can damage to the lateral line be repaired and does function return?
6. Can appropriate assays for stress be applied without causing stress?
7. What are the effects of stress?

8. What types and levels of sound may result in mortality? Are there differences among life stages?
9. Do physostomous fishes respond differently to sound than physoclistous fishes?
10. Are there effects on non-auditory tissues?

The slate is mostly blank with respect to studies on the potential for various sources of sound to affect delayed mortality or irreparable sub-lethal injury in invertebrates. The information gap on invertebrates makes it all but impossible, in most instances, to pass informed scientific opinion on questions related to potential risks associated with sounds from seismic surveying, pile driving, sonar, or vessel traffic. There is a need to develop dose-response relationships for the effects of sound on the health of commercially important invertebrates taking into account the species and sound source in the area of concern. Health effects can be manifested in various ways and parameters for consideration would include effects on behavior, as well as effects that could involve biochemical, histopathological, and overt pathological endpoints. Fundamental research is required on sensory systems in invertebrates in relation to sounds transmitted by sediments as well as water. Detrimental effects need to be determined, which could then afford linkage to animal fitness.

Equally, as for invertebrates, there is a need to develop dose-response relationships for fishes, taking into account species and sound source in the area of concern. In some cases, proxy species would probably need to be considered since work cannot always be done on large, highly mobile, or endangered species. There may be a need to investigate the effects of sound on prey species for fishes and invertebrates or at least for keystone ecologically or commercially important species. Assessment of health effects on fishes and invertebrates in the laboratory or similar locales should give attention to possibly confounding factors such as chemical and parasite loading. Fundamental research is required on the potential effects of sound on the lateral line system in fishes. Although a subject of considerable attention to date, there is need to separate the sensitive physiological (biomarker) response of TTS from other effects such as the production of major organ pathologies which can be more valuable for defining adverse or irreparable biological damage. There was also important discussion as to whether TTS is of significance to fishes, particularly the shift is small.

To model masking, three pieces of information are needed, the critical ratio (CR), the directivity index (DI) of the animal, and knowledge of the ambient noise field. However the production of empirical information through the design of appropriate behavioral assays (as appropriate) should also be considered.

Notwithstanding the difficulty of considering different strata of water (or sediment) where animals may occur, modeling of the total energy budget in an area of concern could have value in assessing risk.

The term stress is commonly used in physiology in conjunction with neurohormonal linked activation of the brain-adrenal-medulla axis or the brain-pituitary-interrenal axis which can involve altering such functions as oxygen uptake, mobilization of energy reserves, reallocation of energy and immunocompetence. This definition of stress denotes disturbance to homeostatic mechanisms which can set in motion a set of adaptive behaviors or physiological responses to remediate the stress. However if an animal is exposed to intense chronic stress, the response may lose its adaptive value and become maladaptive or dysfunctional resulting in effects on growth, reproduction, disease resistance, etc. Thus, there can be a continuum of responses ranging from mild forms of stress that may be adaptive ("eustress") to "distress". Given this continuum, it can be difficult to define the border between eustress and distress.

This aspect of stress is quite different from the more popular concept of "any" stress or factor that may compromise an organism's ability to live out its normal lifespan as well as reproduce normally. For instance, production of severe organ pathologies or injurious effects on behavior may have little or no linkage to neurohormonal disturbance yet have a much greater effect on animal health and fitness.

Over the past years there has been increasing emphasis on the use of biomarkers to assess effects in organisms, with the term biomarker (or health effect indicator) being generally defined as a change in the biochemical, or cellular component of a process, structure, or function. In addition to their use as screening tools in laboratory studies (or similar), biomarkers can be especially valuable for determining the degree and extent to which health effects may be occurring in the environment. This is necessary since it is all but impossible to measure population level reductions or loss of productivity in the environment (except possibly microscale effects on populations such as in a small cove).

It is important to note that all biomarkers are not of equal value. For instance major pathological or histopathological changes in hair cells in the ears of fishes, the internal organs or musculature of fishes, or similarly the internal organs of crustaceans, would generally be considered to be potentially more adverse than a transient change in a blood or hemolymph parameter.

Biomarkers which might be "too sensitive" for assessing adverse health effects may be powerful tools for providing advice and guidance on whether effects might occur in the environment. For instance the sensitive biomarker studies on fishes carried out in conjunction with seismic programs in the McKenzie River in Canada and in offshore Australia - where little or no effects were observed – were quite important for providing advice to regulators in relation to extensive seismic surveys being carried out on the east coast of Canada. Simply put, if little or no effect is observed on sensitive biomarkers in the environment it can be difficult to make a case for more injurious higher level effects. Thus documentation of sensitive as well as more injurious effects in laboratory studies or similar locales, can provide important tools for assessing risk in the environment.

2.2.5 Session Five: Conclusions

Chair: Dr. Jennifer Miksis-Olds, Penn State University

Session Five summarized the topics presented in each session, along with details from each breakout session, and final concluding remarks.

Rapporteurs from Sessions Three and Four presented summaries of topics discussed within breakout groups, as previously described in Sections 2.2.3 and 2.2.4. For details of these presentations, refer to Appendix B. Information needs and data gaps that emerged from each topic are detailed in the Data Gap Analysis (Section 3).

Information Needs and Data Gaps Identified at the Workshop (presentation: Appendix B, p. 99)
Dr. Anthony Hawkins, Loughine Limited

Dr. Hawkins presented a summary of each Workshop session along with data needs identified within that topic.

Session One reiterated that information on the effects of underwater sound is needed to enable BOEM to predict, assess, and manage impacts from offshore energy and marine mineral exploration, and development, and production activities on human, marine, and coastal environments. The information is used by BOEM to direct future research, assist with NEPA and other environmental analyses, develop monitoring and mitigation measures in lease stipulations and provide information to lessees. The priorities of the BOEM study program are established on the basis of mission relevance, scientific merit, technical feasibility, timing and applicability. It is evident that some noise sources will have greater impact than others, and help is needed in identifying those impacts that are most important and which uncertainties should be taken in to account. Finally, mitigation requires close examination to ensure that it protects marine resources.

Session Two attempted to define the fish and invertebrate species, habitats, and fisheries of concern in regards to impacts from noise-generating activities. Impacts on endangered and threatened species are a major concern, because the Endangered Species Act requires BOEM to ensure that authorized activities are not likely to damage protected species or critical habitats. One of the largest knowledge gaps is the lack of data on the acute and cumulative responses of fishes and invertebrates (individuals, subpopulations, and populations) to sound, because this information is necessary for the quantification of any impacts resulting from sound-generating activities. Fisheries managers need clear guidance regarding what information is needed from them to help fill such gaps in knowledge, which includes access to data and information regarding life-history and reproductive periods for vulnerable species.

Session Three identified issues related to the assessment of sound sources, as well as quantifying sound exposure. There is an urgent need to identify international standards for underwater sound, and to agree on terminology as the current use of terminology is inconsistent and not always appropriate. Because of this, an authoritative and critical glossary of international terms currently used is required. There are issues in the descriptions of marine soundscapes, including quantification, identification of trends, identifying impacts, and units used for presentation of noise budgets. The current descriptions of marine soundscapes lack ecological sound data, and there is need to identify which measurements need to be made to help fill this gap in knowledge. There is a clear need for future measurements to focus on assessing the impacts on animals rather than meeting the priorities of the sound-makers.

Session Four focused on the effects on sounds on fishes and invertebrates, and identified the great diversity, both within and between species, of these animals as an important consideration when trying to generalize. Advancing our knowledge of the hearing abilities of fishes and invertebrates, the effects of masking, and effects on behavior and biomarkers is critical, and should be accomplished through research-driven studies.

Final Comments/Summary from BOEM
Dr. Alan Thornhill, Bureau of Ocean Energy Management

The Workshop was attended by over 150 people representing nine countries with collectively well over 2000 years of experience.

The objectives and desired outcomes of the meeting were restated to reflect on the outcomes of the Workshop:

1. Objectives
    a. Identify gaps in our understanding of the effects of noise on marine fishes, fisheries, and invertebrates.
    b. Identify feasible studies that could help plug those gaps.
2. Outcomes
    a. A thorough review of the questions posed to the breakout groups.
        i. Are these the right questions?
        ii. Do we already have a start to answering them?
    b. A path forward!

Industry will continue moving forward, and we need to ensure that management decisions are science-informed, rational, and non-arbitrary. This will be accomplished thorough aggressively seeking knowledge, which will require partnership between science-driven researchers and the applied industry side. BOEM requires that research funded by BOEM be applicable to environmental analyses for making decisions.

Numerous examples of Environmental Impact Statements (EIS) and their supporting documents clearly show that there is a large gap in our knowledge of how underwater sound affects fishes and invertebrates. It was requested of the Workshop participants that any identified information gaps be communicated to BOEM.

The objectives of the Workshop were put into the context of the process of the BOEM Environmental Studies Program (ESP). Workshop participants can help with the first step: to identify gaps in our understanding, and identify topics that can be solved through targeted research. This research will be vetted through government review, and the applicability will be assessed along with identifying who should be involved in the research. This process only works when researchers are actively engaged with BOEM.

3. GAP ANALYSIS

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

- Where are we now?

- Where do we want to be?
- What must be put in place or must happen so that the desired target state can be reached?

Gap analysis helps bridge any gaps by highlighting those requirements that are being met and those that are not. It provides a foundation for deciding what is required to achieve a particular outcome.

For each topic considered at the meeting an attempt has been made to:

- Define BOEM's needs
- Consider which of those needs are currently being met
- Examine those needs that are not being met and how they might be met
- Suggest priorities for research that BOEM might consider for future funding
- Suggest priorities for areas in which BOEM may want to partner with other organizations to either support research, develop policies, or gather data

Information assembled in the Literature Synthesis (Appendix E), presented in plenary sessions at the Workshop, and discussed during the breakout sessions was reviewed to identify the missing pieces of our understanding of the effects of man-made sounds on fishes, fisheries, and invertebrates. Missing information was evaluated in terms of what it could contribute to BOEM's ability to assess impacts to these resources under NEPA as well as the ease with which this information could be obtained.

In performing this analysis, it became apparent that words were being used in different ways by different people. Such varied usage could alter how material is understood and interpreted. In order to try and bring some "sense" to word usage, an attempt has been made to ensure that word usage has been consistent in this document and the Literature Synthesis.

Of these words, the most critical appear to be "impact" and "effect." These words are often used synonymously, but it is clear that there are subtle differences in meaning by different presenters at the BOEM meeting, and by different authors in the literature. Thus, a more specific usage has been adopted. The word "impact" refers to a causal agent, such as the sound from a seismic operation or the wake from a ship. The word "effect" means the resultant response of or on an animal or population. In other words, "impact" is the causal agent and "effect" is the response.

3.1 Information Gaps Identified During Literature Review and Workshop Discussions

The information gaps that were identified through the Literature Synthesis and the discussions at the Workshop are presented below, divided into the major topics covered at the Workshop. The left-hand column ("Drivers for Information Acquisition") describes the underlying concerns or actions that raise the questions for which answers are not readily available from existing research. The right-hand column ("Information Gaps") articulates the types of information that would be needed to fulfill each driver. The complexity of this subject matter is evidenced in the fact that there are a number of recurrent themes – questions that arise under more than one topic. In order to make things easier to follow, and to allow for the fact that many Information Gaps are important to deal with several Drivers, there is some repetition of areas of research within the

Information Gaps. This was done rather than have extensive cross-referencing within the Gap Analysis.

While it is important to retain the breadth of the data gaps and information needs identified during this study, it is also important to consider these needs in terms of BOEM's mandates. Clearly readers with different backgrounds or different research interests are likely to have varied opinions as to what the most important gaps are to fill. BOEM, however, has specific needs in order to advance its missions. BOEM must conduct unbiased, scientifically-based impact assessments throughout its decision-making, regardless of the specific mission.

In order to help resolve this concern, a list of priorities for research and development, prepared with the assistance of the Science Review Panel, is presented at the end of the Gap Analysis in Section 3.2. Priorities on this list have been defined in terms of those that are achievable, have the most relevance to BOEM, and have the greatest potential to advance our understanding of the impact issues in the reasonable future. At the same time, the far broader research questions listed in the Gap Analysis itself provide a picture of where, over the next decade, the field should go. Addressing these broader research questions may, however, have to be the responsibility of many groups around the world.

Table 2. Contents of Information Gaps, Section 3.1.

A. Strategic Requirements

Drivers For Information Acquisition

Information on the effects of underwater sound is needed to enable agencies to predict, assess, and manage the impact of man-made sounds in marine and coastal environments. It is especially important to acquire sufficient information to make scientifically supportable assessments of the effects on fishes, fisheries, and invertebrates resulting from sound-producing activities.

Information Gaps

The priority is to seek information to:

- ***Support assessments of impacts from different sound sources.***
- ***Predict effects of such impacts on marine biota.***
- ***Monitor human, marine, and coastal environments for evidence of these effects.***
- ***Identify mitigation strategies.***

A.1. Assessing and Predicting Impact

Drivers For Information Acquisition

An important mechanism for demonstrating BOEM's adherence to its environmental responsibilities is through careful impact and effect analysis in the NEPA process. The NEPA analysis incorporates all relevant federal regulations, including the ESA and the MSFCMA. Critical to determining whether information is sufficient is an understanding of what defines a significant effect. The definition may differ between species covered under the ESA and other species. An effect may be significant at the level of the individual animal for ESA species, whereas for a non-ESA species the same factor may be considered significant only if a population-level effect were expected. Even at the non-ESA species level, the definition of significant impact may be dependent on the type of population structure and behavior of a given species. For a species with isolated populations or sensitive life stages, a localized impact could have much greater consequences than it would for a species where populations extend over large areas.

Information Gaps

Progress must be made in defining significant impact versus negligible impact and in examining the gradient of effects that might result from different levels of exposure to man-made sound.

A.2. Mitigation

Drivers For Information Acquisition

Actions to mitigate the impact and effects of man-made sounds are important to individual

Information Gaps

Proposals for mitigation must be accompanied by evidence that the

animals and, in some cases, populations. The need to present mitigation measures depends on defining the actual impact. Some mitigation measures, such as efforts to reduce sound-generation or create barriers to sound transmission, may have wide applicability and effectiveness. Other measures may be less efficacious for some organisms. It is desirable to define criteria for evaluating the success of mitigation, in terms of effect reduction, and to demonstrate that mitigation works whenever it is proposed.

mitigation will actually work. Many of the mitigation measures adopted for the protection of marine mammals (e.g. PAM, Protected Species Observers, Ramp-up) may be less effective for fishes and invertebrates.

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

A.3. Cumulative and Aggregate Effects

Drivers For Information Acquisition

For the purposes of this discussion, we are defining ***cumulative effects*** as those that arise from the temporal repetition and accumulation of effects from a particular source—for example the repeated strikes of a pile driver. By contrast, in-combination effects, sometimes described as synergistic or ***aggregate effects***, arise from the accumulation of effects from different types of stressor—for example, from sounds from different sources or from the combined effects of sound exposure, water contamination, and fishing.

Currently there is an inability to conduct appropriate cumulative and aggregate impact assessments. More rigorous methods are required to assess the cumulative impacts of offshore energy by itself and in combination with other human activities that co-occur with it in the marine environment.

Information Gaps

Assessment of sound-producing activities has to assess both cumulative and aggregate effects. The challenge is to compare the effects of repeated exposure to single and multiple stressors and to examine interactions between multiple stressors (both natural and anthropogenic).

There is a need to refine approaches that assess total exposure from all regulated activities, rather than evaluate individual developments while ignoring other approved and ongoing projects. The concept of total allowable exposure may have some value in this context.

B. Priority Habitats, Species and Fisheries

Drivers For Information Acquisition

ESA-listed Species and Habitats

In setting priorities in terms of fishes and invertebrate species, habitats and fisheries of concern to regulators, it is clear that endangered or threatened species are high priority. The ESA requires BOEM and other agencies to ensure that

Information Gaps

ESA-listed Species and Habitats

One major need is information on the responses of endangered and threatened fish and invertebrate species to sound exposure, in terms of either mortalities or other effects that result in changes in

authorized activities are not likely to damage protected species or critical habitats.

For ESA-listed species, information is required on any action leading to mortality or injury, or which causes a change in behavior or habitat use that has the potential to reduce the fitness, life span, or reproductive potential of an individual. Information on the responses of ESA-listed species to sound has limited utility if those responses cannot be linked to one of these two assessment endpoints:

- Increases in mortality
- Decreases in fitness, for which reproductive success is a good measure.

Non-listed Species and Habitats

Other species of concern include:

- Those which are commercially fished, particularly those whose populations are below optimal levels;
- Those exposed to pollutants or other stressors; and
- Vocal species that may be especially vulnerable to sound exposure.

Evaluation of effects on non-ESA species is typically based on factors such as:

- The ecological, commercial, recreational, or scientific importance of the resource;
- The proportion of the resource that would be affected;
- The sensitivity of the resource to the proposed activity;
- The duration of the impacts; and
- Additional impacts from other sources.

Some species (and life stages) may be especially vulnerable to man-made sounds.

Vocal animals may be worthy of special consideration and there is a need to identify and catalogue these species and their sounds. Man-made sounds can also affect non-vocal animals

fitness.

Note that consideration of endangered and threatened species inevitably involves consideration of effects upon their predators, competitors, any symbiotic species and prey.

In many instances there may be too few individual animals of the endangered and threatened species to conduct valid studies or the necessary permits would not be provided by the regulatory agencies. In such instances, studies on other species (i.e, surrogates) that have similar characteristics may be appropriate.

Non-listed Species and Habitats

It is important to establish those taxa and habitats that are most at risk from exposure to man-made sound, and on what spatial and temporal scales.

Better means are required for characterizing the effects of sound on marine animals, linking responses to man-made sound to the survival and current and expected future reproductive success of the fishes and invertebrates that are exposed to it.

More information is required on the characteristics of the sounds produced by vocal species, the range over which the sounds may be detected, their seasonal patterns, their behavioral context, and their ecological significance. Seasonal changes may provide a basis for mitigation of any effects. Key habitats including spawning areas may be investigated by listening for sounds.

The susceptibility of animal calls to masking by man-made sounds needs to be investigated.

More research is needed to establish the validity and importance of larval attraction

as well however and research should be directed to these potentially important effects.

Recent studies have suggested that the larvae of fishes and invertebrates may direct their movements towards the sounds of their particular habitat, although the distances over which this behavior occurs is unknown. Man-made sound may exacerbate the ecological status of these species by interfering with the attraction and settlement of larvae.

Past studies presented during the Workshop[1] have demonstrated different behavioral effects of sound exposure on catchability for fishing gears that differ in the capture mechanisms they employ (e.g., trawls, gillnets, long lines).

Impacts to non-ESA species are likely to be considered major if important resources would be adversely affected over large areas relative to species distribution and diversity within the project area. Such impacts would cause:

- Substantial reductions in population size or changes in distribution of important species;
- Substantial long-term loss of existing habitat;
- Substantial deterioration of existing habitat;
- Substantial interference with the movement, range, spawning, or nursery site of resident or migratory species; or
- Changes to a fishery by:
  (1) Changing the geography of fishing effort either as a result of changes in fish distribution or restricting or reducing access of areas to fishing,
  (2) Reducing the catchability of a species to a particular gear as a result of behavioral responses to sound exposure,
  (3) Reducing the population available to the fisheries, and

to sounds, and those features of the soundscape that attract or are especially important to different life stages.

Information on the behavioral responses of fishes and invertebrates to different sound sources is a major knowledge gap in assessing the effects of man-made sound on fishes and fisheries. Experiments using new technologies (e.g., active acoustics, tagging), at an appropriate scale, for a variety of these sound sources in relation to fish and invertebrate behavior and the effect on catch should be encouraged. Further development of some of these new technologies is also needed, so that sound exposure and behavioral responses of individuals can be measured more readily.

Assessment of effects upon populations and habitats requires considerable knowledge of the ecology and population dynamics of the key species. Much work is already underway on those fishes and invertebrates exploited by the major fisheries. However, fisheries managers are already busy managing their particular fisheries, which are often in a poor state, have a high public profile, and face numerous future threats. With restricted resources they are limited in their ability to assess possible future effects from development of the energy industry.

Liaison with fishery managers, especially in sharing catch and population data is imperative for assessing the impact of man-made sounds upon fishes and invertebrates. Any direct mortality associated with sound exposure can be evaluated in the context of current fishery models used for stock assessment, and compared with mortality from other sources.

Fishery managers already have very detailed time-series of populations and distributions that could be vital in informing potential effects of sound

[1] See the Workshop Presentation on the "Effects of Noise on Catches" by Svein Løkkeborg

(4) Causing substantial economic loss or social effects as a result of loss of fishing or reduced catch.

production at the population level. The commercial fishing community may also be forthcoming with information when it feels it is in its best interests to cooperate.

Data on fishes and fisheries required for use in regulating development of offshore energy and assessing the effects of sound-producing activities include:

- ***Maps which locate and characterize vulnerable species and habitats***
- ***Maps locating fisheries activities by gear type***
- ***High-resolution catch data for evaluating long-term trends near a project or using catch statistics for assessing biological, economic, or social effects of man-made sound on fishes and fisheries***
- ***Calendars identifying critical life history, especially reproductive periods***
- ***Information on behavior, especially of vocal fishes.***

B.1. Priorities in the Atlantic

Drivers For Information Acquisition

Endangered and threatened species of fishes in the Atlantic include: Atlantic salmon, shortnose sturgeon, Atlantic sturgeon, and smalltooth sawfish.

Critical habitat has been designated for smalltooth sawfish and is being considered for Atlantic sturgeon. Offshore waters adjacent to mouths of rivers and estuaries are areas of particular concern for sturgeon.

For invertebrates, no species are currently designated endangered. The threatened species include: elkhorn coral, staghorn coral; additional coral species are candidates for listing. Critical habitat has been designated for elkhorn and staghorn coral.

Priority habitats in the Atlantic include 'live bottom' areas with corals, invertebrates, and

Information Gaps

In addition to information being required on the impact of sound on endangered and threatened species, interest in the Atlantic is also especially focused on effects of sounds upon the valuable commercial fisheries.

The Atlantic is also an area where new renewables, aggregate extraction, and oil and gas developments are or will be under consideration.

The Fishery Management Councils have designated Essential Fish Habitat (EFH) and Habitat Areas of Particular Concern (HAPCs) for managed species to address fishing and non-fishing impacts. Other spatial management measures are in place to protect species and areas of particular concern.

fouling communities (grouper, snapper, porgies). These areas support the offshore fisheries and a wide diversity of marine fishes, birds, mammals and invertebrates. Other important areas are those containing *Occulina* deep-water corals (together with golden crab, shrimp); and inlets and coastal areas <5m offshore (croaker, drums).

Other species of concern because of their vulnerability to fisheries and other factors include: Atlantic bluefin tuna (*Thunnus thynnus),* dusky shark (*Carcharhinus obscures),* porbeagle shark (*Lamna nasus),* and rainbow smelt (*Osmerus mordax*).

In the South Atlantic, commercial fisheries target many species, including the snappers, groupers, herring, shad, menhaden, black-sea bass, porgies, Atlantic croaker and weakfish/red drum/other Sciaenidae, tuna, and migratory species including billfish, dolphin, wahoo and tilefish. Valuable invertebrates include spiny lobster, penaeid shrimp, squid, golden crab, and deep-water shrimp. There are many soniferous species including snappers, groupers and croakers.

In the North Atlantic a very wide range of federally and state managed fish and invertebrate species. Priority species in terms of risks from exposure to high level sounds are:

- ESA-listed species
- Acoustically-sensitive clupeids (herrings) (e.g., Atlantic menhaden [*Brevoortia tyrannus*] and Atlantic herring [*Clupea harengus*], for their commercial importance. River herring (*Alosa aestivalis* and *A. pseudoharengus*) are candidates for ESA listing.
- Fishes (e.g., Atlantic cod, haddock and cusk *Brosme brosme*) that use sound to communicate or locate prey and are overfished or are close to being overfished.
- Fishes (e.g., elasmobranchs and sturgeon) whose populations are reduced and that

The development of ecosystem support tools, including mapping facilities, are important for future management and are the responsibility of a number of agencies.

Fisheries scientists have identified the need for:

- ***Enhanced species and oceanographic monitoring;***
- ***Pelagic/benthic habitat mapping and characterization where existing data are insufficient; and***
- ***Focus on managed species and their prey (priority to address overfished species)***

Specific requirements are to identify critical habitats and reproductive periods. Passive acoustics is one tool for monitoring the presence and reproductive behavior of fishes and invertebrates. Larval surveys and other conventional techniques of fisheries science also have a part to play. These types of data are important for other sources of impacts besides man-made sounds.

are slow-growing, late maturing species with low fecundity

- Commercially valuable invertebrates (e.g., American lobster (*Homarus americanus*), blue crab (*Callinectes sapidus*), and white shrimp ; Atlantic sea scallop (*Placopecten magellanicus*), and squid, that may be vulnerable to sound.

B.2. Priorities in the Arctic

Drivers For Information Acquisition

There are no marine, anadromous, or catadromous fishes or invertebrates currently listed or proposed for listing as endangered or threatened in the Arctic Region.

Priority species from a fisheries standpoint include: Arctic cod, saffron cod, snow crab.

Essential Fish Habitat (EFH) areas in the Arctic OCS have been described for Arctic and saffron cod and snow crab. No Habitat Areas of Particular Concern (HAPCs) have been declared for the Arctic.

Fisheries for pink and chum salmon may also be significant. Subsistence fishing in the Arctic OCS is economically and culturally important for many Alaskans.

There is potential for a shift of fisheries into the Arctic as water temperature rises. Expected changes in environmental conditions may have enormous consequences for the fish stocks in polar and sub-polar regions. An assessment of sound-producing activities associated with energy development in this region could be incorporated into the U.S. Arctic Fishery Management Plan.

Information Gaps

As with the Atlantic, information is required on the impact of sound on any especially vulnerable species or habitats.

Exploration for minerals, oil and gas is new to this area and ways must be found to acquire key information quickly to deal with foreseen or potential development.

Baseline information is required in advance of development on those species and habitats likely to be vulnerable to sound exposure, to aid future decisions.

The Fisheries Management Plan for the U.S. Arctic will provide a valuable tool for assessing the impact of future development in the area.

B.3. Biological Mitigation

Drivers For Information Acquisition

Biological mitigation involves choosing a season or time of day or location where impacts upon fishes from man-made sounds will be minimized. Such mitigation requires a thorough

Information Gaps

To facilitate biological forms of mitigation, information is required on those periods in the lives of marine animals, or those critical locations, when they might be especially

knowledge of the biology and ecology of the animals concerned.

affected by exposure to man-made sound. Such information requires close coordination with fisheries biologists.

C. Sources and Exposure

Drivers For Information Acquisition

The major issues regarding sounds and exposure relate to the need to:

- Explain and demystify terminology of underwater sound;
- Achieve a better understanding of the current acoustic environment (the soundscape) in areas of concern; and
- Understand how man-made sources change the acoustic environment.

Information Gaps

The marine soundscape was altered by human activities long before man-made sound was recognized as a pollutant and there is no real way to measure the effect of this change – the dilemma of the shifting baseline. An important, but probably unanswerable, question is how much man-made sound the environment can receive before changes in ecological status (e.g., biological population or community structure) occur. What constitutes 'good environmental status' with respect to sound? Perhaps the closest scientists can come to answering this is to examine geographic areas that are physically similar and within the same biogeographic region but have been exposed to different levels of man-made sound. How do they differ biologically?

Information is required to evaluate and rank any deleterious effects of different sources upon natural soundscapes and the animals living there.

C.1. Metrics and Terminology

Drivers For Information Acquisition

A wide range of instruments and metrics are used to measure, describe, and analyze underwater sounds. However, to date, sounds are normally described in terms of sound pressure, whereas many organisms respond to particle motion.

Increasingly, biologists and others without specialist knowledge of acoustics are conducting measurements and applying different metrics to different taxa, often without guidance on the most appropriate metrics.

Information Gaps

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

A common terminology needs to be developed for sound measurement and exposure that is useful and understandable

Much of the literature concerned with the effects of underwater sound uses differing and confusing terminology. There are no widely accepted definitions or terminology applicable to underwater sound for universal use. Even the common term ***sound pressure level*** is defined in different ways by ANSI and ISO, the two main standards organizations. There is no widely accepted definition of ***source level***. The lack of a standard terminology creates ambiguities in interpretation of data and effects.

to the whole community – from acousticians to biologists to regulators. An authoritative and critical glossary of terms in current use is required.

There are a number of different organizations around the world attempting to rationalize terminology for use in underwater acoustics, and yet it is not clear that there is sufficient collaboration or cooperation between them. Current efforts could result in "competing" metrics – a situation that would help no one.

C.2. Background Levels of Sound in the Sea

Drivers For Information Acquisition

There is strong interest in describing and analyzing the characteristics of soundscapes in different parts of the ocean, including inshore waters as well as other aquatic environments. How do these vary by locale, season, time of day, weather conditions, etc.? Aquatic soundscapes are the result of:

- Ambient sounds generated by physical factors;
- Biological sounds;
- Man-made sounds; and
- The local sound transmission regime.

The new field of Acoustic Ecology examines the relationship—mediated through sound—between organisms and their environment. Ambient noise is site specific, and more data are required on the soundscapes associated with different habitats and ecological niches.

Appropriate methods for the measurement, description and analysis of soundscapes will be critical in the future and for identifying trends in level and characteristics of the acoustic environment. There is currently no archive for recordings and analyses of natural soundscapes, performed to specified standards.

Monitoring of soundscapes before, during, and after the new developments, like the construction and operation of wind farms, is needed, but is not being carried out. Most observations on soundscapes have been incidental to other

Information Gaps

There is a need to develop and define those physical quantities and metrics that are most useful for describing aquatic soundscapes.

More information is required to assess the contribution to sound levels in aquatic environments from natural sources, including biological sources.

Information is required on the overall contribution to sound levels in aquatic environments from man-made and other sources. There is a need for agreement on how measurements of the outputs from different sources should be measured and compared.

Methodologies that provide a common way to prepare inventories or budgets of the contribution of different sources to the overall aquatic soundscape are required.

There is a particular need to develop scientific programs that monitor trends in soundscapes through the acquisition of long-term data sets. It is especially important to monitor soundscapes now in areas of future change and/or critical habitat.

There are currently only a few ocean observing stations dedicated to 'ecological' sound measurements. A long-term

activities. Commercial companies carry out some monitoring, but the results are not generally made available to others who might have need for such data. There is a need for a repository of data on soundscapes and the sharing of such data.

Presentation of noise budgets can be misleading depending on the units used to derive them.

commitment is required for the establishment of such stations and to programs to survey different ocean soundscapes.

C.3. Characterizing Man-Made Sources

Drivers For Information Acquisition

The nature of the sound field (spectral, temporal, and spatial) generated by various man-made sound sources is crucial to understanding the effects of sound exposure. There are currently few agreed upon standards for measuring the output of different sound sources. Particle motion, which is an important component of sound detection for fishes and invertebrates, is seldom measured. Particle motion needs to be accounted for and it requires vector rather than scalar measurements.

There is currently no archive of sound files, recorded to an agreed-upon standard, providing examples of the sounds generated by different sources.

Sounds of differing characteristics (e.g., impulsive vs. continuous; short vs. long term) have different effects upon animals. We need to know how we can reduce the impact of those sound characteristics that are especially damaging.

The oil and gas industry has conducted some research that describes the outputs of seismic sources. Little research has been done on other potentially damaging sources, including pile driving where substrate borne vibration may be especially important to fishes and invertebrates.

Of considerable concern is how we should measure the output of sound sources and quantitatively assess the effects of different sound sources on fishes and invertebrates. Currently, the particle motion generated by

Information Gaps

Information is required on the characteristics of the sounds generated by different sources, in terms of particle velocity as well as sound pressure. Measurements are done to achieve compliance, but not always to agreed standards or with appropriate metrics.

The characteristics of man-made sources need to be more closely defined, using a common terminology, especially in terms of those features that might especially affect marine animals.

There is scope for funding research on the outputs of different sources, in partnership with industry. Some sound sources, for example pile drivers, where sediment transmission may be important, have not yet been adequately characterized in terms of the sound fields they produce, and in terms of sound pressure, particle motion, and other characteristics (rise time, degree of kurtosis etc.).

Information is especially required on the particle motion associated with interface waves and ground roll that may affect fishes and invertebrates, especially from pile driving and seismic sources.

What are the characteristics of impulsive sounds 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

sources is seldom measured or estimated, though this is the parameter that many fishes and invertebrates respond to. Sound sources and their outputs must be monitored and analyzed from the perspective of the affected animals if we are to understand fully their impact and effects.

There is particularly strong interest in describing sounds appropriately in terms of their cumulative and aggregate effects upon aquatic animals (see section D on Effects).

What future trends should we expect in the development of sound sources? Are aquatic animals likely to be subjected to larger pile drivers, more extensive seismic surveys and wider swathes of dredging and aggregate abstraction in the future as technology develops?

determines whether tissues are damaged?

Which characteristics of continuous sound are most likely to have effects on animals?

Are the effects on fishes and invertebrates similar to one another, or are different metrics and response characteristics needed for different groups?

C.4. Sound Propagation

Drivers For Information Acquisition

As sounds travel away from the source their characteristics change. Examination of the changes accompanying sound propagation are important for interpreting measurements made in the field and require the application of models to assist in estimating effects upon animals.

The propagation of sounds through the sea and seabed can greatly influence the sound received by fishes and invertebrates. Propagation models are available for specific oceanic environments (i.e., shallow, deep, ice covered, and temperate waters). However, those models have primarily been developed by industry for their own purposes. For assessing the exposure to which animals are subjected and predicting effects, researchers and regulators need to be able to estimate the received levels of sound pressure and particle motion to which aquatic animals are exposed in the water column and close to the seabed. Current models have not been designed specifically to do that.

With respect to the masking of biological sounds, there is concern that impulsive sounds

Information Gaps

Models of sound propagation are required that are specifically tailored to estimate the exposure to which fishes and invertebrates will be subjected, expressed in terms of sound pressure and particle motion, for animals in the water column, close to the sea surface, or close to the seabed.

How might the characteristics of man-made sounds change with propagation over larger distances from the source, rendering them likely to mask biological sounds?

There is a particular need for more information about propagation of sound and vibration through the seabed by means of interface waves—this is especially relevant to benthic fishes and invertebrates.

What are the effects over large ocean basins of multiple or continuous activities that alter the soundscape? What, for example, is the effect over the whole Gulf of Alaska of simultaneous seismic studies, even when they are not near one another?

might merge with one another over distances as a result of reverberation and other effects. How might the characteristics of man-made sounds change with propagation over larger distances from the source?

Some sound sources, including seismic airguns and pile drivers, send energy into the seabed, creating substrate vibrations that may affect benthic organisms.

C.5. Masking

Drivers For Information Acquisition

Man-made sounds have considerable potential for masking the detection of biologically relevant signals by animals. Prolonged sounds, such as those from vibroseis, shipping, drilling, dredging, aggregate extraction, vibratory pile driving and fixed platforms for oil and gas operations are especially likely to mask biologically important sounds. There is also potential for discrete but repetitive sounds to merge together as a result of propagation to produce sounds that will effectively mask sounds. Moreover, some man-made sounds may resemble the sounds of animals themselves and may give rise to confusion.

Information Gaps

More information is required on the overall variations in background sound levels (ambient noise) created by man-made sources and the effects of propagation upon them in terms of their risk of masking biologically important sounds.

C.6. Source Mitigation

Drivers For Information Acquisition

For some sources there may be potentially useful mitigation measures applied to the source itself that might decrease the exposure of animals to sound.

Mitigation is often stipulated in issuing leases but there is still a substantial need to demonstrate that source mitigation is actually effective. In some cases, such as in pile driving, little is known about how sound radiates from the pile through the water and through the substrate, and there is substantial variation from site to site (and even pile to pile) on the effectiveness of mitigating devices such as air bubble curtains.

In considering source mitigation it is important

Information Gaps

Research is needed to establish the means for reducing unwanted and damaging sound from a range of sound sources.

Industry should look especially closely at alternative technologies to air guns and impact pile driving.

to examine those characteristics of the sounds that might make them especially likely harmful to fishes and invertebrates (in terms of level, duration rise time, repetition, kurtosis etc.).

Can other less damaging sources replace those sources in current use? Are there technological alternatives? Are there ways of avoiding the use of high-level sound sources or replacing them with other less damaging sources?

C.7. Sound Measurements

Drivers For Information Acquisition

Some sound measurements in water cannot readily be made because appropriate instrumentation is not commonly available. This applies especially to the measurement of particle motion.

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 instrumentation that can operate in the near field, without damage, to measure both pressure and particle motion.

Knowledge of particle motion amplitudes generated by anthropogenic sources is required close to the water surface or close to the seabed where the physics of the adjacent media must be taken into account.

In addition, measurements and analysis techniques are required that can be applied in complex acoustic environments, such as rivers, lakes and estuaries.

A substantial issue is the need to obtain, in the laboratory or in the field, data on the hearing abilities of animals, the effects of sound on their physiology, etc. in terms of both sound pressure and particle motion. The development of special wave tubes and other containers is required where fishes and invertebrates can be maintained and the characteristics of presented sound stimuli

Information Gaps

Inexpensive instrumentation, which does not require specialist skills, is required for the measurement of underwater sound both in the laboratory and in the ocean.

Measurement of particle motion is a particular priority. Ideally, it should be as easy to measure particle motion as it is to measure sound pressure.

Instrumentation is also required to characterize sound sources in the acoustic near field.

Instrumentation is required to measure the directional and other characteristics of sounds in complex acoustic environments, both in the field and in the laboratory.

Special acoustic facilities are required that will enable investigators to present sounds to aquatic animals in the laboratory, or in the field, with full specification of the signals presented both in terms of sound pressure and particle motion.

fully described. One example of such a system is the HICI-FT that has been used in a number of BOEM-supported studies to examine effects of exposure to pile driving sounds on fishes.

D. Effects of Sound on Fishes and Invertebrates

Drivers For Information Acquisition

The great diversity of fishes and invertebrates poses major problems in understanding the effects of sound upon them. It is not just diversity of species within each taxonomic group but also diversity of animal size and life history status within each species. An important question is whether it is possible to identify particular "types" of animals that may serve as models for other species and life history stages. Can we make reliable broad generalizations about effects of sound on such diverse groups?

In considering fishes it is important that cartilaginous species (sharks and rays) be considered along with the bony fishes.

Knowledge of the hearing abilities and behavior of fishes and invertebrates with respect to sound is not just of academic interest. Hearing threshold curves or audiograms are already being used in environmental statements to assess whether animals are potentially affected by man-made sounds. Subjective metrics for impact assessment, and especially those based on weighted frequency responses, require reliable measurement of hearing abilities.

The use of physiological methods to measure hearing abilities is less satisfactory than the use of behavioral methods. Physiological methods (e.g., auditory evoked potentials) only measure detectable responses from the ear or lower portions of the brain. They do not fully reflect the ability of the brain of the animal to process and extract information, or whether there will be a behavioural response by the animal.

Information on the masking of biologically important sounds by 'real' sounds – including

Information Gaps

Because of their great diversity, there is a need to divide both fishes and invertebrates into categories based on their anatomy, relative sensitivity to sound, and ecological associations. We may then be able to make generalized predictions about responses to sounds within these different groups.

Well-equipped field sites, where the response of animals can be examined under approximate 'free-field' acoustic conditions, are required to extend knowledge of the hearing by fishes and invertebrates. Conditions are required where animals can be examined at appropriate depths, under quiet ambient noise conditions, and where sound stimuli can be precisely measured.

Measures of hearing must be made using behavioral analysis since physiological measures (e.g., auditory evoked potentials) do not give an accurate indication of the detection ability of animals.

Specially designed tanks can also play a role in enabling precisely controlled and measured sound stimuli to be presented to fishes and invertebrates so that their detection abilities can be determined.

Appropriate instrumentation is required to accompany these special acoustic conditions. Then representative species might be examined to obtain valid data that may be applicable to a range of similar animals.

Similar conditions are required for experiments to evaluate injury and physiological damage to aquatic animals

man-made sounds is also critically important.

Currently, despite strong interest in determining how fishes and invertebrates use sound and the soundscape and respond to man-made sound, there are remarkably few experimental data. There are almost no observations obtained from fishes and invertebrates exposed to man-made sounds under controlled or field conditions. Valid audiograms are only available for a handful of species. Many studies have been carried out under inappropriate acoustic conditions where the reliability of acoustic measurements has been open to doubt. There is a lack of facilities in which sound signals can be presented to fishes and invertebrates under carefully controlled conditions. If appropriate acoustic conditions can be provided then it should be possible to investigate further the thresholds or criteria for the occurrence of different effects from exposure to sound, the nature of any effects and how they change with different sound types and levels. It should also be possible to determine those source characteristics that cause detrimental effects; e.g., magnitude, rise time, duration, kurtosis, duty-cycle.

including assessment of the relative importance of factors like rise-time and kurtosis, and to assess cumulative effects, recovery from injury and other important aspects of sound exposure.

D.1. Sound Production, Sound Detection and Exposure to Man-made Sounds - Invertebrates

Drivers For Information Acquisition

Almost nothing is known about the detection of sound and vibration by invertebrates. Some invertebrates such as snapping shrimps and lobsters are known to produce specific sounds, but the role of these sounds remains to be determined. The role of sound in lives of these animals has hardly been explored, and information on the impact of man-made sounds is almost totally lacking. There is a particular lack of controlled exposure experiments on invertebrates. In particular, the slate is blank with respect to studies of the potential of sound exposure to affect delayed mortality or sub-lethal injury in invertebrates. The few studies carried

Information Gaps

There is a need to establish which invertebrates are of most concern with respect to exposure to man-made sound.

More information is required on the importance of sound to selected invertebrates. Can we monitor and catalogue the sounds they produce? Determine how well they can detect sounds? Examine how vulnerable they are to masking or suppression of calling following exposure to man-made sounds? Are they engaging in acoustic and other activities related to their long-term fitness, such as spawning? Do they use sound during their

out indicate a potential for sub-lethal biochemical, physiological, or histopathological responses.

In this state of ignorance there needs to be a focus on examining those species that are of greatest interest, either because of their ecological importance, or their role in supporting commercial fisheries, or because sound is suspected of being important to them. Especially important animals might include Crustaceans (crabs, lobsters, shrimps), Mollusks (scallops, clams) and Cephalopods (squid, octopus), and those organisms making up the zooplankton.

Having selected priority species, it will be sensible to investigate how well they can detect sounds, and examine how they use sound in their everyday lives. Do some or all of these invertebrates communicate by means of sound? Is sound important for vital life functions like reproduction, migration, feeding, or choice of habitat? Are the sounds important to invertebrates likely to be suppressed or masked by man-made sounds that alter the soundscape? How does exposure to sound affect invertebrate physiology and their behavior? Are there biomarkers that might indicate effects? What amplitudes of sound and vibration potentially cause effects, and can dose/response curves be developed?

The effects of exposure of invertebrates to man-made sounds has been examined in only a few species, but sufficient work has been done to indicate that there may be tissue injury and other physiological effects from exposure to high level sounds.

There is a particular lack of knowledge on the behavior of invertebrates in response to sound. Do any invertebrates show substantial behavioral reactions that potentially alter fitness (e.g., reductions in settlement within favorable habitats, altered reproductive behavior)? ***migrations or in selecting suitable habitats?***

There is especially a lack of information on the ability of invertebrates to detect sound and vibration. There is particularly a lack of knowledge with respect to:

- ***Whether invertebrates are responsive to sound pressure or particle motion;***
- ***The sound and vibration receptors and their sensitivity;***
- ***Whether high level sounds damage these receptors and/or other tissues;***
- ***Whether the receptors regenerate if they are damaged;***
- ***Whether some invertebrates are especially sensitive to substrate vibration;***
- ***Whether they can distinguish between sources at different distances or from different directions;***
- ***Whether they can distinguish between sounds of differing quality;***
- ***Whether sound detection is masked by man-made sounds and whether invertebrates can detect signals in the presence of biological maskers; and***
- ***Whether hearing loss occurs as a result of exposure to sound.***

Information is almost totally lacking on the effects upon invertebrates of exposure to man-made sounds and substrate vibrations. There is a requirement to investigate the effects of these sounds in terms of injury and effects upon their physiology and behavior.

D.2. Sound Production - Fishes

Drivers For Information Acquisition

Some fishes make sounds that are important in their everyday lives. Commercially important vocal fishes include the families Gadidae (codfishes), Sciaenidae (croakers and drums), and Serranidae (groupers).

There is considerable scope for man-made sounds to suppress or mask those sounds with deleterious effects upon vital functions such as spawning.

Information Gaps

More information is required on the sounds fishes make, and the role of sound production in their lives. It would be especially useful to acquire knowledge of seasonal, demographic, situational or species differences in calling behavior.

How vulnerable are the sounds to suppression or masking by man-made sounds? Which fishes are engaging in acoustic and other activities related to their long-term fitness, such as spawning, and where do aggregations of them occur?

Can fishes compensate for changing noise conditions by changing their calls?

There is a need for a library of sounds produced by marine and freshwater fishes and invertebrates. Its absence hinders use of passive acoustics as a tool for determining effects of sound on behavior, as well as research on the role of the soundscape in fish ecology. There is also a need for new tools that use multiple modalities of observation in combination with passive acoustics to identify unknown biological sound sources and document associated behavior. Better software tools are needed to automate measurements of sound characteristics (such as number, duration, and frequency of knocks, etc.) and to identify particular sounds. Without such software tools, ecologists are extremely limited in statistical analysis of temporal and spatial differences in sounds as well as correlations between sounds and environmental factors, all of which require large sample sizes from each sampling unit.

D.3. Sound Detection – Fishes

Drivers For Information Acquisition

Increased knowledge of the hearing abilities of fishes is required to assist in examining the effects of man-made sound upon these animals, both in terms of sound pressure and particle motion.

An immediate question is whether fishes can be sorted into different functional hearing groups, obviating the need to examine every species. What do we need to know to define the main groups?

There are severe methodological difficulties to be overcome in conducting experiments on the hearing of fishes. The need for appropriate acoustic conditions for the presentation and measurement of sounds in terms of both sound pressure and particle motion has already been emphasized. There is also a need to perform experiments on hearing against different levels of background noise to examine any effects from masking. There are distinct differences between the audiograms derived using different methods. In general, those obtained from Auditory Evoked Potentials (AEP) measurements show lower sensitivity but wider bandwidth than those obtained from behavioral techniques. Currently, impact assessments are being conducted using data on the hearing abilities of fishes that has been determined under less than optimal acoustic conditions and which may not be truly representative of the natural environment. Better data are required.

We know that fishes can discriminate between sounds of differing quality and can determine the direction and distance of sound sources. It also seems likely that some can detect substrate vibrations. The full extent of their hearing capabilities remains to be explored. The discrimination and recognition of sounds may be especially affected in the presence of noise.

Information Gaps

More carefully derived information is required on the sensitivity and frequency range for both sound pressure and particle motion in different species and different life stages. Can fishes be grouped into categories with respect to their hearing abilities and can the hearing characteristics of fish within these groups be described adequately by generalized weighting functions?

Methodological difficulties in presenting measurable sounds to fishes and then determining thresholds to different types of sound need to be resolved. The current plethora of data obtained under unsatisfactory conditions require more critical appraisal.

How sensitive are fishes to substrate vibrations?

How well can fishes discriminate between sounds of differing quality coming from different directions and distances and how does man-made sound affect these abilities?

D.4. Masking

Drivers For Information Acquisition

From information we have on masking with pure tone signals it seems likely that man-made sounds will mask detection of the soundscape and/or biologically relevant sounds in some (if not all) species of fish. However, we have data for only a handful of species and additional research is required to examine the masking of sounds important to fishes (their own calls, and sounds important to them for navigation, habitat detection, prey and predator detection) by changes in ambient noise. It should be possible to predict the extent of masking by man-made sounds based on improved knowledge of hearing capabilities of fishes and of the types of sound generated by different sources under different conditions.

The effects of masking can be of considerable significance. This issue is not currently being given sufficient attention in the preparation of impact assessments. The presence of man-made sound has the potential to inhibit or suppress vocal behavior and may interfere with vital life functions. As mentioned earlier, it is important to gain a wider general knowledge of the importance of sound to fish behavior so that the population level consequences of masking can be assessed.

Periodic and intermittent sounds may affect masking if they are merged together as a result of long distance propagation and reverberation. The masking potential of repetitive sounds from seismic surveys and pile driving operations has yet to be assessed.

Information Gaps

Information is required on the masking of sounds both by natural noise and by man-made noise. Experimental studies need to concentrate on sounds of real importance to fishes.

With additional information it should be possible to model the degree of masking of particular sounds by different man-made sounds under different conditions in the sea.

More general information is required on the importance of sound in the lives of fishes before the impact of masking can be fully assessed.

The masking potential of intermittent sounds from seismic surveys and pile driving operations remains to be assessed.

D.5. Effects of Sound in Terms of Injuries and Effects upon Physiology

Drivers For Information Acquisition

Little is known about the magnitude of the effects of man-made sounds on the physiology of fishes. It is not yet clear whether death, injury, or

Information Gaps

There is a need to develop a broader understanding of any injuries or physiological effects that result from

physiological effects only occur when fishes are close to the sound source or whether such effects are also evident at a distance. Instant mortality is not of particular concern since it is likely to occur in only a small fraction of a fish population that is closest to an intense sound source. Rather, there is interest in sublethal effects and the potential for delayed mortality.

There are a number of ways of assessing physiological effects, including tissue damage (including damage to the auditory tissues), the use of biomarkers (measures of changes in the physiology of the animal), and changes in auditory sensitivity, for example Temporary Threshold Shift (TTS). The importance of these measures needs to be critically assessed. Which injuries can be regarded as potentially lethal, and which are unlikely to affect the animal in the long term?

Which biomarkers are indicative of a real and lasting change to the physiology of the animal, affecting vital life functions, and which are more transient? Effects have been observed from sounds on blood proteins, blood enzymes, blood calcium, food consumption rates, growth rates and the state of the hepatopancreas (liver) in a variety of animals. Free radical damage has been observed in relation to sound exposure.

Is TTS an important indicator of damage? What level of hearing loss and persistence has significant implications for behavior?

In terms of injury and tissue damage it would appear that some fishes, and especially those possessing gas-filled swim bladders or other cavities, might be more susceptible to damage than others, and that the rate of equilibration with depth is important.

The development and application of physiological trauma indices for fish, which quantify a qualitative assessment of injuries, ranking the physiological costs of impairment, is important as a means for assessing the injuries to an animal. A slight change in an enzyme or a hormonal response might not be accorded the

exposure to different sound sources and sound levels.

Are there particular injuries, physiological parameters or biomarkers that might provide evidence of deleterious effects from sounds, and which might be incorporated into trauma indices and applied in determining dose/response relationships?

Are some fish more susceptible than others to injury or tissue damage?

What are the characteristics of man-made sources that cause detrimental effects; e.g., magnitude, rise time, duration, duty-cycle? What is the role of anatomy (e.g., the presence of the swim bladder and other gas spaces) in producing physiological effects? How are physiological effects affected by depth, size, age, season etc.

Is temporary threshold shift of importance when considering effects of some or all man-made sounds? If so, how should TTS be determined and what degree and duration of TTS is most likely to alter behavior?

What are the physiological effects of repeated exposure to sound? Which metrics are most appropriate for expressing the accumulation of sound energy? Is there a better descriptor than sound exposure level (SEL), which is now expressed in two forms: the single strike SEL or the cumulative SEL?

same status as a change in histopathology of a vital organ.

An issue of great importance is the effect of intermittent exposure. Many man-made sounds are repeated, both through repetition of a single source and the recruitment of additional sounds from other sources. Are there cumulative and aggregate effects from these repeated exposures? Is there full recovery of function after damage? Is there is a period of healing if sufficient time passes between sound exposures?

Assessing the effects of cumulative and aggregate exposure has implications both in terms of dose/response relationships and more broadly in terms of designing mitigation measures.

As mentioned earlier, comparison of the relative impact of exposure to different duty cycles (patterns of presentation) also has relevance to the metrics used to describe and measure cumulative effects from multiple pulses from the same source.

D.6. Effects of Sounds upon Behavior

Drivers For Information Acquisition

The potential impact of man-made sounds extend well beyond the distance for physical or physiological impacts, and a major concern is whether these sounds affect behavior, in turn affecting vital functions such as reproduction, migrations or choice of habitat. Behavioral impacts may range from small (and inconsequential) awareness of the sounds to fishes changing their migratory routes, leaving favored sites for feeding and/or breeding, or failing to detect appropriate high-quality habitat.

Experiments on captive fishes, whether in tanks in the laboratory or cages in the sea are unlikely to yield valid results. Fishes show changes in behavior and restrictions in their behavioral repertoire in captivity. Currently we have only poor knowledge of behavioral responses and how they change with different types and levels

Information Gaps

There is a dearth of field studies on fishes, where the free-swimming fish are exposed to relevant sounds and their behavior observed in detail.

Is it possible to grade the significance of different behavioral responses for a given species? To distinguish between inconsequential responses and responses that will affect vital functions? Such knowledge is important for defining dose/response relationships for behavior.

The effects of chronic exposure over long periods to low level sounds on behavior need to be evaluated.

What is the role of habituation, and how does this affect behavioral responses?

of sound. Moreover, impacts from man-made sound on fishes leading to changed behavior must be understood in a species specific, size specific, biological state specific and seasonal context.

Different types of sound sources may elicit different kinds of behavioral reactions or result in onset of behavioral reactions at different sound levels. Responses may vary greatly by species, motivation of animals, and other behavioral and physiological conditions. An important question is whether an observed response results in impaired access to essential habitat for feeding, reproduction, concealment, territoriality, communication, or other life processes.

It is important to consider which aspects of the sound are responsible for a given behavioral response (i.e., exposure level, peak pressure, frequency content, etc.). The effects of chronic exposure over long periods to low level sounds may be as important as exposure to isolated high-level sounds.

It is known that fishes may change their behavioral responses after the repeated presentation of sounds. In some cases their reactions may diminish and they may eventually ignore the sound. The full response may be restored after an interval without sound.

D.7. Effects of Sounds upon Catches

Drivers For Information Acquisition

The distributions of both pelagic fishes and ground fishes, observed by means of sonar and the comparison of catches can change as a result of exposure to man-made sound. There are also indications that there may be long term effects from sound exposure, resulting in highly migratory fishes such as herring and blue whiting leaving or avoiding areas where sound-producing activities are taking place. Other studies have shown that distributions may return to normal some days after exposure has ceased.

Information Gaps

More information is required on the effects of man-made sounds on the distribution of fishes and their capture by different fishing gears. There may be different effects on different species, on different fishing grounds and habitat types. The relationship between sound level and source types and their effects requires examination.

Effects upon catches may differ for different types of fishing gear (bottom trawls, long-lines, gill-nets) since the efficacy of these gears depends on different behavior patterns. Effects may also differ on different fishing grounds.

Overall, comparison of catch data is of limited utility in understanding impacts of sound, because of the spatial and temporal resolution and variability. Specific, planned, large-scale experiments are necessary to compare catches in the presence and absence of sound, similar to those conducted in Norway.

D.8. Effects of Sounds upon Populations

Drivers For Information Acquisition

The ultimate goal is to understand the population consequences of acoustic exposure on fishes and invertebrates. Modeling tools are needed to understand population risk from exposure.

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 aquatic life.

There is increasing recognition that sublethal 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.

Information Gaps

What evidence is there for man-made sounds affecting vital life functions, including feeding, reproduction, leading to effects upon populations?

Information is required to enable the effects of sound exposure upon populations of fishes to be modeled effectively. It may be possible to modify the population models developed by fisheries biologists for this purpose.

D.9. Avoidance Of Effects

Drivers For Information Acquisition

Currently, the exposure of marine mammals to potentially deleterious man-made sounds can be avoided by detecting their presence followed by modification of the noise-making procedures.

Information Gaps

Can PAM or other monitoring systems be developed for use with fishes?

Is there scope for using sonar to detect the

Passive Acoustic Monitoring (PAM) systems are routinely used to detect the animals by registering their natural calls. PAM systems have not yet been developed to detect the presence of fishes, perhaps because there are fewer vocal species and the calls are often low in amplitude. Moreover, unlike marine mammals, fishes and invertebrates do not make their presence known by surfacing at regular intervals.

For marine mammals PAM is often augmented by the presence of human observers to detect the presence of vulnerable animals. Fishes cannot be observed from the sea surface, but they may be detected through the use of sonar systems.

presence of fishes and avoid their exposure to man-made sounds?

D.10. Forms of Behavioral Mitigation

The use of 'ramp-up' or 'soft-start,' or the application of aversive stimuli, is often suggested as a mitigation measure for avoiding exposure of fishes to man-made sounds, and it could potentially be useful for invertebrates as well. It is assumed that initial exposure to low-level sounds may induce fishes to move away from the area, avoiding injury and physiological damage. The efficacy of this method of mitigation with respect to fishes has yet to be demonstrated. Many fishes and invertebrates live within discrete, favored areas. Others have limited swimming capabilities. Clearly, only those species that are able, or are likely, to move beyond the area of potential effect would benefit from 'ramp-up' procedures.

Studies are required to examine the efficacy of ramp-up, soft-start and other aversive techniques. Can fishes and invertebrates be induced to move away from an area in order to allow potentially damaging sounds to be broadcast? What proportion of the local population of a sensitive species must move away for mitigation to be considered effective?

3.2 Priorities for Research Derived from the Gap Analysis

A long list of information needs are listed in the Gap Analysis. Some issues of higher priority for future research that are especially relevant to BOEM have emerged from the analysis. New research in these areas would move science further forward since it would provide better understanding of the effects of sound on fishes and invertebrates. Based on input from the Science Review Panel for this project, and focusing on gaps identified in the Gap Analysis, a shorter list of recommended research priorities for BOEMis presented below. (Note that the letter following each paragraph indicates the section in the Gap Analysis (Section 3.1) in which the issue is raised and, often, discussed in more detail.)

3.2.1 Describing soundscapes within the U.S. Arctic and Atlantic OCS

Information is required on the overall contribution made to sound levels and sound quality in aquatic environments in the U.S. Arctic and Atlantic OCS regions from all sources (C.2)***. These particularly include examining baseline ambient conditions, how they change over time and space, and how they will be affected by additional human activities.***

There is a need to develop scientific programs that monitor trends in soundscapes through the acquisition of long-term data sets. It is especially important to begin the monitoring of soundscapes in areas of future change and/or critical habitat (C.2). There are currently only a few ocean observing stations dedicated to 'ecological' sound measurements. A long-term commitment is required for the establishment of such stations and to programs to survey different ocean soundscapes (C.2). Priority locations for ocean observing stations include areas where BOEM anticipates activities in the foreseeable future, e.g., offshore energy development in the Arctic and Wind Energy Areas or marine minerals extraction areas in the Atlantic. An important question is how much man-made sound the environment can tolerate without its ecological status being changed (C).

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

New tools are required to identify unknown biological sound sources and document associated behaviors. Better software tools are also needed to automate measurements of sound characteristics (D.2).

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

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

3.2.2 Impacts of particular sound sources

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

Information is required on the characteristics of the sounds generated by different sources (C.3). Some sound sources, and in particular pile drivers, where transmission through the seabed may be important, have not yet been adequately characterized in terms of the sound fields they produce (C.3).

In addition, those characteristics of man-made sources that cause detrimental effects on animals need to be defined (D.5). Better knowledge of the propagation of sounds (in terms of both sound pressure and particle motion) is also required, especially for those sounds relevant to fishes and invertebrates (C.4). There is a particular need to investigate the propagation of sound and vibration through the seabed as this is especially relevant to benthic fishes and invertebrates and for exposure to both pile driving and seismic airguns.

There is a need to describe and fully evaluate the effects of the sound fields (nearfield and farfield) produced by explosions, seismic airguns, pile driving, dredging, wind farm operation, vessel noise, fishing activities, and sonar systems. Some research has already been performed by the oil and gas industry to characterize the sound fields generated by seismic airguns and that work should serve as a example for other industries to follow. Research related to the impacts of vessel noise, fishing, activities, and sonar may have lower priority for BOEM, but these areas could potentially be advanced through collaboration with such organizations as the Navy and National Marine Fisheries Service, as well as with the industries concerned.

Sound fields should be expressed in terms of metrics that may be most useful in describing effects upon marine organisms. (See presentation by Ainslie in Section 2.2.3). As many fishes and invertebrates are sensitive to particle motion, rather than sound pressure, it is especially important to monitor particle motion along with sound pressure. The development of instrumentation and software for this purpose should receive a high priority.

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

3.2.3 Effects of man-made sounds on marine animals

What effects do sounds generated by the energy industry, have upon fishes and invertebrates?
More information is required on the effects of sound on fishes and invertebrates, especially in terms of changes to their survival and reproductive success. Experiments are required to evaluate the levels of injury and physiological damage that are experienced by aquatic animals as a result

of exposure to sound, including assessment of the relative importance of acoustical factors like frequency, rise-time, and duty cycle.

Such studies may be performed under controlled laboratory conditions or under field conditions (e.g., cages, pens) but in either case the experiments must include precise measurements of sound pressure and particle motion received by the animal. There is a need to develop a broader understanding of any injuries and/or physiological effects that result from exposure to different sound sources, sound levels, repetition rates, and number of events. Are there particular injuries, physiological parameters or biomarkers that might provide evidence of deleterious effects from sounds, and which might be incorporated into trauma indices and applied in determining dose/response relationships (D.5)?

Assessment of effects has to include both cumulative and aggregate effects of sound exposure. The effects of repeated exposure to single and multiple stressors and interactions between multiple stressors (both natural and anthropogenic) must be considered (A.3). There is a need to decide which metrics are most appropriate for expressing the accumulation of sound energy (D.5).

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

More extensive and detailed knowledge of the hearing abilities of fishes and invertebrates is required. Hearing threshold curves (audiograms) are being used in environmental impact assessments and/or in the preparation of weighting curves to assess whether animals are potentially affected by man-made sounds. Much of the current data do not give an accurate indication of the detection ability of the animals concerned since they were obtained either under unsatisfactory acoustic conditions or by means of physiological measurements (D). Audiograms should be developed using behavioral analysis in carefully designed experiments that can adequately replicate the sound characteristics of man-made sound sources (e.g., pile driving, dredging, seismic airguns, etc.) under “free-field” or “far-field” acoustic conditions. Well-equipped field sites, where the response of animals can be examined under approximate ‘free-field’ acoustic conditions, are required to extend knowledge of the hearing by fishes and invertebrates. Conditions are required where animals can be examined at appropriate depths, under quiet ambient noise conditions, and where sound stimuli can be precisely measured. Specially designed tanks can also play a role in enabling precisely controlled and measured sound stimuli to be presented to fishes and invertebrates so that their detection abilities can be determined.

The susceptibility of animal hearing to masking by man-made sounds especially needs to be investigated (B). The consequences for fishes and invertebrates of changes to the soundscape need to be assessed in terms of the effects this will have on their ability to detect sounds (C). Information on the behavioral responses of fishes and invertebrates to different sound sources is also needed in order to assess the effects of man-made sounds. Information is required on responses over time (for example to repeated exposure) and over long distances. How do animals respond when they encounter a sound? Do they leave an area? Do they return later? Is their fitness impaired? Experiments exploiting new technologies (e.g., active acoustics, tagging), at an appropriate scale, for a variety of sound sources should be encouraged (B). It is important to note that such studies cannot be carried out in the laboratory or even in large cages, but require detailed observations on the behavior of animals in the ocean.

More information is required on the effects of man-made sounds on the distribution of fishes and their capture by different fishing gears. There may be different effects on different species, on different fishing grounds and habitat types (D.7). Access to fisheries statistics at fine spatial and temporal scales collected by the National Marine Fisheries Service may provide useful insight, but fishery-independent surveys using multiple gear types following before-after-control-impact study design may provide better information on the effects of particular man-made sounds to catch rates and distributions (vertical and horizontal) of fishes and commercially important invertebrates.

Selection of appropriate species for further study must be done carefully. Although ESA-listed and candidate species for which habitat occurs in areas that would be affected by BOEM's missions are of great interest, practically-speaking these species are often not readily available for experimentation. Species that are representative of the various anatomical and ecological associations important to the Arctic or Atlantic OCS should receive high priority for examination. Fishes could be grouped by their swim bladder morphology and life stage (eggs, larvae, juvenile, adult) so that emphasis can be placed on species for which sound is likely to be important. Invertebrates selected for study should represent the major taxonomic group and those species of greatest commercial and ecological importance should be prioritized such as bivalves (e.g., scallops, clams), cephalopods (e.g., squid), crustaceans (e.g., lobsters, shrimps), echinoderms (e.g., sea urchin), and corals (e.g., coral larvae). Fishes and invertebrates that should be considered for study based on their high commercial importance (top ten in landings or value) in the Atlantic OCS region (B.1).

While the research questions posed in this section relate directly to BOEM's missions, other users of the OCS would benefit from better understanding of the environmental consequences of underwater noise. Design of field studies is particularly difficult and would benefit from collaboration among those interested in their outcome.

3.2.4 Mitigation of effects

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

To facilitate biological forms of mitigation, information is required on those periods in the lives of marine fishes and invertebrates, or those critical locations, when they might be especially affected by exposure to man-made sound (B.3). Specific requirements are to identify critical habitats, migration routes, and reproductive periods so that exposure might be avoided (B.1). Such information requires close cooperation with fisheries biologists.

For some sources there may be potentially useful mitigation measures applied to the source itself that might decrease the exposure of fishes and invertebrates to sound. Research is needed to establish the means for reducing unwanted and damaging sound from a range of sound sources. Industry must look closely at making changes to those sources or seeking alternatives to them that will cause less harm. Sound shielding technologies capable of effectively and verifiably reducing harm from existing sources should also be investigated (C.6). In considering source mitigation it is important to examine those characteristics of the sounds that might make them especially likely to be harmful to fishes and invertebrates (in terms of level, duration, rise time, duty cycle etc.).

Studies are especially required to examine the efficacy of ramp-up, soft-start and other aversive techniques. Can fishes and invertebrates be induced to move away from an area by using ramp up in order to allow potentially damaging sounds to be produced subsequently (D.10)?

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

It is recommended that BOEM work directly with the industries (e.g., oil and gas exploration; wind farm siting) responsible for the sound-generating activities to investigate potential changes to procedures because these have implications to the ability to collect reliable information for future decision-making.

3.3 Priorities for Other Forms of Action

3.3.1 Evaluating mitigation measures

Where mitigation measures have been implemented to overcome or reduce the effects of exposure to sound, the efficacy of those measures should be monitored and assessed (A.2).

In all cases, the value of mitigation measures that may result in a reduction of the execution performance of the operation being conducted should be weighed against the possible exacerbation of impacts due to the lengthening of its duration. For example, if the mitigation measures require a reduction in the level of an impulsive sound, but this leads to a larger number of impulses (for example if a pile must be struck more times with a weaker force), will the prolongation of exposure lead to stronger effects?

3.3.2 Work in liaison with others

Liaison with fishery managers in the preparation of Fishery Management Plans and sharing catch and population data is imperative for assessing the impact of man-made sounds on fishes and invertebrates. Concurrence on definitions of significant impacts is important to shape permit or mitigation requirements and understand potential cumulative effects (A) and can feed into (or from) Fishery Management Plans. Any direct mortality associated with sound exposure can be evaluated in the context of current fishery models used for stock assessment, and compared with mortality from other sources (B). It may be possible to modify the population models developed by fisheries biologists to enable the effects of sound exposure upon populations of fishes to be examined more effectively (D.8).

The development of ecosystem support tools, including mapping facilities, are important for future management and are the responsibility of a number of agencies. These tools might include enhanced species and oceanographic monitoring; pelagic/benthic habitat mapping and characterization where existing data is insufficient; with focus on managed species and their prey (priority to address overfished species).

3.3.3 Measurement and description of sounds and the conduct of acoustic experiments

There is a requirement for agencies to come to a consensus on the adoption of relevant and universally acceptable metrics that describe sounds appropriately and enable comparison of the effects of sounds of different types on different taxa. This has to be done for both sound pressure and particle motion (C.1).

A common terminology needs to be developed for sound measurement and exposure that is useful and understandable to the whole community – from acousticians to biologists to regulators (C.1).

Inexpensive instrumentation, which does not require specialist skills, is required for the measurement of underwater sound, both in the laboratory and in the ocean. Measurement of particle motion is a particular priority (C.7).

Special acoustic facilities are required that will enable investigators to present sounds to aquatic animals in the laboratory, or in the field, with full specification of the signals presented both in terms of sound pressure and particle motion (C.7). Such field sites are required to extend knowledge of the hearing by fishes and invertebrates, as well as their behavioral responses.

3.4 Conclusions

The Workshop and Literature Synthesis both demonstrated that our knowledge of the effects of noise on fish, fisheries, and invertebrates in the Arctic and Atlantic Oceans (and, likely, the Gulf of Mexico as well) is far from complete. However, sufficient information is available to confirm that man-made sources of noise can and do affect some of these resources adversely. There may be ways of reducing and mitigating these impacts. BOEM can overcome deficiencies in the current state of the science in several ways: continued coordination with resource managers; participation in additional research; and, coordination with the offshore energy and marine minerals industries.

Continued contact with other agencies and resource advocates can keep BOEM aware of the changing status of knowledge of the species of concern, as resource agencies are continuing to identify important habitat areas and acquire information about the species for which they are responsible. This will enable BOEM both to make environmentally sound decisions about the activities under their purview and to help focus research on sound impact. In addition, discussions with resource managers can clarify which responses to sound constitute significant impact.

BOEM's need to conduct rigorous impact assessments puts them in a position to seek better information about how sound affects fish and invertebrates. Through their Environmental Studies Program, BOEM is able to identify key research areas to help define the impacts. The Workshop and Literature Synthesis have helped to identify those research questions and some of the critical experimental conditions that must be met.

Finally, BOEM has to balance the activities of the offshore energy and marine minerals industries with the need to protect the environment. By explaining the concerns of the resource agencies to these industries, BOEM will enable these industries to be active participants in reducing any environmental effects.

4. LITERATURE CITED

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Appendix A: Agenda

AGENDA: Welcome & Day One

All sessions will be held in the Meeting House Conference Center. Lunch and breaks will be held at the Tiki Pavilion.

The framework for the presentations, discussion, and breakout groups is based on the Literature Synthesis that was completed prior to the workshop (and is available for download on the workshop website www.boemsoundworkshop.com). In addition to the Literature Synthesis, the workshop leads came up with key questions for discussion and review. These questions complement the sessions and are listed in this program beginning on page 9.

WELCOME: Monday, March 19, 2012	
8:00–9:30 p.m.	Registration and Meet and Greet Reception *Location: Tiki Pavilion*

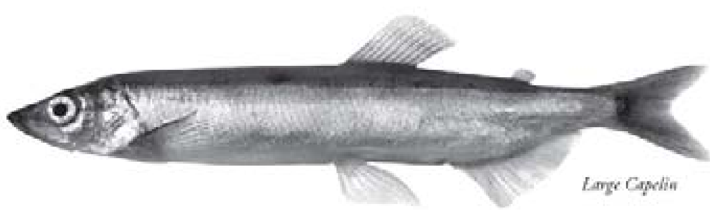
Tuesday, March 20, 2012	
7:30–8:45 a.m.	Registration *Location: Outside of the Sunrise Room*
	Session One: Introduction and Overview *Location: Sunrise Room* *Chair: Ann Pembroke, Normandeau Associates, Inc.* *Rapporteur: Jennifer Miksis-Olds, Penn State*
9:00–9:15 a.m.	Introduction to Workshop, Purpose, and Goals *Ann Pembroke, Normandeau Associates*
9:15–9:40 a.m.	BOEM Introduction and Overview *Alan Thornhill, BOEM*
9:40–9:50 a.m.	Impact Statements and Regulatory Requirements for Offshore Developments *Kim Skrupky, BOEM*
9:50–10:10 a.m.	State of the Science—Introduction to the Literature Synthesis *Arthur N. Popper, University of Maryland and Anthony Hawkins, Loughine Ltd.*
10:10–10:30 a.m.	Questions and Discussion
10:30–11:00 a.m.	**BREAK** *Please assemble at the Tiki Pavilion at 10:35 a.m. for a group photo.*

	Session Two: Priority Habitats, Species, and Fisheries *Location: Sunrise Room* *Chair: Christopher Glass, University of New Hampshire* *Rapporteur: Joseph Luczkovitch, East Carolina University*
11:00–11:20 a.m.	Protected Species/Habitats *Craig Johnson, NOAA*
11:20–11:40 a.m.	Arctic Fisheries and Habitat *Steve MacLean, North Pacific Fishery Management Council*
11:40–12:00 p.m.	South Atlantic Fisheries and Habitat *Jaclyn Daly, NOAA, and Roger Pugliese, South Atlantic Fishery Management Council*
12:00–12:20 p.m.	North Atlantic Fisheries and Habitat *Kevin Friedland, NOAA*
12:20–12:40 p.m.	Questions and Discussion
12:40–2:00 p.m.	LUNCH *(provided)* *Location: Tiki Pavilion*
	Session Three: Sources and Sound Exposure *Location: Sunrise Room* *Chair: Roberto Racca, JASCO Applied Sciences* *Rapporteur: James Miller, University of Rhode Island*
2:00–2:20 p.m.	Measurements, Metrics, and Terminology *Michael Ainslie, TNO Defense, Security, and Safety*
2:20–2:50 p.m.	Sea Noise *Rob McCauley, Curtin University* *and Christine Erbe, Curtin University*
2:50–3:10 p.m.	Seismic Sources *Michael Jenkerson, Exxon Mobil Exploration Company*
3:10–3:40 p.m.	**BREAK**
3:40–4:00 p.m.	Pile Driving *James Reyff, Illingworth & Rodkin, Inc.*
4:00–4:20 p.m.	Wind Farms *Jeremy Nedwell, Subacoustech Ltd.*
4:20–4:40 p.m.	Other Anthropogenic Sources of Interest *Michael Ainslie, TNO Defense, Security, and Safety*
4:40–5:00 p.m.	Questions and Discussion
8:00–10:00 p.m.	**LIGHTNING SESSIONS** *Location: Sunrise Room* A rapid session of five minute, three-slide presentations on current research, ideas, and theories. *Chairs: Arthur N. Popper, University of Maryland, and Anthony Hawkins, Loughine Ltd.*

AGENDA: Day Two

Wednesday, March 21, 2012	
7:30–8:30 a.m.	Registration *Location: Outside of the Sunrise Room*
8:30–10:15 a.m.	**Breakout Groups For Session Three** *Location: A: Sunset Room; B: Esquire Room; C: Towne Room* A. Noise Generation: Characterizing Sources and Determining Exposure *Chair: James Miller, University of Rhode Island* *Rapporteur: Roger Gentry, E&P Sound and Marine Life Joint Industry Programme* B. Noise Mitigation for Different Sources: Can Outputs be Reduced? Are There Quieter Alternatives? *Chair: Roberto Racca, JASCO Applied Sciences* *Rapporteur: James Reyff, Illingworth & Rodkin, Inc.* C. Noise Measurements and Metrics that are Especially Relevant to Determining Sound Exposure: Including Cumulative and Aggregate Effects *Chair: Brandon Southall, Southall Environmental Associates, Inc.* *Rapporteur, John Stadler, NOAA*
10:15–10:45 a.m.	**BREAK**
	Session Four: Effects of Sound on Fishes and Invertebrates *Location: Sunrise Room* *Chair: Rob McCauley, Curtin University* *Rapporteur: Thomas Carlson, Battelle Pacific Northwest National Library*
10:45–11:00 a.m.	Recap of Prior Sessions and Introduction *Ann Pembroke, Normandeau Associates, Inc.*
11:00–11:20 a.m.	Diversity of Fishes *Brandon Casper, University of Maryland*
11:20–11:40 a.m.	Invertebrates *Michel Andre, University of Catalonia*
11.40 a.m.–12:00 p.m.	Injury and Effects on Fish Physiology *Michele Halvorsen, Battelle PNNL*
12:00–12:15 p.m.	Questions and Discussion

12:15–1:15 p.m.	**LUNCH** *(provided)* *Location: Tiki Pavilion*
1:15–1:35 p.m.	Injury and Effects on Invertebrates *Jerry Payne, Department of Fisheries and Oceans*
1:35–1:55 p.m.	Importance of Sounds for Animals–Sound Production and Sound Detection: Changes in Behavior *David Mann, University of South Florida*
1:55–2:15 p.m.	The Auditory Scene, Communication, and Effects of Masking *Richard R. Fay, Loyola University Chicago*
2:15–2:35 p.m.	Behavior of Pelagic Fish in Response to Anthropogenic Sources *John Dalen, Institute of Marine Research*
2:35–3:00 p.m.	Questions and Discussion
3:00–3:30 p.m.	**BREAK**
3:30–3:50 p.m.	Responses of Fish to Ship Noise *Alex De Robertis, NOAA*
3:50–4:10 p.m.	Effects of Noise on Catches *Svein Løkkeborg, Institute of Marine Research*
4:10–4:30 p.m.	Assessing Effects of Noise on Catches: Statistical Approaches *Steven Murawski, University of South Florida*
4:30–5:00 p.m.	Questions and Discussion



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AGENDA: Day Three

Thursday, March 22, 2012	
	Session Four: Effects of Sound on Fishes and Invertebrates, Continued *Location: Breakout Rooms—Esquire, Towne, Sunset*
8:30–10.30 a.m.	**Breakout Groups For Session Four** *Location: A: Esquire Room; B: Sunset Room; C: Towne Room* A. Effects of Exposure to Sound on Catches *Chair, Alex De Robertis, NOAA* *Rapporteur, John Dalen, Institute of Marine Research* B. What Do We Need to Know About Behavior of Wild Fishes and Invertebrates in Relation to Sound Exposure? *Chair, Rob McCauley, Curtin University* *Rapporteur, Michel Andre, University of Catalonia* C. Injury, Physiological Damage, and Stress as a Result of Sound Exposure *Chair, Michele Halvorsen, Battelle PNNL* *Rapporteur, Jerry Payne, Department of Fisheries and Oceans*
10:30–11:00 a.m.	**BREAK**
	Session Five: Conclusions *Location: Sunrise Room* *Chair: Jennifer Miksis-Olds, Penn State*
11:00–11:15 a.m.	Recap of Prior Sessions and Introduction *Ann Pembroke, Normandeau Associates, Inc.*
11:15 a.m.–12:00 p.m.	Presentation from Session Three Breakout Groups on Sources and Exposure followed by General Discussion
12:00–1:00 p.m.	**LUNCH** *(Provided)* *Location: Tiki Pavilion*
1:00–1:45 p.m.	Presentation from Session Four Breakout Groups on Effects of Noise on Fishes and Invertebrates followed by General Discussion
1:45–2:15 p.m.	Information Needs and Data Gaps Identified at Workshop *Anthony Hawkins, Loughine Ltd*
2:15–3:15 p.m.	Questions and Discussion
3:15–3:45 p.m.	**BREAK**
3:45–4:15 p.m.	General Discussion
4:15–4:30 p.m.	Final Comments/Summary from BOEM *Alan Thornhill, BOEM*
4:30–4:45 p.m.	Workshop Closing *Ann Pembroke, Normandeau Associates, Inc.*

LIGHTNING SESSIONS

"Lightning" sessions held from 8 p.m. to 10 p.m. Tuesday evening will feature five-minute, three-slide presentations of current research, ideas the researchers want to discuss, theories, or anything else related to the overall interests of the workshop. The goal of these sessions is to allow people to share their current work with others. We hope that these short presentations will provide ideas and opportunities for discussion and interaction over the remainder of the workshop. Lightning session registration will remain open at the registration table until 5 p.m. on Tuesday, March 20.

LIGHTNING SESSION AGENDA

Name	Title	Affiliation	Lightning Session Title
Joseph Lafrate	Biologist	Naval Undersea Warfare Center - Newport	*Effects of Pile-Driving on Movement Behavior of Wild Reef Fish*
Brian Anderson	Vice President	Liquid Robotics, Inc.	*Wave Glider - An Unmanned Silent Passive Acoustic Monitor Platform*
Mark Liddiard	Business Manager	HR Wallingford Ltd	*Filling Data Gaps in a New 3D Predictive Noise Model*
Rick Bruintjes	Independent Research Fellow/Dr.	University of Bristol, UK	*The Impact of Boat Noise on Parental Behaviour in a Social Cichlid Fish*
Lars Petter Myhre	Leading Advisor	Statoil	*Fish Observations Using Rov From O&G Installation During Seismic Survey*
Michael Stocker	Director	Ocean Conservation Research	*Expressing Signal Characteristics as an Exposure Impact Factor*
Mark Wochner	Research Associate	Applied Research Laboratories, The University of Texas at Austin	*Underwater Noise Abatement Technology to Minimize the Impact of Industrial Activity on Marine Life*
Rodney Rountree	Senior Scientist	Marine Ecology and Technology App Inc	*Regional Catalogs of Biological Sound Sources: A Prerequisite to Understand Noise Impacts on Marine Ecosystems*
Jackson Gross	Biologist	USGS Northern Rocky Mountain Science Center	*Delayed Mortality and Barotrauma in Northern Pike Exposed to Water Guns*

Name	Title	Affiliation	Lightning Session Title
Robert Dooling	Professor of Psychology	Univ of Maryland	*What Do We Mean By 'Hearing'?*
Gail Scowcroft	Associate Director, Office of Marine Programs	University of Rhode Island	*Discovery of Sound in the Sea*
Ingebret Gausland	Consultant		*The IMR 1992 Nordkappbanken Study Revisited*
Alex De Robertis	Fisheries Research Biologist	Alaska Fisheries Science Center	*Radiated Noise Measurements of A Noise-Reduced Fisheries Research Vessel*
Brandon Casper	Postdoctoral Research Scientist	University of Maryland	*Summary of Recent Experiments on Effects of Pile Driving Exposure in Fishes*
Erica Dazey	Senior Marine Scientist	Geo-Marine, Inc.	*Bio-Acoustic Monitoring During Marine Construction Projects*
Petr Krysl	Professor	University of California, San Diego	*Angular Oscillation of Solid Scatterers in Response to Progressive Planar Acoustic Waves: Do Fish Otoliths Rock?*
Ted Cranford	Chief Scientist	Quantitative Morphology Consulting, Inc.	*Virtual Experiments in Bioacoustics: Fish, Sound, and Finite-Element Modeling*
Jeremy Nedwell	Director	Subacoustech Environmental Ltd	*The Use of Acoustic Modelling for Assessing Windfarm Impact*
Brandon Southall	President and Senior Scientist	Southall Environmental Associates; University of California, Santa Cruz	*Behavioral Response Study Methods Used in a Study off Southern California*

Appendix B: Presentations


BOEM
Effects of Noise on Fish, Fisheries, and Invertebrates A BOEM Workshop on Data Gaps and Research Needs
March 20-22, 2012
San Diego, CA
Bureau of Ocean Energy Management
ENVIRONMENTAL STUDIES PROGRAM | Applied Science for Informed Decisions on Ocean Energy
NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS


BOEM
Acknowledgements
Concept: Ms. Kim Skrupky, BOEM
Driving Forces: Dr. Arthur N. Popper, UMD
Dr. Anthony Hawkins, Loughine
Science Review Panel: Dr. Christopher Glass, UNH
Dr. David Mann, USF
Dr. Jennifer Miksis-Olds, Penn State
Dr. Roberto Racca, JASCO
Logistics: Ms. Christine Denny, Normandeau
Ms. Alexis Hampton, Normandeau
NORMANDEAU ASSOCIATES
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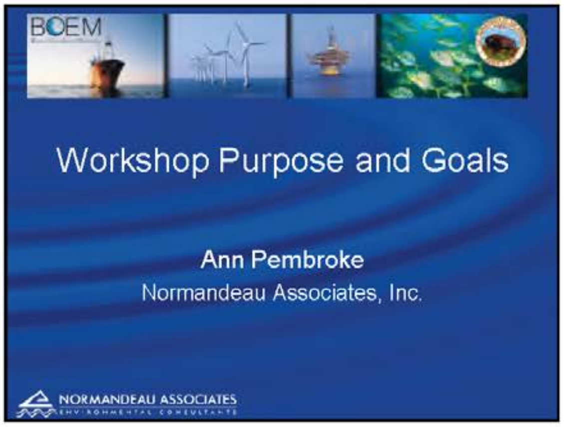
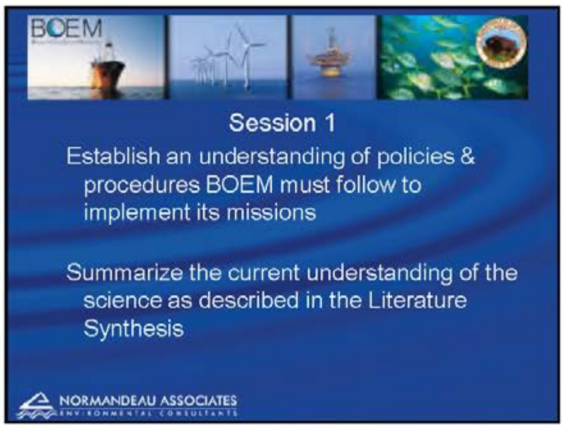
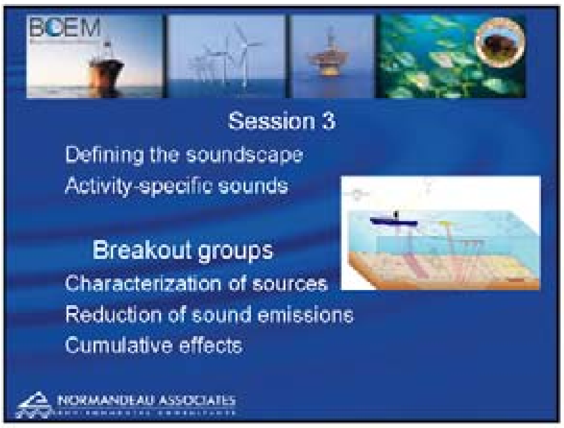

BOEM
Workshop Purpose and Goals
Ann Pembroke
Normandeau Associates, Inc.
NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS

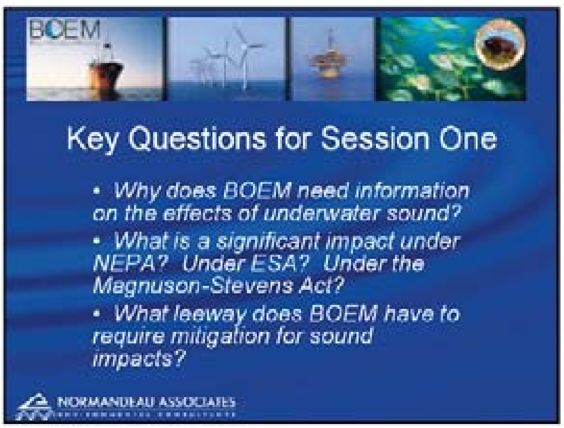

BOEM
Tuesday
Session 1 Introduction & overview
Session 2 Priority Habitats, Species & Fisheries
Session 3 Sources and Sound Exposure
Lightning Session
NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS


BOEM
Session 1
Establish an understanding of policies & procedures BOEM must follow to implement its missions
Summarize the current understanding of the science as described in the Literature Synthesis
NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS

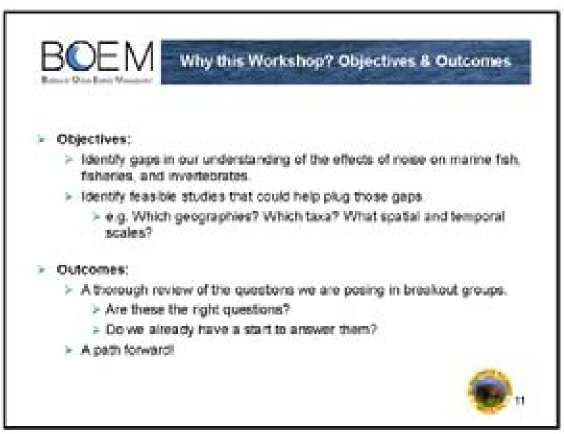

BOEM
Session 2
Define the organisms of concern to regulators, managers, and the fishing community
NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS


BOEM
Session 3
Defining the soundscape
Activity-specific sounds
Breakout groups
Characterization of sources
Reduction of sound emissions
Cumulative effects
NORMANDEAU ASSOCIATES

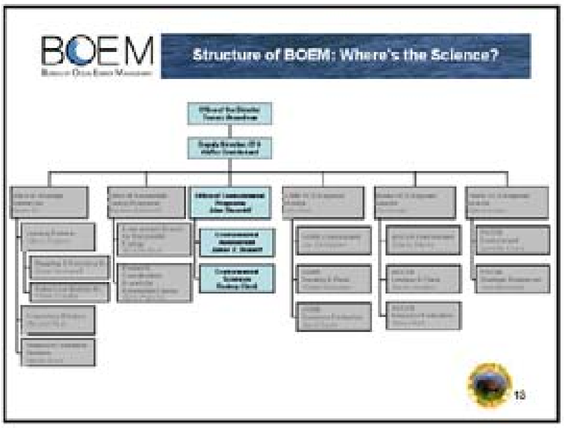

BOEM
Session 4
Who hears? Who speaks?
How are they affected?
Breakout groups
Implications for fishing
Behavioral responses
Injury
NORMANDEAU ASSOCIATES


BOEM
Key Questions for Session One
• Why does BOEM need information on the effects of underwater sound?
• What is a significant impact under NEPA? Under ESA? Under the Magnuson-Stevens Act?
• What leeway does BOEM have to require mitigation for sound impacts?
NORMANDEAU ASSOCIATES

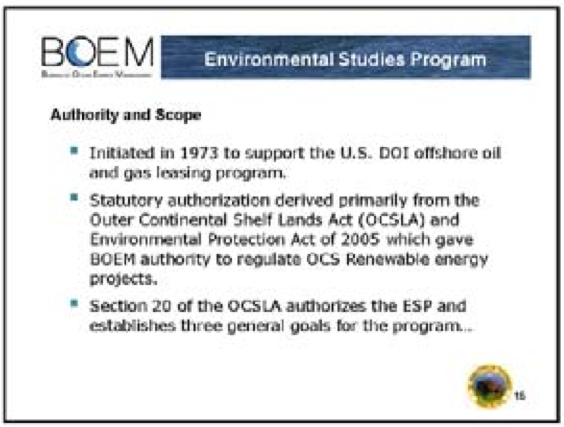

BOEM
Effects of Noise on Fish, Fisheries, and Invertebrates
A BOEM Workshop on Data Gaps and Research Needs
Alan D. Thornhill, Ph.D.
Chief Environmental Officer
Office of Environmental Programs
Alan.Thornhill@boem.gov

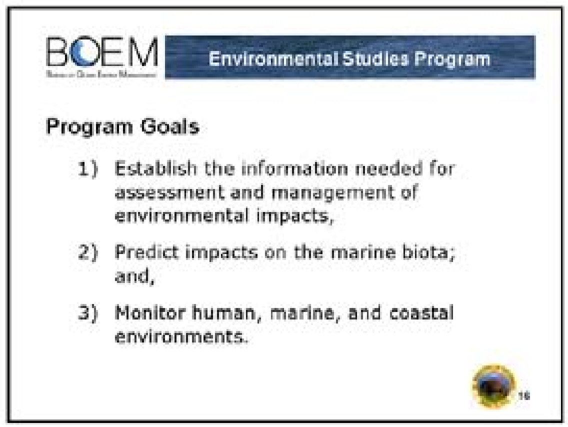

BOEM
Why this Workshop? Objectives & Outcomes
Objectives:
Identify gaps in our understanding of the effects of noise on marine fish, fisheries, and invertebrates.
Identify feasible studies that could help plug those gaps.
e.g. Which geographies? Which taxa? What spatial and temporal scales?
Outcomes:
A thorough review of the questions we are posing in breakout groups.
Are these the right questions?
Do we already have a start to answer them?
A path forward!
11

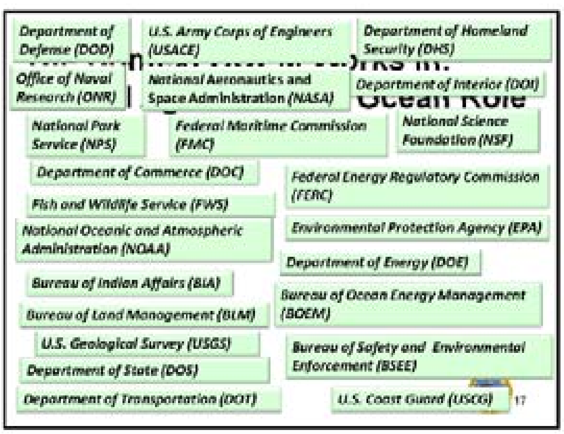

BOEM
Our Organization(s)
BOEM
Bureau of Ocean Energy Management
BOEM manages development of the nation's offshore resources in an environmentally and economically responsible way.
BSEE develops and enforces safety and environmental regulations.
BSEE
Bureau of Safety and Environmental Enforcement
12

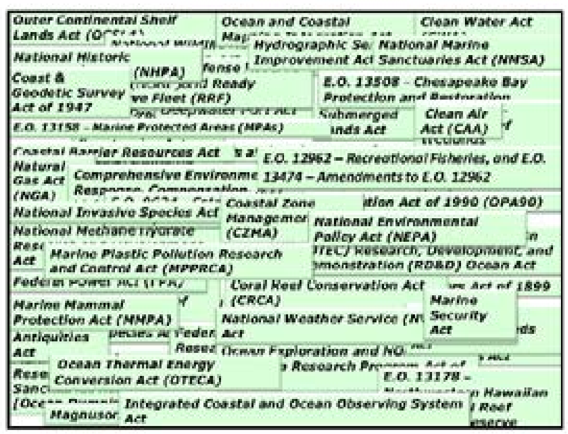

BOEM
Structure of BOEM: Where's the Science?
13


BOEM
Environmental Studies Program
Applied science for informed decisions on ocean energy
Mission:
Provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.
14


BOEM
Environmental Studies Program
Authority and Scope
Initiated in 1973 to support the U.S. DOI offshore oil and gas leasing program.
Statutory authorization derived primarily from the Outer Continental Shelf Lands Act (OCSLA) and Environmental Protection Act of 2005 which gave BOEM authority to regulate OCS Renewable energy projects.
Section 20 of the OCSLA authorizes the ESP and establishes three general goals for the program...
15

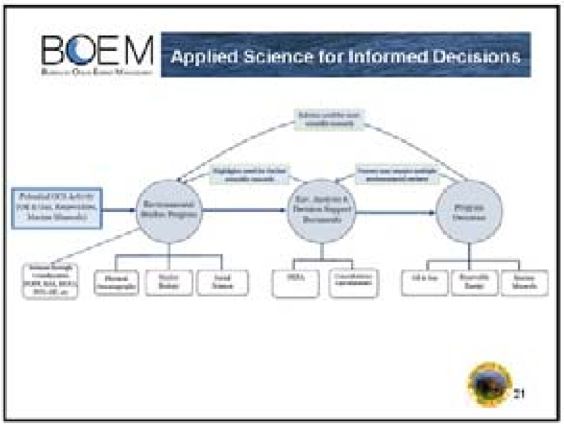

BOEM
Environmental Studies Program
Program Goals
1) Establish the information needed for assessment and management of environmental impacts,
2) Predict impacts on the marine biota; and,
3) Monitor human, marine, and coastal environments.
16

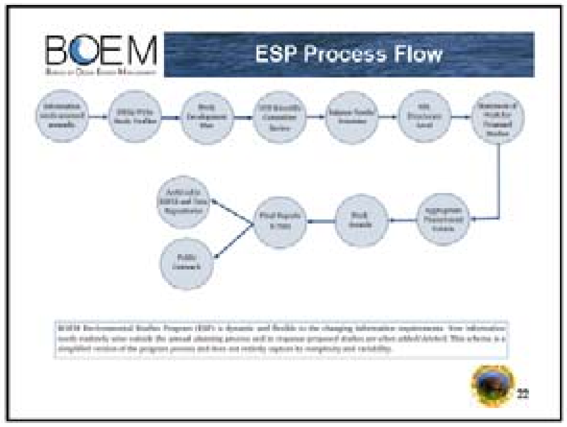

Department of Defense (DOD)
U.S. Army Corps of Engineers (USACE)
Department of Homeland Security (DHS)
Office of Naval Research (ONR)
National Aeronautics and Space Administration (NASA)
Department of Interior (DOI)
National Park Service (NPS)
Federal Maritime Commission (FMC)
National Science Foundation (NSF)
Department of Commerce (DOC)
Federal Energy Regulatory Commission (FERC)
Fish and Wildlife Service (FWS)
National Oceanic and Atmospheric Administration (NOAA)
Environmental Protection Agency (EPA)
Department of Energy (DOE)
Bureau of Indian Affairs (BIA)
Bureau of Ocean Energy Management (BOEM)
Bureau of Land Management (BLM)
U.S. Geological Survey (USGS)
Bureau of Safety and Environmental Enforcement (BSEE)
Department of State (DOS)
Department of Transportation (DOT)
U.S. Coast Guard (USCG)
17

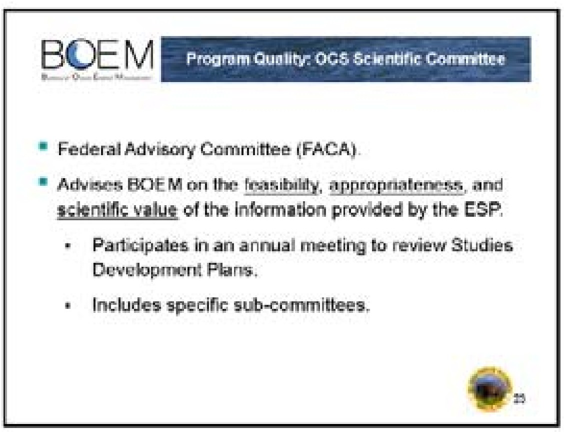

Outer Continental Shelf
Ocean and Coastal
Clean Water Act
National Marine Sanctuaries Act (NMSA)
(NHPA)
Coast & Geodetic Survey Act of 1947
E.O. 13508 – Chesapeake Bay
Clean Air Act (CAA)
E.O. 13158 – Marine Protected Areas (MPAs)
E.O. 12962 – Recreational Fisheries, and E.O. 13474 – Amendments to E.O. 12962
Natural Gas Act (NGA)
National Invasive Species Act
Coastal Zone
(CZMA)
National Environmental Policy Act (NEPA)
Marine Plastic Pollution Research and Control Act (MPPRCA)
Coral Reef Conservation Act (CRCA)
Marine Mammal Protection Act (MMPA)
Marine Security Act
Antiquities Act
Ocean Thermal Energy Conversion Act (OTECA)
Integrated Coastal and Ocean Observing System Act


BOEM
Determining Study Priorities
Mission relevance
Scientific merit
Technically feasible
Timing
Applicability
Affordable
19

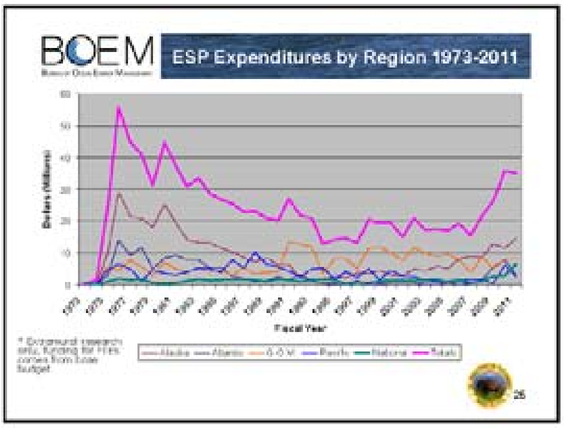

BOEM
Mission Relevance: Scope
National
Partnerships: NOPP
Inter-Agency, Intra-Agency
Five year schedule
Pacific
Developed/ producing leases
Renewable energy
Atlantic
Sand and gravel
Renewable energy
Alaska
Beaufort and Chukchi Sea exploration
Gulf of Mexico
Deepwater
Active Leasing
Sand and gravel
20

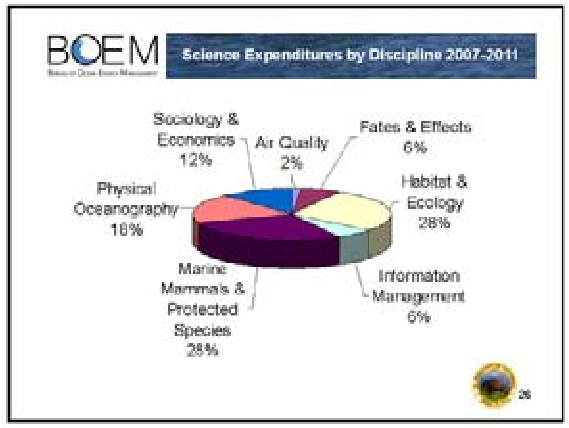

BOEM
Applied Science for Informed Decisions
21

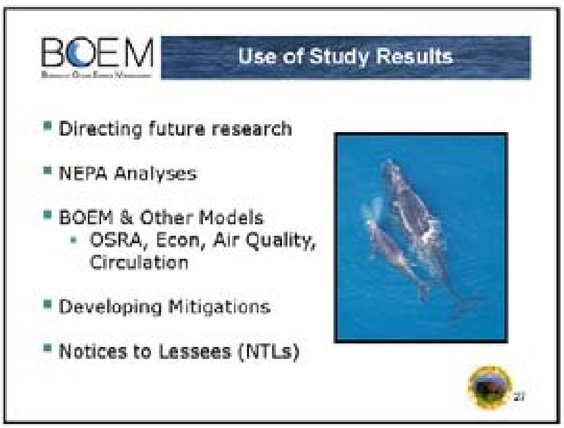

BOEM
ESP Process Flow
22


BOEM
Program Quality: OCS Scientific Committee
Federal Advisory Committee (FACA).
Advises BOEM on the feasibility, appropriateness, and scientific value of the information provided by the ESP.
Participates in an annual meeting to review Studies Development Plans.
Includes specific sub-committees.
23

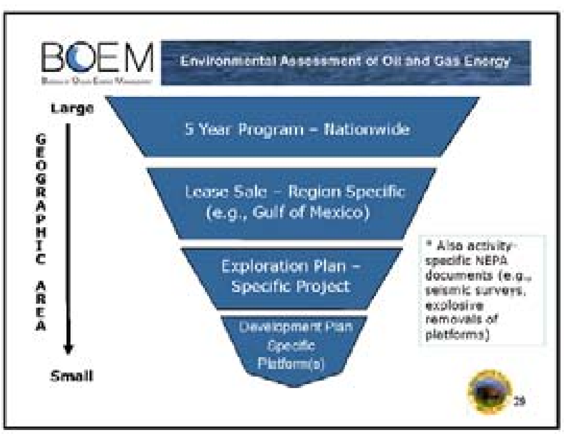

BOEM
Program Funds Research Through...
Competitive Contracts
Inter-Agency Agreements
Partnering NOPP; NOAA; ONR; NASA; NSF; USGS; FWS; NPS; DOE; etc.
Cooperative Agreements
Coastal Marine Institutes (CMI)
Cooperative Ecosystem Studies Units (CESU)
24

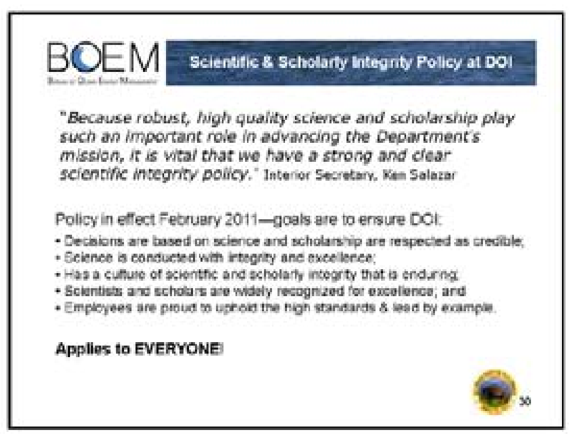

BOEM
ESP Expenditures by Region 1973-2011
Dollars (Millions)
Fiscal Year
Alaska Atlantic G.O.M. Pacific National Totals
26


BOEM
Science Expenditures by Discipline 2007-2011
Sociology & Economics 12%
Air Quality 2%
Fates & Effects 6%
Habitat & Ecology 28%
Physical Oceanography 18%
Marine Mammals & Protected Species 28%
Information Management 6%
26


BOEM
Use of Study Results
Directing future research
NEPA Analyses
BOEM & Other Models
OSRA, Econ, Air Quality, Circulation
Developing Mitigations
Notices to Lessees (NTLs)
27


BOEM
Environmental Assessment: OEP's Second Arm
NEPA and other tools…
Public Disclosure and Involvement
Accurate Scientific Analysis
Foster Better Decisions
Focus on What is Affected
Consider Cumulative Effects
Consider Alternatives
Identify and Assess Mitigation
Adaptive Management


BOEM
Environmental Assessment of Oil and Gas Energy
Large
GEOGRAPHIC AREA
Small
5 Year Program – Nationwide
Lease Sale – Region Specific (e.g., Gulf of Mexico)
Exploration Plan – Specific Project
Development Plan Specific Platform(s)
* Also activity-specific NEPA documents (e.g., seismic surveys, explosive removals of platforms)


BOEM
Scientific & Scholarly Integrity Policy at DOI
"Because robust, high quality science and scholarship play such an important role in advancing the Department's mission, it is vital that we have a strong and clear scientific integrity policy." Interior Secretary, Ken Salazar
Policy in effect February 2011—goals are to ensure DOI:
• Decisions are based on science and scholarship are respected as credible;
• Science is conducted with integrity and excellence;
• Has a culture of scientific and scholarly integrity that is enduring;
• Scientists and scholars are widely recognized for excellence; and
• Employees are proud to uphold the high standards & lead by example.
Applies to EVERYONE!
30

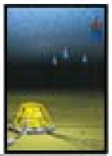
ESP Information Sharing

- Environmental Studies Program Information System (**ESPIS**)
- BOEM Hosted Meetings & Workshops
- Participation and Sponsorship of Symposia and Conferences
- Multipurpose Marine Cadastre (**MMC**)
- Professional Journal Publications
- BOEM Ocean Science
- Education and Outreach

31

Renewable Energy Program

- Energy Policy Act 2005 gave authority to DOI and Secretary delegated to BOEM
- Final Rule published in April 2009
- First Commercial Lease Issued – Cape Wind – in 2010
- Moving forward in Maryland, Virginia, New Jersey, Delaware Rhode Island and Massachusetts



32

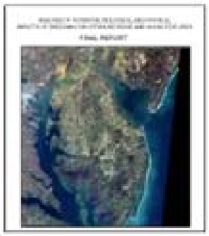
Marine Minerals Program

- 58 million cubic yards of OCS sand conveyed through 31 negotiated noncompetitive agreements
- Projects completed in Florida, Louisiana, Maryland, South Carolina and Virginia
- 180 miles of the Nation's shoreline have been replenished/restored

33

Marine Minerals Program: 20 Years

- $12 million spent on Environmental Studies
- More than 40 studies
  - Site- Specific and Programmatic
- 8 Ongoing programmatic studies
- Have been referenced or represented in:
  - International Studies
  - Nationwide Studies
  - Peer Reviewed Journal Articles
  - USACE Analysis and Research
  - FWS/NMFS documents
  - Master thesis and PhD dissertations
  - Conference Presentations/Proceedings
  - In-house documents



34

Studies Program: Take Home Messages

- The ESP is Mission-focused
- Clear Goals & Clear Strategy
- Highly Participatory
- Frequent Internal & External Review
- Coordination, Collaboration, and Leveraging
- Quality Science for the Bureau Mission
- The Landscape is Continually Evolving

35

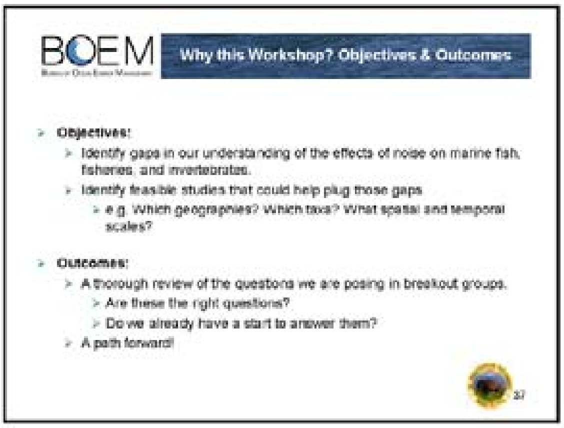
BOEM: So, why do we care about noise?

Exploration, Construction, Development, Operations, Maintenance, Decommissioning – all make noise!

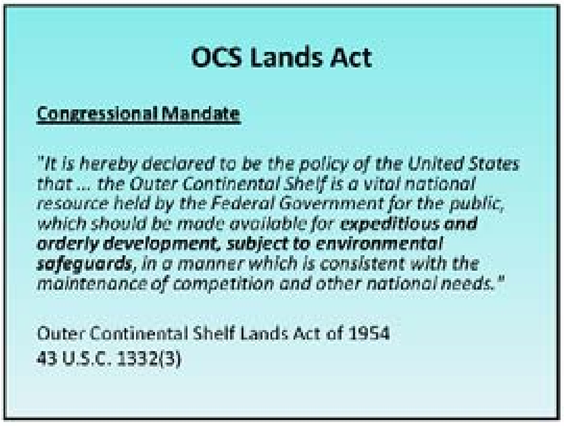
- Looking for conventional energy reservoirs (seismic surveys)
- Surveying for sand sources (multi-beam sonar surveys)
- Surveying for wind turbine site selection
- Surveying for marine archeological sites
- Dredging noise
- Pile driving
- Explosive removal of platforms

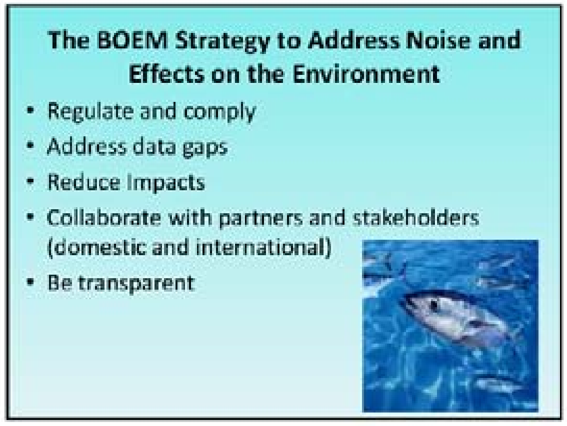
We need to understand the potential impacts of all of this on various taxa and the systems.

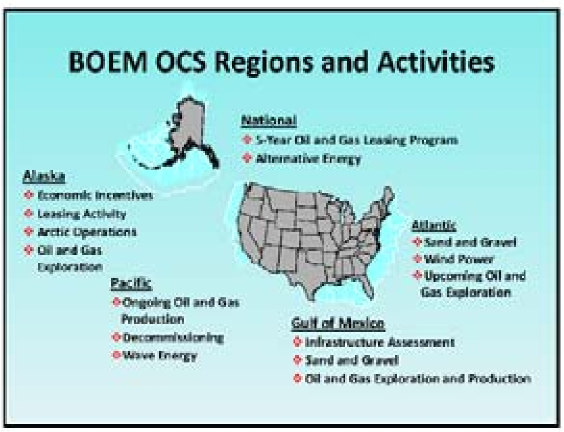
36


BOEM
Why this Workshop? Objectives & Outcomes
Objectives:
Identify gaps in our understanding of the effects of noise on marine fish, fisheries, and invertebrates.
Identify feasible studies that could help plug those gaps
e.g. Which geographies? Which taxa? What spatial and temporal scales?
Outcomes:
A thorough review of the questions we are posing in breakout groups.
Are these the right questions?
Do we already have a start to answer them?
A path forward!
37


BOEM
Environmental Impact Statements and Regulatory Requirements for Offshore Developments
Kimberly Skrupky
Bureau of Ocean Energy Management
March 20, 2012


OCS Lands Act
Congressional Mandate
"It is hereby declared to be the policy of the United States that ... the Outer Continental Shelf is a vital national resource held by the Federal Government for the public, which should be made available for expeditious and orderly development, subject to environmental safeguards, in a manner which is consistent with the maintenance of competition and other national needs."
Outer Continental Shelf Lands Act of 1954
43 U.S.C. 1332(3)


The BOEM Strategy to Address Noise and Effects on the Environment
Regulate and comply
Address data gaps
Reduce Impacts
Collaborate with partners and stakeholders (domestic and international)
Be transparent


BOEM OCS Regions and Activities
National
5-Year Oil and Gas Leasing Program
Alternative Energy
Alaska
Economic Incentives
Leasing Activity
Arctic Operations
Oil and Gas Exploration
Pacific
Ongoing Oil and Gas Production
Decommissioning
Wave Energy
Atlantic
Sand and Gravel
Wind Power
Upcoming Oil and Gas Exploration
Gulf of Mexico
Infrastructure Assessment
Sand and Gravel
Oil and Gas Exploration and Production


Integrate Environmental Consultations and Coordination with NEPA
NEPA Process

Environmental Protection – an Ongoing Integrated Process

Noise Regulated by BOEM

- Within the three program areas, noise is produced in several ways
- Geological and Geophysical sources
  - air guns, boomers, sparkers, chirpers, sub-bottom profilers, depth sounders, gravity, side-scan sonar, and magnetic/electromagnetic
- Construction, Drilling, Production and Decommissioning
  - pile driving, operational noise from rigs and platforms, vessel noise, dynamic positioning systems, explosives, dredging, ice breaking (Arctic)

Monitoring and Mitigation Measures

- Hiring Protected Species Observers to work on the vessel(s)
- Monitoring exclusion zones
- Passive Acoustic Monitoring (PAM)
- Sound Source Verification (SSV)
- Ramp-up
- Shut-down
- Time-of-Year closures
- But most of these don't work for fish!

Environmental Studies Program

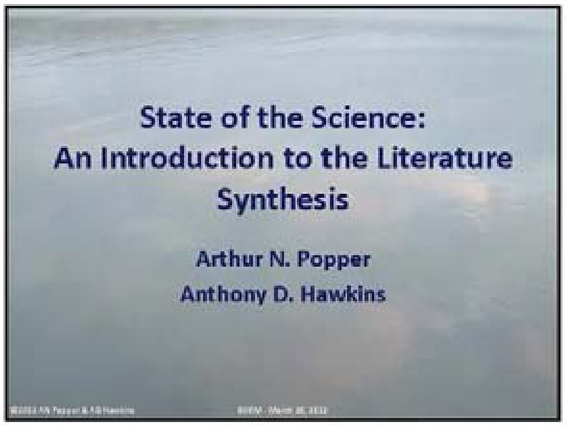
- BOEM develops, conducts and oversees world-class scientific research specifically to inform policy decisions regarding development of Outer Continental Shelf energy and mineral resources
- Research covers:
  - Physical oceanography
  - Atmospheric sciences
  - Biology
  - Protected species
  - Social sciences and economics
  - Submerged cultural resources
  - Environmental fates and effects

Funding Studies

- To provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.
- ~$30 million*
- ~$40 million on ground-breaking protected species research and acoustic issues
- ~$2 million provided annually through USGS
- ~ 50 % for ongoing
- ~ 50 % available for <u>New</u> starts annually
- Over 50 new projects for FY12
- Currently managing more than 300 active studies

* BOEM's FTE's not supported by ESP funds

Questions?

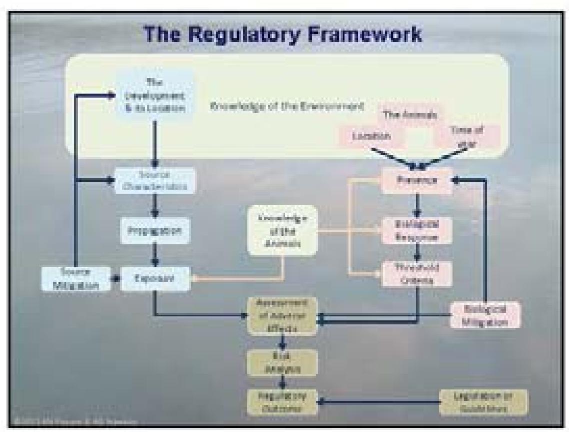

State of the Science:
An Introduction to the Literature Synthesis
Arthur N. Popper
Anthony D. Hawkins


The Geographical Focus


Atlantic
United States


Arctic
Chukchi Sea Planning Area
Beaufort Sea Planning Area
Barrow
Prudhoe Bay
Alaska
United States
Hope Basin Planning Area
Kotzebue
Arctic Circle
Russia
Canad


The Workshop Goal
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


The Regulatory Framework
The Development & its Location
Knowledge of the Environment
The Animals
Location
Time of year
Source Characteristics
Presence
Propagation
Knowledge of the Animals
Biological Response
Source Mitigation
Exposure
Threshold Criteria
Assessment of Adverse Effects
Biological Mitigation
Risk Analysis
Regulatory Outcome
Legislation or Guidelines

What do we know?

- Energy developments can generate transient high level sounds & increase overall background levels
- Many marine fish and invertebrates are sensitive to sound and use sounds in their everyday lives
- There is therefore potential for energy developments to have adverse effects upon species and habitats, and also to affect activities like fisheries

The Big Questions

- Are levels of sound in the sea changing as a result of human activities?
- Do man-made sounds have detrimental effects upon fish and invertebrates?
- Which sound-generating activities are most damaging to fish and invertebrates?
- How might the effects be reduced or mitigated?

Priority Habitats & Species

- Which species or habitats are particularly vulnerable to man-made sounds?
- Do any require protection?
- What protection can be provided?

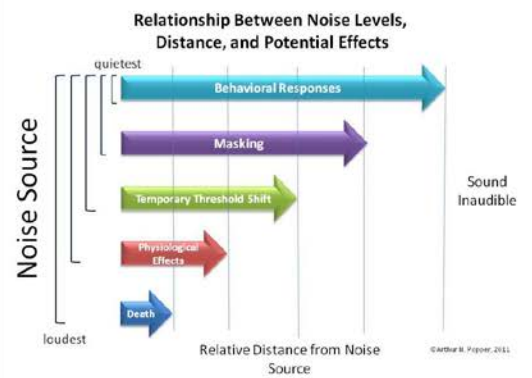
Are any fisheries likely to be affected by man-made sounds?

Natural Sounds

- What is the contribution to sound levels from natural sources, including biological sources?
- What physical quantities and metrics are most useful for describing ocean soundscapes?
- Are natural soundscapes at risk from man-made sounds?
- Which natural sounds will be masked by man-made sounds

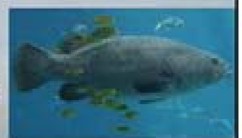
Sound Sources

- What is the contribution to sound levels from different man-made sources?
- Which man-made sources are likely to have the greatest adverse effects?
- What are the likely future trends in sound levels?
- Do we have appropriate standards and metrics for characterizing man-made sources?



In Determining Effects We Need to Consider Differences in:

- Species
- Size/age of animals
- Time of year
- Physiological state of the animal
- "Motivation" of the animal
- Numerous other factors that result in our not being able to refer to "the" fish or "the" invertebrate, but instead thinkof individual species, and even age-classes and other aspects of the animals biology
- All this makes reaching conclusions about effects that much harder



The Effects of Sounds

- Can we identify thresholds or criteria for the occurrence of different effects?
- What is the nature of the effects and how do they change with different sound types and levels?
- What are the source characteristics that cause detrimental effects; e.g., magnitude, rise time, duration, duty-cycle?
- How do animals differ in their response?

Hearing & Sound Detection

- Can fishes and invertebrates be sorted into different functional hearing groups?
- Can the hearing characteristics of these groups be described by generalized weighting functions?
- Is masking of biological sounds a particular problem?

A Significant Point

- Some fishes detect sound pressure
- However, many fishes and perhaps all invertebrates are sensitive to particle motion
- This finding has implications for examining the impact of different sources, but is often ignored

Behavior

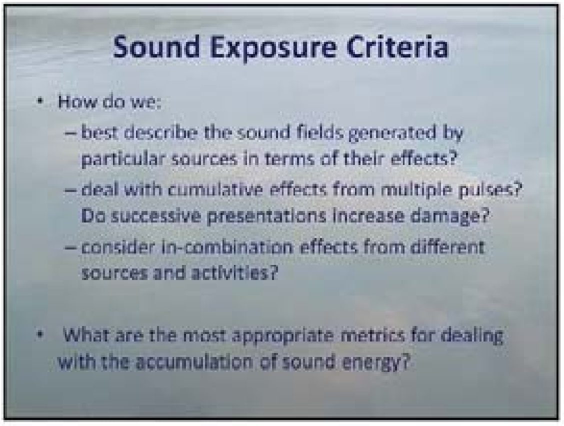
- What is the range and kinds of behavioral responses that occur?
- Which are significant in terms of impairing fitness?
- Which aspects of the sound source are responsible for the behavioral response (i.e., exposure level, peak pressure, frequency content, etc.)?
- Animals may habituate to man-made sounds. How do we deal with that?

Assessment of Adverse Effects

Which levels of pressure and particle motion cause:

- Temporary Threshold Shift
- Hair cell loss
- Physiological stress
- Significant behavioral responses
- Injury
- Mortality

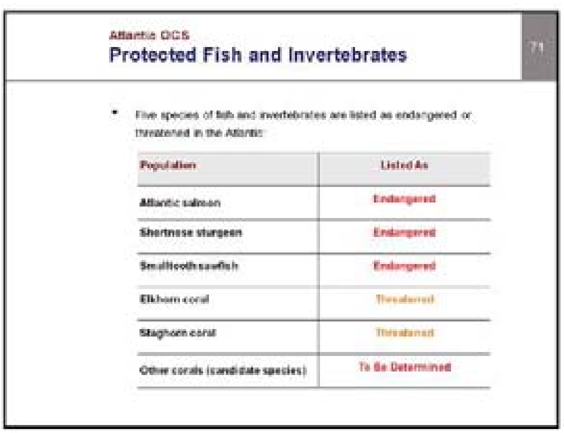
Do different sources elicit responses at different sound levels?

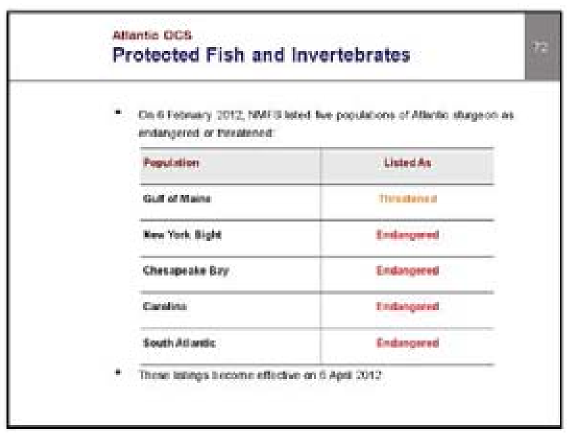

Sound Exposure Criteria
• How do we:
– best describe the sound fields generated by particular sources in terms of their effects?
– deal with cumulative effects from multiple pulses? Do successive presentations increase damage?
– consider in-combination effects from different sources and activities?
• What are the most appropriate metrics for dealing with the accumulation of sound energy?

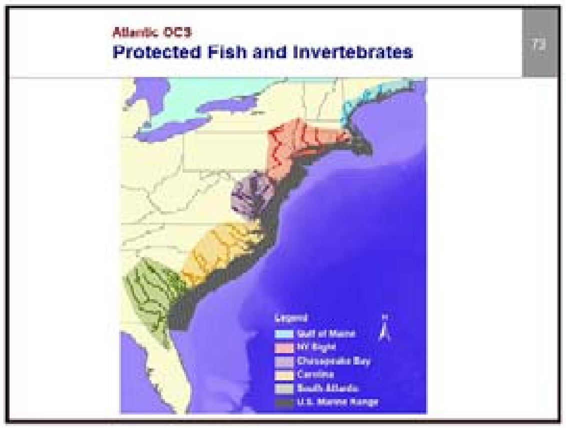

Mitigation
• Can we avoid using high level sources?
• Are there technological alternatives?
• Can sources be redesigned to make them less damaging?
• Can monitoring systems detect vulnerable animals before they are exposed?

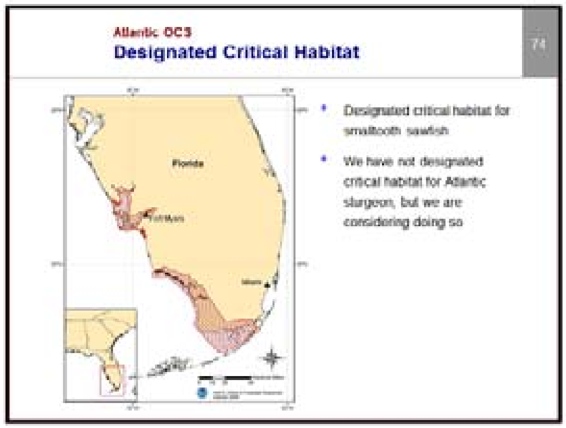

Other Mitigation Options
• Do ramp-up procedures work for fish & invertebrates?
• Can sound-making be restricted to times when animals are less likely to be affected by sound?

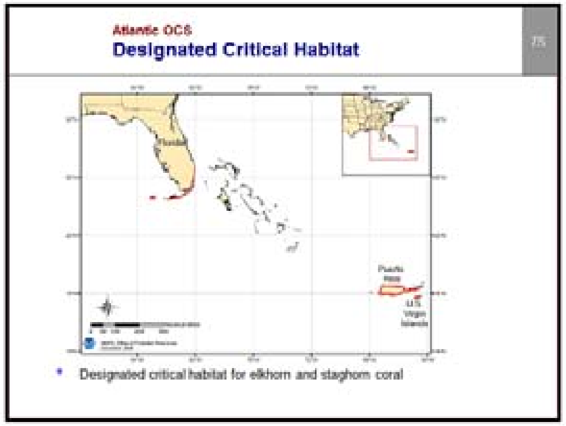

Protected Species/Habitats
San Diego | California | 20 March 2012
Craig Johnson
NOAA Fisheries
Silver Spring, Maryland

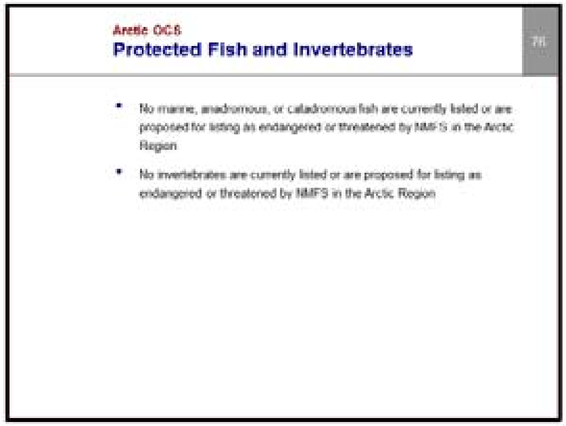

Atlantic OCS
Protected Fish and Invertebrates
71
• Five species of fish and invertebrates are listed as endangered or threatened in the Atlantic:
Population | Listed As
Atlantic salmon | Endangered
Shortnose sturgeon | Endangered
Smalltooth sawfish | Endangered
Elkhorn coral | Threatened
Staghorn coral | Threatened
Other corals (candidate species) | To Be Determined

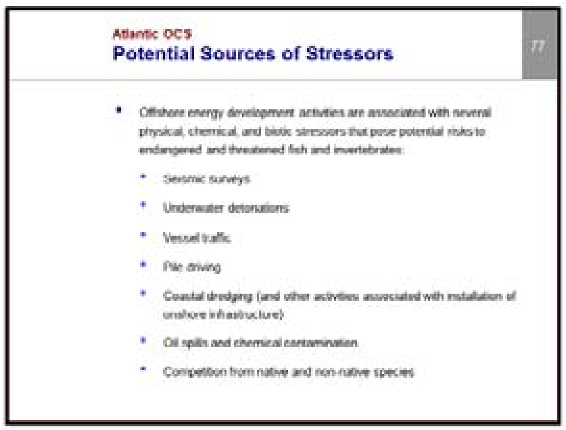

Atlantic OCS
Protected Fish and Invertebrates
72
• On 6 February 2012, NMFS listed five populations of Atlantic sturgeon as endangered or threatened:
Population | Listed As
Gulf of Maine | Threatened
New York Bight | Endangered
Chesapeake Bay | Endangered
Carolina | Endangered
South Atlantic | Endangered
• These listings become effective on 6 April 2012

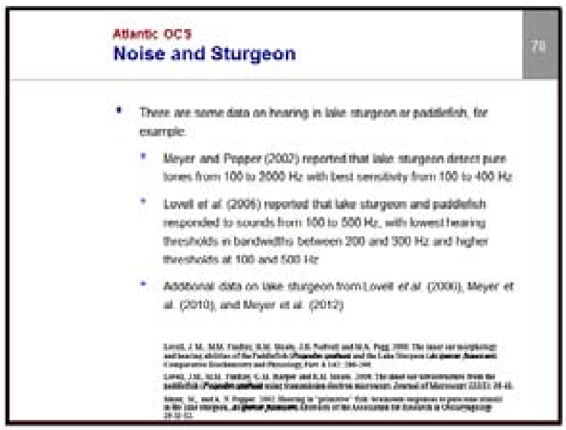

Atlantic OCS
Protected Fish and Invertebrates
73
Legend
Gulf of Maine
NY Bight
Chesapeake Bay
Carolina
South Atlantic
U.S. Marine Range


Atlantic OCS
Designated Critical Habitat
74
Florida
Fort Myers
Miami
Designated critical habitat for smalltooth sawfish
We have not designated critical habitat for Atlantic sturgeon, but we are considering doing so


Atlantic OCS
Designated Critical Habitat
75
Florida
Puerto Rico
U.S. Virgin Islands
Designated critical habitat for elkhorn and staghorn coral


Arctic OCS
Protected Fish and Invertebrates
76
No marine, anadromous, or catadromous fish are currently listed or are proposed for listing as endangered or threatened by NMFS in the Arctic Region
No invertebrates are currently listed or are proposed for listing as endangered or threatened by NMFS in the Arctic Region


Atlantic OCS
Potential Sources of Stressors
77
Offshore energy development activities are associated with several physical, chemical, and biotic stressors that pose potential risks to endangered and threatened fish and invertebrates:
Seismic surveys
Underwater detonations
Vessel traffic
Pile driving
Coastal dredging (and other activities associated with installation of onshore infrastructure)
Oil spills and chemical contamination
Competition from native and non-native species


Atlantic OCS
Noise and Sturgeon
78
There are some data on hearing in lake sturgeon or paddlefish, for example:
Meyer and Popper (2002) reported that lake sturgeon detect pure tones from 100 to 2000 Hz with best sensitivity from 100 to 400 Hz
Lovell et al. (2006) reported that lake sturgeon and paddlefish responded to sounds from 100 to 500 Hz, with lowest hearing thresholds in bandwidths between 200 and 300 Hz and higher thresholds at 100 and 500 Hz
Additional data on lake sturgeon from Lovell et al. (2006), Meyer et al. (2010), and Meyer et al. (2012)

Atlantic OCS

Noise and corals

79

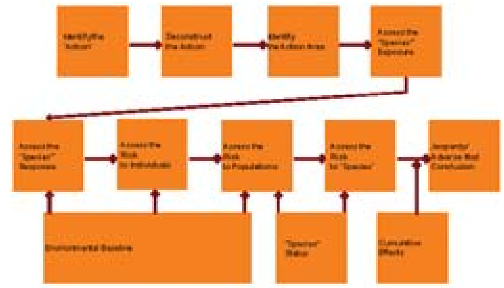
- Data on interactions between corals and sounds are the most limited, but include
  - Vermeij et al (2010) reported that free-swimming larvae of tropical corals detect and use sounds as a cue for orientation
  - They did not report how these larvae detect the sounds or components of the sound field that provide the cues
  - Numerous authors have demonstrated the effects of sound on larvae of fish that are part of coral reef ecosystems

Vermeij, M.J.A., K.L. Marhaver, C.M. Huijbers, I. Nagelkerken, and S.D. Simpson. 2010. Coral larvae move toward reef sounds. PLoS ONE 5(5): e10660.

ESA Consultations

A Generalized Assessment Model

80



ESA Consultations

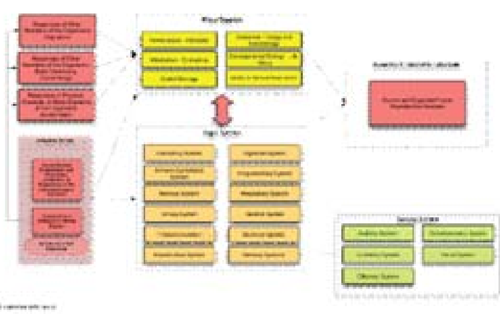
Generalized Assessment Model

81

- One of the most challenging steps of this assessment model links individual responses to individual risks
- A complete assessment of the risks of offshore energy projects must consider two risks to individuals
  - reductions in probability of survival (increases in mortality)
  - reductions in reproductive success (which is determined by age at first reproduction, interval between reproductive events, natality, recruitment into the adult population, and age at last reproduction)
- Data on the responses of fish and marine invertebrates to noise has limited utility if we cannot somehow link those responses to one of these two assessment endpoints
- That is our largest data or knowledge gap

Sub-Model for Individual Organisms

82



ESA Consultations

Emerging Challenges

83

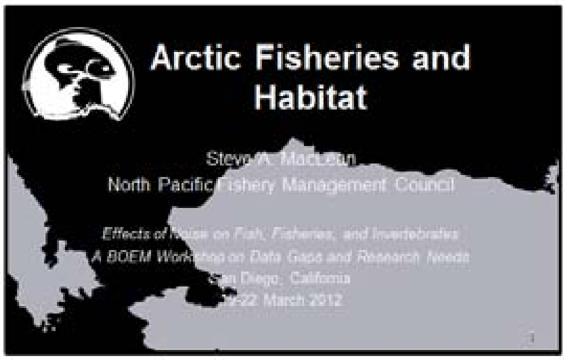
- Over the past five years, every assessment of noise-producing activities in the marine environment has had to deal with one constant and growing challenge: our inability to conduct rigorous cumulative impact assessments
- Challenges to our assessments have focused on
  - repeated exposures to single and multiple stressors
  - time- and space-crowded effects
  - interactions between multiple stressors (both natural and anthropogenic)
- We still lack rigorous methods for assessing these effects or the data we would need to execute such a method

Protected Species/Habitats

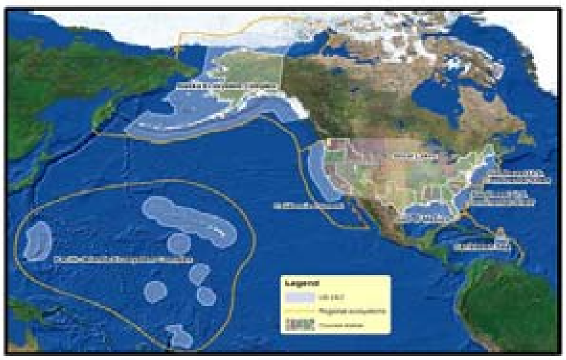
Craig Johnson, NOAA Fisheries

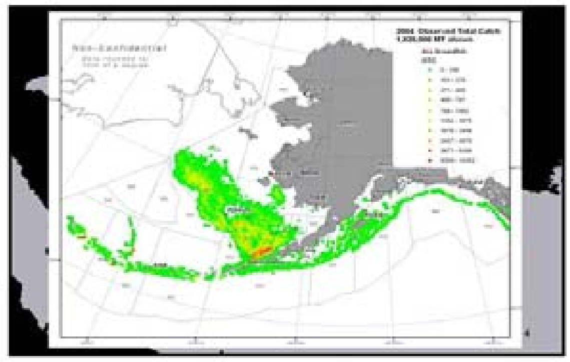
84

- Information needs
  - We need to be able to characterize how invertebrates perceive their acoustic environment and the effects of sound on their ecology
  - We need better ways of characterizing the effects of noise on the predators, competitors, symbionts, and prey of listed fish and invertebrates
  - We need to link responses to "noise" to the current and expected future reproductive success of the fish and invertebrates that are exposed to the "noise"
  - We need more rigorous methods to assess the cumulative impacts of offshore energy by itself and in combination with other human activities that co-occur with it in the marine environment

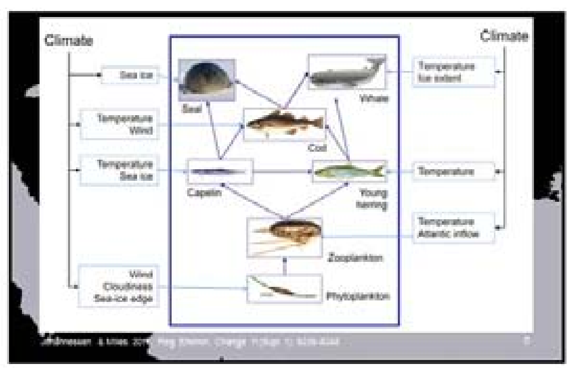

Arctic Fisheries and Habitat
Steve A. MacLean
North Pacific Fishery Management Council
Effects of Noise on Fish, Fisheries, and Invertebrates
A BOEM Workshop on Data Gaps and Research Needs
San Diego, California
22 March 2012

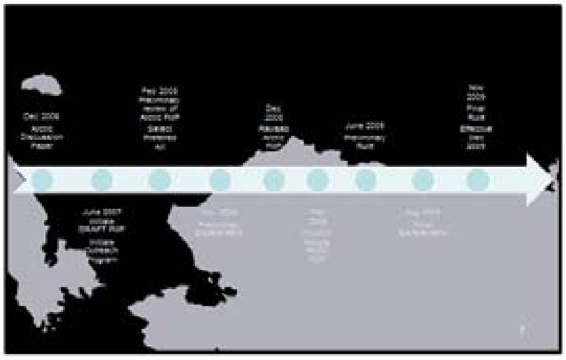

Development of the Arctic Fishery Management Plan
Current Status of Arctic fisheries
Data needs for the Arctic Fishery Management Plan

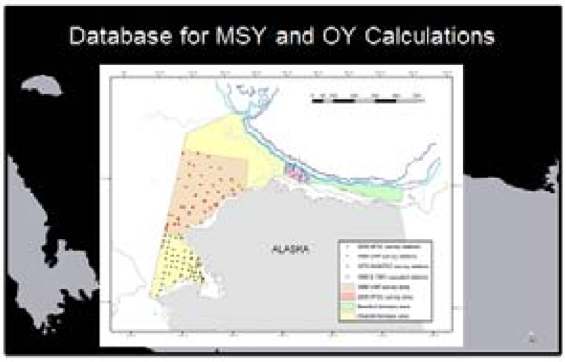

Legend

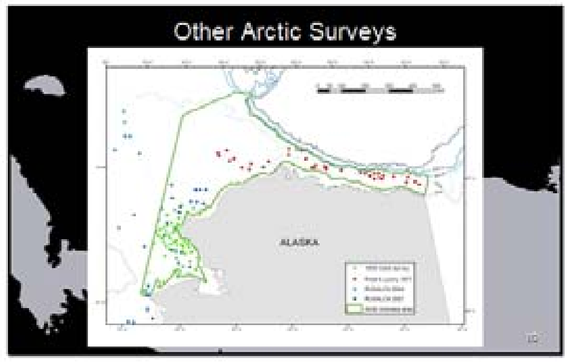

Non-Confidential
2004 Observed Total Catch

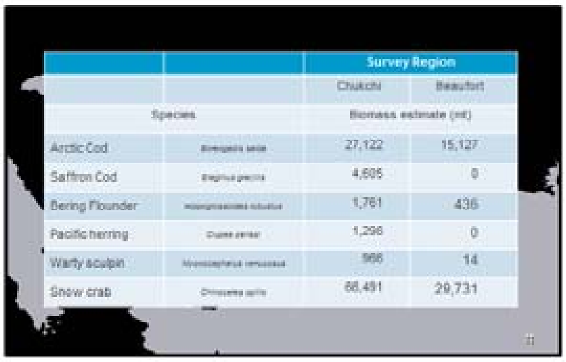

Arctic Management Area
Alaska State Waters
Arctic Management Area
Russia
Alaska
Canada


Climate
Climate
Sea ice
Temperature
Wind
Temperature
Sea ice
Wind
Cloudiness
Sea-ice edge
Seal
Whale
Cod
Capelin
Young herring
Zooplankton
Phytoplankton
Temperature
Ice extent
Temperature
Temperature
Atlantic inflow

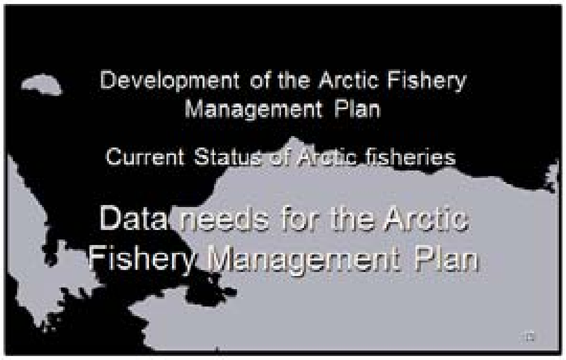


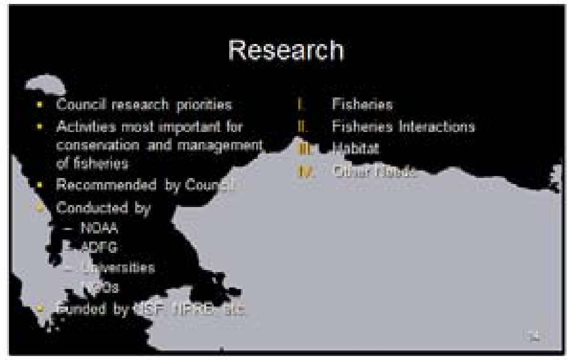


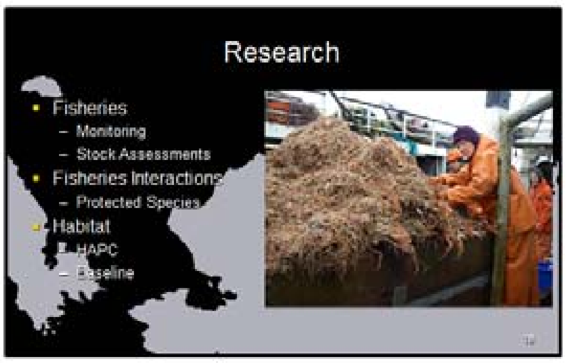


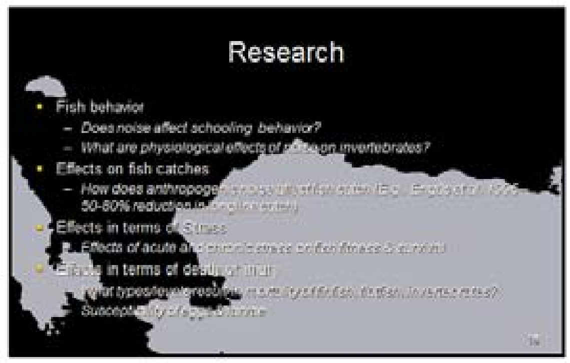


		Survey Region	
		Chukchi	Beaufort
Species		Biomass estimate (mt)	
Arctic Cod	[illegible]	27,122	15,127
Saffron Cod	[illegible]	4,606	0
Bering Flounder	[illegible]	1,761	436
Pacific herring	[illegible]	1,298	0
Warty sculpin	[illegible]	966	14
Snow crab	[illegible]	66,491	29,731

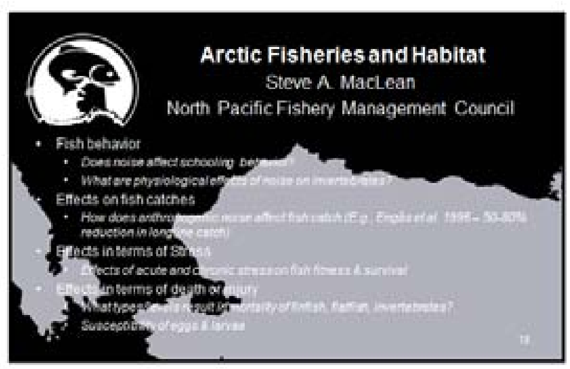

Development of the Arctic Fishery Management Plan
Current Status of Arctic fisheries
Data needs for the Arctic Fishery Management Plan

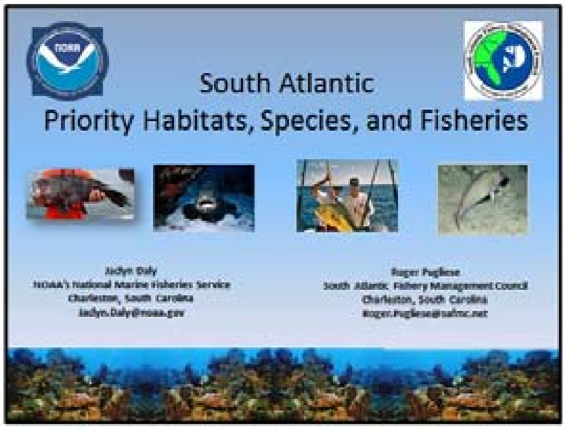

Research
Council research priorities
Activities most important for conservation and management of fisheries
Recommended by Council
Conducted by
– NOAA
– ADFG
– Universities
– NGOs
Funded by NSF, NPRB, etc.
I. Fisheries
II. Fisheries Interactions
III. Habitat
IV. Other Needs


Research
Fisheries
– Monitoring
– Stock Assessments
Fisheries Interactions
– Protected Species
Habitat
– HAPC
– Baseline

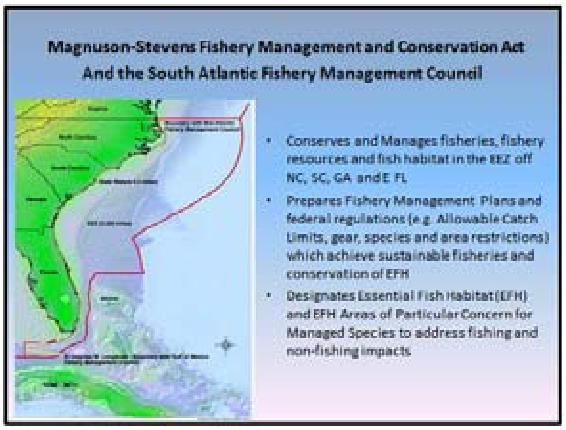

Research
Fish behavior
– Does noise affect schooling behavior?
Effects on fish catches
Effects in terms of Stress
Effects in terms of death or injury

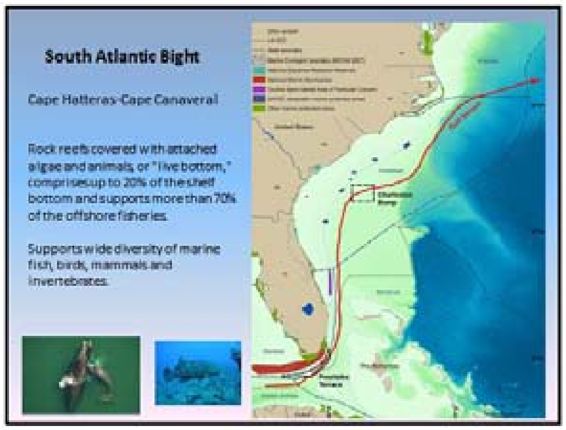

Thank You
Contact:
North Pacific Fishery Management Council
605 West 4th Ave, Suite 306
Anchorage, AK 99501
907-271-2809
907-271-2817 (fax)
Steve MacLean


Arctic Fisheries and Habitat
Steve A. MacLean
North Pacific Fishery Management Council
Fish behavior
Effects on fish catches
Effects in terms of death or injury


South Atlantic
Priority Habitats, Species, and Fisheries
Jaclyn Daly
NOAA's National Marine Fisheries Service
Charleston, South Carolina
Jaclyn.Daly@noaa.gov
Roger Pugliese
South Atlantic Fishery Management Council
Charleston, South Carolina
Roger.Pugliese@safmc.net


Overview
• Magnuson-Stevens Fishery Management and Conservation Act and the South Atlantic Fishery Management Council
• South Atlantic Ecosystem, Species, Fisheries
• Ecological requirements and Essential Fish Habitat
• Habitat and Ecosystem Information Systems
• Present and emerging issues/data needs


Magnuson-Stevens Fishery Management and Conservation Act
And the South Atlantic Fishery Management Council
• Conserves and Manages fisheries, fishery resources and fish habitat in the EEZ off NC, SC, GA and E FL
• Prepares Fishery Management Plans and federal regulations (e.g. Allowable Catch Limits, gear, species and area restrictions) which achieve sustainable fisheries and conservation of EFH
• Designates Essential Fish Habitat (EFH) and EFH Areas of Particular Concern for Managed Species to address fishing and non-fishing impacts

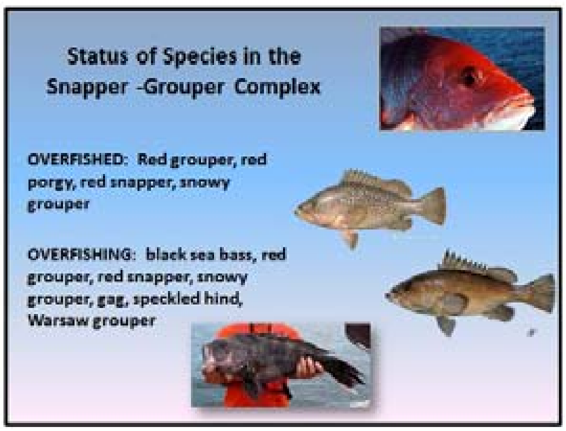

South Atlantic Bight
Cape Hatteras-Cape Canaveral
Rock reefs covered with attached algae and animals, or "live bottom," comprises up to 20% of the shelf bottom and supports more than 70% of the offshore fisheries.
Supports wide diversity of marine fish, birds, mammals and invertebrates.


South Atlantic Ecosystem: Oceanography
Characteristics of the South Atlantic
Range of shelf widths
Along shelf break –
major boundary current
Loop Current
Florida Current
Gulf Stream
Freshwater input –
Distributed input from a number of rivers, river drainage basins primarily in these coastal states
Biogeographically –
temperate to sub-tropical transition zone


Fishery Management Plans
Shrimp Fishery Management Plan
brown shrimp - Farfantepenaeus aztecus
pink shrimp - F. duorarum
rock shrimp - Sicyonia brevirostris
royal red shrimp - Pleoticus robustus
white shrimp - Litopenaeus setiferus
Coastal Migratory Pelagics Fishery Management Plan
cobia - Rachycentron canadum
king mackerel - Scomberomorus cavalla
Spanish mackerel - S. maculatus
Cero - Scomberomorus regalis
Little tunny - Euthynnus alletteratus
Dolphin-Wahoo Fishery Management Plan
Dolphinfish - Coryphaena hippurus
Wahoo - Acanthocybium solandri
Spiny Lobster Fishery Management Plan
spiny lobster - Panulirus argus
Golden Crab Fishery Management Plan
golden crab - Chaceon fenneri

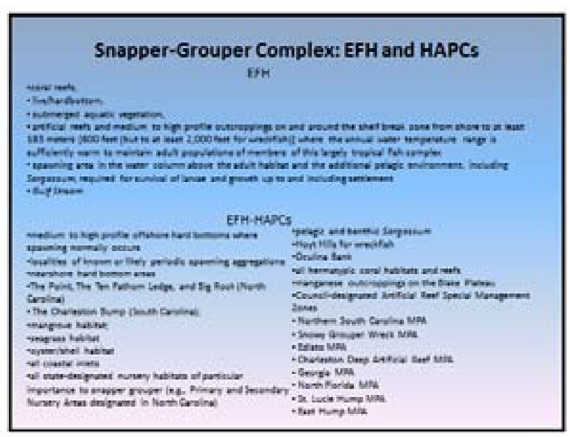

Fishery Management Plans
Snapper-Grouper Complex Fishery Management Plan

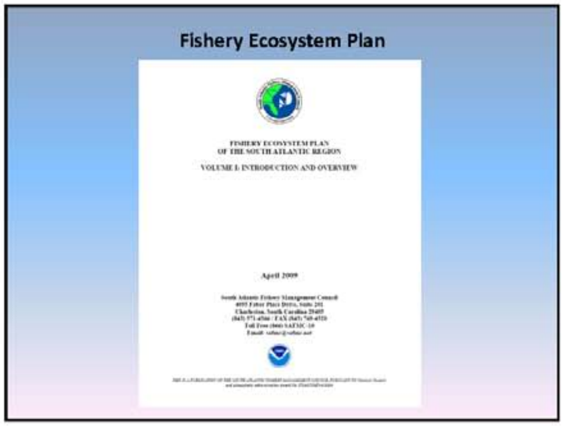

Fishery Management Plans
Habitat Based Fishery Management Plans
Coral, Coral Reef and Live Hard Bottom Habitat Fishery Management Plan
Pelagic Sargassum Habitat Fishery Management Plan
Sargassum fluitans
Sargassum natans

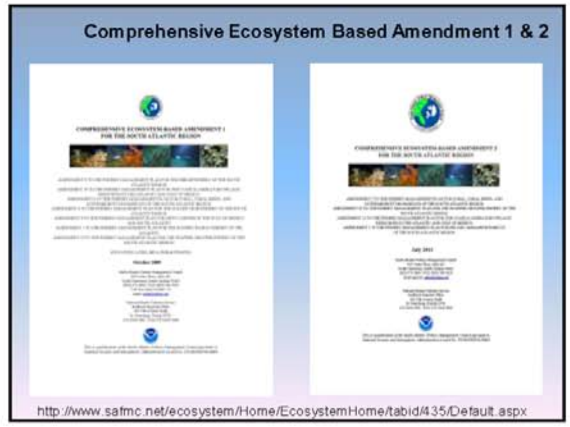

Status of Species in the Snapper -Grouper Complex
OVERFISHED: Red grouper, red porgy, red snapper, snowy grouper
OVERFISHING: black sea bass, red grouper, red snapper, snowy grouper, gag, speckled hind, Warsaw grouper

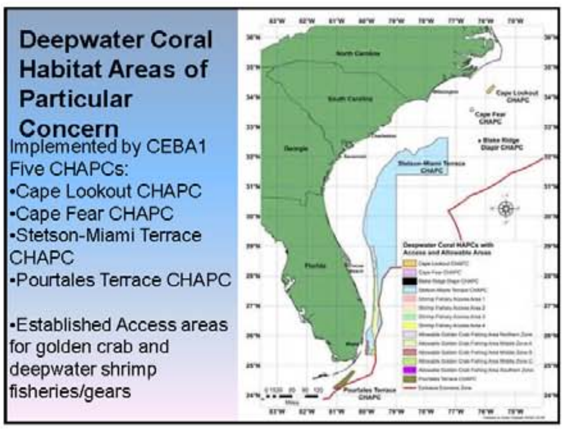

Essential Fish Habitat
The South Atlantic Fishery Management Council designates Essential Fish Habitat (EFH) and EFH Areas of Particular Concern (HAPCs) for Managed Species to address fishing and non-fishing impacts.
EFH is defined as "all waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity"
EFH-HAPCs is as a subset of EFH where:
•Ecological function provided by the habitat is important;
•Habitat is sensitive to human-induced environmental degradation;
•Development activities are or will be stressing the habitat type; and
•Habitat type is rare

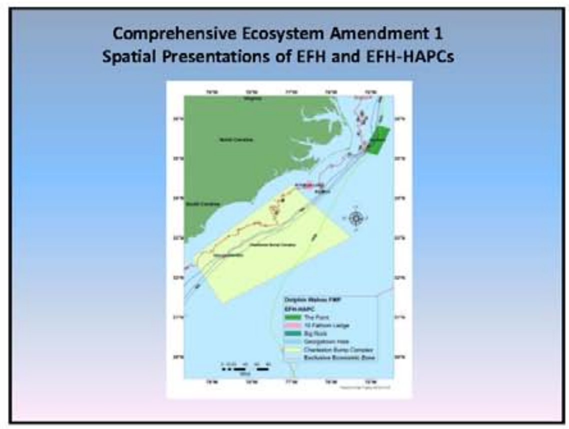

Snapper-Grouper Complex: EFH and HAPCs
EFH
EFH-HAPCs


Snapper-Grouper Complex: EFH and HAPCs
EFH
EFH-HAPCs

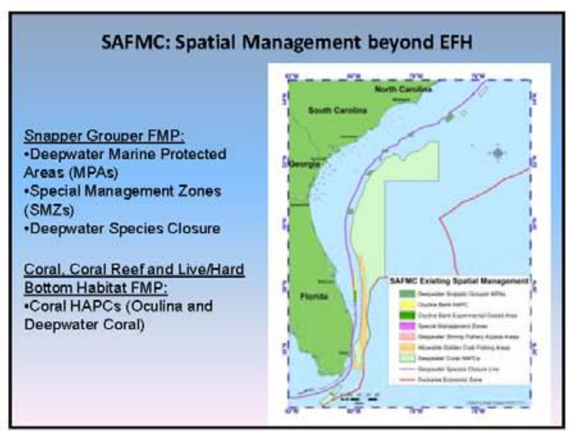

Fishery Ecosystem Plan
FISHERY ECOSYSTEM PLAN
OF THE SOUTH ATLANTIC REGION
VOLUME I: INTRODUCTION AND OVERVIEW
April 2009

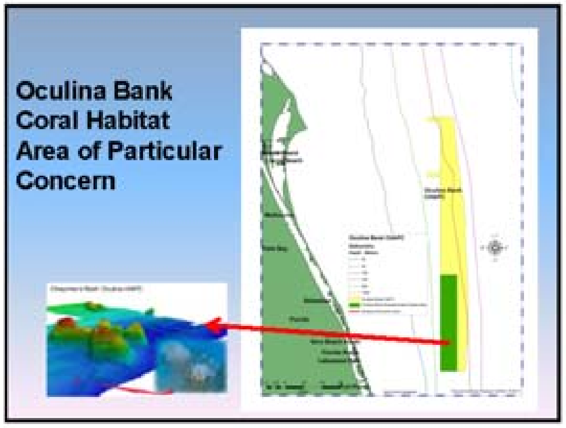

Comprehensive Ecosystem Based Amendment 1 & 2
http://www.safmc.net/ecosystem/Home/EcosystemHome/tabid/435/Default.aspx

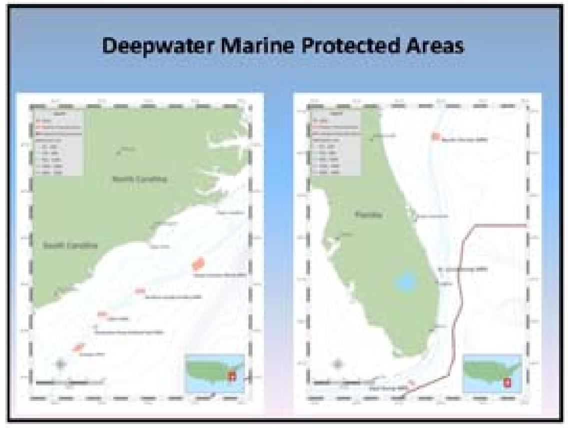

Deepwater Coral Habitat Areas of Particular Concern
Implemented by CEBA1
Five CHAPCs:
•Cape Lookout CHAPC
•Cape Fear CHAPC
•Stetson-Miami Terrace CHAPC
•Pourtales Terrace CHAPC
•Established Access areas for golden crab and deepwater shrimp fisheries/gears
North Carolina
South Carolina
Georgia
Florida
Cape Lookout CHAPC
Cape Fear CHAPC
Blake Ridge Diapir CHAPC
Stetson-Miami Terrace CHAPC
Pourtales Terrace CHAPC
Deepwater Coral HAPCs with Access and Allowable Areas


Comprehensive Ecosystem Amendment 1
Spatial Presentations of EFH and EFH-HAPCs
Dolphin Wahoo FMP
EFH-HAPC


Spatial Management Measures
• Coral Habitat Areas of Particular Concern
• Special Management Zones
• Gear and Seasonal Closures
• Deepwater Marine Protected Areas
• Essential Fish Habitat and Essential Fish Habitat Areas of Particular Concern


SAFMC: Spatial Management beyond EFH
Snapper Grouper FMP:
•Deepwater Marine Protected Areas (MPAs)
•Special Management Zones (SMZs)
•Deepwater Species Closure
Coral, Coral Reef and Live/Hard Bottom Habitat FMP:
•Coral HAPCs (Oculina and Deepwater Coral)
North Carolina
South Carolina
Georgia
Florida
SAFMC Existing Spatial Management





Development of Ecosystem Support Tools:

South Atlantic Habitat and Ecosystem Webpage

South Atlantic Habitat and Ecosystem Internet Map Server (IMS)

Transition to linked GIS Services for Regulations, Essential Fish Habitat, SA Fisheries, Ocean Energy and Ecospecies Data System as Part of a Digital Dashboard

- Developed in cooperation with Florida Fish and Wildlife Research Institute to support ecosystem-based resource management, habitat, species and ecosystem research, and regional collaboration
  - Web Services provide access to related GIS data
  - Ecosystem Section of the Website provides links to FEP and Digital Dashboard
  - Developing Ecospecies data system will provide online access to South Atlantic species life history data

SAFMC Habitat and Ecosystem IMS

- Since 2003, the Fish and Wildlife Research Institute (FWRI) has collaborated with SAFMC staff to compile, create and host GIS data of essential habitats in the South Atlantic ecosystem.
- The IMS was designed as a one-stop shop for managers, scientists and the public to explore marine resources of the South Atlantic region.

GIS Data Layers

- **Base Map Layers** – Bathymetry, Marine Facilities, ATONS, Land Cover
- **Ocean Observing Systems** - National Data Buoys, SABSOON, CORMP
- **Coral Habitat Areas of Particular Concern (HAPCs)** – Oculina studies: Clelia and ROV dive tracks, multibeam survey, proposed deep water lophelia CHAPCs
- **SAFMC Gear Restrictions –** Roller Rig Trawls, Bottom Longlines, Sargassum, Fish Traps, Black Sea Bass Pots
- **SAFMC Essential Fish Habitat and HAPCs -** Snapper Grouper, Shrimp, Red Drum, Spiny Lobster, Coastal Migratory Pelagics, Dolphin Wahoo, Coral, and Golden Crab
- **Management and Regulatory** – special management zones, marine protected areas, state waters, EEZ, sea turtle sanctuary, crab spawning sanctuary
- **Marine Sanctuaries** – habitat data for Gray's Reef and Florida Keys
- **Unique Habitats** – Right Whale Critical Habitat, Southeast US

  Restricted Area
- **General Habitats** – artificial reefs, fish nursery areas, seagrass, mangroves, salt marsh, tidal flats

SAFMC Map Services

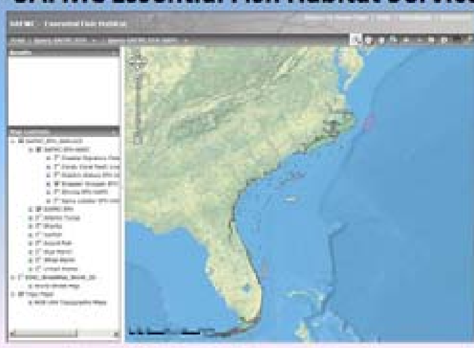
- **Essential Fish Habitat (EFH)** – displays EFH and EFH-HAPCS for SAFMC managed species and NOAA Fisheries Highly Migratory Species.
- **Fisheries** - displays Marine Resources Monitoring, Assessment, and Prediction (MARMAP) and Southeast Area Monitoring and Assessment Program (SEAMAP) data.
- **Managed Areas**- displays a variety of regulatory boundaries (SAFMC and Federal) or management boundaries within SAFMC's jurisdiction.
- **Habitat*** – displays habitat data collected by SEADESC, Harbor Branch Oceanographic Institute (HBOI) and Ocean Exploration dives, as well as the SEAMAP shallow and ESDIM deepwater bottom mapping projects, multibeam imagery, and scientific cruise data.

* Habitat service is forthcoming

SAFMC Managed Areas

The graphic displays the initial view of the SAFMC Managed Areas viewer. Deepwater Coral HAPCs, Marine Protected Areas, Special Management Zones, and the Oculina CHAPC are visible.

SAFMC Essential Fish Habitat Service



SAFMC Fisheries

SAFMC Fisheries

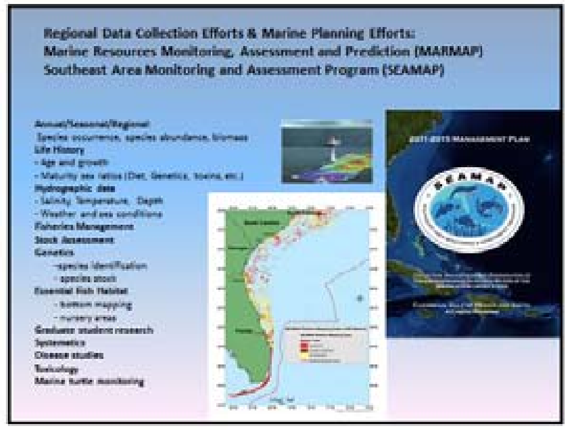
- SEAMAP species data
  - Catch
  - length
- MARMAP species data
  - SAFMC Managed species
  - Other species
- MARMAP gear types
- focal species distributions
  - General area
  - Dominant area
  - Spawning area
- bathymetry
- boundaries for the continental shelf, US Federal State and US Territorial Seas
- features custom query for SEAMAP species catch data for 2010

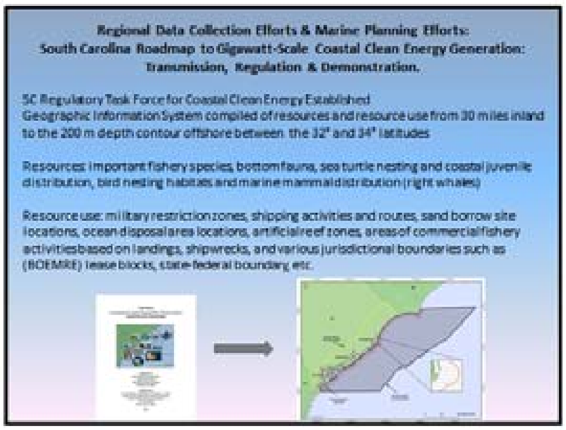
Prototype available at http://ocean.floridamarine.org/SA_Fisheries

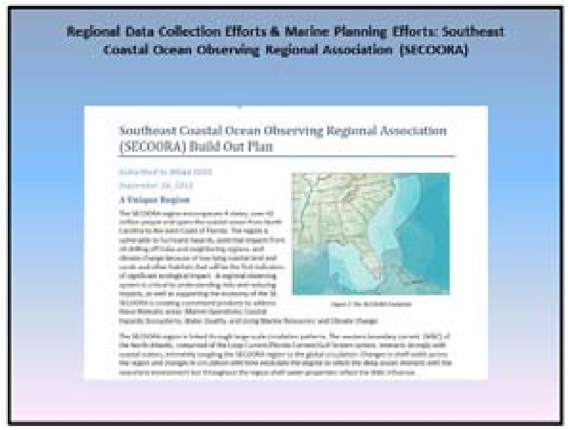
South Atlantic Web Accessible Materials (SAFMC)

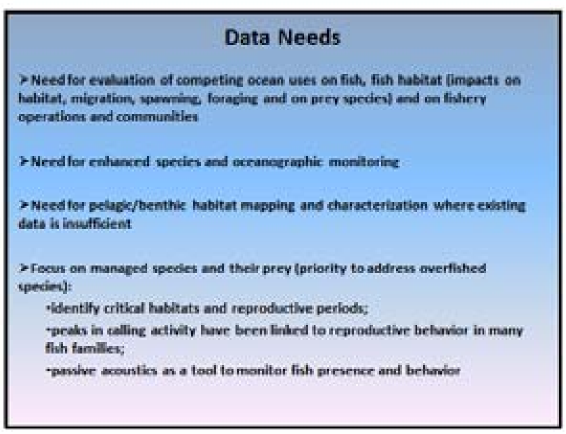
- Fishery Ecosystem Plan- (viewable and downloadable by Section)- http://www.safmc.net/ecosystem/Home/EcosystemHome/tabid/435/Default.aspx
- CEBA1 - http://www.safmc.net/Portals/6/Library/FMP/CE-BA1%20FINAL%20(Oct%202009).pdf
- Habitat and Ecosystem Internet Map Server - http://www.safmc.net/EcosystemManagement/EcosystemBoundaries/MappingandGISData/tabid/632/Default.aspx
- Managed Areas Web Service - http://ocean.floridamarine.org/safmc_managedareas/
- Essential Fish Habitat Web Service - http://ocean.floridamarine.org/sa_efh/
- Fisheries Web Service – http://ocean.floridamarine.org/sa_fisheries/
- Ocean Energy and Habitat Services – Under development
- Ecospecies online species life history data system- Under development
- Habitat and Ecosystem Digital Dashboard – Online June 2012

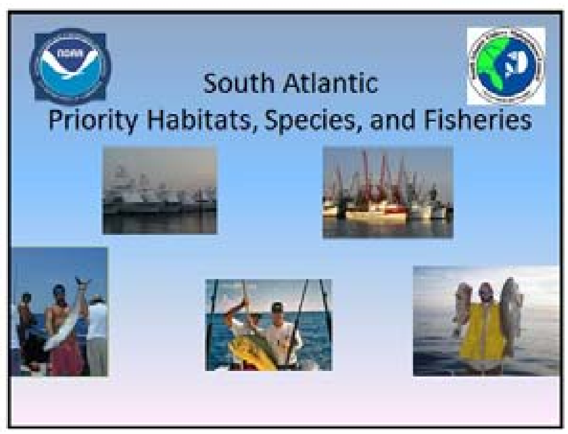

Regional Data Collection Efforts & Marine Planning Efforts:
South Atlantic Alliance
Priority Issues:
• Healthy Ecosystems
• Working Waterfronts
• Clean Coastal and Ocean Waters
• Disaster Resilient Communities
• Technical Teams Membership
Healthy Ecosystems Action Items, Sept. 2011
•Map known distributions of key estuarine/marine habitats/land use cover in each state; determine spatial extent (beach-out first), develop query template for states to capture all appropriate data elements, summarize, and identify common concerns.
•Marine spatial plan for location of key coastal/marine resources and activities for multi-use management decisions: identify major activities (shipping lanes, artificial reefs, ocean disposal areas, sand borrow areas, military use, etc.), determine locations and what data exists, and determine common framework of mapping standards and how to bring data into portal.
Governors' South Atlantic Alliance
http://www.southatlanticalliance.org/

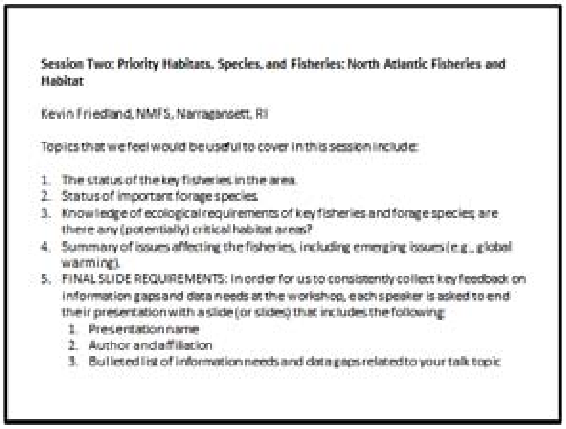

Regional Data Collection Efforts & Marine Planning Efforts:
Marine Resources Monitoring, Assessment and Prediction (MARMAP)
Southeast Area Monitoring and Assessment Program (SEAMAP)
Annual/Seasonal/Regional
Species occurrence, species abundance, biomass
Life History
- Age and growth
- Maturity sex ratios (Diet, Genetics, toxins, etc.)
Hydrographic data
- Salinity, Temperature, Depth
- Weather and sea conditions
Fisheries Management
Stock Assessment
Genetics
-species identification
- species stock
Essential Fish Habitat
- bottom mapping
- nursery areas
Graduate student research
Systematics
Disease studies
Toxicology
Marine turtle monitoring
2011-2015 Management Plan
SEAMAP

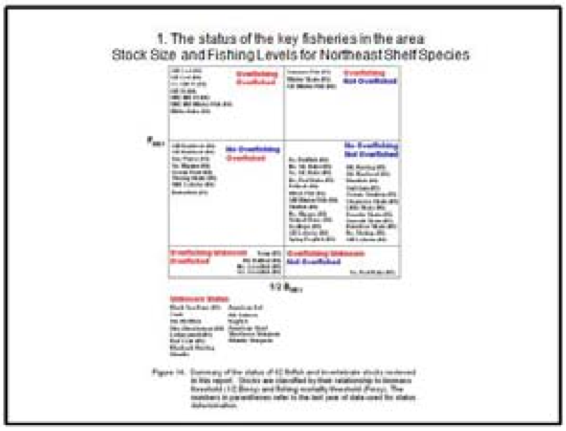

Regional Data Collection Efforts & Marine Planning Efforts:
South Carolina Roadmap to Gigawatt-Scale Coastal Clean Energy Generation:
Transmission, Regulation & Demonstration.
SC Regulatory Task Force for Coastal Clean Energy Established
Geographic Information System compiled of resources and resource use from 30 miles inland to the 200 m depth contour offshore between the 32° and 34° latitudes
Resources: important fishery species, bottom fauna, sea turtle nesting and coastal juvenile distribution, bird nesting habitats and marine mammal distribution (right whales)
Resource use: military restriction zones, shipping activities and routes, sand borrow site locations, ocean disposal area locations, artificial reef zones, areas of commercial fishery activities based on landings, shipwrecks, and various jurisdictional boundaries such as (BOEMRE) lease blocks, state-federal boundary, etc.

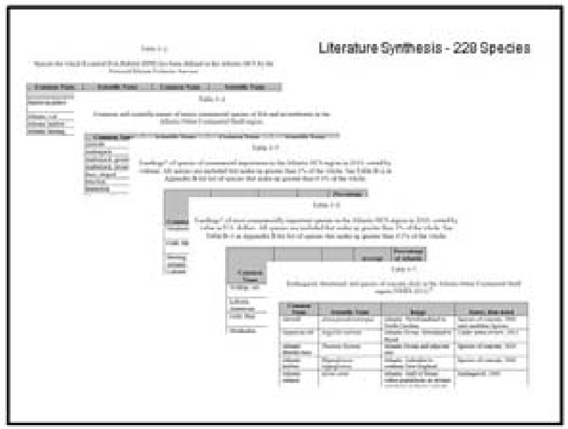

Regional Data Collection Efforts & Marine Planning Efforts: Southeast Coastal Ocean Observing Regional Association (SECOORA)
Southeast Coastal Ocean Observing Regional Association (SECOORA) Build Out Plan
A Unique Region


Data Needs
➤Need for evaluation of competing ocean uses on fish, fish habitat (impacts on habitat, migration, spawning, foraging and on prey species) and on fishery operations and communities
➤Need for enhanced species and oceanographic monitoring
➤Need for pelagic/benthic habitat mapping and characterization where existing data is insufficient
➤Focus on managed species and their prey (priority to address overfished species):
•identify critical habitats and reproductive periods;
•peaks in calling activity have been linked to reproductive behavior in many fish families;
•passive acoustics as a tool to monitor fish presence and behavior

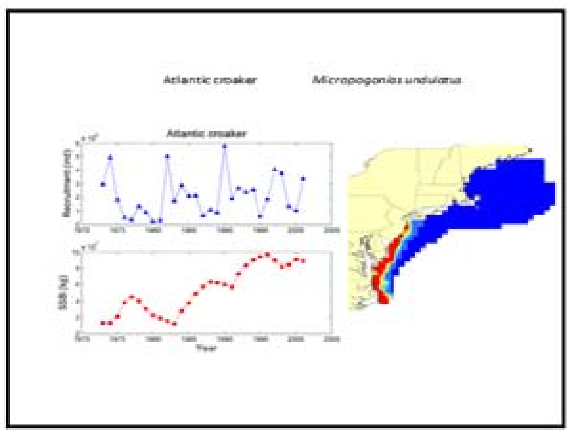

NOAA
South Atlantic
Priority Habitats, Species, and Fisheries

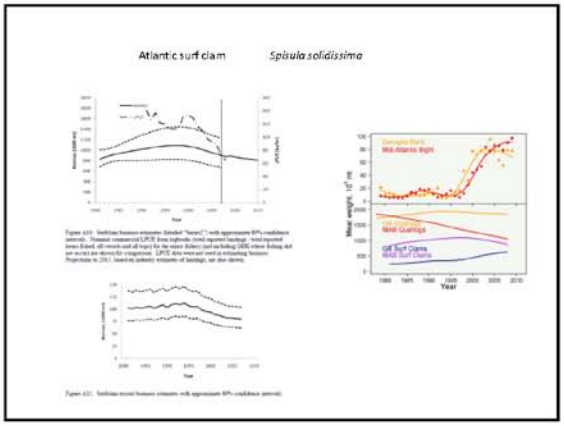


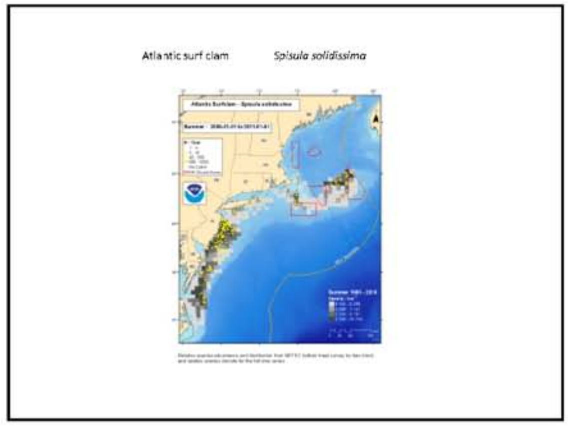


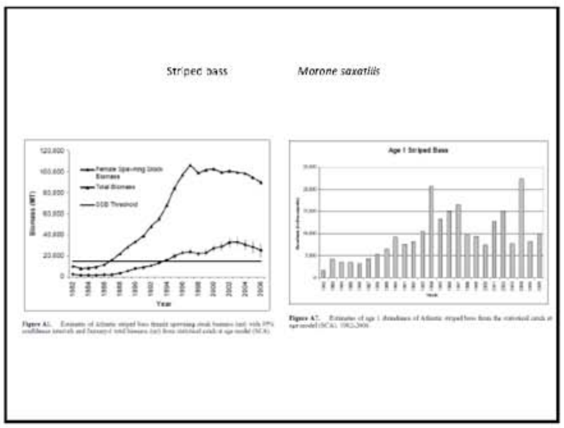


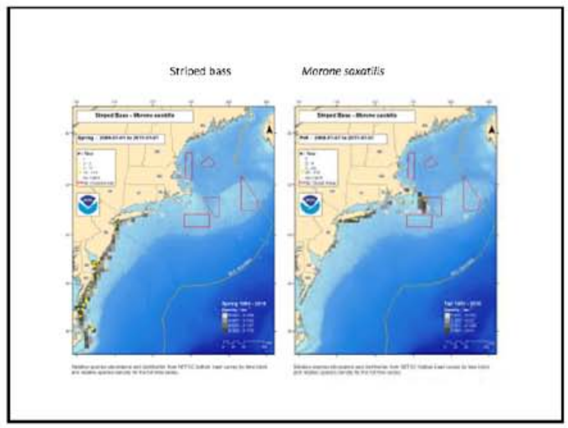
Common Name	Scientific Name	Assess	Map
American lobster	Homarus americanus	x	x
Atlantic cod	Gadus morhua	x	x
Atlantic croaker	Micropogonias undulatus	x	x
Atlantic herring	Clupea harengus	x	x
Atlantic mackerel	Scomber scombrus	x	x
Atlantic surf clam	Spisula solidissima	x	x
Blue crab	Callinectes sapidus	x	x
Eastern oyster	Crassostrea virginica	x	Des
Goosefish (monkfish)	Lophius americanus	x	x
Haddock	Melanogrammus aeglefinus	x	x
Longfin squid	Loligo pealei	x	x
Menhaden	Brevoortia tyrannus	x	x
Northern quahog	Mercenaria mercenaria	x	Des
Ocean quahog	Arctica islandica	x	x
Sea scallop	Placopecten magellanicus	x	x
Shortfin squid	Illex illecebrosus	x	x
Silver hake	Merluccius bilinearis	x	x
Softshell clam	Mya arenaria	-	Des
Striped bass	Morone saxatilis	x	x
Summer flounder	Paralichthys dentatus	x	x
White shrimp	Litopenaeus setiferus	-	Des

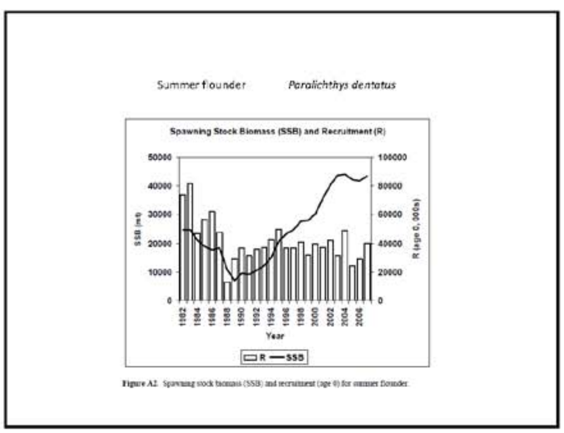


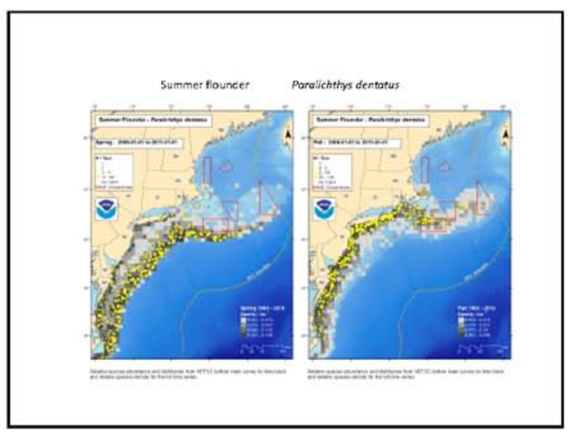

Atlantic surf clam
Spisula solidissima
Meat weight, 10³ mt
Year
Year

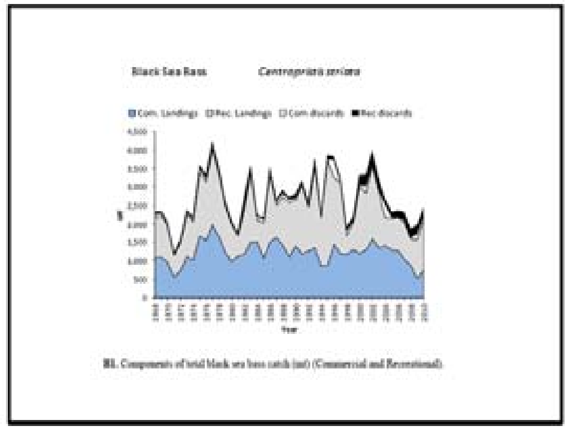

Atlantic surf clam
Spisula solidissima

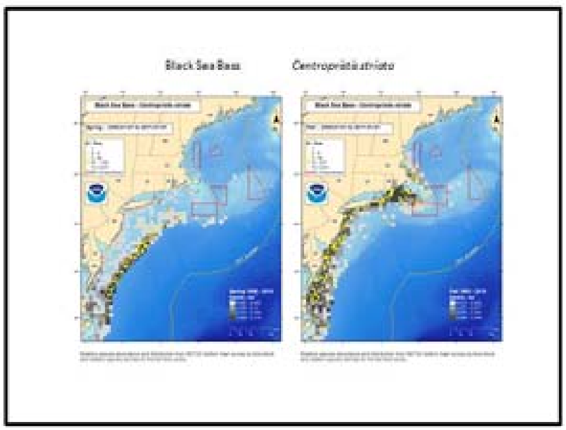

Striped bass
Morone saxatilis
Female Spawning Stock Biomass
Total Biomass
SSB Threshold
Biomass (MT)
Year
Age 1 Striped Bass

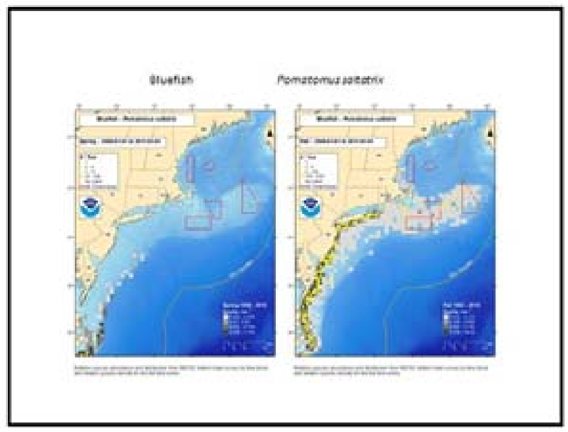

Striped bass
Morone saxatilis

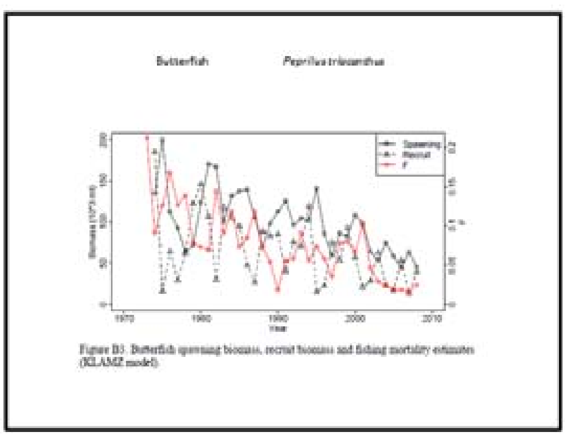

Summer flounder
Paralichthys dentatus
Spawning Stock Biomass (SSB) and Recruitment (R)
SSB (mt)
R (age 0, 000s)
Year
R
SSB
Figure A2. Spawning stock biomass (SSB) and recruitment (age 0) for summer flounder.

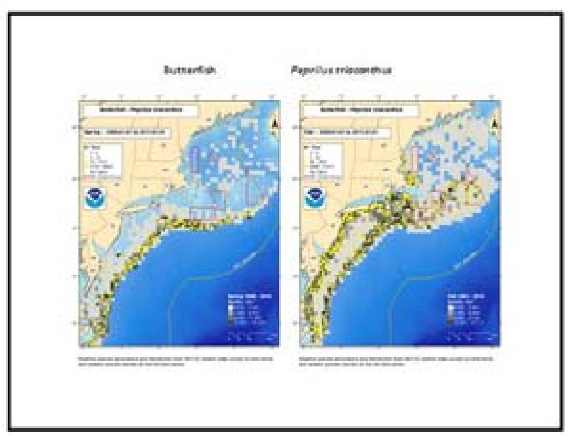

Summer flounder
Paralichthys dentatus

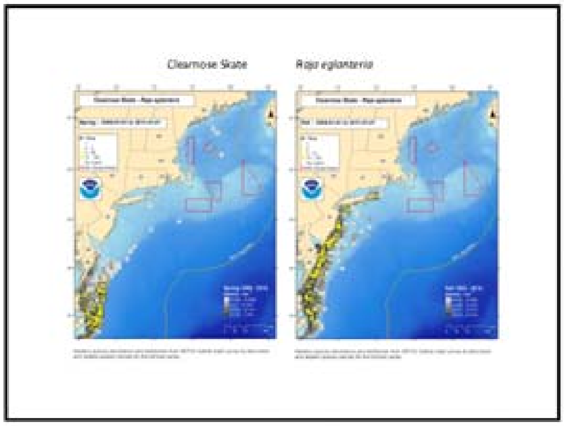

Black Sea Bass
Centropristis striata
Com. Landings
Rec. Landings
Com discards
Rec discards
Year
B1. Components of total black sea bass catch (mt) (Commercial and Recreational).

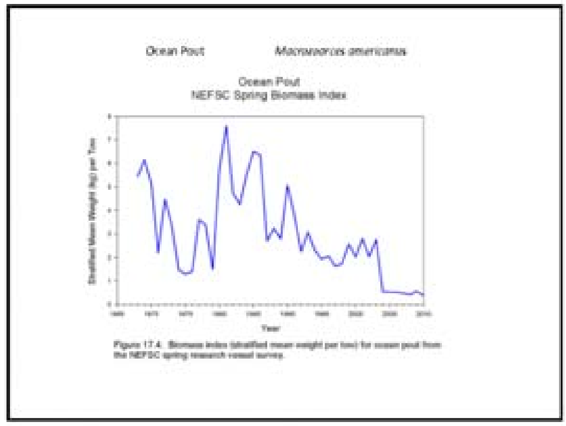

Black Sea Bass
Centropristis striata

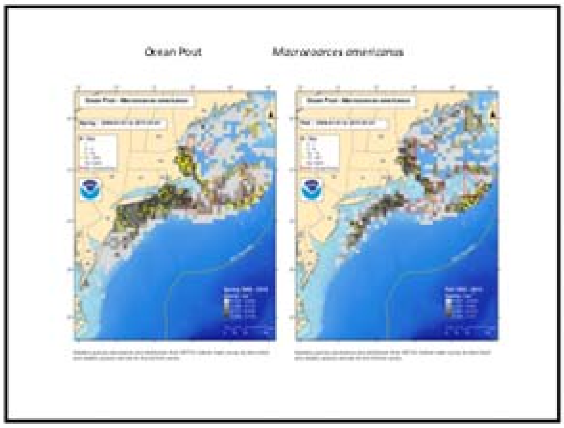

Bluefish
Pomatomus saltatrix

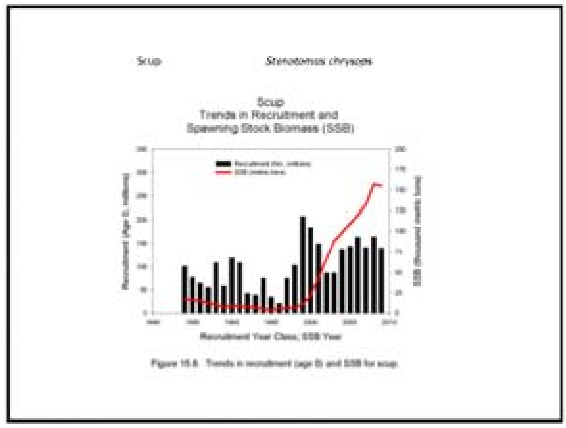

Butterfish
Peprilus triacanthus
Spawning
Recruit
F
Year
Figure B3. Butterfish spawning biomass, recruit biomass and fishing mortality estimates (KLAMZ model).

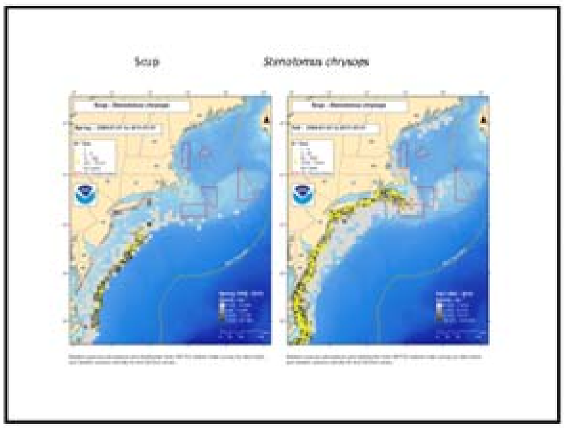

Butterfish
Peprilus triacanthus

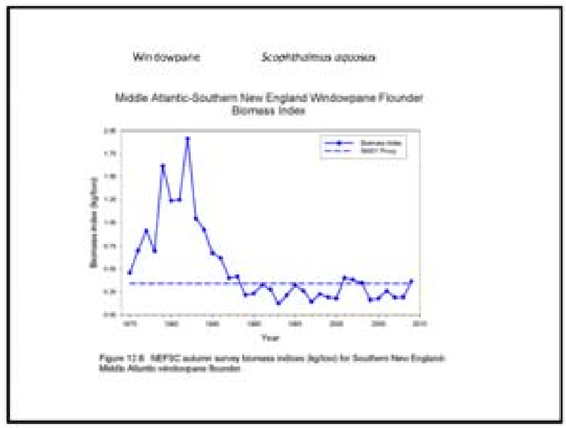

Clearnose Skate
Raja eglanteria

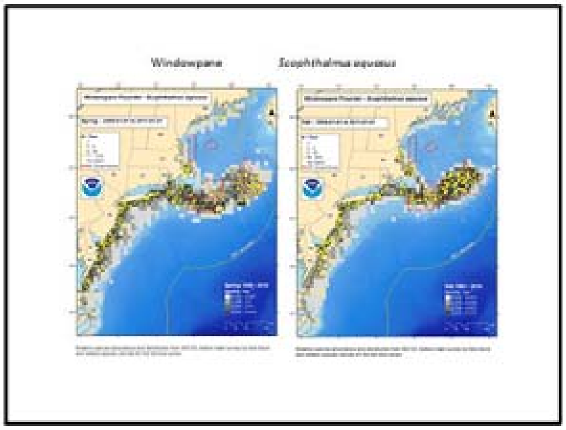

Ocean Pout
Macrozoarces americanus
Ocean Pout
NEFSC Spring Biomass Index
Year

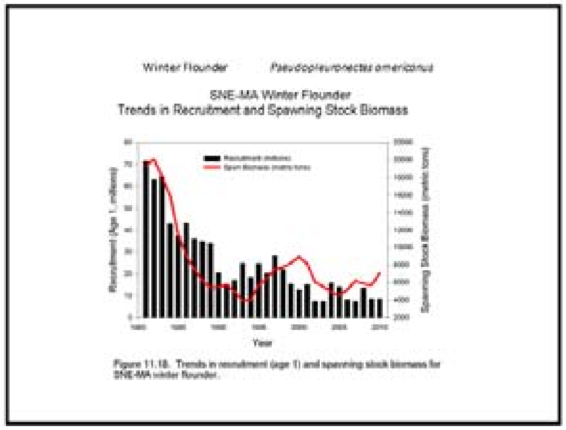

Ocean Pout
Macrozoarces americanus

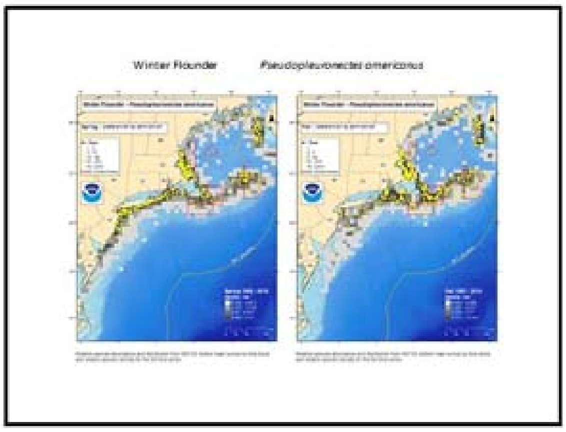

Scup
Stenotomus chrysops
Scup
Trends in Recruitment and
Spawning Stock Biomass (SSB)
Recruitment Year Class, SSB Year


Scup
Stenotomus chrysops

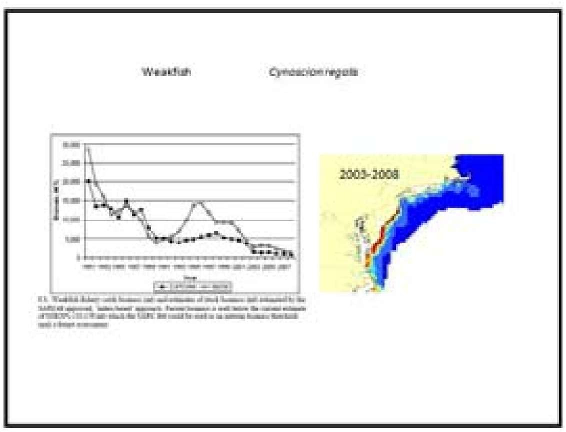

Windowpane
Scophthalmus aquosus
Middle Atlantic-Southern New England Windowpane Flounder
Biomass Index
Year

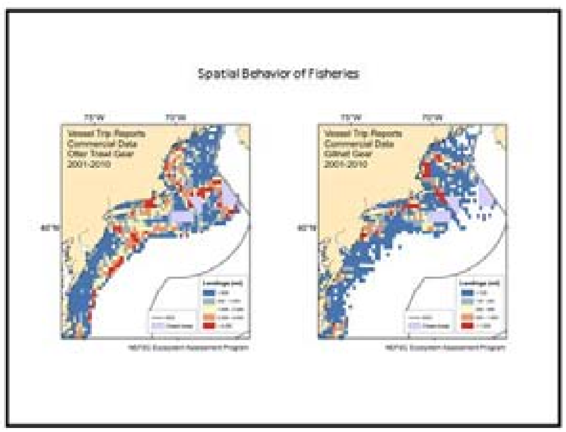


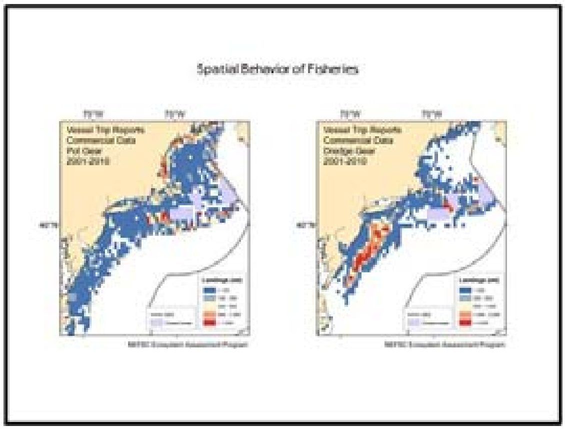


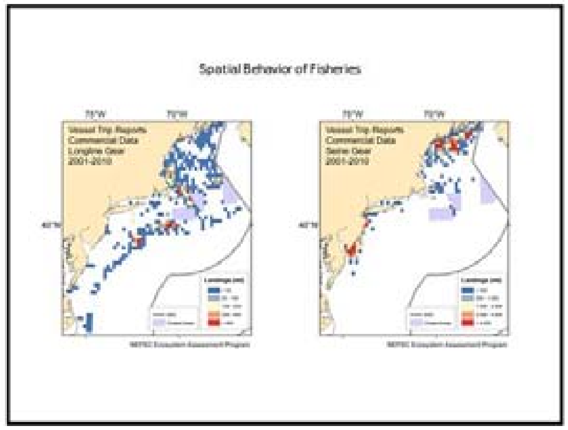


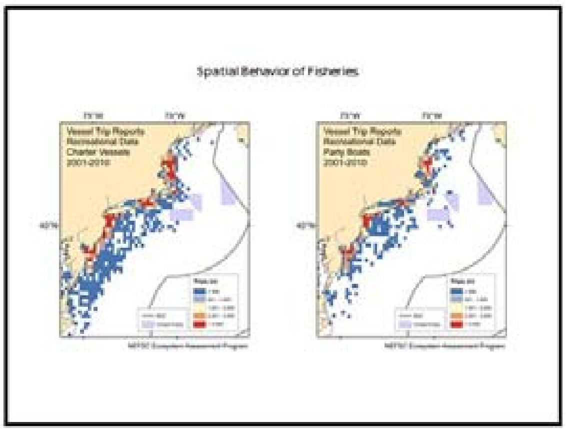
Common Name	Scientific Name	Assess	Map
Horseshoe Crab	*Limulus polyphemus*	X	Des
Red Drum	*Sciaenops ocellatus*	X	Des
Spanish Mackerel	*Scomberomorus maculatus*	X	Des
Spot	*Leiostomus xanthurus*	X	Des
Spotted Seatrout	*Cynoscion nebulosus*	X	Des
Tautog	*Tautoga onitis*	X	Des
Weakfish	*Cynoscion regalis*	X	X

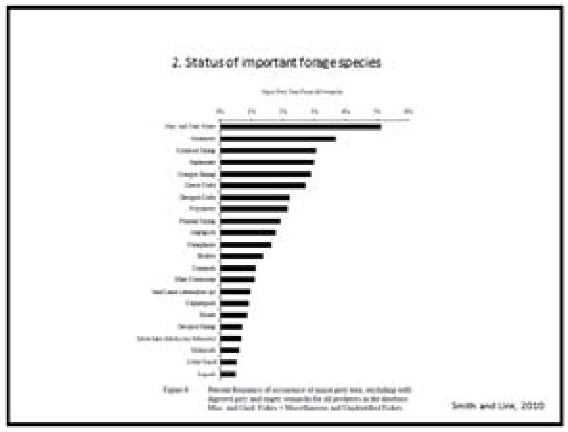


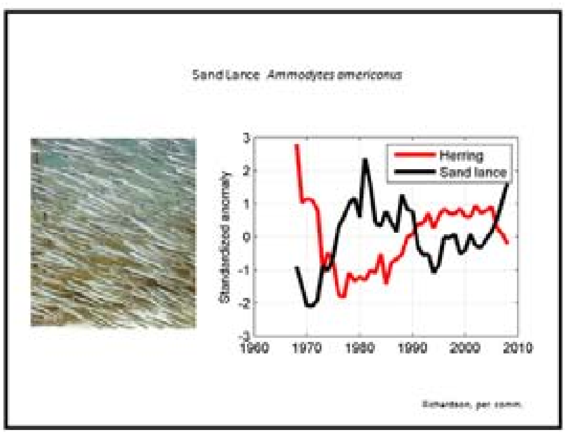


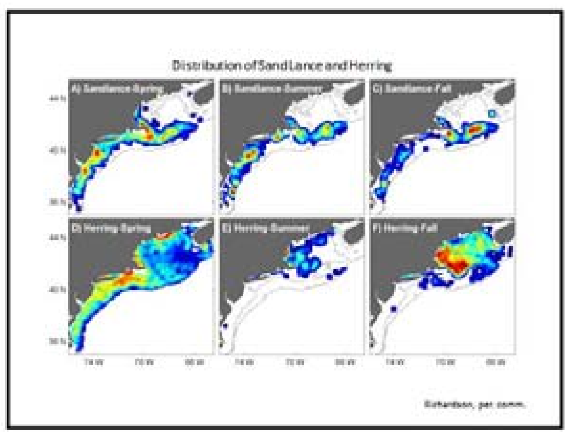

Spatial Behavior of Fisheries
Vessel Trip Reports
Commercial Data
Pot Gear
2001-2010
Vessel Trip Reports
Commercial Data
Dredge Gear
2001-2010

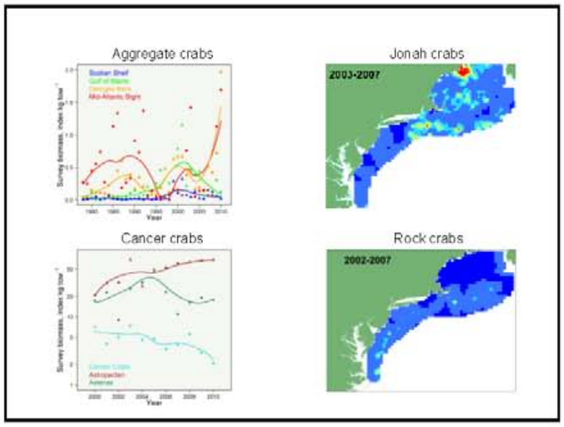

Spatial Behavior of Fisheries
Vessel Trip Reports
Commercial Data
Longline Gear
2001-2010
Vessel Trip Reports
Commercial Data
Seine Gear
2001-2010

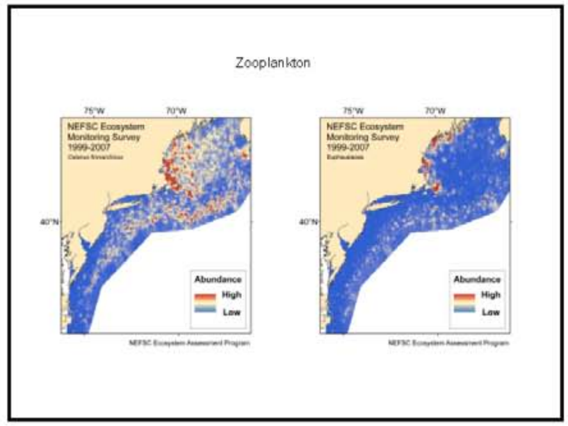

Spatial Behavior of Fisheries
Vessel Trip Reports
Recreational Data
Charter Vessels
2001-2010
Vessel Trip Reports
Recreational Data
Party Boats
2001-2010

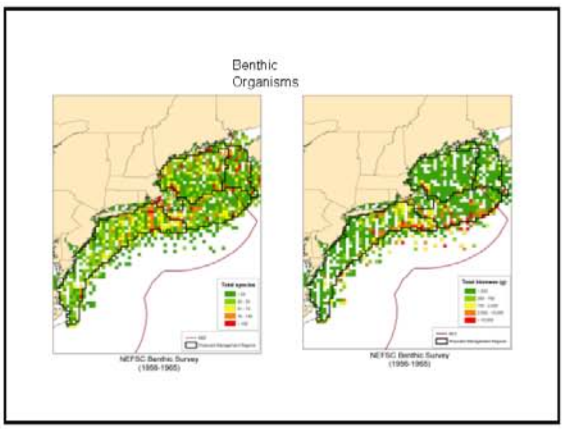

2. Status of important forage species
Smith and Link, 2010

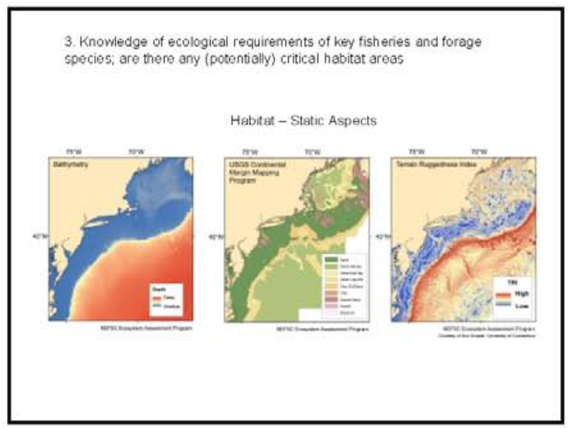

Sand Lance *Ammodytes americanus*
Herring
Sand lance
Standardized anomaly
3
2
1
0
-1
-2
-3
1960
1970
1980
1990
2000
2010
Richardson, per comm.

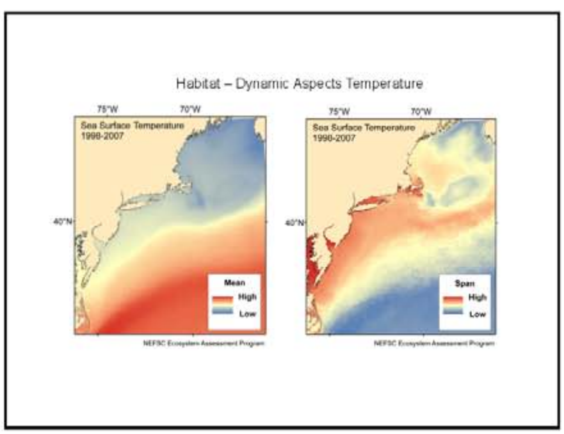

Distribution of Sand Lance and Herring
A) Sandlance-Spring
B) Sandlance-Summer
C) Sandlance-Fall
D) Herring-Spring
E) Herring-Summer
F) Herring-Fall
Richardson, per comm.

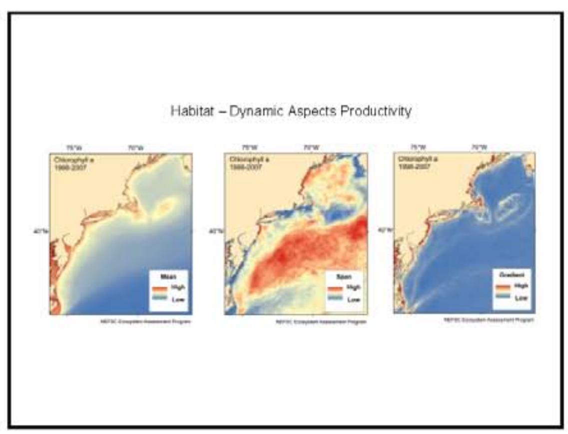

Aggregate crabs
Jonah crabs
2003-2007
Cancer crabs
Rock crabs
2002-2007
Year

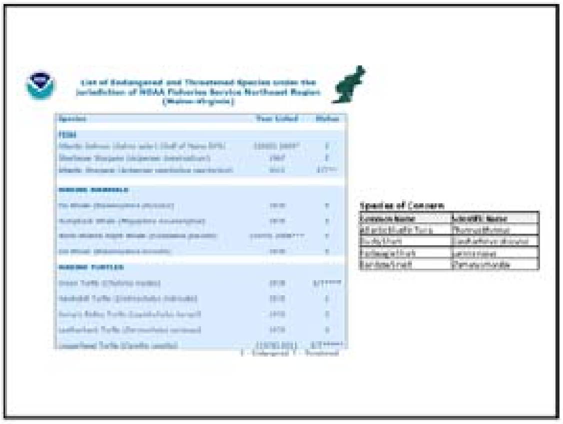

Zooplankton
75°W
70°W
NEFSC Ecosystem
Monitoring Survey
1999-2007
40°N
Abundance
High
Low
NEFSC Ecosystem Assessment Program


Benthic
Organisms
NEFSC Benthic Survey
(1956-1965)


3. Knowledge of ecological requirements of key fisheries and forage species; are there any (potentially) critical habitat areas
Habitat – Static Aspects

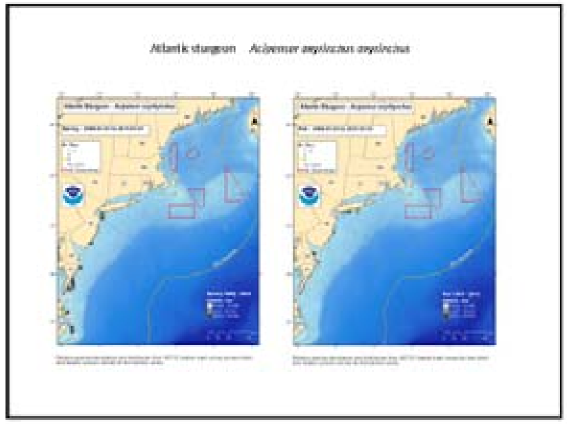

Habitat – Dynamic Aspects Temperature
75°W
70°W
Sea Surface Temperature
1998-2007
40°N
Mean
Span
High
Low
NEFSC Ecosystem Assessment Program

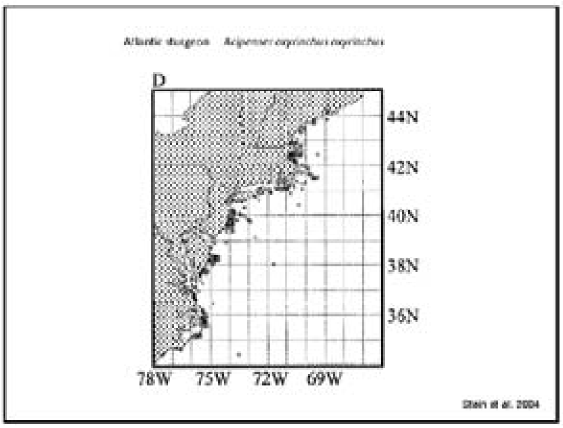

Habitat – Dynamic Aspects Productivity
Mean
Span
Gradient
High
Low

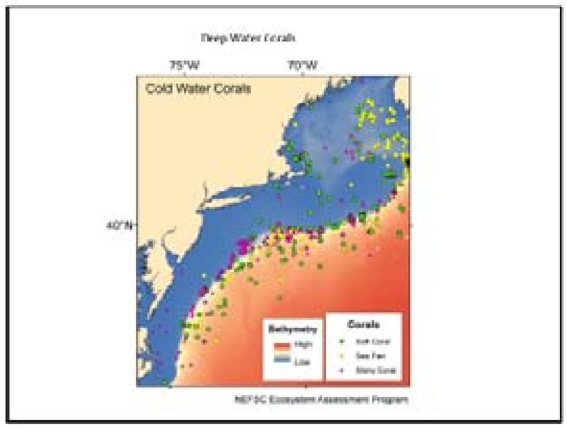


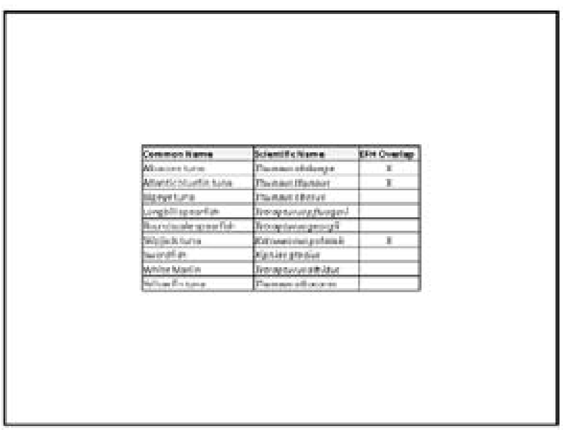
Species of Concern

Common Name	Scientific Name
Atlantic Bluefin Tuna	Thunnus thynnus
Dusky Shark	Carcharhinus obscurus
Porbeagle Shark	Lamna nasus
Sandbar Shark	Carcharhinus plumbeus









Common Name	Scientific Name	EFH Overlap
Albacore tuna	*Thunnus alalunga*	X
Atlantic bluefin tuna	*Thunnus thynnus*	X
Bigeye tuna	*Thunnus obesus*	
Longbill spearfish	*Tetrapturus pfluegeri*	
Roundscale spearfish	*Tetrapturus georgii*	
Skipjack tuna	*Katsuwonus pelamis*	X
Swordfish	*Xiphias gladius*	
White Marlin	*Tetrapturus albidus*	
Yellowfin tuna	*Thunnus albacares*	

Atlantic Bluefin Tuna *Thunnus thynnus*

Stein et al. 2004

Atlantic Skipjack Tuna *Katsuwonus pelamis*

Common Name	Scientific Name	EFH Overlap
Basking shark	*Cetorhinus maximus*	X
Bigeye thresher	*Alopias superciliosus*	
Blue shark	*Prionace glauca*	X
Common thresher	*Alopias vulpinus*	X
Dusky shark	*Carcharhinus obscurus*	X
Longfin mako shark	*Isurus paucus*	
Porbeagle	*Lamna nasus*	
Sand tiger shark	*Carcharias taurus*	X
Sandbar shark	*Carcharhinus plumbeus*	X
Scalloped hammerhead	*Sphyrna lewini*	X
Shortfin mako shark	*Isurus oxyrinchus*	
Silky shark	*Carcharhinus falciformis*	
Smooth dogfish	*Mustelus canis*	X
Tiger shark	*Galeocerdo cuvier*	X
Great white shark	*Carcharodon carcharias*	X

Sandbar Shark (coastal sharks) *Carcharhinus plumbeus*

Figure 1.4.3.1.15d. Habitat Areas of Particular Concern for sandbar shark

Blue Shark (pelagic sharks) *Prionace glauca*

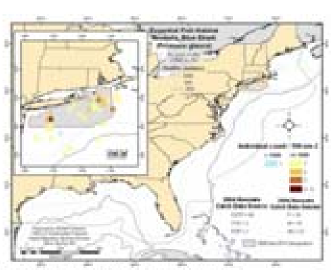
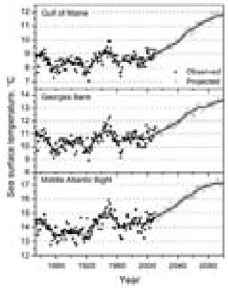


Figure 1.4.3.1.26a. Essential fish habitat for neonate blue shark

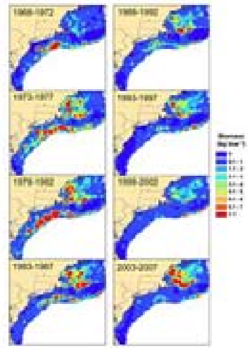
4. Summary of issues affecting the fisheries, including emerging issues (e.g., global warming)

Change in the thermal habitats
Plankton community shift
Habitat impacts of fishing
Eutrophication
Sea level rise
Wind
Precipitation
Phenological Effects
Extreme Weather Events
Thermohaline Circulation
Carbon Dioxide Concentration

Time series of sea surface temperatures in eco-regions of the Northeast Shelf Large Marine Ecosystem with projected temperature based on an ensemble of climate projection models.

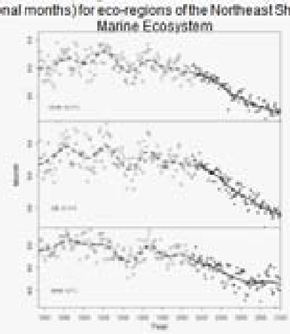


Change in Distribution – Red Hake



Nye et al. 2009

Date of arrival spring transition sea surface temperature (in fractional months) for eco-regions of the Northeast Shelf Large Marine Ecosystem



FINAL SLIDE

1. Presentation name: **North Atlantic Fisheries and Habitat**
2. Kevin Friedland, NMFS, Narragansett, RI
3. Bulleted list of information needs and data gaps:

- NEFSC data serving outside the firewall for maintained datasets.
- Continuation of ECOMON cruises providing a platform for mammal and bird surveys.
- Refinement of essential fish habitat definition and information on fine scale movements of pelagic/coastal species.
- Assessment of community change with the addition of fixed structures.

Acknowledgements: C. Keith, J. Nye, S. Lucey, R. Gamble, M. Fogarty, N. Kohler, C. McCandless, J. Hoey, R. Langton, D. Packer

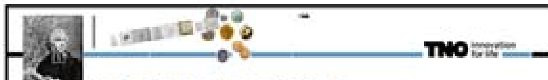
Resources:

NEFSC Fish and Fisheries information
http://www.nefsc.noaa.gov/rcb/fish/

NEFSC Data Web-serving and Google Ocean Interface Developmental

Essential Fish Habitat Mapper
http://sharpfin.nmfs.noaa.gov/website/EFH_Mapper/map.aspx

Atlantic Highly Migratory Species
http://www.nmfs.noaa.gov/sfa/hms/EFH/index.htm



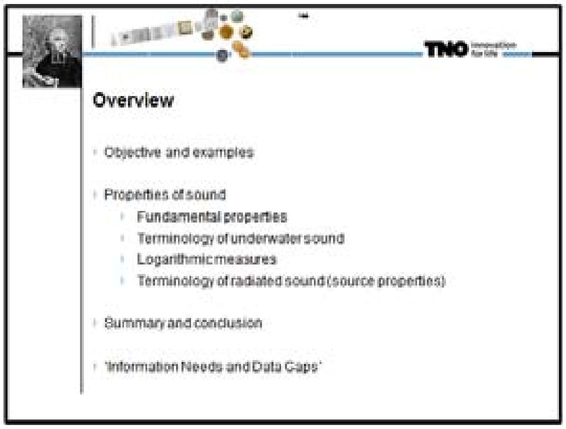
Terminology for Underwater Sound

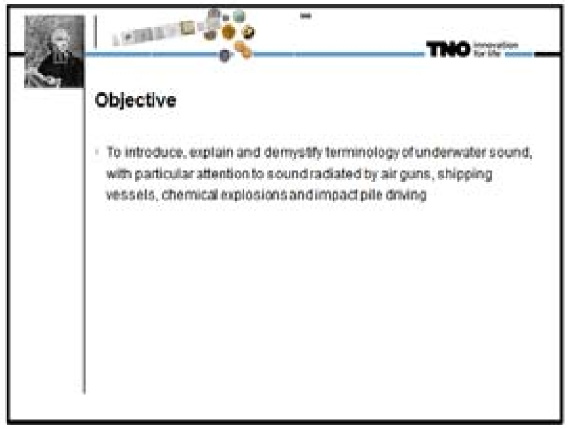
M A Ainslie

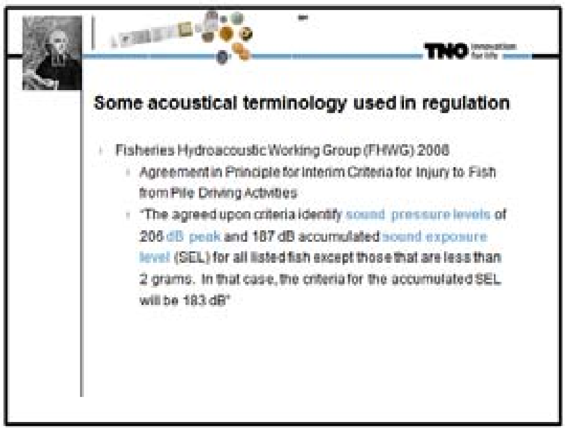
Effects of Noise on Fish, Fisheries, and Invertebrates: A BOEM Workshop on Data Gaps and Research Needs, 20-22 March 2012, Town and Country Resort, San Diego, CA

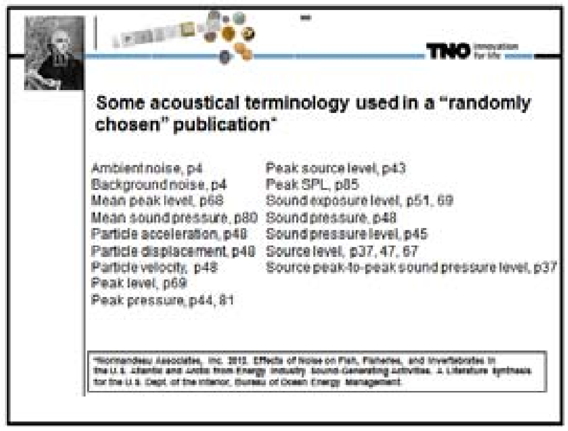
Every science requires a special language because every science has its own ideas. It seems that one ought to begin by composing this language, but people begin by speaking and writing and the language remains to be composed

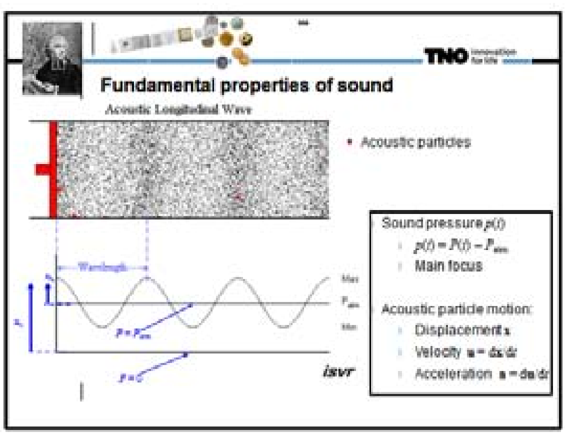
Étienne Bonnot de Condillac (1715-1780)

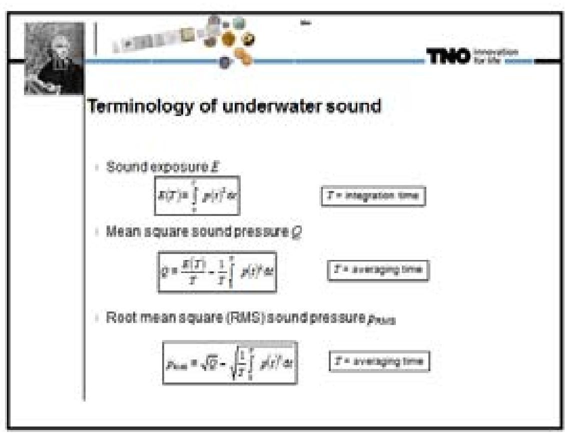

Overview
Objective and examples
Properties of sound
Fundamental properties
Terminology of underwater sound
Logarithmic measures
Terminology of radiated sound (source properties)
Summary and conclusion
'Information Needs and Data Gaps'

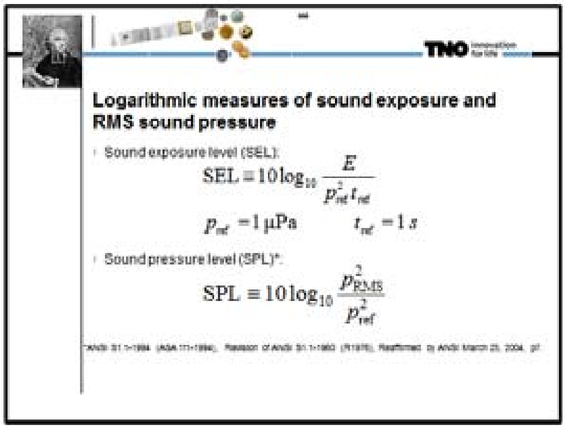

Objective
To introduce, explain and demystify terminology of underwater sound, with particular attention to sound radiated by air guns, shipping vessels, chemical explosions and impact pile driving

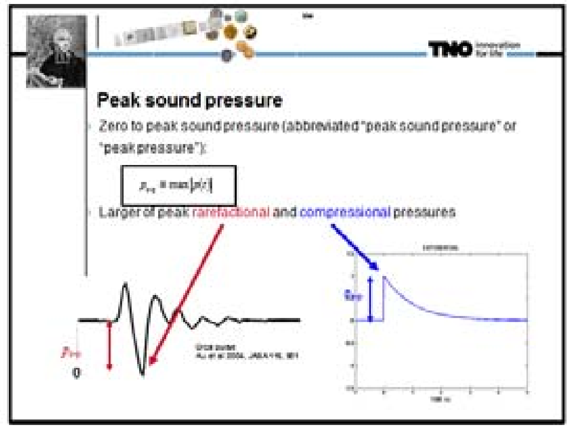

Some acoustical terminology used in regulation
Fisheries Hydroacoustic Working Group (FHWG) 2008
Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities
"The agreed upon criteria identify sound pressure levels of 206 dB peak and 187 dB accumulated sound exposure level (SEL) for all listed fish except those that are less than 2 grams. In that case, the criteria for the accumulated SEL will be 183 dB"

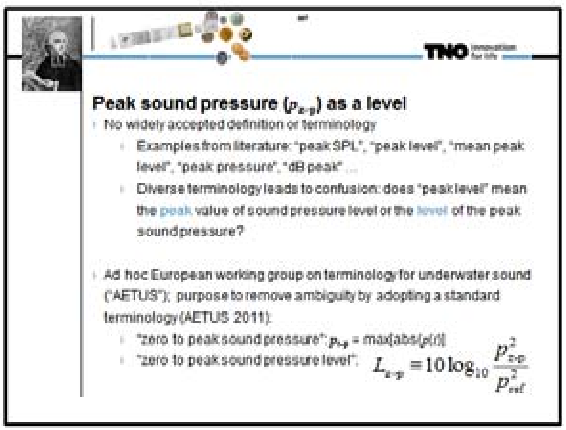

Some acoustical terminology used in a "randomly chosen" publication*
Ambient noise, p4
Background noise, p4
Mean peak level, p68
Mean sound pressure, p80
Particle acceleration, p48
Particle displacement, p48
Particle velocity, p48
Peak level, p69
Peak pressure, p44, 81
Peak source level, p43
Peak SPL, p85
Sound exposure level, p51, 69
Sound pressure, p48
Sound pressure level, p45
Source level, p37, 47, 67
Source peak-to-peak sound pressure level, p37

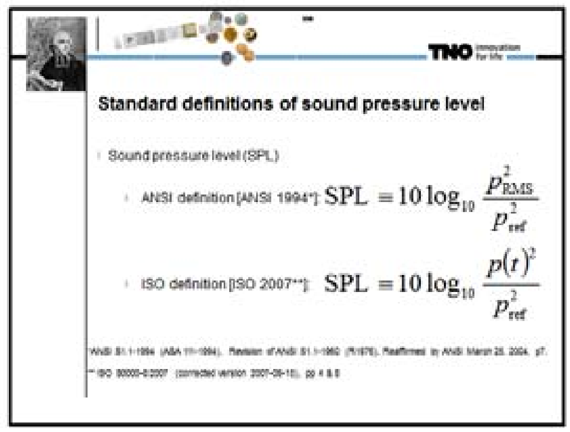

Fundamental properties of sound
Acoustic Longitudinal Wave
Acoustic particles
Wavelength
Sound pressure p(t)
$p(t) = P(t) - P_{atm}$
Main focus
Acoustic particle motion:
Displacement x
Velocity u = dx/dt
Acceleration a = du/dt
isvr

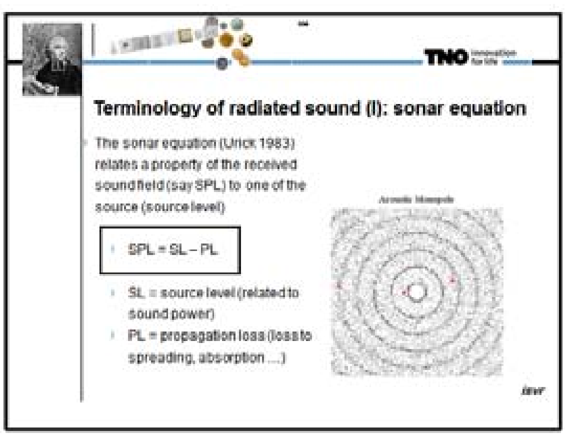

Terminology of underwater sound
Sound exposure E
$E(T) = \int_0^T p(t)^2 dt$
T = integration time
Mean square sound pressure Q
$Q = \frac{E(T)}{T} = \frac{1}{T}\int_0^T p(t)^2 dt$
T = averaging time
Root mean square (RMS) sound pressure p_{RMS}
$p_{RMS} = \sqrt{Q} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt}$
T = averaging time

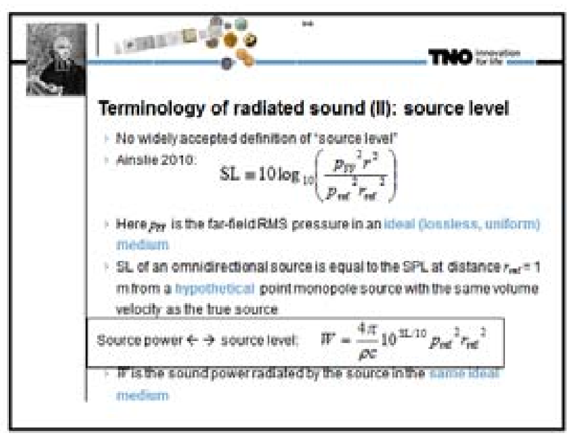

TNO innovation for life
Logarithmic measures of sound exposure and RMS sound pressure
Sound exposure level (SEL):
$\mathrm{SEL} \equiv 10\log_{10}\frac{E}{p_{ref}^2 t_{ref}}$
$p_{ref} = 1\,\mu\mathrm{Pa}$ $t_{ref} = 1\,s$
Sound pressure level (SPL)*:
$\mathrm{SPL} \equiv 10\log_{10}\frac{p_{RMS}^2}{p_{ref}^2}$

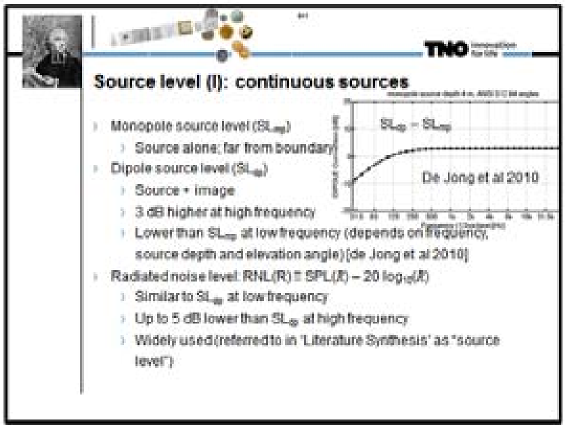

TNO innovation for life
Peak sound pressure
Zero to peak sound pressure (abbreviated "peak sound pressure" or "peak pressure"):
$p_{z\text{-}p} \equiv \max|p(t)|$
Larger of peak rarefactional and compressional pressures
0

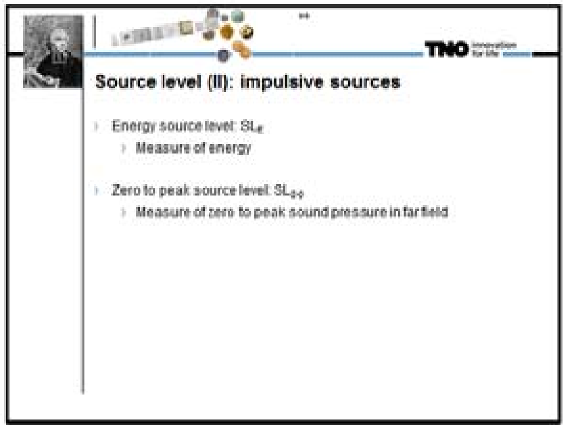

TNO innovation for life
Peak sound pressure ($p_{z\text{-}p}$) as a level
No widely accepted definition or terminology
Examples from literature: "peak SPL", "peak level", "mean peak level", "peak pressure", "dB peak" ...
Diverse terminology leads to confusion: does "peak level" mean the peak value of sound pressure level or the level of the peak sound pressure?
Ad hoc European working group on terminology for underwater sound ("AETUS"): purpose to remove ambiguity by adopting a standard terminology (AETUS 2011):
"zero to peak sound pressure": $p_{z\text{-}p}$ = max(abs(p(t))
"zero to peak sound pressure level": $L_{z\text{-}p} \equiv 10\log_{10}\frac{p_{z\text{-}p}^2}{p_{ref}^2}$

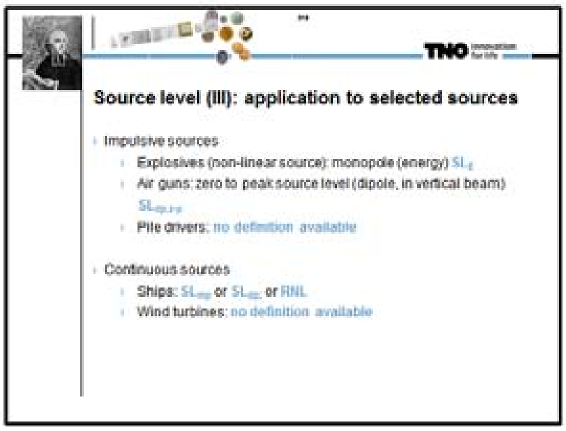

TNO innovation for life
Standard definitions of sound pressure level
Sound pressure level (SPL)
ANSI definition [ANSI 1994*]: $\mathrm{SPL} \equiv 10\log_{10}\frac{p_{RMS}^2}{p_{ref}^2}$
ISO definition [ISO 2007**]: $\mathrm{SPL} \equiv 10\log_{10}\frac{p(t)^2}{p_{ref}^2}$

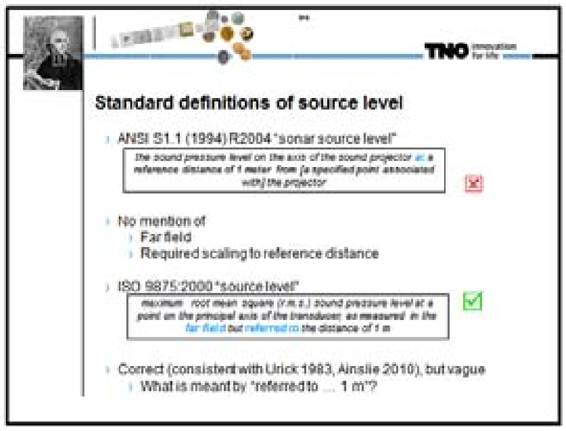

TNO innovation for life
Terminology of radiated sound (I): sonar equation
The sonar equation (Urick 1983) relates a property of the received sound field (say SPL) to one of the source (source level)
SPL = SL – PL
SL = source level (related to sound power)
PL = propagation loss (loss to spreading, absorption ...)
Acoustic Monopole

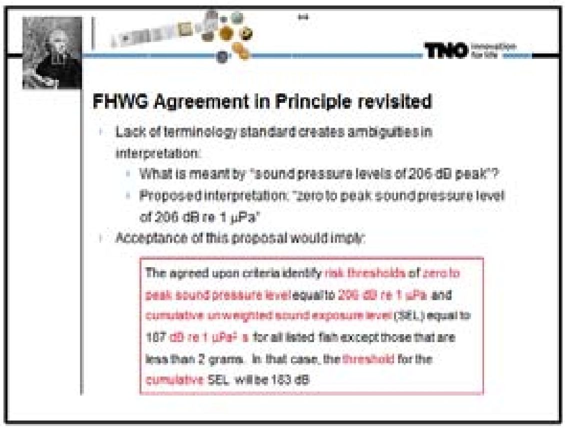

TNO innovation for life
Terminology of radiated sound (II): source level
No widely accepted definition of "source level"
Ainslie 2010: $\mathrm{SL} \equiv 10\log_{10}\left(\frac{p_{FF}^2 r^2}{p_{ref}^2 r_{ref}^2}\right)$
Here p_{FF} is the far-field RMS pressure in an ideal (lossless, uniform) medium
SL of an omnidirectional source is equal to the SPL at distance r_{ref} = 1 m from a hypothetical point monopole source with the same volume velocity as the true source
Source power ←→ source level: $W = \frac{4\pi}{\rho c}10^{SL/10} p_{ref}^2 r_{ref}^2$
W is the sound power radiated by the source in the same ideal medium

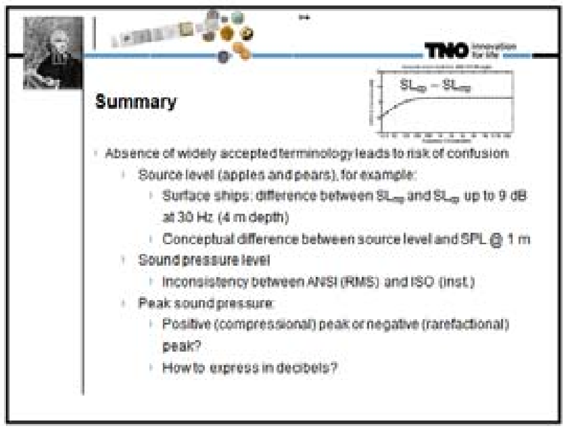

Source level (I): continuous sources
Monopole source level (SLmp)
Source alone; far from boundary
Dipole source level (SLdp)
Source + image
3 dB higher at high frequency
Lower than SLmp at low frequency (depends on frequency, source depth and elevation angle) [de Jong et al 2010]
Radiated noise level: RNL(R) ≡ SPL(R) – 20 log10(R)
Similar to SLdp at low frequency
Up to 5 dB lower than SLdp at high frequency
Widely used (referred to in 'Literature Synthesis' as "source level")
SLdp – SLmp
De Jong et al 2010

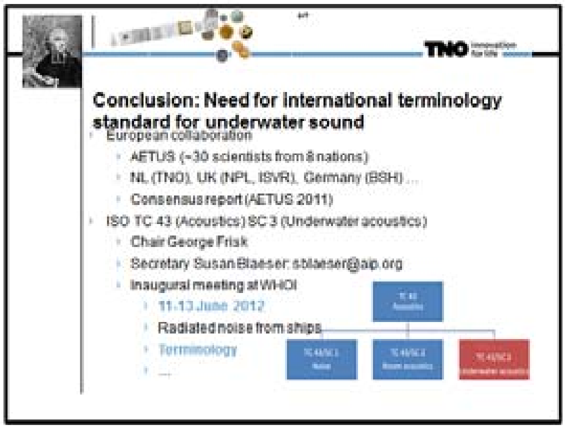

Source level (II): impulsive sources
Energy source level: SLE
Measure of energy
Zero to peak source level: SL0-p
Measure of zero to peak sound pressure in far field

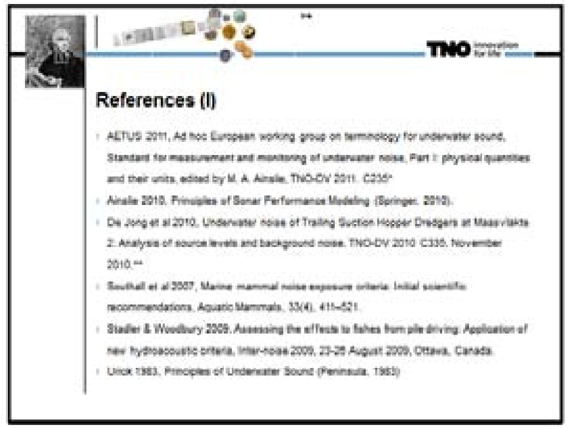

Source level (III): application to selected sources
Impulsive sources
Explosives (non-linear source): monopole (energy) SLE
Air guns: zero to peak source level (dipole, in vertical beam) SLdp,0-p
Pile drivers: no definition available
Continuous sources
Ships: SLmp or SLdp or RNL
Wind turbines: no definition available


Standard definitions of source level
ANSI S1.1 (1994) R2004 "sonar source level"
the sound pressure level on the axis of the sound projector at a reference distance of 1 meter from [a specified point associated with] the projector
No mention of
Far field
Required scaling to reference distance
ISO 9875:2000 "source level"
maximum root mean square (r.m.s.) sound pressure level at a point on the principal axis of the transducer, as measured in the far field but referred to the distance of 1 m
Correct (consistent with Urick 1983, Ainslie 2010), but vague
What is meant by "referred to … 1 m"?


FHWG Agreement in Principle revisited
Lack of terminology standard creates ambiguities in interpretation:
What is meant by "sound pressure levels of 206 dB peak"?
Proposed interpretation: "zero to peak sound pressure level of 206 dB re 1 μPa"
Acceptance of this proposal would imply:
The agreed upon criteria identify risk thresholds of zero to peak sound pressure level equal to 206 dB re 1 μPa and cumulative unweighted sound exposure level (SEL) equal to 187 dB re 1 μPa² s for all listed fish except those that are less than 2 grams. In that case, the threshold for the cumulative SEL will be 183 dB


Summary
SLdp – SLmp
Absence of widely accepted terminology leads to risk of confusion
Source level (apples and pears), for example:
Surface ships: difference between SLmp and SLdp up to 9 dB at 30 Hz (4 m depth)
Conceptual difference between source level and SPL @ 1 m
Sound pressure level
Inconsistency between ANSI (RMS) and ISO (inst.)
Peak sound pressure
Positive (compressional) peak or negative (rarefactional) peak?
How to express in decibels?


TNO innovation for life
Conclusion: Need for international terminology standard for underwater sound
European collaboration
AETUS (~30 scientists from 8 nations)
NL (TNO), UK (NPL, ISVR), Germany (BSH) ...
Consensus report (AETUS 2011)
ISO TC 43 (Acoustics) SC 3 (Underwater acoustics)
Chair George Frisk
Secretary Susan Blaeser: sblaeser@aip.org
Inaugural meeting at WHOI
11-13 June 2012
Radiated noise from ships
Terminology
...
TC 43 Acoustics
TC 43/SC 1 Noise
TC 43/SC 2 Room acoustics
TC 43/SC 3 Underwater acoustics


TNO innovation for life
References (I)
AETUS 2011, Ad hoc European working group on terminology for underwater sound, Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units, edited by M. A. Ainslie, TNO-DV 2011. C235*
Ainslie 2010, Principles of Sonar Performance Modeling (Springer, 2010).
De Jong et al 2010, Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: Analysis of source levels and background noise, TNO-DV 2010 C335, November 2010.**
Southall et al 2007, Marine mammal noise exposure criteria: Initial scientific recommendations, Aquatic Mammals, 33(4), 411–521.
Stadler & Woodbury 2009, Assessing the effects to fishes from pile driving: Application of new hydroacoustic criteria, Inter-noise 2009, 23-26 August 2009, Ottawa, Canada.
Urick 1983, Principles of Underwater Sound (Peninsula, 1983)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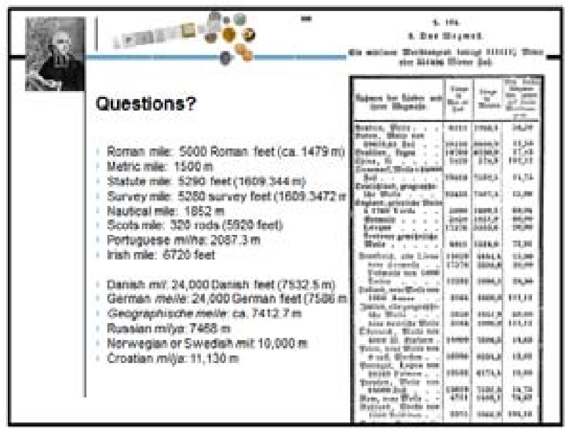
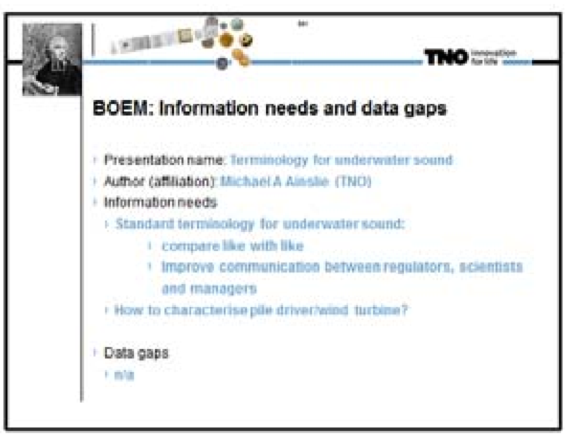
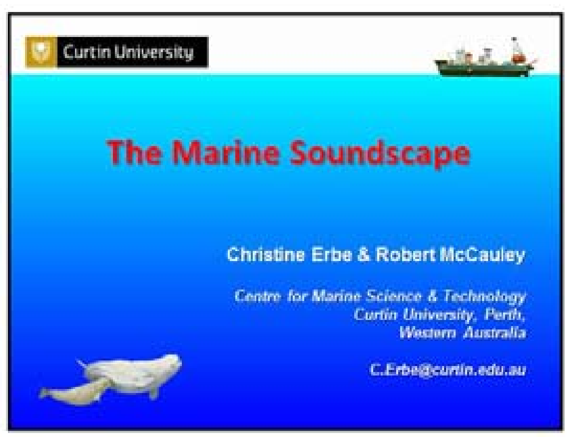
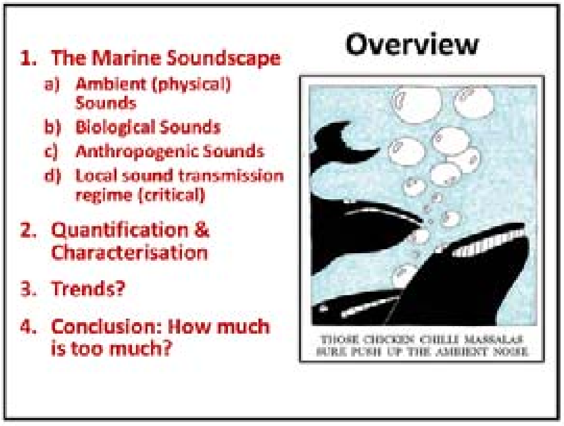
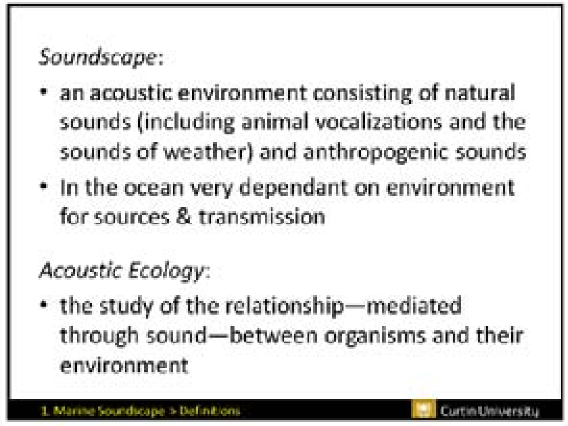
Internet addresses
*http://www.informatiehuismarien.nl/ihm/themas/Shortlist_Ecologische_Monitoring_Wind_op_Zee/Geluidsonderzoek/
**http://www.noordzeeloket.nl/overig/bibliotheek.asp
(Zandwinning ... onderwatergeluid)


TNO innovation for life
Questions?
Roman mile: 5000 Roman feet (ca. 1479 m)
Metric mile: 1500 m
Statute mile: 5280 feet (1609.344 m)
Survey mile: 5280 survey feet (1609.3472 m)
Nautical mile: 1852 m
Scots mile: 320 rods (5920 feet)
Portuguese milha: 2087.3 m
Irish mile: 6720 feet
Danish mil: 24,000 Danish feet (7532.5 m)
German meile: 24,000 German feet (7586 m)
Geographische meile: ca. 7412.7 m
Russian milya: 7468 m
Norwegian or Swedish mil: 10,000 m
Croatian milja: 11,130 m

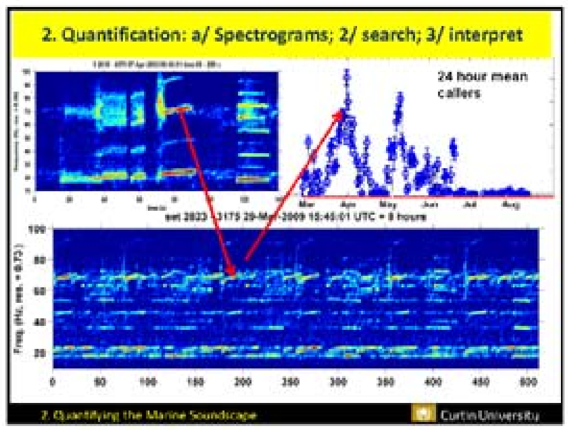

TNO innovation for life
BOEM: Information needs and data gaps
Presentation name: Terminology for underwater sound
Author (affiliation): Michael A Ainslie (TNO)
Information needs
Standard terminology for underwater sound:
compare like with like
improve communication between regulators, scientists and managers
How to characterise pile driver/wind turbine?
Data gaps
n/a

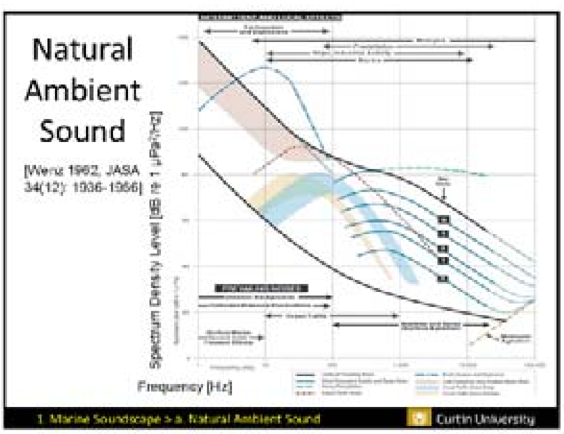

Curtin University
The Marine Soundscape
Christine Erbe & Robert McCauley
Centre for Marine Science & Technology
Curtin University, Perth,
Western Australia
C.Erbe@curtin.edu.au

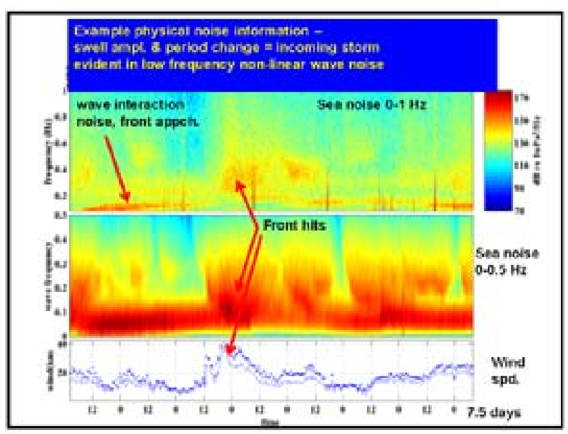

Overview
1. The Marine Soundscape
a) Ambient (physical) Sounds
b) Biological Sounds
c) Anthropogenic Sounds
d) Local sound transmission regime (critical)
2. Quantification & Characterisation
3. Trends?
4. Conclusion: How much is too much?
THOSE CHICKEN CHILLI MASSALAS SURE PUSH UP THE AMBIENT NOISE

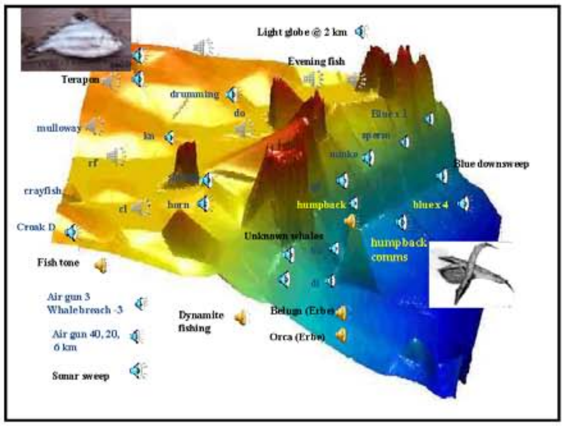

Soundscape:
• an acoustic environment consisting of natural sounds (including animal vocalizations and the sounds of weather) and anthropogenic sounds
• In the ocean very dependant on environment for sources & transmission
Acoustic Ecology:
• the study of the relationship—mediated through sound—between organisms and their environment
1. Marine Soundscape > Definitions
Curtin University

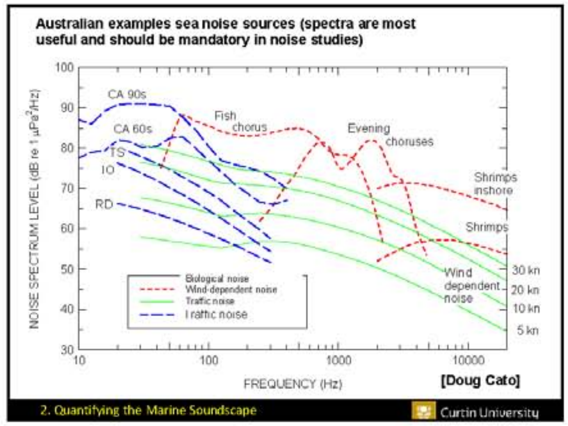

How do we measure soundscapes?
CRITICAL to understand what one is to measure, instrument nature & artefacts - otherwise get misleading results
1- Shiny instrument
2- Load into vehicle & boat
3- Throw it away

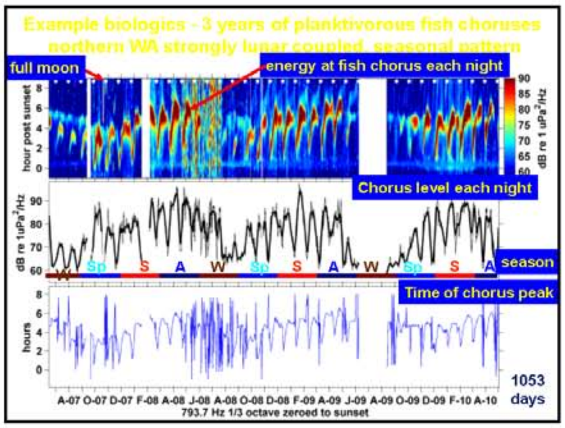

2. Quantification: a/ Spectrograms; 2/ search; 3/ interpret
24 hour mean callers
2. Quantifying the Marine Soundscape
Curtin University

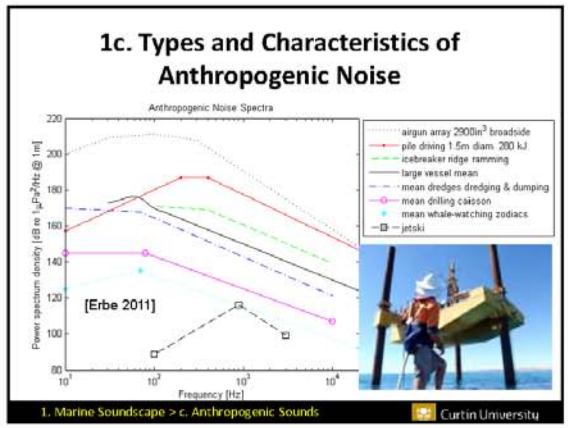

Natural Ambient Sound
[Wenz 1962, JASA 34(12): 1936-1956]
Spectrum Density Level [dB re 1 μPa²/Hz]
Frequency [Hz]
1. Marine Soundscape > a. Natural Ambient Sound
Curtin University

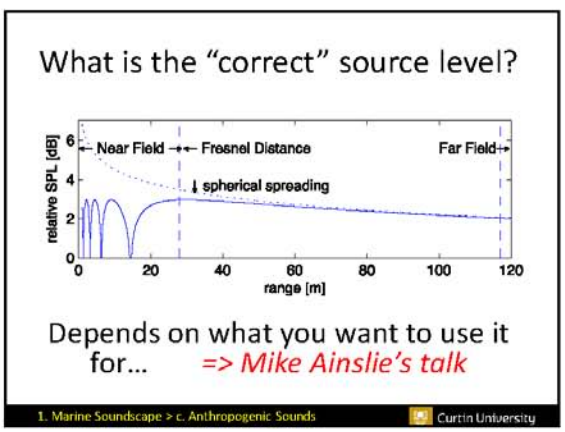

Example physical noise information –
swell ampl. & period change = incoming storm
evident in low frequency non-linear wave noise
wave interaction noise, front appch.
Sea noise 0-1 Hz
Front hits
Sea noise 0-0.5 Hz
Wind spd.
7.5 days

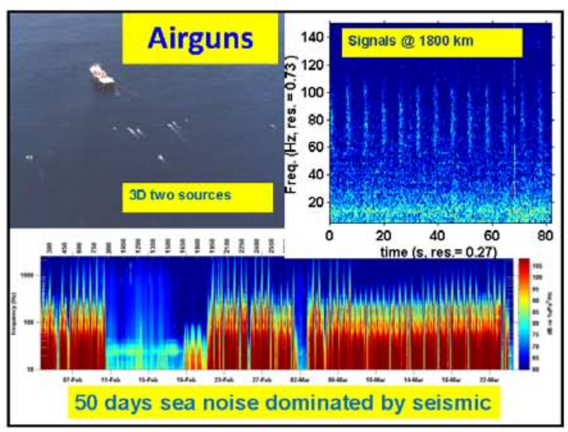

Light globe @ 2 km
Evening fish
Terapon
drumming
mulloway
crayfish
Croak D
Fish tone
humpback
bluex4
Blue downsweep
Unknown whales
humpback comms
Air gun 3
Whalebreach -3
Air gun 40, 20, 6 km
Dynamite fishing
Beluga (Erbe)
Orca (Erbe)
Sonar sweep

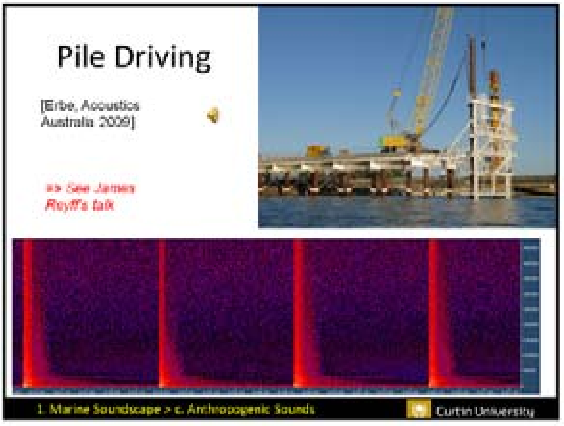

Australian examples sea noise sources (spectra are most useful and should be mandatory in noise studies)
NOISE SPECTRUM LEVEL (dB re 1 µPa²/Hz)
FREQUENCY (Hz)
[Doug Cato]
Fish chorus
Evening choruses
Shrimps inshore
Shrimps
Wind dependent noise
Biological noise
Wind-dependent noise
Traffic noise
Traffic noise
2. Quantifying the Marine Soundscape
Curtin University


Example biologics - 3 years of planktivorous fish choruses northern WA strongly lunar coupled, seasonal pattern
full moon
energy at fish chorus each night
hour post sunset
Chorus level each night
season
Time of chorus peak
hours
1053 days
793.7 Hz 1/3 octave zeroed to sunset

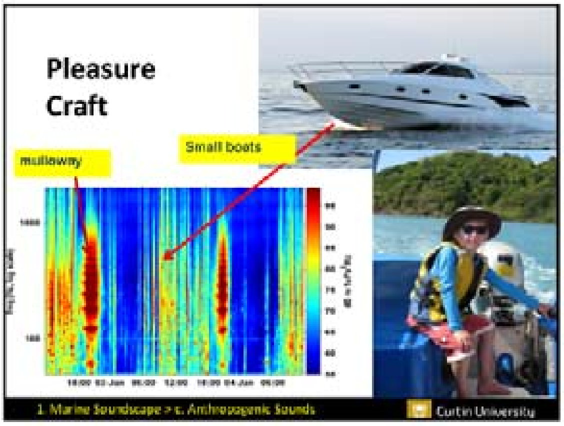

1c. Types and Characteristics of Anthropogenic Noise
Anthropogenic Noise Spectra
[Erbe 2011]
Frequency [Hz]
1. Marine Soundscape > c. Anthropogenic Sounds
Curtin University

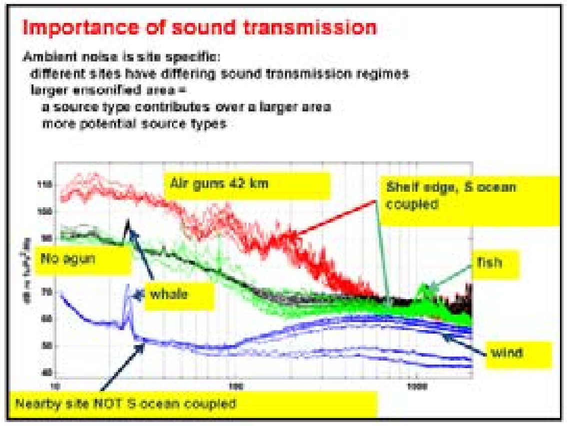

What is the "correct" source level?
Near Field
Fresnel Distance
Far Field
spherical spreading
relative SPL [dB]
range [m]
Depends on what you want to use it for… => Mike Ainslie's talk
1. Marine Soundscape > c. Anthropogenic Sounds
Curtin University

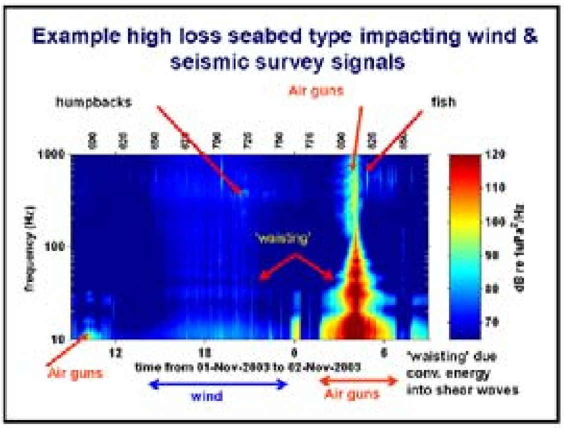

Airguns
3D two sources
Signals @ 1800 km
Freq. (Hz, res. = 0.73)
time (s, res.= 0.27)
50 days sea noise dominated by seismic

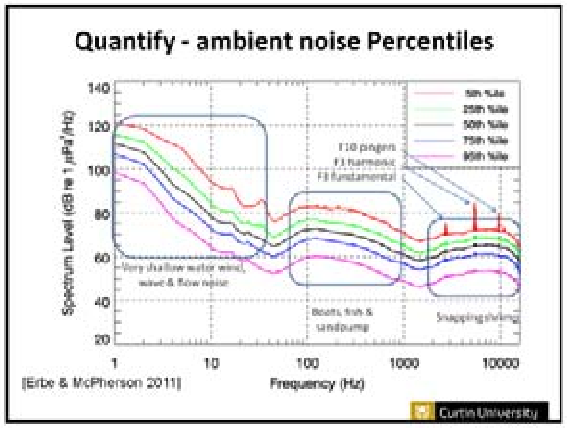

Pile Driving
[Erbe, Acoustics Australia 2009]
=> See James Reyff's talk
1. Marine Soundscape > c. Anthropogenic Sounds
Curtin University

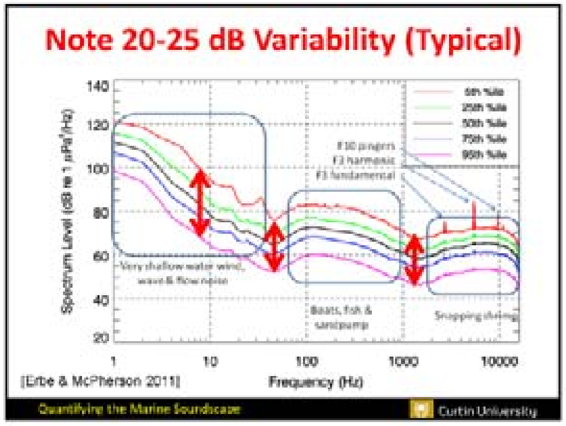

Large Vessels
Propeller cavitation noise dominant when underway
small number noisy ships dominate ocean noise
International effort to quieten shipping
[Erbe & Farmer, DSRII JASA 1998, 2000]
1. Marine Soundscape > c. Anthropogenic Sounds
Curtin University


Pleasure Craft
mulloway
Small boats
1. Marine Soundscape > c. Anthropogenic Sounds
Curtin University

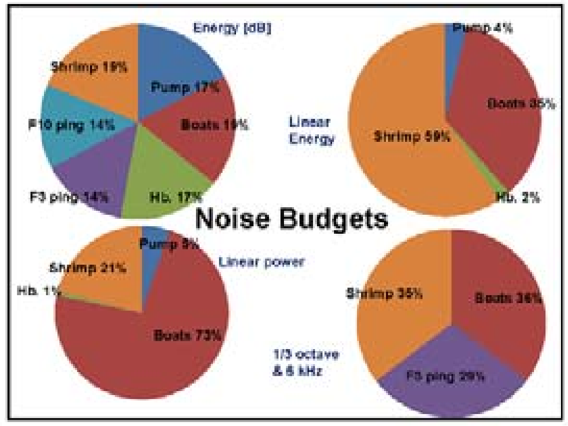

Importance of sound transmission
Ambient noise is site specific:
different sites have differing sound transmission regimes
larger ensonified area =
a source type contributes over a larger area
more potential source types
Air guns 42 km
Shelf edge, S ocean coupled
No agun
whale
fish
wind
Nearby site NOT S ocean coupled


Example high loss seabed type impacting wind & seismic survey signals
humpbacks
Air guns
fish
'waisting'
frequency (Hz)
time from 01-Nov-2003 to 02-Nov-2003
Air guns
wind
Air guns
'waisting' due conv. energy into shear waves
dB re 1uPa²/Hz


Quantify - ambient noise Percentiles
Spectrum Level (dB re 1 μPa²/Hz)
Frequency (Hz)
5th %ile
25th %ile
50th %ile
75th %ile
95th %ile
[Erbe & McPherson 2011]
Curtin University

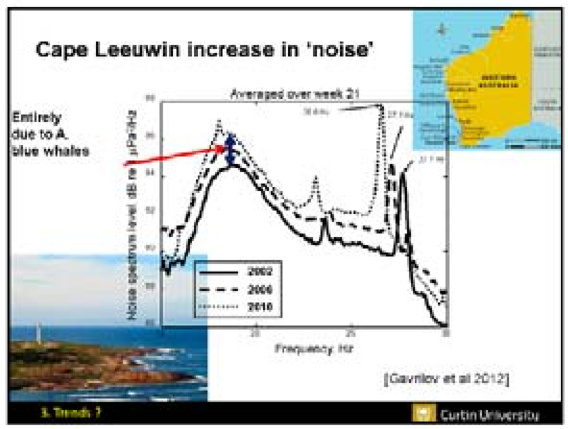


Note 20-25 dB Variability (Typical)
Spectrum Level (dB re 1 µPa²/Hz)
5th %ile
25th %ile
50th %ile
75th %ile
95th %ile
F10 pingers
F3 harmonic
F3 fundamental
Very shallow water wind, wave & flow noise
Boats, fish & sandpump
Snapping shrimp
Frequency (Hz)
[Erbe & McPherson 2011]
Quantifying the Marine Soundscape
Curtin University

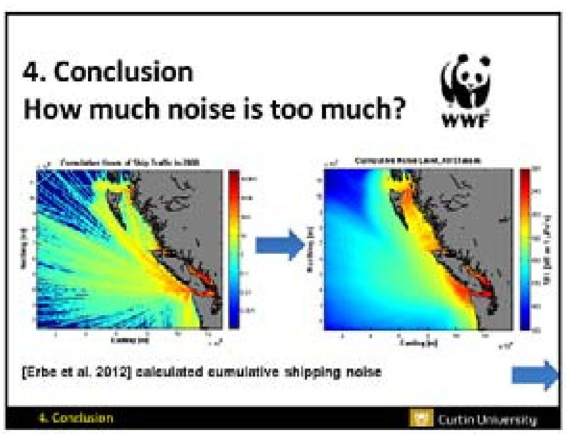


Energy [dB]
Shrimp 19%
Pump 17%
F10 ping 14%
Boats 19%
F3 ping 14%
Hb. 17%
Linear Energy
Pump 4%
Boats 35%
Shrimp 59%
Hb. 2%
Noise Budgets
Pump 5%
Linear power
Shrimp 21%
Hb. 1%
Boats 73%
Shrimp 35%
Boats 36%
1/3 octave & 6 kHz
F5 ping 29%

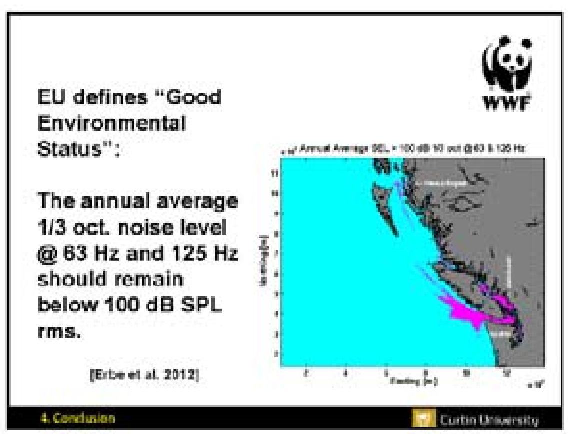
3. Trends
[Andrew et al. 2002, Chapman & Price 2011
For deep sound channel coupled North Pacific WHICH,
IS NOT EVERYWHERE !!!!
APL UW 1994-2001
Can. Def. 1978, 1980
Wenz 1963-1965
@ 31 Hz:
0.25 dB/yr
0.55 dB/yr
BUT THIS SITE DOES NOT
EQUAL ALL WORLDS OCEANS !
3. Trends ?
Curtin University



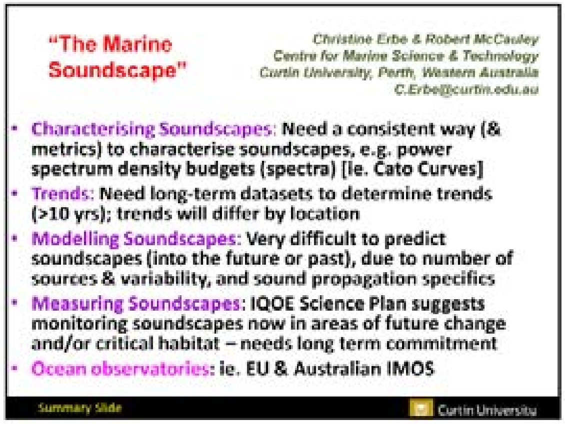
Cape Leeuwin increase in 'noise'
Averaged over week 21
Entirely due to A. blue whales
Noise spectrum level dB re µPa²/Hz
2002
2006
2010
Frequency, Hz
[Gavrilov et al 2012]
3. Trends ?
Curtin University



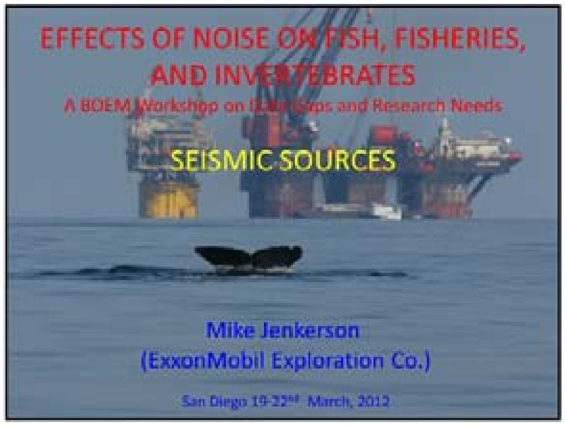
4. Conclusion
How much noise is too much?
WWF
[Erbe et al. 2012] calculated cumulative shipping noise
4. Conclusion
Curtin University

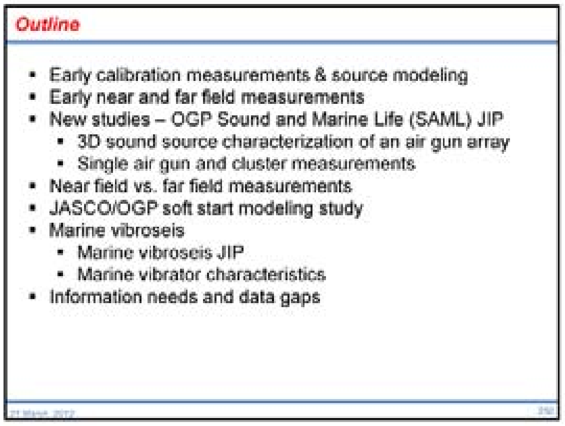


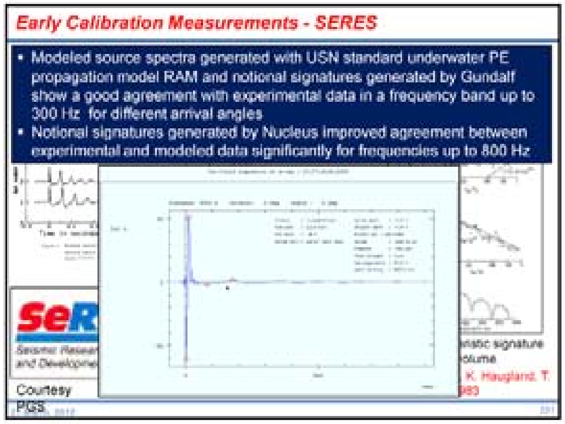
EU defines "Good Environmental Status":
The annual average 1/3 oct. noise level @ 63 Hz and 125 Hz should remain below 100 dB SPL rms.
[Erbe et al. 2012]
WWF
4. Conclusion
Curtin University

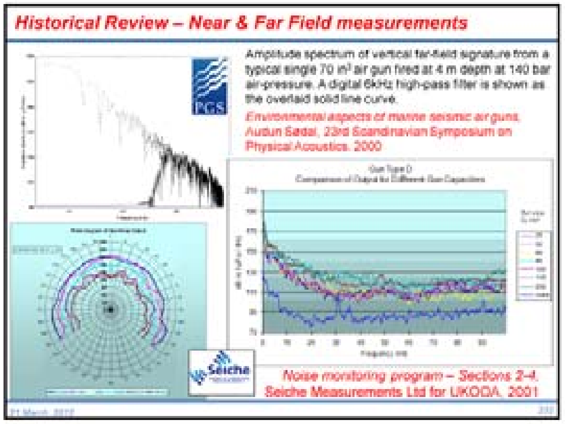

"The Marine Soundscape"
Christine Erbe & Robert McCauley
Centre for Marine Science & Technology
Curtin University, Perth, Western Australia
C.Erbe@curtin.edu.au
• Characterising Soundscapes: Need a consistent way (& metrics) to characterise soundscapes, e.g. power spectrum density budgets (spectra) [ie. Cato Curves]
• Trends: Need long-term datasets to determine trends (>10 yrs); trends will differ by location
• Modelling Soundscapes: Very difficult to predict soundscapes (into the future or past), due to number of sources & variability, and sound propagation specifics
• Measuring Soundscapes: IQOE Science Plan suggests monitoring soundscapes now in areas of future change and/or critical habitat – needs long term commitment
• Ocean observatories: ie. EU & Australian IMOS
Summary Slide
Curtin University

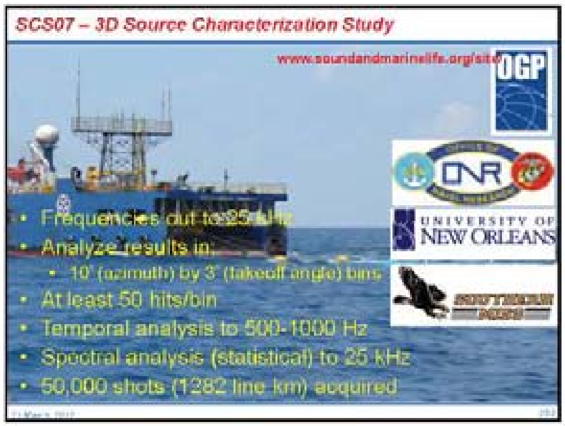

Now what ?!

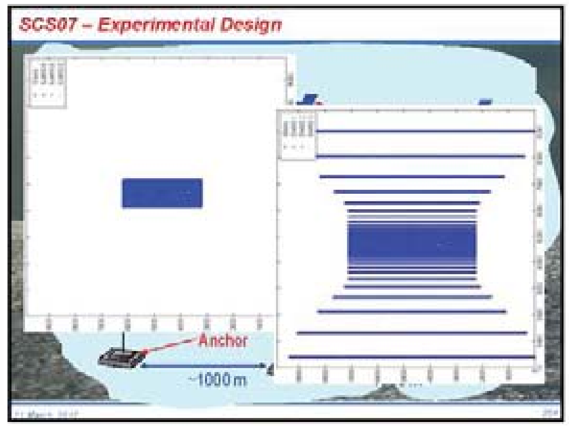

EFFECTS OF NOISE ON FISH, FISHERIES, AND INVERTEBRATES
A BOEM Workshop on Data Gaps and Research Needs
SEISMIC SOURCES
Mike Jenkerson
(ExxonMobil Exploration Co.)
San Diego 19-22nd March, 2012

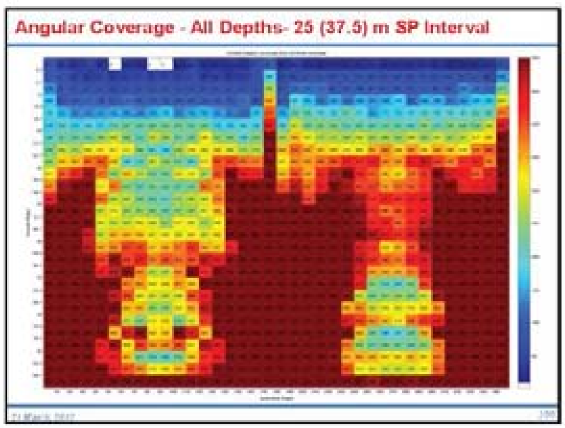

Outline
• Early calibration measurements & source modeling
• Early near and far field measurements
• New studies – OGP Sound and Marine Life (SAML) JIP
• 3D sound source characterization of an air gun array
• Single air gun and cluster measurements
• Near field vs. far field measurements
• JASCO/OGP soft start modeling study
• Marine vibroseis
• Marine vibroseis JIP
• Marine vibrator characteristics
• Information needs and data gaps

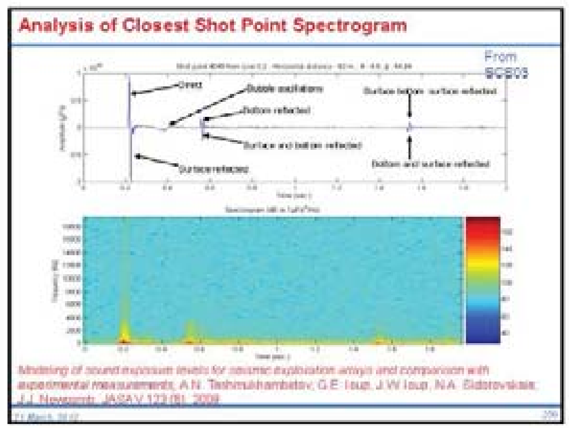

Early Calibration Measurements - SERES
• Modeled source spectra generated with USN standard underwater PE propagation model RAM and notional signatures generated by Gundalf show a good agreement with experimental data in a frequency band up to 300 Hz for different arrival angles
• Notional signatures generated by Nucleus improved agreement between experimental and modeled data significantly for frequencies up to 800 Hz
Courtesy PGS

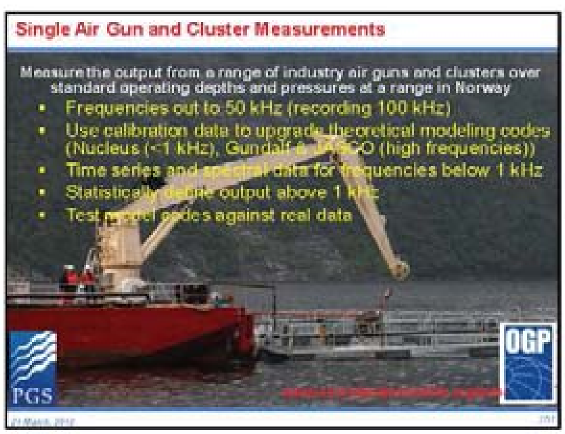

Historical Review – Near & Far Field measurements
Amplitude spectrum of vertical far-field signature from a typical single 70 in³ air gun fired at 4 m depth at 140 bar air-pressure. A digital 6kHz high-pass filter is shown as the overlaid solid line curve.
Environmental aspects of marine seismic air guns, Audun Sødal, 23rd Scandinavian Symposium on Physical Acoustics, 2000
PGS
Noise monitoring program – Sections 2-4, Seiche Measurements Ltd for UKOOA, 2001
Seiche

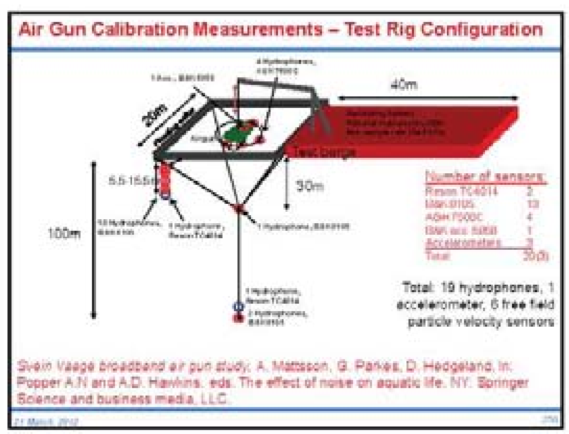

SCS07 – 3D Source Characterization Study
www.soundandmarinelife.org/site
OGP
UNIVERSITY OF NEW ORLEANS
• Frequencies out to 25 kHz
• Analyze results in:
• 10° (azimuth) by 3° (takeoff angle) bins
• At least 50 hits/bin
• Temporal analysis to 500-1000 Hz
• Spectral analysis (statistical) to 25 kHz
• 50,000 shots (1282 line km) acquired

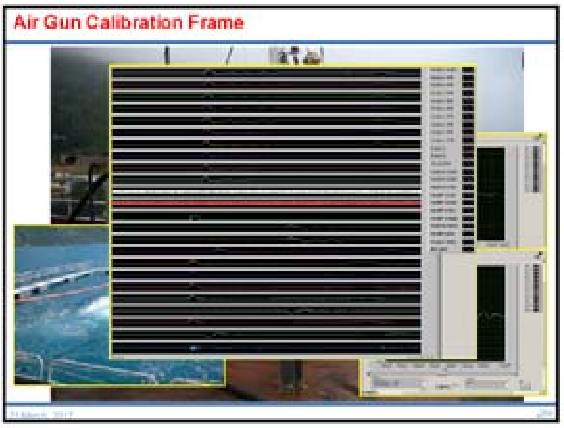

SCS07 – Experimental Design
Anchor
~1000 m

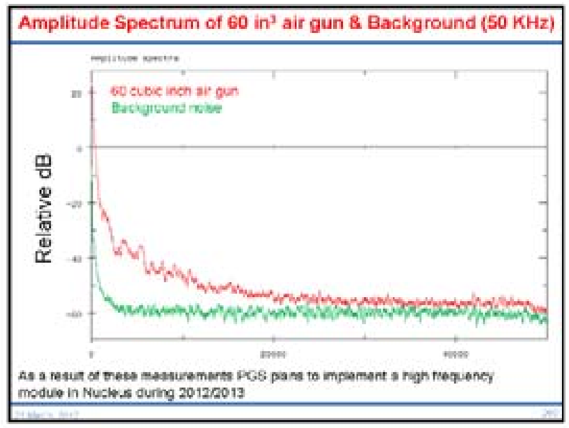

Angular Coverage - All Depths- 25 (37.5) m SP Interval

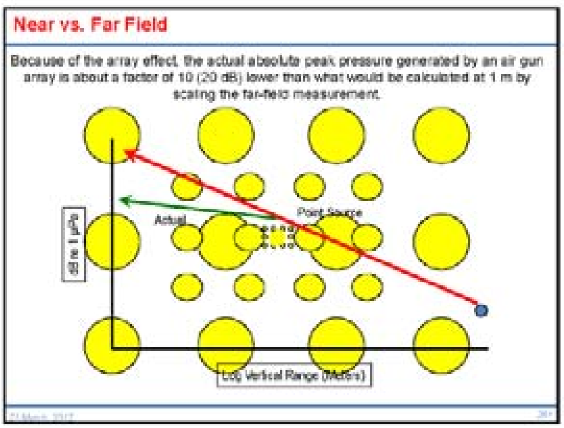

Analysis of Closest Shot Point Spectrogram
From SCS09
Direct
Bubble oscillations
Bottom reflected
Surface and bottom reflected
Surface reflected
Surface bottom surface reflected
Bottom and surface reflected
Modeling of sound exposure levels for seismic exploration arrays and comparison with experimental measurements, A.N. Tashmukhambetov, G.E. Ioup, J.W Ioup, N.A. Sidorovskaia, J.J. Newcomb, JASA V 123 (6), 2008

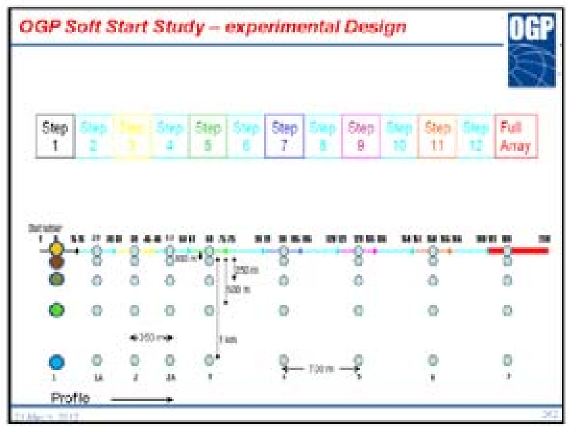

Single Air Gun and Cluster Measurements
Measure the output from a range of industry air guns and clusters over standard operating depths and pressures at a range in Norway
• Frequencies out to 50 kHz (recording 100 kHz)
• Use calibration data to upgrade theoretical modeling codes (Nucleus (<1 kHz), Gundalf & JASCO (high frequencies))
• Time series and spectral data for frequencies below 1 kHz
• Statistically define output above 1 kHz
• Test model codes against real data
PGS
OGP

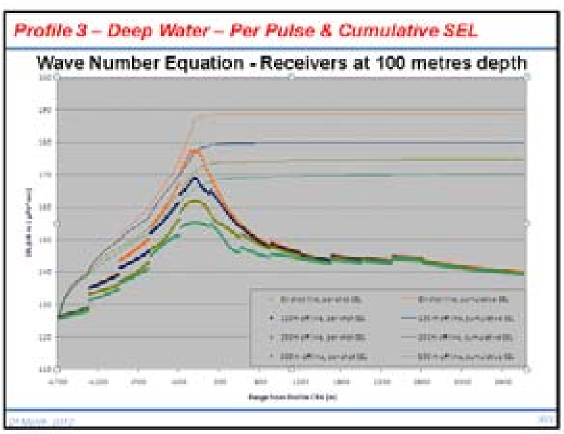

Air Gun Calibration Measurements – Test Rig Configuration
40m
20m
Test barge
30m
100m
Number of sensors
Reson TC4014 2
Total: 19 hydrophones, 1 accelerometer, 6 free field particle velocity sensors
Svein Vaage broadband air gun study, A. Mattsson, G. Parkes, D. Hedgeland, In: Popper A.N and A.D. Hawkins, eds. The effect of noise on aquatic life. NY: Springer Science and business media, LLC.

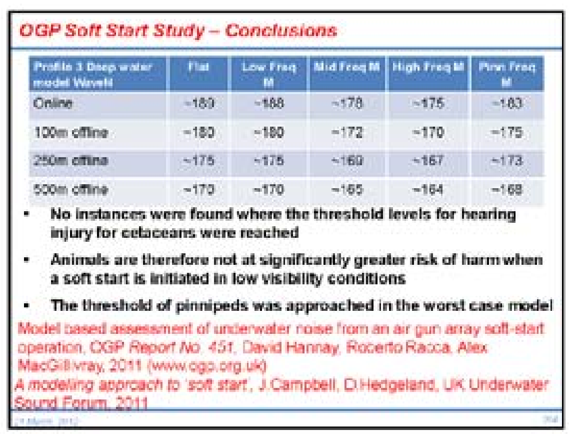

Air Gun Calibration Frame

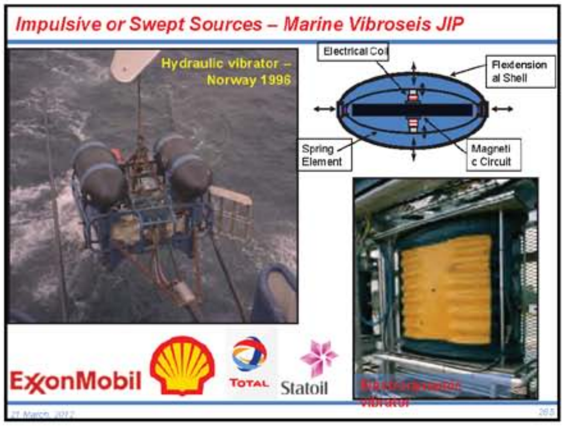

Amplitude Spectrum of 60 in³ air gun & Background (50 KHz)
60 cubic inch air gun
Background noise
Relative dB
As a result of these measurements PGS plans to implement a high frequency module in Nucleus during 2012/2013

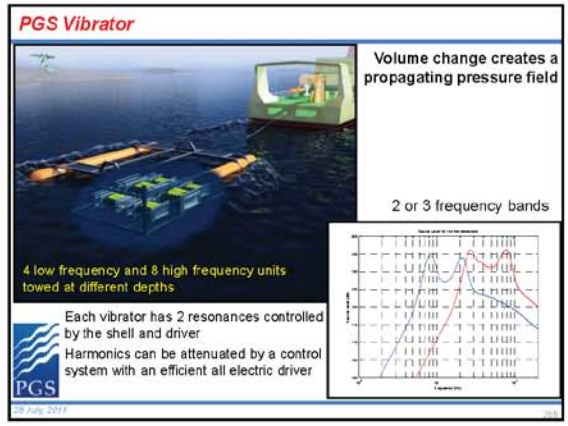

Near vs. Far Field
Because of the array effect, the actual absolute peak pressure generated by an air gun array is about a factor of 10 (20 dB) lower than what would be calculated at 1 m by scaling the far-field measurement.
Actual
Point Source
dB re 1 μPa
Log Vertical Range (Meters)

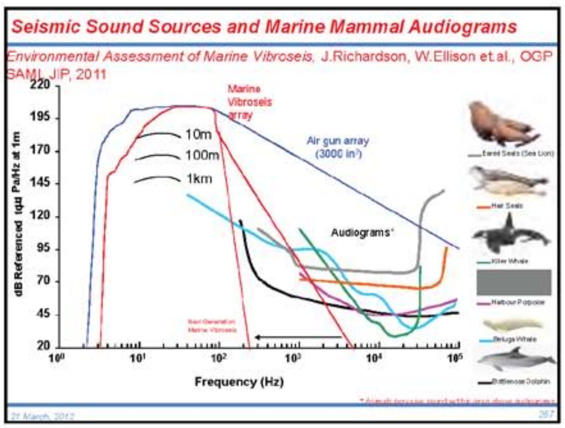

OGP Soft Start Study – experimental Design
OGP
Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Step 7
Step 8
Step 9
Step 10
Step 11
Step 12
Full Array
250 m
500 m
1 km
700 m
Profile

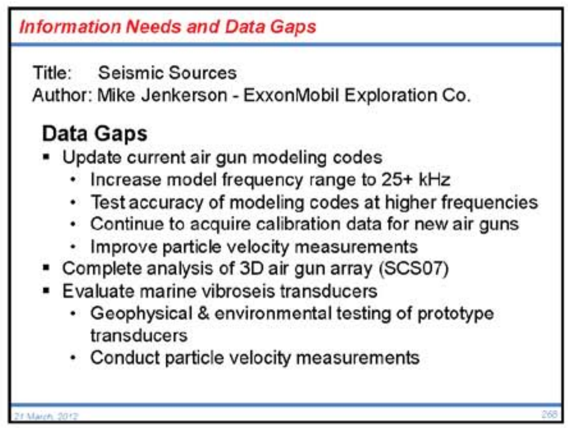

Profile 3 – Deep Water – Per Pulse & Cumulative SEL
Wave Number Equation - Receivers at 100 metres depth

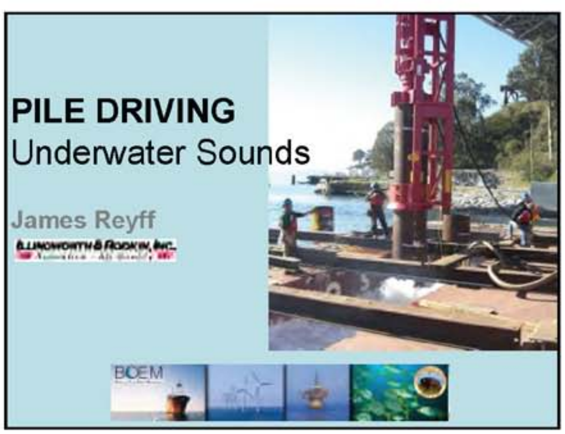

OGP Soft Start Study – Conclusions
Profile 3 Deep water model Wavelet | Flat | Low Freq M | Mid Freq M | High Freq M | Pinn Freq M
Online | ~189 | ~188 | ~178 | ~175 | ~183
100m offline | ~180 | ~180 | ~172 | ~170 | ~175
250m offline | ~175 | ~175 | ~169 | ~167 | ~173
500m offline | ~170 | ~170 | ~165 | ~164 | ~168
No instances were found where the threshold levels for hearing injury for cetaceans were reached
Animals are therefore not at significantly greater risk of harm when a soft start is initiated in low visibility conditions
The threshold of pinnipeds was approached in the worst case model
Model based assessment of underwater noise from an air gun array soft-start operation, OGP Report No. 451, David Hannay, Roberto Racca, Alex MacGillivray, 2011 (www.ogp.org.uk)
A modeling approach to 'soft start', J.Campbell, D.Hedgeland, UK Underwater Sound Forum, 2011

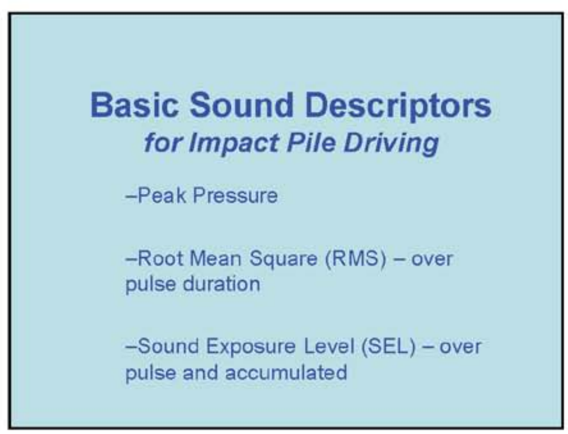

Impulsive or Swept Sources – Marine Vibroseis JIP
Hydraulic vibrator – Norway 1996
Electrical Coil
Flexdension al Shell
Spring Element
Magneti c Circuit
ExxonMobil
TOTAL
Statoil
21 March, 2012
265

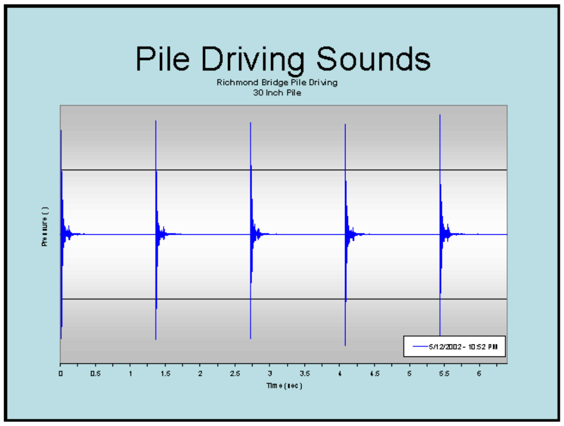

PGS Vibrator
Volume change creates a propagating pressure field
2 or 3 frequency bands
4 low frequency and 8 high frequency units towed at different depths
Each vibrator has 2 resonances controlled by the shell and driver
Harmonics can be attenuated by a control system with an efficient all electric driver
PGS
28 July, 2011
266

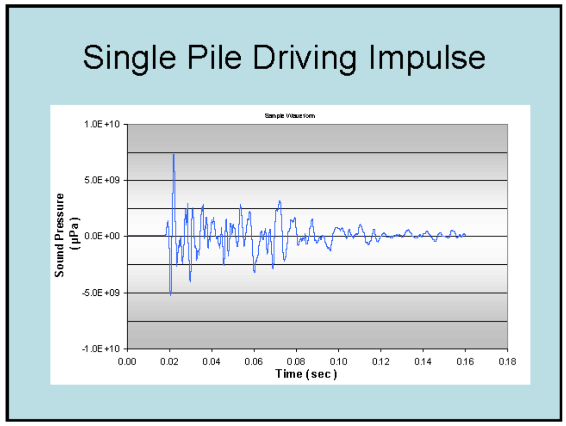

Seismic Sound Sources and Marine Mammal Audiograms
Environmental Assessment of Marine Vibroseis, J.Richardson, W.Ellison et.al., OGP SAML JIP, 2011
dB Referenced 1µPa/Hz at 1m
220
195
170
145
120
95
70
45
20
Marine Vibroseis array
10m
100m
1km
Air gun array (3000 in³)
Audiograms*
Frequency (Hz)
Eared Seals (Sea Lion)
Hair Seals
Killer Whale
Harbour Porpoise
Beluga Whale
Bottlenose Dolphin
21 March, 2012
267

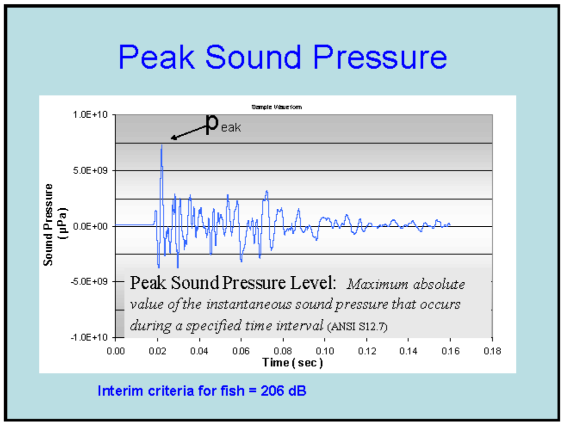

Information Needs and Data Gaps
Title: Seismic Sources
Author: Mike Jenkerson - ExxonMobil Exploration Co.
Data Gaps
▪ Update current air gun modeling codes
• Increase model frequency range to 25+ kHz
• Test accuracy of modeling codes at higher frequencies
• Continue to acquire calibration data for new air guns
• Improve particle velocity measurements
▪ Complete analysis of 3D air gun array (SCS07)
▪ Evaluate marine vibroseis transducers
• Geophysical & environmental testing of prototype transducers
• Conduct particle velocity measurements
21 March, 2012
268

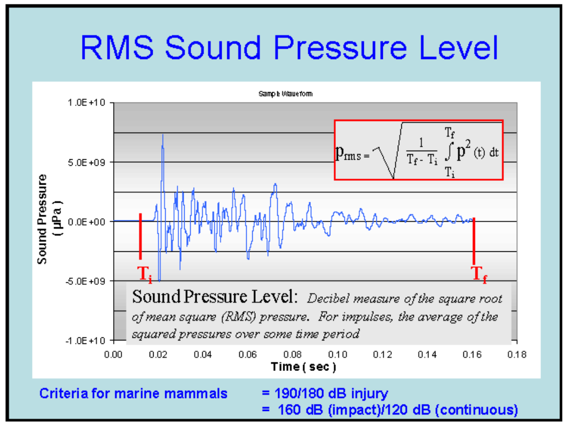

PILE DRIVING
Underwater Sounds
James Reyff
ILLINGWORTH & RODKIN, INC.
BOEM

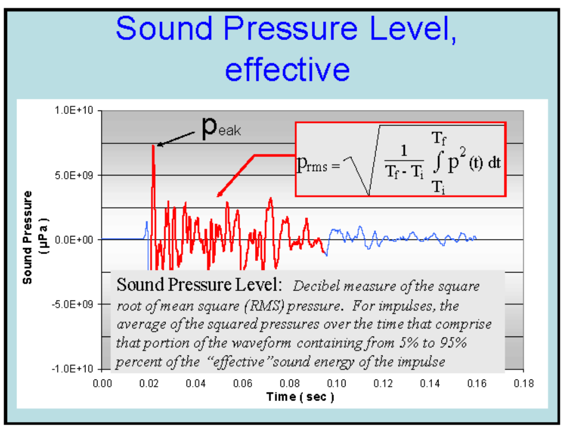

Basic Sound Descriptors
for Impact Pile Driving
–Peak Pressure
–Root Mean Square (RMS) – over pulse duration
–Sound Exposure Level (SEL) – over pulse and accumulated

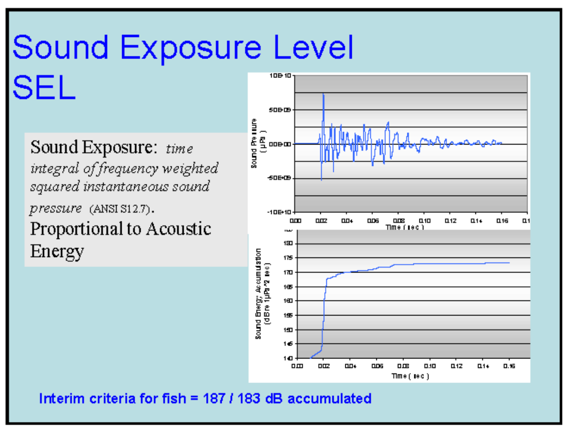

Pile Driving Sounds
Richmond Bridge Pile Driving
30 Inch Pile
5/12/2002 - 10:52 PM


Single Pile Driving Impulse
Sample Waveform
Sound Pressure (µPa)
1.0E+10
5.0E+09
0.0E+00
-5.0E+09
-1.0E+10
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18
Time (sec)


Peak Sound Pressure
Sample Waveform
Peak
Sound Pressure (µPa)
1.0E+10
5.0E+09
0.0E+00
-5.0E+09
-1.0E+10
Peak Sound Pressure Level: Maximum absolute value of the instantaneous sound pressure that occurs during a specified time interval (ANSI S12.7)
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18
Time (sec)
Interim criteria for fish = 206 dB


RMS Sound Pressure Level
Sample Waveform
$p_{rms} = \sqrt{\frac{1}{T_f - T_i} \int_{T_i}^{T_f} p^2(t)\, dt}$
Sound Pressure (µPa)
1.0E+10
5.0E+09
0.0E+00
-5.0E+09
-1.0E+10
T_i
T_f
Sound Pressure Level: Decibel measure of the square root of mean square (RMS) pressure. For impulses, the average of the squared pressures over some time period
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18
Time (sec)
Criteria for marine mammals
= 190/180 dB injury
= 160 dB (impact)/120 dB (continuous)


Sound Pressure Level, effective
Peak
$p_{rms} = \sqrt{\frac{1}{T_f - T_i} \int_{T_i}^{T_f} p^2(t)\, dt}$
Sound Pressure (µPa)
1.0E+10
5.0E+09
0.0E+00
-5.0E+09
-1.0E+10
Sound Pressure Level: Decibel measure of the square root of mean square (RMS) pressure. For impulses, the average of the squared pressures over the time that comprise that portion of the waveform containing from 5% to 95% percent of the "effective" sound energy of the impulse
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18
Time (sec)

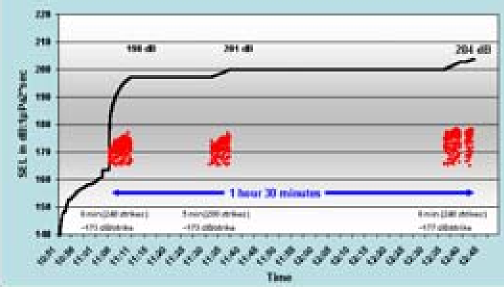

Sound Exposure Level
SEL
Sound Exposure: time integral of frequency weighted squared instantaneous sound pressure (ANSI S12.7).
Proportional to Acoustic Energy
Interim criteria for fish = 187 / 183 dB accumulated

Accumulated SEL

Accumulated SEL

1.3-Meter Diameter Steel Piles

SEL Measured at 10 Meters



Vibratory Pile Driving

- Much lower amplitude sounds than impact pile driving (20 to 30 dB lower)
- Noise tends to be more continuous
- Higher Frequency sounds

Vibratory Pile Driving

Potential Impacts

- No restrictive levels identified for fish
  - No Peak or SEL levels
- Potential injury thresholds for marine mammals unlikely (i.e., levels generally less than 180 dB RMS near source)
- Harassment to marine mammals likely to extend many kilometers from pile based on 120 dB RMS level

Computing RMS Level

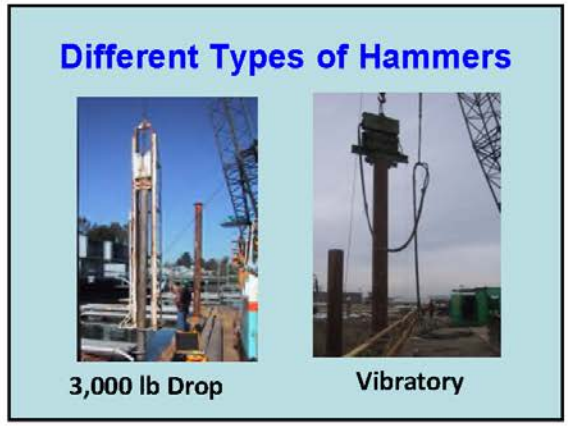
Max	Average Leq	Average 10 sec	Average 1 sec
183	173	169	168

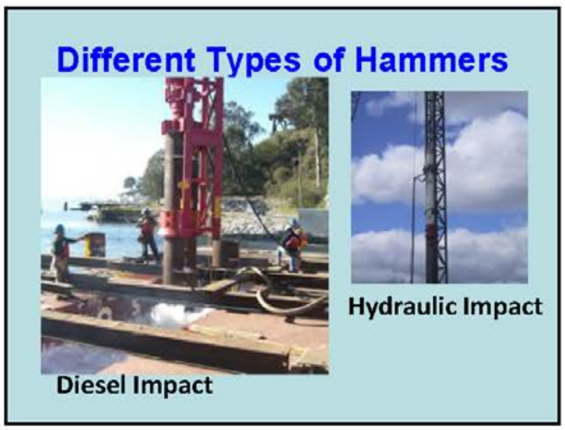
How Much Sound Does Pile Driving Make?

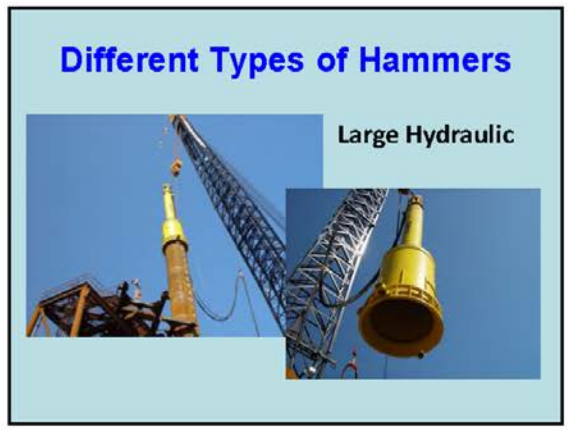
Depends on …

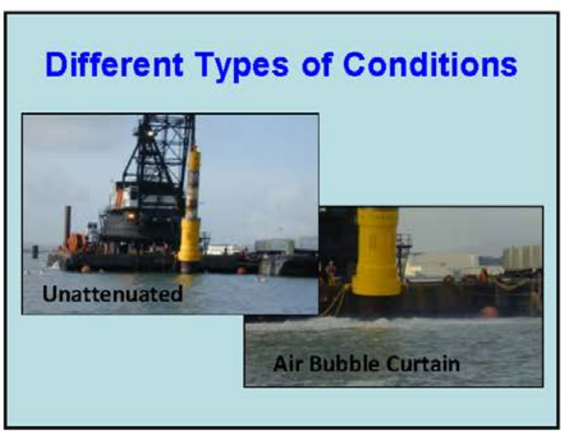
- Type and size of Pile
- Type of Driving Method
- Hammer Size and Energy
- Attenuation methods
- Substrate Conditions
- Sound propagation conditions


Different Types of Piles


Different Types of Hammers
3,000 lb Drop
Vibratory


Different Types of Hammers
Hydraulic Impact
Diesel Impact


Different Types of Hammers
Large Hydraulic


Different Types of Conditions
Unattenuated
Air Bubble Curtain


Different Types of Conditions
On Land Near Water

Summary Table – Impact Driving

Pile Type and Size	Relative Water Depth	Average Sound Pressure Measured in dB		
		Peak	RMS*	SEL
0.30-meter Steel H-type - Thin	<5 meters	190	175	160
0.6-meter AZ Steel Sheet	~15 meters	205	190	180
0.61-meter Concrete Pile	~15 meters	188	176	166
0.36-meter Steel Pipe Pile	~15 meters	200	184	174
0.61-meter Steel Pipe Pile	~15 meters	207	194	178
0.8-meter Steel Pipe Pile	~10 meters	210	193	183
1.5-meter Steel CISS	<5 meters	210	195	185
2.4-meter Steel CISS	~15 meters	220	205	195

* Impulse level
**SEL for 1 second of continuous driving

Summary Table – Vibratory Driving

Pile Type and Approximate Size	Relative Water Depth	Average Sound Pressure Measured in dB		
		Peak	RMS*	SEL
0.30-meter Steel H-type	<5 meters	165	150	150
0.30-meter Steel Pipe Pile	<5 meters	171	155	155
0.8-meter Steel Pipe Pile	~5 meters	180	170	170
0.6-meter AZ Steel Sheet	~15 meters	175	160	160
1-meter Steel Pipe Pile - Loudest	~5 meters	185	175	175
1.8-meter Steel Pipe Pile	~5 meters	183	170	170

* 1 sec RMS
**SEL for 1 second of continuous driving

RMS levels based on 1-sec RMS

Minimization Measures

- Air bubble curtains/Dewatered casings
  - Confined / unconfined
- Dewatered cofferdams
- Avoid in water driving
  - Move footings out of water
- Use Vibratory Drivers???
- Construction windows
  - Avoid times when species are present

Reducing Sounds

Reducing Sounds

Air Bubble Curtain

Reducing Sounds

Dewatered Casing

Reducing Sounds

Dewatered Casing

Reducing Sounds

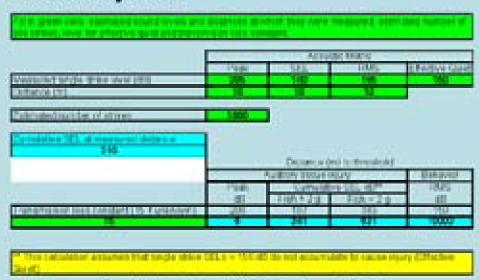
Dewatered Cofferdam

Underwater Sound Propagation

- Default 15 Log_{10} Rate (4.5 dB per doubling of distance)
- Measurement Examples
  - Large piles in relatively deep water
  - Piles in very shallow water
  - Large piles in varying water depth

NOAA Worksheet for

Stationary Fish

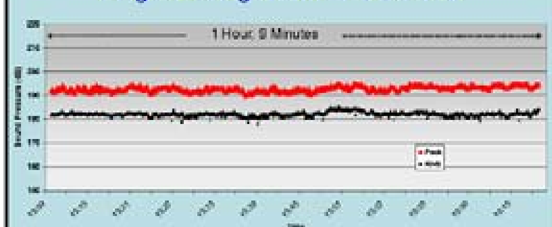


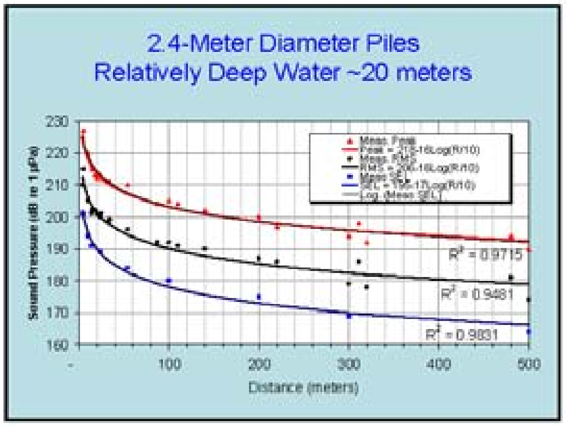
Credit – *David Woodbury, NMFS Southwest Division*

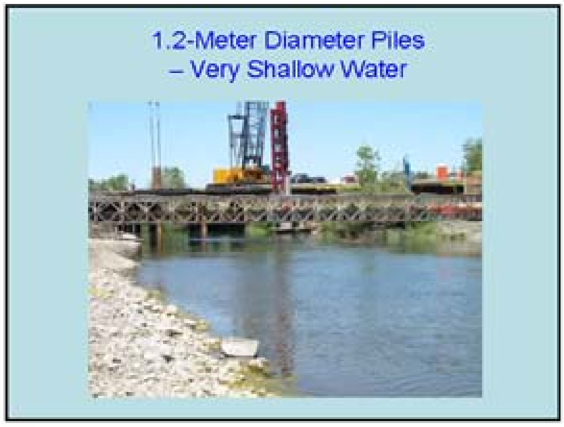
Propagation of Impact Sounds

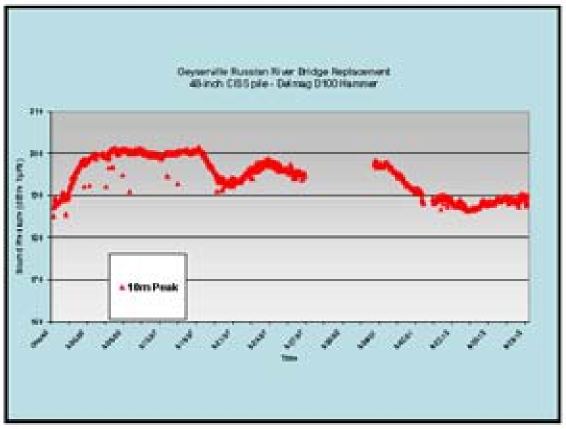
2.4-Meter Diameter Piles

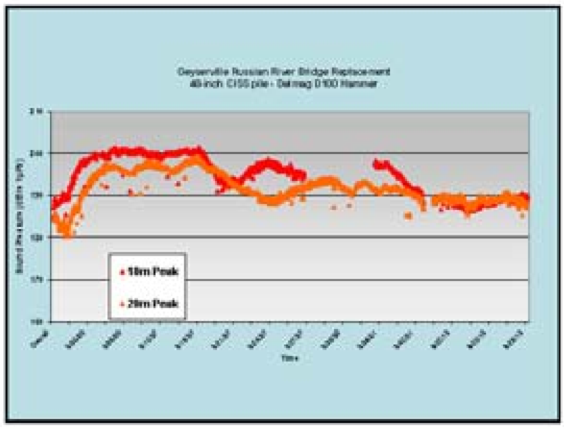
2.4-Meter Diameter Pile
Single Driving Event - Attenuated

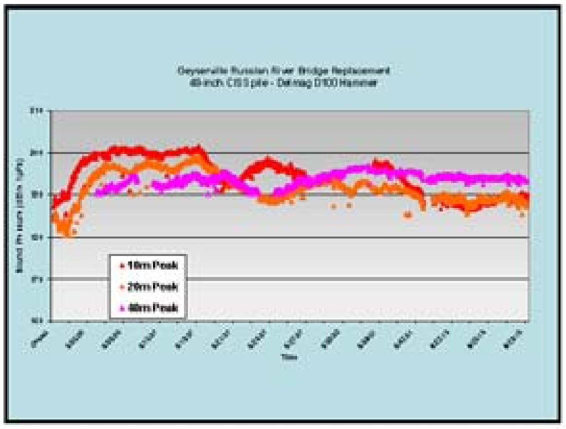


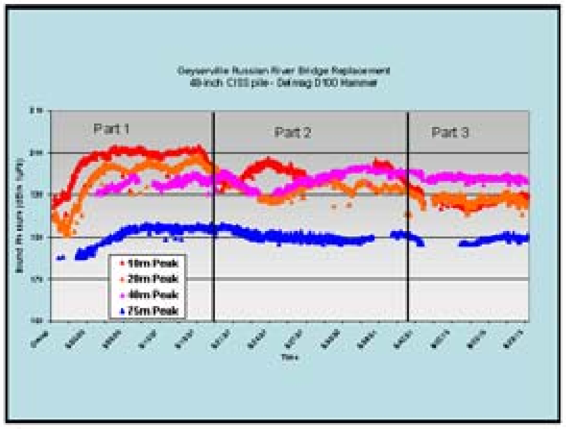

2.4-Meter Diameter Piles
Relatively Deep Water ~20 meters
Sound Pressure (dB re 1 μPa)
Distance (meters)
R^2 = 0.9715
R^2 = 0.9481
R^2 = 0.9831

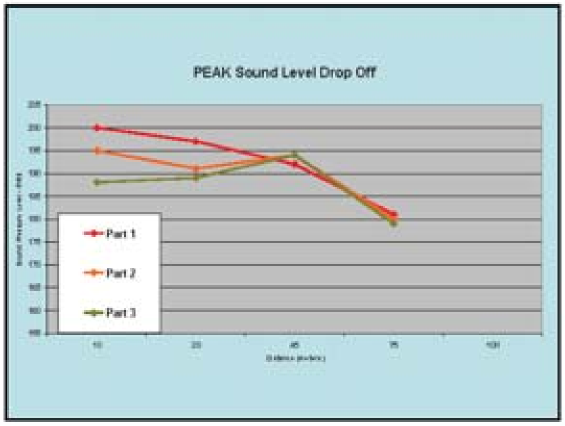

1.2-Meter Diameter Piles
– Very Shallow Water

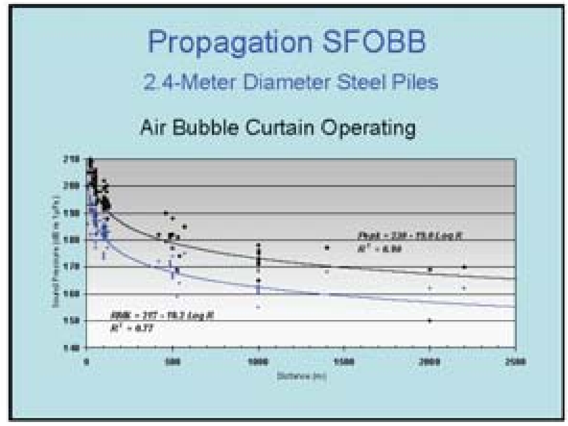

10m Peak

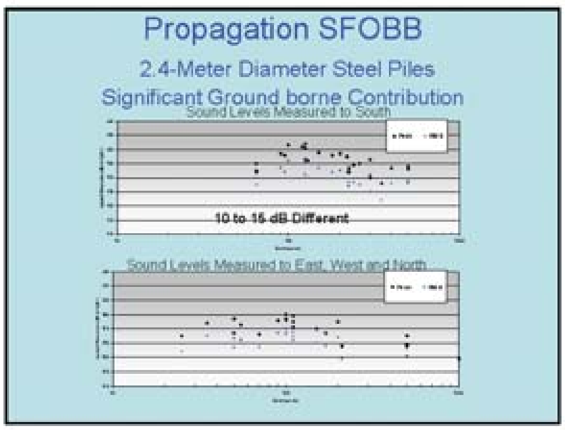

10m Peak
20m Peak

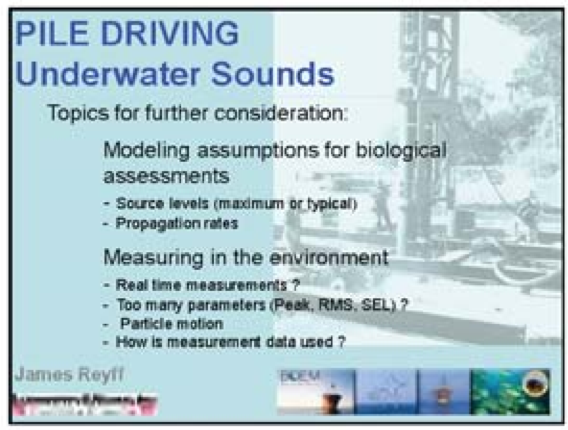

10m Peak
20m Peak
40m Peak


Part 1
Part 2
Part 3
10m Peak
20m Peak
40m Peak
75m Peak


PEAK Sound Level Drop Off
Part 1
Part 2
Part 3


Propagation SFOBB
2.4-Meter Diameter Steel Piles
Air Bubble Curtain Operating


Propagation SFOBB
2.4-Meter Diameter Steel Piles
Significant Ground borne Contribution
Sound Levels Measured to South
10 to 15 dB Different
Sound Levels Measured to East, West and North


PILE DRIVING
Underwater Sounds
Topics for further consideration:
Modeling assumptions for biological assessments
- Source levels (maximum or typical)
- Propagation rates
Measuring in the environment
- Real time measurements ?
- Too many parameters (Peak, RMS, SEL) ?
- Particle motion
- How is measurement data used ?
James Reyff
BOEM


Are windfarms noisy?
BOEM Workshop on the Effects of Noise on Fish, Fisheries, and Invertebrates
Tuesday, March 20, 2012
Dr J Nedwell
subacoustech


Offshore wind power in UK
• United Kingdom world's 8th biggest producer of wind power; unique wind resource
• Currently 6000 MW, 321 operational wind farms and 3,500 wind turbines
• British electricity suppliers required by law to provide proportion of their supply from renewables
• Further 5 wind farms, 1,300 MW becoming operational in 2012
• Round 3; 2,000 MW installed per year for the next five years, about 28,000 MW of wind capacity by 2020
• Environmental effects of noise biggest environmental issue facing industry.
subacoustech


Impacts of underwater sound
• Impact piling known to be very significant sound source
• Piles up to 7m being considered
• Hearing injury especially to marine mammals recognised as issue
• Behavioural response: many 10's kms – probably biggest issue in UK waters
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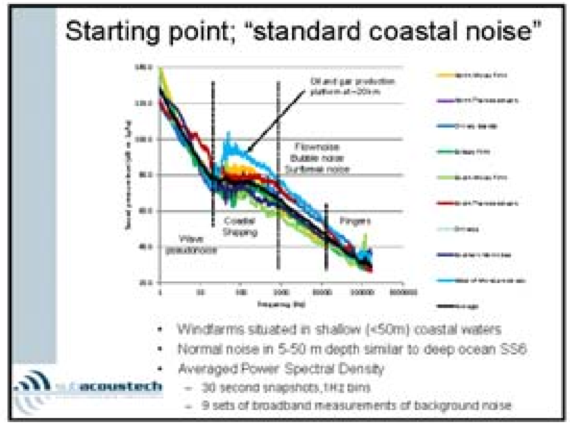
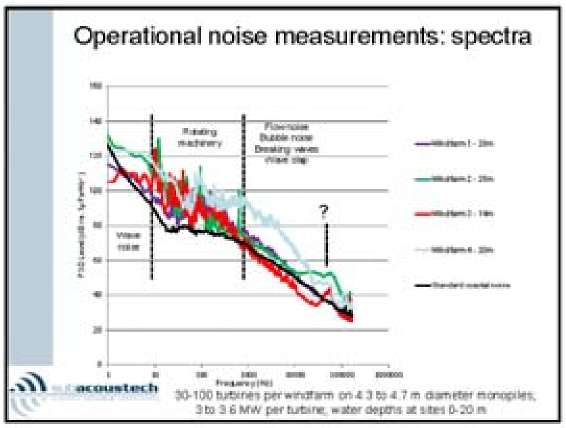

Starting point; "standard coastal noise"
Oil and gas production platform at ~20km
Flownoise
Bubble noise
Surf/wind noise
Coastal Shipping
Wave pseudonoise
Fingers
• Windfarms situated in shallow (<50m) coastal waters
• Normal noise in 5-50 m depth similar to deep ocean SS6
• Averaged Power Spectral Density
– 30 second snapshots, 1Hz bins
– 9 sets of broadband measurements of background noise
subacoustech


Operational noise measurements: spectra
Rotating machinery
Flownoise
Bubble noise
Breaking waves
Wave slap
Wave noise
?
Standard coastal noise
30-100 turbines per windfarm on 4.3 to 4.7 m diameter monopiles; 3 to 3.6 MW per turbine; water depths at sites 0-20 m
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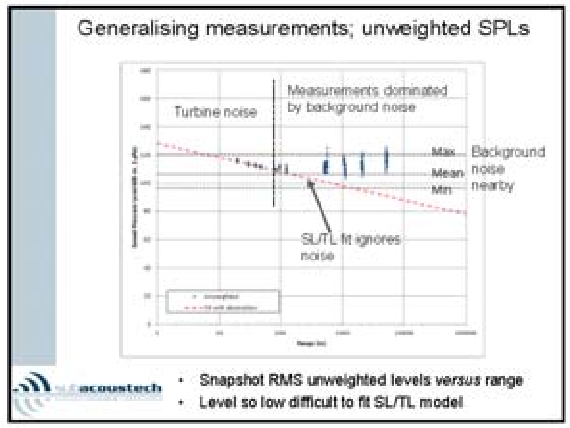
Generalising measurements; unweighted SPLs
Turbine noise
Measurements dominated by background noise
Max
Mean
Min
Background noise nearby
SL/TL fit ignores noise
• Snapshot RMS unweighted levels *versus* range
• Level so low difficult to fit SL/TL model
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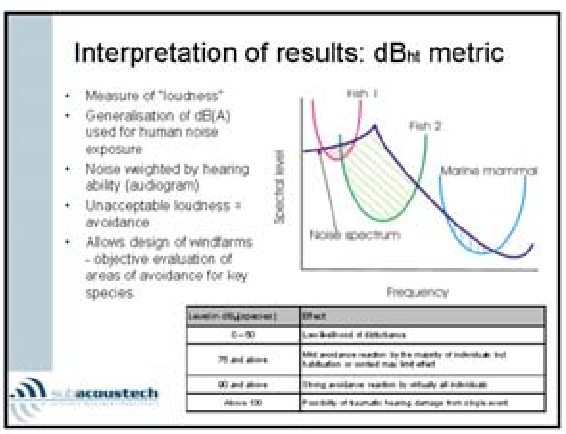
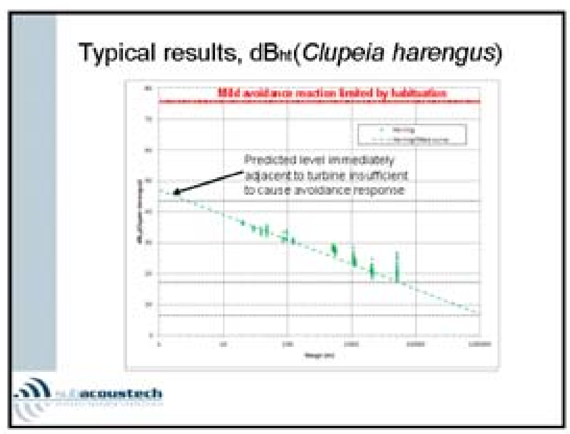

Interpretation of results: dBht metric
• Measure of "loudness"
• Generalisation of dB(A) used for human noise exposure
• Noise weighted by hearing ability (audiogram)
• Unacceptable loudness = avoidance
• Allows design of windfarms - objective evaluation of areas of avoidance for key species
Fish 1
Fish 2
Marine mammal
Noise spectrum
Spectral level
Frequency
subacoustech


Typical results, dBht(*Clupeia harengus*)
Mild avoidance reaction limited by habituation
Predicted level immediately adjacent to turbine insufficient to cause avoidance response
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Temporal considerations

- Area of sea excluded by a individual turbine small, but for 25 years
- Consider habitat loss (area excluded as area times time) based on 50 dBht (toughest criterion)

Assumptions:

Impact Piling:	A 4m diameter pile installed over 3 hours
Vessel Noise:	3 vessels on site for 7 days
Suction Dredging:	1 vessel on site for 2 days
Trenching:	1 vessel on site for 1 day
Operational Turbine:	Operational for a period of 25 years

50dBht Area of Sea Excluded	Impact Piling (km²-hrs)	Vessel Noise (km²-hrs)	Suction Dredging (km²-hrs)	Trenching (km²-hrs)	Operational Turbine (km²-hrs)
Cod	14,000	48	98	37	1
Dab	4,200	< 1	2	< 1	< 1
Herring	17,000	31	100	880	11
B.Dolphin	11,000	2,200	800	980	< 1
H.Porpoise	18,000	1,800	3,800	2,700	8
H.Seal	13,000	330	390	340	< 1

Conclusion: Even allowing for time, estimates of habitat loss caused by operation are dwarfed by all other sources and especially noise from piling

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Summary

If noise during windfarm construction can be controlled, best information indicates that noise during operation is unlikely to be a problem

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Commercial blasting

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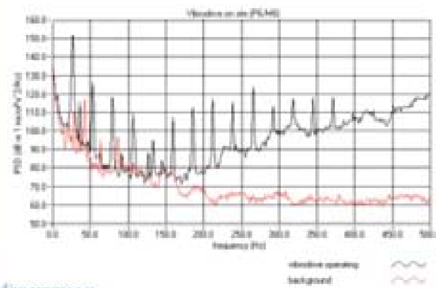
Subacoustech Ltd Commercial in Confidence

Vibrodrive on site (24 metres)



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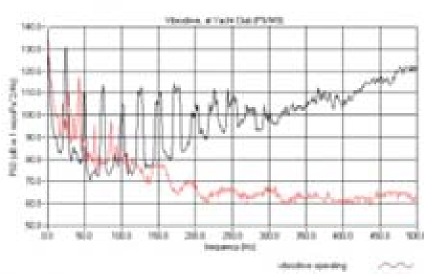
Vibrodrive at yacht club (82 metres)



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Range to 50 dBht at Windfarm 2

Species	Herring	Cod	Dab	Bottle-nose Dolphin	Striped Dolphin	Harbour porpoise	Harbour seal
Max	90	88	64	88	82	83	84
Mean	80	69	43.4	71	75	21.8	64
Range to 50 dBht	110	110	5	450	450	5000	800

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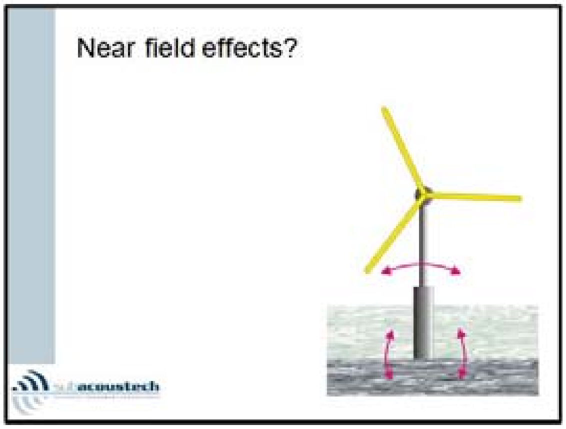
Near field effects?
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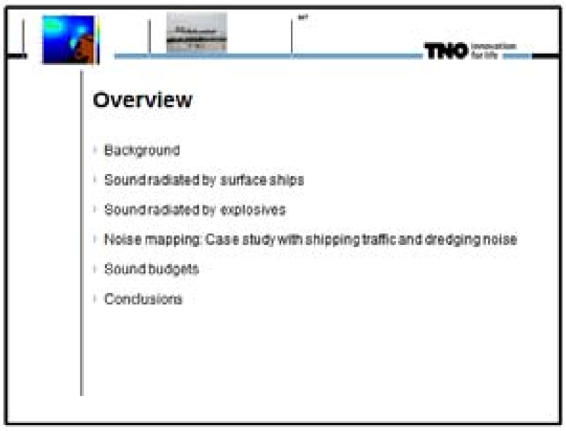
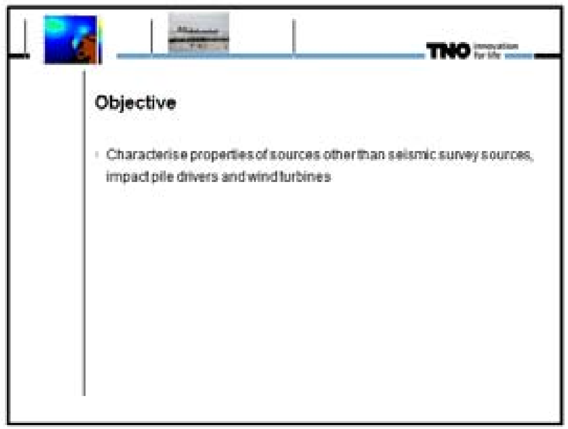
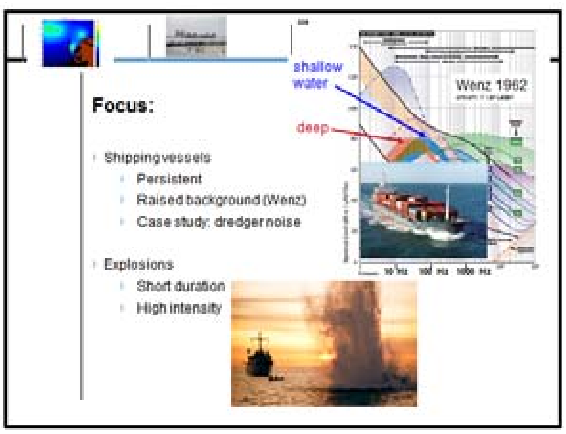
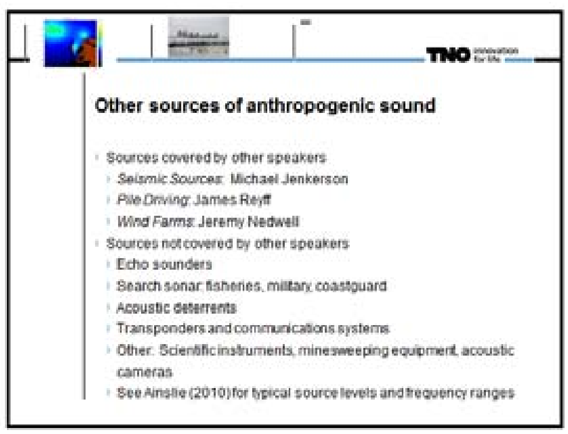
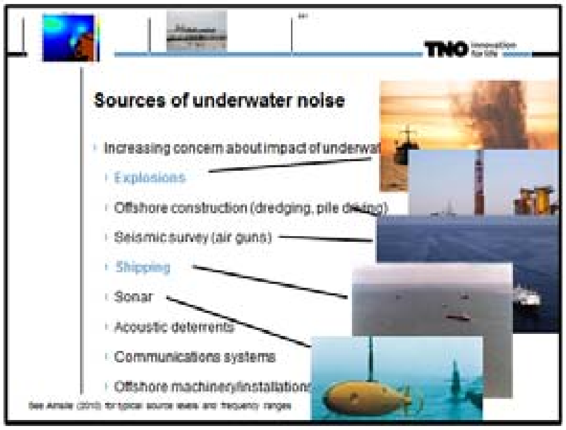
TNO innovation for life
Other Anthropogenic Sources of Interest
M A Ainslie
Effects of Noise on Fish, Fisheries, and Invertebrates: A BOEM Workshop on Data Gaps and Research Needs, 20-22 March 2012, Town and Country Resort, San Diego, CA


TNO innovation for life
Overview
Background
Sound radiated by surface ships
Sound radiated by explosives
Noise mapping: Case study with shipping traffic and dredging noise
Sound budgets
Conclusions

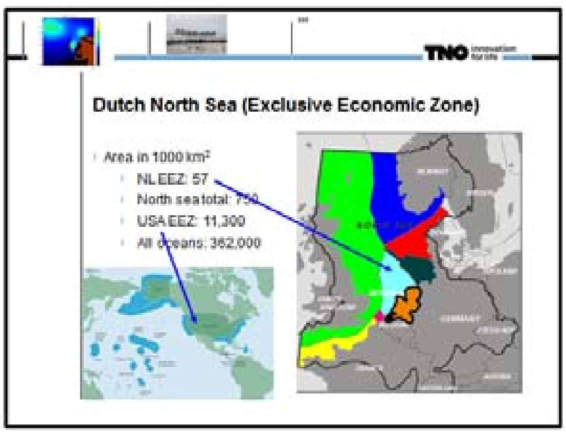

TNO innovation for life
Objective
Characterise properties of sources other than seismic survey sources, impact pile drivers and wind turbines

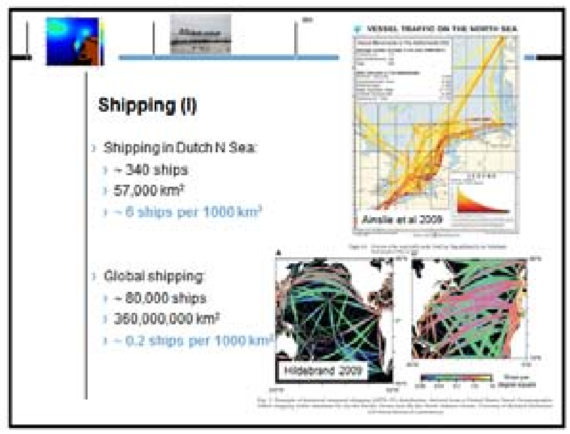

Focus:
Shipping vessels
Persistent
Raised background (Wenz)
Case study: dredger noise
Explosions
Short duration
High intensity
shallow water
deep
Wenz 1962
10 Hz
100 Hz
1000 Hz

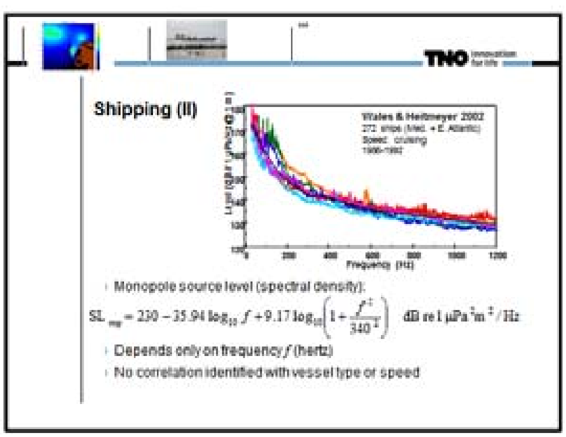

TNO innovation for life
Other sources of anthropogenic sound
Sources covered by other speakers
Seismic Sources: Michael Jenkerson
Pile Driving: James Reyff
Wind Farms: Jeremy Nedwell
Sources not covered by other speakers
Echo sounders
Search sonar: fisheries, military, coastguard
Acoustic deterrents
Transponders and communications systems
Other: Scientific instruments, minesweeping equipment, acoustic cameras
See Ainslie (2010) for typical source levels and frequency ranges

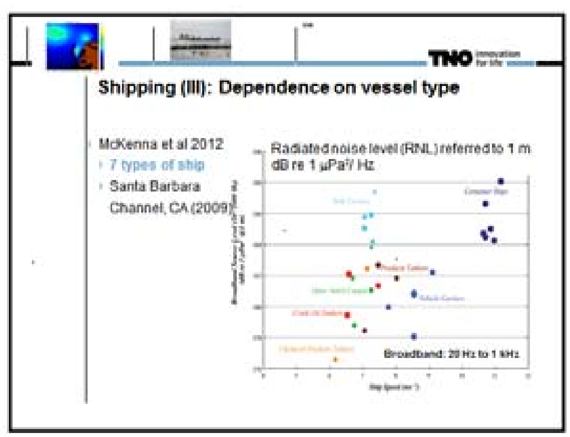

TNO innovation for life
Sources of underwater noise
Increasing concern about impact of underwat
Explosions
Offshore construction (dredging, pile driving)
Seismic survey (air guns)
Shipping
Sonar
Acoustic deterrents
Communications systems
Offshore machinery/installations
See Ainslie (2010) for typical source levels and frequency ranges

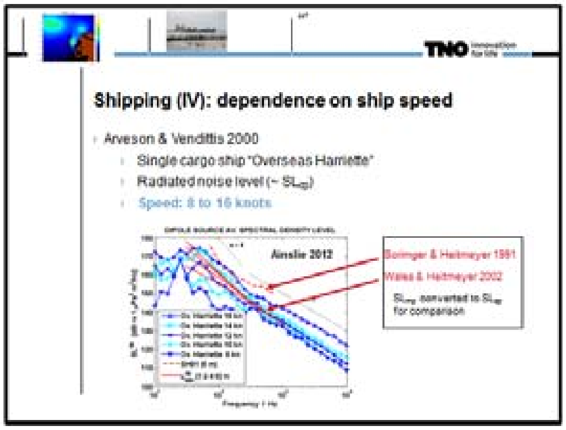

TNO innovation for life
Sources of underwater noise
Increasing concern about impact of underwater sound:
Explosions
Offshore construction (dredging, pile driving): James Reyff
Seismic survey (air guns): Michael Jenkerson
Shipping
Sonar
Acoustic deterrents
Communications systems
Offshore machinery/installations (wind turbines): Jeremy Nedwell


TNO innovation for life
Dutch North Sea (Exclusive Economic Zone)
Area in 1000 km²
NL EEZ: 57
North sea total: 750
USA EEZ: 11,300
All oceans: 362,000

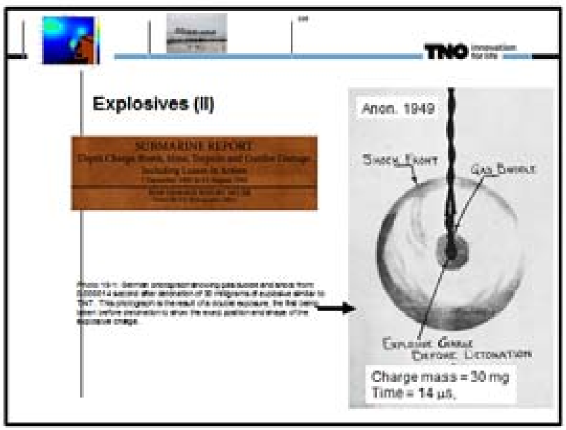

TNO innovation for life
Shipping (I)
Shipping in Dutch N Sea:
~ 340 ships
57,000 km²
~ 6 ships per 1000 km²
Global shipping:
~ 80,000 ships
360,000,000 km²
~ 0.2 ships per 1000 km²
VESSEL TRAFFIC ON THE NORTH SEA
Ainslie et al 2009
Hildebrand 2009

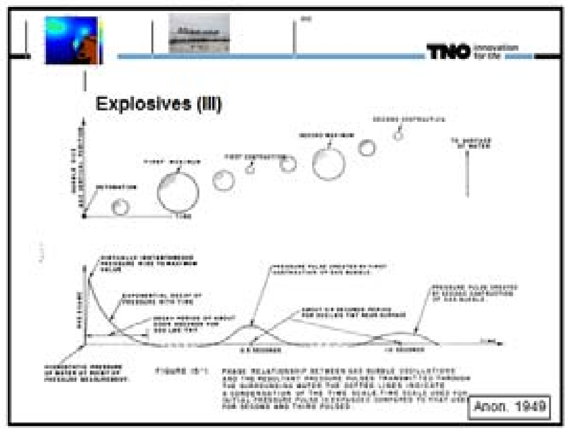

TNO innovation for life
Shipping (II)
Wales & Heitmeyer 2002
272 ships (Med. + E. Atlantic)
Speed: cruising
1986-1992
Frequency (Hz)
Monopole source level (spectral density):
$SL_{avg} = 230 - 35.94 \log_{10} f + 9.17 \log_{10}\left(1 + \frac{f^2}{340^2}\right)$ dB re 1 μPa²m²/Hz
Depends only on frequency f (hertz)
No correlation identified with vessel type or speed

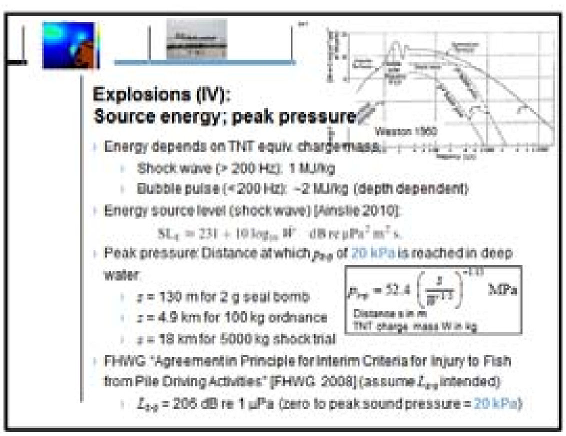

TNO innovation for life
Shipping (III): Dependence on vessel type
McKenna et al 2012
7 types of ship
Santa Barbara Channel, CA (2009)
Radiated noise level (RNL) referred to 1 m
dB re 1 μPa²/ Hz
Broadband: 20 Hz to 1 kHz

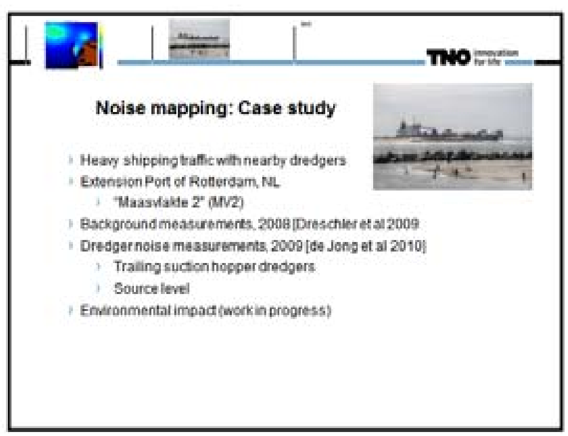

TNO innovation for life
Shipping (IV): dependence on ship speed
Arveson & Vendittis 2000
Single cargo ship "Overseas Harriette"
Radiated noise level (~ SL)
Speed: 8 to 16 knots
Ainslie 2012
Borlinger & Heitmeyer 1991
Wales & Heitmeyer 2002
SL converted to SL for comparison

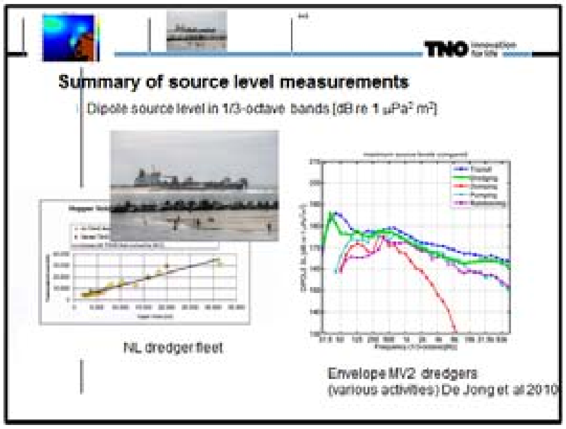

TNO innovation for life
Explosions (I)
Dutch North Sea:
Disposal WW2 ordnance: ~10 GJ/y [Ainslie et al 2009] (shock wave)
Estimated order of magnitude requirement for total North Sea
~ 300,000 tonnes ordnance (300,000 gigajoules)
requires 100 GJ/y for 3,000 years
Beaufort's Dyke (Irish Sea)
~ 1,00,000 tonnes ordnance (1,000,000 gigajoules)
requires 100 GJ/y for 10,000 years
Global:
Ship shock trials: 3300 GJ/y [Hildebrand 2004]


TNO innovation for life
Explosives (II)
SUBMARINE REPORT
Anon. 1949
Shock Front
Gas Bubble
Explosive Charge Before Detonation
Charge mass = 30 mg
Time = 14 µs.

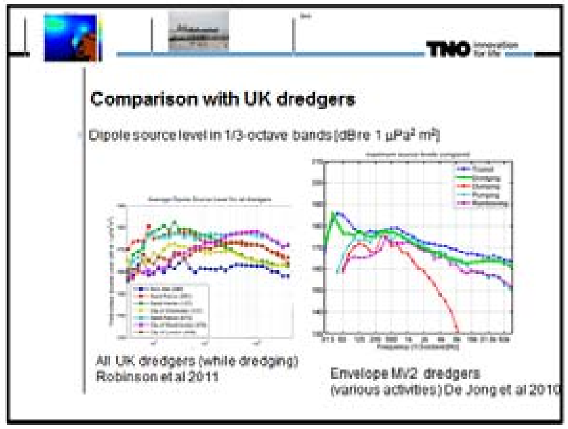

TNO innovation for life
Explosives (III)
Anon. 1949


Explosions (IV):
Source energy; peak pressure
Weston 1960
Energy depends on TNT equiv. charge mass
Shock wave (> 200 Hz): 1 MJ/kg
Bubble pulse (< 200 Hz): ~2 MJ/kg (depth dependent)
Energy source level (shock wave) [Ainslie 2010]:
$SL_E = 231 + 10\log_{10} W$ dB re µPa² m² s.
Peak pressure: Distance at which $p_{0\text{-}p}$ of 20 kPa is reached in deep water:
s = 130 m for 2 g seal bomb
s = 4.9 km for 100 kg ordnance
s = 18 km for 5000 kg shock trial
$p_{0\text{-}p} = 52.4 \left(\frac{s}{W^{1/3}}\right)^{-1.13}$ MPa
Distance s in m
TNT charge mass W in kg
FHWG "Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities" [FHWG 2008] (assume $L_{z\text{-}p}$ intended)
$L_{z\text{-}p}$ = 206 dB re 1 µPa (zero to peak sound pressure = 20 kPa)

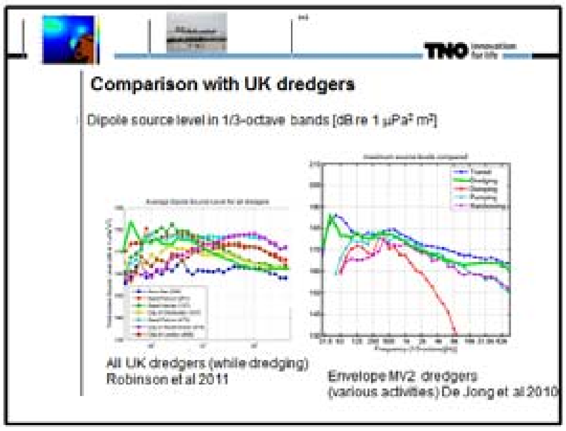

TNO innovation for life
Noise mapping: Case study
Heavy shipping traffic with nearby dredgers
Extension Port of Rotterdam, NL
"Maasvlakte 2" (MV2)
Background measurements, 2008 [Dreschler et al 2009
Dredger noise measurements, 2009 [de Jong et al 2010]
Trailing suction hopper dredgers
Source level
Environmental impact (work in progress)



Summary of source level measurements
Dipole source level in 1/3-octave bands [dB re 1 μPa² m²]
NL dredger fleet
Envelope MV2 dredgers
(various activities) De Jong et al 2010



Comparison with UK dredgers
Dipole source level in 1/3-octave bands [dB re 1 μPa² m²]
All UK dredgers (while dredging)
Robinson et al 2011
Envelope MV2 dredgers
(various activities) De Jong et al 2010



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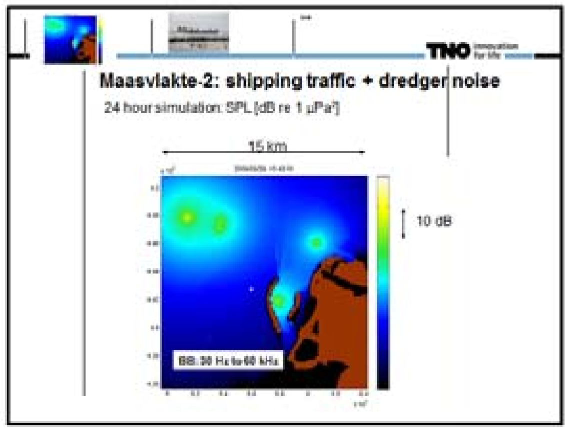
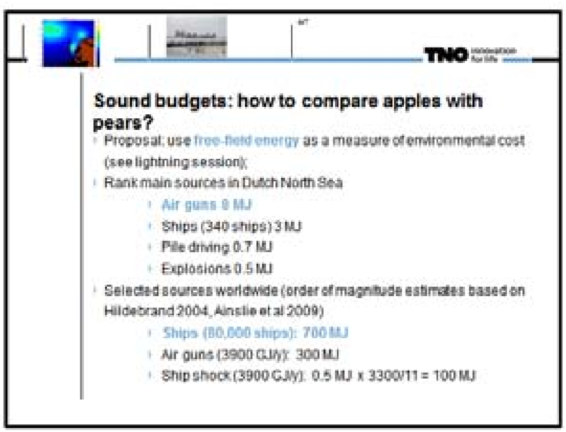
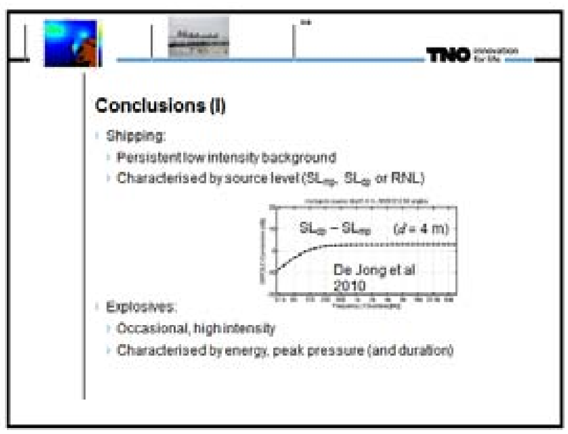


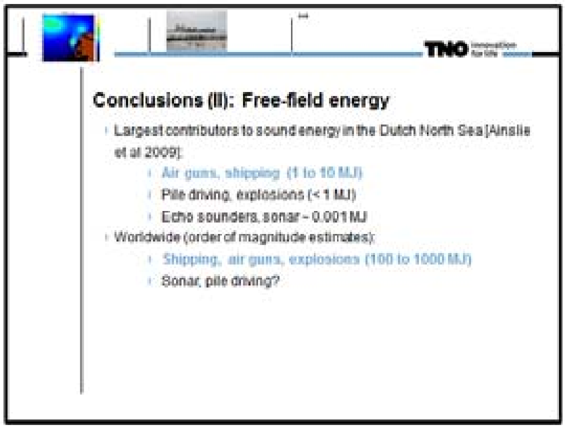
Maasvlakte-2: shipping traffic + dredger noise
24 hour simulation: SPL [dB re 1 μPa²]
15 km
10 dB
BB: 30 Hz to 60 kHz

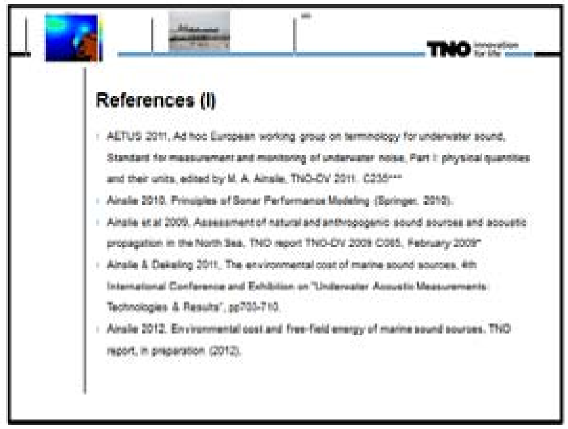


Sound budgets: how to compare apples with pears?
Proposal: use free-field energy as a measure of environmental cost (see lightning session);
Rank main sources in Dutch North Sea
Air guns 8 MJ
Ships (340 ships) 3 MJ
Pile driving 0.7 MJ
Explosions 0.5 MJ
Selected sources worldwide (order of magnitude estimates based on Hildebrand 2004, Ainslie et al 2009)
Ships (80,000 ships): 700 MJ
Air guns (3900 GJ/y): 300 MJ
Ship shock (3900 GJ/y): 0.5 MJ x 3300/11 = 100 MJ



Conclusions (I)
Shipping:
Persistent low intensity background
Characterised by source level (SLmp, SLdp or RNL)
SLdp – SLmp (d = 4 m)
De Jong et al 2010
Explosives:
Occasional, high intensity
Characterised by energy, peak pressure (and duration)


TNO innovation for life
Conclusions (II): Free-field energy
Largest contributors to sound energy in the Dutch North Sea [Ainslie et al 2009]:
Air guns, shipping (1 to 10 MJ)
Pile driving, explosions (< 1 MJ)
Echo sounders, sonar ~ 0.001 MJ
Worldwide (order of magnitude estimates):
Shipping, air guns, explosions (100 to 1000 MJ)
Sonar, pile driving?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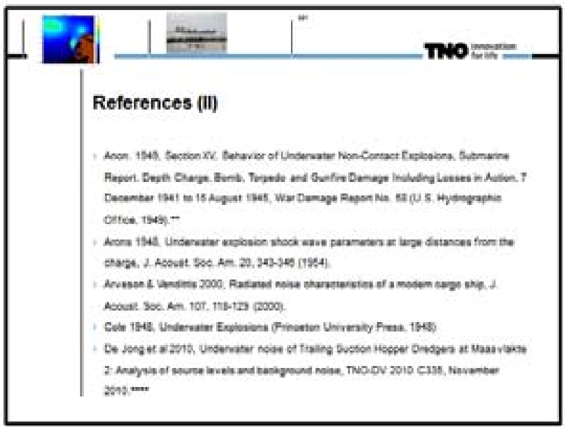
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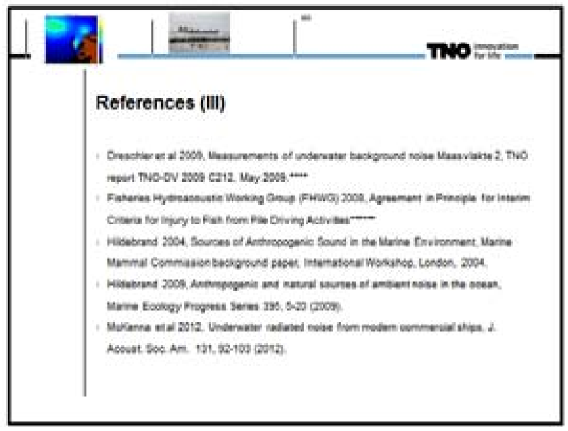
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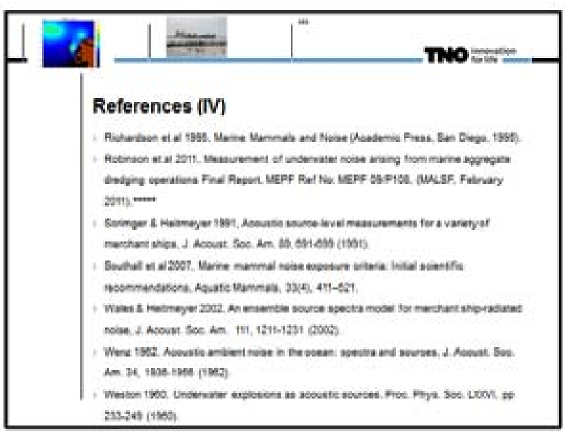
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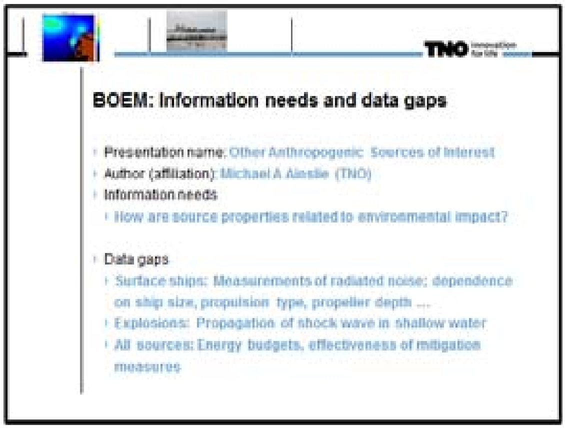
www addresses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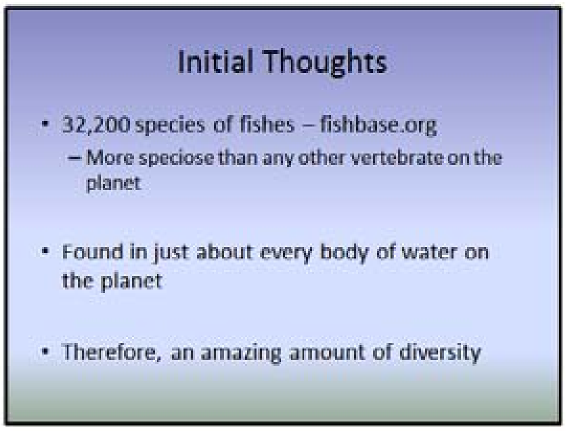
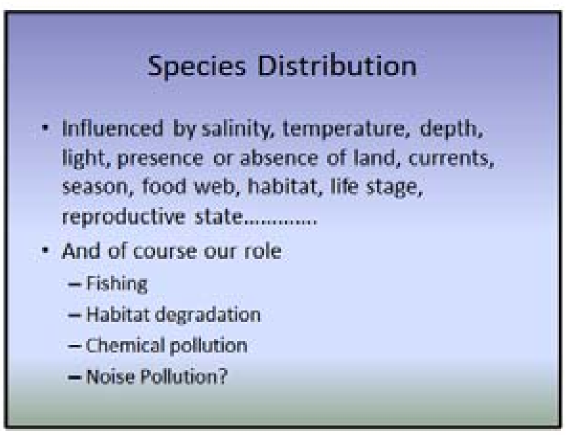
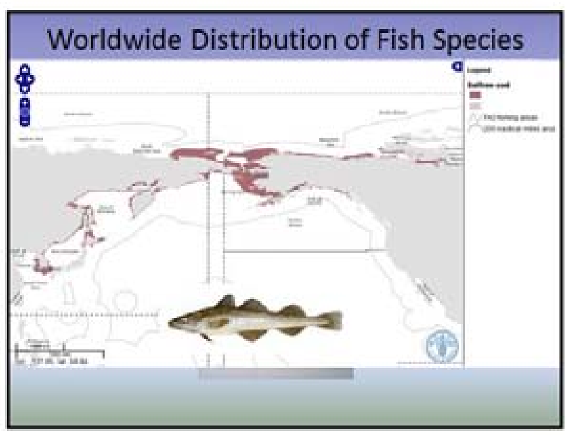
BOEM: Information needs and data gaps
Presentation name: Other Anthropogenic Sources of Interest
Author (affiliation): Michael A Ainslie (TNO)
Information needs
How are source properties related to environmental impact?
Data gaps
Surface ships: Measurements of radiated noise; dependence on ship size, propulsion type, propeller depth ....
Explosions: Propagation of shock wave in shallow water
All sources: Energy budgets, effectiveness of mitigation measures


Diversity in Fishes
Brandon M. Casper
University of Maryland

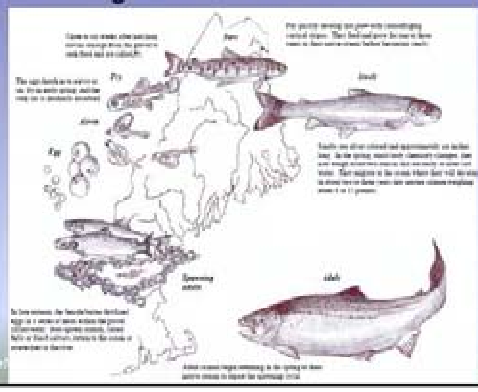

Initial Thoughts
• 32,200 species of fishes – fishbase.org
– More speciose than any other vertebrate on the planet
• Found in just about every body of water on the planet
• Therefore, an amazing amount of diversity


Goals for this Talk
• Acknowledge this diversity, but try to promote categories that fishes can be placed in to allow us to make some generalized predictions of noise exposure responses
• Briefly present several ichthyological topics when considering noise exposure in order to promote further discussion and ideas


Species Distribution
• Influenced by salinity, temperature, depth, light, presence or absence of land, currents, season, food web, habitat, life stage, reproductive state............
• And of course our role
– Fishing
– Habitat degradation
– Chemical pollution
– Noise Pollution?


Worldwide Distribution of Fish Species

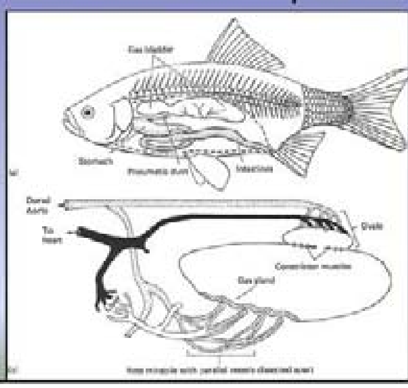
Life Stage Affects Distribution



Anatomical Feature Worth Considering

- Skeleton- cartilage versus bone
  - Chondrichthyans vs. teleosts
  - Cartilage higher elasticity, bone is stronger
- Could extra fat or muscle provide a cushioning from impact--- or be more damaging?
- Reproductive maturity could also have an effect
  - Larger, developed ovaries or testes could also be more susceptible to damage
- Size of the fish---Whale shark vs. anchovy?
  - Life stage sizes

Swim Bladder—A Key Variable



Swim Bladder Size

Physiological Responses

- Extreme differences in response to noise exposure likely dependent on the presence or absence of swim bladder
- Other physiological responses could be conserved throughout most fishes
  - Rapid change in state of gasses in blood, tissues, etc..
  - Production of stress hormones or other stress responses
- See Halvorsen talk on Injury and Effects on Fish Physiology

Hearing Abilities of Fishes

- High diversity and species specific
- Fairly easy to divide fish into different categories based on a continuum of ear adaptations
  - Though it should be acknowledged that only a small fraction of fishes have had their hearing examined
- Important when considering potential masking of auditory scene as well as detection distance of a noise source
  - How different is the auditory scene between different species?
  - Between different life stages?
- See Mann and Fay talks on fish hearing, communication, and auditory scene

Hearing Thresholds for Select Species

160

Table 1: Groupings of Fish by Sensitivity to Seismic Sound and Ecological Association

Fish Categories Arranged by Sensitivity to Sound		Large Pelagic	Small Pelagic	Demersal	Reef	Shallow/Estuary	In River
	gas bladder connected to ear		Herring Sprat Shad	Weakfish Deep-sea cod	Squirrel-fish	Catfish Carp Goldfish	Dace Minnow
	gas bladder close to ear			Cod Haddock Saithe	Red Snapper		
	gas bladder distant from ear	Dorado	Horse Mackerel	Spot	Wrasse	Sand smelt	Salmon Eel
	no gas bladder	Sharks	Mackerel	Plaice Sole		Flounder	
	fish eggs and larvae	Dorado larvae	Herring Larvae	Cod larvae	Red Snapper larvae	Catfish larvae	Salmon eggs

100 1000

Frequency in Hz

Communication

- Many species use sound for communication
  - Sounds typical occur during spawning or agonistic encounters
  - Species specific call rates, frequencies
  - Species call at different times of the year
  - Different methods for producing sounds
  - We likely have only begun to understand the extent that acoustic communication exists among fishes
- Anthropogenic noise could be masking these important sounds

Diversity in Fishes
Brandon M. Casper
University of Maryland

- Can we reliably make broad generalizations about effects of sound on such a diverse group of species?
- Can we safely predict injury response based on the type as well as presence or absence of the swim bladder?
- What other anatomical features may be useful when predicting effects of noise exposure?

Diversity in Fishes
Brandon M. Casper
University of Maryland

- Are physiological effects of noise exposure not caused by swim bladder motions consistent in all fishes?
- Can we correlate a fish's hearing category and/or ability to produce sounds for communication with its auditory scene?
- If anthropogenic noise is masking a fish's auditory scene, how important is masking in terms of the overall fitness of the fish?

Low frequency Controlled Exposure Experiments on cephalopods

BOEM Workshop 2012, San Diego, Effects of Noise on Fish, Fisheries and Invertebrates

Antecedents:

- Between September and October 2001 and in October 2003 the natural rhythm of annual records of giant squids (*Architeuthis dux*) stranded in the area of the West coast of Asturias (Spain) experienced a significant increase (Guerra et al., 2004a, 2004b; 2011)

- These events were coincident with the proximity of vessels using compressed air guns for geophysical prospection, producing sound waves of low frequency (below 100 Hz) and high intensity (200 dB re 1 µPa at 1m)

- None of the lesions could be related to known causes of death, however, the presence of geophysical prospecting vessels suggested that the death of these animals could be related to effects produced by noise exposure (Guerra et al., 2004b)

- The concern on the effects of climate change and of increasing ambient noise levels on cephalopods sensory systems combined with a lack of information on the sensitivity of the statocysts when exposed to noise, lead to a series of Controlled Exposure Experiments on Mediterranean *Sepia officinalis*, *Octopus vulgaris*, *Loligo vulgaris* and *Illex coindeti*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Capture and Maintenance :
- Cephalopod specimens were caught from the Catalan Coast (NW Mediterranean Sea) over a period of 2 years, between February 2008 and August 2010, and kept in a closed system of recirculating natural seawater (at 18-20ºC, salinity 35‰ and natural oxygen pressure) consisting of 2 mechanically filtered fiberglass reinforced plastic tanks of 2000L capacity that were connected to each other.


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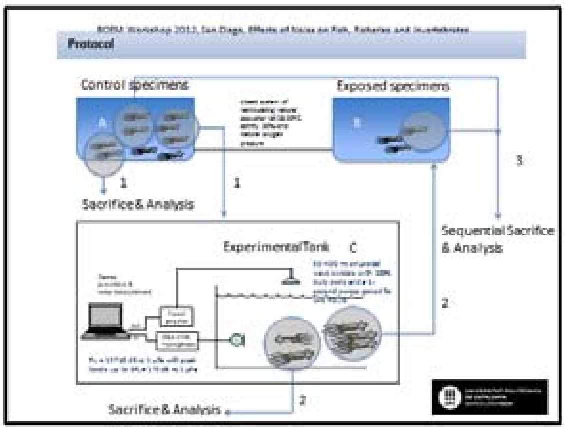
Cephalopod specimens :
- A first set of 30 individuals of Sepia officinalis were caught and kept for several weeks to observe and analyse their adaptation to captivity. These animals were swimming, eating, mating, laying eggs and behaving normally over the entire observation period.
- The analysis (LM, SEM & TEM) of their inner sensory statocyst epithelium was used as a first control and did not reveal any lesion.
- 164 adult and young specimens from Sepia officinalis, 10 from Octopus vulgaris, 9 from Loligo vulgaris and 4 from Illex coindetii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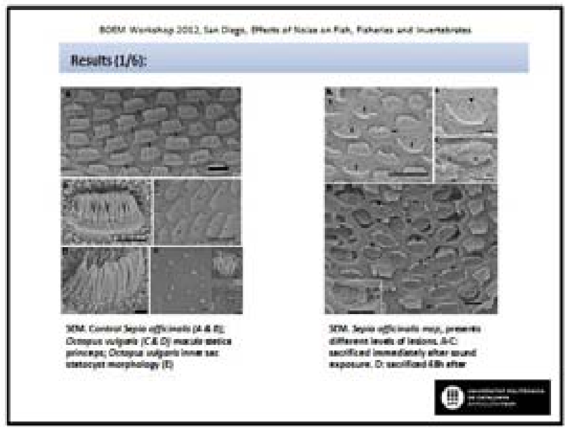
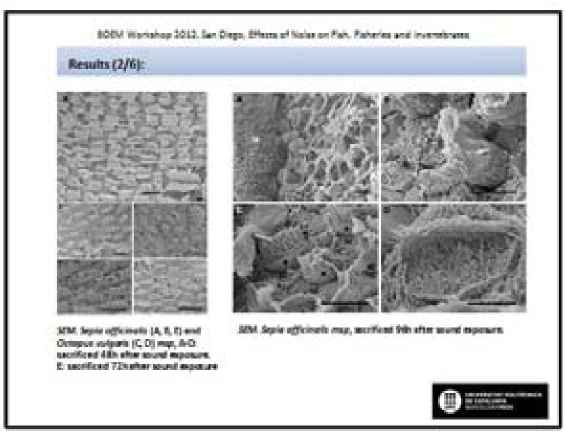
Protocol
Control specimens
Exposed specimens
A
B
1
1
3
Sacrifice & Analysis
Experimental Tank
C
Sequential Sacrifice & Analysis
2
2
Sacrifice & Analysis


BOEM Workshop 2012, San Diego, Effects of Noise on Fish, Fisheries and Invertebrates
Results (1/6):
SEM. Control Sepia officinalis (A & B); Octopus vulgaris (C & D) macula statica princeps; Octopus vulgaris inner sac statocyst morphology (E)
SEM. Sepia officinalis msp, presents different levels of lesions. A-C: sacrificed immediately after sound exposure. D: sacrificed 48h after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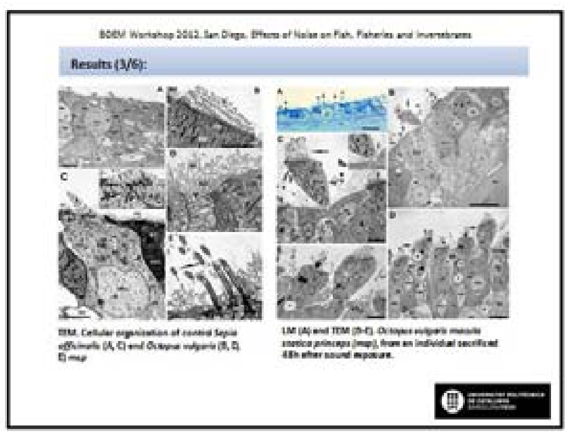
Results (2/6):
SEM. Sepia officinalis (A, B, E) and Octopus vulgaris (C, D) msp, A-D: sacrificed 48h after sound exposure. E: sacrificed 72h after sound exposure
SEM. Sepia officinalis msp, sacrificed 96h after sound exposure.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Results (3/6):
TEM. Cellular organization of control Sepia officinalis (A, C) and Octopus vulgaris (B, D, E) msp
LM (A) and TEM (B-E). Octopus vulgaris macula statica princeps (msp), from an individual sacrificed 48h after sound exposure.

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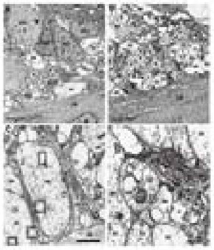
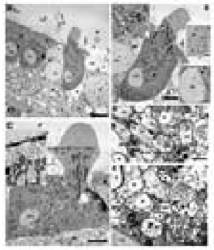
Results (4/6):



TEM. General nervous organization of *Sepia officinalis macula statica princeps* (A, B) and afferent and efferent innervations of the *macula* epithelium in the statocyst of *Octopus vulgaris* (C, D). Control animals.



TEM. *Octopus vulgaris macula statica princeps (msp), from an individual sacrificed 48h after* sound exposure

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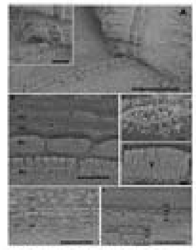
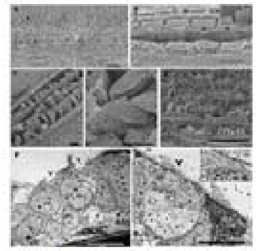
Results (5/6):



SEM. *Sepia officinalis* (A-D) and *Octopus vulgaris* (E, F) crista-cupula system. Control animals.



SEM (A-E) and TEM (F, G). *Sepia officinalis* crista. A, B, insert in D: sacrificed immediately after sound exposure. C-E: sacrificed 96h after sound exposure. F, G: sacrificed 24h after sound exposure. Insert in G: sacrificed 48h after sound exposure

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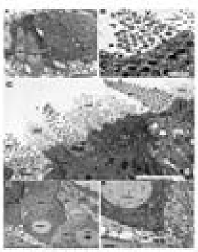
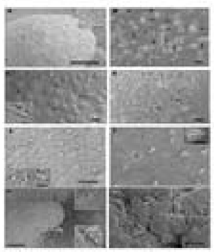
Results (6/6):



TEM. *Octopus vulgaris* crista general morphology (A-C) and nervous organization (D, E). Control animals



SEM. *Sepia officinalis*. Lining epithelium of animals affected by sound (A-F) and control specimens (G, H)

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Conclusion, Future Research and Perspective:

These results showed:
- lesions new to cephalopod pathology
- exposure to sounds may cause serious lesions on the statocyst sensory epitheliums.
- these lesions are consistent with a massive acoustic trauma found in terrestrial species.

Further investigation is needed to:
- determine threshold levels and to quantify the lesions in the statocysts;
- explain the mechanism onset of these lesions, in particular to determine if the laboratory conditions can be reproduced in open environments;
- definitively understand if these animals are more sensitive to particle motion or acoustic pressure, or to a combination of both.

Future electrophysiological experiments coupled with post-mortem imaging techniques are needed to determine the tolerance to noise thresholds of cephalopods.

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Low frequency Controlled Exposure Experiments on Cephalopods

Corresponding author:

Michel André
Technical University of Catalonia, BarcelonaTech, Spain
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Needs to:

- **determine sound characteristics, threshold levels and quantify the lesions in the statocysts under controlled exposure experiments;**
- **explain the mechanism onset of these lesions, in particular to determine if the laboratory conditions can be reproduced in open environments;**
- **look for effects on larvae and possible recovery processes**
- **definitively understand if these animals are more sensitive to particle motion or acoustic pressure, or to a combination of both.**

Injury and Effects on Fish Physiology

Michele B. Halvorsen

Michele.halvorsen@pnnl.gov

Bureau of Ocean Energy Management Workshop
San Diego, CA March 2012

Pacific Northwest National Laboratory
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Underwater Noise - Components

- Sound is energy that can do work – thus, it can cause damage
  - Frequency
  - Intensity
  - Spectrum
- Two components of any sound wave
  - Pressure
  - Particle motion
- Near field (pressure & particle motion)
- Far field (mostly pressure, but some motion)

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Underwater Noise Effects

- Energy development in marine environments
  - Installation
  - Decommissioning
  - Exploring
- Concern for aquatic animals
  - Behavioral responses
  - Onset of effects
    - Barotrauma
    - Auditory - TTS
- Pile driving exposures in the laboratory
- Blasting exposures
- Tidal turbine exposures

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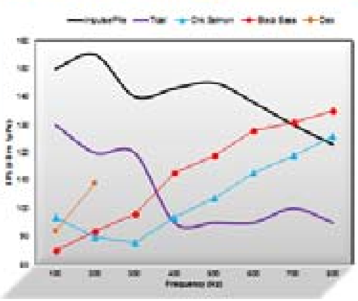
Underwater Noise Effects - Auditory

Auditory

- Changes in hearing threshold
- Hair cell damage



Salmon: Halvorsen et al., 2009; Bass: Holt et al., 2010; Dab: Chapman & Sand 1973; Karl von Frisch-ear

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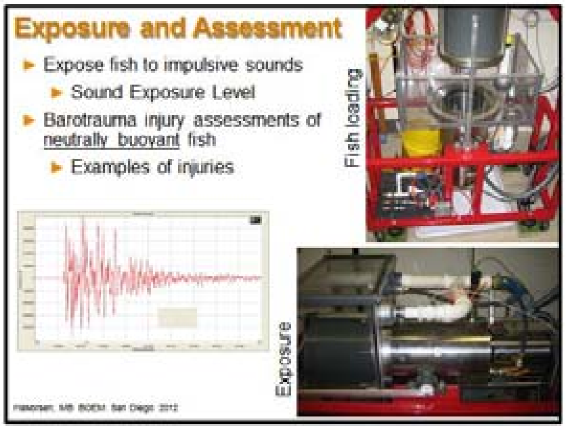
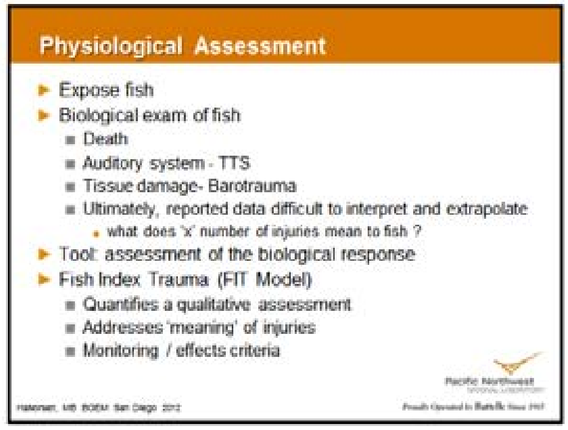
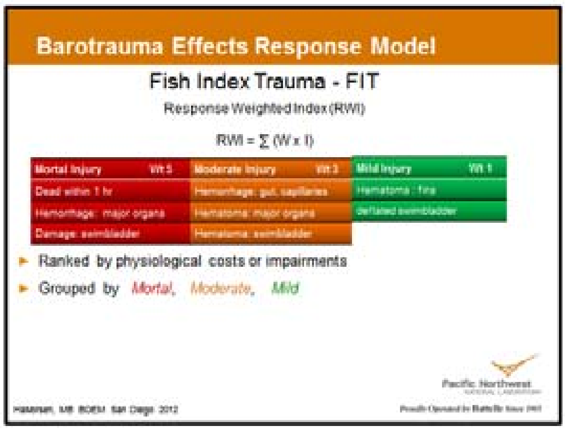
Underwater Noise Effects - Barotrauma

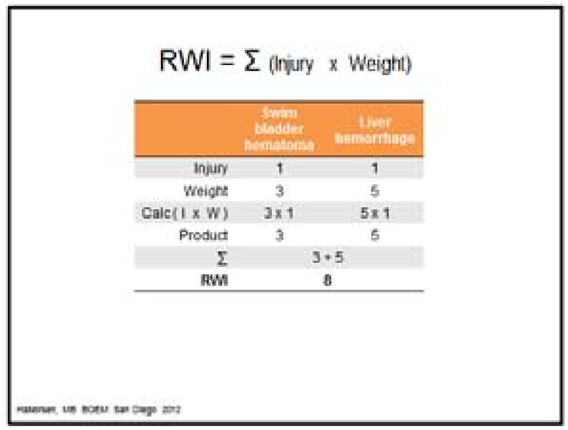
- Contraction and expansion of free gas in body
- Change in state of gas from soluble to free-form
- Swim bladder – (buoyancy state, hearing)
  - Rupture
  - Damage surrounding tissues
- Natural blood-gases
  - Solubility changes
  - Gas comes out of solution
    - Bubbles form in blood and tissues
    - Damage to tissues, vessels, organs
- Equilibration state is very important
  - Neutrally buoyant fish
  - Tissue-gas equilibration with surrounding water
  - Physiological state of fish at exposure is critical



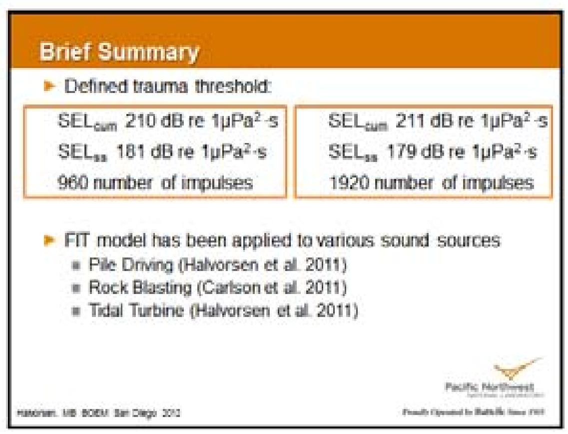




Mortal Injury Wt 5	Moderate Injury Wt 3	Mild Injury Wt 1
Dead within 1 hr	Hemorrhage: gut, capillaries	Hematoma : fins
Hemorrhage: major organs	Hematoma: major organs	deflated swimbladder
Damage: swimbladder	Hematoma: swimbladder	



	Swim bladder hematoma	Liver hemorrhage
Injury	1	1
Weight	3	5
Calc(I x W)	3 x 1	5 x 1
Product	3	5
Σ	3 + 5	
RWI	8	



Injury and Effects on Fish Physiology
Michele B. Halvorsen Battelle, Pacific Northwest National Laboratory

Data Gaps:

- 2 injury pathways; Hearing and Barotrauma
- Define a level of detrimental TTS, probably specific to hearing sensitivity group
- Combining TTS with Barotrauma? – Barotrauma may be more sensitive
- Further development of the FIT Model
- Performance testing on fish after ensonification
  - TTS and Barotrauma

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Injury and Effects on Fish Physiology
Michele B. Halvorsen Battelle, Pacific Northwest National Laboratory

Needs/ Gaps

- Effects of depth on fish response (depth might be protective)
- Extrapolation of biological responses to other signals
- Testing various size classes within a species
- Different groups: Physoclistous, physostomous, no swim bladder
- Understand process of injury accrual (do silent breaks = "restart" for accumulation?)
- Exploration of assays to detect the presence of specific proteins (biomarkers) in blood
- Appropriate metric or group of metrics
- Received sound levels: pressure and particle motion

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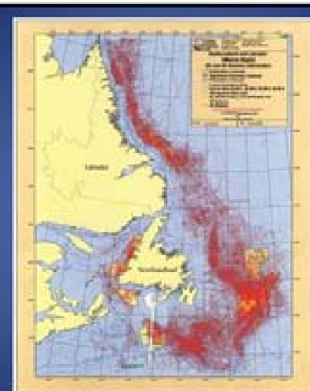
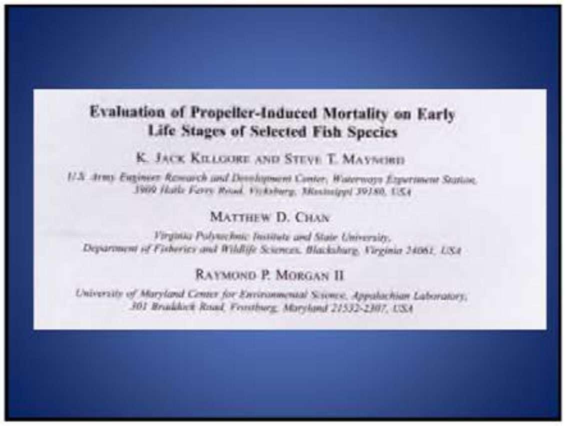
A FEW WORDS ABOUT SOUND AND INVERTEBRATE INJURY

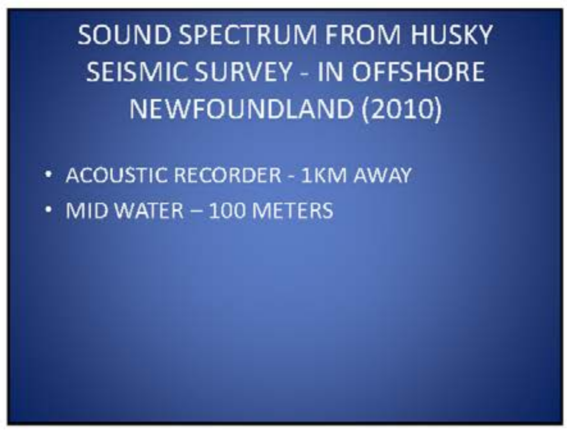
Dr. Jerry Payne
Fisheries and Oceans
Canada

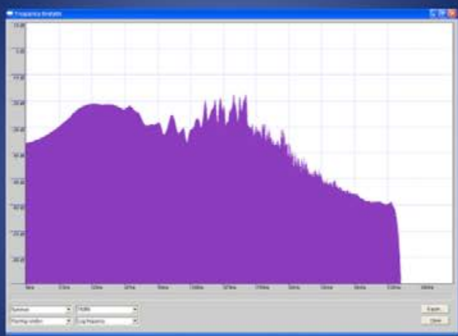



Evaluation of Propeller-Induced Mortality on Early
Life Stages of Selected Fish Species
K. JACK KILLGORE AND STEVE T. MAYNORD
U.S. Army Engineer Research and Development Center, Waterways Experiment Station,
3909 Halls Ferry Road, Vicksburg, Mississippi 39180, USA
MATTHEW D. CHAN
Virginia Polytechnic Institute and State University,
Department of Fisheries and Wildlife Sciences, Blacksburg, Virginia 24061, USA
RAYMOND P. MORGAN II
University of Maryland Center for Environmental Science, Appalachian Laboratory,
301 Braddock Road, Frostburg, Maryland 21532-2307, USA


Areas of Interest
• Biochemical Injury
• Cellular Injury
• Organ Injury
• Reproductive Injury
• Behavioral Injury


HIGH LEVEL EXPOSURES
The airgun was deployed at 2m depth from a fishing vessel with caged animals positioned 2m below the gun. Levels received were ~227dB, peak-to-peak.


SOUND SPECTRUM FROM HUSKY SEISMIC SURVEY - IN OFFSHORE NEWFOUNDLAND (2010)
• ACOUSTIC RECORDER - 1KM AWAY
• MID WATER – 100 METERS



Instant Mortality is Not a Concern with Seismic – It's the Question of Important Sub-lethal Effects.

Codfish
Crab
Lobster
Smelt
Jellyfish
Shrimp
Cunners
Capelin

UNDERSTANDING ENVIRONMENTAL STRESSORS

- "THE APPARENT PARADOX IS THAT IT IS THE HARD TO DETECT SUB-LETHAL EFFECTS WHICH ARE THE CHIEF CAUSE OF CONCERN."
- OR AS DICK CHENEY MIGHT SAY "IT'S THE UNKNOWN UNKNOWNS."

Animals were maintained in aquaria at DFO for long term observation and sampling.

EFFECTS INVESTIGATED

- Lobster survival
- Turnover rates
- Leg loss
- Blood (hemolymph) proteins
- Blood enzymes
- Blood calcium
- Food consumption
- Tissue damage

EFFECTS WERE OBSERVED ON

- Blood proteins
- Blood enzymes
- Blood calcium
- Food consumption
- Hepatopancreas (liver)

- RESULTS DEMONSTRATED THE VALUE OF STUDIES ON SUBLETHAL EFFECTS
- WITH THE UNDERSTANDING THAT SERIOUS INJURY IS NOT NECESSARILY IMPLIED
- A SLIGHT CHANGE IN AN ENZYME OR HORMOMAL RESPONSE WOULD NOT BE ACCORDED THE SAME STATUS AS HISTOPATHOLOGY
- WEIGHT OF EVIDENCE APPROACH REQUIRED

BIOMARKERS AND PROVISIONAL ADVICE FOR HIGHER ORDER EFFECTS

- LOBSTER MORBIDITY
- EGG DEVELOPMENT IN SNOWCRAB
- IF ANY SUCH INJURY HAD BEEN FOUND, ADVICE TO REGULATORS WOULD HAVE BEEN "COLORED".

- LIKEWISE, BIOMARKER STUDIES ON FISH HAVE BEEN IMPORTANT FOR ADVICE
- E.G. STUDY BY SONG, MAN, COTT, HANNA, POPPER (SEISMIC IN A CANADIAN RIVER).
- HASTINGS (SEISMIC OFF AUSTRALIA)

Snow Crabs Seismic

CAN ANIMALS HABITUATE TO SOME EXTENT TO THE POTENTIAL INJURIOUS EFFECT OF NOISE

Increased resistance to free radical damage induced by low-level sound conditioning.

Arthur N. Popper · Michael Salmon
Kenneth W. Horch

Acoustic detection and communication by decapod crustaceans

Accepted: 8 January 2001 / Published online: 22 February 2001
© Springer-Verlag 2001

BIG ISSUE: CRUSTACEAN BEHAVIOR AND FISHERIES

- NO OVERT SIGNS OF SCARING IN EITHER SNOWCRAB, LOBSTER OR SHRIMP

GUIDANCE FROM OLD TESTAMENT

"ASK THE FISH OF THE SEA AND THEY WILL DECLARE UNTO THEE"

BOOK OF JOB 12:8

HOW GOOD WILL THEIR ADVICE BE?

SCARING RADIUS FOR COMMERCIAL CRUSTACEANS: IF SCARED

- DIFFICULT TO ANSWER IN ANY QUANTITATIVE SENSE
- FIRST ROUGH CUT: STUDY ON CORRELATION BETWEEN SEISMIC TRACKS AND CATCH

Effect of Seismic Energy on Snow Crab (*Chionoecetes opilio*)

By

LGL LIMITED
environmental research associates

and

Oceans LTD.

For

Environmental Studies Research Fund
444-7th Avenue S.W.
Calgary, AB
T2P 0X8

File No.: CAL-1-00364

7 November 2003
SA694

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FISHERIES RESEARCH

The effect of seismic surveys on catch rates of rock lobsters in western Victoria, Australia

Gregory D. Parry, Anne Gason

News and events > News Archive

New marine noise research to inform offshore wind farm rollout

30 November 2011

A new study of the impact of noise on the behaviour of fish and crustaceans is to inform the development of offshore wind farms around the UK.

The innovative new University of Hull research project uses underwater television, high frequency sonar and playback system to replicate and monitor the effect of any artificial noise in the sea, such as ships, concrete piling strokes or offshore wind turbines.

<Dr Rafael Perez-Dominguez

WHAT ABOUT ZOOPLANKTON?

- MAJOR KNOWLEDGE GAP ALL AROUND
- FOLLOW THE FOOT STEPS OF SUCH AGENCIES AS PARCOM AND ICES IN TOXICITY ASSESSMENTS WHEREBY FOCUS IS ON A FEW REPRESENTATIVE SPECIES, E.G. A COPEPOD IN THE CASE OF AN INVERTEBRATE?
- SCARING OF ZOOPLANKTON ASSEMBLAGES

CALANUS FINMARCHICUS: A KEYSTONE CANDIDATE

- ONE OF THE MOST COMMONLY FOUND SPECIES IN THE NORTH SEA AND NORWEGIAN SEA, AS WELL AS IN ARCTIC AND SUB-ARCTIC WATERS OF THE N.W. ATLANTIC
- PROVIDES FOOD FOR A VARIETY OF MARINE ORGANISMS – FISH, WHALES, SHRIMP
- AMENABLE TO LAB AND FIELD MESOCOSM STUDIES: BEHAVIOR, INJURY

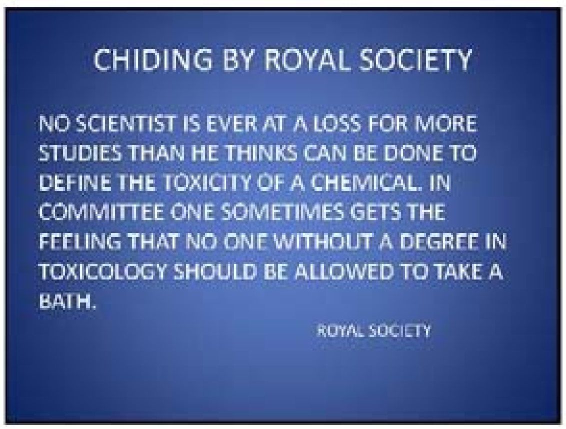
WHAT ABOUT POTENTIAL EFFECTS ON SEDIMENTARY INVERTEBRATE COMMUNITIES

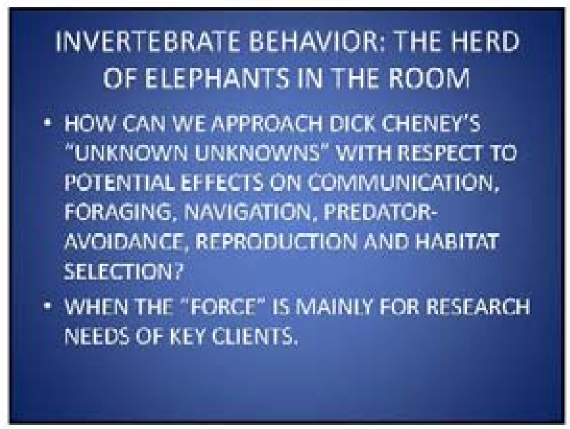
- SEISMIC
- MULTIBEAM - SOUNDERS

SQUID: HIGH PROFILE SPECIES

- THE STUDY NOTING EFFECTS ON EXPOSURE TO SOUND/VIBRATION INDICATES NEED FOR FURTHER INVESTIGATION.
- ALSO RELEVANT FOR CONCERNS ABOUT FIELD OBSERVATIONS ON GIANT SQUID


GROWTH OF AQUACULTURE SHRIMP
• THE STUDY NOTING EFFECTS ON CHRONIC EXPOSURE TO LOW LEVELS OF SOUND/VIBRATION INDICATES NEED FOR FURTHER INVESTIGATION
• SEAHORSE AS SUPPORTING EVIDENCE


CHIDING BY ROYAL SOCIETY
NO SCIENTIST IS EVER AT A LOSS FOR MORE STUDIES THAN HE THINKS CAN BE DONE TO DEFINE THE TOXICITY OF A CHEMICAL. IN COMMITTEE ONE SOMETIMES GETS THE FEELING THAT NO ONE WITHOUT A DEGREE IN TOXICOLOGY SHOULD BE ALLOWED TO TAKE A BATH.
ROYAL SOCIETY


INVERTEBRATE BEHAVIOR: THE HERD OF ELEPHANTS IN THE ROOM
• HOW CAN WE APPROACH DICK CHENEY'S "UNKNOWN UNKNOWNS" WITH RESPECT TO POTENTIAL EFFECTS ON COMMUNICATION, FORAGING, NAVIGATION, PREDATOR-AVOIDANCE, REPRODUCTION AND HABITAT SELECTION?
• WHEN THE "FORCE" IS MAINLY FOR RESEARCH NEEDS OF KEY CLIENTS.


On the attraction of larval fishes to reef sounds


SOUND AND INVERTEBRATE INJURY
DR. JERRY PAYNE
FISHERIES AND OCEANS, CANADA
CONCLUSIONS (1 SLIDE)
RECOMMENDATIONS (2 SLIDES)

CONCLUSIONS

1. The slate is mostly blank with respect to studies on the potential for various sources of sound to effect delayed mortality or sub-lethal injury in invertebrates.
2. The few studies that have been carried out with crustaceans and a cephalopod indicate a potential for sound to elicit sub-lethal biochemical/physiological/histopathological responses.
3. It is important to note that such biomarker responses come in different colors, from the benign to potentially injurious.
4. The information gap on invertebrates makes it all but impossible – in most instances – to pass informed opinion on questions related to potential risks/no risks associated with sounds from seismic, pile-driving, sonar or vessel traffic.

RECOMMENDATIONS

1. Carry out laboratory or small scale mesocosm studies to assess the effects of sound on commercially important invertebrates such as lobster, crab, shrimp, scallop and squid. Parameters for consideration would include behavior and pathology which could involve biochemical, physiological and histopathological endpoints.
2. Although difficult, a special attempt should be made to focus on deriving some dose-response relationships, including under chronic conditions of exposure.
3. Carry out exposures with actual sources of sound or sound tracks, to the extent feasible.

4. Guide agencies and industry on the extent to which field studies could be useful for assessing effects on animal behavior – e.g. the question of seismic and alteration of crustacean catch.
5. Avail of opportunistic field studies to obtain biomarker data e.g. caging of animals in relation to pile driving or seismic programs.
6. Provide information (if only for assurance) on whether zooplankton assemblages might be significantly affected by loud sounds e.g. seismic surveys. Carry out dose-response studies to assess sub-lethal and potentially injurious effects in a keystone zooplankton species such as Calanus.
7. Encourage basic studies to grapple with the difficult issue of subtle but possibly important effects on animal behavior. Priority would likely be regionally driven in relation to specific species and concern.

RECENT LEGAL RULINGS

- Environmentalists failed to establish that there was a probability of irreparable harm to marine mammals – Justice Michael Kelen
- " I am satisfied that the Inuit will suffer irreparable harm if an injunction is not granted" – Justice Sue Cooper

Importance of Sounds for Animals– Sound Production and Sound Detection

David Mann

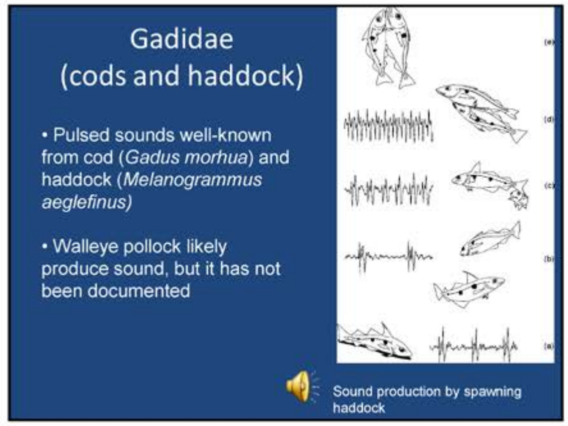
USF UNIVERSITY OF SOUTH FLORIDA COLLEGE OF MARINE SCIENCE

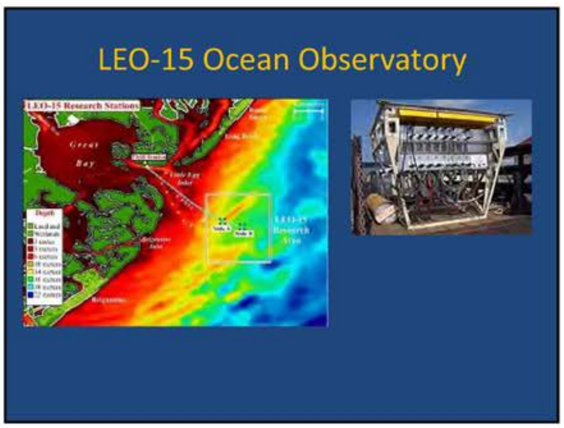
Loggerhead INSTRUMENTS

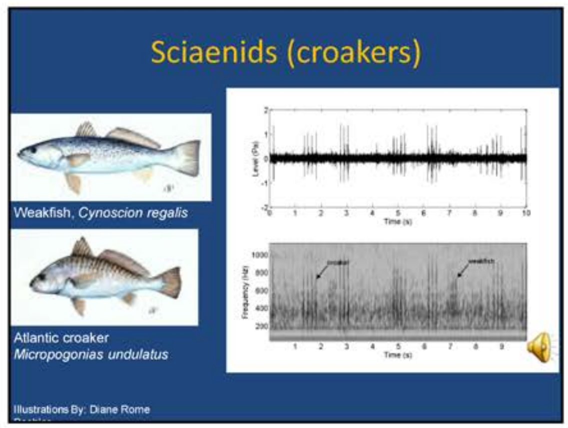
Invertebrate Sound Production

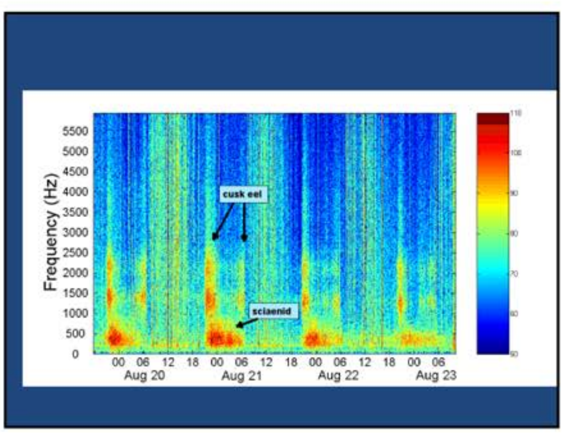
- Snapping shrimp—generate a cavitation bubble to produce very loud, broad-band sound
- Spiny lobster—associated with defense. Not clear it is audible to the lobster.
- No known sounds from squids or octopi

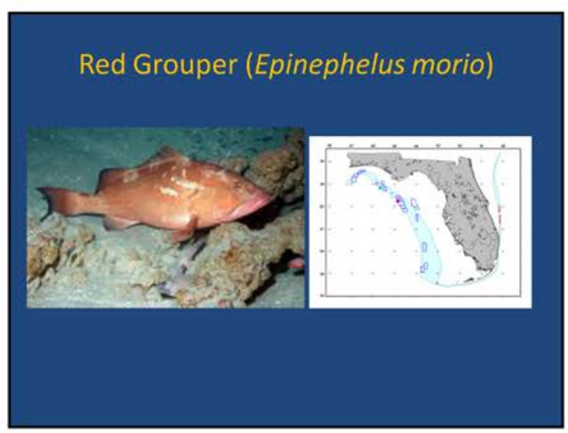

Commercially Important Soniferous Fish Families
• Gadidae (cods)
• Sciaenidae (croakers and drums)
• Serranidae (groupers)


Gadidae (cods and haddock)
• Pulsed sounds well-known from cod (Gadus morhua) and haddock (Melanogrammus aeglefinus)
• Walleye pollock likely produce sound, but it has not been documented
Sound production by spawning haddock

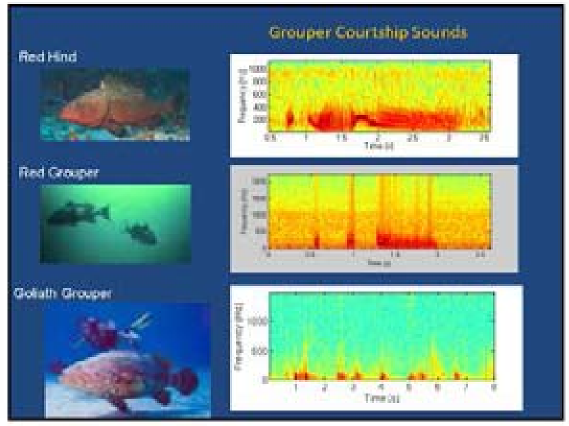

LEO-15 Ocean Observatory
LEO-15 Research Stations

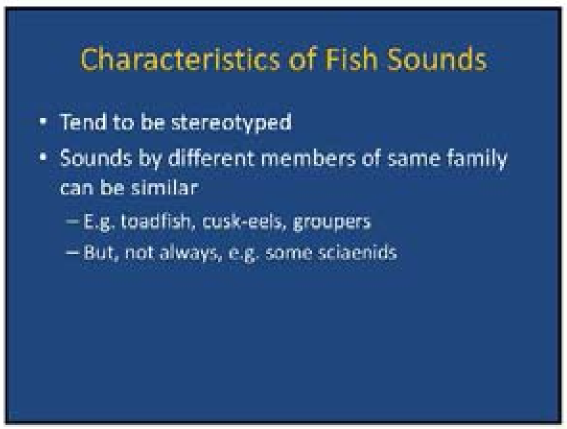

Sciaenids (croakers)
Weakfish, Cynoscion regalis
Atlantic croaker
Micropogonias undulatus
Illustrations By: Diane Rome
Time (s)

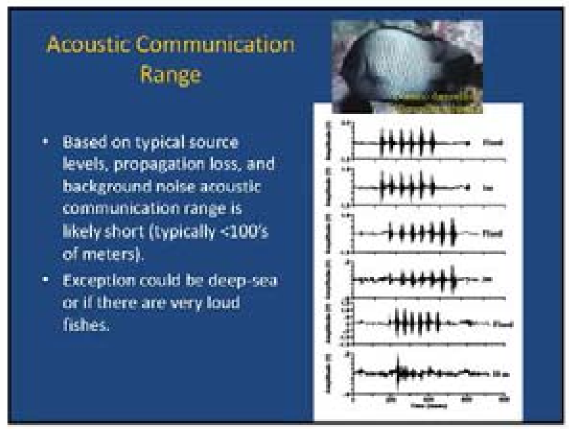

Frequency (Hz)
cusk eel
sciaenid
Aug 20
Aug 21
Aug 22
Aug 23

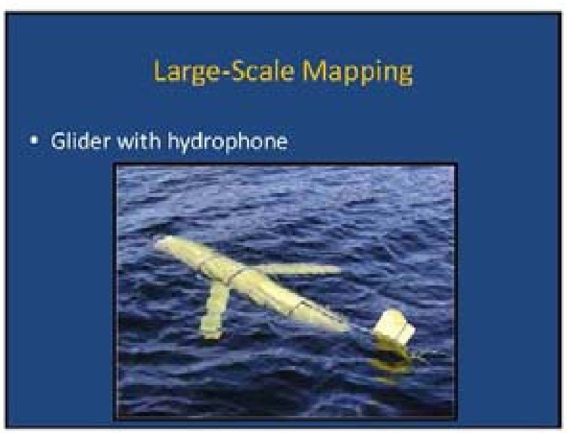

Red Grouper (Epinephelus morio)

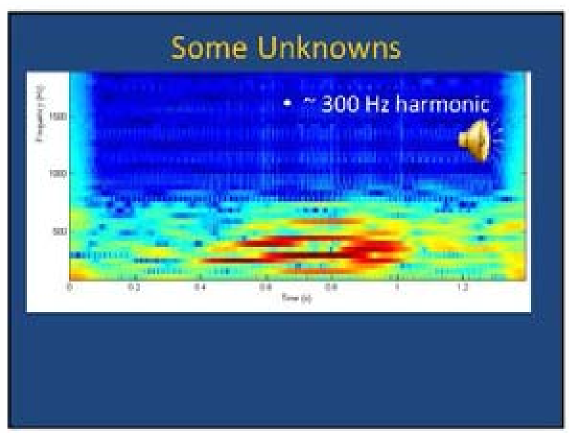

80 m depth

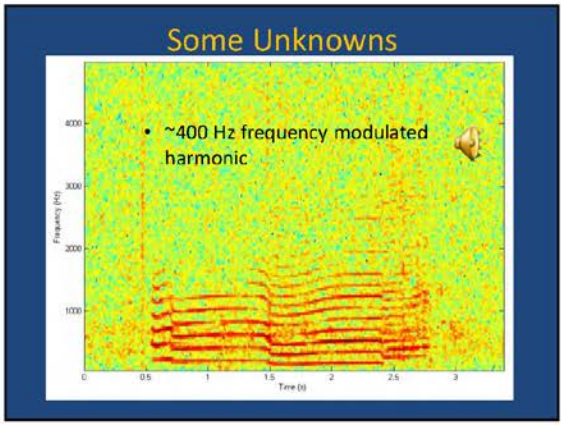

Grouper Courtship Sounds
Red Hind
Red Grouper
Goliath Grouper

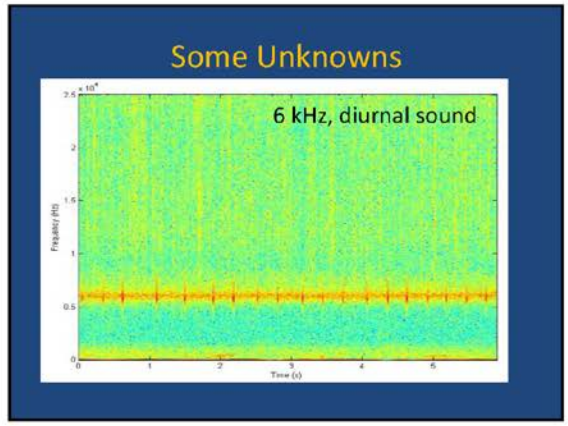

Characteristics of Fish Sounds
• Tend to be stereotyped
• Sounds by different members of same family can be similar
– E.g. toadfish, cusk-eels, groupers
– But, not always, e.g. some sciaenids

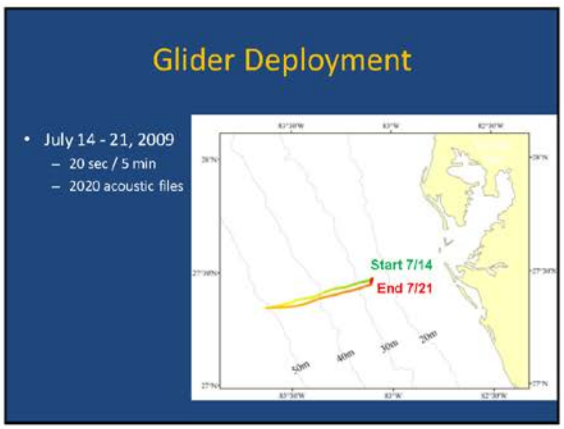

Acoustic Communication Range
• Based on typical source levels, propagation loss, and background noise acoustic communication range is likely short (typically <100's of meters).
• Exception could be deep-sea or if there are very loud fishes.

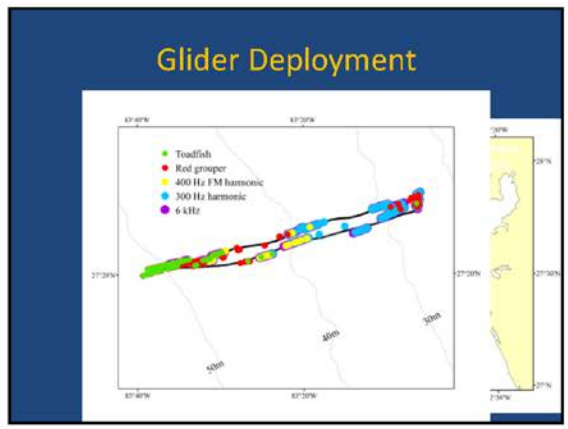

Large-Scale Mapping
• Glider with hydrophone

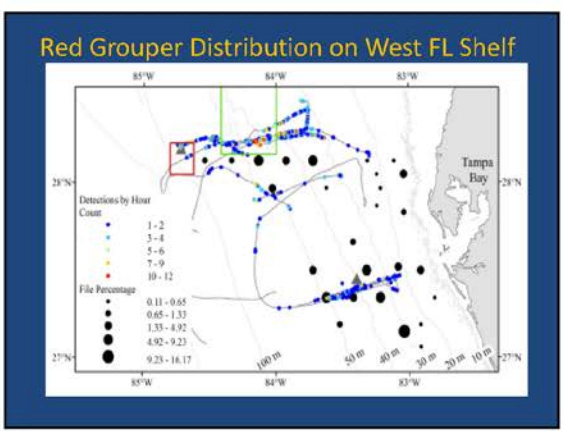

Some Unknowns
• ~ 300 Hz harmonic


Some Unknowns
• ~400 Hz frequency modulated harmonic

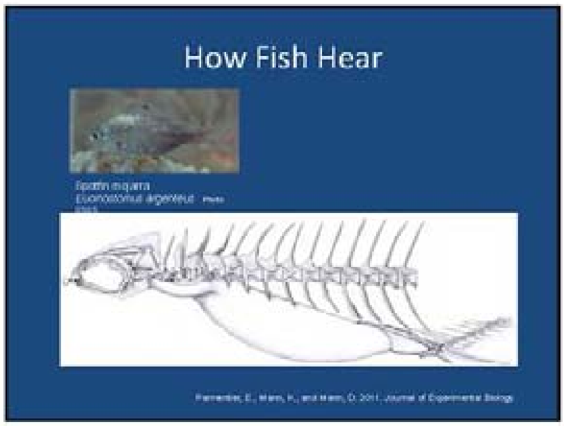

Some Unknowns
6 kHz, diurnal sound

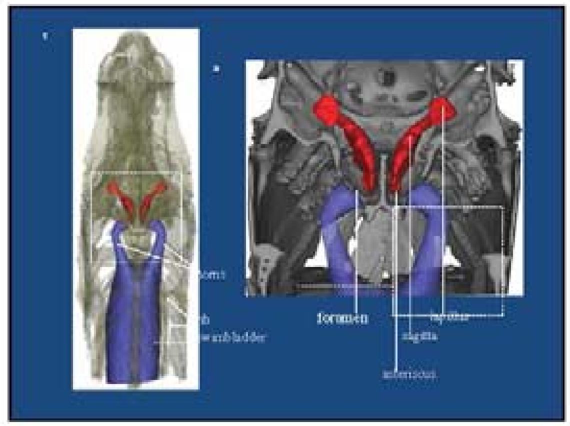

Glider Deployment
• July 14 - 21, 2009
– 20 sec / 5 min
– 2020 acoustic files
Start 7/14
End 7/21

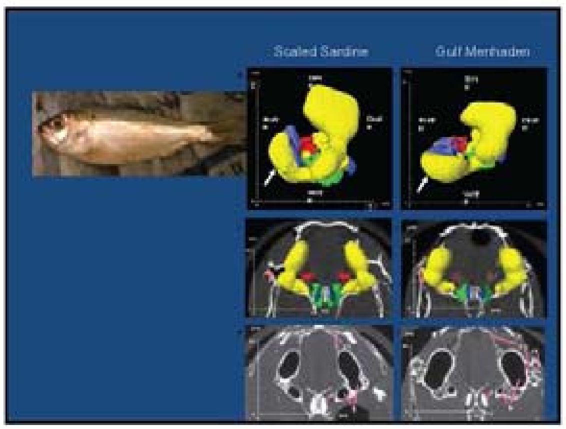

Glider Deployment
Toadfish
Red grouper
400 Hz FM harmonic
300 Hz harmonic
6 kHz

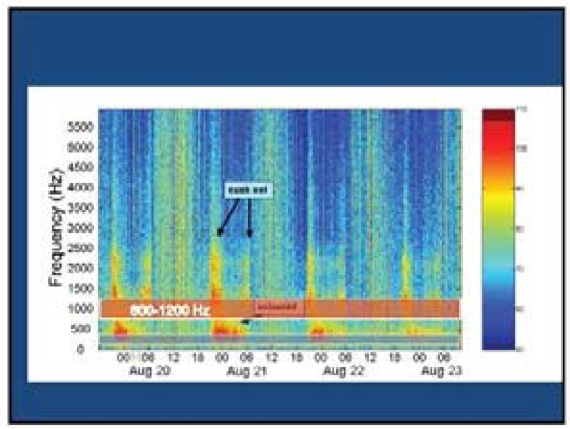

Red Grouper Distribution on West FL Shelf
Tampa Bay
Detections by Hour Count
File Percentage

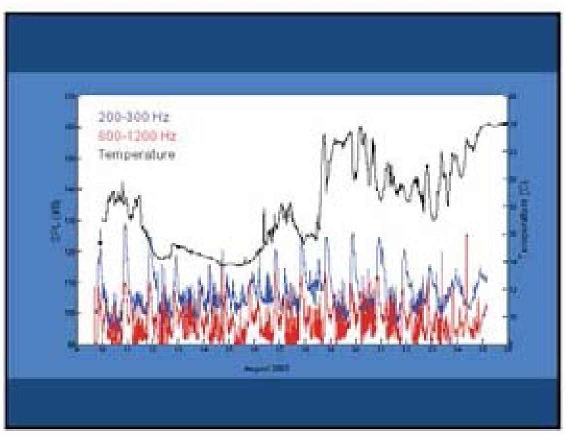

Needs and Data Gaps
David Mann
University of South Florida
Loggerhead Instruments
• Invertebrates: Little is known about how sound is used in communication or hearing sensitivity.
• Library of sounds produced by fishes.
– This hinders use of passive acoustics as tool in determining effects of sound on behavior.
• New methods to identify which species produce which sounds.
– Common tools, such as video, are difficult to use in open ocean environments.
– Develop tags similar to acoustic tags deployed on marine mammals.
• What are impacts of reduced communication range on important behavior, such as spawning?
• Do we care about all fishes?

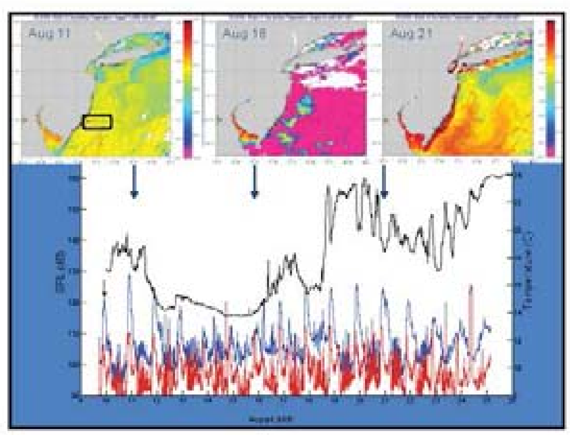

How Fish Hear
Spotfin mojarra
Eucinostomus argenteus
Parmentier, E., Mann, K., and Mann, D. 2011. Journal of Experimental Biology


swimbladder
foramen
sagitta


Scaled Sardine
Gulf Menhaden


Frequency (Hz)
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
800-1200 Hz
00 06 12 18 00 06 12 18 00 06 12 18 00 06
Aug 20
Aug 21
Aug 22
Aug 23


200-300 Hz
800-1200 Hz
Temperature


Aug 11
Aug 18
Aug 21

Masking and Auditory Scene Analysis: Implications for Fish Behavior and Survival.

Richard R. Fay
Marine Biological Laboratory
Woods Hole, MA

Masking – definition: the reduction in the detectability of a signal of interest due to the presence of another sound – usually noise.

Auditory Scene Analysis (ASA)
– definition: the process by which the human auditory system organizes sound into individual, perceptually segregated streams according to their likely sources.
The term was coined to describe human hearing by psychologist Albert Bregman (1990).

These are related concepts that help define the hearing process of human beings and all other animals.

Masking – Originally described aspects of human hearing performance (e.g., Fletcher, 1940)

First applied and developed for human hearing

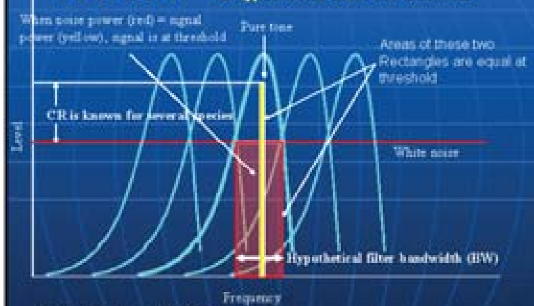
Simplest case –

Signal of interest – pure tone
Interfering sound – white noise

Masking assumptions (Fletcher):
- The receiver is the human ear composed of many independent, frequency-selective channels (filters).
- Detection of the signal tone uses a detection channel or filter centered on the signal frequency.
- Detection filters have a finite bandwidth that admits both the tone signal and noise components falling within the filter.
- When the tone is at masked threshold, the noise power equals the signal power within the filter.
- At the detection threshold for the signal, the ratio between tone signal power and noise power (level per Hz) can be specified. This is the S/N at threshold.
- The signal-to-noise ratio in dB at signal threshold is called the Critical Masking Ratio (CR).
- The CR in dB can be used to estimate the width of the detection filter (Bandwidth=$10^{CR/10}$).

Masking Fundamentals and Assumptions

Filter bank of hypothetical detection channels



$BW(Hz) = 10^{(CR/10)}$

- For Human listeners, the width of the detection filters increases with center frequency according to a linear function (Glasberg & Moore, 1990).
- Masking will be in effect for all noise levels that can be detected (i.e. from the threshold of hearing the noise).
- Masking is a linear function of noise level (1 dB increment in masking for 1 dB increment in noise level).
- These aspects of masking have been confirmed in a variety of animals (mammals - including marine mammals, birds, amphibians and fishes), including that all ears contain a filterbank of detection channels.
- **It is likely that masking functions similarly in all animals, including sea turtles and invertebrates.**

The usual or "natural" ambient noise already causes masking for most fishes in most environments.

So, any increment in these noise levels by anthropogenic sources will most likely cause additional masking.

Masking effects are analogous to a hearing impairment in that, while the masking noise is present, the thresholds for detecting the usual sources will be raised (i.e., all sources will be harder to detect).

•However, most of what we know about masking applies only to pure tone signals against a flat-spectrum (white) noise masker.

•Real signals and noises are more complex than this, with both signals and noise having arbitrary spectral shapes and bandwidths.

•There has been very little research on this aspect of masking in fishes, and no certain way to make quantitative predictions about the masking effects of arbitrary spectral shapes on arbitrary signals.

•e.g., the masking effect of vibratory pile driving on the detection of communication sounds of the cod cannot be predicted without further research. All we can be sure of is that only the noise levels in the vicinity of the communication sound spectrum cause the masking.

Consequences of masking for the fitness of fishes

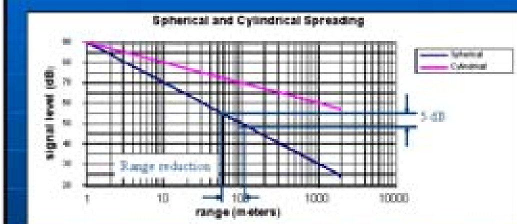
There is no research on this question, so we don't know what effects on fitness and survival might occur caused by anthropogenic noise.

We can guess that extra noise in the environment could interfere with communication (social and reproductive), predator and prey interactions, and orientation to environmental features.

One thing is certain – As noise levels are raised above the "natural" ambient levels, all noise sources may –

- **Render the weakest sounds undetectable**
- **Render all sound sources less detectable**
- **Reduce the distance at which sound sources can be detected.**

Masking Effects on Distance of Source Detection



Any increase in ambient noise reduces the distance at which any source can be detected.
Spherical spreading – **56% distance reduction / 5 dB**
Cylindrical spreading – **32% distance reduction / 5 dB**

There is no threshold – any noise increment = distance reduction

Auditory Scene Analysis

The ability to segregate sounds from different sources, and to assign sounds to independent sources.

Bregman (1990) introduced the notion of Auditory Scene Analysis (ASA) generally, with the focus on human speech and music perception.

"Dividing evidence between distinct perceptual entities (visual objects or auditory streams) is useful because there really are distinct physical objects and events in the world that we humans inhabit. Therefore, the evidence that is obtained by our senses really ought to be untangled and assigned to one or another of them" (Bregman 1990, pg. 13).

Bregman –

2 types of ASA –

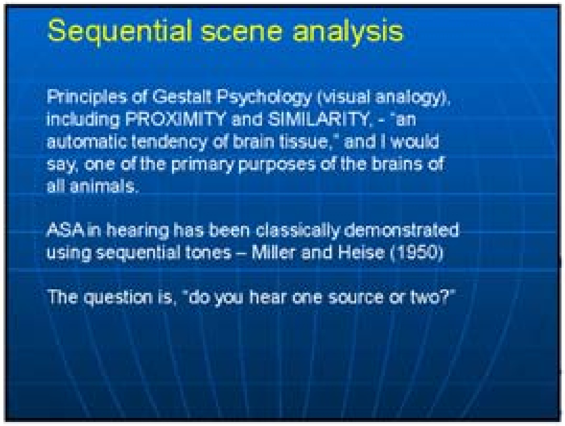
PRIMITIVE – Bottom up, involuntary, not dependent on cognition or attention, automatic, and I would say, the ASA shared with all animals.

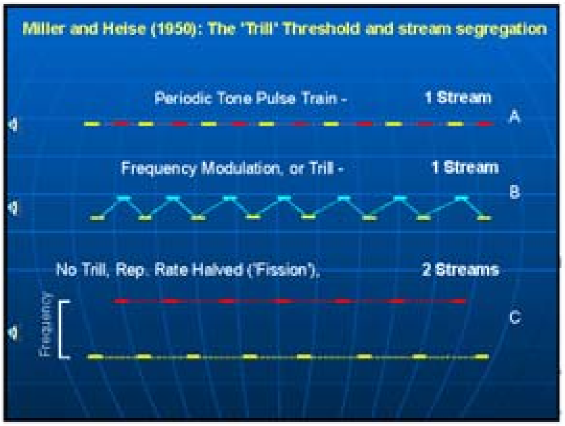
SCHEMA-BASED – Top down, memory-based, arising from learning and experience.

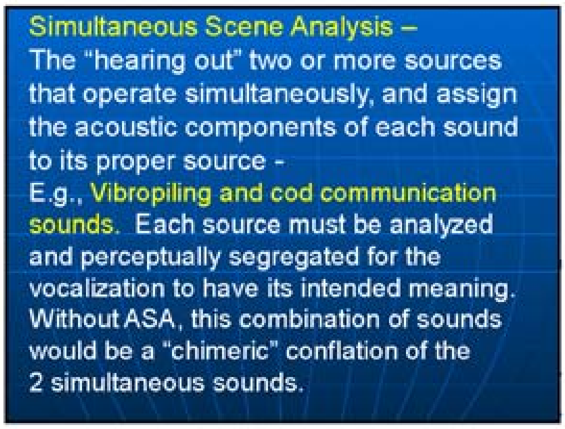
2 further types –

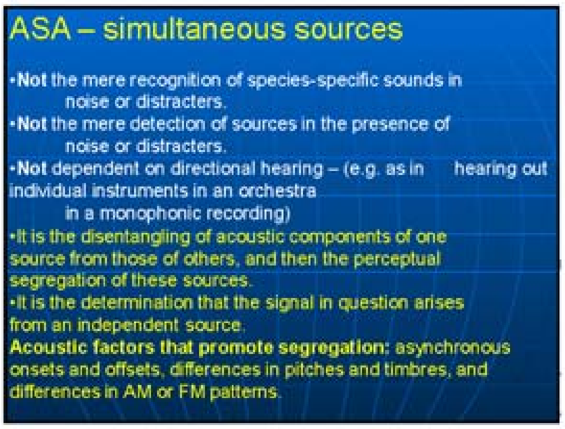
SEQUENTIAL – Those sensory features that tie together a temporal stream as if from a single source.

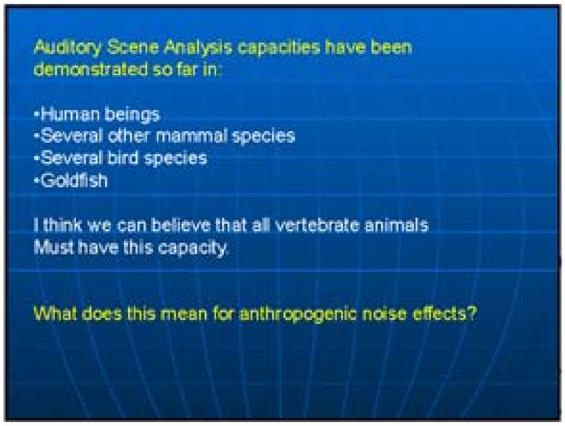
SIMULTANEOUS – Features of a sound that distinguish one simultaneous source from another

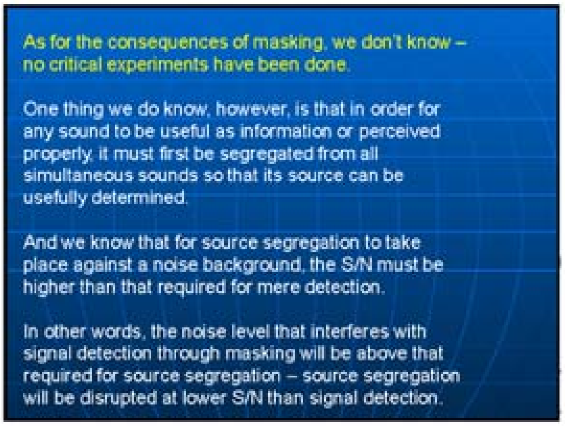

Sequential scene analysis
Principles of Gestalt Psychology (visual analogy), including PROXIMITY and SIMILARITY, - "an automatic tendency of brain tissue," and I would say, one of the primary purposes of the brains of all animals.
ASA in hearing has been classically demonstrated using sequential tones – Miller and Heise (1950)
The question is, "do you hear one source or two?"

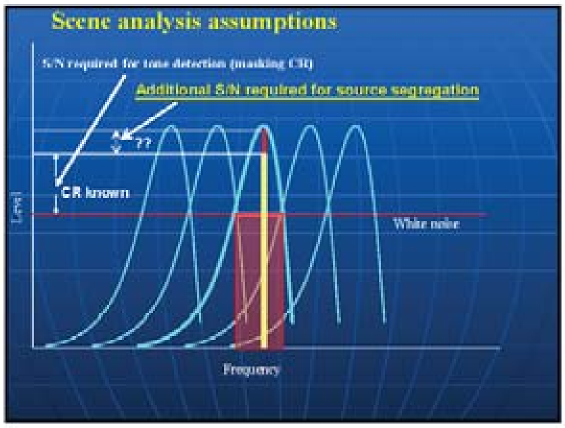

Miller and Heise (1950): The 'Trill' Threshold and stream segregation
Periodic Tone Pulse Train -
1 Stream
A
Frequency Modulation, or Trill -
1 Stream
B
No Trill, Rep. Rate Halved ('Fission'),
2 Streams
Frequency
C


Simultaneous Scene Analysis –
The "hearing out" two or more sources that operate simultaneously, and assign the acoustic components of each sound to its proper source -
E.g., Vibropiling and cod communication sounds. Each source must be analyzed and perceptually segregated for the vocalization to have its intended meaning. Without ASA, this combination of sounds would be a "chimeric" conflation of the 2 simultaneous sounds.


ASA – simultaneous sources
•Not the mere recognition of species-specific sounds in noise or distracters.
•Not the mere detection of sources in the presence of noise or distracters.
•Not dependent on directional hearing – (e.g. as in hearing out individual instruments in an orchestra in a monophonic recording)
•It is the disentangling of acoustic components of one source from those of others, and then the perceptual segregation of these sources.
•It is the determination that the signal in question arises from an independent source.
Acoustic factors that promote segregation: asynchronous onsets and offsets, differences in pitches and timbres, and differences in AM or FM patterns.


Auditory Scene Analysis capacities have been demonstrated so far in:
•Human beings
•Several other mammal species
•Several bird species
•Goldfish
I think we can believe that all vertebrate animals Must have this capacity.
What does this mean for anthropogenic noise effects?


As for the consequences of masking, we don't know – no critical experiments have been done.
One thing we do know, however, is that in order for any sound to be useful as information or perceived properly, it must first be segregated from all simultaneous sounds so that its source can be usefully determined.
And we know that for source segregation to take place against a noise background, the S/N must be higher than that required for mere detection.
In other words, the noise level that interferes with signal detection through masking will be above that required for source segregation – source segregation will be disrupted at lower S/N than signal detection.



The additional S/N required for source segregation is not known, but for goldfish the value is about 4 dB greater than the critical masking ratio for tone-in-white noise masking (Fay, 2011).

The point is that the mere detection of a signal is not enough for useful source processing. All effective sources must be above masked threshold by at least 4 dB for the information to be properly used (the source segregated).

Conclusions

- **We know a lot about tone-in-white noise masking in fishes.**
- We know very little about the masking of arbitrary signals by arbitrary noise spectra.
- We know almost nothing about the consequences of masking for fish behavior and survival, except that the distance from a sound source required for detection is reduced by noise levels above ambient.
- **We know that fish are capable of Auditory Scene Analysis.**
- We know that sounds must be segregated to convey all the information about their sources.
- We know almost nothing about the consequences of a failure of ASA for fish behavior and survival, except that the S/N required for segregation is greater than the masking CR.

Behavior of Pelagic Fish in Response to Man-made Sources

John Dalen
Institute of Marine Research, Norway

Effects of Noise on Fish, Fisheries, and Invertebrates
A BOEM Workshop on Data Gaps and Research Needs
San Diego, 20-22 March 2012

INSTITUTE OF MARINE RESEARCH

What to include

- **Species**
  True "small" pelagic and mesopelagic ones (no bentho-pelagic ones)
  - herring (*Clupea harengus*)
  - mackerel (*Scomber scombrus*)
  - blue whiting (*Micromesistius potassou*)
  - sandeel (*Ammodytes sp., Hyperoplus sp.*,++)
  - mesopelagic species (Myctophids,++)
  - salmon and trout (xx, *Salmo salar, S. trutta*)

What to include, cont

Sources

- **Only sources producing sound energy within the frequency ranges of hearing in actual fish species, i.e. at low and very low frequencies < 1000 Hz**
  - hammers (piling)
  - fishing gear - trawls
  - explosives – blasting (construction and demolition)
  - sparker (seismic)
  - airgun (seismic)
  - very low frequency sonar (mostly military – a few within geophysics)

What to include, cont

Surroundings and habitats

- free swimming fish – shoals/schools or single specimen
- caged fish have as often undesired and rarely known restrictions in behaviour responses and patterns
  => left out here!

Overall recognition

- Studying behaviour of free swimming pelagic fish species is a very challenging task with regards to:
  - observation methodology
  - instrumentation
  - data analysis and interpretation

There is no general fish species in this context!

All impacts from man-made sound on fish and such stimuli leading to changed behaviour must be understood in a species specific, size specific and biological state specific context, and seasonal context!

From hammers - piling

- All potential relevant studies are either on caged fish and/or on demersal and bentho-pelagic species

From fishing gear - trawls

2 relevant kinds of trawl

- demersal trawls / bottom trawls
- pelagic trawls

Swimming behaviour of herring during acoustic surveying and pelagic trawl sampling

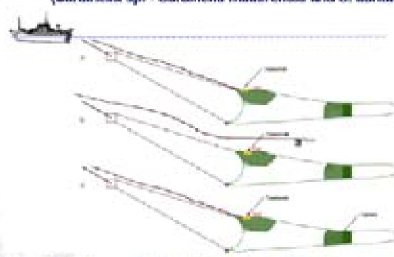
A study showing herring beaviour related to pelagic trawling in the North Sea but the reponses to the trawl are rather difficult to distinguish from the response to the ship – re Alex De Robertis "Responses of Fish to Ship Noise"

- Major findings: The herring avoided the trawl by:
  - increasing the horizontal swimming speed
  - undertook vertical migration towards the bottom

Misund, O.A., & Aglen, A. 1992. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic trawl sampling. ICES J. Mar.Sci. 49: 325-334.

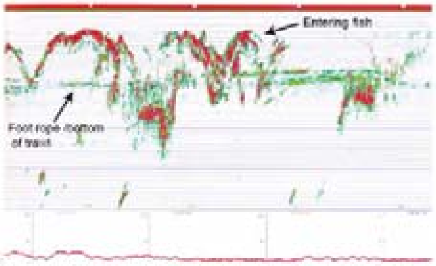
Pelagic Fish Behaviour during Trawl Sampling off Angola

(*Sardinella* sp. - *Sardinella maderensis* and *S. aurita*)



Kyrkjebø, E. & Misund, O.A. 2011. Pelagic Fish Behaviour during Trawl Sampling off Angola. OpenOceanJour 2011, 5, 22-29.

Pelagic Fish Behaviour - Trawl Sampling - Angola, cont



Echogram from the trawl sonde (echo sounder on the head rope looking downwards) – fish entering the trawl.

Pelagic Fish Behaviour - Trawl Sampling - Angola, cont

Main outcome of shoal behaviour

- Depending on the intensity and type of reactions, the altered behaviour patterns were classified into two categories:
  - *Adjust Reactions*: did not lead to a sudden disintegration of the school organisation but caused the whole school gradually to change swimming direction and move closer to one side or to the bottom of the trawl.
  - *Fright Reactions*: Characterised by a sudden simultaneous mass response, with individual fish swimming in different directions and the collective school organisation collapsing for a few seconds.

From explosives

Most studies are either on caged fish and/or on demersal and bentho-pelagic species

Cited study: Exposing blue whiting to small charges of explosives just behind a fishing vessel to "force" the fish to the bottom to be more exposed/catchable to the bottom trawl (increase catches).

- Depth of fish: 150-200 m
- **Blasting:** The fish concentrated and moved towards the bottom – stayed there for 10-15 min and then lifted again to previous preferred depths
- The blue whiting got habituated after 5-8 blasts with 5-10 min between each stimulation/blast

Dalen, J. 1973. Controlling behaviour of blue whiting in relation to trawling. Experiments in the North Sea. SINTEF Working Report 73-116-K, SINTEF, Div. 48, NTNU.

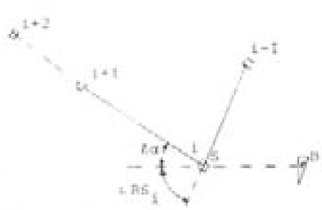
From sparkers (seismic)

Investigations of impacts on herring in a nearly closed bay

The bay holding herring shoal(s), vessel and features of the positioning system

Dalen, J. 1973. Stimulating herring shoals with sound. Report to the Norwegian Research Council of Tevhnology and Natural Sciences.

Investigations of impacts on herring in a bay, cont



Shoal trajector from time/ position i-1 to i+2, response angle α = Δα + BSi; S: shoal B: boat with sonar

Investigations of impacts on herring in a bay, cont

Main results for changes in swimming speed, v, and swimming direction, α, prior to and after stimulation

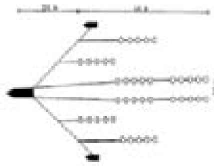
Plot	Average			Variance		
	v [m/s] prior	v [m/s] after	α [°] after	v [m/s] prior	v [m/s] after	α [°] after
1-7	0,37	0,33	51	0,15	0,11	27
8-13	0,41	0,40	50	0,13	0,12	37

- No significant changes in swimming speed
- Significant changes in swimming direction

From airgun(s) - seismic

- **Studies based on 3D seismic surveys**
- **Based on experimental studies**

Pilot study 1984: 3D seismic survey North Sea (SOO)

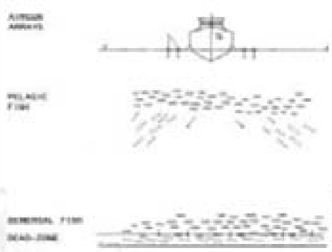


System set-up

Source: 1 airgun array (44 x 57 m); 40 airguns
Towing depth: 6 m
Chamber volume: 77 932 cm³ (4752 cu.in.)
Source level: 249,9 dB//1μPa re 1 m (calibrated)
Supply pressure: 138 Bar (2000 psi)
Firing interval: 10 s / 25 m

-Dalen, J. & Knutsen, G.M. 1987. Scaring effects in fish and harmful effects on eggs, larvae and fry by offshore seismic explorations. In Merklinger: Proc. Symp. "Progress in underwater acoustics", 1987: 93-99. Halifax 1986.

Pilot study 1984: 3D seismic survey North Sea (SOO), cont



Sketch of fish behaviour during seismic blasting

Seismic area: 6 x 9 nautical miles (11 x 17 km)
Observation area: 35 x 18 nautical miles (65 x 33 km)

Estimated SPEL:
210 dB//1 μPa at 100 m 204 dB//1 μPa at 200 m 200 dB//1 μPa at 300 m

Pilot study 1984: 3D seismic survey North Sea (SOO)

Main outcome: The horizontal and vertical distributions of both pelagic fish and groundfish as observed by hydroacoustic methods and trawling within the observation area surrounding the seismic operations area, were consistently changed after 6 days of airgun operations compared to the distributions prior to the operations.

=> **Blue whiting**: Changes in distribution were observed out to ca. 17 nautical miles from the centre of the seismic area.

=> **Blue whiting**: The echo abundance in the seismic area was reduced by 54 % after 6 days of air gun operations compared to that prior to the operations.

Pilot study: 3D seismic survey North Sea (SOO), cont

Specific observation:

Changes of the fish distributions and behaviour patterns of the fish along the course lines of the seismic vessel from immediately before to just after airgun shooting proved that the fish were affected.

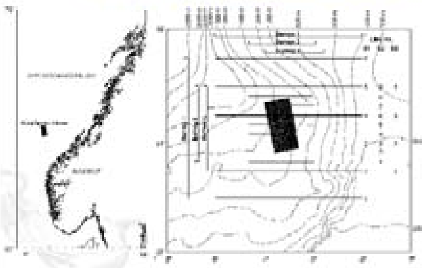
Pelagic fish distribution and abundance in relation to a seismic shooting off the Norwegian west coast (SOO) -1999

System set-up

- Source: 2 airgun arrays, flip-flop operated
- 10 streamers
- Towing depth: 8 m
- Firing interval: 10 s / 25 m
- 51 parallel transect, each 51 km long,
- Adjacent transects separated by 500 m.

Slotte, A., Hansen, K., Dalen, J. & Ona, E. 2003. Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. FishRes 67 (2004) 143–150.

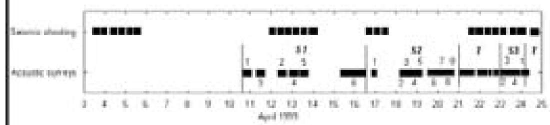
Pelagic fish and seismic shooting off the Norwegian west coast (SOO), cont.



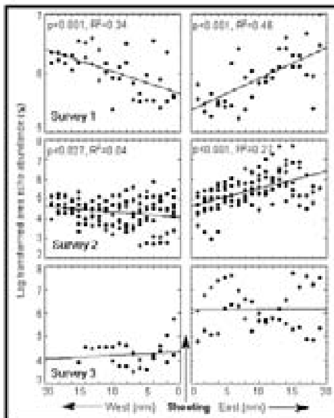
Ringhorne Dome. Survey lines and bathymetry of the surrounding area.

Seismic area Ringhorne Dome off the Norwegian west coast.

Pelagic fish and seismic shooting off the Norwegian west coast (SOO), cont.



Time lines of seismic blasting and the three acoustic surveys (S1–S3). S1: 6 lines, S2: 9 lines, S3: 4 lines



Pelagic fish and seismic shooting off the Norwegian west coast (SOO), cont.

Area echo abundance (S_A) of pelagic fish inceased significantly both in western and eastern direction from the shooting in survey 1 (6 days / 6 lines), survey 2 (4½ days / 9 lines), but not in survey 3 (1½ day / 4 lines)

Pelagic fish and seismic shooting off the Norwegian west coast (SOO), cont.

Main outcome

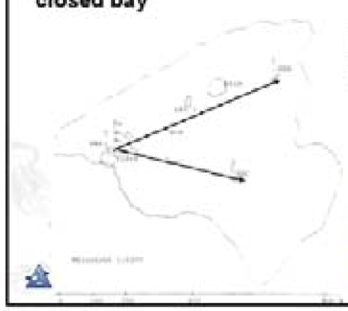
- The study indicates there could be a long term effect of the seismic shooting: i.e. that highly migratory fish like herring and blue whiting tends to leave and/or avoid seismic blasting areas.
- The fish distribution were found at larger depths during seismic blasting than with no blasting.
- The study indicates that the fish distributions may turn back to "normal" within some days after the blasting ceases.

Fishermen's stories (anecdotal expressions)

- **Mackerel**
- When a seismic vessel comes into the area the fish "gets wild" (echo sounder observations):
  - => more difficult to catch by purse-seining
  - => for trolling the catches are strongly reduced and stay low as long as the seismic
- **Sandeel**
- When a seismic vessel comes into the area the catch rates are strongly reduced

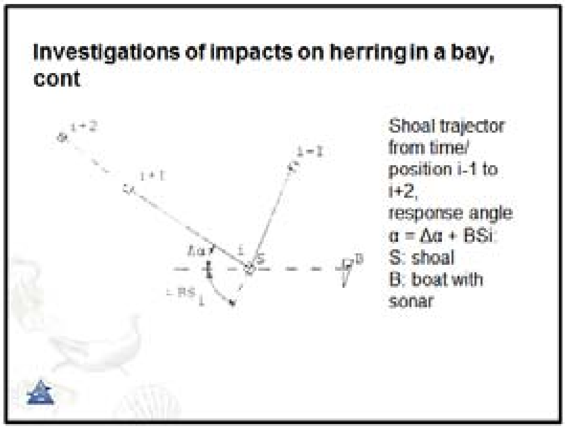
Experimental studies: From airguns

Investigations of impacts on herring in a nearly closed bay



The bay holding herring shoal(s), vessel and features of the positioning system

Dalen, J. 1973. Stimulating herring shoals with sound. Report to the Norwegian Research Council of Tevhnology and Natural Sciences.



Impacts on herring in a bay, cont

Main results of changes in swimming speed, v, and swimming direction, α, prior to and after stimulation

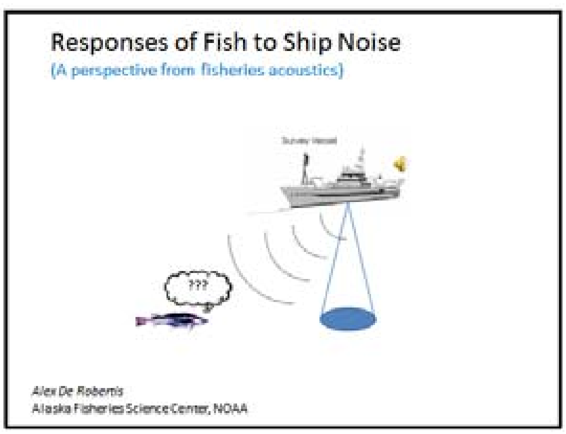
Plot	Average			Variance		
	v [m/s] prior	v [m/s] after	α [°] after	v [m/s] prior	v [m/s] after	α [°] after
1-4	0,58	0,80	75	0,06	0,20	26
5-9	0,32	0,59	99	0,11	0,24	37

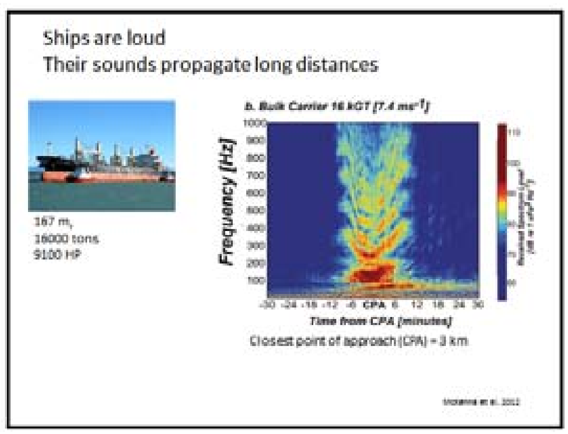
- **Significant changes in swimming speed**
- **Significant changes in swimming direction**

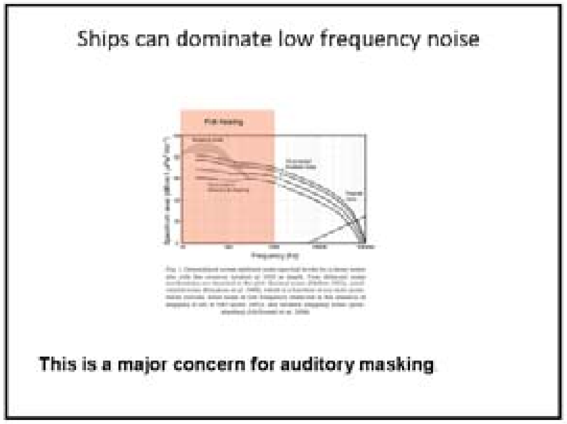
Dalen, J. 1973. Stimulating herring shoals with sound. Report to the Norwegian Research Council of Technology and Natural Sciences.

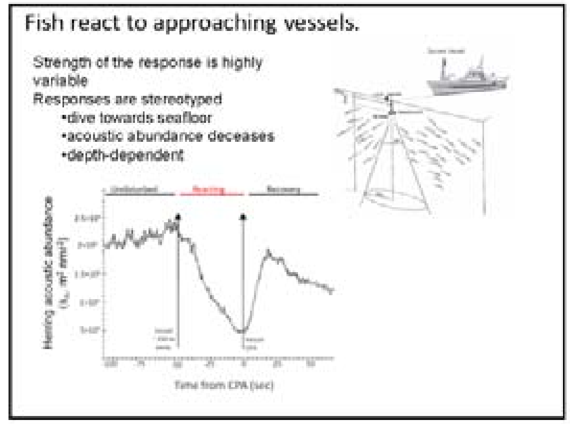
Knowledge gaps

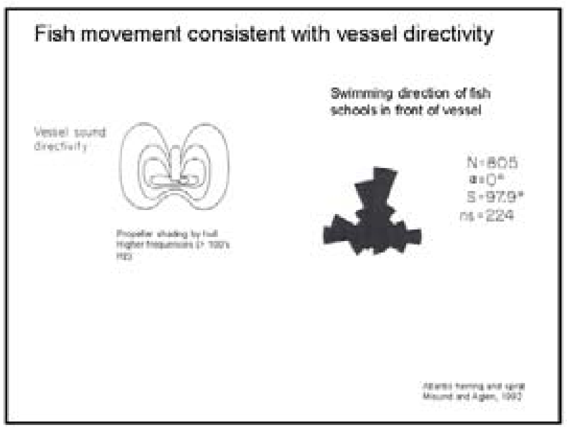
- Perform studies on "seismics and herring":
  => impact distances, behaviour studies, impact on catching effort,
  "prior to – during – after the seismic activity"
- Perform studies on "seismics and mackerel":
  => impact distances, behaviour studies, impact on catching effort,
  "prior to – during – after the seismic activity"
- The studies should **not** be undertaken in relation to seismic surveys of opportunity

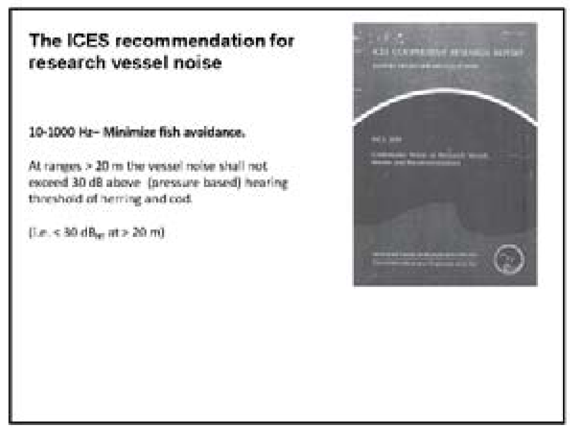


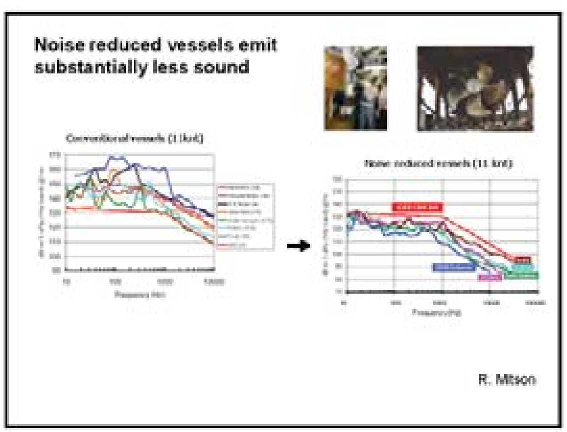


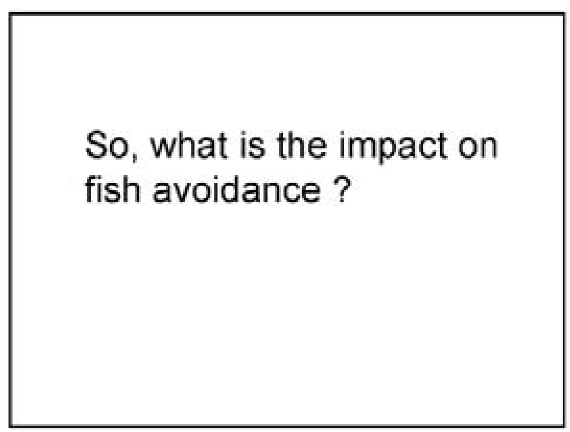

Ships can dominate low frequency noise
Fish hearing
This is a major concern for auditory masking

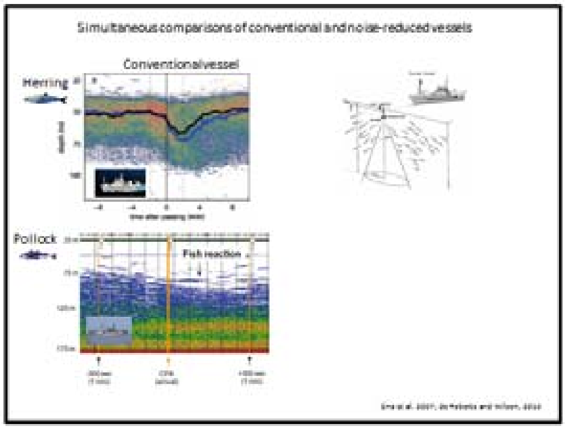

Fish react to approaching vessels.
Strength of the response is highly variable
Responses are stereotyped
•dive towards seafloor
•acoustic abundance deceases
•depth-dependent
Herring acoustic abundance
Time from CPA (sec)


Fish movement consistent with vessel directivity
Vessel sound directivity
Swimming direction of fish schools in front of vessel
N=805
a=0°
S=97.9°
ns=224

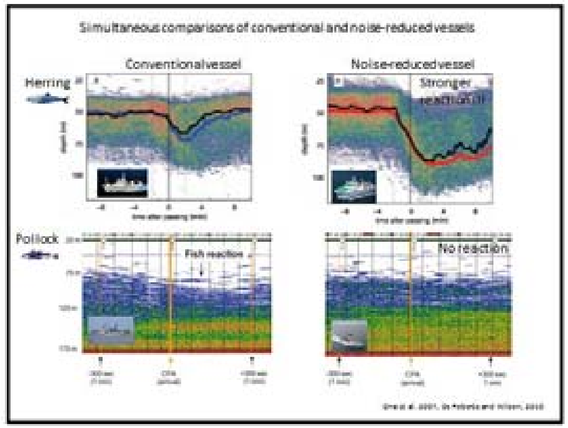

The ICES recommendation for research vessel noise
10-1000 Hz– Minimize fish avoidance.
At ranges > 20 m the vessel noise shall not exceed 30 dB above (pressure based) hearing threshold of herring and cod.


Noise reduced vessels emit substantially less sound
Conventional vessels (11 knt)
Noise reduced vessels (11 knt)
R. Mitson

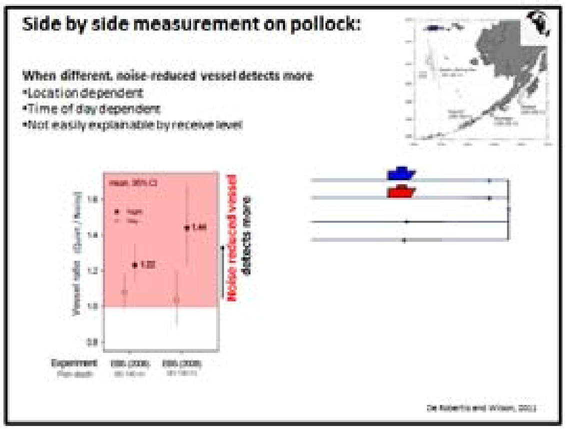

So, what is the impact on fish avoidance ?



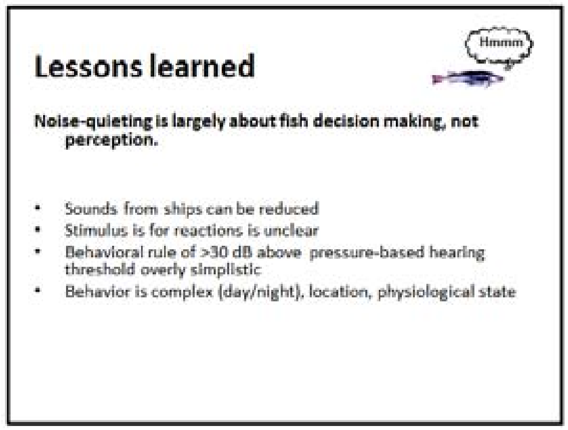
Simultaneous comparisons of conventional and noise-reduced vessels
Conventional vessel
Herring
Pollock
Fish reaction



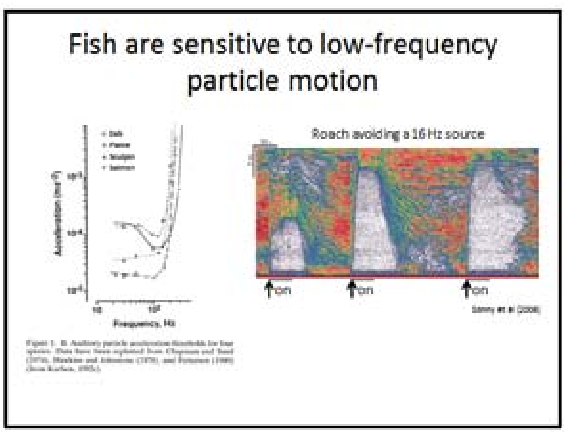
Simultaneous comparisons of conventional and noise-reduced vessels
Conventional vessel
Noise-reduced vessel
Herring
Stronger reaction !!
Pollock
Fish reaction
No reaction



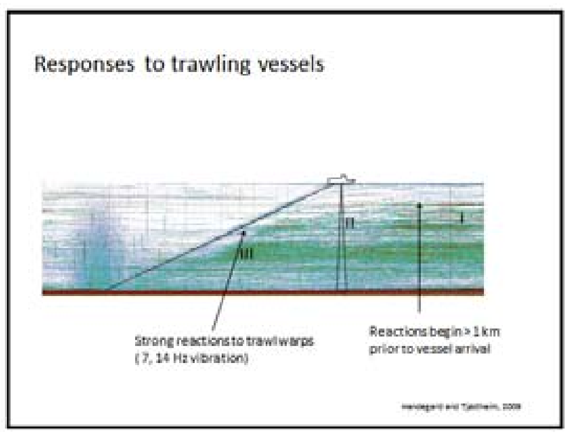
Side by side measurement on pollock:
When different, noise-reduced vessel detects more
•Location dependent
•Time of day dependent
•Not easily explainable by receive level
Noise reduced vessel detects more
De Robertis and Wilson, 2011



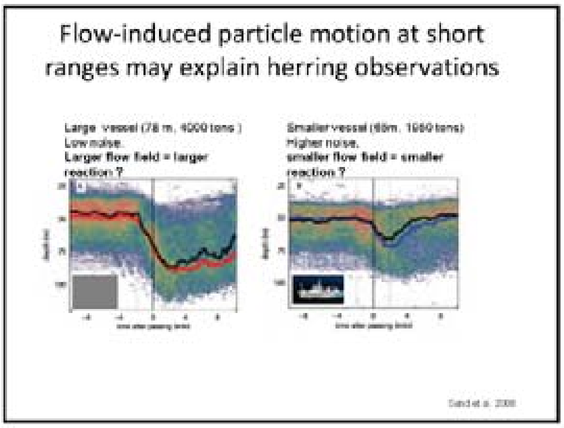
Lessons learned
Hmmm
Noise-quieting is largely about fish decision making, not perception.
• Sounds from ships can be reduced
• Stimulus is for reactions is unclear
• Behavioral rule of >30 dB above pressure-based hearing threshold overly simplistic
• Behavior is complex (day/night), location, physiological state

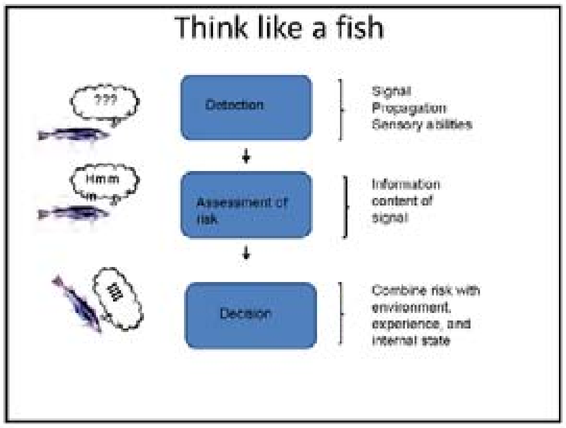


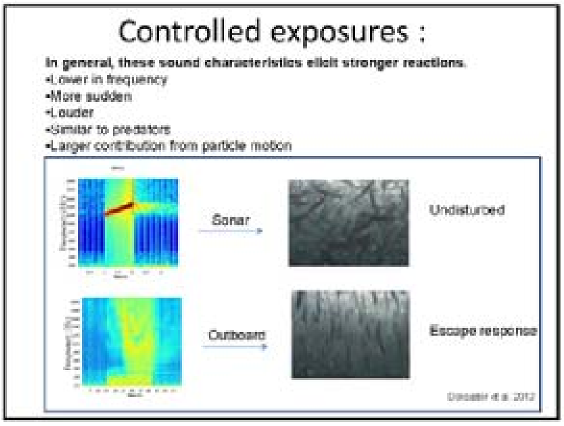
Fish are sensitive to low-frequency particle motion
Roach avoiding a 16 Hz source
Frequency, Hz
on
on
on

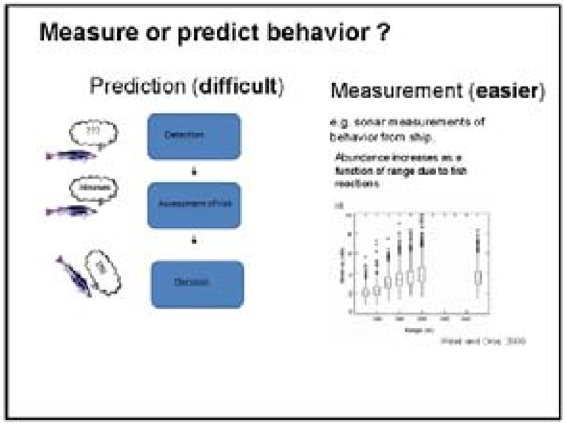


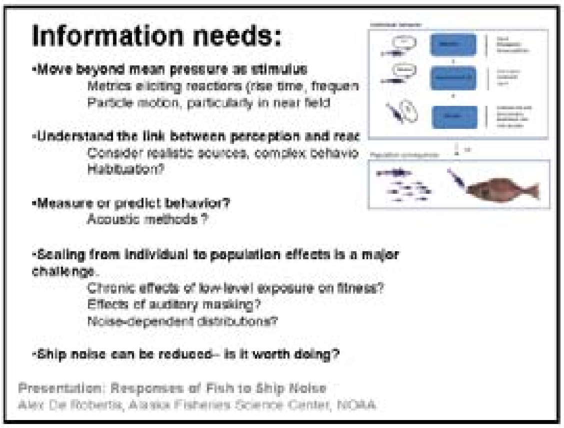
Responses to trawling vessels
Strong reactions to trawl warps (7, 14 Hz vibration)
Reactions begin > 1 km prior to vessel arrival


Flow-induced particle motion at short ranges may explain herring observations
Large vessel (78 m, 4000 tons)
Low noise.
Larger flow field = larger reaction ?
Smaller vessel (69m, 1960 tons)
Higher noise,
smaller flow field = smaller reaction ?


Think like a fish
???
Detection
Signal
Propagation
Sensory abilities
Hmm
Assessment of risk
Information content of signal
Decision
Combine risk with environment, experience, and internal state


Controlled exposures :
In general, these sound characteristics elicit stronger reactions.
•Lower in frequency
•More sudden
•Louder
•Similar to predators
•Larger contribution from particle motion
Sonar
Undisturbed
Outboard
Escape response


Measure or predict behavior ?
Prediction (difficult)
Measurement (easier)
e.g. sonar measurements of behavior from ship.
Abundance increases as a function of range due to fish reactions.


Information needs:
•Move beyond mean pressure as stimulus
Metrics eliciting reactions (rise time, frequen
Particle motion, particularly in near field
•Understand the link between perception and reac
Consider realistic sources, complex behavio
Habituation?
•Measure or predict behavior?
Acoustic methods ?
•Scaling from individual to population effects is a major challenge.
Chronic effects of low-level exposure on fitness?
Effects of auditory masking?
Noise-dependent distributions?
•Ship noise can be reduced– is it worth doing?
Presentation: Responses of Fish to Ship Noise
Alex De Robertis, Alaska Fisheries Science Center, NOAA


Effects of Noise on Catches:
Gear- and species-specific effects of air-gun sounds
HAVFORSKNINGSINSTITUTTET
INSTITUTE OF MARINE RESEARCH
Svein Løkkeborg

Gear-Specific Effects

- Bottom trawls: fish at the bottom
- Longlines: food search behaviour
- Gillnets: swimming activity

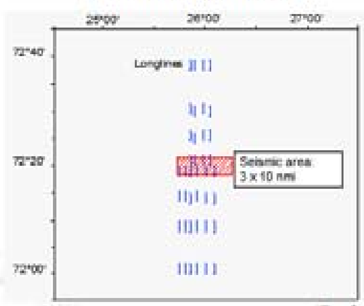
Different catching principles

Species-Specific Effects

- Hearing ability
- Swimming capacity
- Habitat preference/site fidelity
- Predator avoidance behaviour

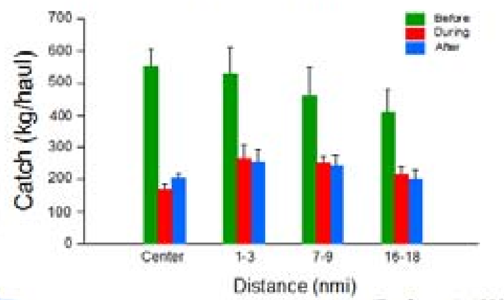
Different behaviour patterns

Trawls and Longlines
Cod and Haddock



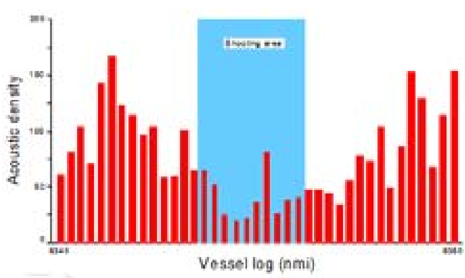
(Engås et al. 1996)

Trawls/Longlines – Cod/Haddock:
Seismic Sounds Cause Catch Reductions



(Engås et al. 1996)

Cod and Haddock:
Seismic Sounds Scare Them Away



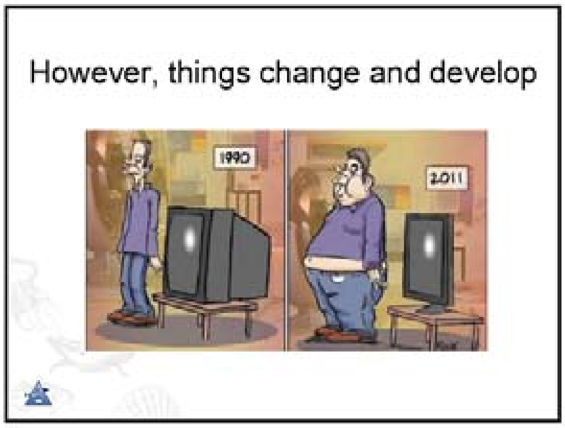
(Engås et al. 1996)

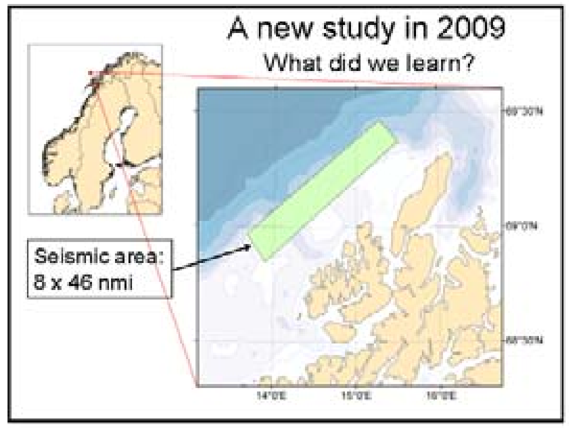
Conclusions:

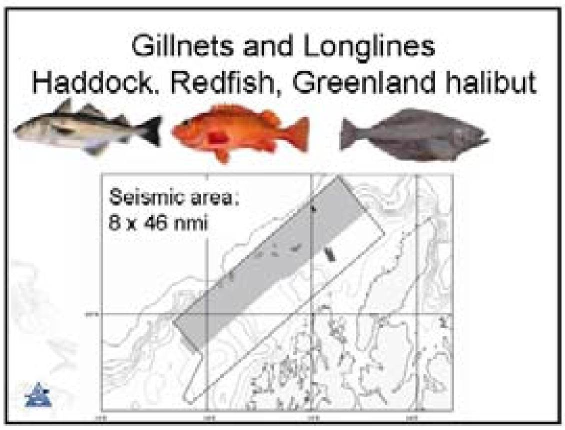
- Trawls and longlines: decreased catch rates
- Cod and haddock: avoidance responses

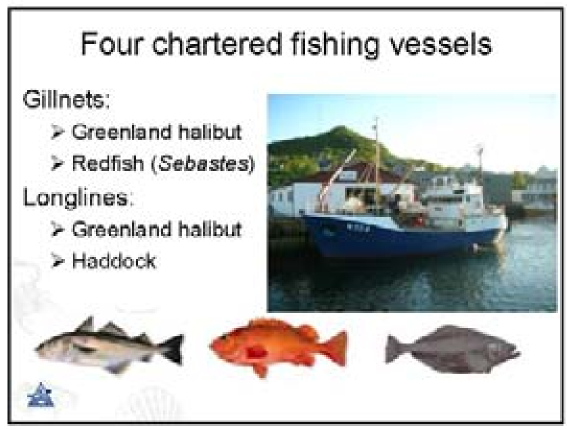
Conclusions supported by three peer review studies:

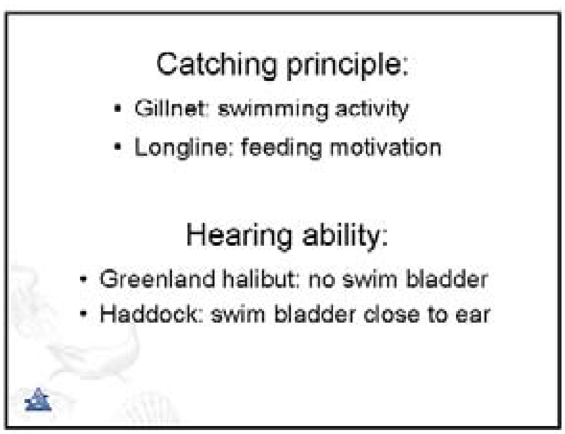
- 50 – 70% for cod and haddock (Engås et al. 1996)
- 55 – 80% for cod (Løkkeborg and Soldal 1993)
- 52% for rockfish (Skalski et al. 1992)

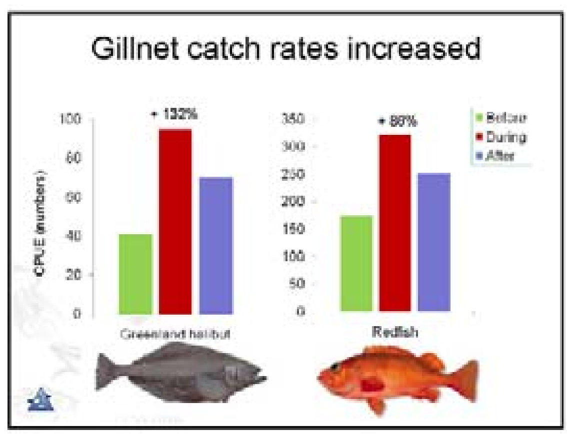

However, things change and develop
1990
2011

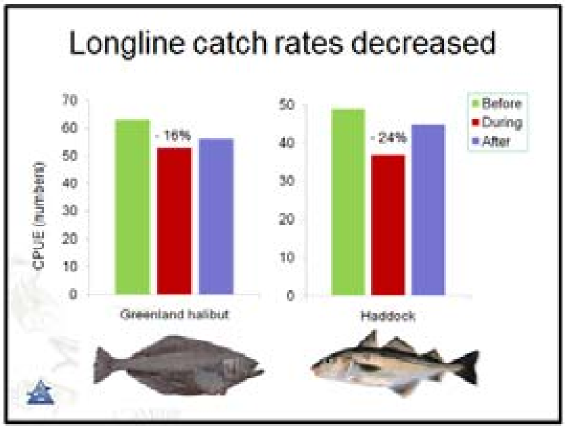

A new study in 2009
What did we learn?
Seismic area:
8 x 46 nmi

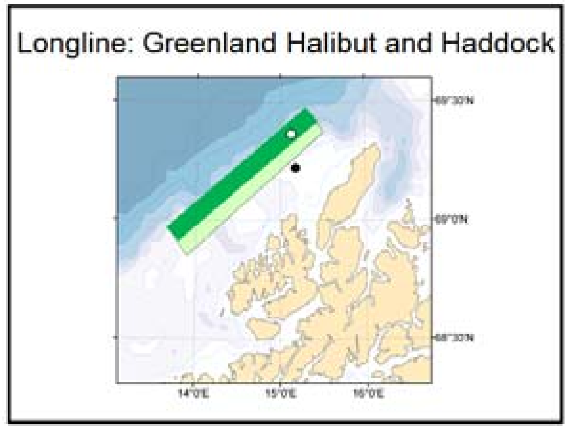

Gillnets and Longlines
Haddock, Redfish, Greenland halibut
Seismic area:
8 x 46 nmi

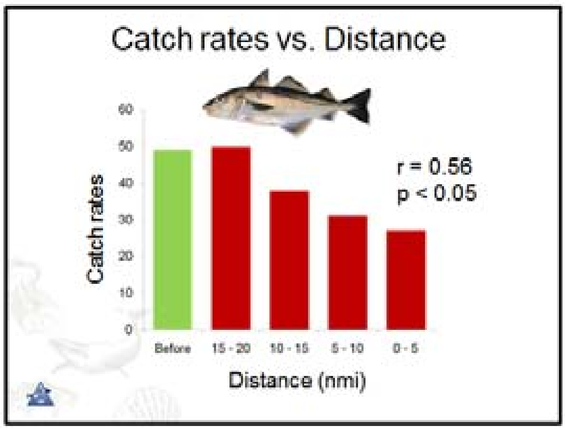

Four chartered fishing vessels
Gillnets:
➢ Greenland halibut
➢ Redfish (*Sebastes*)
Longlines:
➢ Greenland halibut
➢ Haddock

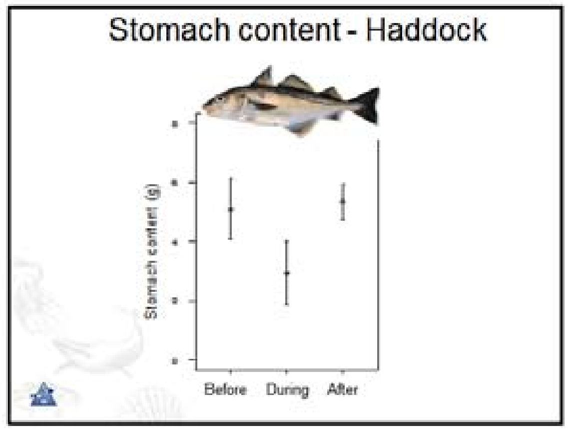

Catching principle:
• Gillnet: swimming activity
• Longline: feeding motivation
Hearing ability:
• Greenland halibut: no swim bladder
• Haddock: swim bladder close to ear

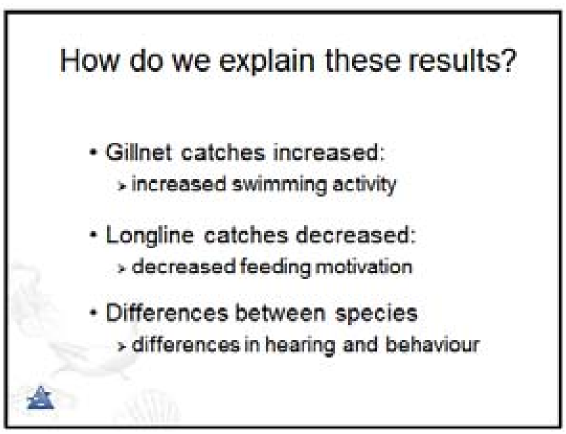

Gillnet catch rates increased
CPUE (numbers)
+ 132%
+ 86%
Before
During
After
Greenland halibut
Redfish

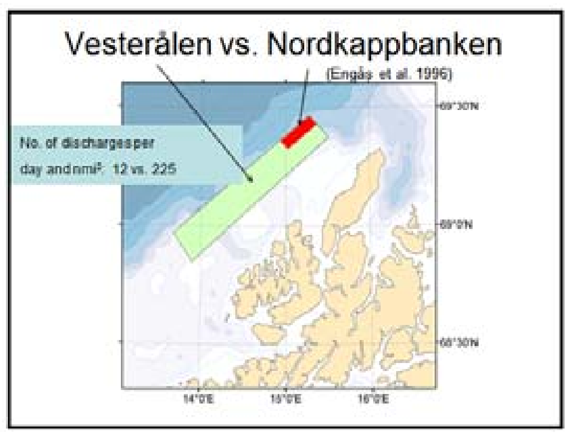

Longline catch rates decreased
CPUE (numbers)
- 16%
- 24%
Before
During
After
Greenland halibut
Haddock


Longline: Greenland Halibut and Haddock
14°0'E
15°0'E
16°0'E


Catch rates vs. Distance
Catch rates
r = 0.56
p < 0.05
Before
15 - 20
10 - 15
5 - 10
0 - 5
Distance (nmi)


Stomach content - Haddock
Stomach content (g)
Before
During
After


How do we explain these results?
• Gillnet catches increased:
› increased swimming activity
• Longline catches decreased:
› decreased feeding motivation
• Differences between species
› differences in hearing and behaviour


Vesterålen vs. Nordkappbanken
(Engås et al. 1996)
No. of discharges per
day and nmi²: 12 vs. 225
14°0'E
15°0'E
16°0'E

Effects of noise on catches depend on:

- Type of fishing gear – Catching principle
- Fishing ground (topography, depth)

- Hearing ability
- Swimming capasity
- Habitat preference/site fidelity
- Fright/avoidance response (hide or flee)

- Sound source characteristics

Thus: Extrapolation between species, gear and habitats???

Conclusions:

"Effects of Noise on Catches"

Svein Løkkeborg

Institute of Marine Research, Bergen, Norway

Fish respond to air guns and may show:

- increased swimming
- decreased feeding motivation
- displacement away from fishing grounds
- species-specific differences in behaviour
- decreased longline and trawl catches
- increased gillnet catches

Information needs and data gaps:

"Effects of Noise on Catches"

Svein Løkkeborg

Institute of Marine Research, Bergen, Norway

- Effects on pelagic and schooling species, but also on more demersal species:
  - i.e. species-specific differences
- The impacts of topography and habitat type
- Relationship between sound level and effect
- Effects of different sound sources

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Effects of Sound on Fish Catches: Statistical Approaches & Considerations

BOEM Workshop – Impacts of Marine Noise

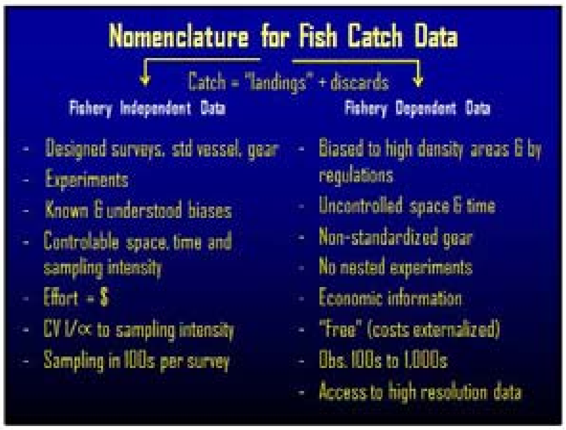
Steve Murawski
University of South Florida
College of Marine Science

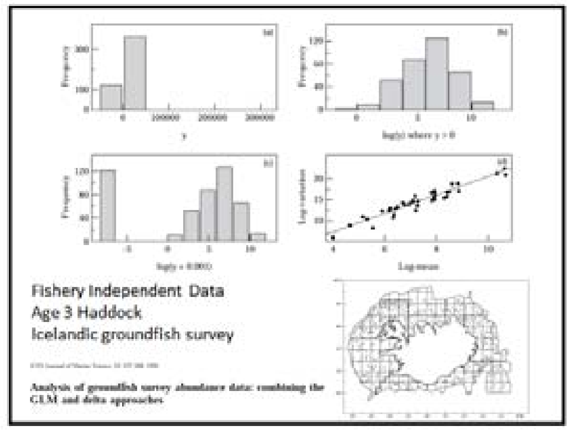
March 21, 2012

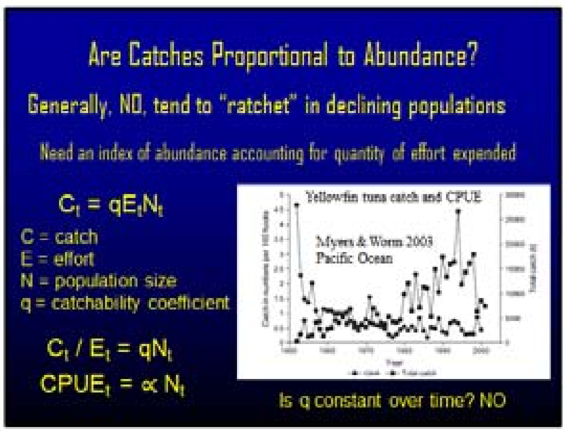
smurawski@usf.edu

Overview

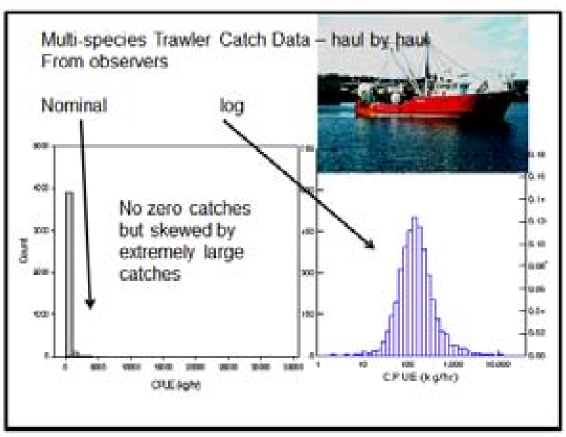
- Definition of terms in analyzing fish catch data
- Collection & statistical properties of catch data
- Some examples of analysis of spatial catch data
- Considerations in the design of studies analyzing

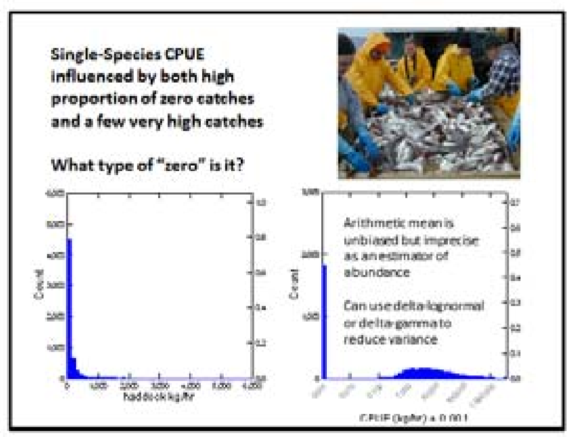

Nomenclature for Fish Catch Data
Catch = "landings" + discards
Fishery Independent Data
Fishery Dependent Data
- Designed surveys, std vessel, gear
- Experiments
- Known & understood biases
- Controlable space, time and sampling intensity
- Effort = $
- CV 1/∝ to sampling intensity
- Sampling in 100s per survey
- Biased to high density areas & by regulations
- Uncontrolled space & time
- Non-standardized gear
- No nested experiments
- Economic information
- "Free" (costs externalized)
- Obs. 100s to 1,000s
- Access to high resolution data

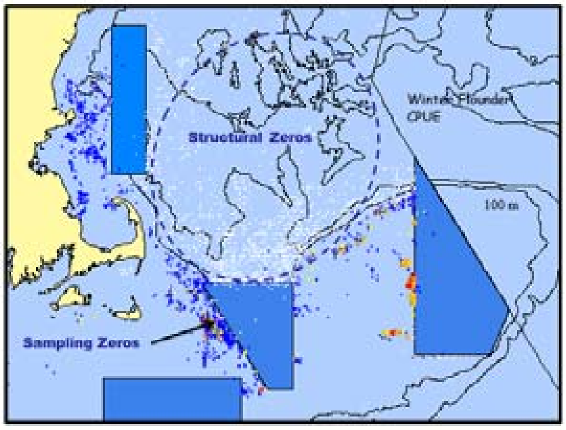

Fishery Independent Data
Age 3 Haddock
Icelandic groundfish survey
Analysis of groundfish survey abundance data: combining the GLM and delta approaches


Are Catches Proportional to Abundance?
Generally, NO, tend to "ratchet" in declining populations
Need an index of abundance accounting for quantity of effort expended
$C_t = qE_tN_t$
C = catch
E = effort
N = population size
q = catchability coefficient
$C_t / E_t = qN_t$
$CPUE_t = \propto N_t$
Yellowfin tuna catch and CPUE
Myers & Worm 2003
Pacific Ocean
Is q constant over time? NO

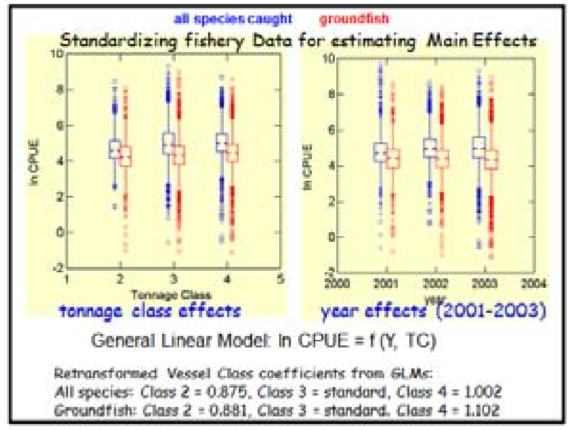

Sources of Fishery Catch & Effort Data
Data From:
- self-reported logbooks
- fish dealer records
- port "agent" interviews
- at-sea observers (the "best")
- recent advent of satellite tracking for effort (high accuracy)
Limits of resolution depend on gear, ability to collect data


Multi-species Trawler Catch Data – haul by haul
From observers
Nominal
log
No zero catches but skewed by extremely large catches
CPUE (kg/hr)

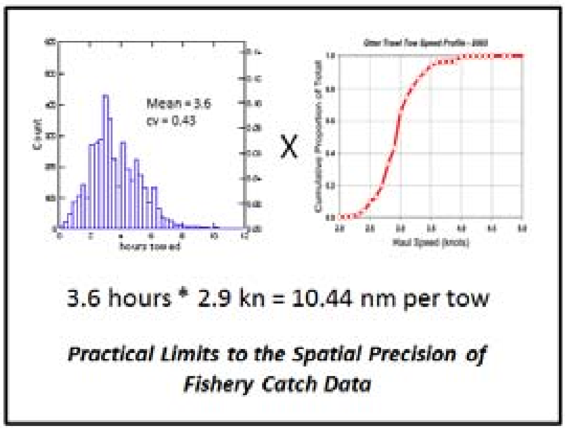

Single-Species CPUE influenced by both high proportion of zero catches and a few very high catches
What type of "zero" is it?
Arithmetic mean is unbiased but imprecise as an estimator of abundance
Can use delta-lognormal or delta-gamma to reduce variance
Count
haddock kg/hr



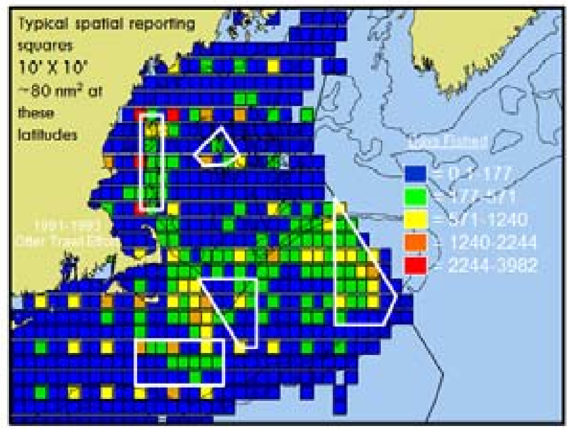
Winter Flounder CPUE
Structural Zeros
100 m
Sampling Zeros



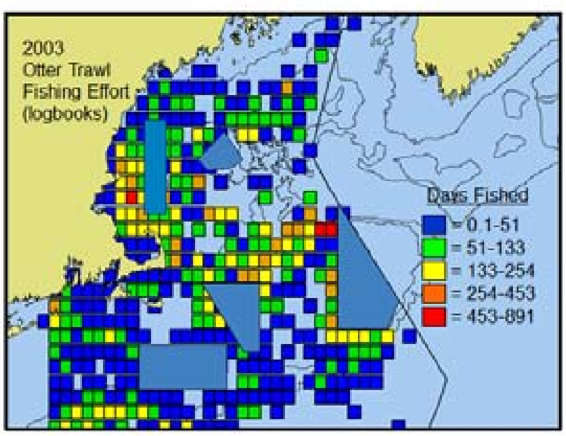
all species caught
groundfish
Standardizing fishery Data for estimating Main Effects
ln CPUE
Tonnage Class
year
tonnage class effects
year effects (2001-2003)
General Linear Model: ln CPUE = f (Y, TC)
Retransformed Vessel Class coefficients from GLMs:
All species: Class 2 = 0.875, Class 3 = standard, Class 4 = 1.002
Groundfish: Class 2 = 0.881, Class 3 = standard, Class 4 = 1.102



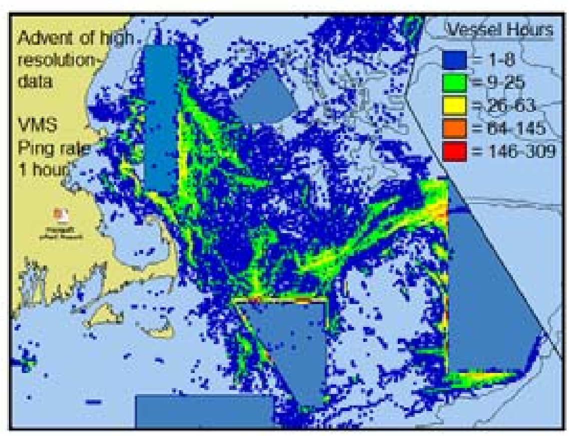
Mean = 3.6
cv = 0.43
Count
hours towed
X
Cumulative Proportion of Total
Haul Speed (knots)
3.6 hours * 2.9 kn = 10.44 nm per tow
Practical Limits to the Spatial Precision of Fishery Catch Data



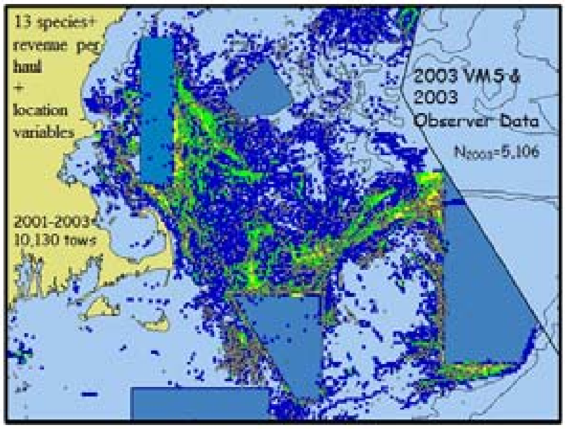
Typical spatial reporting squares
10' X 10'
~80 nm² at these latitudes
1991-1993 Otter Trawl Effort
Days Fished
= 0.1-177
= 177-571
= 571-1240
= 1240-2244
= 2244-3982

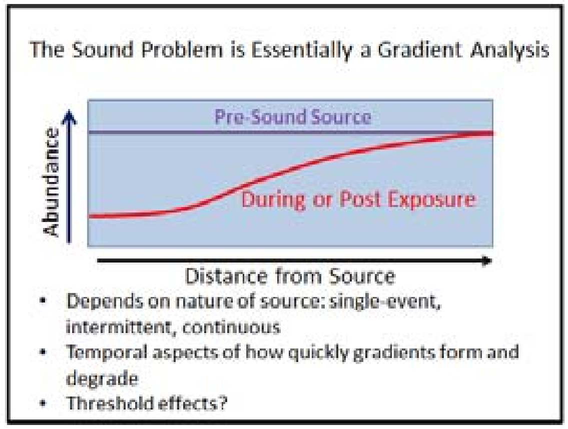


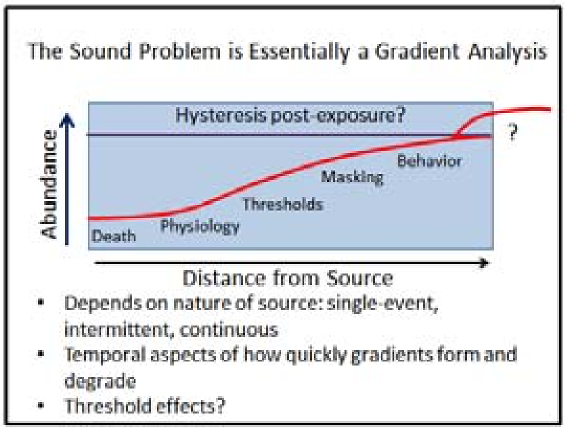
2003 Otter Trawl Fishing Effort (logbooks)
Days Fished
= 0.1-51
= 51-133
= 133-254
= 254-453
= 453-891

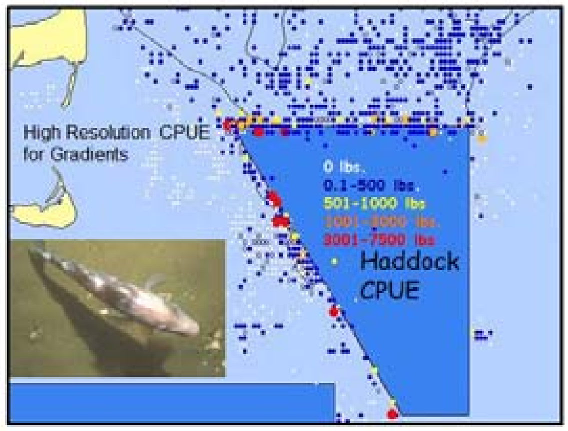


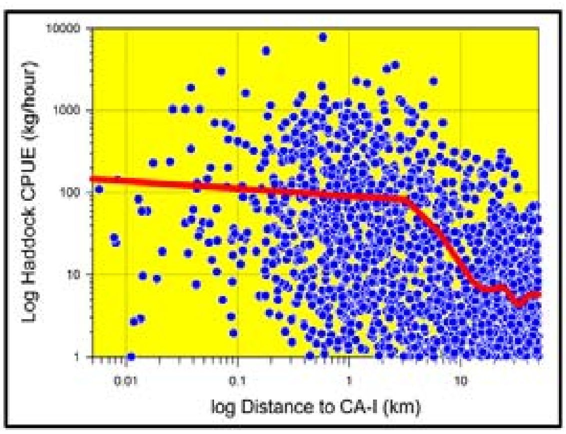
Advent of high resolution data
VMS Ping rate 1 hour
Vessel Hours
= 1-8
= 9-25
= 26-63
= 64-145
= 146-309

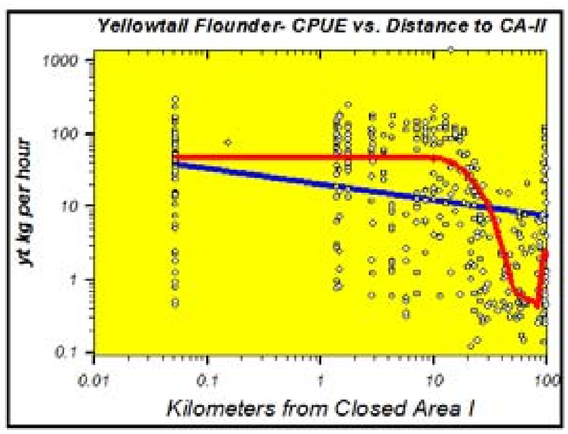

13 species+
revenue per
haul
+
location
variables
2003 VMS &
2003
Observer Data
N2003=5,106
2001-2003
10,130 tows

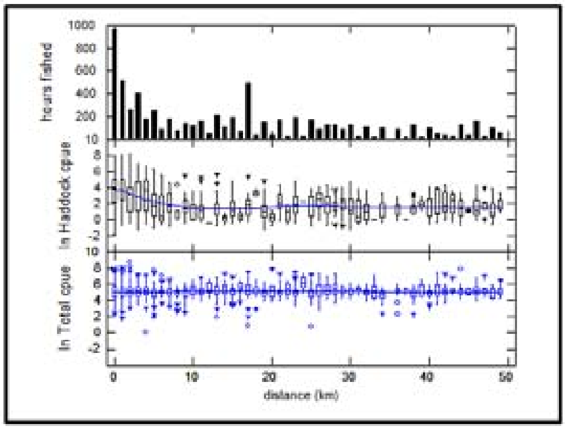

The Sound Problem is Essentially a Gradient Analysis
Pre-Sound Source
During or Post Exposure
Abundance
Distance from Source
• Depends on nature of source: single-event, intermittent, continuous
• Temporal aspects of how quickly gradients form and degrade
• Threshold effects?

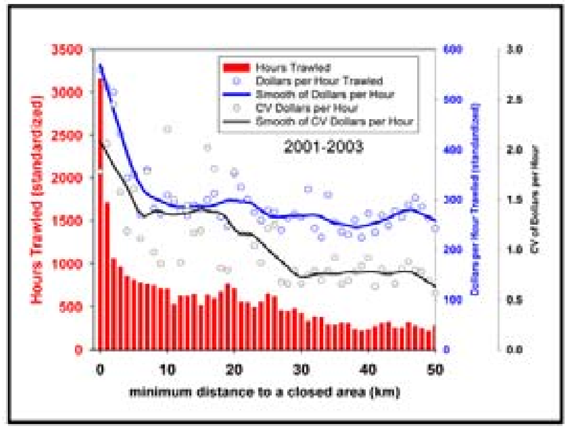

The Sound Problem is Essentially a Gradient Analysis
Hysteresis post-exposure?
?
Behavior
Masking
Thresholds
Physiology
Death
Abundance
Distance from Source
• Depends on nature of source: single-event, intermittent, continuous
• Temporal aspects of how quickly gradients form and degrade
• Threshold effects?

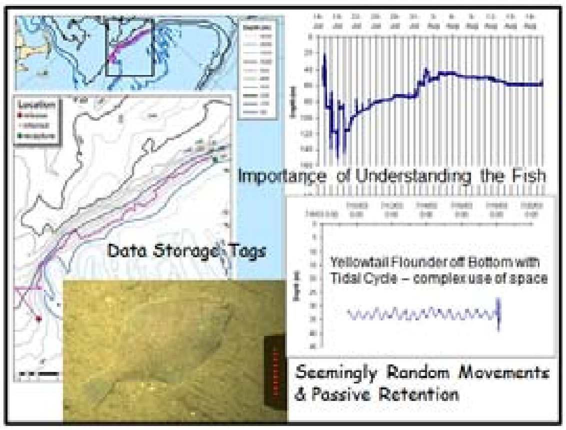

High Resolution CPUE
for Gradients
0 lbs.
0.1-500 lbs.
501-1000 lbs
1001-3000 lbs.
3001-7500 lbs
Haddock
CPUE

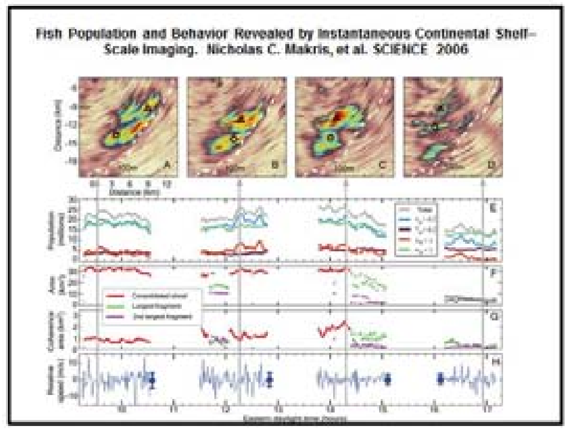

Log Haddock CPUE (kg/hour)
10000
1000
100
10
1
0.01
0.1
1
10
log Distance to CA-I (km)


Yellowtail Flounder- CPUE vs. Distance to CA-II
yt kg per hour
1000
100
10
1
0.1
0.01
0.1
1
10
100
Kilometers from Closed Area I



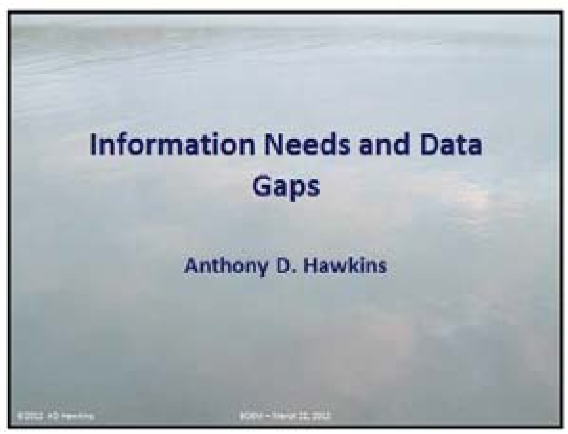


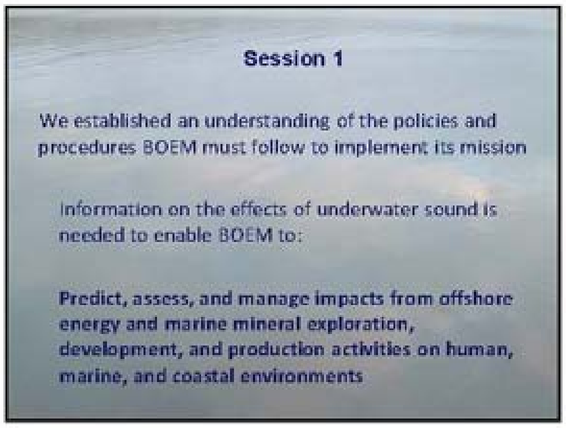


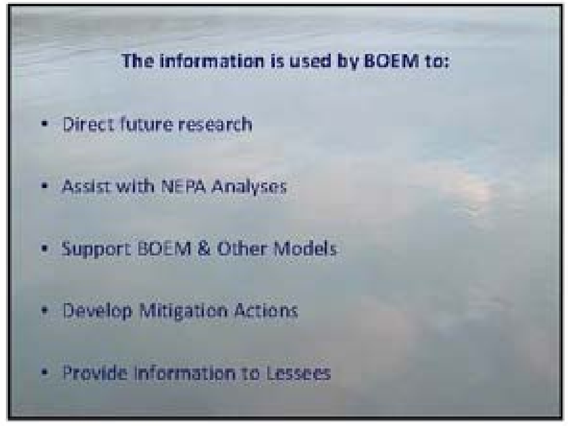


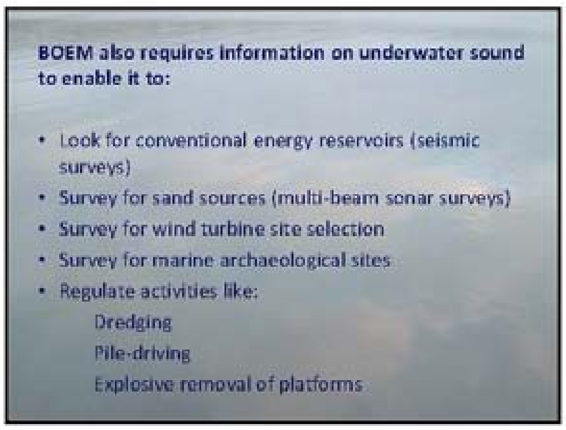
Summary

- Catch data are of limited utility in understanding impacts of sound, depending on their spatial and temporal resolution and variability – many observations, multispecies
- Experimental surveys control for many factors affecting abundance but are imprecise
- Variety of statistical methods can be applied to address the gradient issue and standardize catch rates
- Understanding fish behavior by using new technologies such as DSTs & Waveguide - important new developments

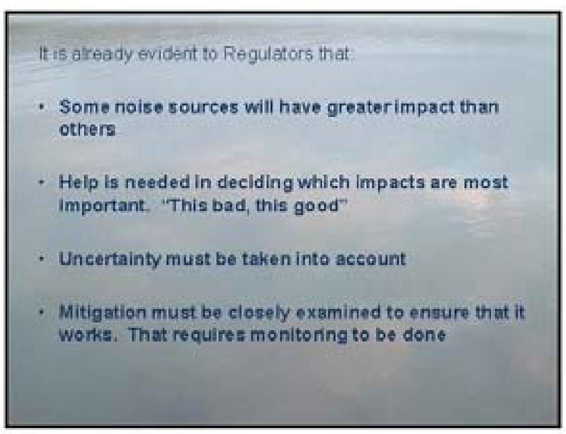



Session 1
We established an understanding of the policies and procedures BOEM must follow to implement its mission
Information on the effects of underwater sound is needed to enable BOEM to:
Predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments

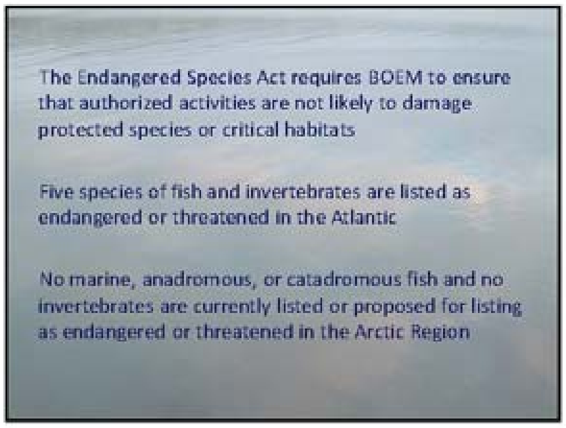

The information is used by BOEM to:
• Direct future research
• Assist with NEPA Analyses
• Support BOEM & Other Models
• Develop Mitigation Actions
• Provide Information to Lessees

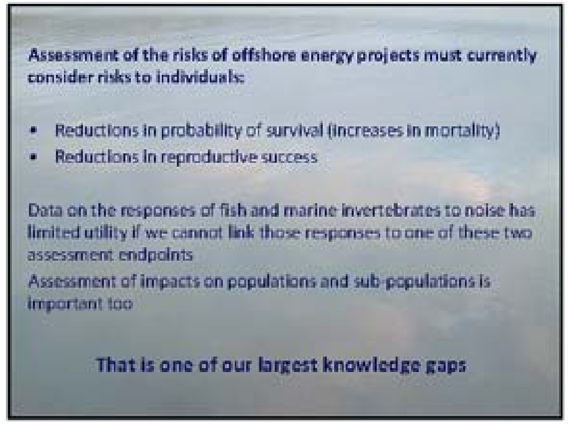

BOEM also requires information on underwater sound to enable it to:
• Look for conventional energy reservoirs (seismic surveys)
• Survey for sand sources (multi-beam sonar surveys)
• Survey for wind turbine site selection
• Survey for marine archaeological sites
• Regulate activities like:
Dredging
Pile-driving
Explosive removal of platforms

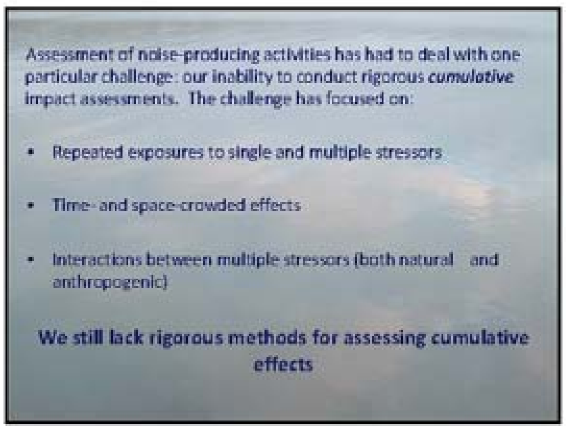

The Study Program of BOEM is crucial to taking knowledge forward. It establishes priorities on the basis of:
• Mission relevance
• Scientific merit
• Technical feasibility
• Timing
• Applicability

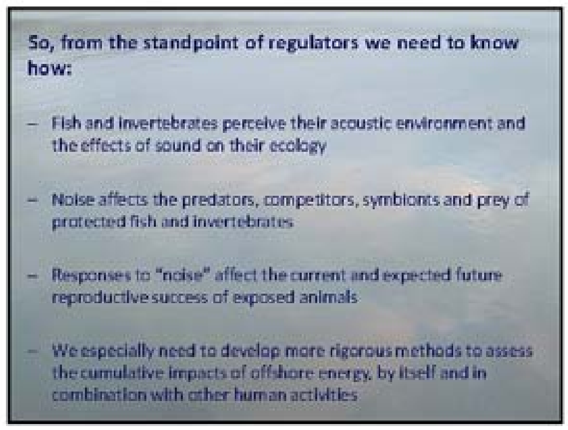

It is already evident to Regulators that:
• Some noise sources will have greater impact than others
• Help is needed in deciding which impacts are most important. "This bad, this good"
• Uncertainty must be taken into account
• Mitigation must be closely examined to ensure that it works. That requires monitoring to be done

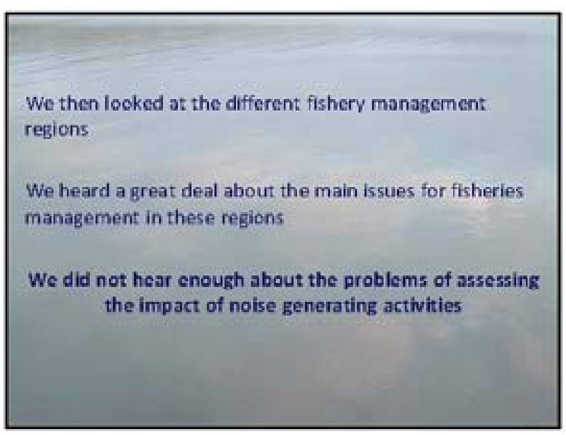

In Session 2 we tried to define the fish and invertebrate species, habitats and fisheries of concern to regulators, fishery managers and the fishing community
We first considered endangered or threatened species – which are at the top of the list in terms of concern

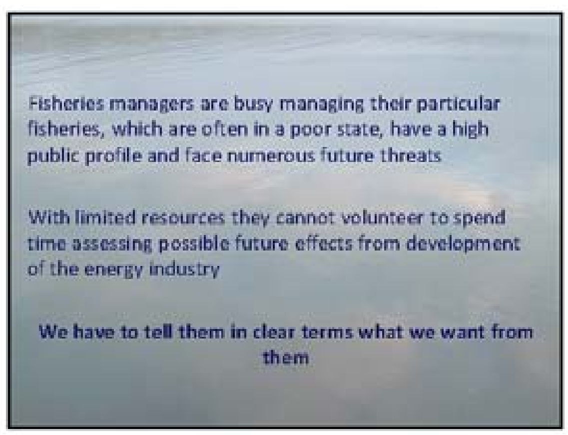

The Endangered Species Act requires BOEM to ensure that authorized activities are not likely to damage protected species or critical habitats
Five species of fish and invertebrates are listed as endangered or threatened in the Atlantic
No marine, anadromous, or catadromous fish and no invertebrates are currently listed or proposed for listing as endangered or threatened in the Arctic Region

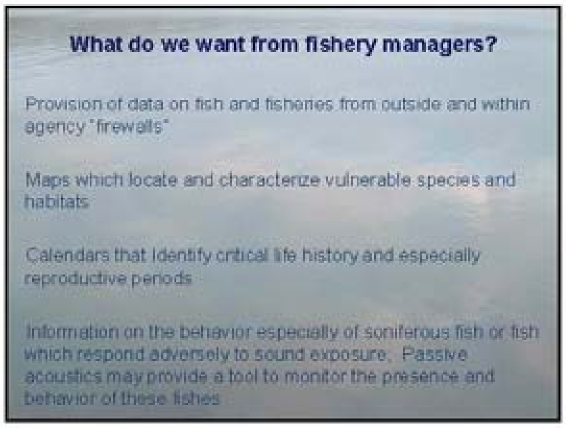

Assessment of the risks of offshore energy projects must currently consider risks to individuals:
• Reductions in probability of survival (increases in mortality)
• Reductions in reproductive success
Data on the responses of fish and marine invertebrates to noise has limited utility if we cannot link those responses to one of these two assessment endpoints
Assessment of impacts on populations and sub-populations is important too
That is one of our largest knowledge gaps

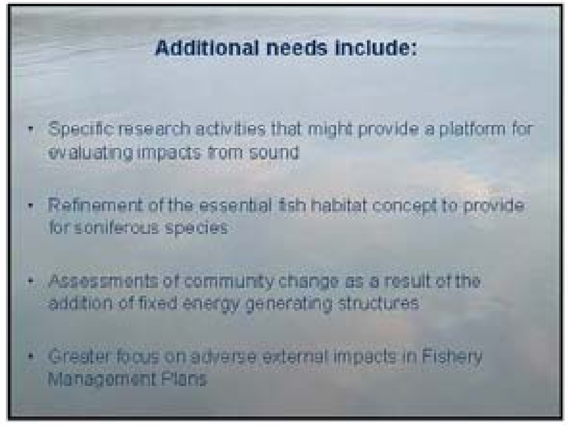

Assessment of noise-producing activities has had to deal with one particular challenge: our inability to conduct rigorous *cumulative* impact assessments. The challenge has focused on:
• Repeated exposures to single and multiple stressors
• Time- and space-crowded effects
• Interactions between multiple stressors (both natural and anthropogenic)
We still lack rigorous methods for assessing cumulative effects


So, from the standpoint of regulators we need to know how:
– Fish and invertebrates perceive their acoustic environment and the effects of sound on their ecology
– Noise affects the predators, competitors, symbionts and prey of protected fish and invertebrates
– Responses to "noise" affect the current and expected future reproductive success of exposed animals
– We especially need to develop more rigorous methods to assess the cumulative impacts of offshore energy, by itself and in combination with other human activities


We then looked at the different fishery management regions
We heard a great deal about the main issues for fisheries management in these regions
We did not hear enough about the problems of assessing the impact of noise generating activities

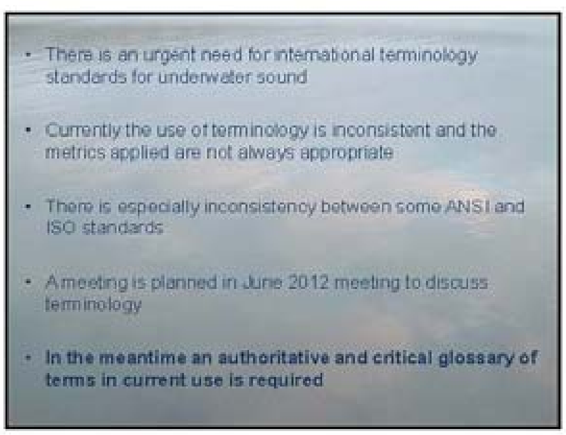

Fisheries managers are busy managing their particular fisheries, which are often in a poor state, have a high public profile and face numerous future threats
With limited resources they cannot volunteer to spend time assessing possible future effects from development of the energy industry
We have to tell them in clear terms what we want from them


What do we want from fishery managers?
Provision of data on fish and fisheries from outside and within agency "firewalls"
Maps which locate and characterize vulnerable species and habitats
Calendars that identify critical life history and especially reproductive periods
Information on the behavior especially of soniferous fish or fish which respond adversely to sound exposure. Passive acoustics may provide a tool to monitor the presence and behavior of these fishes

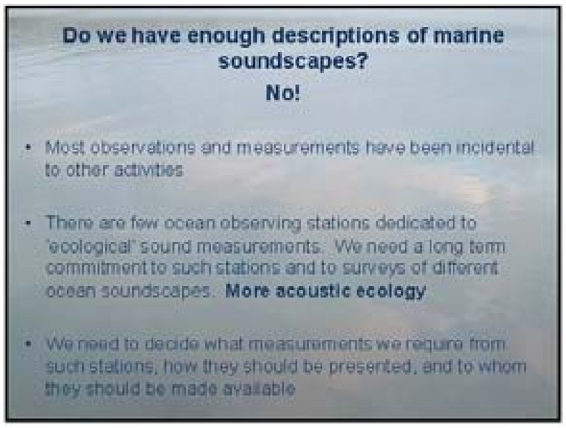

Additional needs include:
• Specific research activities that might provide a platform for evaluating impacts from sound
• Refinement of the essential fish habitat concept to provide for soniferous species
• Assessments of community change as a result of the addition of fixed energy generating structures
• Greater focus on adverse external impacts in Fishery Management Plans

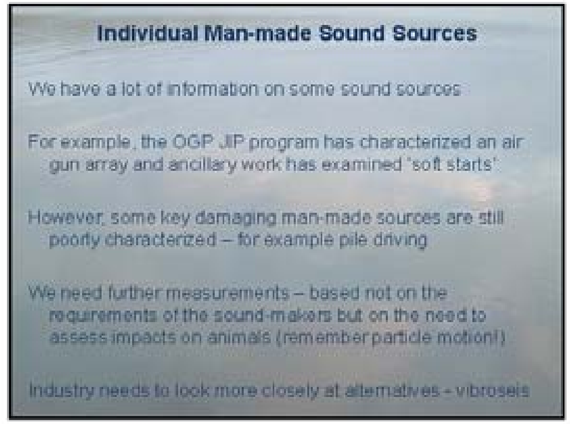

In all the fisheries management areas:
• Some species (and life stages) are especially vulnerable to man-made sounds – for example during spawning
• There is potential for energy developments to have adverse effects upon these species and their habitats
• However, these species and habitats have rarely been identified, let alone considered within fishery management plans. The degree of risk to individuals or populations has not been assessed
• More information is needed on these species, their location and their habitat requirements

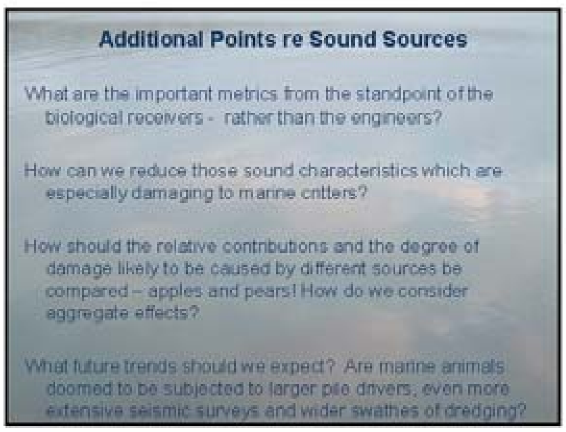

Session 3 considered Sources and Sound Exposure
We first considered the Terminology for describing Underwater Sounds

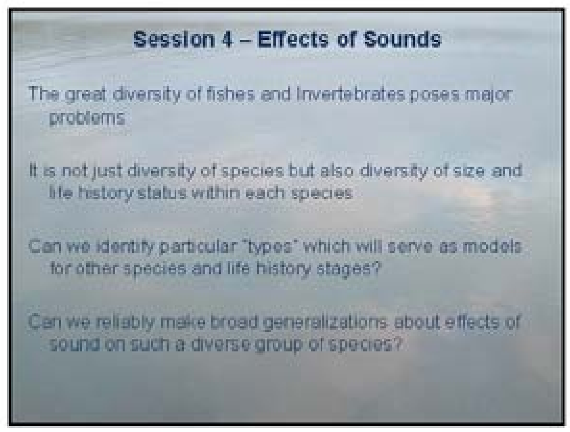

• There is an urgent need for international terminology standards for underwater sound
• Currently the use of terminology is inconsistent and the metrics applied are not always appropriate
• There is especially inconsistency between some ANSI and ISO standards
• A meeting is planned in June 2012 meeting to discuss terminology
• In the meantime an authoritative and critical glossary of terms in current use is required


The next topic we addressed was the description of marine soundscapes
There are issues over:
• the description and quantification of soundscapes
• identifying trends in levels and characteristics
• Deciding when soundscapes are adversely affected by man-made sounds
• Presentation of noise budgets can be misleading depending on the units used









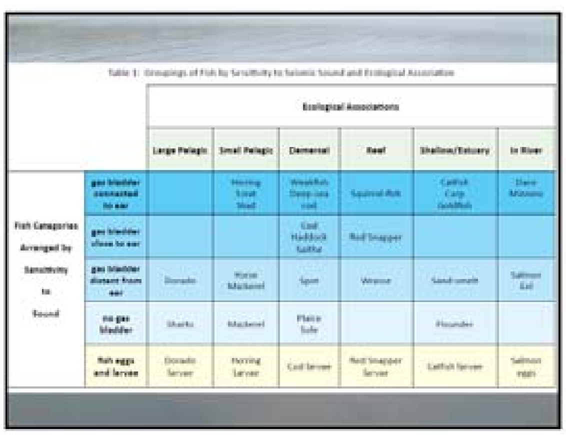
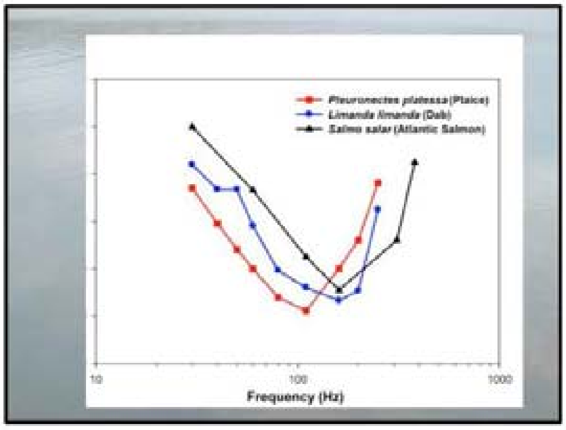
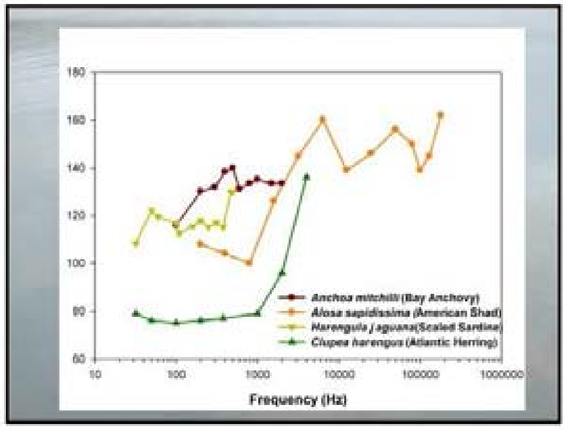


Table 1: Groupings of Fish by Sensitivity to Seismic Sound and Ecological Association

		Ecological Associations					
		Large Pelagic	Small Pelagic	Demersal	Reef	Shallow/Estuary	In River
Fish Categories Arranged by Sensitivity to Sound	gas bladder connected to ear		Herring Sprat Shad	Weakfish Deep-sea cod	Squirrel fish	Catfish Carp Goldfish	Dace Minnow
	gas bladder close to ear			Cod Haddock Saithe	Red Snapper		
	gas bladder distant from ear	Dorado	Horse Mackerel	Spot	Wrasse	Sand-smelt	Salmon Eel
	no gas bladder	Sharks	Mackerel	Plaice Sole		Flounder	
	fish eggs and larvae	Dorado larvae	Herring larvae	Cod larvae	Red Snapper larvae	Catfish larvae	Salmon eggs





How can we obtain better data on hearing and especially masking?

We need well equipped field sites for examining the hearing abilities of a range of species (and perhaps also their behavior) in the sea, at depth, under quiet ambient noise conditions

Specially designed tanks can also enable precisely controlled sound stimuli to be presented to fish and invertebrates

Instrumentation is urgently needed that will allow us to monitor the particle motion stimuli presented to fish and invertebrates

Then we might examine representative species and obtain valid data applicable to a range of similar animals

Similar principles apply to the evaluation of injury and physiological damage to animals

Michele has shown us what can be achieved using specially designed facilities – and more importantly well defined protocols - in terms of measuring effects

These pioneering techniques can now be rolled out to examine effects both in the laboratory and in the field

It should be possible to look at the effects of different stimuli including sound pressure and particle motion, and to look at factors like rise-time, kurtosis, cumulative effects, recovery and other important aspects of sound exposure

We can then look at:

Thresholds or criteria for the occurrence of different effects

The nature of the effects and how they change with different sound types and levels

The source characteristics that cause detrimental effects; e.g., magnitude, rise time, duration, kurtosis, duty-cycle

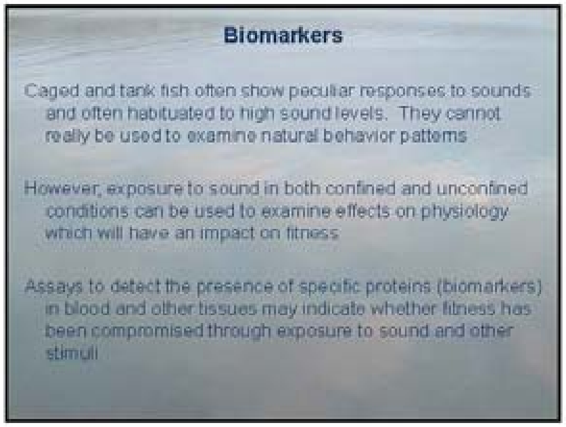
The responses of different types of animal

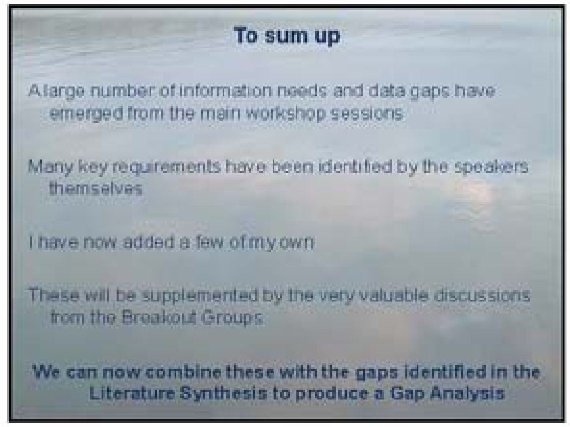
Behavior

Alex, John and Svein showed us what can now be achieved in terms of examining responses of fish in the actual sea. **Fish do react to sounds (sometimes!)**

Sonar and echo-sounding observations, analysis of catches and other techniques like the examination of the tracks of tagged fish and the use of Waveguide can enlarge our knowledge of how fish behave in response to real sounds. **We should be able to define behavioral thresholds from these field experiments**

We still have the problem of deciding which responses are significant in terms of impairing fitness


Biomarkers
Caged and tank fish often show peculiar responses to sounds and often habituated to high sound levels. They cannot really be used to examine natural behavior patterns
However, exposure to sound in both confined and unconfined conditions can be used to examine effects on physiology which will have an impact on fitness
Assays to detect the presence of specific proteins (biomarkers) in blood and other tissues may indicate whether fitness has been compromised through exposure to sound and other stimuli


To sum up
A large number of information needs and data gaps have emerged from the main workshop sessions
Many key requirements have been identified by the speakers themselves
I have now added a few of my own
These will be supplemented by the very valuable discussions from the Breakout Groups
We can now combine these with the gaps identified in the Literature Synthesis to produce a Gap Analysis


The future
This meeting has demonstrated clearly that there are benefits to be gained from bringing together Regulators, Noise-makers, Environmentalists, Fishery Managers to discuss the effects of underwater sounds
There are also advantages in combining discussion on the effects on different animals. There are even benefits from having marine mammal specialists present for discussions on fish!
How can we ensure that these fruitful contacts are maintained?

Appendix C: Biosketches of Invited Participants

Michael Ainsle
Senior Scientist at TNO- The Hague, Netherlands
Visiting Professor at ISVR -University of Southampton, UK

Dr. Ainslie graduated in physics from Imperial College (University of London) and in mathematics from the University of Cambridge. He carried out his PhD research at the Institute of Sound and Vibration Research (University of Southampton) on the interaction of underwater sound with the seabed. Dr. Ainslie has 25 years' experience in underwater acoustics, with special interest in its application to sonar performance modeling, the impact of underwater sound on marine life and the international standardization of acoustical terminology. He retains strong ties with ISVR, where he currently holds the position of Visiting Professor. His publications include the book ' Principles of Sonar Performance Modeling' (Springer, 2010) and 32 peer reviewed journal articles. He is a fellow of the Acoustical Society of America and of the UK Institute of Acoustics (IOA), and in 1998 was awarded the IOA's A B Wood medal for his work on seabed interactions and sonar performance modeling.

Michel André
Professor at the Technical University of Catalonia (BarcelonaTech, UPC)
Director of the Laboratory of Applied Bioacoustics (LAB)

Dr. André is an Engineer in Biotechnologies graduated from the Institut National des Sciences Appliquées, INSA, Toulouse, France. He holds a Master degree in Bioquemistry, a Master degree in Animal Physiology from the Université Paul Sabatier de Toulouse, France and a PhD on sperm whale acoustics from the University of Las Palmas de Gran Canaria (Spain).

His research involves the development of acoustic technologies for the control of noise pollution in the marine environment; the study of the biological and pathological impact of noise pollution on cetacean acoustic pathways and marine organisms; the mathematical, physical, morpho- and electro-fisiological mechanisms of the cetacean bio-sonar, as well as the extraction of the information from their acoustic signals.

Thomas Carlson
Program Manager
Marine Sciences Laboratory
Department of Energy Pacific Northwest National Laboratory

D.r. Carlson has over 30 years of experience working in underwater acoustics and risk assessment. Current activities are investigation of the effects of anthropogenic sound on fish and marine mammals and development and application of active and passive acoustic systems for detection, classification, and localization of fish and marine mammals. He is also currently active in the development of models to quantify the exposure and assess the risk of barotrauma and hearing system impacts to fish and marine mammals and laboratory and field studies to obtain data required for risk assessment.

Brandon M. Casper
Department of Biology
University of Maryland

Dr. Brandon M. Casper is a postdoctoral research scientist in the Aquatic Bioacoustics Lab of Dr. Arthur Popper at the University of Maryland, College Park. Dr. Casper's research interests have centered on the structure and function of auditory systems in aquatic vertebrates. He has published a number of peer reviewed scientific papers and has authored several review chapters on the auditory system of sharks, rays, and other aquatic animals. Dr. Casper's recent work at the University of Maryland has been exploring the physiological responses to impulsive pile driving stimuli in fishes. These experiments, currently in the data analysis and manuscript writing stages, will provide some of the first qualitative and quantitative controlled studies of the effects of pile driving on fishes. He has been an invited speaker at several Acoustical Society of America annual meetings and the Second International Conference on the Effects of Noise on Aquatic Life in Cork, Ireland. He also recently returned from an international collaboration focusing on shark hearing abilities in Perth, Australia with labs from University of Western Australia and Dartmouth College. Dr. Casper received his Biology degree from Ohio University, his Master's degree in Marine Biology from Boston University, and his Ph.D. in Biological Oceanography from the University of South Florida.

John Dalen
Principal Research Scientist
Institute of Marine Research, Bergen, Norway

Dr. Dalen conducts a variety of fisheries research including hydro-acoustic abundance estimation and size classification of fish and plankton, developing methods for direct in situ observations of fish, and assessing impact of the behaviour of single fish and shoals on assessment methods. He has specific expertise in long range omni-directional and multibeam sonars, fish behaviour vs. anthropogenic sound, lethal impact on fish vs. seismic investigations, and blasting. Other work interests include total quality management and organizational development.

Jaclyn Daly
Fisheries Biologist
NOAA National Marine Fisheries Service

Jaclyn Daly is a fisheries biologist with NOAA's National Marine Fisheries Service in Charleston, South Carolina. She has extensive experience in assessing impacts to marine mammals from anthropogenic noise under the Marine Mammal Protection Act and currently works within NOAA's Office of Habitat Conservation to protect fisheries and their habitat in a regulatory capacity. Jaclyn specializes in working with action agencies to minimize and mitigate for adverse impacts from coastal construction activities such as pile driving and renewable energy development.

Alex De Robertis
Research Fisheries Biologist
National Marine Fisheries Service's Alaska Fisheries Science Center
Seattle, Washington

Dr. DeRobertis is a research fisheries biologist with the National Marine Fisheries Service's Alaska Fisheries Science Center in Seattle, Washington. His interests have been slowly increasing in latitude and up the food chain; he started as a zooplankton ecologist working off the west coast and now works primarily on fish in Alaska. His work is focused on fisheries acoustics, and involves the application of sonar to understand the abundance, distribution and behavior of marine organisms. He has a longstanding interest in sensory biology and animal behavior, and has worked extensively on the reactions of fish to approaching research vessels. He enjoys messing around in boats both when at work and play.

Christine Erbe
Centre for Marine Science & Technology, Curtin University
Perth, Western Australia

Dr. Erbe holds an MSc in physics (University of Dortmund, Germany) and a PhD in geophysics (University of British Columbia, Canada). She accidentally landed in marine bioacoustics in 1994 and has never looked back. Having grown up in Germany's coal belt, she relished Canada's sea breeze, yet discovered she got terribly seasick, hence chose to train captive beluga whales for masked hearing experiments. Christine worked for the Canadian Government (Fisheries & Oceans) from 1994-2001 on underwater noise, effects on marine mammals and noise regulation. She worked as a private consultant performing bioacoustic impact assessments until she joined JASCO as Director of Australian Operations in 2006. In 2011 she couldn't resist the temptation to get back into academia, and became Director of the Centre for Marine Science & Technology at Curtin University in Perth, Western Australia. Christine's interests are underwater sound (ambient, anthropogenic & biological), sound propagation and effects on marine fauna. Dr. Erbe was unable to attend the Workshop but was instrumental in preparing the paper presented by Dr. Rob McCauley

Richard Fay
Adjunct Scientist
Marine Biological Laboratory

Richard R. Fay graduated from Bowdoin College with a BA (1966), Connecticut College with an MA (1968), and from Princeton University with a Ph.D (1970), all in experimental Psychology. He held a poat-doctoral position with Georg von Bekesy at the Laboratory of Sensory Sciences, Honolulu, HI from 1972-1974. Dr. Fay spent one year (1974-1975) as Assistant Professor of Otolaryngology at the Bowman Gray School of Medicine before being appointed Associate Professor of Psychology at Loyola University Chicago in 1975. He stayed at Loyola, reaching the rank of Professor and Distinguished Research Professor, Director of the Interdisciplinary Neuroscience Minor, and Director of the Parmly Hearing Institute until 2011. He began summer research at the Marine Biological Laboratory, Woods Hole, MA in 1993 where he was a Whitman Investigator until 2010. Dr. Fay was appointed Adjunct Scientist at the MBL in 2011 and retired from Loyola University Chicago with Emeritus status in 2011. His entire academic career has focused on hearing mechanisms in vertebrates, and especially the hearing and sensory behavior of goldfish, oyster toadfish, and plainfin midshipman fish. Dr. Fay's research has been continuously supported by the NIH and the NSF since 1975, and he has over 140 publications in peer-reviewed journals. He is the founding co-editor of the Springer Handbook of Auditory Research, with 43 volumes appearing so far and is an Associate Editor for Animal Bioacoustics for the Journal of the Acoustical Society of America.

Kevin Friedland
Researcher, National Marine Fisheries Service at the Narragansett Laboratory
Rhode Island, USA

Dr. Friedland is a researcher with the National Marine Fisheries Service at the Narragansett Laboratory in Rhode Island, USA. He holds a bachelors degree in ecology from Rutgers College in New Jersey and a doctorate from the College of William and Mary in Virginia. His dissertation research was on the distribution and feeding ecology of Atlantic menhaden. During his professional career he has done research on menhaden, bluefish, sea herring, sturgeon, eel, haddock, and salmon. His publications cover a range of topics including: estuarine ecology of fishes, functional morphology, feeding ecology, recruitment processes, fisheries oceanography, stock identification, ecosystem ecology, and climate change. His current research is on the effects of growth on the early maturation and survival of Atlantic salmon and the factors controlling the recruitment of haddock. He has served as chair of several ICES committees including the North Atlantic Salmon Working Group, the Study Group on Stock Identification, and the ICES standing committee on Anadromous and Catadromous Fishes.

Roger Gentry
Special Advisor to the Joint Industry Program
President, ProScience Consulting LLC

Roger L. Gentry was born in 1938, completed a Master's degree in 1966 in marine mammal acoustics, a Ph. D. in animal behavior at the University of California, Santa Cruz in 1970, and in 1971 a postdoctoral fellowship on fur seals at the University of Adelaide, South Australia. He worked as a field biologist at the National Marine Mammal Laboratory in Seattle from 1974 to 1998 conducting field research on whales, penguins and many species of seals. He helped pioneer Time-Depth recorders, published papers and books on fur seals, and convened an international symposium on fur seal biology. From 1995 through 2005 he created an acoustics program for NOAA in Silver Spring, Maryland that advised regulators on marine acoustic issues including ATOC, low- and mid-frequency sonar, seismic air guns, and explosions. There he convened expert panels to write noise exposure criteria for marine mammals (published 2007) and for fish and turtles (being written). He led workshops on acoustic resonance, rectified diffusion, shipping noise, and monitoring underwater ambient noise. He has also worked on acoustics from legal (Department of Justice) and treaty (Department of State) standpoints. From 2006 to 2009 he was Program Manager for the Joint Industry Program, a London-based consortium of oil companies funding research on the effects of underwater noise on animals to meet the needs of international regulators. Presently he is an advisor to that group, speaks for it in international meetings on acoustics, and continues to publish about marine mammals.

Christopher Glass
Research Professor
University of New Hampshire

Dr. Glass is Director of the northeast Consortium and Research professor in the Ocean Process Analysis Laboratory of EOS. A specialist in animal behavior and marine biology, Dr. Glass has a long record of conservation gear research in New England's fisheries. Prior to joing The Northeast Consortium, he served for 9 years as Director of Marine Conservation at Manomet Center for Conservation Sciences where he specialized in the study of fish behavior and applying knowledge of this subject to develop more selective fishing gears directed at reducing bycatch and discard in commercial fisheries. Previously he worked for 14 years at the marine Laboratory in Aberdeen, Scotland and has worked extensively on bycatch reduction and conservation engineering programs throughout Europe and North America. Dr. Glass has been a featured lecturer on sustainable fisheries topics at numerous international conferences and has published extensively in scientific journals. His education includes a B.SC in Zoology (Marine Biology and Animal Behavior) from The Queens University, Belfast and a Ph.D. from The University of Glasgow.

Michele B. Halvorsen
Senior Scientist
Battelle – Pacific Northwest National Laboratory
Sequim, WA

Dr. Halvorsen has been conducting research in neuroethology and neurophysiology of mammals and fish since 1997. Since 2004 she has studied the impacts of anthropogenic underwater noise on marine animals. Her current research focus involves the effects of anthropogenic sound on the physiology and behavior of freshwater and marine fish and development of the tools needed to assess the environment and the animals. Dr. Halvorsen has been PI and Co-PI for projects involving the effects of noise on fish, these projects were funded by Naval Operations (ERD), BOEMRE, CALTRANS, NCHRP, Snohomish PUD, and DOE. Recent research completions include assessment of the barotrauma response of juvenile salmon to high energy impulsive sounds generated by pile driving and the effect of the US Navy's low- and mid- frequency sonar on the hearing of several fish species. Current research underway addresses the barotrauma and hearing response of marine fish species to noise generated by tidal power electric power generators, and development of analysis models to obtain response metrics from diverse physiological observations of animal condition. Additionally, she is involved with oversight of a team on the development of sound recording tools and software (called aquatic acoustic metrics interface- AAMI), along with the development of a passive acoustic tetrahedral array system for monitoring areas around tidal turbine power generators.

Anthony Hawkins
Loughine Limited and University of Aberdeen UK

Dr. Anthony Hawkins is currently the Managing Director of Loughine Limiteed, a small company carrying our research and providing advice for a variety of clients including the UK government, the Scottish Government, and the European Commission. His interests include marine fisheries and their management; underwater acoustics, including the sounds made by marine organisms and the imact of man-made sounds on aquatic organisms; fish behavior and fish migrations; and the marine environment and its evaluation and conservation. His 46-year research career has focused on the behavior of fish, including the sensory abilities of fish, fish migrations and movements, the response of fish to pollutants, and the management of marine and freshwater fisheries. He is the author of a series of key papers on the hearing abilities of fish – conducted on an acoustic range in the sea. He is a member of the Advisory Board of the sound and Marine Life Joint Industry Programme (JIP) run by the International Association of Oil and Gas producers (funding research into the impact of underwater noise).

Mike Jenkerson
Geophysical Advisor
ExxonMobil Exploration Company

Mike Jenkerson has worked in geophysical operations for the past 33 years; for the last 15 years he has specialized in the environmental evaluation, acoustic analysis and mitigation of sound generated by oil and gas exploration and production operations. Mike Jenkerson has worked on the environmental program for western gray whales offshore Sakhalin Island since 2001. Mike Jenkerson has also been the research category chair for the category on sound source generation and propagation for the OGP sound and marine life JIP. Mike Jenkerson has been researching alternative marine sources for over 15 years and has been evaluating marine vibrator seismic sources. He has been the ExxonMobil representative on the marine vibroseis JIP project for the last 4 years.

Craig Johnson
Fishery Biologist
National Marine Fisheries Service
Endangered Species Division

Mr. Johnson has worked on fish and wildlife conservation issues for the past 34 years, specializing in assessing the effects of human activity on endangered and threatened species. Mr. Johnson has studied bowhead whales in the Beaufort Sea, fur seals in the Bering Sea, anadromous fish throughout coastal Alaska, wolves in northern Canada, and wetlands throughout North America. Mr. Johnson supervised the U.S. Fish and Wildlife Service's endangered species program in the Great Lakes Region and Upper Mississippi River; was an advisor to the Assistant Secretary for Fish and Wildlife and Parks in the Department of the Interior on endangered species, marine mammals, and biodiversity; and supervised the U.S. Fish and Wildlife Service's South Florida Office, which was responsible for fish and wildlife protection associated with the effort to restore the Everglades. Since 1998, Mr. Johnson has overseen the National Marine Fisheries Service's interagency consultation program.

Svein Løkkeborg
Principal Scientist
Research Group Fish Capture
Institute of Marine Research, Bergen, Norway

Dr. Løkkeborg obtained his PhD at the University of Bergen in 1990. He has conducted many behavioural field investigations using underwater camera and telemetry technology to study swimming pattern, activity rhythms and foraging strategies in fishes and crabs. Dr. Løkkeborg has been involved in numerous fishing-gear related studies including most fishing gears, and he has studied problems such as methods for fish abundance estimation, harvest strategies, selectivity and bycatch. He has been working on three aspects related to ecosystem effects of fishing activities: mitigation measures to reduce bycatch of seabirds in longline fisheries, impacts of trawling on benthic communities and lost fishing gears (ghost fishing). Dr. Løkkeborg has also been working with issues related to interactions between fishing activities and the oil industry, in particular effects of seismic activity on fish behaviour and fisheries. Dr. Løkkeborg has published 50 peer-review papers based on his scientific research activities. During his two sabbaticals, he worked as visiting scientist at Hatfield Marine Science Center in Newport (Oregon, USA) and at the Fishing Technology Service (FIIT) of the Fisheries Department of FAO (Rome, Italy). He is member of ASA Standards Working Group on Effects of Sound on Fishes and Sea Turtles, ICES-FAO Working Group on Fishing Technology and Fish Behaviour, ACAP Seabird Bycatch Working Group, and Referral Group of Southern Seabird Solutions Trust.

Joseph Luczkovich
Associate Professor of Biology and an Associate Scientist
Institute for Coastal Science and Policy
East Carolina University

Joseph Luczkovich is an Associate Professor of Biology and an Associate Scientist in the Institute for Coastal Science and Policy at East Carolina University. He was educated at Lehigh University (B.S. Biology), Rutgers University (M.S. Ecology), The Florida State University (PhD Biological Sciences), and completed post-doctoral fellowship at the Harbor Branch Oceanographic Institute, in Ft. Pierce, Florida. It was at Harbor Branch that he was introduced to the sound production of drums and croakers (Family Sciaenidae) by R. Grant Gilmore. After this post-doc, he worked at Humboldt State University and NC State University, and then joined the faculty at East Carolina University. He has published extensively on the use of passive acoustics in monitoring sound-producing fishes. Dr. Luczkovich has used the passive acoustic approach to determining spawning areas of Sciaenidae, which make sounds during their spawning activities, with males making the sounds as advertisement calls to attract females. By recording sounds of captive specimens of each of the four species (silver perch, *Bairdiella chrysoura*, weakfish, *Cynoscion regalis*, spotted seatrout, *C. nebulosus*, and red drum, *Sciaenops ocellatus*), Dr. Luczkovich and colleagues were able to identify the species making the calls simply by listening to captive fish and comparing these sounds to field recordings. These recordings were analyzed for their spectral properties and correlated with plankton samples, which lead to the maps of spawning areas for each species. One sound recorded in this study was difficulty to identify: "the chatter" sound. Previous researchers had misidentified it as being produced by weakfish, but the ECU group realized that it was produced instead by striped cusk eels (*Ophididon marginatum*). From these recordings, Luczkovich and the ECU Sciaenid Acoustics Research Team (SART) discovered that silver perch became acoustically inactive when bottlenose dolphins (*Tursiops truncatus*) making signature whistles were in the area. He has recently being using acoustic data loggers to monitor the impact of anthropogenic noises from vessels on fish sound production and is interested in role the species-specific sounds may play in reproductive isolation of the Sciaenidae, which could lead to speciation events within this group. Dr. Luczkovich continues to study the sound production of fishes and marine mammals in Pamlico Sound, Atlantic Ocean and the Caribbean Sea.

Steve A. MacLean
Protected Species Coordinator/Fishery Analyst
North Pacific Fishery Management Council

Stephen Ahgeak MacLean is the Protected Species Coordinator and Fishery Analyst for the North Pacific Fishery Management Council. Mr. MacLean joined the Council staff in May, 2011. Before joining the Council staff, he spent six years as the Bering Sea and Polar Marine Program Director for The Nature Conservancy where he worked closely with Bering Sea commercial fishing interests to reduce potential impacts to protected species and habitat. Mr. MacLean has also worked for a private ecological consulting firm and State and University wildlife management departments. He has extensive experience living and working in rural Alaska. Mr. MacLean received a Bachelor of Arts degree in Biology from Whitman College in Walla Walla, Washington and a Master of Science degree in Wildlife and Fisheries Sciences from Texas A&M University. His MS thesis concerned the occurrence, behavior, and genetic diversity of bowhead whales in the Sea of Okhotsk in the Russian far east.

David Mann
Associate Professor
University of South Florida

Dr. Mann is Associate Professor of Biological Oceanography at the University of South Florida. His laboratory studies marine bioacoustics with a focus on hearing and sound production in fishes and marine mammals. Laboratory studies utilize neurophysiological techniques to investigate the neural mechanisms of hearing and sound production. His lab also uses SCUBA dividing with underwater video to identify and study sounds produced by fishes during courtship and spawning. Recent work has focued on sound production by sciaenids (croakers and drums) in the estuaries of Florida. New research is aimed at studies on spawning aggregations of groupers. One major thrust over the next few years is the deployment of a large, sparse passive acoustic array on the West florida Shelf to track the locations of cetaceans relative to physical oceanography. His labe is also involved in studies of the hearing abilities of manatees and dolphins with both captive trained marine mammals, and wild and stranded cetaceans. Dr. Mann received his Ph.D. from MIT/Woods Hole Oceanographic Institution.

Rob McCauley
Associate Professor
Centre Marine Science and Technology, Curtin University, Western Australia

Dr. McCauley has been studying sound in the ocean since 1987, having amassed an extensive and strategic collection of Australian ambient sea noise. His primary research interest is the study of the production, reception and use of sound and of the impacts of sound on marine fauna. Dr. McCauley has long term sampling regimes using passive acoustic technology developed at Curtin, spread between north Western Australia, around the southern Australian coast to the central NSW coast. Since 1994 he has carried out research projects studying the impacts of vessel and oil exploration noise (seismic) on humpback whales, on impacts of seismic on turtles, fish and invertebrates and in elaborating marine fauna habits, migratory routes and abundance using passive acoustics.

Jennifer Miksis-Olds
Research Associate and Assistant Professor
Penn State University

Dr. Miksis-Olds is a Research Associate, Applied Research Laboratory; Assistant Professor, Graduate Program in Acoustics, College of Engineering; and Assistant Professor, Wildlife and Fisheries Sciences, College of Agreiculture at Penn State University. In terms of current research, Dr. Miksis-Olds' research employes acoustic methodologies to answer biological questions in both the marine and terrestrial environments. Her primary interests include animal behaviour and communication, the effect of anthropogenic activities on animals and their environment, and the development of technology to observe animals in their natural environment. Aspects of acoustics, biologiy, oceanography, ecology, and engineering are combined to create the interdisciplinary approach necessary to extend the study of animals in their natural environment beyond where it is today. Dr. Miksis-Olds received her Ph.D. from the University of Rhode Island, Graduate School of Oceanography.

James H. Miller
NATO Undersea Research Centre
University of Rhode Island

James H. Miller earned his BSEE in 1979 from Worcester Polytechnic Institute, his MSEE in 1981 from Stanford University, and his Doctor of Science in Oceanographic Engineering in 1987 from Massachusetts Institute of Technology and Woods Hole Oceanographic Institution. Dr. Miller was on the faculty of the Department of Electrical and Computer Engineering at the Naval Postgraduate School from 1987 through 1995. Since 1995 he has been on the faculty of The University of Rhode Island where he holds the rank of Professor of Ocean Engineering and Oceanography. Dr. Miller is currently on leave from URI at the NATO Undersea Research Centre in La Spezia, Italy. He has more than 100 publications in the area of sonar, acoustical oceanography, signal processing and marine bioacoustics. In 2003, Dr. Miller was elected Fellow of the Acoustical Society of America.

Steven Murawski
Professor, St. Petersburg Downtown- Peter Betzer Endowed Chair
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Dr. Steven Murawski is a Population Dynamics/Marine Ecosystem Analysis Professor and the St. Petersburg Downtown - Peter Betzer Endowed Chair in Biological Oceanography at the University of South Florida's College of Marine Science. Dr. Murawski is currently engaged in research contributing to improved understanding of the impacts of human activities on the sustainability of ocean ecosystems. He serves as Director and Principal Investigator of the Center for Integrated Modeling and Analysis of Gulf Ecosystems (C-IMAGE), which is a 13 institution consortium investigating the Gulf oil spill impacts. His current areas of interest include understanding the Gulf of Mexico Large Marine Ecosystem in terms of multiple, simultaneous stressors through the application of integrated ecosystem assessments. Specific research includes understanding the prevalence of fish diseases in relation to the Deepwater Horizon spill, and work on new assessment techniques for Gulf reef fishes.

From 2005 to 2010, Dr. Murawski served as the Director of Scientific Programs and Chief Science Advisor for NOAA Fisheries Service. In addition to these duties, he was also the NOAA Ecosystem Goal Team Lead. As Goal Team Lead, he was responsible for out-year strategic planning and budget development for all of NOAA's ecosystem activities which amount to $1.2 billion in 2008. Prior to this, he was the Director of the NOAA Fisheries Office of Science and Technology and served as Chief Stock Assessment Scientist for the Northeast Fisheries Science Center in Woods Hole, Massachusetts (1990-2004).

During his career, Dr. Murawski has been a key representative on several national and international committees and councils. He roles included: official U.S. delegate to the International Council for the Exploration of the Sea, NOAA representative and co-chair of the White House interagency Joint Sub-Committee on Science and Technology, and member of the US steering committee for the International Institute for Applied Systems Analysis. He received his Ph.D. from the University of Massachusetts-Amherst in 1984.

Jeremy Nedwell
Director
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Dr. Jeremy Nedwell was from 1984 the Admiralty Research Lecturer in Underwater Acoustics at The Institute of Sound and Vibration Research, Southampton University, setting up the A B Wood laboratory. In 1993 he left to set up Subacoustech Ltd, a specialist consultancy in underwater acoustics. For the last 30 years, he has been interested in underwater bioacoustics, from the subtle behavioural effects of noise on the environment up to the effects of blast on divers. He has first-hand experience of underwater sound, having acted as an investigator and diving experimental subject for many military trials. In 1998 he proposed the dB_{ht} metric, which has become the chief means by which the environmental effects of windfarms are estimated and regulated in the UK.

Jerry Payne
Department of Fisheries and Oceans
Newfoundland, Canada

Jerry Payne has considerable experience in ecotoxicology and has carried out a variety of sub-lethal effect studies on issues related to oil and gas as well as pulp-mill and mining effluents. More recent work has involved pilot studies on the sublethal effects of sound. He has received awards for his contribution to environmental science.

Ann Pembroke
Vice President
Normandeau Associates, Inc.

A graduate from the University of Delaware's College of Marine Studies, Ann Pembroke has studies marine resources and impacts on coastal and OCS ecosystems for over 30 years. Her role as an environmental consultant supporting impact assessment and permitting for offshore projects brings the applied research perspective to this workshop. Ann has recent and on-going experience with deepwater port and offshore wind development projects in Maine, Massachusetts, Rhode Island, New York, New Jersey, and Delawate. Permitting for thise projects required an understanding of the activities during site exploration, development, construction, and operation that affect marine resources. Ann's background is in marine benthic and plankton ecology, specializing in impact assessment. She has managed environmental impact assessments for major coastal and offshore projects, with a particular emphasis on energy, dredging, dredged material disposal, port development, and offshore wind. Ann also recently completed an evaluation of the effects of EMF from underwater cables on marine species for BOEM.

Arthur N. Popper
Professor
University of Maryland

Associate Dean of the Graduate School and a Professor of Biology, Dr. Popper's work for many years has been directed towards understanding basic structure and function of the auditory system in vertebrates, with particular interest in the ear of fishes and its sensory hair cells. These investigations frequently involved a wide number of teleost species (e.g., goldfish, zebrafish, cichlids, American shad, sleeper gobies) and the use of the comparative approach in order to understand the function of the ear as well as its evolution. More recently, the focus of his work has become redirected to apply our expertise on fish bioacoustics to more applied questions that examine the effects of human-generated (anthropogenic) sound on fish. Dr. popper received his Ph.D. from the City University of New York and his undergraduate degree from New York University.

Roger Pugliese
Senior Fishery Biologist
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Roberto Racca
President
JASCO Applied Science

Dr. Roberto Racca has been for many years at the senior management level of JASCO Research (V.P. for Research and Development since 1992 and President since 2000), and has extensive experience in the coordination and running of complex research projects. Dr. Racca's communication and leadership abilities have been formed and demonstrated in years o scientific work both in academia and in the private sector, including active participation in many scientific symposia. Although his current professional activities are primarily in acoustics, he has worked with distinctionin orther fields including medical physics and electro-optics. In 1994 Dr. Racca was awarded the Hubert Schardin Gold Medal of the german Physical Institute in recogniction, among other work, of his innovative use of CCD imagers in high-speed videography applications. In his long professional relationship with JASCO Research Dr. Racca has played a major role in many acoustics-related projects. His research interests, along with acoustic source detection and localization, include propagation modeling and monitoring of underwater and airborne sound. His is active in the development of methods and standards for assessment of acoustic impact on marine species. Dr. Racca received his Ph.D. (Physics – Electro-Optics) from the University of Victoria.

James A. Reyff
Project Scientist
Illingworth & Rodkin, Inc.

Mr. Reyff is a nationally known expert in the measurement and evaluation of underwater sounds from marine construction projects. He has led investigations on numerous projects that involved underwater sound impacts. He has been the lead acoustical investigator on numerous projects studying impacts to marine mammals and fish. He provided testimony to the national Fisheries and Hydroacoustic Working Group, as well as resource agencies and blue ribbon commissions investigating these issues. His work in this field has been recognized by the Federal Highway Administration, California Department of Transportation and the American Association of State Highway and Transportation Officials. More importantly, his expertise, flexibility and timely efficient work have assisted projects in sensitive agency consultations regarding underwater noise impacts to aquatic species. His expertise in this area includes the measurement of underwater sound, evaluation of methods to reduce underwater construction sounds, and prediction of underwater sound levels from marine pile driving. Mr. Reyff has authored several papers on this subject and submitted many papers at national and international scientific conferences.

Kimberly Skrupky
Marine Biologist
BOEM

Ms. Skrupky holds a Bachelor of Science degree in Environmental Science with a concentration in Wildlife Conservation and Resource Management from the University of Maryland. She has been working on issues involving protected species and acoustics for 13 years- working at NOAA for over five years, Marine Acoustics, Inc. for over four years, the last three years spent at the Bureau of Ocean Energy Management.

Brandon Southall
President and Senior Scientist
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Dr. Brandon Southall is President and Senior Scientist for Southall Environmental Associates (SEA), Inc. based in Santa Cruz, CA and a Research Associate with the University of California, Santa Cruz (UCSC). He completed Master and Ph.D. degrees at UCSC in 1998-2002, studying communication and hearing in seals and sea lions. From 2004 to 2009, Dr. Southall directed the U.S. National Oceanic and Atmospheric Administration (NOAA) Ocean Acoustics Program, within the National Marine Fisheries Service, Office of Science and Technology. In 2009, Dr. Southall founded SEA, a research and consulting small business focusing primarily, but not exclusively, on noise impacts on marine life (see: www.sea-inc.net). Brandon has an extensive technical background in leading laboratory and field research programs, as well as applying science in national and international policies. He also serves as a technical advisor and to international organizations regarding environmental impacts of conventional and alternative offshore energy development, as well as commercial shipping. He has published nearly 50 peer-reviewed scientific papers and technical reports, and has given hundreds of presentations on related subjects to scientific, regulatory, Congressional, and general public audiences internationally.

John H. Stadler
Marine Habitat Coordinator, Habitat Conservation Division, Northwest Region
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Dr. Stadler has a B.S. in Biology from the University of Washington, a M.S. in Fishery Sciences from the School of Fishery, University of Washington, and a Ph.D. in marine biology from the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami. He was introduced to the world of acoustics during his Ph.D. research, which examined species recognition by the notchtongue goby, *Bathygobius curacao*. He joined the National Marine Fisheries Service in 2000, where he has worked on ESA-listed salmon and essential fish habitat issues. He is the staff lead for acoustic issues, primarily relating to pile driving, for the Habitat Conservation Division, and participated in a mulit-agency work group that established interim criteria for assessing the risk of pile driving to fishes along the U.S. West Coast.

Alan Thornhill
Chief Environmental Officer
BOEM

Dr. Alan Thornhill was named as the first Chief Environmental Officer (CEO) in November 2011, transitioning into the new Bureau from his previous tenure as Science Advisor to the Director (both MMS and BOEMRE) which he began in March 2010. Previously (2001-2010), Dr. Thornhill was the first Executive Director of the Society for Conservation Biology, where he launched the executive office, oversaw the development of a professional staff, and initiated programs that saw the global membership triple in seven years. Other experience includes, the Director of Learning and Communications for the Science Division at The Nature Conservancy, and Professor of Ecology and Evolutionary Biology at Rice University in Houston, Texas. For the past six years, Dr. Thornhill has taught in the Masters Program in the College of Natural Resources at Virginia Polytechnic Institute and State University. Dr. Thornhill earned his Bachelors and Ph.D. degrees in Ecology from the University of California, Irvine.

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Appendix E: Literature Synthesis

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

Literature Synthesis

U.S. Department of the Interior
Bureau of Ocean Energy Management

October 31, 2012

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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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

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
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
lb	pound
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)
nmi	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
SEL_{cum}	Cumulative Sound Exposure Level
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 convened a workshop in March 2012 (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 Literature Synthesis (or Synthesis) was prepared to summarize current knowledge of the topic as of January 2012.

While the focus of this Literature Synthesis and Workshop is on fish, fisheries, and invertebrates of U.S. Atlantic and Arctic Outer Continental Shelf (OCS), the findings 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 considered 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 also covered 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 were not, therefore, given prominence at the Workshop, although this Literature Synthesis is informed by appropriate studies and findings with respect to those developments.

The Workshop itself served as the basis for a final report identifying information needs and data gaps. The final document from the Workshop (the Report) comprises this Literature Synthesis (which has been updated since the meeting), a Meeting Report, and a Gap Analysis.

This Literature Synthesis summarizes existing recent literature through January 2012. 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 was 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 was prepared to enable all speakers and participants at the Workshop to focus on new data and ideas rather than review older material. The Workshop itself was intended to 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 developed revised lists of information gaps and data needs and provided guidance on priorities for agencies and researchers. Indeed, the lists were modified during the Workshop and then underpinned the Gap Analysis presented as part of the overall Report to BOEM.

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:

- Van der Graaf et al. (2012) – A report of a technical Working Group on underwater sound, prepared to inform Member States of the European Union on good environmental status for underwater noise and other forms of energy.
- 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. (2008)—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 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 often referred to as elasmobranchs). Two groups of jawless vertebrates also regarded as fish, the lampreys (class Agnatha) and hagfishes (class Myxini),[2] are not included in this synthesis due to a paucity of information on their 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. 2012a). However, since elasmobranchs are critical parts of the marine eco system, 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.

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[2] 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.

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). 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, as 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 and is gender-neutral.

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), fishes (Tavolga 1971; Myrberg 1978, 1980; Hawkins and Myrberg 1983; Popper et al. 2003; Bass and Ladich 2008), and invertebrates (Popper et al. 2001). 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. In relation to exposure to man-made sound, NOAA guidelines define two levels of harassment for marine mammals: Level A harassment with the potential to injure a marine mammal in the wild (SPL of 180 dB re 1 μPa for cetaceans and 190 dB re 1 μPa for pinnipeds) 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 (SPL of 160 dB_{rms} re 1 μPa for impulse sound such as pile driving, averaged over 90% of the pulse energy and SPL of 120 dB re 1 μPa for continuous sound such as vessel thrusters). Similar guidelines have not yet been established for other ESA marine species, but effects of sound 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 human activity affecting the long-term background level of sound in the oceans (either directly or indirectly – for example through climate change)?*
- *Does man-made sound in the sea harm marine fishes and invertebrates? Do man-made sounds have a significant and detrimental effect upon the fitness of fishes 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 fishes and invertebrates or that lower levels of continuous sound may lead to chronic effects?*
- *If man-made sounds do affect fishes 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 fishes 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 fishes 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[3] 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.

[3] 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/.

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 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.

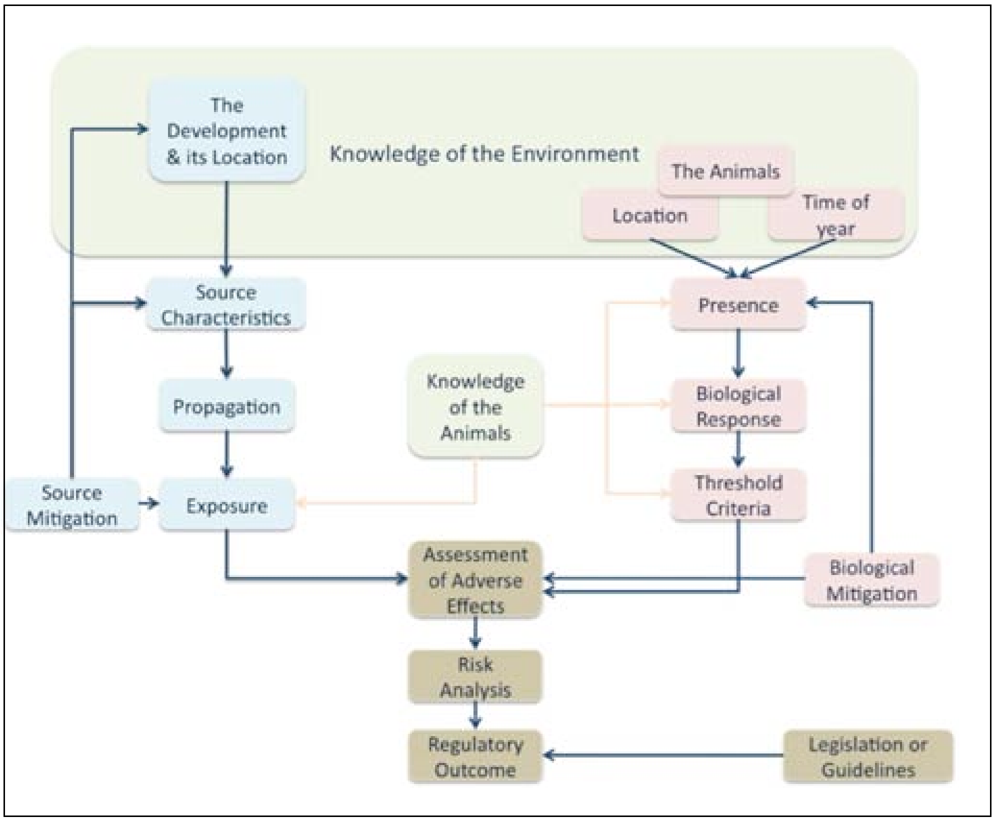

Figure 2–1. The decision-making process to assess adverse effects and perform a risk analysis to inform the regulatory outcome.

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.

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 fishes 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[4](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*

[4] 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.

what is known of the biology of key species or by employing other mitigation measures to reduce the received sound levels?

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 km² 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.

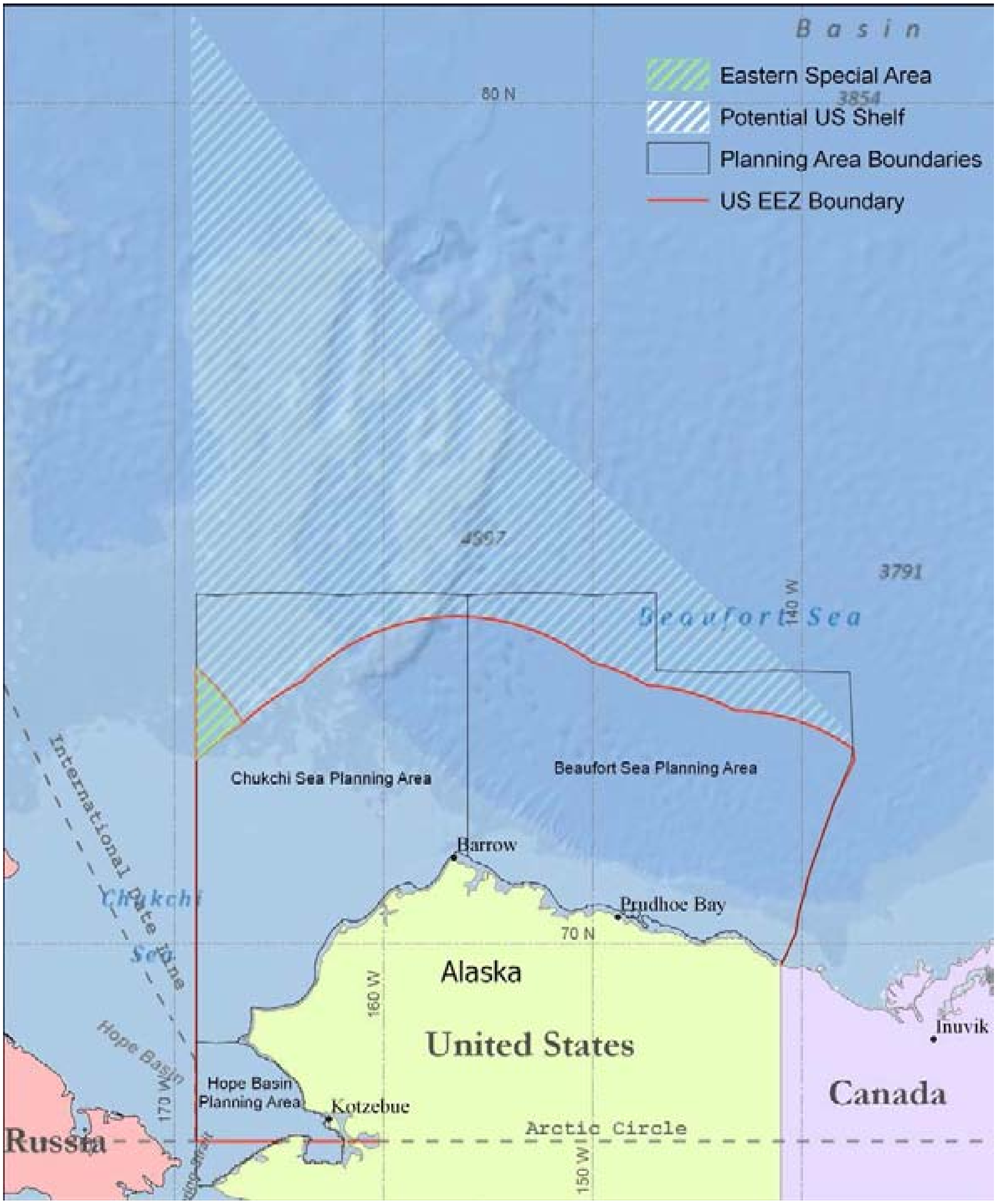

Figure 3–1. U.S. Arctic Outer Continental Shelf (OCS) region showing the Bureau of Ocean Energy Management Planning Area boundaries, the U.S. Exclusive Economic Zone (EEZ) boundary, approximate areas of potential claims of the U.S. OCS, and the Eastern Special Area that lies beyond 200 nautical miles (nmi) (370.4 kilometers [km]) and less than 200 nmi (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 fishes 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 fishes 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). Species designated with an asterisk (*) on this table are known or suspected to be soniferous or sound-sensitive. Many HAPCs exist for certain habitat, species or life stages in the Atlantic OCS: from river mouths in Downeast Maine[5] (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.

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 fishes and invertebrates. The Arctic

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

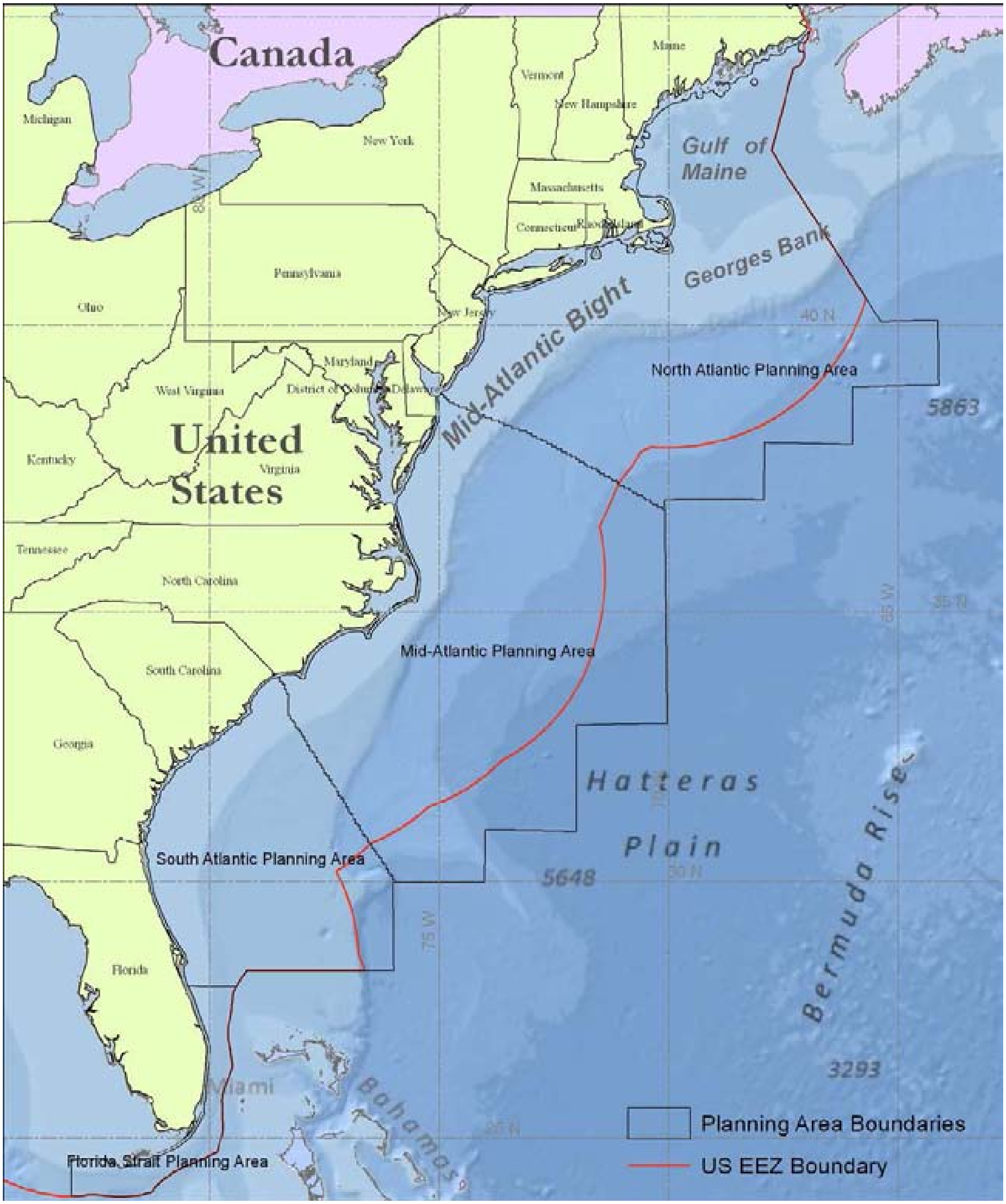

Figure 3–2. U.S. Atlantic Outer Continental Shelf region showing the Bureau of Ocean Energy Management Planning Area boundaries and the U.S. Exclusive Economic Zone (EEZ) boundary.

Table 3–2

Species for which Essential Fish Habitat (EFH) has been defined in the Atlantic OCS by the National Marine Fisheries Service. *soniferous or sound sensitive; (*) potentially sound sensitive

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 bass*	*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*	Nassau grouper*	*Epinephelus striatus*
Atlantic spadefish*	*Chaetodipterus faber*	Ocean triggerfish	*Canthidermis sufflamen*
Banded rudderfish*	*Seriola zonata*	Pink shrimp(*)	*Farfanteoenaeus duorarum*
Bank sea bass*	*Centropristes ocyurus*	Queen snapper*	*Etelis oculatus*
Bar jack	*Caranx ruber*	Queen triggerfish	*Balistes vetula*
Black grouper*	*Mycteroperca bonaci*	Red drum	*Sciaenops ocellatus*
Black margate	*Anisostremus surinamensis*	Red grouper*	*Epinephelus morio*
Black sea bass*	*Centropristes striata*	Red hind*	*Epinephelus guttatus*
Black snapper*	*Apsilus dentatus*	Red porgy*	*Pagrus pagrus*
Blackfin snapper*	*Lutjanus buccanella*	Red snapper*	*Lutjanus campechanus*
Blue striped grunt	*Haemulon sciurus*	Rock hind*	*Epinephelus adscensionis*
Bluefish	*Pomatomus saltatrix*	Rock sea bass*	*Centropristis philadellphica*
Blueline tilefish	*Caulolatilus microps*	Rock shrimp (*)	*Sicyonia brevirostris*

Common Name	Scientific Name	Common Name	Scientific Name
Blue runner*	*Caranx crysos*	Royal red shrimp (*)	*Pleoticus robustus*
Brown shrimp(*)	*Farfantepenaeus aztecus*	Sailfish	*Istiophorus platypterus*
Cobia	*Rachycentron canadum*	Sailor's choice*	*Haemulon parra*
Coney*	*Cephalopholis fulva*	Sand tilefish	*Malacanthus plumier*
Cottonwick*	*Haemulon melanurum*	Saucereye porgy*	*Calamus calamus*
Cubera snapper*	*Lutjanus cyanopterus*	Scamp*	*Mycteroperca phenax*
Dog snapper*	*Lutjanus jocu*	Schoolmaster*	*Lutjanus apodus*
Dolphinfish	*Coryphaena hippurus*	Scup*	*Stenotomus chrysops*
French grunt	*Haemulon flavolineatum*	Sheepshead	*Archosargus probabtocephalus*
Gag grouper*	*Mycteroperca microlepis*	Silk snapper*	*Lutjanus vivanus*
Golden crab(*)	*Chaceon fenneri*	Snowy grouper*	*Hypothodus niveatus*
Golden tilefish	*Lopholatilus chamaeleonticeps*	Spanish mackerel	*Scomberomorus maculatus*
Goliath grouper*	*Epinephelus itajara*	Speckled hind*	*Epinephelus drummondhayi*
Gray snapper*	*Lutjanus griseus*	Spiny lobster(*)	*Panulirus argus*
Gray triggerfish*	*Balistes capriscus*	Tiger grouper	*Mycteroperca tigris*
Graysby*	*Cephalopholis cruentata*	Tilefish	*Lopholatilus chamaelionticeps*
Greater amberjack*	*Seriola dumerili*	Tomtate*	*Haemulon aurolineatum*
Hogfish*	*Lachnolaimus maximus*	Vermilion snapper*	*Rhomboplites aurorubens*
Jolthead porgy*	*Calamus bajonado*	Wahoo	*Acanthocybium solandri*
King mackerel	*Scomberomorus cavalla*	Warsaw grouper*	*Hyporthodus nigritus*
Knobbed porgy*	*Calamus nodosus*	Weakfish	*Cynoscion rgalis*
Lane snapper*	*Lutjanus synagris*	White grunt*	*Haemulon plumierii*
Lesser amberjack*	*Seriola fasciata*	White shrimp(*)	*Litopenaeus setiferus*
Little tunny	*Euthynnus alleteratus*	Whitebone porgy*	*Calamus leucosteus*
Longspine porgy*	*Stenotomus caprinus*	Wreckfish	*Polyprion americanus*
Mahogany snapper*	*Lutjanus mahogoni*	Yellowedge grouper*	*Epinephelus flavolimbatus*
Margate*	*Haemulon album*	Yellowfin grouper*	*Mycteroperca venenosa*
Misty grouper*	*Hyporthodus mystacinus*	Yellowmouth grouper*	*Mycteroperca interstitialis*
Mutton snapper*	*Lutjanus analis*	Yellowtail snapper*	*Ocyurus chrysurus*
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*		

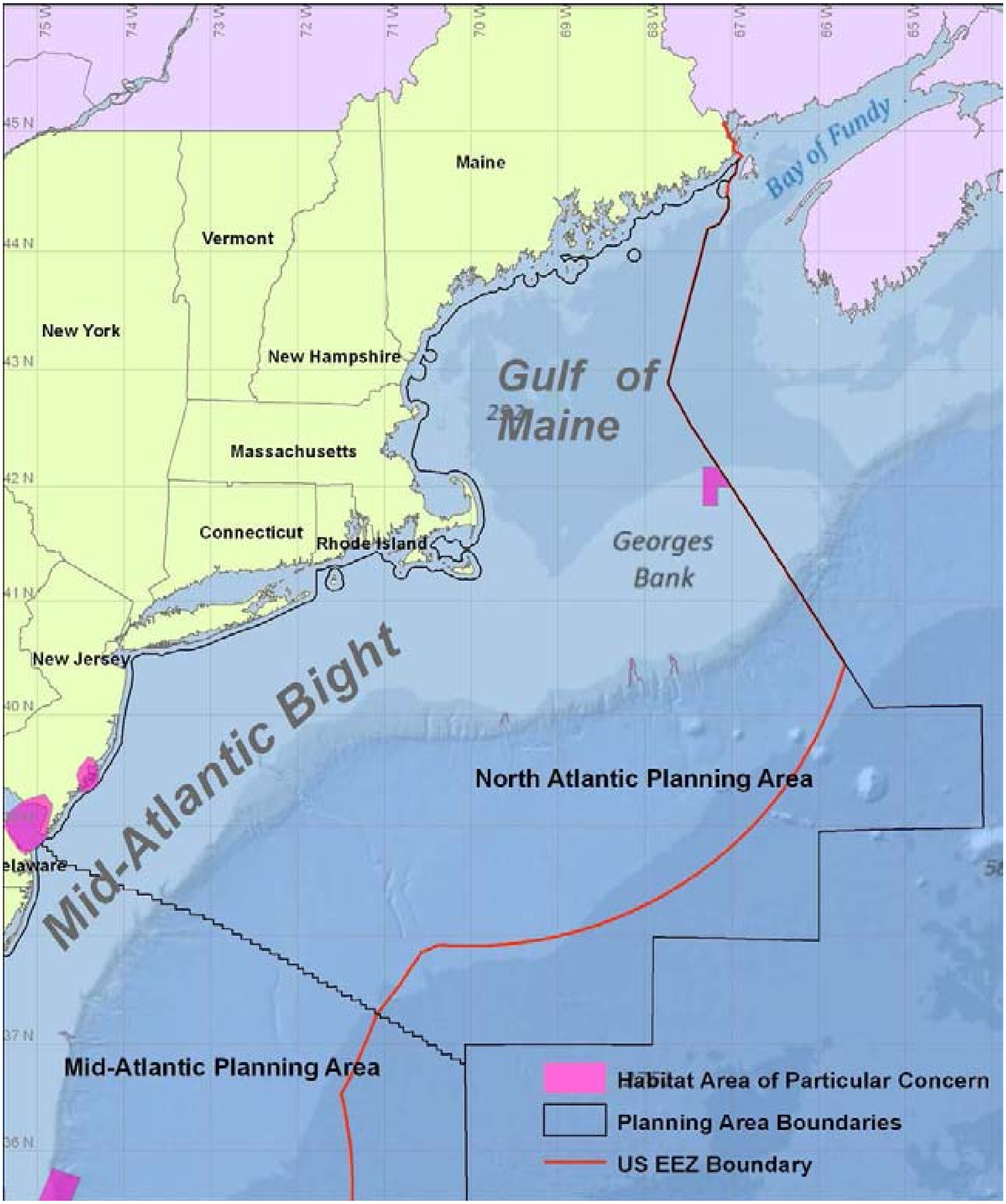

Figure 3–3. U.S. Atlantic Outer Continental Shelf region showing the Habitat Areas of Particular Concern within the Bureau of Ocean Energy Management North Atlantic Planning Area.

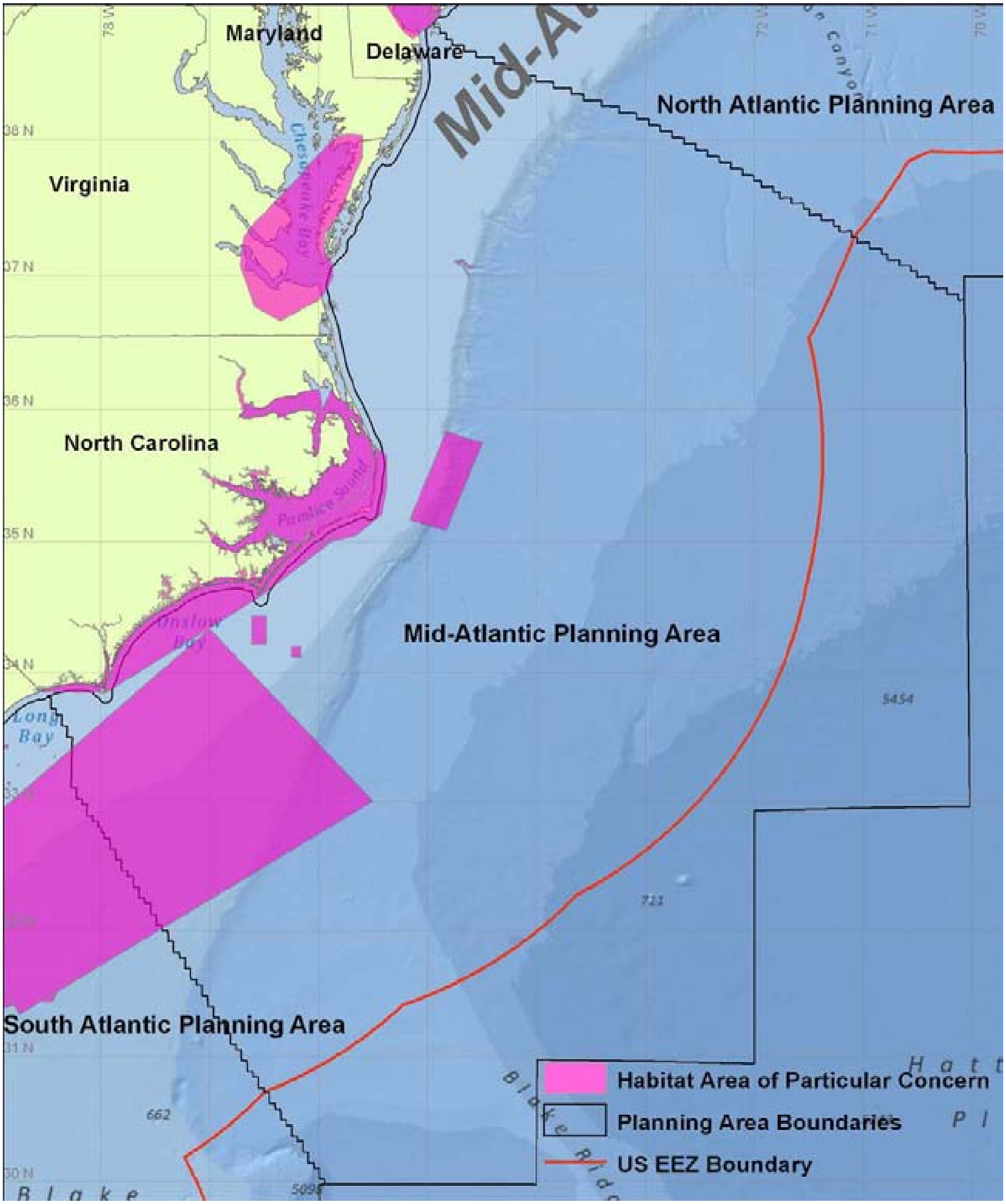

Figure 3–4. U.S. Atlantic Outer Continental Shelf region showing the Habitat Areas of Particular Concern within the Bureau of Ocean Energy Management Mid-Atlantic Planning Area.

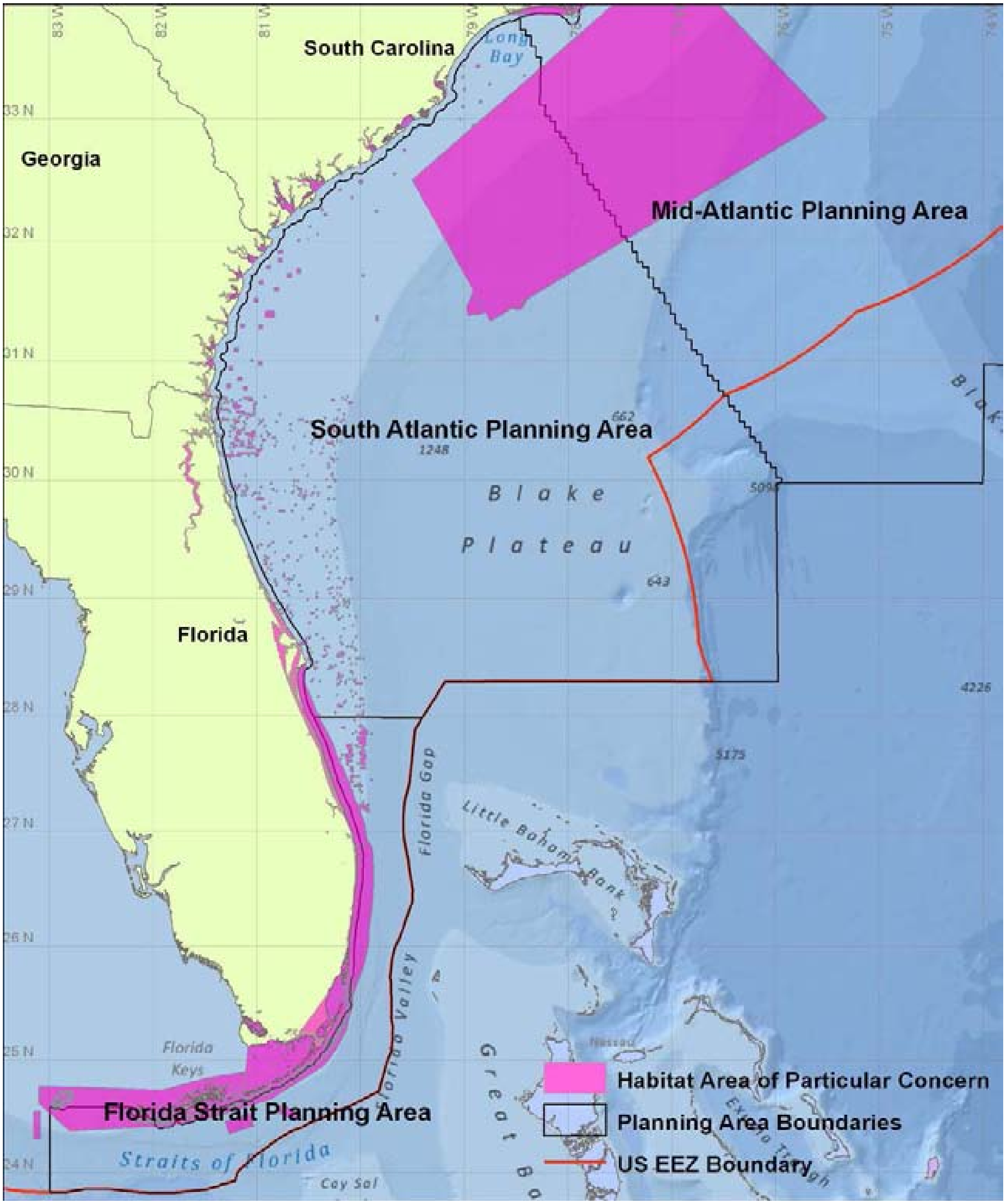

Figure 3–5. U.S. Atlantic Outer Continental Shelf region showing the Habitat Areas of Particular Concern within the Bureau of Ocean Energy Management South Atlantic Planning Area.

Table 3–3

Major fishes and invertebrates 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*

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.

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[6] and managed in state waters by the Alaska Department of Fish and Game (ADFG).[7] The ADFG defines subsistence fishing as "the taking of, fishing for, or possession of fish, shellfish, or other fisheries resources

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

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

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,[8] the 2007 harvest by subsistence fishing in the State Arctic region was estimated at 163,182 pounds (lb) (74,018 kilograms [kg]) of salmonids, 5,463 lb (2,478 kg) of saffron cod, 690 lb (313 kg) of Arctic cod, and 87 lb (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.

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 the revenue 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.

[8] 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 fishes 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, joltheads	*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*

Table B–4 in Appendix B lists the status of the fishery for the managed stocks in the Atlantic OCS region.

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 fishes 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

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.

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

[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."*

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.[10]

Elkhorn (*Acropora palmata*) and staghorn (*A. cervicornis*) are both listed under the ESA as threatened. An additional 82 coral species (some of which may occur within BOEM's Atlantic regions) are under review as candidate species for protection under the ESA.

3.5 Priorities

Both fish species (Arctic cod and saffron cod) for which EFH has been designated in the Arctic OCS are related to Atlantic 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.

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[11] 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

[10] 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.

[11] 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)

- 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
- Fishes protected under the ESA

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 ambient noise levels in busy shipping lanes have increased by as much as 12 dB (Andrew et al. 2002; Hildebrand 2009; Cato 2012; Stocker and Reuterdahl 2012). It is likely that part of this increase comes from shipping, with perhaps other contributions from other sources including baleen whales and seismic airguns.

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.[12] 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.

[12] 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/.

Ambient noise from 1 to 10 Hz mainly comprises 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[13] (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 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,[14] 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.

[13] For information on hydrophones, see this website: http://dosits.org/science/soundmeasurement/measure/.
[14] For specific data, see: http://www.marisec.org/shippingfacts/worldtrade/volume-world-trade-sea.php.

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 the impact of any additional man-made sounds may be reduced since fishes 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 fishes 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)[15] 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.

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?

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

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.[16] 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 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[17] now requires member states to define qualitative descriptors for determining good environmental status[18] 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

[16] Some of these sites are given, and can be listened to at http://www.listentothedeep.com/acoustics/index.html.
[17] See this website for the Directives:
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF.
[18] For more information on good environmental status, see this website:
http://ec.europa.eu/environment/water/marine/ges.htm.

other reefs or areas where sound-producing fishes 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
- 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 sound 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 [members of the family Alpheidae]; 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 peak-to-peak source levels for snapping shrimp are 183 to 189 dB re 1 µPa m over a frequency range of 2 to 200 kHz (Au and Banks 1998). Versluis et al. (2000) report that the snapping sound reaches peak to peak source levels as high as 190 to 210 dB re: 1 µPa 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 to 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 (>32,400 known to date),[19] 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 fishes 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

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

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 800, 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*),[20] 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 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 significance for the species (Tavolga 1956; Mann and Lobel 1997).

[20] 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

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 fishes 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 fishes 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 fishes 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 fish species. 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 use of sounds by fishes in order 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 Fishes

- *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 man-made. 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).[21] The air bubble initially rapidly expands creating an impulsive signal with a slower rise time to the peak sound 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 greatest 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-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 array measured in the far field and back calculated to a point source is up to a zero to peak source level of 260 dB re 1 µPa m 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

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

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 fishes 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 (Brekhovskikh and Lysanov 1982). Such waves are much more likely to affect bottom-living fishes than those in the water column. Shear waves and interface waves travel slower than sound waves in the seabed 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 at zero to peak sound pressure levels 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). However, the actual peak sound pressure 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 in to 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 sediment properties—to excavate hard, cohesive and consolidated sediment, 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).

De Jong et al. (2010) reported measurements of radiated noise from Dutch dredgers involved in the extension to the Port of Rotterdam. Robinson et al. (2011) carried out an extensive study of the noise generated by a number of trailing suction hopper dredgers during marine aggregate extraction. Source levels (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. There were significant differences between source level measurements reported by de Jong et al. (2010) and Robinson et al. (2011), especially at high frequencies. Both reports estimate the *dipole* source levels.

Very little research has been carried out on the effects of sound from dredging on 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; Arveson and Vendittis 2000; NRC 2003). Source levels of vessels can range from < 150 dB re: 1 µPa m to over 190 dB for the largest commercial vessels (Scrimger & Heitmeyer 1991; Richardson et al. 1995; Arvenson and Vendittis 2000; Wales & Heitmeyer 2002; Hildebrand 2009; McKenna et al. 2012). Note that it is not always clear whether authors are reporting estimated source levels or radiated noise levels.

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 vessels, and shipping industry analysts forecast that the amount of cargo shipped will again double or triple by 2025, with an attendant increase in the amount of ambient noise entering the ocean from commercial shipping (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 fishes like the haddock.[22]

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 spectra is currently available.

It is evident that many fishes 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 fishes is poorly understood (Wardle 1983).

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

There has long been interest in how the sound radiated by fishing vessels affects fishes (e.g., De Robertis et al. 2012). There has been particular concern over the reactions of pelagic fishes to research vessels conducting abundance surveys. Through the International Council for Exploration of the Sea (ICES), low-frequency (1 to 1000 Hz) limits for the underwater sound 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. The principles of sonar operation are described by Ainslie (2010). Sonars work at frequencies from 10 to 800 kHz with source levels up to and even exceeding 240 dB re 1 µPa 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 sound pressure levels lower than those observed in impulses generated by impact pile driving. The principle of operation is that counter-rotating, out-of-balance masses rotate in an enclosure attached to the top of the pile. The rotating masses generate a resultant vertical vibratory force that slowly forces the pile into the substrate. Sound signals generated by vibratory pile driving usually consist of a low fundamental frequency characteristic of the speed of rotation of the revolving mass in the vibratory hammer, typically on the order of 30 Hz, and its higher harmonics (e.g., Laughlin 2006).

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, most 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 fishes 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?*
- *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?*[23]

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 research 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.

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

[23] Subgroups are currently being established by ISO to develop standards for underwater sound sources, including sounds radiated by ships. An ANSI standard is also currently available.

- Sound source characterization in the near field
- Identification of the transition point from the near field to the far field.
- 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 fishes 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 fishes 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 fishes (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 approach 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 Sound Exposure Criteria

Studies are needed to document and quantify any impacts upon fishes and invertebrates by sounds 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 Sources with Differing Characteristics

- *What are the characteristics of impulsive sound 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 sound 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.

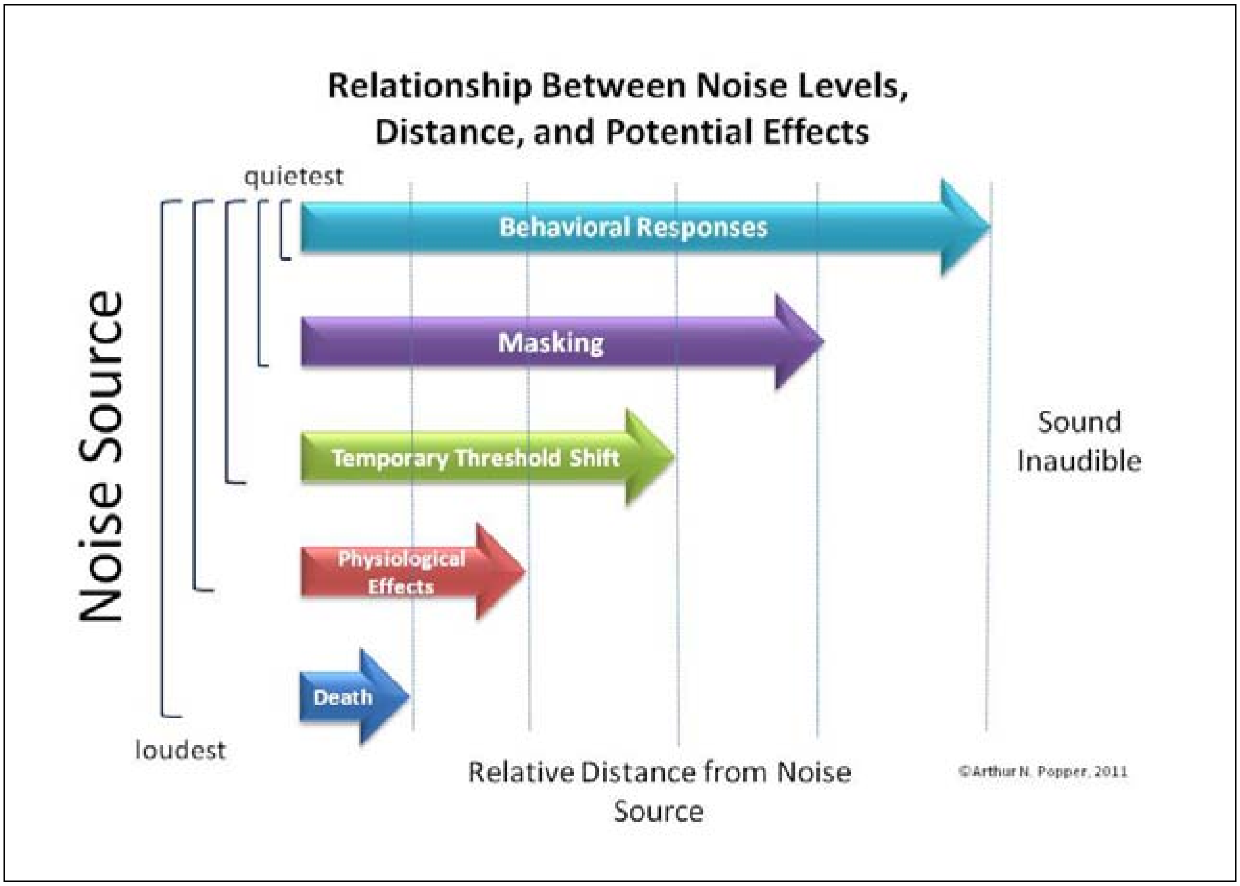

Figure 8–1. Relationship between sound levels and potential effects on animals (see text for discussion).

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 fishes 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.

There is a 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, and pollution.

9 Hearing and Sound Detection

Sound is important to fishes 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 fishes 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, 2012b; Casper et al. 2012b) 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 fishes (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 bigfin 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 fishes 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 fishes 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 fishes have been carried out under appropriate acoustical conditions and the results from many of the measurements made in tanks, and expressed solely in terms of sound pressure, are unreliable.

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).

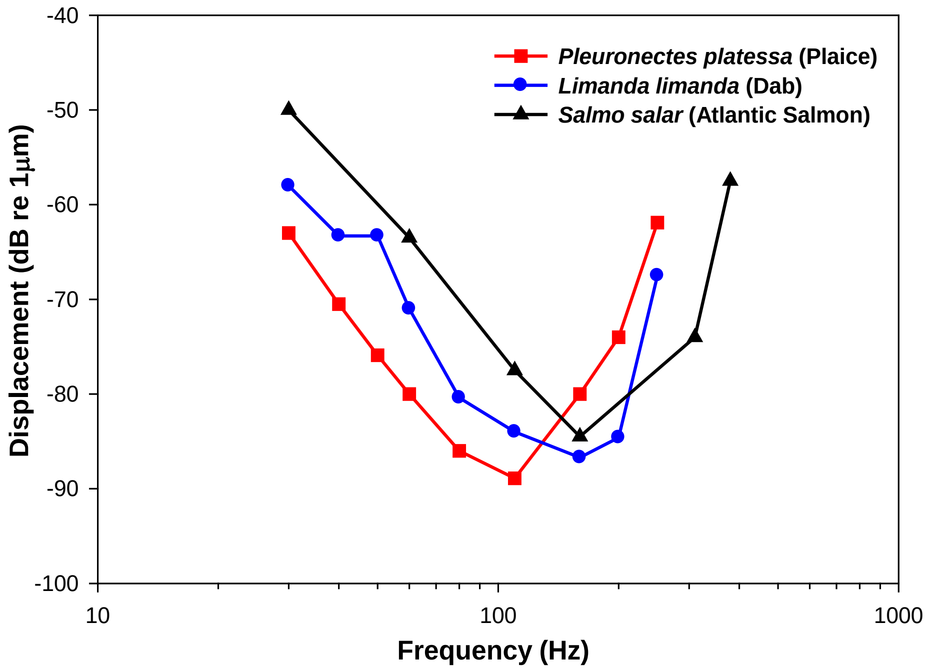

Figure 9–1. Audiograms for plaice (Chapman and Sand 1974), dab (Chapman and Sand 1974), and Atlantic salmon (Hawkins and Johnstone 1978). Acoustic thresholds for all three species were obtained by cardiac conditioning to pure tones against a natural sea noise background.

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).
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).

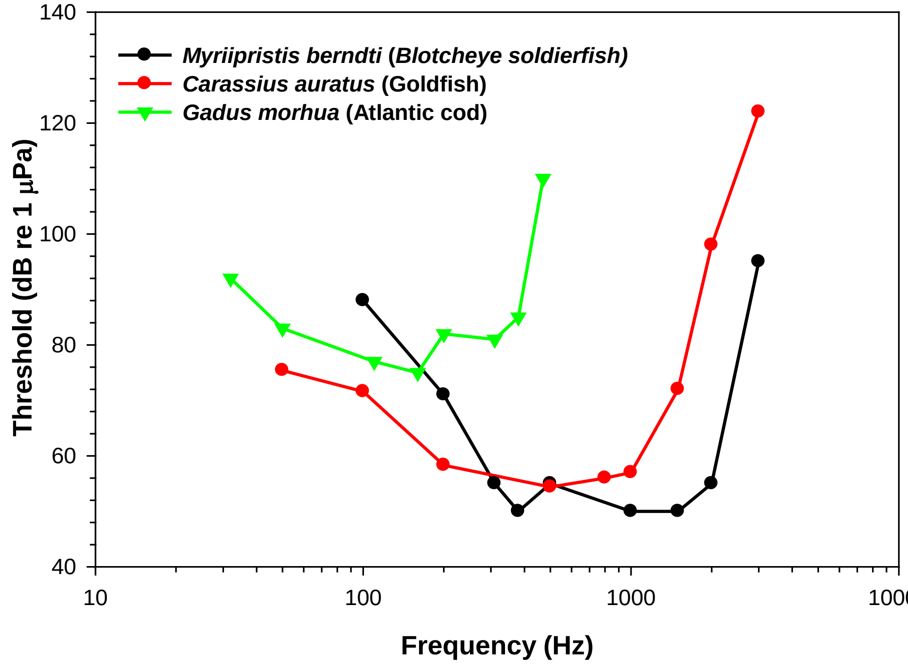

Figure 9–2. Audiogram for blotcheye soldier fish (Coombs and Popper 1979), goldfish (Jacobs and Tavolga 1967), and Atlantic cod (Chapman and Hawkins 1973) . The thresholds for Atlantic cod were obtained by cardiac conditioning to pure tones against a natural sea noise background. Thresholds for the soldier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

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 fishes, such as 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 fishes 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 fishes 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.

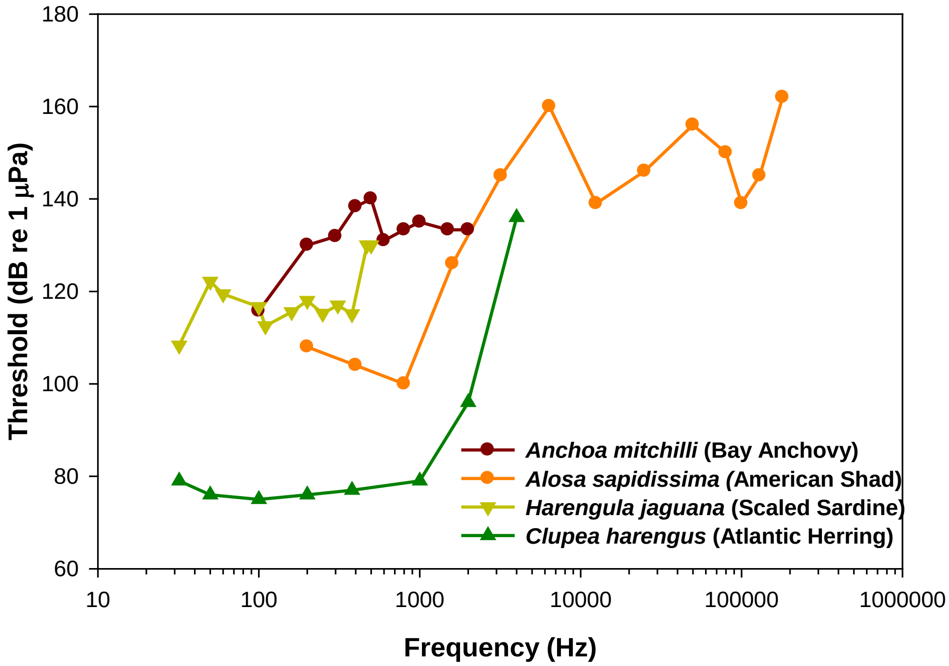

Figure 9–3. Audiograms for clupeid fishes. Thresholds for the Atlantic herring (Enger 1967) were determined by monitoring microphonic potentials in the laboratory. Thresholds for American shad (Mann et al. 1997) were obtained using classical conditioning of heart-rate in a quiet tank, whereas thresholds 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 fishes 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 fishes 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.[24] 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 Fishes

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;[25] Retzius 1881; Popper et al. 2003; Popper and Schilt 2008). This diversity is well documented in a classic 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 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.

[24] 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.

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

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 fishes 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 fishes rather than the kinds of data obtained with AEP where data only reflect electrical activity within the ear and the initial stages of processing of sound in the central nervous system and ignores the critical processing of sound that takes place before the animal makes a response to indicate that it heard, or did not hear, a sound. Thus, 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 fishes 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 fishes 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 events within 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 environmental conditions. It is therefore likely that hearing evolved for detection of the acoustic scene (Fay and Popper 2000), and that fishes 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 fishes 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 is 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 Fishes 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 Fishes 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. (2012a), 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 from an air gun array with total capacity 635 in^3 (10 L) and pressure 2000 psi (13.8 MPa) (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 (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. 2012a). 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, fishes 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 fishes from migratory routes (e.g., salmon or 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 lack of data includes not only immediate effects on fishes that are close to the source but also effects on fishes 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 fishes during and after a seismic airgun study although they were not able to actually observe the behavior of fishes 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 fishes 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 fishes 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. (2012a, b) 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 (zero to peak sound pressure level) (see also Pearson et al. 1987, 1992). They also demonstrated that fishes would show a startle response to sounds at a level 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 fishes 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 µ Pa^2·s and zero to peak sound pressure levels were over 200 dB re 1 µ Pa (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).[26] 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 fishes from feeding and/or reproductive sites, thereby affecting population survival?*
- *Will fishes 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?*

[26] 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.

- *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 fishes (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 fishes 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 a, b). 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 fishes over large bodies of water.

Those fishes 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 fishes 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. Fishes 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., sound exposure level, peak sound pressure level, 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. 2012a, b). 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 fishes to capture, not just because fishes 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 fishes encounter 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 fishes 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 fishes 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., SPL well over 190 dB re 1 µPa) 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 fishes that do not hear well (e.g., striped bass [*Morone saxatilis*], sturgeon, and flatfish) compared to fishes 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 fishes 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 fishes are in an area where there is a long-term increase in sound level, there may be masking, and in addition the ability of fishes 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[27] 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. 2008). The lateral line is critical in schooling behavior, including in feeding for many

[27] 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).

(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.

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 fishes 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 fishes as a result of sound 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 sound cause stress in fishes, (level, duration, etc.)?*
- *What are the effects (chronic, acute) of stress on fishes (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 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. 2012a). 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 fishes 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 fishes 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 fishes 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. 2012a), 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. 2012b.; Halvorsen et al. 2012b.). 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, 2012b) (see Section 10.12.2) found a clear correlation between the magnitude of the injury and the intensity of the sound exposure. Significantly, Casper et al. (2012b) 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 fishes 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, where the mean value of the peak sound pressure was found to be high as 3.51 bar (351 kPa, which corresponds to a zero to peak sound pressure level of 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 total capacity 635 in^3 (10 L) and pressure 2000 psi (13.8 MPa)No significant deleterious impact of seismic prospecting was observed for the studied species.

André et al. (2011) suggested, based on studies of captive 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 fishes 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 fishes 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 fishes 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 fishes because of their small size and physical fragility. However, there are very few data on the effects of sounds on fish eggs and larvae. Kostyuchenko (1973) and Booman et al. (1996) found indications of effects 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, 2012b).

Most recently, Halvorsen et al. (2011, 2012b) 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 SEL_{cum} of 210 dB re 1 $\mu Pa^2 \cdot s$, 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 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 $\mu Pa^2 \cdot s$ 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 SEL_{cum} was as high as 213 dB re 1 $\mu Pa^2 \cdot s$ (Casper et al. 2012b). Studies with additional species have shown that while there is some variation in timing of the onset of physiological effects, this is always at SEL_{cum} of greater than 203 dB re 1 $\mu Pa^2 \cdot s$. In flatfish species without a swim bladder, there was no effect with an SEL_{cum} as high as 216 dB re 1 $\mu Pa^2 \cdot s$.

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 fishes 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 problematical 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, 2012b).

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, 2012b). 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, 2012b) 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. 2012b).

11.1 Current Criteria for Onset of Physiological Effects

The only current criteria in use for onset of physiological effects on fishes are interim criteria developed on the United States west coast by the Fisheries Hydroacoustics Working Group[28] (see reviews in Stadler and Woodbury 2009; Woodbury and Stadler 2009).[29] The interim criteria are:

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

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

- Zero to peak sound pressure level: 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; 2012b; Casper et al. 2012b) 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 fishes 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 fishes 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, 2012b), Bolle et al. (2012) found no damage to different larval stages even at an SEL_{cum} of 206 dB re 1 μPa^2·s.

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 sound pressure level of 150 dB re 1 μPa 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 fishes under different conditions to support these assumptions, but few tests have been done at sound levels sufficiently intense to determine how fishes 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 fishes 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 fishes start to show substantial behavioral reactions that potentially alter fitness (e.g., change migration routes, move fishes 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 fishes 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 already requires EU Member States to monitor underwater sound and register the use of selected man-made sources of underwater 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 fishes 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.[30]

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 than PAM for monitoring the presence of vulnerable fish and shellfish in an area?*
- *Can fishes 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?*

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?*

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

- *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 fishes 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 numerical value of a power ratio expressed in decibels is 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 RMS pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micropascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., dB re 1 µ Pa). A difference of 20 dB corresponds to a factor of 10 in RMS 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 sound pressure to either zero pressure or the minimum sound 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 sound 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 sound 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 sound 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 root mean square (RMS) 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.

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 micropascal (1 µPa). The conventional definition of sound pressure level is in terms of root mean square sound pressure.

Source level – characterizes the sound power (or RMS sound pressure) radiated by an underwater sound source expressed in decibels. It is often expressed as the SPL referred to a standard reference distance from a point monopole, placed in a lossless uniform medium and extending to infinity in all directions. See Ainslie (2010) for definitions of zero to peak source level and peak to peak source level.

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 hearing 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 hearing 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.

Zero to peak sound pressure level – Ten times the base ten logarithm of the ratio of the zero to peak sound pressure to the reference pressure.

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.[31]

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

[31] 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.