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National Capital Region **Habitat Status Report 2004/002**

Review of Scientific Information on Impacts of Seismic Sound on Fish, Invertebrates, Marine Turtles and Marine Mammals

Background

A Workshop to develop a "Decision Framework for Seismic Survey Referrals" held in March 2003 produced an inventory of ecological factors that DFO should consider when dealing with referrals for seismic surveys in Canadian waters. The workshop also discussed the sources of uncertainty about effects of seismic sounds on those ecological factors, and ways that the uncertainty could be presented in science documents evaluating possible impacts. The workshop did not attempt to review critically the scientific literature on impacts of seismic sounds or effectiveness of mitigation options. Consequently the meeting did not address tolerances for ecological impacts, if any, or operational standards for respecting such tolerances.

Following that Workshop, teams of scientists prepared major literature reviews of the primary and secondary literature that reports on experimental studies and field monitoring of effects of sound, particularly seismic sound, on marine organisms. Reviews were also contracted of the standards and mitigation methods applied by other national and international bodies which regulate seismic surveys in marine ecosystems, and of the strengths and problems with various sound propagation models in marine environments. These papers were reviewed at a National Advisory Process meeting on Seismic Impact Evaluation Framework in May 2004, although time did not allow a detailed critical review of the paper on standards and mitigation methods.

Figure 1: Map of Canada

Summary

- From the evidence available, it can be concluded that seismic sounds in the marine environment are neither completely without consequences nor are they certain to result in serious and irreversible harm to the environment. In the huge range of effects between those extremes, however there are many *potential* detrimental consequences. In general risks of these consequences are poorly quantified, often unknown, and likely to be variable with both conditions of the environment and of the organisms exposed to the sounds. The long and widespread history of seismic surveys globally in marine environments with no documented fish or invertebrate kills, and only circumstantial evidence of associations with infrequent strandings of marine mammals and giant squid, suggest that seismic surveys with fairly routine mitigation measures in place are unlikely to pose high risk of mortality of marine organisms. However, this suggestion must be qualified, because sublethal or longer-term effects could have occurred and not have been detected by the monitoring programs typically in place.

- Immediate behavioral reactions to exposure to seismic sound have been widely documented in marine organisms, especially marine mammals; particularly behaviors which would result in avoiding the immediate area where the sounds are being produced, or reducing vocalisations. The possible longer-term consequences of these short-term behavioral changes are debated among experts. The debate is largely speculative and there is little empirical basis to determine the likelihood of the full chain of events which would lead to serious longer-term consequences of the short-term behavioral reactions. However, the risk to be managed would be the combined probability of all the events in the chain occurring.

- Whatever the absolute level of risk posed by seismic sounds, there are mitigation measures available which the evidence available suggests can reduce the risk by varying, but sometimes substantial, amounts. The effectiveness of specific mitigation measures was not reviewed in detail at the meeting, but was generally agreed likely to depend on the effect of concern and how the measures are implemented. The impact on the seismic operations of application of some mitigation methods, such as not conducting surveys in critical times and places, will also vary with many factors, but sometimes also could be large. Clearly much more research and monitoring are needed to better clarify and quantify the unknown risks and uncertain effects, if they occur, and the effectiveness of mitigation measures to a wider range of potential effects. Towards that end, some key research needs are listed below.

Introduction

Literature reviews of the primary and secondary literature that reports on experimental studies and field monitoring of effects of sound, particularly seismic sound, on marine organisms were evaluated in May 2004, by a group of scientists from DFO, other federal and international agencies, the hydrocarbon exploration industry and environmental groups. The review indicated that information was incomplete to varying degrees in essentially all areas related to impacts of seismic sound on marine ecosystems. Nonetheless, the background papers and scientific deliberations resulted in a body of information that allowed the following conclusions to be reached.

These conclusions provide a science basis for developing a regulatory framework for use of sound in aquatic environments, at least in the frequencies used for seismic surveys. Some of the conclusions based on the laboratory studies reviewed may generalise to higher frequencies as well, but the review focused on scientific studies directly applicable to seismic sound. The conclusions also contribute to the scientific basis for an integrated approach to managing human impacts on marine ecosystems, and for dealing with referrals of applications for seismic surveys at the regional to national level within DFO.

Habitat Concern

The issue of concern was the effects of sound, particularly seismic sound, on marine organisms. Advice was sought to provide a scientific basis for developing a regulatory framework for use of sound in aquatic environments, at least in the frequencies used for seismic surveys.

Management Considerations

Overall Considerations:

1) The following statements and conclusions are based on information available and presented at the time of the Seismic Impacts Evaluation Framework workshop. Additional research is needed in many areas, and a number of these are identified in the meeting proceedings. These statements and conclusions

should be re-evaluated as new information becomes available.

2) When considering the possible impacts of seismic sounds on the marine ecosystem, it makes sense to embed these considerations within the larger framework of the impact of all anthropogenic noise on the ecosystem. The major anthropogenic sources of noise that might be appropriate to consider in a holistic view would include seismic sounds, shipping, explosives, construction, and low-frequency SONAR. Moreover, the significance of impacts of sound in the environment, if any, should be evaluated in the context of other uses of ecosystem.

3) The dearth of scientific information, especially concerning field experiments on fish, invertebrates, and the larger marine mammals, makes it extremely difficult to evaluate the impact of a particular type of seismic sound, or more generally noise, on a particular species. Restricting our consideration to only seismic sound impacts would have reduced the already-sparse information base to one that would not have supported any conclusions with an acceptable level of confidence, so we have looked more widely for relevant information.

4) If was not just for convenience that we looked for information more widely than just considering publications on effects of seismic sound on marine species. Given the scarcity of hard information on so many facets of this multi-dimensional problem, it is likely that a meaningful appreciation of risk can only be obtained by taking an integrated view of all the sources of information available.

5) Many conclusions refer to the likelihood of various biological effects, if animals were exposed to seismic sound. Likelihood is used in a relative sense, and not as the product of quantitative risk assessments, which are not possible with the information available. Saying that an event has a "high likelihood" does not mean we necessarily expect to see it in nine out of every ten animals exposed to the sound, or even in nine out of ten replicates of the same experiment. Rather, it means that compared to the expectation of the event in the absence of seismic sound, the likelihood of the event has increased substantially, and it would be observed if sought with due diligence. However, it still may not be the typical event. Where quantification of the probability of an event is possible, we use the term "probability" rather than "likelihood".

6) The conclusions that follow often refer to "seismic sound" and "field operating conditions". These terms are used colloquially and are not defined prescriptively. In this document "seismic sound" refers generally to that produced by the types of airguns and arrays normally used at present in Canadian waters. "Field operating conditions" refers to 2-D and 3-D seismic surveys using measures such as ramp-up of sound level at onset, and ceasing sound emissions when cetaceans are known to be in the proximity of the operations.

7) Both the likelihood and severity of biological effects that may result from seismic surveys are likely to vary with local conditions of the environment (ice coverage, bottom topography, sea state, etc.) and conditions of the organisms (breeding state, nutritive condition, etc.). These conditions should not be ignored when evaluating risks and the potential for mitigation, however regulatory frameworks do not need complex rules to be effective.

Limitations for quantitative conclusions:

8) It was agreed that the biologically meaningful aspect of seismic sound is the "received sound" by the organism(s) potentially being affected. However, "received sound" is multi-dimensional. Seismic sound (or noise in general) can

be characterised by its frequency spectrum (acoustic energy or pressure as a function of acoustic frequencies), peak pressure (a time domain concept, referring to the maximum instantaneous amplitude of the pressure signal), rms pressure (mean pressure averages over a time interval), Sound Exposure Level (a measure of the "dosage" of sound energy received over a time interval), and in other ways.

9) The mechanisms by which exposure to seismic sound could result in biological impacts are sufficiently varied that no one metric may be sufficient to describe the risk of impact from a particular type of seismic sound. Some mechanisms may be well characterised by one or two of these metrics; others may not be well characterised by any of them. For example, peak pressure may be the most relevant parameter for risk of trauma, whereas rms pressure may be the most relevant parameter for non-trauma effects such as Temporary Threshold Shifts [TTS]. The frequency band, intensity, and duration of exposure all contribute to auditory effects, because although the impact must occur within the frequency band of exposure, we anticipate that auditory impact is greater within the hearing range of a species, and will decline towards the margins of its hearing threshold.

10) Many studies of the impacts of seismic sound on marine animals reduce the information about the sound used or received to a few numbers. This practice often discards important information, and makes inter-comparison of results across studies very difficult.

11) Although careful experimentation ought to be able to determine which feature(s) of the sound stimulus caused the observed reactions (when they occurred), the existing literature on experiments with marine fish and invertebrates rarely describes completely enough the characteristics of the sounds used to allow biological observations to be interpreted with confidence.

12) The literature on experiments and field observations of marine mammals exposed to sound stimuli is more extensive than the literature on effects on other types of marine organisms, and therefore likely to provide a more complete (but still partial) basis for setting thresholds. However the results, taken together, were complex and inconsistent and were an insufficient basis for agreement on quantitative thresholds for impacts on marine mammals, even from those studies where there were adequate descriptions of the sound characteristics. The major review by the NMFS Acoustic Criteria Panel is devoting much more time to this information, and may contain a quantitative synthesis of stimulus-response relationships from the information available at present. That review, when released, may comprise a useful source of information for defining regulatory tolerances. Where sensitivities of marine turtles, fish, or invertebrates are documented to be greater than sensitivities of marine mammals those factors should be taken into account in the Canada standards, guidelines and/or regulations. It was conjectured that sedentary species that cannot leave an area may experience higher levels of exposure to seismic sound than mobile animals, and this factor may be taken into account in management as well.

13) Ecological "significance" can be a value-laden term, although in these conclusions "significant" is used only in the context of DFO's areas of responsibility. Specifically, DFO has a responsibility for conservation of aquatic species (except birds) and ecosystems, and where detrimental population-scale impacts are considered likely, DFO must ensure that the impacts are mitigated or remediated. Likewise, for aquatic species protected under Schedule 1 of SARA, if deaths, harm or harassment of individuals is considered likely to occur, DFO must

either act to ensure the impacts are ameliorated, or issue permits under the provisions of Section 73 of SARA.

Other limitations:

14) A number of studies reported sub-lethal effects on marine organisms, such as elevated stress-related chemicals, and damage to ears or other morphological structures. The dearth of long-term studies of marine organisms exposed to seismic sounds means that the long-term consequences of these effects, when they occur, are unknown.

15) The severity of impact at the population level may be higher for an effect like auditory masking, if it occurs, because masking has the potential to affect a very large geographical area for low frequency sounds. Masking also may have few immediately observable signs that impacts are occurring, so mitigation may be less likely to be triggered than with individual mortalities due to trauma, (which have limited geographical extent and are more easily observable).

Conclusions Regarding Fish

Physical Effects

1) There are no documented cases of fish mortality upon exposure to seismic sound under field operating conditions. With regard to the detectability of fish kills, if they occurred, it was noted that in Canada seismic surveys have frequently, but not always, included follow-on vessels instructed to watch for fish kills, and none have been observed. It was also noted that fish kills are not necessarily cryptic events, and kills caused by anoxic events, toxic spills etc are often readily detected. However, it was also argued that the efficiency of detecting fish kills by the follow-on vessels was not tested independently, so the possibility of undetected fish kills cannot be eliminated.

2) Under experimental conditions one study found that some subjects from three of four species tested suffered lethal effects from low-frequency (<500 Hz) tonal sounds, under exposure levels of 24 h at >170 dB. Participants noted that the experimental regime differed greatly from field operating conditions of seismic surveys, so extrapolation of the results to seismic surveys was not warranted. However some participants argued that the result indicates that risk of direct fish mortality from sounds with some characteristics of seismic sound cannot be discounted completely.

3) One anecdotal report of fish mortality upon exposure to an airgun less than 2 m away was discussed and found to be inconclusive when considered relative to field operating conditions. Overall, exposure to seismic sound is considered *unlikely* to result in direct fish mortality.

4) Under experimental conditions, sub-lethal and/or physiological effects, including effects on hearing, have sometimes been observed in fish exposed to an airgun. The experimental design made it impossible to determine to the satisfaction of all experts what intensity of sound was responsible for the observed damage to ear structures, nor the biological significance of the damage that was observed. Simulated field experiments attempting to study such effects have been inconclusive. Currently, information is inadequate to evaluate the likelihood of sub-lethal or physiological effects under field operating conditions. The ecological significance of sub-lethal or physiological effects, were they occur, could range from trivial to important depending on their nature.

Behavioral Effects

5) There is high likelihood of obtaining the following effects in some fish exposed to seismic sound:

   - startle response,

- change in swimming patterns (potentially including change in swimming speed, and directional orientation), and
- change in vertical distribution.

6) These effects are expected to be short-term, with duration of effect less than or equal to the duration of exposure, are expected to vary between species and individuals, and be dependant on properties of received sound. The ecological significance of such effects is expected to be low, except where they influence reproductive activity.

7) Several scientific studies have investigated other behavioral effects on fish during seismic surveys. Some have found the effects listed below and some have not:

- Change in horizontal distribution of fish not closely associated with habitat structures such as a reefs or pinnacles,
- Change in catchability of fish possibly related to changes in behavior. Differences in experimental regimes and lack of adequate controls in some of the experiments means that the published results are an insufficient basis to predict the nature of any change that may occur, or even if a change will occur.

8) The duration of these effects may or may not extend beyond the duration of exposure, are expected to vary between species and individuals, and be dependant on the properties of received sound. The ecological significance of such effects is expected to be low, except when they may lead to a dispersion of spawning aggregations or deflection from migration paths. The magnitude of effect in these cases will depend on the biology of the species and the extent of the dispersion or deflection.

Functional Uses of Sound

9) The potential for seismic sound to disrupt communication, detection of predators/prey, navigation and other functional uses of sound by fish has not been studied. There is speculation that the discontinuous nature of seismic signals may allow these functions to occur between sound "pulses". There is also speculation that behavioral responses may include cessation of sound production by fish. If it were to occur, hearing damage would also be expected to impact these functions. Ecological significance of such effects is unknown.

Conclusions Regarding Invertebrates

Physical Effects

1) There are no documented cases of invertebrate mortality upon exposure to seismic sound under field operating conditions. An anecdotal report of beachings of giant squid on two occasions, which corresponded to periods of seismic activity, was discussed and found to be inconclusive.

2) Under experimental conditions, lethal and/or sub-lethal effects, including effects on external structure, have sometimes been observed in invertebrates exposed close to (less than 5 m) an airgun.

3) Therefore, exposure to seismic sound is considered *unlikely* to result in direct invertebrate mortality.

Physiological Effects

4) There is a series of publications showing effects of extended exposure to non-seismic sounds on the physiology of crustacean under experimental conditions. Effects include reduced growth and reproduction rates and behavioral changes, which indicate the

sensitivity of some invertebrates to noise. In a gastropod (mollusc) the physiological effects (sign of stress) were reported under field seismic operating conditions. In other species such effects were rarely present, except for some sign of excitation of ensonified crabs compared to control crabs.

5) Currently, information is lacking to evaluate the likelihood of sub-lethal or physiological effects on crustaceans during pre-molt, molting and post-molt periods.

6) The ecological significance of sub-lethal or physiological effects, were they occur, could range from trivial to important depending on their nature.

Behavioral Effects

7) There is high likelihood of obtaining the following effects in some invertebrates exposed to seismic sound:

   - startle response,
   - change in swimming/movement patterns (potentially including change in swimming/movement speed, and directional orientation).

8) Both increases and decreases in catch rates of commercially exploited species have been documented, but changes do not occur consistently.

9) These effects are expected to be short-term, with duration of effect often less than the duration of exposure, are expected to vary between species and individuals, and be dependent on properties of received sound.

10) Some invertebrates are sedentary or have limited locomotive capacity. Therefore their capacity to avoid seismic sound is extremely limited compared to many fish and marine mammals. This may increase their exposure to seismic sounds, but there is no basis on which to assume that increased exposure makes such species inherently more or less sensitive to those sounds.

11) The ecological significance of the effects is expected to be low, except if effects of exposure to seismic sounds were to influence reproductive or growth (molting) activities, or lead to a dispersion of spawning aggregations or deflection from migration paths. The magnitude of effect in these cases will depend on the biology of the species and the extent of the dispersion or deflection.

Functional Uses of Sound

12) The potential for seismic sound to disrupt communication, orientation, detection of predators/prey, locomotion and other functional uses of sound by invertebrates has not been studied. Loud sounds will reduce the efficiency of communication and other functional uses of sounds, but the severity and conditions under which this occurs with invertebrates are unknown. It is not known if invertebrates can communicate acoustically during the inter-pulse intervals that occur between seismic transmissions. Ecological significance of such effects, if they occur, is unknown.

Conclusions about Zooplankton, Eggs and Larvae of Fish and Invertebrates

1) Few studies of the effects of seismic sound on eggs and larvae or on zooplankton were found. A number of these provided inadequate description of experiment design, properties of the sound applied as treatments, or had methodological shortcomings.

2) Data are generally insufficient to evaluate the potential damage to eggs and larvae of fish and shellfish (or other planktonic organisms) that might be caused by seismic sound under field operating conditions.

3) From the experiments reported to date, results do show that exposure to sound may arrest development of eggs, and cause developmental anomalies in a small proportion of exposed eggs and/or larvae; however these results occurred at numbers of exposures much higher than are likely to occur during field operation conditions, and at sound intensities that only occur within a few meters of the sound source.

4) Effects of seismic sounds on behavioral functions and sensory perception of fish and invertebrate eggs and larvae are unknown;

5) In general, the magnitude of mortality of eggs or larvae that models predict could result from exposure to seismic sound would be far below that which would be expected to affect populations. However, special life history characteristics such as extreme patchiness in distribution and timing of key life history events in relation to the duration and coverage of seismic surveys may require case by case assessment.

6) No studies were found which specifically investigated the role of seismic sounds in recruitment variation of marine fish or invertebrates. There have been a large number of research studies on causes of variation in recruitment of marine fish or invertebrates, and none has considered that there are recruitment anomalies (positive or negative) which might be linked in space or time to seismic survey operations. This negative evidence applies at the scale of stocks, but does not provide information about the potential for effects on local-scale recruitment dynamics.

Conclusions Regarding Marine Turtles

1) Auditory studies suggest that sea turtles, specifically loggerhead and green turtles, are able to hear and respond to low frequency sound, but their hearing threshold appears to be high.

2) In three studies, the following behavioral responses of sea turtles in enclosures exposed to airgun sounds were sometimes observed:

   - increased swimming speed,
   - increased activity,
   - change in swimming direction, and
   - avoidance.

3) Sea turtles may become accustomed to seismic sound over time, but results of three studies were inconclusive on this matter.

4) Loss of hearing sensitivity and physiological stress response has also been considered as a possible consequence of exposure of sea turtles to seismic sound, but the one study reviewed was inconclusive.

5) The response, if any, of free-ranging sea turtles to seismic sound conducted under field operating conditions is unknown.

6) Based on studies that have been conducted to date, it is considered *unlikely* that sea turtles are more sensitive to seismic operations than cetaceans or some fish. Therefore, mitigation measures designed to reduce risk or severity of exposure of cetaceans to seismic sounds may be informative about measures to reduce risk or severity of exposure of sea turtles to seismic sounds. However sea turtles are harder to detect both visually and acoustically than are many species of cetaceans, so mitigation strategies based on sightings or acoustic detection of turtles, are expected to be less effective for turtles than for cetaceans.

Conclusions Regarding Marine Mammals

Mortality and Physical Effects

1. There are no documented cases of marine mammal mortality upon exposure to oil and gas exploration seismic surveys. There is one case of a stranding event involving two whales coincident in space and time with a research vessel conducting seismic operations. There is one stranding event involving the same vessel and whales, coincident in time but not space, with no obvious mechanism that could bridge the distance between the vessel and the stranding site. In both cases the research vessel was also operating mid-frequency airgun systems that produce sound significantly more similar in character to the tactical mid-frequency sonar implicated in whale mass stranding events, than is seismic sound. The role of the different sound sources in the stranding events could not be resolved by the study. Therefore, although whale strandings have been linked to exposure to anthropogenic sound, exposure to seismic sound is considered *unlikely* to cause direct marine mammal mortality.

2. Under experimental conditions, sub-lethal, temporary elevations in hearing thresholds (TTS) have sometimes been observed in captive marine mammals exposed to pulsed sounds. Currently, the likelihood of these effects have not been evaluated under field operating conditions; for some species of marine mammals the levels and types of sounds which may produce TTS can be predicted, so such evaluations may be possible. The significance of such TTS effects, were they occur, are likely to be unimportant, unless:

    a. the threshold was elevated repeatedly or for an extended period of time, which could result in a Permanent Threshold Shift [PTS]; or

    b. other threats were present at the same time as the temporary elevations in hearing thresholds, and the threats were ones normally avoided by acoustic means, such as predators or entanglements in fishing gear.

3. There are no documented cases of a marine mammal experiencing damage to non-auditory body tissues upon exposure to seismic surveys under field operating conditions. Therefore, exposure to seismic sound under field operating conditions is considered *unlikely* to result in such types of tissue damage to marine mammals, but the presence of other sound sources operating simultaneously with seismic operations should be taken into account when proposals are evaluated.

Direct Behavioral Effects

<u>Displacement and Migratory Diversion:</u>

4) There is documented displacement and migratory diversion in some marine mammal species exposed to seismic sound. The duration of these effects may or may not extend beyond the duration of exposure. The effects are expected to vary between contexts, species, gender and age class, and individuals, and be dependant on the properties of received sound. The ecological significance of such effects is expected to be low, but may be higher if they:

- displace feeding marine mammals from areas where there are no alternates,
- displace marine mammals from resting areas where there are no alternates,
- displace marine mammals from breeding or nursery areas, or
- divert migrating animals from routes for which their alternate routes either do not exist or would incur substantially greater costs to traverse.

5) The magnitude of effect in these cases will depend on the biology of the species and the extent and duration of the dispersion or deflection. Also, there is a risk that a seismic project occurring in another area could cause incursion of displaced competitors into the critical habitat or area of high biological productivity occupied by other species.

6) In summary, exposure to seismic sound can result in displacement and/or migratory diversion in some marine mammals, but this effect is species, individual, and contextually-related. The ecological significance of such effects is *unknown*, but there are conditions under which the worst-case scenarios could be high.

Changes in Dive and Respiratory Patterns

7) There are documented changes in dive and respiratory patterns in some marine mammal species (e.g., bowhead whales, harbour and grey seals) exposed to seismic sound. There are records of the duration of these effects extending beyond the duration of exposure. The effects are expected to vary between contexts, species and individuals, and be dependant on the properties of received sound. The ecological significance of such effects is expected to be low, except if such effects:

   - interfere with feeding, or
   - incur substantial energetic costs;

   The magnitude of effect in these cases will depend on the biology of the species and the extent and duration of the dispersion or deflection.

8) In summary, exposure to seismic sound can result in changes in dive and respiratory patterns in some marine mammals, but this effect is expected to vary with species, individual, and context. The ecological significance of such effects is *unknown*, but there are conditions under which the worst-case scenarios could be high.

Changes in Social Behavior

9) Social behavior can include a wide variety of activities such as mating, cooperative feeding, play, aggressive interactions, and communication (see below). Studies of behavioral changes in other subsections of this summary describe effects on some of the activities that could be considered "social". However, there have been no directed studies of the effects of seismic sounds on mating, cooperative feeding, play, or aggressive interactions.

10) In summary, it is *unknown* if exposure to seismic sound can result in changes in marine mammal social behavior, but if it were to occur there are conditions under which the worst-case consequences of such changes could be highly significant.

Changes in Vocalisation Patterns

11) There have been direct studies of the potential for anthropogenic sound to cause changes in the vocalisation patterns of marine mammals. For most cetacean species studied, there were measurable changes in vocalisation patterns, but these studies were not conducted during seismic operations. In the UK, Norway, and the Sable Gully, sperm whales did not stop calling when exposed to seismic sounds. A study off Heard Island, found that sperm whales did not call during distant (690-1070 km away) seismic transmissions in some parts of the study, but did call during seismic transmissions during another part of the study. Blue whales in the NE Pacific stopped calling for approximately one hour when within 10 kilometers of a small (1600 in^3) seismic array; they resumed calling as they swam away from the array.

12) There is evidence that exposure specifically to seismic sounds has sometimes caused changes in vocalisation patterns in marine mammals. However, it has not been possible to measure the functional consequences of

these changes (such as loss of contact between individuals or reduced ability to coordinate social behaviors), if any, nor the percent of time which they would occur.

13) In summary, it is *known* that exposure to seismic sound can result in changes in marine mammal vocal behavior, and when it occurs there are conditions under which the worst-case consequences could be highly significant.

Functional Consequences of Physical and Behavioral Effects

Reduced Communication Efficiency

14) Many species of marine mammals both produce and respond to sounds. Studies have shown these vocalisations to sometimes communicate information that is functionally important for feeding, breeding, parental care, predator avoidance, or maintenance of social groupings. Studies have also found vocalisations can occur when there are no observable functional consequences, although in such cases it is unclear if the vocalisations had no consequences, or if the effects were longer term or farther afield than the studies. Hence it is difficult for research to produce conclusive results about the frequency of occurrence and consequences of disruption of communication by anthropogenic activities, including seismic sounds.

15) There have been no published studies of the potential for seismic sound to reduce the efficiency of communication in marine mammals. Loud sounds will reduce the efficiency of communication but the severity and conditions under which this occurs with marine mammals are poorly known. When seismic sounds are produced there are inter-pulse intervals which present the opportunity for cetaceans to place vocal communication signals, but cetaceans have not been shown to use this mechanism in the field. Moreover, there is unpublished information that when multi-path echoes occur, such as in areas of complex bathymetry, the pulses of the seismic sound may smear over distance and time, such that the quieter inter-pulse intervals may be reduced or eliminated. This creates the potential for calls of cetaceans such as blue whales to be masked by seismic sounds although the distances over which the masking would be effective, if it were to occur, are unknown. It is unknown if whales could reduce the effects of masking through processes such as changes in their calling patterns, and the consequences of these changes (if they occur) are unknown. This facultative response has been documented in some other marine mammal species exposed to loud manmade sounds. Therefore, it is *unknown* if exposure to seismic sound can result in such reduced communication efficiency in marine mammals.

Reduced Echolocation Efficiency

16) There have been no direct studies of the potential for seismic sound to reduce the efficiency of echolocation in marine mammals. Therefore, it is *unknown* if exposure to seismic sound can result in reduced echolocation efficiency in marine mammals.

Hampered Passive Acoustic Detection of Prey

17) There have been no direct studies of the potential for seismic sound to hamper the passive acoustic detection of prey by marine mammals. In a published study on the effects of whale watching vessels on killer whale behavior, it was postulated that sounds from these vessels could reduce the ability of killer whales to detect their prey. It is not known if such an effect could result during exposure to seismic sounds, or even which species of marine mammals use passive acoustic detection of prey as an important feeding strategy. However the potential for an effect is greatest for mysticetes whose best hearing sensitivity is thought to be at lower frequencies than other marine mammals. Therefore, it is *unknown* whether exposure to seismic sound could hamper the passive acoustic detection of prey by marine mammals.

Hampered Passive Acoustic Detection of Predators

18) There have been no direct studies of the potential for seismic sound to hamper the passive acoustic detection of predators by marine mammals. The potential for an effect is greatest for mysticetes, whose best hearing sensitivity is thought to be at lower frequencies than other marine mammals. However it is not known if such an effect occurs during exposure to seismic sounds, and if so, to what extent. Therefore, it is *unknown* whether exposure to seismic sound could increase the vulnerability of marine mammals to predators.

Hampered Avoidance of Anthropogenic Threats (such as ship strikes, net entanglement)

19) There have been no direct studies of the potential for seismic sound to reduce the ability of marine mammals to avoid anthropogenic threats. There are published reports of other types of sounds interfering with the ability of individual whales to avoid anthropogenic threats such as ship strikes and net entanglements, but it is not known how widespread this response is. It is also not known if such an effect could result from exposure to seismic sounds. Therefore, it is a *concern* that exposure to seismic sound could reduce the ability of marine mammals to avoid anthropogenic threats, but the risk has not been demonstrated.

Hampered Parental Care or Bonding

20) There have been no direct studies of the potential for seismic sound to hamper parental care or bonding in marine mammals. Therefore, it is *unknown* if exposure to seismic sound can hamper parental care or bonding in marine mammals.

Chronic Effects (e.g., stress-related physiological changes, reduced fecundity)

21) There have been no studies of the potential for seismic sound to induce chronic effects, such as immunosuppression or reduced fecundity, in marine mammals. Therefore, it is *unknown* if exposure to seismic sound can result in such chronic effects on marine mammals.

Indirect Effects (e.g., reduced prey availability)

22) There have been no studies of the potential for seismic sound to reduce prey availability, through displacement or reduced catchability, for marine mammals. Therefore, it is *unknown* if exposure to seismic sound can result in such indirect effects on marine mammals.

Research Needs

In the review a large number of areas of future research were identified. Some emerged as particularly helpful in increasing the information available to those quantifying and those managing the risks of seismic surveys in marine ecosystems.

1) More work is required to determine the sound characteristics and environmental conditions under which seismic effects on behavior, physiology, and physical well-being of all types of marine species might occur.

2) The available information on the effectiveness of mitigation measures needs to be more fully evaluated, as a basis for both interim advice on appropriate operational requirements in the short term and additional research needs to increase our knowledge in the longer term.

3) In addition to targeted research, there is great value to linking a program of structured collection of information to the conduct of seismic surveys, to facilitate learning-by-doing. However, such information collection programs must be well coordinated, and accompanied by the resources to analyse, interpret, and apply the new information, as it is collected and submitted to scientific authorities.

4) A few representative studies on distance-effect relationships for all taxa, but particularly eggs and larvae, would greatly aid understanding of potential risks posed by seismic sound. The potential for effects stemming from sound exposure level (cumulative over a survey) as well as peak received sound pressure level should be considered, including under conditions of 3-D surveys.

5) Specific research is needed on the level of received sound experienced by sessile invertebrates, and the effects of seismic sounds on such organisms. The physics of the sound levels to which benthic organisms are exposed is complicated due to shear effects interacting with pressure effects, and the proximity to the bottom substrates. Hence results of generic sound propagation models are likely to be misleading with regard to exposure levels of sessile benthic species. However, the errors could be in any direction, and in sites of complex bathymetry there could be very patchy distributions of areas with higher intensities of exposure than predicted by sound propagation models and other areas with lower intensities.

6) There is a specific absence of information on the effects of seismic sounds on molting of invertebrates with hard exoskeletons.

7) There is a need to further clarify the best sound propagation models for the areas likely to host seismic exploration, and how habitat characters should influence model selection. Generic models also need to be evaluated relative to the sensitivity and precision of their predictions relative to requirements for evaluating potential impacts, although site-specific implementations of generic models will continue to be desirable.

8) Better data input is needed during modelling of the expected pattern of spread of seismic sounds during surveys. Near-and far-field sound measurements should be encouraged as part of seismic operations planned for an area that has not been surveyed previously, or if previous models have been shown to be inaccurate.

9) Further research on potential impacts of seismic sound on marine mammals is urgently needed. The issues in most need of attention through scientific research or further analysis of existing data include:

    a) An important scientific unknown limiting our ability to predict the effects of seismic surveys on marine mammal populations is knowledge of their spatio-temporal distribution, and physiological state and needs. Without knowledge about what species are present in which areas at what time of the year and for what purpose, there will always be risks of disturbance and injury to sensitive species. An effort should also be made to characterise the degree of

long-term natural variation in abundance and residency.

b) There is a need for significantly more information regarding the reactions of marine mammals (and their prey) to underwater sound from seismic arrays. Baseline studies prior to seismic operations, plus comparative reports during periods with and without seismic would contribute important new data.

c) There is a need for better and more accurate information on naturally-occurring and man-made noise in the ocean.

d) The effectiveness of all potential mitigation measures needs to be explored and documented more fully. In particular there is a need to document the extent to which passive and/or active acoustic monitoring of marine mammals from the source vessel is an effective mitigation strategy.

e) There is a particular need for directed studies of social behavior of marine mammals during seismic exposures, given the importance of these activities to marine mammals' biology.

f) The effects of anthropogenic sounds on the vocalisation patterns of marine mammals are well documented, but the effects of specifically seismic sounds are poor known, and warrant further study.

Many of these factors are also poorly known for many taxa of marine turtles, fish, and invertebrates. Research to fill in such knowledge gaps, particularly with regard to spatio-temporal distribution of important prey taxa and their reactions to seismic sound, would be valuable, although the topics listed above were given higher priority. A number of other topics requiring additional research were proposed by various individuals, and are recorded in the meeting proceedings.

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