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Potential Effects of Seismic Energy on Fish and Shellfish: An Update Since 2003

Effets possibles de l'énergie sismique sur les poissons, les mollusques et les crustacés : mise à jour depuis 2003

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ABSTRACT

Literature appearing since 2003 to February 2008 on the effects of seismic on fish and shellfish was reviewed. A few studies are now available indicating absence of effects at the population level. However, if seismic surveys are having effects on fish or shellfish at the population level, it is understood that they would not be readily measurable due to confounding factors such as natural variability, fishing pressure and animal migration. The primary concern would seem to be in relation to the potential for producing impacts at the stock or sub-stock level, such as in a particular region or bay, or in shallow coastal or Arctic waters. There is some evidence suggesting a potential for seismic to have sublethal effects at the individual level viz physiological and histopathological. Thus, there is need for selected dose-response studies to investigate for effects at this particular level in order to provide a better informed opinion on any risk that may be associated with seismic surveys. Selected studies would also be of value for the development of potential indices which might be of interest for use in any required monitoring programs.

A few representative studies focused on elucidating potential chronic effects, such as under the conditions of a 3D survey, are also warranted. For instance, would exposure of codfish to seismic sounds over a 3-week survey period perturb neurohormonal systems to a sufficient degree to affect the internal development of eggs or sperm? Such representative studies are needed if only for assurance. They would also help to identify any need for airgun-based sound reference levels for fish and shellfish, an undertaking which would be gargantuan in nature given the myriad numbers of species that could be invoked for study.

Seismic airguns can produce low levels of noise at considerable distance from source. However, with respect to ambient ocean noise and animal behavior, the cacophony of noise associated with ships could be of greater importance.

RÉSUMÉ

Les documents rédigés de 2003 à février 2008 au sujet des effets de l'énergie sismique sur les poissons, les mollusques et les crustacés ont fait l'objet d'un examen. Quelques études disponibles indiquent l'absence d'effets sur la population. Cependant, si les levés sismiques ont des effets sur les populations de poisson, de mollusque ou de crustacé, ces effets ne seraient pas faciles à mesurer en raison de facteurs confusionnels, notamment la dispersion naturelle, les pressions de la pêche et la migration des animaux. Les impacts possibles au niveau du stock ou du sous-stock, comme dans une région particulière ou une baie, ou dans les eaux côtières ou arctiques peu profondes, semblent constituer la préoccupation première. Il existe certaines preuves suffisantes suggérant la possibilité que la prospection sismique provoque des effets sublétaux au niveau individuel, c'est-à-dire sur le plan physiologique et histopathologique. Par conséquent, il est nécessaire de procéder à des études dose-réponse sélectionnées afin d'investiguer les effets à ce niveau en particulier dans le but d'arriver à une opinion plus éclairée sur tout risque qui pourrait être associé aux levés sismiques. De telles études sélectives auraient également une grande valeur pour le développement d'indices éventuels représentant un certain intérêt dans le cadre de programmes de surveillance.

Quelques études représentatives visant à élucider les effets chroniques possibles, y compris dans des conditions de levés sismiques tridimensionnels, seraient également justifiées. À titre d'exemple, l'exposition de la morue à des bruits sismiques durant une période de prospection de trois semaines perturberait-elle les systèmes neurohormonaux à un degré suffisant pour toucher le développement interne des œufs ou du sperme? De telles études représentatives seraient nécessaires uniquement à des fins d'assurance. Elles contribueraient aussi à déterminer la nécessité d'établir des niveaux de référence pour les bruits des canons à air relatifs aux poissons, aux mollusques et aux crustacés, bien que ce serait une entreprise immense vu le nombre d'espèces qui pourraient être des objets d'étude.

Les canons à air sismiques peuvent produire de faibles niveaux de bruits à une distance considérable de la source. Toutefois, par rapport aux bruits ambiants de l'océan et au comportement animal, la cacophonie des bruits associés aux navires pourrait avoir une plus grande importance.

Note: Various studies carried out since 2003 to February, 2008 are reviewed. In most cases the original abstracts are presented with only minor modification.

STUDIES FOCUSING ON THE EFFECTS OF AIRGUN EXPOSURE

- Parry and Gason (2006) investigated the effect of seismic surveys on catch rates of rock lobsters in western Victoria, Australia between 1978 and 2004. In 12 depth-stratified regions, the number of acoustic pulses during seismic surveys was correlated with catch per unit effort in the years following seismic surveys. In another three regions subject to intense seismic surveys, two-way analysis of variance was used to detect weekly changes in catch per effort during and after seismic surveys. Catch rates were found to be unaffected in the weeks or years following the surveys. However, the authors note that most surveys occurred in deep water where impacts would be expected to be minimal. The sensitivity of analysis in shallow water was limited by the low levels of surveying. It is also noted that although short term changes in catch rates appeared to be unaffected in areas subjected to intense seismic surveying, a change in catch rates of the order of 50% would have been required to detect change.

- Boeger et al. (2006) carried out a study on coral reef fishes caged in the near vicinity of sound exposure from an array of 8 airguns generating peak pressure levels of 196 dB re 1µPa. Trial 1 involved 2 passes of the gun boat under the following conditions: depth of cage in water, 5 m; horizontal distance from guns, 7 m; depth of water at experimental site, 50-60m. Trial 2 similarly involved 2 passes of the gun boat under the following conditions: depth of cage in water, 7.5 m; horizontal distance from airguns, 0.5 m; depth at experimental site, 7.5 m. Trial 3 involved 50 shots of static airguns under the following conditions: depth of cage in water, 5 m; horizontal distance from airguns, 1 m; depth at experimental site, 61 m.

  No mortalities or visible external damage was recorded. The most obvious effect being temporary startle responses. Repeated exposure to airguns seemed to result in increasingly less obvious startle responses, indicating possible habituation.

- Andriguetto-Filho et al. (2005) investigated the effect of seismic surveys on shrimp fisheries in relatively shallow waters (2-15 m) in Camamu Bay, northwestern Brazil. Catch rates of various shrimp species were measured before and after use of a four airgun array with a source peak pressure of 196 dB re 1µPa at 1 m. Catch rates were found to be unaffected. The experiment was carried out over a period of a few days whereby “in-migration” would not be a confounding factor. It is also noted that the authors carried out histopathological studies on gonadal and hepatopancreatic tissue and reported that there was no damage that could be associated with exposure.

- Popper et al. (2005) investigated the effects of exposure to a 730 in^3 airgun array on hearing of 3 fish species in the Mackenzie River Delta, the northern pike (*Esox lucius*), broad whitefish (*Coregonus nasus*), and lake chub (*Couesius plumbeus*). Fish were placed in cages in 1.9 m of water and exposed to five or 20 airgun shots, while controls were placed in the same cage but without airgun exposure. Three standard metrics for received sound levels were recorded: (a) mean peak sound pressure level (SPL) of 207.3 dB re 1µPa, (b) a mean 90% rms SPL of 197.4 dB re 1µPa and (c) a mean sound exposure level (SEL) of 177.7 dB re $1µPa^2 \cdot s$. Hearing in both exposed and control fish were then tested using the auditory brainstem response (ABR). Threshold shifts were found for exposed fish as compared to controls in the northern pike and lake chub, with recovery within 24 hrs of exposure, while there was no threshold shift in the broad whitefish. It was concluded that these three species are not likely to be substantially impacted by exposure to an airgun array used in a river seismic survey. The authors cautioned about extrapolation to other species and to fish exposed to airguns in deeper water or where the animals are exposed to a larger number of airgun shots over a longer period of time.

- Guerra et al. (2004) suggested that seismic surveys may have caused or contributed to the massive organ damage observed in giant squid stranded in waters of northern Spain. Any such observations are of importance if only associative. However post-mortem changes can be a confounding factor in studies of stranded animals. Also, any major visible organ damage in other animals has only been found, if at all, under rather high level exposure conditions in the laboratory (Worcester 2006). However, it cannot be discounted that the organ damage observed in some stranded squid could reflect post-mortem changes in animals traumatized by seismic exposure resulting in rapid ascent to the surface and premature death.

- In the winter of 2003 and spring of 2004, DFO conducted a study on the effects of seismic on snow crab in conjunction with a seismic survey off the western coast of Cape Breton (DFO, 2004). Crabs were caged at water depths of 63 and 73 m (experimental site) and 85 m (control site). The seismic survey involved 132 hrs of survey time with a low volume (1,310 in^3) airgun array. Maximum rms SPL received at the test and control sites were 174 dB re 1µPa and 118 dB re 1µPa, respectively. The caging experiment examined short (12 days) and medium (5 months) term differences in the morphology and physiology of snow crab at test and control sites. Snow crabs from both groups were also observed under laboratory conditions for differences in mortality, morphology, physiology, feeding and orientation (turnover rate) over a five month period. This seismic survey did not cause any acute or mid-term mortality of the crab, nor was there any evidence of changes to feeding in the laboratory. Survival of embryos being carried by female crabs, and locomotion of the resulting larvae after hatch, were unaffected by the seismic survey. In the short term, gills, antennules and statocysts (balance organs) were soiled in the test group but they were found to be completely cleaned of sediment when sampled five months later. The sound pressure measured at the test site would not be expected to stir up sediment at a depth of 60 or more meters. Therefore, the soiling of gills was likely due to natural factors or method of animal collection.

  Some differences were reported between the test and control animals. There was indication of some slight histological differences in the control and test groups but the differences can reasonably be attributed to natural variability associated with the different oceanography/feeding regimes at the locations where the control and experimental animals were collected and held in the environment. The two groups were also different in size, the exposed animals being smaller. There was a little more leg loss in test animals shipped to Newfoundland but this could have been shipping related.

  Evidence supporting the hypothesis that the various effects observed were due to normal variability has also recently been obtained from an ESRF supported study in Newfoundland (DFO, NL Region, unpublished). Female crab were exposed to higher sound levels than those measured at the test site in the Cape Breton study and maintained in the lab over several months. No difference was observed with respect to mortality, leg loss, egg loss, or hepatopancreas and ovary histopathology. The results support the earlier preliminary study on snow crab carried out by Christian et al. (2004).

In initial meetings carried out to review the results of the Cape Breton snow crab study, considerable interest was displayed about the possible effects of the seismic survey on crab populations in the area. Comparisons of abundance and distributions of different classes of snow crabs were carried out based on bottom trawl surveys conducted before the seismic survey (September, 2003) and thereafter (June, 2004). No statistically significant change in snow crab abundance was resolved through analysis of current statistical assessment data (DFO, Gulf Region, unpublished).

- Payne et al. (2007) reported on pilot studies conducted in the laboratory and field that investigated the potential for effects of exposure to seismic on lobster health. The authors noted that the basic purpose of the studies was to explore for change in various biological endpoints and identify any which might require further assessment in a more comprehensive manner. Such studies are also of value for the determination of potential indices which might be of interest for use in any required biological monitoring programs. A number of endpoints were assessed, including (a) lobster survival, (b) food consumption, (c) turnover rate, (d) leg loss, and (e) various serum parameters. A small histopathological study was also carried out on lobsters used in one of the trials. Exposures of usually 20-50 shots were conducted with a 10-in^3 and a 40-in^3 sleeve gun in the laboratory and field, respectively. The lower-level exposures were carried out in a large aquarium (dimensions 3.63 m x 2.39 m x1.27 m in depth) while the higher–level exposures were carried out in the field. Animals were caged during exposure. After exposure, animals were maintained in aquaria for long-term observation and sampling. Observations were made over a period of a few days to several months, depending on the specific trial. Sound measurements were conducted on three occasions in the laboratory to determine the received levels at the cage site. Peak-to-peak SPLs averaged ~202 dB re 1µPa with energy densities ranging from 144 to 169 dB re 1µ Pa^2 /Hz. Three separate measurements were also carried out in the field. The back calculation provided an average received peak-to-peak SPL of approximately 227 dB re 1µPa and an average peak energy density of 187 dB re 1µPa^2 /Hz. Exposure of lobster to "low" (~202 dB re 1µPa peak-to-peak} and "high"(~227 dB re 1µPa peak-to-peak) SPLs had no effects on delayed mortality up to 8 months post-exposure, mechano-balancing systems (as demonstrated by lack of effects in righting ability), or loss of appendages. However, sub-lethal effects were observed with respect to feeding and serum biochemistry, with statistically significant effects ($P<0.05$) sometimes being observed weeks to months after low-level exposures. Feeding was generally characterized by an increase in food consumption which is of interest since food intake has been reported to increase in humans subjected to brain trauma (Henson et al. 1993). A histochemical change (elevated deposits of carbohydrate) was also noted in the hepatopancreas of animals exposed 4 months previously.

- Andrews et al. (2007) have also conducted preliminary studies with codfish to explore for changes in various biological endpoints and identify any which might then warrant further assessment in a more comprehensive manner. Fish were exposed to a relatively large number of shots (200) with peak-to-peak SPLs approximating 202 dB re 1 µPa and the indices subsequently examined included survival, feeding, behavior and alteration of gene expression in the brain. No mortality occurred over the 2-month post exposure period, but interestingly, as was the case for lobster, food consumption increased in the exposed fish. Exposed fish ate 95% more than controls 2 weeks following exposure and

33% more than controls 1 month post-exposure. It was also noted through independent observations that seismic exposed fish remained near the bottom of the aquarium for 2 weeks following exposure while fish in the control group swam at all depths in the water column. Genomic studies also indicated alteration of gene expression in the brains of exposed fish. Studies to obtain an appreciation of dose-response relationships for effects of seismic on feeding in lobster, codfish and American plaice are planned.

- McCauley et al. (2003) demonstrated that the ears of fish exposed to an operating airgun sustained substantial damage to their sensory epithelia characterized by ablation of hair cells. Peak-to-peak SPLs of 212 dB re 1μPa were recorded but as noted by Worcester (2006), the exact levels/distance at which such damage may have occurred is unknown since the airgun was towed repeatedly from a maximum distance of 800m to a minimum of 5 m. Damage may have occurred at any period during their exposure, or as a result of cumulative exposure.

  This particular study has generated considerable attention over the past few years and the issue of potential for seismic to damage fish ears needs confirmation. Although the study by McCauley et al. (2003), has not, to our knowledge, been confirmed, information has been obtained on the ability of fish to regenerate damaged hair cells. There is information available on hair cell regeneration in fish exposed to ototoxic antibiotics, but regeneration capabilities have not been explored until recently, following fish exposure to noise.

- Smith et al. (2006) examined the relationship between hair cell damage and physiological changes in goldfish. Goldfish were exposed to white noise (120 dB re 1μPa rms) for 48 hr and monitored for 8 days following exposure. Auditory thresholds along with morphological hair damage were studied. The study demonstrated that although both auditory thresholds and hair cell morphological characteristics were altered, the fish were capable of significant regeneration responses similar to that seen in previous studies with ototoxic antibiotics. It is also noted that functional recovery preceded morphological recovery, suggesting that only a subset of hair cells is necessary for normal auditory responses.

STUDIES, EXCEPTING BEHAVIOR, ON NOISE SOURCES OTHER THAN AIRGUNS

The following two studies were considered to be of interest since the metrics have some relevance for airgun based exposure:

- Popper et al. (2007) investigated the effects of low-frequency sonar on rainbow trout. Effects of sonar on hearing were tested using the auditory brainstem response. Effects were also examined on inner ear morphology using scanning electron microscopy and on nonauditory tissues using general pathology and histopathology. Animals were exposed to a maximum received rms SPL of 193 dB re 1 μ Pa^2 for either 324 or 648 s. The most significant effect was a 20 dB auditory threshold shift at 400 Hz. However, the results varied with different groups of trout suggesting developmental and/or genetic impacts on how sound exposure affects hearing. There was no fish mortality during or after exposure. Sensory tissue of the inner ears did not show morphological damage several days post exposure. Similarly, gross and histopathological observations demonstrated no effects on nonauditory tissues. Sonars generally operate at a much higher frequency range than airguns but the results are of general interest. Noted in this regard are the pressure levels which are relevant for airgun exposure.

- Simpson et al. (2005) measured the heart rates of embryonic clownfish exposed on each day of incubation to sounds in the range of 100 to 1200 Hz with source SPLs of 80 to 150 dB re 1 µPa at 1 m. Three days after fertilization, the heart rates of the embryos significantly increased when exposed to sound. As the embryos developed, a response in heart rate was found over a broader spectrum of sound (from 400 to 700 Hz at 3 d post fertilization to a maximum of 100 to 1200 kHz at 9 d post fertilization). Sensitivity also increased, with response threshold minima at 700 Hz decreasing from 139.1 dB at 3 d post fertilization to 88.3 dB at 9 d post fertilization.

STUDIES ON FISH BEHAVIOR IN RELATION TO SHIP AND OTHER NOISE

There is considerable interest in behavioral responses to sound exposure resulting in potential adverse outcomes for feeding, reproduction, migration etc. Worcester (2006) reviewed studies on sound reception and use of sound by fish. Many of these studies were of a more fundamental nature. Since 2003, a few studies, including field studies have appeared which are of general interest for this review.

- Kastelein et al. (2008) carried out a study of the startle response of fish to tones between 0.1 and 64 kHz. The lower frequency may be of some relevance for seismic surveys. Response thresholds were determined for eight marine species held in a large tank. Response threshold levels varied by frequency within and between species. For sea bass, the 50% reaction threshold occurred for signals of 0.1-0.7 kHz, for thicklip mullet 0.4-0.7 kHz, for pout 0.1-0.25 kHz, for horse mackerel 0.1-2 kHz, and for Atlantic herring 4 kHz. For cod, pollack and eel, no 50% reaction thresholds were reached. Reaction threshold levels increased from ~100 dB re 1µPa rms at 0.1 kHz to ~160 dB re 1µPa rms at 0.7 kHz. The 50% reaction thresholds did not run parallel to the hearing curves. This study demonstrated that fish species react very differently to sound, and that generalizations about the effects of sound on fish should be made with care. It was also noted that context as well as sound levels may be important in affecting behavioral responses with context including such variables as location, physiological state and school size.

- Sara et al. (2007) investigated the effect of boat noise on the behavior of bluefin tuna (*Thunnus thynnus*) in the Mediterranean Sea. Behavior of captive tuna was observed when exposed to ambient sound and sound generated by hydrofoil passenger ferries, small boats and large car ferries. Acoustical and behavioral analyses were conducted with and without extraneous sound to define a list of behavioral categories. Each vessel produced different engine sounds with regard to their composition and bandwidth, and all were distinctly different from ambient sound levels. In the absence of boat noise, tuna assumed a concentrated coordinated school structure with unidirectional swimming and without a precise shape. When a car ferry approached, tuna changed swimming direction and increased their vertical movement toward surface or bottom; the school exhibited an un-concentrated structure and uncoordinated swimming behavior. Hydrofoils appeared to elicit a similar response, but for shorter periods. Agonistic behavior was more evident when exposed to sounds from outboard motors of small boats. The paper includes graphs of sound pressure spectra in the bandwidth 70 to 200 Hz and the data are of interest with respect to seismic produced sound.

- Vasconcelos et al. (2007) investigated the effects of ship noise on sound detectability in the Lusitanian toadfish. Ambient noise, ferry-boat noise and noise produced by toadfish were recorded in the Tagus River estuary (Portugal), and their sound pressure levels determined. Hearing sensitivities were measured under quiet lab conditions and in the presence of these masking noises at levels encountered in the field, using the auditory evoked potentials recording technique. The Lusitanian toadfish is a hearing generalist, with best hearing sensitivity at low frequencies between 50 and 200 Hz below 100 dB re 1µPa. Under ambient noise conditions, hearing was only slightly masked at lower frequencies. In the presence of ship noise, auditory thresholds increased considerably (maximum increase of 36 dB) at most frequencies tested.

- Wysocki et al. (2007) measured the linear equivalent SPLs of twelve European freshwater habitats in order to assess the detectability of sounds by fish. Stagnant habitats such as lakes and backwaters are quiet, with noise levels below 100 dB re 1µPa (L_{Leq}) under no-wind conditions. Typically, most environmental noise is concentrated in the lower frequency range below 500 Hz. Noise levels in fast-lowing waters were typically above 110 dB and peaked at 135 dB (Danube River in a free-flowing area). Contrary to stagnant habitats, high amounts of sound energy were present in the high frequency range above 1 kHz, leaving a low energy "noise window" below 1 kHz. Comparisons between the habitat noise types and prior data on auditory masking indicate that fishes with enhanced hearing abilities are only moderately masked in stagnant, quiet habitats, whereas they would be considerably masked in fast-flowing habitats.

- Sonny et al. (2006) studied reactions of cyprinids to infrasound in a lake and at the cooling water inlet of a nuclear power plant. Acute avoidance responses, at a distance up to 10m from a 16 Hz infrasound projector were revealed by echosounding.

- Wysocki et al. (2006) addressed the effects of ship noise and continuous Gaussian noise on adrenal activity in three European freshwater species. Underwater ship noise recorded in the Danube River and two Austrian lakes was played back to fish at levels encountered in the field (153 dB re 1µPa, 30 min.) In the first series, two hearing specialists, the common carp (*Cyprinus carpio*) and the gudgeon (*Gobio gobio*), and one hearing generalist, the European perch (*Perca fluviatilis*) were exposed to ship noise. The noise level was well above hearing thresholds in these species. In a second series, fish were exposed to continuous Gaussian noise at a similar level (156 dB re 1µPa) which is known to induce temporary hearing loss in hearing specialists. All three species responded with increased cortisol secretion when exposed to ship noise but no elevation was observed when fish were exposed to continuous Gaussian noise. Results indicate that ship noise characterized by amplitude and frequency fluctuations, constitutes a potential stressor in contrast to continuous noise. The data also demonstrate no apparent differences between hearing specialists and species with less sensitive hearing abilities (i.e., hearing generalists), such as perch.

DETECTION OF SOUND BY INVERTEBRATES

The mechanism of sound reception and hearing ability of invertebrates is an area of interest in relation to seismic and other sources of sound in the aquatic environment. Studies on prawn and lobster have appeared since 2004. Prawn (*Palaemon serratus*) has been shown to be sensitive to sounds ranging in frequency from 100 to 3000 Hz (Lovell et al. 2005). Immature lobsters detected sounds in the range of 20-1000 Hz while sexually mature lobsters exhibit two distinct peaks: 20-300 Hz and 1000-5000 Hz (Pye and Watson 2004). The ranges of these frequencies, especially the lower ranges, would be relevant for seismic surveys. Unlike fish, no literature has been found documenting major startle or movement responses upon exposure of crustaceans to sound. We have also observed no startle responses in aquarium experiments with lobsters and shrimp exposed to peak-to-peak SPLs of approximately 200 dB re 1µPa (unpublished observation).

FISH STOCK DISPLACEMENT

The issue of the potential for seismic surveys to affect displacement of fish stocks has been in the spotlight for some time and was covered in a balanced manner by Worcester (2006) who tabled studies as well as other anecdotal information, both pro and con. Regarding cod, Engås et al. (1996) provided strong evidence for effects but the results have been critiqued by Gausland (2003) who noted that the catch rates were not statistically different than normal variation in catch rates. For the purpose of this review, we had two senior scientists with expertise in cod science review the original work and the critique. They agreed that the study of Engås et al. (1996) was of note but Gausland’s critique was also of merit. Granting the difficulty in carrying out such studies, the scientists noted the lack of a control(s) for the study of Engås et al. (1996). Concern was also expressed that a number of replicates would generally be required for statistical validity. Confounding factors between control and test groups in any such experiments could also include such factors as locale, fish size, school size, nature of prey on which fish might be feeding at the time (e.g. capelin which are sensitive to sound and may move away from the area versus shrimp which are indicated not to be sensitive to sound), whether the fish were “migrating”, and whether other ship traffic might be traversing the area at the time.

- Hassel et al. (2004) carried out a field experiment to study sandeel behavior and survival during a seismic survey in the southern part of the North Sea. The seismic source was of a 28 airgun array having a sound pressure source level of 256 dB re 1µPa. Three sandeel cages were placed at a depth of 55 m in the center of the shooting area with the control fish being caged about 35km from the experimental site. Fish activity was monitored with cameras placed in the cages and by a remotely-operated vehicle.

  Startle or flight responses were observed in association with shooting. Distribution and/or abundance of fish were also monitored through acoustic surveys and grab surveys of sediments. Both acoustic surveys and grab samples of sediments indicated no apparent changes in sandeel abundance between control eel experiment sites. Mortality which was likely due to handling and confinement stress was high in both control and caged animals, around 35% on average.

- Slotte et al. (2004) carried out a further study on the influence of seismic activities on the behavior of pelagic fish (herring, blue whiting, and mesopelagic species). The possible influence of seismic activities was investigated in two ways.

  First, the distribution and abundance within the seismic area and the surrounding waters up to 30-50 km away were mapped acoustically three times. In all three surveys the acoustic abundance of pelagic fish was higher outside than inside the seismic shooting area, indicating a long-term effect of the seismic activity. Secondly, the acoustic abundance was recorded directly prior to and after shooting along some of the seismic transects. In these comparisons no differences were found, indicating that the shooting had insignificant short-term scaring effects. However, both blue whiting and mesopelagic species were found in deeper waters in periods with shooting compared to periods without shooting, indicating that vertical movement rather than horizontal movement could be a short-term reaction to this noise.

Regarding any effects on fish behavior in association with seismic surveys, it is in perspective, also important to point out that fish often avoid steaming research vessels and such behavior is a topic in fisheries science in relation to biasing abundance estimates (e.g. Mitson 1995; Vabo et al. 2002; Mitson and Knudson 2003). It is also of interest to note that fish can be attracted to freely drifting ships (Rostad et al. 2006).

GUIDELINES FOR AIRGUN BASED SEISMIC OPERATIONS

At the end of the day, “all the science” is supposed to offer guidance if not guidelines for noise exposure. Although no guidelines exist for seismic induced noise for fish, it has been recommended in the past that 180 dB re 1µPa rms be set as the SPL above which there was potential to cause serious physiological and hearing effects in marine mammals.

GUIDELINES FOR PILE DRIVING

With respect to pile driving, the National Marine Fisheries Service in the US has set a peak SPL of 180 dB re 1µPa as the level for mitigating adverse effects. Popper et al. (2006) proposed a provisional criterion for the onset of direct physical injury for pile driving: a SEL of 187 dB re 1µPa^2 · s, and a peak SPL of 208 db re 1µPa. Their suggested provisional criterion does not address behavioral responses or sub-lethal effects due to the absence of underlying information. The lack of data on the chronic or cumulative effects of pile driving or other sources of sound was also noted.

GUIDELINES FOR EXPLOSION BASED SEISMIC OPERATIONS

In contrast to airgun based seismic activity, there are guidelines in place for fish for explosion based seismic exposures. Canada has a current guideline of 100 kPa maximum peak pressure (10 kPa = 200 dB re 1µPa; 100 kPa =220 dB re 1µPa). However, a recent study found histopathological damage at lower levels of exposure and on the basis of this new data, DFO Western Arctic Area, recommended that the maximum peak pressure not exceed 50 kPa (Cott et al. 2003; Cott and Hanna 2004). In the meantime, Alaska has a guideline of 17.5 kPa (Alaska DNR 2003). It is recognized that guidelines for explosion based seismic operations are of little or no value for airgun based seismic activities where the same peak pressures have much lower rise times and are accordingly much less injurious.

DISCUSSION

POPULATION LEVEL EFFECTS

What have we learned about the potential effects of seismic at the population level? In order to resolve any seismic induced effects on populations after a seismic survey, impacts would likely have to be quite large to differentiate any seismic induced effects from such factors as varying mortality, animal movement and fishing practices. For instance, although considered to exhibit limited migration compared to many finfish, both lobster and snow crab have been recorded to travel tens of kilometers in a year (Lawton and Lavalli 1995; Bailey and Jamieson 1990). The problem would also be greatly compounded if effects occurred in small moulting animals, for example. These juvenile animals would not be expected to recruit into a fishable population for a number of years. Regarding shellfish displacement, the study of Andriguetto-Filho et al. (2005) on shrimp was of particular interest. They found that catch rates were not affected during an experiment carried out in relatively shallow waters where seismic energy could likely have more effect compared to deeper water areas where the shrimp might occur at greater distance from the seismic source. Moreover, the experiment was carried out over a period of a few days, whereby in-migration would not be as likely a confounding factor. The study by Andriguetto-Filho et al. (2005) is supported by pilot observations carried out by DFO on commercially important northern shrimp (*Pandulus borealis*) where no “flight or fright” reactions were found in animals exposed to relatively high sound levels in the laboratory. Thus, although crustaceans can be expected to detect the particle motion component of sound as revealed by sensitive electrophysiological or other techniques (e.g. Lovell et al. 2005), this does not mean that they would be “scared” and subsequently move away from a seismic operation, thereby causing ramifications for catchability.

Regarding broad scale surveys over a number of years in which population level effects were questioned, Parry and Gason (2006) found no effects on overall lobster catches, but cautioned that seismic induced mortality rates would have to be relatively high before seismic impacts could be resolved from other factors. Snow crab catches were also found not to be affected after a seismic survey off Cape Breton, but again, although the weight of evidence from studies on effects at the individual level might suggest no impacts, a considerable population level impact would likely be required in order to resolve any seismic impacts from other factors.

INDIVIDUAL LEVEL EFFECTS

What have we learned since 2003 about the potential effect of seismic on fish or shellfish at the individual level? Information obtained in the Mackenzie River study (Popper et al. 2005) indicated that hearing was not substantially impacted in 3 species exposed to an airgun array. Given the interest surrounding a previous study demonstrating some hair cell ablation in the ears of fish exposed close to a seismic array (McCauley et al. 2003), it is of note that Smith et al. (2006) documented significant regeneration capacity in goldfish subjected to extensive hair cell ablation upon noise exposure. Results followed in line with what is known about hair cell regeneration in fish exposed to ototoxic drugs. The study also demonstrated that functional recovery preceded morphological recovery, suggesting that only a subset of hair is necessary for normal auditory response.

There was no evidence for delayed mortality, egg loss or reduction in feeding in snow crab exposed under the conditions of an actual seismic program in deep waters off Cape Breton and subsequently maintained in the laboratory for several months. There was also no evidence for effects on egg hatch with eggs of test groups hatching a few days later in animals held in Moncton yet a few days earlier in animals held in Newfoundland.

There was indication of some slight histological differences between the control and test animals from the Cape Breton study but these can reasonably be attributed to different oceanographic and habitat conditions at the locations where the control and test animals were collected and held. This was supported in subsequent studies carried out in Newfoundland.

Lobster is one of the most commercially important species in Atlantic Canada with substantial fisheries occurring in “shallow” waters where exposure to seismic energy could be relatively high. Some pilot studies have been recently conducted to investigate the potential effects of seismic on animal health (Payne et al. 2007). The basic purpose of the study was to evaluate for change in various biological endpoints and identify any which might then warrant further assessment in a more comprehensive manner. Sound pressure levels measured at the cage site when the animals were exposed were ~202 dB peak-to-peak. Assuming spherical spreading of sound pressure, guns having a source level of 240 dB would be expected to produce sound pressure levels ~200 dB down to a depth of ~100m. Lobsters are generally found at much shallower depths. No effects were noted on important endpoints such as lobster survival, turnover rates, leg loss and egg loss. These observations are of importance in relation to the review of assessments for seismic survey programs. Interestingly, there is evidence for effects on feeding (increased food consumption by exposed animals). Some serum parameters, as well as a histological change in the hepatopancreas which may be related to feeding, were also altered in exposed animals and these alterations sometimes persisted for a number of days.

Most exposures were carried out in the laboratory at peak-to-peak SPLs of approximately 202 dB re 1 µPa. A higher exposure level of approximately 227 dB re 1 µPa peak-to-peak was also used in one study. Why use an exposure sound pressure level which is considerably higher than what the animal would likely experience under natural conditions? Very high exposure levels resulting in no observable effects can provide important information. For instance, if a particular effect is not observed at very high exposure levels, it is difficult to make a case for that effect at much lower levels. Noted in this study were the lack of effects on delayed mortality, loss of appendages and ability of animals to obtain normal posture at very high exposure levels. This and other information collected from snow crab studies has already been useful for review of seismic programs in the NL Region.

In Newfoundland, some preliminary studies have also been conducted in which cod fish were exposed to approximate peak-to-peak SPLs of 202 dB re 1 µPa. No mortality was observed in animals held for 2 months, but it was of interest that like lobster, feeding rates increased in the exposed animals. Evidence for behavior disturbance was also produced with a tendency for exposed animals to stay near the bottom.

Gausland (2003) previously noted reports of fishermen getting larger catches in the immediate track of a seismic survey. He further noted that the possible reason for this could be that the fish will have moved closer to the sea bottom in response to the seismic sound, leading to higher concentrations of fish in the area covered by bottom trawling. The preliminary tank experiments of Andrews et al. (2007) tend to support this hypothesis.

Regarding effects on fish behavior in general, it is presently well established that sound can produce startle and movement responses in finfish. Any startle or slight responses in movement would seem to be of little importance, but movement might have consequences, for functions such as mating and feeding, if found to persist.

Are there recent experimental trials that have been carried out with sound sources other than seismic which may be of interest? Although the frequency range of sonar can be quite distinct from airgun frequency, sound pressure levels have relevance. Popper et al. (2007) noted little effects on auditory and non-auditory tissue in rainbow trout exposed to sonar but noted that effects varied with different groups of fish.

To our knowledge, other than sound detection, the most sensitive effect noted to date in relation to sound exposure has been with embryonic clownfish. Heart rates were disturbed at sound levels of 80-150 dB in the range of 100-1200 Hz. (Simpson et al. 2005). By way of note, in relation to potential effects on developing embryos, the Fish Food and Allied Workers Union in Newfoundland is presently leading an ESRF- supported study on the effects of seismic on monkfish eggs which float in veils at the sea surface.

THE STATUS OF GUIDELINES

Are we in a position to suggest guidelines for fish and shellfish for airgun based seismic operations? The current recommended guideline for marine mammals is based on physiological and hearing effects and is rather strict: 180 db re 1µPa rms. Regarding explosion based seismic operations, it has been recommended by DFO Western Arctic Area that the present Canadian guideline of 100 kPa be reduced to 50 kPa. (10 kPa = 200 dB re 1µPa; 100 kPa = 220 dB re 1µPa). In the meantime, Alaska has a guideline of 17.5 kPa. Note that explosion based guidelines are of little relevance for extrapolation to airgun based discharges

In the case of pile driving, the National Marine Fisheries Service in the US has set a peak sound pressure guideline of 180 dB re 1µPa. Popper et al. (2006) have proposed a provisional peak sound pressure guideline of 208 dB re 1µPa measured 10m from source. However, this provisional guideline does not cover sub-lethal effects due to absence of sufficient data. There is also a lack of information regarding any chronic effects. Guidelines for pile driving have only partial relevance for airgun based discharges.

Effects of pile driving can be very limited in scope in comparison with a 3D seismic survey, for example, which can concentrate activity over a few hundred km^2 for upwards of a month. Other than some information on fish hearing and startle responses, there are virtually no data available for the development of useful guidelines for the safety of fish and shellfish exposed to airgun based seismic energy.

THE NEED FOR DOSE-RESPONSE STUDIES

Sub-lethal effects are very difficult to detect and serious physiological and anatomical damage may be occurring at much greater depths than previously thought. There are no boundary limits or numbers of studies that can be invoked for innumerable species. However, fairly comprehensive dose-response relationships need to be developed for a few representative species. Field studies are logistically difficult and can be prohibitively expensive but important range finding data can be obtained in a very cost effective manner through laboratory and small scale field experiments. Also, many important endpoints cannot be studied with any degree of scientific validity in field studies.

For instance, the results of our preliminary studies with lobster (Payne et al. 2007) indicate that sub-lethal effects may be delayed and/or persist to varying degrees after animal exposures. This indicates the importance of periodic assessment of various parameters which would not be logistically feasible after a field survey type experiment where animals would have to be left on the sea-bottom for several months. Also, any repeated lifting of animals from the sea-bottom for sampling could introduce serious artifacts for many physiological parameters. Furthermore, important endpoints like feeding which can affect growth and reproduction could not be assessed at all. Starvation of animals through holding in cages would also greatly compromise histopathological criteria. Given the potential for variability of response throughout the year with respect to feeding, moulting, etc., replicate field trials would be required. This is not to say that opportunistic “monitoring” studies carried out during an authentic field study would not be important, but it is difficult to determine at this time what should be monitored in the absence of more comprehensive experimental studies or indeed if monitoring studies are warranted at all.

It is recognized that when experiments are carried out in large tank systems, sound is reflected and the test animals likely receive variable exposure. It is also reasonable to note that many benthic animals, such as lobster and other invertebrates, reside in rocky habitats of variable complex geometry, and, therefore, the received sound levels from seismic exposures in this habitat type would also be expected to be highly variable.

PRIORITY SETTING

How might we approach priority setting at this time for the purpose of providing information related to seismic operations and their potential effects on fish and shellfish? In any priority setting, it is recognized that species selection should be based on area of seismic operation or potential operation with the understanding that one species can often serve as a reasonable proxy for many similar species. Particular attention is required for any extensive surveys which might take place in relatively shallow waters in the Arctic as well as shallow coastal (or other) waters in general. For instance, in Atlantic Canada, lobster can reasonably be listed as an important candidate for “comprehensive” studies including studies on moulting. In the meantime, preliminary screening studies might reasonably be considered for a bivalve such as scallop, or for a selected species at risk.

Of course any proposed priority studies of relevance for seismic surveys is not meant to derogate the continual importance of basic studies on the effects of sound in the aquatic environment in general-a challenging topic that will probably take decades for understanding.

CUMULATIVE EFFECTS

As often noted, there is a complete gap with respect to understanding cumulative or chronic effects which might be occurring in areas subjected to relatively high levels of sound for extended periods (e.g. during a 3D survey). For instance, chronic elevation of neurohormones such as adrenaline and cortisol often occur in fish under stressful conditions and has been associated with reproductive effects in codfish, for example.

Morgan et al. (1999) documented production of abnormal larvae (thus potential for impacts on populations) in eggs hatched from codfish exposed to chronic stress in the laboratory. This was documented in experiments carried out as a proxy for chronic stress which may be associated with trawler activity. Since seismic surveys involve the deployment of intense sound emitting airguns from a survey vessel producing hundreds to thousands of shots over a 24 hr period for 3 weeks or more, the chronic stress of seismic surveys could be markedly greater than any trawler–induced stress. And as noted above, we have already documented behavioral and feeding differences in fish transiently exposed to seismic energy.

Thus there is some importance in investigating seismic surveys as a potential risk factor for effects on reproduction in a species such as codfish, Arctic cod or haddock. Indeed, chronic effects on internally developing eggs could be much more important than the often raised question of possible interference with mating and spawning activities or effects on eggs and larvae in the water column, a concern which has garnered most attention to date in relation to the question of potential for reproductive effects.

CONCLUSIONS

If seismic surveys were having effects on fish or shellfish at the population level, they would not be readily measurable. The primary concern would seem to be in relation to the potential for producing impacts at the stock or sub-stock level such as in a particular region or bay or in shallow coastal or Arctic waters. There is need for selected studies to investigate potential effects at the individual level (viz physiological, histopathological) in order to provide a better informed opinion on any risks that may be associated with seismic surveys. Some attention should also be given to the potential for chronic effects during surveys that may last some weeks. However, regarding animal behavior and ambient noise in the ocean, the constant cacophony of noise associated with ships could be of much greater importance than seismic sounds.

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