Best Available Technology (BAT) + Best Environmental Practice (BEP) for Three Noise Sources:

Shipping, Seismic Airgun Surveys, and Pile Driving

by Lindy Weilgart

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To prevent and reduce marine pollution, the application of Best Available Techniques/ Technologies (BAT) and Best Environmental Practice (BEP) is a requirement recognized and promoted within decisions and resolutions adopted by the parties under several international agreements and conventions, e.g., under the Convention on Migratory Species and the Convention on Biological Diversity. Regional Agreements, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention), as well as species-focused regional agreements, including the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and Contiguous Atlantic Area, also require BAT and BEP.

Shipping

Excessive underwater noise from ships is mainly caused by poor propeller design or one not correctly matched to the vessel and its usual operating conditions; poor ship hull design especially of the aft end of the ship, causing an uneven water flow into the propeller (poor wake field); or a fouled (dirty) or damaged propeller. A particularly noisy propeller means the ship is probably operating inefficiently. Solutions to existing ships include installing new, more efficient propellers; good maintenance of propellers (cleaning and repairing damaged ones); using devices to improve the wake flow into the propeller; and maintaining the hull well.

Propeller Cavitation

Propeller cavitation is a major source of shipping noise (Figure 1). It is caused by the formation and collapse of air bubbles on the surface of a rotating propeller when the pressure falls below the vapour pressure of water, causing a hissing noise. Some cavitation occurs even with efficient propellers, but excessive cavitation from the noisiest ships is a sign they may be operating inefficiently, with poor wake flow into the propeller and/or poor propeller design.

Focus on the Noisiest Vessels

The noisiest 10-15% of ships contribute to about 50-88% of the total acoustic footprint (area over which ship noise increases the background noise). Most of these worst polluters are cargo and container ships.

Overlap between Increased Energy Efficiency and Noise Reduction

Many propellers are probably not currently designed for optimum efficiency. As their design improves for efficiency, there are stages where more efficient propellers are also quieter.

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Propellers designed for maximal quieting may not be the most efficient, however, as once optimal efficiency is attained, there is a trade-off between efficiency and noise quieting. Most propellers in existence now are likely neither optimally efficient nor optimally quiet, though, so there is room for improvement on both fronts where the same modifications can work towards both goals. In situations where excessive cavitation is associated with poor efficiency, the solution would also lower noise.

The other major factor involved in reducing propeller cavitation is improving the wake flow around the hull ahead of the propeller. Ideally, the wake should be as uniform as possible. Propellers should be clean and well-maintained, with no nicks or imperfections, especially on the leading edge. Such damage can cause more cavitation, reduce efficiency, and cause noise. Care should also be taken to design the propeller and hull as a unit, so that the wake field is taken into account, and for *actual* operating conditions, not the *ideal*. Efficiency gains and noise reduction can be achieved by well-designed hub caps as well as devices that can be affixed to the hub such as Boss Cap Fins. Wake inflow devices, such as the Schneekluth duct, Mewis duct, the Simplified Compensative Nozzle, and Grothues spoilers, can improve the wake going into the propeller, reducing cavitation and likely increasing efficiency while reducing noise.

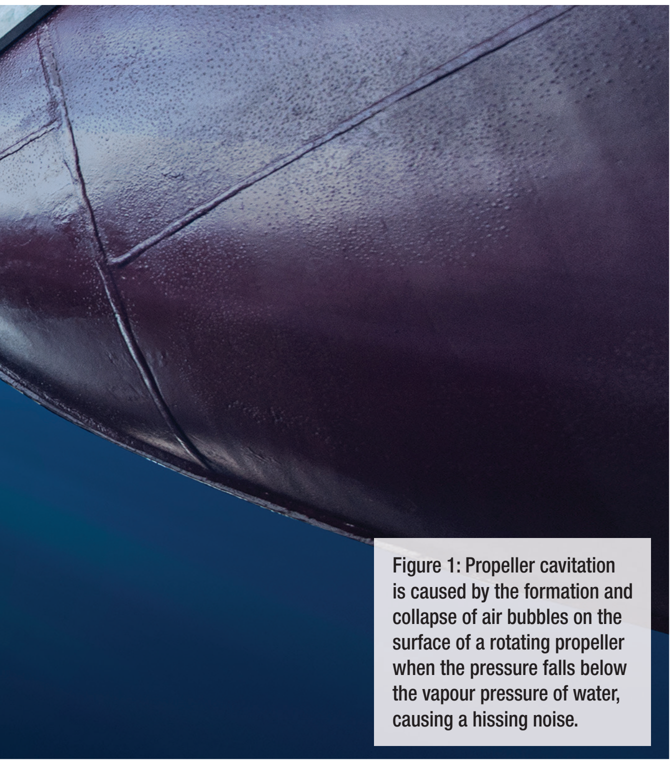

Figure 1: Propeller cavitation is caused by the formation and collapse of air bubbles on the surface of a rotating propeller when the pressure falls below the vapour pressure of water, causing a hissing noise.

In 2009, the International Maritime Organization (IMO) recommended that member states should identify the vessels in their merchant fleets that would benefit most from efficiency-improving technologies as these would also likely make their ships quieter. Most importantly, as fuel efficiency and greenhouse gas emissions are tackled, it would be a missed opportunity to not address noise at the same time, as there is certainly some overlap. Small changes in propulsive efficiency can dramatically lower noise output.

Hull Vibration, Engine, and Machinery Noise
Vibration isolation, noise insulation, and damping are the main treatments to reduce noise and vibration to the hull. The most challenging to quiet are large, slow-speed diesels, variable speed equipment, very light equipment, and emergency generators.

Slow Steaming to Reduce Noise and Greenhouse Gas Emissions
Slow steaming is the practice of operating transoceanic cargo ships, especially container ships, at substantially slower speeds than their maximum, mainly to save fuel. For ships with a fixed pitch propeller, which are the majority, reducing the speed reduces the overall noise, though levels may not necessarily decrease across all frequency bands. Slow steaming from an average of 16 knots to 14 knots (12% speed reduction), as was done in the Mediterranean Sea from 2007 to 2013, probably reduced the overall broadband acoustic footprint by over 50%. Slow steaming across shipping fleets has also been shown to be an effective short-term measure to reduce greenhouse gas emissions. In April 2018, the IMO adopted the goal to reduce the total annual greenhouse gas emissions by at least 50% by 2050 compared to 2008. Russell Leaper with the International Fund for Animal Welfare reviewed work on greenhouse gas emissions, and how that related to underwater noise, ship-whale collision risk, and ship speed. He took into account research which considered that slow steaming would increase the number of vessels needed to transport the same volume of goods, the cost of operating those extra

vessels, and the increase in ship construction that might be necessary. Research showed that the savings in total fuel consumption from slowing down was usually higher than the cost of operating the extra vessels necessary to transport equivalent goods. In addition, slow steaming also had business advantages beyond saving fuel in that it increased delivery time reliability. Leaper concluded that modest (10%) reductions in speeds across the global fleet could reduce the total sound energy produced by shipping by around 40%. He also found that the reduced risk of ships striking whales was harder to estimate, but could be around 50%. Slow steaming has the advantage that no retrofitting is required and so can be implemented immediately.

Cold Ironing
Cold ironing is the practice of using a shore-side electrical power connection when a ship is at berth in port while its main and auxiliary engines are turned off. There is obviously less underwater noise with cold ironing, as well as fewer emissions. There may be an added advantage of cold ironing in that it may reduce biofouling on ship hulls as ship or generator noise may attract barnacles or other biofouling organisms. Reducing biofouling can save money, reduce noise (biofouling increases turbulence), increase efficiency, and even avoid the spread of invasive species on hulls.

Maintenance
Keeping the hull and propeller clean and repaired can yield cost savings, efficiency gains, and noise reductions. Other onboard machinery and engines will almost certainly be quieter and more efficient when well-maintained.

Shipping Lane Re-routing around Important Habitat
Re-routing shipping lanes around areas rich in marine life can reduce ship-whale collision risk as well as reduce exposing sensitive areas to noise. Routing measures already exist within Particularly Sensitive Sea Areas (PSSAs) designated by the IMO. Noise should be added as another criterion in choosing or expanding the size of PSSAs. Sensitive areas need additional noise buffers as noise can travel long distances.

Avoiding Times/Areas of High Sound Propagation
Sound propagates or travels further in certain conditions. Noise produced at the surface can enter the deep sound channel (where sound travels long distances very efficiently) where the channel intersects with features such as the continental slope. The sound channel is very close to the surface in high latitudes. In colder months, sound is also transmitted further. Thus, to reduce the spread of shipping noise, ships should avoid or reduce the amount of time travelling parallel to the continental slope or shelf by staying further offshore and if they must cross the continental shelf, do so at right angles, avoid or reduce time at colder, higher latitude waters, and operate in the warmer months where possible.

Port Incentives
The Port of Vancouver and the Port of Prince Rupert, both in British Columbia, Canada, give incentives to quieter ships in that they offer reductions in docking fees and harbour dues of up to almost 50%. Such incentives should be expanded to other ports worldwide to create a level playing field.

Certification Programs
Green certification programs that incentivize quieter ships such as Green Marine can help reduce ocean noise pollution from shipping. Ships that reduce emissions and are otherwise more environmentally friendly can gain standing and ranking, and are able to advertise their green credentials.

Underwater Noise Management Plans
Underwater noise management plans should be developed for entire fleets. Transport Canada has encouraged Canadian fleet operators to have plans to reduce their fleets' overall noise output.

Figure 2: Seismic airgun surveys are used to find oil and gas reserves under the seafloor.

Seismic Airgun Surveys

Seismic airgun surveys are used to find oil and gas reserves under the seafloor (Figure 2). Marine mammal observers are employed to spot marine mammals and turtles in the area around the seismic survey ship, to power or shut down the airguns in hopes of minimizing harm to marine life. However, many marine mammals and turtles are very hard to sight as they are cryptic, elusive, often underwater, and also since survey activities often take place at night and in other limited-visibility conditions. Consequently, probably the most effective mitigation for seismic airgun surveys is to: a) separate the surveys from areas rich in marine life and sensitive species; and b) lower the source level (quiet the noise).

Despite seismic airgun noise extending into the high frequencies (pitches), geophysicists and the oil and gas industry do not make use of, nor even record, any energy over the low frequencies. This wasted energy, therefore, needlessly impacts marine life, especially animals with mid- or high-frequency hearing, such as dolphins, porpoises, and many of the smaller whale species. There is thus a need to replace the short, loud airgun shot spanning many frequencies with a much longer, quieter signal, with the same acoustic energy in the frequency band required for the seismic survey, but with as little energy as possible outside that band. In a nutshell, the useful signal would have the same energy, just spread over a longer duration, allowing for a lower source level and less wasted energy at frequencies that are not used. A longer, quieter signal should be just as effective as a shorter, louder one provided they have the same energy and cover the necessary low frequencies. The quieter signal should reduce the risk of damage to an animal's hearing at short range, and the narrower bandwidth should reduce the risk of negative impacts to species with mid- and high-frequency hearing.

Marine Vibroseis

A so-called "controlled" source such as a marine vibrator (Figure 3) or marine Vibroseis (MV) is one such option. The sound it produces can be changed (pitch, duration, loudness, etc.) in real-time to suit the particular environmental conditions. A controlled source also can produce the necessary seismic information using lower levels of energy, for instance, through improved signal processing. Researchers have estimated that a MV survey would expose only about 1-20% of whales and dolphins to high noise levels when compared to those exposed to an airgun survey, based on their models. The high levels and rapid rise time or onset (sounds quickly increasing in loudness), both of which describe airgun shots, are two characteristics of sound thought to be particularly injurious to living tissues. These would be avoided by using MV, which is about a hundred-fold quieter, and does not have a "shot-like" quality.

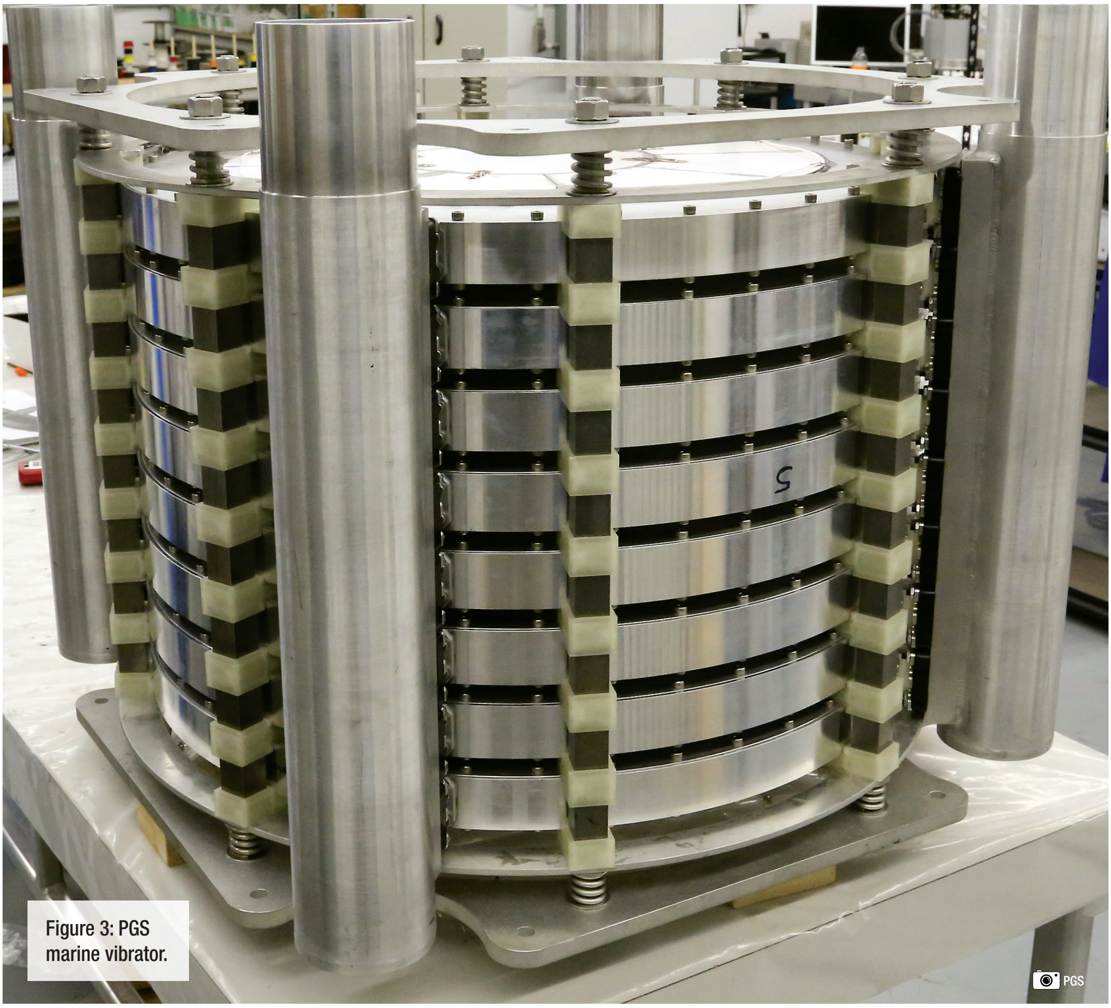

Figure 3: PGS marine vibrator.

Monitoring Technology
To assess the population density, abundance, and distribution of marine life before, during, and after seismic surveys, monitoring, especially ahead of time, of the proposed survey area should be carried out with fixed acoustic detectors (buoys, bottom recorders, etc.) or mobile gliders that are remotely operated and can travel up and down through the water column. This can help detect and avoid concentrations of marine life ahead of time as well as detect any impacts that may be occurring from the seismic survey.

Infrared or thermal imaging shows promise in detecting warm-blooded marine life, which can help in nighttime monitoring, especially of baleen whales. It does not function well in some conditions, such as fog, nor with smaller whale species, and seems to work best in polar regions.

Passive acoustic monitoring (PAM) with hydrophones (underwater microphones) should be used anytime there are vocal species in the area, during daytime or nighttime. PAM should be mandatory for night operations or when visibility is scarce. However, PAM may be inadequate mitigation for night operations if species in the area are not vocal or easily heard.

Mitigation
In order to separate seismic surveys from marine life, there must be good, current knowledge of the abundance and distribution

Figure 4: Pile driving is used for the construction of offshore windfarms, piers, and bridges, for example. Pile driving noise abatement systems could reduce sound exposure levels using a combination of systems.

of that life. Therefore, baseline studies of biological abundance and distribution must occur at least a year, preferably two, in advance of seismic surveys. These must be of sufficient quality and statistical power to meaningfully mitigate impacts. Sensitive and important habitats and seasons (spawning, breeding, feeding, etc.) should be avoided, and not just for marine mammals. Turtles, fish, and invertebrates must be included in mitigation and monitoring wherever possible, as almost all marine species are sensitive to sound and use it for practically all of their vital functions. Acoustic refuges of still quiet habitat should be established, and Marine Protected Areas should be managed for noise and include acoustic buffer zones around them, considering the possible impact of long-range noise propagation, which can extend for thousands of kilometres. Mitigation measures should show proof of their efficacy and seismic surveys should not proceed in conditions of poor visibility such as at night, unless monitoring can be shown to be just as effective as during the day.

Pile Driving

Pile driving is used for the construction of offshore windfarms in addition to the construction of structures such as piers and bridges (Figure 4). Many new quieting technologies and alternative low-noise foundation concepts have been developed for pile driving, mainly due to the German government setting an action-forcing standard and noise limit. Noise abatement systems

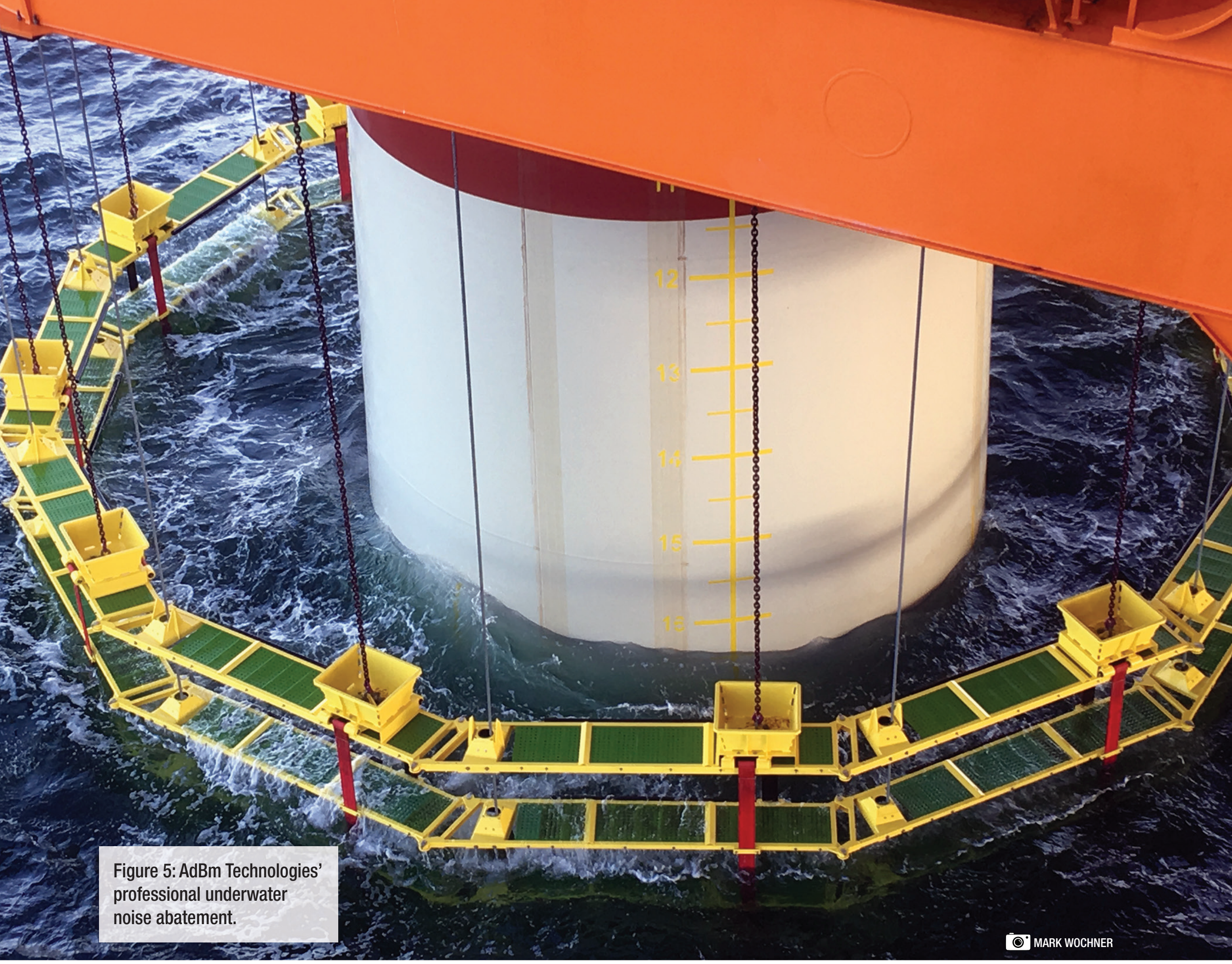

Figure 5: AdBm Technologies' professional underwater noise abatement.

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include surrounding the pile driving with bubble curtains, using vibrohammers, the Hydrosound Damper, the IHC Noise Mitigation System, the AdBm Noise Abatement System (Figure 5), etc. Pile driving noise abatement systems could reduce sound exposure levels by a factor of 10 to almost 1,000, using a combination of systems. It is harder to reduce noise in the low frequencies, however. Some systems have been deployed in water depths up to 77 m but most are limited to under 45 m depth. Pile diameters are getting larger for offshore windfarms, which can also alter the types of foundations and pile driving techniques that are necessary. Gravity-based foundations, vibropiling, BLUE piling, Smart Pile Driving, drilling, push-in and helical piles, suction bucket jackets, mono bucket foundations, crane-free gravity foundations, and floating wind turbines are all different options, depending on the substrate type and water depth.

The great variety of quieting technologies and noise abatement systems for pile driving is in stark contrast to the lack of innovation that is occurring for quieter alternatives to the seismic airgun. This may be due to offshore windfarms being a relatively new development compared with seismic airgun surveys, but it does raise questions. Certainly having governments, like the German, Dutch, and Belgian ones, that are prepared to regulate the construction of offshore windfarms for noise, mainly due to the noise-sensitive and protected harbour porpoise, helps, as do European laws, but it is high time that regulators insist on quieter alternatives to airguns, something that seems well within technological capabilities. After all, explosions on land to search for hydrocarbons were replaced with vibroseis because explosions were no longer acceptable to humans.

Conclusions

One of the difficulties in responsibly managing ocean noise pollution is the challenge in detecting the ecosystem and population consequences of underwater noise. There is sufficient evidence that impacts are occurring in at least 130 marine species (around 100 fish and invertebrate species alone), but being able to ascertain exactly to what degree, in which contexts, for which species, and at what sound types and levels these impacts occur remains imprecise. Because of the large natural variability in ocean systems (e.g., in currents, prey availability, chemistry), detecting human-caused changes in ecosystems and populations in the first place is a daunting task. The ocean is not a controlled laboratory. On top of that, isolating changes that are solely due to ocean noise pollution and not other human-caused stressors such as climate change, overfishing, and toxins is formidable. As such, it makes more sense to take a precautionary approach, one of simply turning down the volume of ocean noise pollution. Especially in cases where there are ancillary benefits of quieting, such as reducing greenhouse gas emissions by finding the overlap between greater efficiency and less underwater noise in shipping, and by encouraging technological innovation through quieter technological alternatives to airguns and by quieting pile driving, progress and improvements are highly likely. Keeping more fossil fuels in the ground would also reduce our need for seismic surveys and cut greenhouse gases. With humans, we do not find the precise point where noise is just tolerable to newborns in neonatal intensive care units, we do not fund countless studies on exactly how stressed and disturbed they have to be for us to take remedial action – we simply try and quiet the noise, wherever possible and safe to do so. If we value our life-sustaining oceans, we should provide them with the same care and protection.

Acknowledgements

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Lindy Weilgart is an Ocean Policy Consultant for OceanCare (a Swiss non-governmental organization) and Adjunct Professor, Department of Biology, Dalhousie University, Canada. Dr. Weilgart has specialized in underwater noise pollution and its effects on marine animals, particularly cetaceans, since 1994. She has served as an invited noise expert for the United Nations, Food and Agriculture Organization, Convention on Biodiversity, NATO, European Parliament, U.S. Marine Mammal Commission, Department of Fisheries and Oceans Canada, among others.