A key to quieter seas: half of ship noise comes from 15% of the fleet

Scott Veirs[1], Val Veirs[2], Rob Williams[3], Michael Jasny[4], and Jason Wood[5]

[1]Beam Reach (Social Purpose Corporation)
[2]Colorado College
[3]Pew Fellow in Marine Conservation
[4]Natural Resources Defense Council
[5]SMRU Consulting

February 9, 2018

Abstract

Underwater noise pollution from ships is a chronic, global stressor impacting a wide range of marine species. Ambient ocean noise levels nearly doubled each decade from 1963-2007 in low-frequency bands attributed to shipping, inspiring a pledge from the International Maritime Organization to reduce ship noise and a call from the International Whaling Commission for member nations to halve ship noise within a decade. Our analysis of data from 1,582 ships reveals that half of the total power radiated by a modern fleet comes from just 15% of the ships, namely those with source levels above 179 dB re 1 μPa @ 1 m. We present a range of management options for reducing ship noise efficiently, including incentive-based programs, without necessarily regulating the entire fleet.

Introduction

At its June 2016 meeting, the Scientific Committee of the International Whaling Commission (IWC) agreed that chronic ocean noise is increasing in many regions and adversely affecting populations of whales and other cetaceans (IWC Scientific Committee, 2016). Emerging evidence links chronic ocean noise to negative effects not only on marine mammals (Rolland et al., 2012; Williams et al., 2015) but also fish (Popper and Hawkins, 2016) and invertebrates (Wale et al., 2013). Ships are a major source of chronic ocean noise, responsible for doubling low-frequency levels every decade throughout the second half of the 20th century

(McDonald et al., 2006; Andrew et al., 2011). In some coastal and other high-traffic areas, ship noise has reached levels that degrade habitat for endangered species of whales and other marine wildlife (Hatch et al., 2012; Erbe et al., 2014).

These developments have inspired a number of recent policy initiatives to reduce noise pollution from ships. Prominently, the International Maritime Organization issued voluntary guidelines in 2014, building on earlier targets (Wright, 2008) and encouraging industry to reduce underwater radiated ship noise in the 10-300 Hz band (Dekeling et al., 2014; IMO/MEPC, 2014). In 2016 the U.S. National Oceanic and Atmospheric Administration launched an agency-wide Ocean Noise Strategy to better integrate risk assessment and mitigation of chronic ambient noise pollution into federal planning actions. European legislation treats ocean noise as a pollutant, and requires member states ultimately to attain "good environmental status" with respect to noise across multiple marine regions (URN, 2014; Audoly et al., 2015; Garrett et al., 2016; Merchant et al., 2016). In some jurisdictions, most recently Canada, governments have committed themselves to regulate shipping noise, but none have yet devised a management system to meet a ship noise reduction target.

In addition to aspirational targets to improve global ocean health, efforts to reduce ship noise also have immediate implications for economic development and endangered species conservation. The southern resident killer whale (SRKW) is an endangered population with critical habitat that spans the international (Canada-U.S.) border and encompasses shipping lanes serving the ports of Vancouver (British Columbia, Canada) and Seattle-Tacoma (WA, U.S.). Both Canada and the U.S. have recognized ocean noise as a threat to SRKW recovery (NMFS, 2008; DFO Canada, 2011). There are a number of large-scale industrial development proposals pending for this region (Gaydos et al., 2015) that could increase ship traffic and raise ocean noise levels. Both countries must consider ocean noise in SRKW critical habitat when assessing environmental impacts of proposed developments, and balance economic growth with conservation of endangered species. All of SRKW summertime critical habitat is ensonified already at levels exceeding one European threshold defining good environmental status (Christine Erbe et al., 2012), so it could be argued that noise reduction has become a necessary precursor to additional industrial development in this region.

What would be required of industry to substantially reduce noise from commercial ships (which originates primarily from cavitation at the propeller, but also from shipboard machinery noise transmitted through the hull)? To understand what would be necessary, we considered the quantitative noise reduction target reaffirmed in the summer of 2016 by the IWC's Scientific Committee, namely reducing the contributions of shipping to ocean ambient noise in the 10-300 Hz frequency band by 3 dB (halving the total radiated power) within 10 years, and by 10 dB within 30 years (IWC Scientific Committee, 2016). We explored various mechanisms to attain this -3 dB/decade target, including reducing the number, acoustic source level, or speed of ships.

Methods

We assessed four distinct management options by using an R script (see supplemental information) to analyze 2,800 source level measurements of 1,582 unique, isolated ships recorded as they transited northbound in Haro Strait, a shipping channel within the Salish Sea (Veirs et al., 2016). For ships in the data set with multiple transits we averaged the source spectrum levels (power spectral density) over all available transits.

To assess the relative noise contributions of different ships in our sample of the local fleet (the population of 1,582 ships in 12 ship classes northbound in Haro Strait), we integrated the source spectrum levels for each unique ship to acquire the total power (watts) radiated by each ship in a frequency band relevant to SRKWs (10-40,000 Hz). This band is wider than the 10-300 Hz band stipulated in the noise reduction target endorsed by the IWC. We chose to broaden the band because ship noise at ranges less than ˜3 km extends beyond 300 Hz to frequencies where SRKW hearing is most sensitive (Veirs et al., 2016).

After integration, we sorted the total radiated power levels for all ships, ranking them from lowest to highest. Then we summed the power from all ships, yielding the cumulative total radiated power – a distribution we used to assess quantitatively a range of management options that would accomplish a 3 dB reduction in the total noise radiated by this population of ships. Finally, we converted individual ship source levels from watts to dB re 1 µPa @ 1m. (Note, however, that we abbreviate the resulting broadband (10-40,000 Hz) source levels as "dB" in this paper for brevity.)

We used an iterative method to understand the first two management options: removal of gross polluters (ships with the highest source levels of the fleet); and reduction of gross polluter source levels to a threshold that achieves the desired halving of power overall. For the first option, we removed the loudest ship from the population and re-calculated the total radiated power of the remaining fleet. If the initial total power was not yet halved, then we repeated the process. For the second option, we also calculated the reduction threshold iteratively. We lowered the source level of the loudest ship to the level of the next-loudest ship in each iteration until the total power radiated by the fleet was halved.

To help managers more deeply understand the practical implications of these two management options, we tabulated the number of ships affected (Table 1). To allow easy extrapolation to the global fleet or other regional subpopulations of it, we also tabulated the number of affected ships as a percentage of both our population and, where applicable, the total number of ships in each class.

The third noise management option was motivated by the observation that for many ships a 1 knot reduction in speed leads to 1 dB reduction in broadband underwater source level (Veirs et al., 2016). We found the speed limit needed to achieve the 3 dB reduction iteratively by: reducing the speed of each loudest ship to the selected speed limit; making a proportional reduction in the source levels (assuming the -1dB/knot relationship applied to all ships); re-integrating the new source level distribution; and checking to see if the reduced total power equaled half of the initial total power.

The fourth management option was requiring a 3 dB reduction of every ship in the fleet. Assessing this option required no new computation.

Results and discussion

The cumulative distribution of source levels (Figure 1) in our dataset ranges from 141-186 dB and has two inflection points, with ~80% of the population having intermediate source levels of 165-180 dB. The absolute value the calibrated source levels in this distribution may differ in other regions (which may host a different subset of the global fleet) or in other studies of the Haro Strait fleet (e.g. with different assumptions about transmission loss), but the distribution of values will have a similar form.

From a policy perspective, the most important aspect of the source level distribution is that half the total power is radiated by just 15% of the ships in the fleet (i.e., those with source levels greater than 179.0 dB). More than two-thirds of these gross polluters are cargo and container ships, with each class containing ˜90 such vessels in our population (Table 1, Figure 2). About 43% of container ships are gross polluters, by far the highest proportion of any ship class in our dataset.

Management options could focus on gross polluters by targeting fleet size or operations. In the region where our data originated, for example, managers could halve the total power radiated by this ship population by removing the loudest 15% of the fleet (n=˜240 ships) or by reducing the source levels of the loudest 42.8% of the fleet (n=˜677 ships) to 175.4 dB (Table 1). These results confirm empirically the idea of dramatically reducing acoustic pollution by targeting the noisiest ships for quieting (Leaper et al., 2014). The maximum reduction required by the 175.4 dB threshold, about 10 dB, should be attainable with existing quieting technologies (Southall and Scholik-Schlomer, 2008) and techniques (Audoly et al., 2015), or for many types of new ships with only a 1% increase in design/build costs (Spence and Fischer, 2016).

Because container ships had the highest average source levels (178+/-4 dB) of the 12 ship classes we analyzed (Veirs et al., 2016), they would be most affected by policies that target gross polluters (Table 1). In our population of container ships, 43% would be affected by the removal option, while almost 90% would be affected by the noise reduction option. By contrast, some ship classes would be completely unaffected by any management option that limits source levels. No fishery, pleasure, or military ships in our population had source levels exceeding 175 dB, possibly due to military, fishery, and research classes having already adopted ship-quieting technologies (Southall and Scholik-Schlomer, 2008), including propulsion systems that reduce cavitation, quieter onboard machinery, and shock-absorbing mounts.

Of the management options considered, speed limits appear most likely to reduce noise quickly – by making an operational change, rather than undertaking replacements, retrofits, or maintenance. Because most ships can reduce their broadband source level by ˜1 dB by slowing down by 1 knot (Veirs et al., 2016), in our study area the 3 dB noise reduction target could be met by enforcing a speed limit of 11.8 knots (6.1 m/s) which would affect 83% of the ship population. For comparison, the mean and standard deviation of the speed distribution is 14.1 ± 3.9 knots for the ship population and 19 ± 2 knots for the fastest class, container ships (Veirs et al., 2016). While the compliance burden would fall more broadly across the fleet than with the removal or reduction options (Figure 2), faster-moving ships would be required to reduce speed more than other ships, and slow-moving classes would be unaffected. If a uniform speed limit of 11.8 knots conflicts with the "bare steerage" speed required for safe navigation of ships in a particular class, the 3 dB reduction could also be achieved by having all ships in the fleet decrease their speed by 3 knots (Figure 2).

Any noise reduction achieved by decreasing ship speed will increase the time that species are exposed to the lower noise levels. Behavioral response and masking are driven not only by the noise level, but also by a temporal overlap between the noise and the animal. A reduction of 3 dB in the total radiated power of ships does not address this temporal overlap, but in our study area, it would likely increase the functional acoustic space of SRKWs substantially and lower the maximum ship noise exposures that could cause behavioral responses or masking in the species (Holt, 2008; Williams et al., 2013, 2014, 2016). Such benefits should be weighed against the increase in temporal overlap that may result from speed reduction. At the same time, other environmental effects of a speed limit should be considered, including altered fuel efficiency (air pollution) and risk of collisions (oil spills and ships striking baleen whales).

Proven technologies and techniques (Southall and Scholik-Schlomer, 2008; Audoly et al., 2015) exist for reducing ship noise. Combinations of them, without necessarily altering speed, could be used to reduce source levels by 3 dB in each ship across the entire fleet, or just in gross-polluting ships. To date, however, minimal mitigation has been undertaken by the commercial shipping industry, either due to lack of regulation or incentives to adopt them. Management vehicles include, at least: regulated vessel speed limits in biologically important habitat, like those mandated off the U.S. East Coast to reduce ship strike mortality in North Atlantic right whales; tax incentives or subsidies to retrofit or replace noisy ships with quieter ones, for which designs already exist (Leaper et al., 2014); regulated noise emission standards for all or some ships entering into a state's internal waters; or port-based incentives and other measures. As examples of the latter, the Port of Vancouver, one of the largest ports in SRKW critical habitat, is reducing berthing fees through its EcoAction program to reward ships that are accredited as quiet by ship-classification societies, and in 2017 piloted a voluntary slow-down in Haro Strait with a speed limit of 11 knots (speed through water) in which compliant ships could receive a $500 stipend.

Studies of the distribution of acoustic polluters, along with what determines the maximum and minimum source levels in each ship class, will help guide the creation of regional or port-devised incentives or regulatory requirements to reduce underwater noise pollution. Although our sample is drawn from one site in the northeastern Pacific Ocean, it represents one of the largest archives of calibrated source characteristics for ships anywhere in the world. If the distribution of source levels in our data set is statistically representative of the noise output from the global fleet, or other regional subsets of it, then our results may be used to assess options for managing oceanic noise beyond our study area.

Conclusions

The distribution of source levels in our ship population indicates an opportunity to halve radiated noise levels by managing as little as 15% of the fleet. If removal of the gross polluters is not feasible, reducing the source levels of the top 42.8% to an achievable threshold or setting a speed limit of 11.8 knots (affecting 83% of the fleet) could also yield major environmental improvements. Despite projections of ship noise rising through 2030 (Frisk, 2012), optimal management of the global fleet could begin to reduce the current detrimental levels of noise without necessarily regulating the entire fleet.

Acknowledgements

We thank Liam Reese for his graphic design of Figure 2. R.W. thanks the Pew Fellowship in Marine Conservation program for support of his work on ocean noise. The authors declare no competing financial interests. Source spectrum level data are available in the R data file, data_1_3_BB_100.Rdata at `https://doi.org/10.7717/peerj.1657/supp-1`. S.V., V.V., and J.W. provided the ship source level data set. V.V. processed the data to assess noise management options that were developed in consultation with S.V. R.W., M.J., and J.W. provided policy context and strategy prioritization. S.V. coordinated data product generation. All authors contributed to the writing of the manuscript.

Figures and tables

Figure 1

Figure 2

Table 1

¿0

Table 1. Proportions of fleet and classes affected by two management options aimed at gross polluters

One option removes gross polluters (ships with source levels greater than 179 dB) while the other requires them to use quieting technologies or techniques to reduce their source levels below a threshold of 175.4 dB. The 2nd column lists the total number of ships in the fleet ("All classes") and in each class. Then for each option and ship class we tabulate the number of ships affected, along with that number expressed as a percentage of the whole fleet (1,582 ships) and as a percentage of the ship class (where applicable or non-zero).

References

Rex K. Andrew, Bruce M. Howe, and James A. Mercer. Long-time trends in ship traffic noise for four sites off the North American West Coast. *The Journal of the Acoustical Society of America*, 129(2):642–651, feb 2011. doi: 10.1121/1.3518770. URL `https://doi.org/10.1121%2F1.3518770`.

Christian Audoly, Maarten Flikeema, Eric Baudin, and Holger Mumm. Guidelines for Regulation on Underwater Noise from Commercial Shipping. Technical report, AQUO/SONIC, nov 2015. URL `http://www.sonic-project.eu/media/download_gallery/f68bebf80e2828939ee36d434948b88b-D5.4%20AQUO-SONIC%20Guidelines_v4.3.pdf`.

Christine Erbe, A. MacGillivray, and Rob Williams. Mapping Ocean Noise: Modelling Cumulative Acoustic Energy from Shipping in British Columbia to Inform Marine Spatial Planning. Technical report, WWF Canada, 2012.

René Dekeling, Mark Tasker, Sandra Van Der Graaf, Michael Ainslie, Mathias Andersson, André Michel, J F Borsani, Karsten Brensing, Castellote Manuel, Donal Cronin, John Dalen, J Folegot, R Leaper, J Pajala, P Redman, S P Robinson, P Sigray, G Sutton, F Thomsen, S Werner, D Wittekind, and J V Young. Monitoring Guidance for Underwater Noise in European Seas-Part I: Executive Summary. Technical Report EUR 26557 EN, Publications Office of the European Union, Luxembourg, 2014. URL `http://publicationsjrceceuropa.ourtownypd.com/repository/handle/111111111/30979`.

DFO Canada. Recovery Strategy for the Northern and Southern Resident Killer Whales (Orcinus orca) in Canada. Technical Report Species at Risk Act Recovery Strategy Series, Fisheries and Oceans Canada, 2011. URL `http://www.registrelep-sararegistry.gc.ca/virtual_sara/files/plans/rs_epaulard_killer_whale_1011_eng.pdf`.

Christine Erbe, Rob Williams, Doug Sandilands, and Erin Ashe. Identifying Modeled Ship Noise Hotspots for Marine Mammals of Canada's Pacific Region. *PLoS ONE*, 9(3):e89820, mar 2014. doi: 10.1371/journal.pone.0089820. URL `https://doi.org/10.1371%2Fjournal.pone.0089820`.

George V Frisk. Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. *Scientific reports*, 2, 1 jun 2012. doi: 10.1038/srep00437. URL `http://www.nature.com/srep/2012/120601/srep00437/full/srep00437.html?WT.ec_id=SREP-704-20120702`.

J K Garrett, Ph Blondel, B J Godley, S K Pikesley, M J Witt, and L Johanning. Long-term underwater sound measurements in the shipping noise indicator bands 63 Hz and 125 Hz from the port of Falmouth Bay UK. *Marine pollution bulletin*, 110(1):438–448, 15 sep 2016. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2016.06.021. URL `http://www.sciencedirect.com/science/article/pii/S0025326X16304258`.

Joseph K Gaydos, Sofie Thixton, and Jamie Donatuto. Evaluating Threats in Multinational Marine Ecosystems: A Coast Salish First Nations and Tribal Perspective. *PloS one*, 10(12):e0144861, 21 dec 2015. doi: 10.1371/journal.pone.0144861. URL `http://dx.doi.org/10.1371/journal.pone.0144861`.

Leila T. Hatch, Christopher W. Clark, Sofie M. Van Parijs, Adam S. Frankel, and Dimitri W. Ponirakis. Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary. *Conservation Biology*, 26(6):983–994, aug 2012. doi: 10.1111/j.1523-1739.2012.01908.x. URL `https://doi.org/10.1111%2Fj.1523-1739.2012.01908.x`.

Marla M Holt. *Sound Exposure and Southern Resident Killer Whales: A review of current knowledge and data gaps.* NMFS-NWFSC, 2008.

IMO/MEPC. Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life. Technical Report MEPC.1/Circ.833, 7 apr 2014.

IWC Scientific Committee. Report of the Workshop on Acoustic Masking and Whale Population Dynamics. Technical Report IWC/SC/66B/REP10, International Whaling Commission, Bled, Slovenia, 2016.

Russell Leaper, Martin Renilson, and Conor Ryan. Reducing underwater noise from large commercial ships: current status and future directions. *Journal of Atmospheric and Oceanic Technology*, 9(1), 2014. ISSN 0739-0572.

Mark A. McDonald, John A. Hildebrand, and Sean M. Wiggins. Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island California. *The Journal of the Acoustical Society of America*, 120(2):711–718, aug 2006. doi: 10.1121/1.2216565. URL `https://doi.org/10.1121%2F1.2216565`.

Nathan D Merchant, Kate L Brookes, Rebecca C Faulkner, Anthony W J Bicknell, Brendan J Godley, and Matthew J Witt. Underwater noise levels in UK waters. *Scientific reports*, 6:36942, 10 nov 2016. ISSN 2045-2322. doi: 10.1038/srep36942. URL `http://www.nature.com/articles/srep36942`.

NMFS. Recovery Plan for Southern Resident Killer Whales (Orcinus orca). Technical report, National Marine Fisheries Service, Northwest Region, Seattle, Washington, 2008.

Arthur N Popper and Anthony Hawkins. *The Effects of Noise on Aquatic Life II.* Springer, 2016. ISBN 9781493929818. URL `https://market.android.com/details?id=book-gdMLCwAAQBAJ`.

R. M. Rolland, S. E. Parks, K. E. Hunt, M. Castellote, P. J. Corkeron, D. P. Nowacek, S. K. Wasser, and S. D. Kraus. Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences*, 279(1737):2363–2368, feb 2012. doi: 10.1098/rspb.2011.2429. URL `https://doi.org/10.1098%2Frspb.2011.2429`.

B L Southall and A Scholik-Schlomer. Potential application of vessel-quieting technology on large commercial vessels. In *Final Report of the National Oceanic and Atmospheric Administration (NOAA) International Conference. 1-2 May, 2007 NOAA Fisheries, Silver Spring, MD*, 2008.

J H Spence and R W Fischer. Requirements for Reducing Underwater Noise From Ships. *IEEE Journal of Oceanic Engineering*, PP(99):1–11, 2016. ISSN 0364-9059. doi: 10.1109/JOE.2016.2578198. URL `http://dx.doi.org/10.1109/JOE.2016.2578198`.

URN. Underwater Radiated Noise (URN). Technical Report Rule Note NR614 DT R00 E, Bureau Veritas, oct 2014. URL http://www.veristar.com/portal/veristarinfo/files/sites/veristarinfo/web%20contents/bv-content/generalinfo/giRulesRegulations/bvRules/rulenotes/documents/NR614%20Oct2014.pdf.

Scott Veirs, Val Veirs, and Jason D Wood. Ship noise extends to frequencies used for echolocation by endangered killer whales. *PeerJ*, 4:e1657, 2 feb 2016. doi: 10.7717/peerj.1657. URL http://dx.doi.org/10.7717/peerj.1657.

M. A. Wale, S. D. Simpson, and A. N. Radford. Noise negatively affects foraging and antipredator behaviour in shore crabs. *Animal Behaviour*, 86(1):111–118, jul 2013. doi: 10.1016/j.anbehav.2013.05.001. URL https://doi.org/10.1016%2Fj.anbehav.2013.05.001.

R Williams, C W Clark, D Ponirakis, and E Ashe. Acoustic quality of critical habitats for three threatened whale populations. *Animal conservation*, 2013. ISSN 1367-9430.

R Williams, A J Wright, E Ashe, L K Blight, R Bruintjes, R Canessa, C W Clark, S Cullis-Suzuki, D T Dakin, C Erbe, P S Hammond, N D Merchant, P D O'Hara, J Purser, A N Radford, S D Simpson, L Thomas, and M A Wale. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. *Ocean & coastal management*, 115:17–24, oct 2015. ISSN 0964-5691. doi: 10.1016/j.ocecoaman.2015.05.021. URL http://www.sciencedirect.com/science/article/pii/S096456911500160X.

Rob Williams, Christine Erbe, Erin Ashe, Beerman Amber, and Jodi Smith. Severity of killer whale behavioral responses to ship noise: A dose–response study. *Marine pollution bulletin*, 79(1–2):254–260, 15 feb 2014. ISSN 0025-326X. doi: 10.1016/j.marpolbul.2013.12.004. URL http://www.sciencedirect.com/science/article/pii/S0025326X13007376.

Rob Williams, Len Thomas, Erin Ashe, Clark Christopher W, and Philip S Hammond. Gauging allowable harm limits to cumulative, sub-lethal effects of human activities on wildlife: A case-study approach using two whale populations. *Marine Policy*, 70:58–64, 2016. ISSN 0308-597X. doi: 10.1016/j.marpol.2016.04.023. URL http://linkinghub.elsevier.com/retrieve/pii/S0308597X16301956.

Andrew J Wright. International Workshop on Shipping Noise and Marine Mammals. Technical report, Okeanos - Foundation for the Sea, Hamburg, Germany, 2008. URL http://www.sound-in-the-sea.org/download/ship2008_en.pdf.

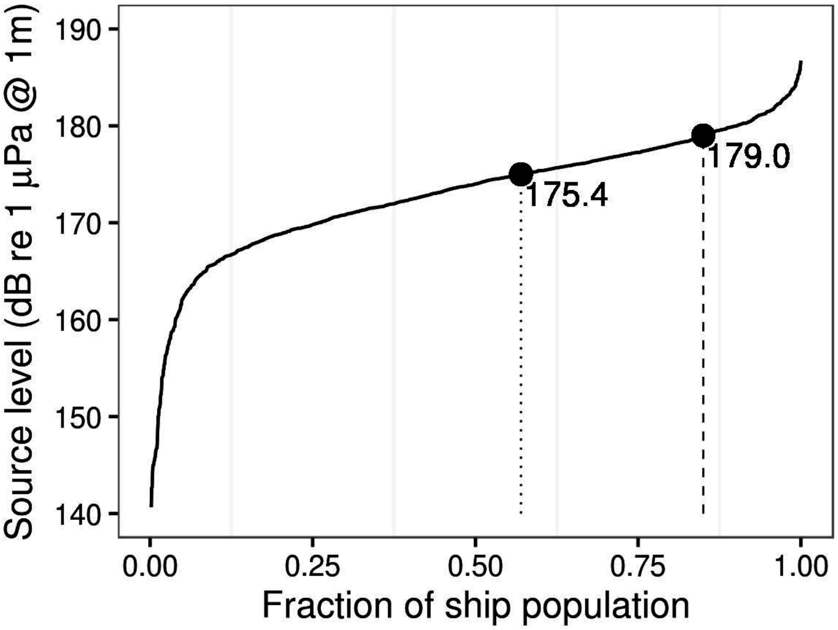

Figure 1: **Cumulative distribution of source levels with two management options** Cumulative distribution of source levels for the ship population (solid curve). Two management options for halving of the total power radiated by the fleet are depicted by vertical lines: removing the 15% of ships with source levels > 179.0 dB (dashed line); and reducing source levels of 42.8% of the ships to 175.4 dB (dotted line).

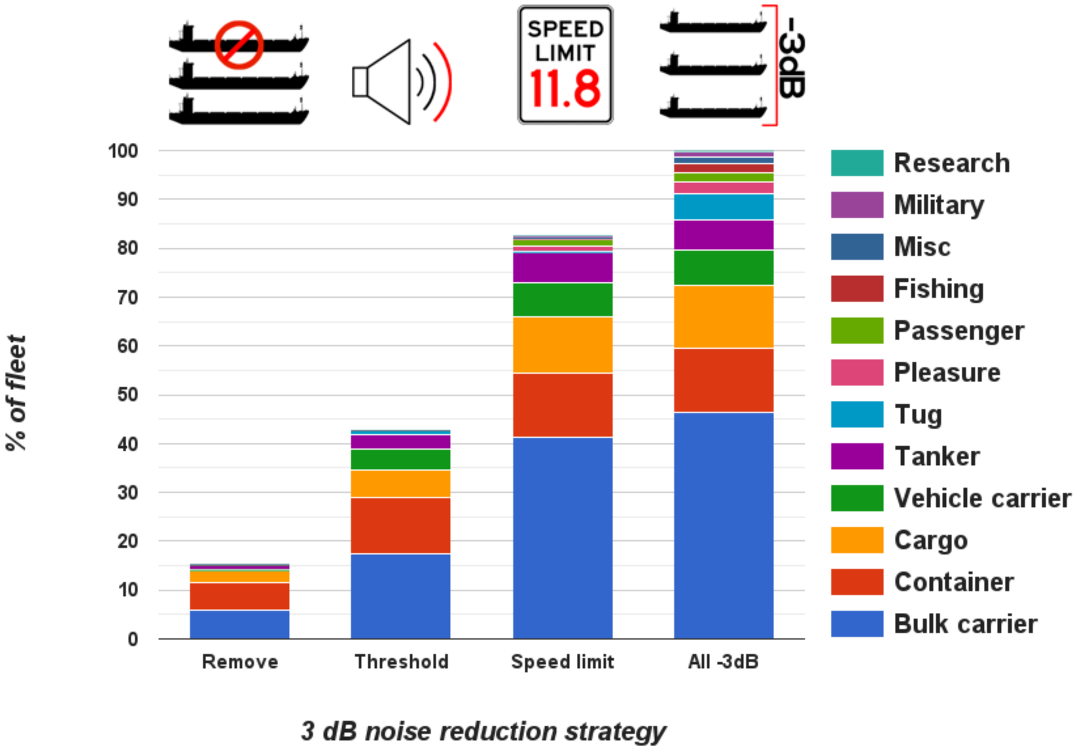

Figure 2: **Proportion of fleet affected by four noise reduction strategies** The height of each stacked bar represents the percentage of the fleet (population of 1,582 ships) that would be affected by four different strategies for halving the total radiated power. Removal of gross polluters affects 15%; limiting them to a noise threshold of 175.4 dB affects 42.8%; enforcing a speed limit of 11.8 knots affects 83%; and having all ships reduce their source level by 3 dB affects 100%. Colors indicate the classes of affected ships and the thickness of any colored bar section depicts the portion of the fleet that has affected ships in the class associated with the color.