Marine Pollution Bulletin xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Viewpoint

Quiet(er) marine protected areas

Rob Williams [a,b,*], Christine Erbe [c], Erin Ashe [a,b], Christopher W. Clark [d]

[a] Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews KY16 8LB, Scotland, UK
[b] Oceans Initiative, Pearse Island, BC V0N 1A0, Canada
[c] Centre for Marine Science & Technology, Curtin University, Perth, WA 6102, Australia
[d] Bioacoustics Research Program, Cornell University, 159 Sapsucker Woods Rd., Ithaca, NY 14850, USA

ARTICLE INFO

Article history:
Received 5 July 2015
Received in revised form 7 September 2015
Accepted 7 September 2015
Available online xxxx

Keywords:
Cetacean
Conservation
Marine mammal
Ocean noise
Shipping
Whale

ABSTRACT

A core task in endangered species conservation is identifying important habitats and managing human activities to mitigate threats. Many marine organisms, from invertebrates to fish to marine mammals, use acoustic cues to find food, avoid predators, choose mates, and navigate. Ocean noise can affect animal behavior and disrupt trophic linkages. Substantial potential exists for area-based management to reduce exposure of animals to chronic ocean noise. Incorporating noise into spatial planning (e.g., critical habitat designation or marine protected areas) may improve ecological integrity and promote ecological resilience to withstand additional stressors. Previous work identified areas with high ship noise requiring mitigation. This study introduces the concept of "opportunity sites" — important habitats that experience low ship noise. Working with existing patterns in ocean noise and animal distribution will facilitate conservation gains while minimizing societal costs, by identifying opportunities to protect important wildlife habitats that happen to be quiet.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Sound can travel through the ocean across vastly greater ranges than light (i.e., 100s of km versus 10s of meters). The marine environment imposes constraints on the sensory systems marine animals use for orientation, feeding, predator detection, navigation and social interactions, and these constraints have shaped the evolution of marine mammals, their predators and their prey. The acoustic channel is the primary modality available for social interactions and the only one that allows interaction over distances greater than a few body lengths. Human-generated noise is now a persistent feature of many ocean acoustic environments, especially the Northern Hemisphere (Hildebrand, 2009). Underwater noise can have a variety of effects on acoustically sensitive marine species, particularly marine mammals, including hearing impairment, physiological responses (e.g., stress), changes in behavior and acoustic masking (Clark et al., 2009; Erbe, 2012; Finneran et al., 2005; Hatch et al., 2012; Richardson et al., 1995; Rolland et al., 2012; Weilgart, 2007). The first policies used to protect marine mammals from noise have involved shutting off high-amplitude sound sources if an animal is seen within a given safety zone (i.e., animal-centric; Southall et al., 2007). More recently, research suggests that some noise sources, such as from shipping and seismic airgun surveys, are better treated as environmental-level stressors that lend themselves to area-based management (i.e., habitat-centric, Hatch and Fristrup, 2009; Miller et al., 2009; Weilgart, 2007).

Assessing the risk that ocean noise poses to marine wildlife inherently lends itself to a quantitative, spatially explicit framework that quantifies the probability that an undesirable outcome will occur. Quantifying the ecological risks associated with exposing marine mammals to a given noise level (either in one acute dose or a cumulative exposure over time) requires an estimate of the overlap of a predicted sound field and marine mammal density (Ellison et al., 1999; Shyu and Hillson, 2006). Spatio-temporal-spectral overlap does not necessarily mean that marine mammals are impacted by noise, but overlap is a necessary precursor for impact to occur. We consider *sensitivity* as the extent to which species respond to a potential stressor (e.g., anthropogenic noise) and *vulnerability* as the extent to which a species will be exposed to a stressor to which it is sensitive (Zacharias and Gregr, 2005). The term "acoustic environment" carries no implication about how the sound is perceived by a particular listener, whereas the term "acoustic habitat" is inherently species-specific. Although we illustrate our study with marine mammals, there is a large body of evidence that fishes and invertebrates are acoustically sensitive, and like marine mammals, use acoustic cues to navigate, choose mates, find prey, avoid predators and choose settlement sites (Popper and Hawkins, 2011; Slabbekoorn et al., 2010). Given the potential for underwater noise from shipping to act as a chronic, habitat-level stressor that can affect both individual animals and ecosystem linkages (e.g., via disruption of predator–prey interactions), it makes sense to consider adding ocean noise to the suite of threats mitigated through the application of marine protected

* Corresponding author at: Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews KY16 8LB, Scotland UK.
E-mail address: rmcw@st-andrews.ac.uk (R. Williams).

http://dx.doi.org/10.1016/j.marpolbul.2015.09.012
0025-326X/© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

areas (MPAs) and other marine spatial planning tools in area-based management (Wright et al. 2011). A number of national and international efforts are underway to include marine mammals explicitly in spatial planning efforts (e.g., IUCN's World Commission on Protected Areas' Marine Mammal Task Force[1]; Important Marine Mammal Areas as Ecologically or Biologically Significant Marine Areas under the Convention on Biological Diversity (Corrigan et al., 2014); and in the US, NOAA's Cetacean Density and Distribution Mapping Working Group's Biologically Important Areas[2] for cetaceans). Because marine mammal biologists have been tasked fairly recently with including marine mammals in broader protected-areas planning initiatives (Corrigan et al., 2014), it will be important for marine mammal scientists to get up to speed quickly on lessons learned over the last decades of spatial planning, management and enforcement (Agardy et al., 2003; Edgar et al., 2014; Game et al., 2008) to improve our ability to protect highly mobile or migratory whale species from sublethal disturbance. This is especially relevant given that spatial fishing effort patterns are inextricably linked to spatial patterns in ocean productivity or biodiversity, whereas spatial shipping patterns, and therefore their resultant aggregate noise patterns, are primarily determined by distributions of people and ports, not ocean productivity.

Policy-makers have not yet articulated overarching ocean noise mandates in explicit, quantitative terms. Qualitatively, one can interpret ocean noise policies generically as intending to keep quiet areas quiet and make noisy areas quieter. Strictly speaking, *loud* is a percept that relates the amount of acoustic energy as perceived by a given hearing apparatus, such as the human auditory system. In practice, this means that a particular marine environment could be dominated by anthropogenic underwater noise that is perceived as being loud to one species, but quiet to another. A number of spatio-temporal and acoustic frequency content overlap approaches have been used to identify places where acoustically sensitive species are vulnerable to ocean noise, using dynamic or static methods. Such risk assessments offer a way to prioritize areas where mitigation is needed most for species that are vulnerable to the existing increase in anthropogenic noise (Boyd et al., 2011; Rolland et al., 2012). Few studies have examined the complement — namely, places where marine mammals are present in high densities, but where anthropogenic noise levels are low. Our own work reflects this tradition: we have published risk maps previously (Erbe et al., 2014), but present the opposite – namely opportunity maps – for the first time here.

We do not intend to minimize the amount of work that it will take to make noisy areas quieter. But one of the lessons learned from other pollution-prevention exercises is that it pays to start with so-called "low-hanging fruit" (Hart and Ahuja, 1996). Shipping noise is expected to follow a power law, such that quieting the noisiest 10% of ships or so should result in much larger reductions in ambient noise (Leaper and Renilson, 2012). While waiting for such mitigation measures to take place, we have a time-limited period to identify important areas that are still quiet. Canada has a backlog of species whose endangered status mandates identification and protection of critical habitat (Taylor and Pinkus, 2013). In our professional opinion, if two places are equally important to whales, with one being noisy and the other being quiet, it would be helpful to identify those areas and present that information to decision-makers. The noisy area may require mitigation, whereas the quiet area may make a more attractive or convenient candidate for critical habitat protection, either because it represents higher quality habitat to the animals or because it imposes lower economic costs to society to mitigate anthropogenic threats. Most countries' critical habitat designation processes involve some degree of socio-economic tradeoff analyses; areas that are both quiet and important to whales are, from first principles, likely to involve fewer industrial stakeholders. Using previously peer-reviewed and published data on marine mammals and noise from continental shelf waters of British Columbia (BC), Canada, we conducted overlap analyses in the spatial, seasonal and frequency domains to find areas where the highest density regions for marine mammals co-occurred with sites in which anthropogenic noise levels are relatively low. This allowed us to identify general areas (referred to subsequently as "opportunity" sites or regions) where acoustic stressors are relatively low, and the task of protected-areas management may involve simply maintaining the acoustic *status quo*. A recent study has shown that some sites where industrial activities are low may be avoided by industry because they are unproductive (Devillers et al., 2014). We do not advocate the formation of token, "residual" reserves (Devillers et al., 2014). On the contrary, our analyses integrate empirical data on both wildlife and threats, so the opportunity sites we identify are demonstrably important to the target species. We offer some practical advice to work *with* existing variability in wildlife distribution and noise to identify quiet sites that could be protected with the least disruption to existing shipping patterns.

2. Methods

These spatially explicit risk analyses require spatial surfaces (a grid of predicted values) for both shipping noise and marine mammal density. A recent study mapped cumulative sound energy from ships throughout Canada's Pacific Exclusive Economic Zone (Erbe et al., 2012). We reran that noise model to account for noise energy during the summer months (June–September) when data were available on average distribution and abundance of marine mammals (see below). Ship locations were determined based on positions reported by vessel crew to a Coast Guard traffic centre (96 hour pre-arrival notification), manual dead reckoning, and by radar tracking. Source spectra were computed based on length and speed, and propagation was modeled on a 5 km × 5 km grid according to a geometric spreading law and frequency-dependent absorption (Erbe et al., 2012). We refer to any 5 km × 5 km area as a cell. The resultant predicted sound energy surface was validated against empirical measurements of ambient noise at 12 sites, including heavily and rarely trafficked locations (Williams et al., 2014a). This validation exercise found a strong and statistically significant correlation between the rankings, from noisy to quiet, of the predicted and measured noise levels in low (17–28 Hz), medium (71–708 Hz) and high (1500–3500 Hz) frequency bands (Erbe et al., 2014). A limitation is that our noise levels are in different currencies. The soundfield model predicts cumulative noise energy over a summer or a year (Erbe et al., 2012), whereas the empirical measurements reported daily, monthly and longer average sound pressure levels (Williams et al., 2014a). This would need to be resolved before practical implementation, but is no barrier to introducing the concept of identifying opportunity sites. Our study area includes cells that span six orders of magnitude in terms of cumulative number of ship-hours (Erbe et al., 2012), which swamps any differences in terms of correlating relative versus absolute sound measurements. In fact, the cumulative sound field map looks broadly similar to the map of the absolute number of ship transits (Williams and O'Hara, 2010), suggesting that we would have identified the same risk (Erbe et al., 2014) and opportunity (this study) sites, regardless of whether we had used ship counts, average sound pressure levels, or cumulative sound energy. This will not be the case in all applications, but was sufficient for our purposes of introducing the concept of opportunity sites.

To estimate audibility of ship noise by various marine mammal species living off the coast of British Columbia (BC), Canada, we reviewed the literature on hearing sensitivity (Erbe et al., 2014) and derived an audiogram (i.e., a graph of hearing sensitivity as a function of frequency) for 10 marine mammal species known to occur in BC continental shelf waters: Pacific white-sided dolphins (*Lagenorhynchus obliquidens*), killer whales (*Orcinus orca*), porpoises (one audiogram for both harbor (*Phocoena phocoena*) and Dall's (*Phocenoides dalli*) porpoise), harbor

[1] http://www.iucn.org/about/work/programmes/species/who_we_are/ssc_specialist_groups_and_red_list_authorities_directory/task_forces/.
[2] http://cetsound.noaa.gov/important.

Please cite this article as: Williams, R., et al., Quiet(er) marine protected areas, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.09.012

seals (*Phoca vitulina*), northern elephant seals (*Mirounga angustirostris*), Steller sea lion (*Eumetopias jubatus*), fin whale (*Balaenoptera physalus*), humpback whale (*Megaptera novaeangliae*) and common minke whale (*B. acutorostrata*). For baleen whale species, an audiogram has never been measured for any species, so we followed previous recommendations (Clark and Ellison, 2004) to derive one ambient-noise limited audiogram for a generic baleen whale. Note that this list includes species for which we have audiograms derived from behavioral and electrophysiological data as well as expert opinion. No attempt was made to account for variability among individuals within species (e.g., due to differences in age, sex, health or sound exposure history). For these reasons, it is appropriate for this "proof of concept" paper to compare spatial patterns in noise levels within a species, but not among species. For all species, the best estimate of received spectra were filtered with the corresponding audiogram and integrated over frequency, yielding a species-specific measure of audible energy integrated over all ships and over the summer months (June–September) of 2008. A ship audibility index ranging from 0 to 1 was computed by normalization, i.e., subtracting the minimum audible level over the geographic area from the noise map and then dividing by the maximum audible energy over the geographic area. This resulted in a species-specific ship noise audibility map that ranged from 0 to 1, for each species. Because of this need to place all species in the same currency, our approach identifies risk and opportunity sites within species, but should not be used to compare absolute risk (e.g., loss of communication space; expected number of behavioral disturbances) among species.

Spatially explicit density data were used to approximate average population distributions in BC continental shelf waters for each of the 10 marine mammal species, based on previously reported results from systematic line transect surveys (see Williams et al. (2014c) and references therein for details of survey design, data collection and analytical methods). Total abundance varied by 2 orders of magnitude among species, so gridded count data could not be compared directly across all species. Instead, counts for each species in each cell were normalized between 0 and 1 by dividing the predicted abundance of each species in each cell by the maximum count in the highest density cell for that species.

The density map was multiplied by the audibility map, and normalized, to indicate the co-occurrence of a species and ship noise, yielding a species-specific "risk index" throughout the study region, which has been described previously (Erbe et al., 2014). The density map was also further multiplied by the inverse of the audibility map (i.e., audibility minus 1) and normalized to 0–1 again, to yield a species-specific "opportunity index" for each cell. Cells with opportunity index values close to 0 are considered low-priority cells, either because density is low or noise is high, and an area within which many cells have low opportunity index values is considered a low-priority area. In contrast, cells with opportunity index values close to 1 are considered high-priority cells (high animal density and low noise) and a high priority area: i.e., an opportunity for area-based management tools (e.g., zoning, critical habitat designation, ship speed restrictions or marine protected areas) to protect vulnerable species.

3. Results

Fig. 1 shows results using harbor porpoise as the example of the processes by which risk and opportunity areas were identified for all species. Note the contrast between Fig. 1C and D, where some red areas in one are blue in the other. Fig. 2 contrasts risk and opportunity sites for three other species: a baleen whale (minke whale); a toothed whale (Dall's porpoise); and a seal (elephant seal). Fig. 3 shows photographs for four of the study species, ranging in specialization from a low-frequency baleen whale (e.g., humpback whale) to a high-frequency specialist (e.g., Pacific white-sided dolphin). Fig. 4 shows the main result, the opportunity maps (i.e., highest density and lowest noise), for each of the remaining nine species. Note that the marine mammal density surface models, which show the average distribution over a 4-year period, have been published previously (Williams et al., 2011a, 2014c), as have the "risk" sites (Erbe et al., 2014). Here we highlight, for the first time, the concept of opportunity areas, where marine mammal densities are high, but shipping noise levels are low.

For the baleen whales, high-density regions for fin and humpback whales (Fig. 4) co-occur with quiet waters off Haida Gwaii. Minke whales show a fairly uniform distribution throughout BC's continental shelf waters, and although some minke whales are found in waters off Haida Gwaii, some mainland waters can provide equally important opportunity sites.

Critical habitats for northern and southern resident killer whales (i.e., off northeastern and southeastern Vancouver Island, respectively; Fig. 1A) are among the noisiest sites in BC. For other odontocetes (toothed whales, dolphins and porpoises), Pacific white-sided dolphins and Dall's porpoise show good overlap between high density and low noise levels off southeastern Haida Gwaii (Fig. 4). Harbor porpoises show a wide distribution with two pronounced peaks in density (Fig. 1). Their southern habitat (e.g., Strait of Juan de Fuca) spans a busy shipping lane and is unlikely to include any quiet refuges. For this species, southeastern Haida Gwaii protects a quiet, high-density region.

For pinnipeds (seals and sea lions), the harbor seal has a peak density near shore, and many sites along the BC coast could provide opportunities to protect quiet habitats. Steller sea lions and northern elephant seals have widespread distributions, and the waters off southern Haida Gwaii would protect high-density, quiet habitats for both species.

4. Discussion

There are many motivations for setting aside priority areas to protect, including, but not limited to: to capture a sample of biodiversity, especially irreplaceable or threatened elements; to protect ecosystem services they provide to people; or to separate vulnerable biodiversity elements from threatening anthropogenic pressures (Gaston et al., 2008). Marine protected areas (MPAs) are one such tool, but there are a number of spatial tools that could be used to protect marine mammal species from chronic ocean noise, such as ship speed restrictions, critical habitat designations for endangered species, or changes to shipping lanes (Dolman, 2007; Hatch and Fristrup, 2009; Zacharias and Gregr, 2005). Previous research has shown that the area off southeastern Haida Gwaii is the most species-rich habitat for marine mammals in British Columbia (Williams et al., 2014c). Here we show that those same waters also hold the greatest potential to protect a quiet acoustic environment for marine mammals (Fig. 4).

In a systematic conservation planning framework it is necessary to compile best available information on abundance and distribution of species, and quantify the protection already offered by existing conservation areas (Margules and Pressey, 2000). The opportunity sites we identify for fin, humpback, and minke whales, Pacific white-sided dolphins, Dall's porpoise, northern elephant seals and Steller sea lions (Fig. 4) straddle the boundaries of the eastern portion of Gwaii Haanas National Marine Conservation Area (NMCA). The Gwaii Haanas NMCA was at the forefront of efforts to retain globally significant sites of ocean wilderness, but very little of the area would qualify as a fully protected, no-take, no-entry MPA (Sloan, 2002). From a strictly spatial perspective, expanding the management objectives of the Gwaii Haanas NMCA to include acoustic factors in its management plan would be a more efficient (i.e., faster) way to protect irreplaceable quiet sites than starting a number of entirely new efforts to include acoustic factors in a suite of single-species conservation, recovery and action plans (Taylor and Pinkus, 2013). The GHNMCA authorities may not want to include noise as an indicator in their management plans. In that case, the opportunity maps we have produced may simply form an information layer in a Marxan zoning exercise (Ball et al., 2009), regional

Please cite this article as: Williams, R., et al., Quiet(er) marine protected areas, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.09.012

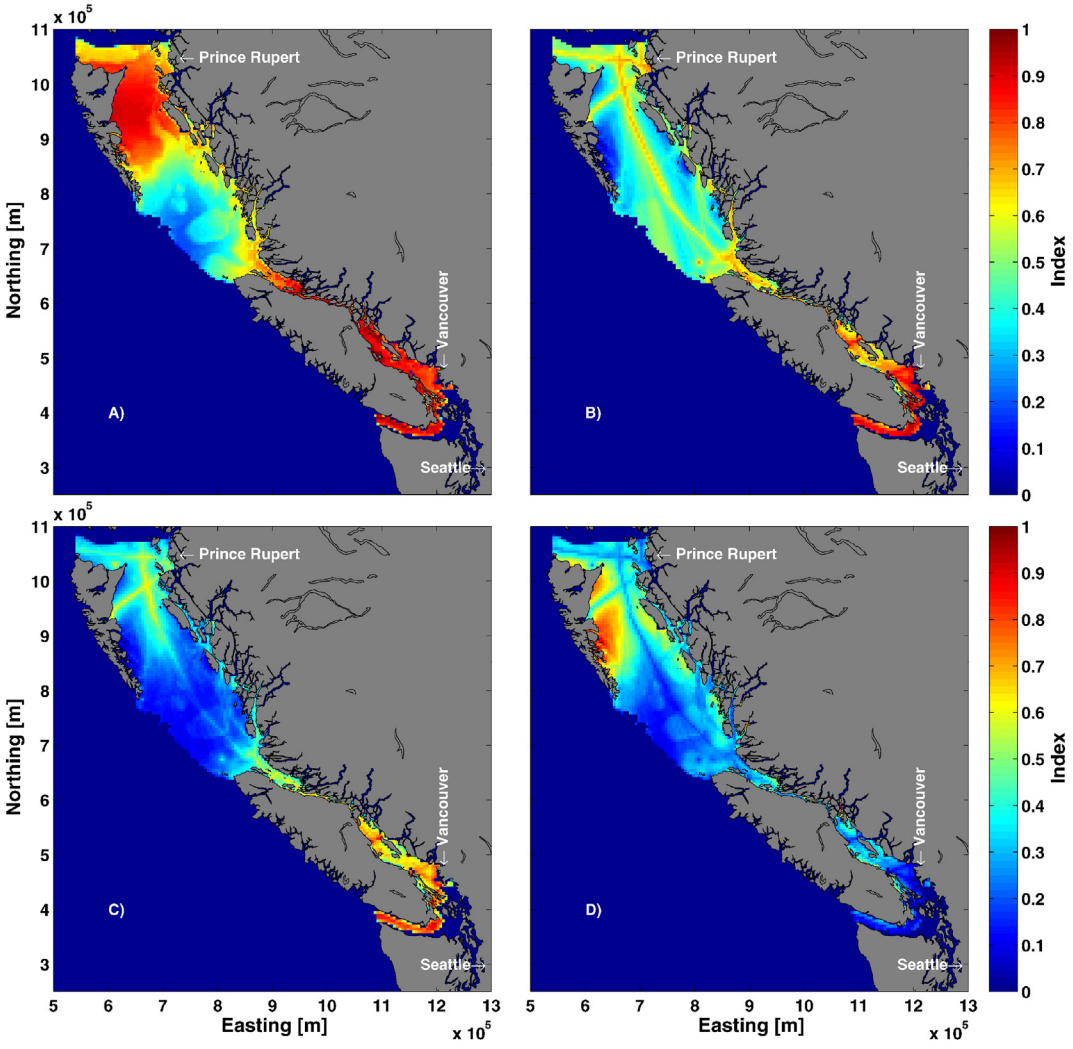


Fig. 1. Example results using harbor porpoise data identifying high "risk" areas (high levels of animal density and anthropogenic noise) and high "opportunity" areas (high levels of animal density and low levels of anthropogenic noise). Map (A): Normalized harbor porpoise density (averaged over 4 surveys conducted June–Sept between 2004 and 2007) showing two regions of high density. Map (B): Cumulative, audiogram-weighted sound energy from ship traffic (June–Sept 2008), normalized to 0–1 and plotted only in geographic cells that had harbor porpoise density data. Map (C): the "risk" map, indicating the co-occurrence of cumulative ship noise and porpoises. Map (D): the "opportunity" map, indicating where porpoise density is high and ship noise is low.

planning effort, or for consideration as Canada identifies critical habitats for species at risk (Taylor and Pinkus, 2013).

Given the role of acoustic cues in mediating many marine predator–prey interactions, the evidence suggests that chronic noise from ships can affect not only the welfare and behavior of individual animals (Rolland et al., 2012; Williams et al., 2014b), but also trophic pathways in marine ecosystems (Popper and Hawkins, 2011; Wale et al., 2013). For example, boat noise disrupts predation on Chinook salmon by endangered killer whales, which are both specialist foragers and food-limited (Ford and Ellis, 2006; Lusseau et al., 2009; Williams et al., 2006, 2011b). Endangered species recovery plans in Canada and the USA have called for reduction of this stressor to promote recovery of endangered species (Fisheries and Oceans Canada, 2011; National Marine Fisheries Service, 2008). Similarly, feeding rates of sperm whales decline in the presence of seismic surveys (Miller et al., 2009). Further, experimental research at large spatial scales will be needed to assess whether incorporating anthropogenic noise in MPA management plans will improve our ability to preserve ecosystem function (Boyd et al., 2011). Managers of MPAs will have a key role to play in processes that assess environmental impacts of proposed activities (e.g., offshore oil and gas exploration and extraction). At a minimum, preserving acoustic integrity of marine protected areas would require MPA management authorities advocating strongly for reducing noise-generating activities (e.g., seismic surveys, sonar activities, or large-scale changes to shipping traffic) that are outside the protected area but could substantially raise noise levels in MPA waters. Greater engagement with such efforts can help managers conduct priority-setting exercises to gauge how important ocean noise is in a given area, to a given species or ecosystem, relative to all the other stressors that are also occurring. What may be a high priority for ensuring the persistence of a critically endangered killer whale population may pale in comparison to coral bleaching, catastrophic cyclones or industrial development activities taking place simultaneously in the Great Barrier Reef (Game et al., 2008). Nevertheless, any area-based management framework will require recognition of internal and external factors that affect ecosystem integrity (Hatch and Fristrup, 2009; Jameson et al., 2002), and must include the ability to adapt as new information on stressors becomes available (McCook et al., 2010).

For MPAs whose mandate involves separating species from threatening processes, we show that this is not strictly a spatial question, but also has implications for the temporal and acoustic frequency domains. Some species (e.g., harbor porpoise) have poor hearing ability in the low frequency range (<1 kHz), although they respond to relatively low intensities of man-made noise (Tougaard et al., 2009). On the other

Please cite this article as: Williams, R., et al., Quiet(er) marine protected areas, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.09.012

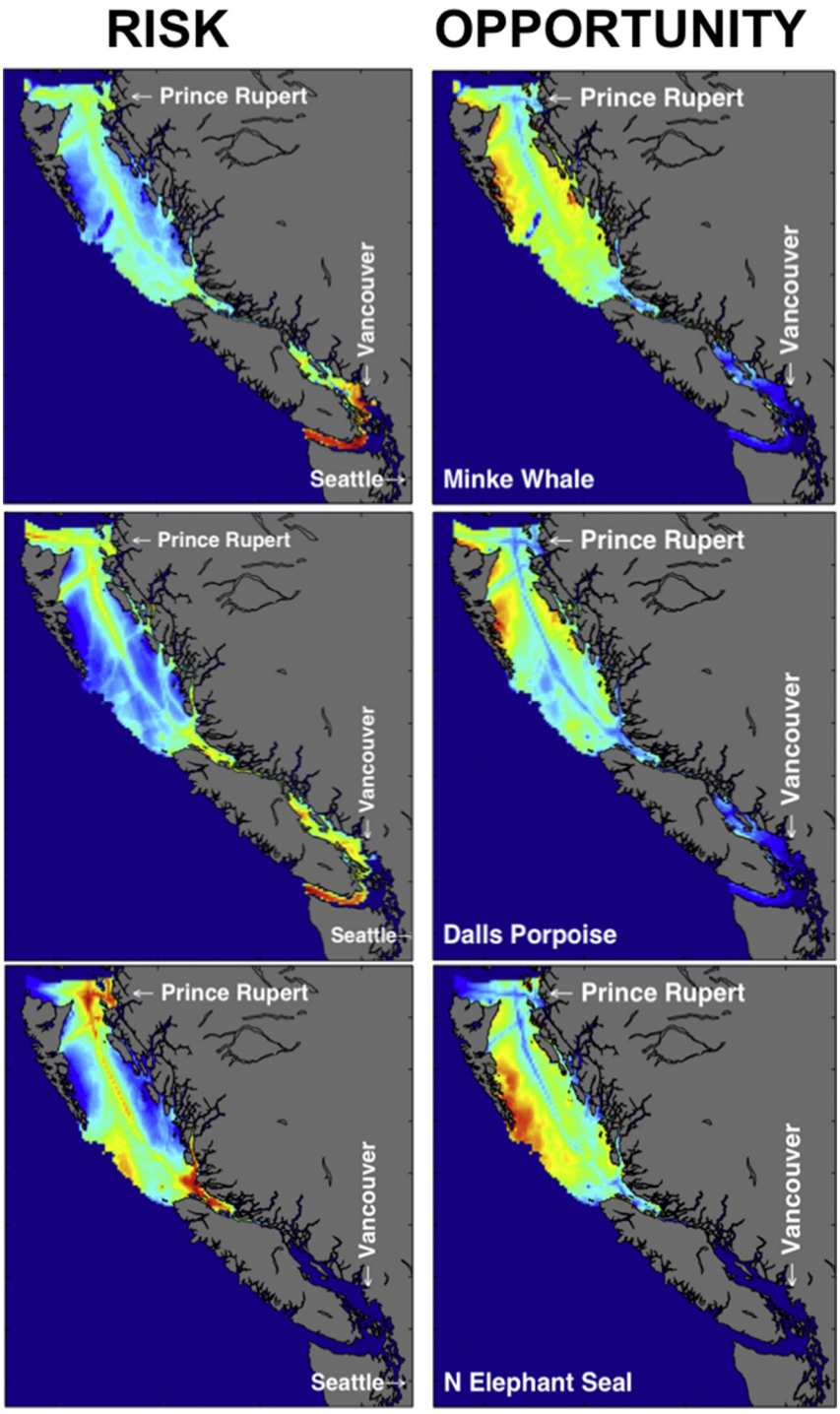


Fig. 2. Contrasting risk and opportunity maps for three species from three broad taxonomic groups: a baleen whale (top; minke whale); a toothed whale (middle; Dall's porpoise); and a seal (bottom; elephant seal).

end of the spectrum, some populations, such as southern resident killer whales (not included) display extreme fidelity to south coast waters that are so noisy that area-based management will have to be achieved by noise reduction efforts — there are no quiet spots left to protect in BC's south coast waters. Even areas that are estimated to have equally low noise levels averaged over time may differ in extremes: one may be continually subject to low levels of noise, whereas the other may have long periods of silence with infrequent occurrences of moderate noise. These scenarios may be mathematically equivalent when summing or averaging energy over time, but ecologically quite different; science is lacking as to what the effects of these different exposure histories might be.

Shipping lanes have imposed persistent acoustic patterns into the marine environment (Erbe et al., 2012; Hatch and Fristrup, 2009). We encourage spatial planners to work *with* existing gradients in noise distribution levels and marine mammal distributions, where known, to slow the inevitable process of attrition and habitat degradation that may otherwise take place, while waiting for successes from the harder work of quieting the noisiest sites. Where marine mammal distribution is unknown, a number of methods are available to make predictions from habitat suitability, local knowledge, expert opinion or niche envelope models (Williams et al., 2014c). Recent efforts to move shipping channels off Boston, MA or Long Beach, CA show that such management

Please cite this article as: Williams, R., et al., Quiet(er) marine protected areas, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.09.012



Fig. 3. Four of the study species, which differ in both spatial distribution and hearing abilities: (A) humpback whale; (B) harbor seal; (C) Pacific white-sided dolphin; and (D) killer whale.

actions can be effective (McKenna et al., 2012). Given the expense and logistical challenges associated with moving shipping lanes, we see value in pointing out opportunities where maintaining the *status quo* would offer conservation benefit with little socio-economic cost (Fig. 4). Despite the challenges of implementing and enforcing policies and management strategies to reduce ocean noise, spatial planners can use existing gradients in niose distribution and marine mammal distribution, if such data are available, to produce opportunity maps that can support broader efforts in spatial planning, zoning or MPA design.

Our study's primary objective was to integrate information on cumulative noise energies with average distributions and hearing abilities of 10 marine mammal species during summer months to assess whether some sites or species that already reside in quiet acoustic environments could benefit from formal protection. Based on the local sound propagation environment (made up of its bathymetry, seafloor geology, and water column sound speed profile) and based on the geographic locations and positions within the water column of the noise sources (i.e., we know that their distribution is not uniform in 3D space, but rather ship noise originates mostly from the propeller at a few meters below the sea surface, and from geographic focus areas, namely shipping lanes) and of the receivers (i.e., we know that certain species prefer certain geographic regions and remain within a certain water depth), natural acoustic focus (convergence) and buffer (shadow) zones exist that may ease the process of separating marine mammals from noise.

Anatomically, some hearing apparatuses will be more sensitive to acoustic energy in the frequencies dominated by ship noise than others. In terms of sensitivity, we need better audiograms for many species of marine mammals, most species of fish and invertebrates, and empirical data on how life functions (i.e., feeding, mating, navigating, maintaining social cohesion, and evading predators) are affected by presence or absence of anthropogenic noise. In some cases, anatomical data alone could reveal whether a species is naturally protected from noise in particular frequencies. If animals are unambiguously separated from a noise source in the temporal, spatial and spectral domains, there is no conservation concern. More research is needed to assess the responsiveness of predators and prey to anthropogenic sounds that occur at the edge of audibility, as well as the non-auditory effects of sound.

In our future work, we aim to move beyond single-species management and begin to make some predictions about influences of noise on ecological communities. The MPA community has moved from single-species protection to protecting or supporting ecosystem function or services years ago, so those concerned with marine mammals and noise have a large body of work to learn from (e.g., (Halpern et al., 2010)). Because anthropogenic noise can mask the signals used by predators to find prey, and vice versa, there will be winners and losers when we artificially introduce or remove noise (Clark et al., 2009). We simply do not know enough yet to predict which species may win or lose, or the time scales of such complex processes. Some of the species we map as being insensitive to noise (Fig. 4) may be affected indirectly, via effects on prey.

In the temporal domain, some highly migratory species are absent from the region for half the year, so clearly, mandatory noise restrictions should be more permissible than during the core summertime feeding season. Even temporal conservation prioritization requires explicit targets to be set: by protecting one species, one may inadvertently schedule noise-generating activities when non-migratory species are present.

Finally, it should be reiterated that we do not advocate ignoring acoustically degraded sites. On the contrary, habitat restoration is a

Please cite this article as: Williams, R., et al., Quiet(er) marine protected areas, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.09.012

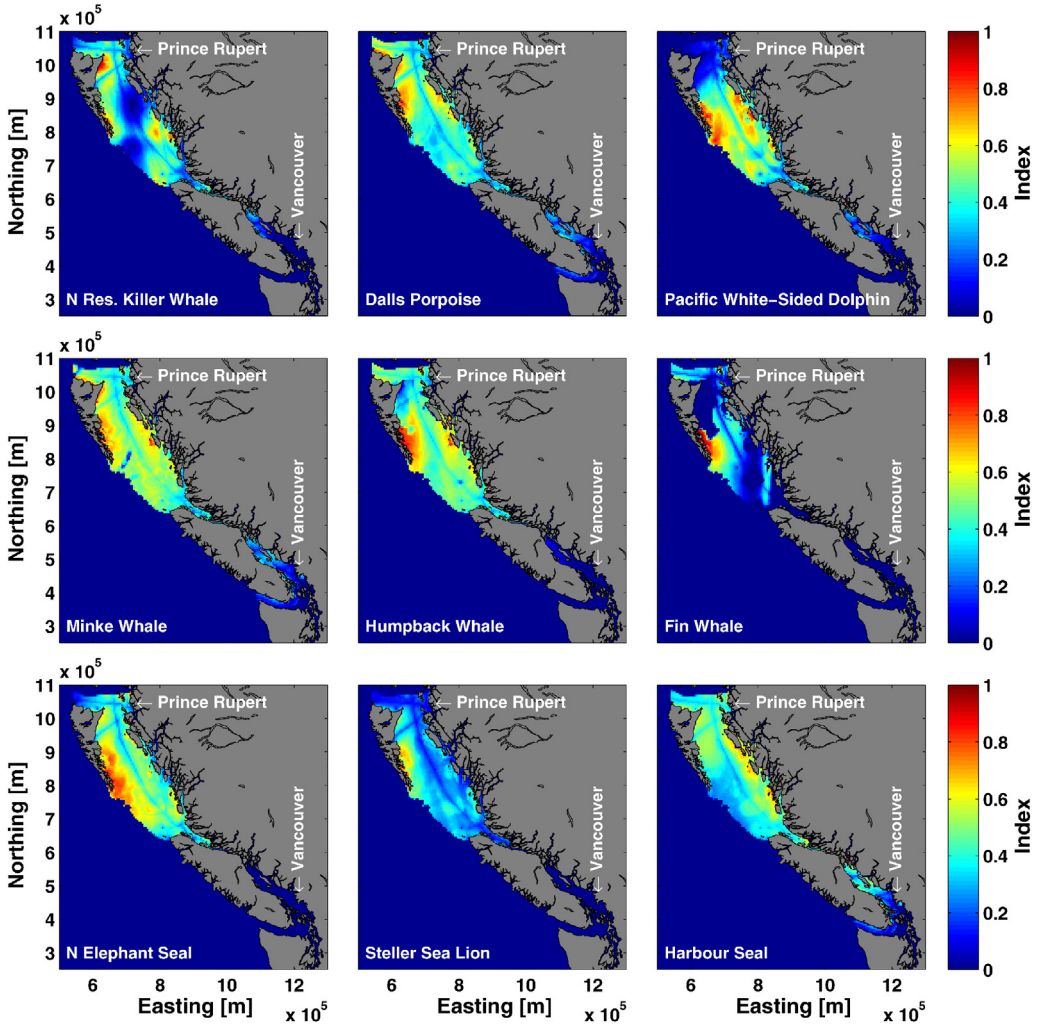


Fig. 4. The "opportunity" maps (highest density, lowest noise levels) for nine species.

central task in conservation biology. It is just that it is exceedingly difficult to reduce input of anthropogenic noise from sources outside a protected area (Hatch and Fristrup, 2009). Here we show that some areas are already protected, either in the spatial or frequency domain. Therefore, including acoustic metrics in spatial plans will allow us to meet conservation targets faster than by trying to mitigate after a habitat has been degraded. This may seem obvious, but if we fail to identify pockets where important wildlife habitats are still quiet and also manage human activities in order to keep them that way, we can expect those acoustic sanctuaries or refugia to disappear eventually.

Acknowledgments

We thank Patrick O'Hara and his colleagues in the Oil-in-Canadian-Waters research group (Rosaline Canessa, Ron Pelot and Norma Serra) for extensive analysis of vessel count, speed and location data to facilitate our acoustic analyses. RW was supported by a Marie Curie International Incoming Fellowship within the 7th European Community Framework Programme (Project CONCEAL, FP7, PIIF-GA-2009-253407) and a Pew Fellowship in Marine Conservation during the writing. These analyses were funded by a grant to RW and EA from Marisla Foundation. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. We thank Doug Sandilands for assistance with producing the figures, and Dr Norm Sloan for feedback on management objectives of the Gwaii Haanas National Marine Conservation Area. We thank anonymous reviewers for their helpful comments.

References

Agardy, T., Bridgewater, P., Crosby, M.P., Day, J., Dayton, P.K., Kenchington, R., Laffoley, D., McConney, P., Murray, P.A., Parks, J.E., 2003. Dangerous targets? Unresolved issues and ideological clashes around marine protected areas. Aquat. Conserv. Mar. Freshwat. Ecosyst. 13, 353–367.

Ball, I.R., Possingham, H.P., Watts, M., 2009. Marxan and relatives: software for spatial conservation prioritisation. In: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools. Oxford University Press, Oxford.

Boyd, I.L., Frisk, G., Urban, E., Tyack, P., Ausubel, J., Seeyave, S., Cato, D., Southall, B., Weise, M., Andrew, R., 2011. An international quiet oceans experiment. Oceanography 24, 174–181.

Clark, C.W., Ellison, W.T., 2004. Potential use of low-frequency sounds by baleen whales for probing the environment: evidence from models and empirical measurements. In: Thomas, J.A., Moss, C., Vater, M. (Eds.), Echolocation in Bats and Dolphins. The University of Chicago Press, Chicago, pp. 564–582.

Clark, C.W., Ellison, W.T., Southall, B.L., Hatch, L., Van Parijs, S.M., Frankel, A., Ponirakis, D., 2009. Acoustic masking in marine ecosystems: intuitions, analysis, and implication. Mar. Ecol. Prog. Ser. 395, 201–222.

Corrigan, C.M., Ardron, J.A., Comeros-Raynal, M.T., Hoyt, E., Notarbartolo Di Sciara, G., Carpenter, K.E., 2014. Developing important marine mammal area criteria: learning from ecologically or biologically significant areas and key biodiversity areas. Aquat. Conserv. Mar. Freshwat. Ecosyst. 24, 166–183.

Devillers, R., Pressey, R.L., Grech, A., Kittinger, J.N., Edgar, G.J., Ward, T., Watson, R., 2014. Reinventing residual reserves in the sea: are we favouring ease of establishment over need for protection? Aquat. Conserv. Mar. Freshwat. Ecosyst. http://dx.doi.org/10.1002/aqc.2445 (Online Early).

ARTICLE IN PRESS

Dolman, S.J., 2007. Spatio-temporal restrictions as best practice precautionary response to ocean noise. J. Int. Wildl. Law Policy 10, 219–224.

Edgar, G.J., Stuart-Smith, R.D., Willis, T.J., Kininmonth, S., Baker, S.C., Banks, S., Barrett, N.S., Becerro, M.A., Bernard, A.T.F., Berkhout, J., Buxton, C.D., Campbell, S.J., Cooper, A.T., Davey, M., Edgar, S.C., Forsterra, G., Galvan, D.E., Irigoyen, A.J., Kushner, D.J., Moura, R., Parnell, P.E., Shears, N.T., Soler, G., Strain, E.M.A., Thomson, R.J., 2014. Global conservation outcomes depend on marine protected areas with five key features. Nature 506, 216–220.

Ellison, W.T., Weixel, K., Clark, C.W., 1999. An acoustic integration model (AIM) for assessing the impact of underwater noise on marine wildlife. J. Acoust. Soc. Am. 106, 2250-2250.

Erbe, C., 2012. The effects of underwater noise on marine mammals. In: Popper, A.N., Hawkins, A.D. (Eds.), The Effects of Noise on Aquatic LifeAdvances in Experimental Medicine and Biology 730. Springer Verlag, New York, pp. 17–22.

Erbe, C., MacGillivray, A., Williams, R., 2012. Mapping cumulative noise from shipping to inform marine spatial planning. J. Acoust. Soc. Am. 132, EL423–EL428.

Erbe, C., Williams, R., Sandilands, D., Ashe, E., 2014. Identifying modelled ship noise hotspots for marine mammals of Canada's Pacific region. PLoS One 9, e89820.

Finneran, J.J., Carder, D.A., Schlundt, C.E., Ridgway, S.H., 2005. Temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. J. Acoust. Soc. Am. 118, 2696.

Fisheries and, 2011. Recovery Strategy for the Northern and Southern Resident Killer Whales (*Orcinus orca*) in Canada. Fisheries and Oceans Canada, Species at Risk Act Recovery Strategy Series, Ottawa (p. ix + 80 pp.).

Ford, J.K.B., Ellis, G.M., 2006. Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. Mar. Ecol. Prog. Ser. 316, 185–199.

Game, E.T., McDonald-Madden, E.V.E., Puotinen, M.L., Possingham, H.P., 2008. Should we protect the strong or the weak? Risk, resilience, and the selection of marine protected areas. Conserv. Biol. 22, 1619–1629.

Gaston, K.J., Jackson, S.F., Cantu-Salazar, L., Cruz-Pinon, G., 2008. The ecological performance of protected areas. Annu. Rev. Ecol. Evol. Syst. 39, 93–113.

Halpern, B.S., Lester, S.E., McLeod, K.L., 2010. Placing marine protected areas onto the ecosystem-based management seascape. Proc. Natl. Acad. Sci. 107, 18312–18317.

Hart, S.L., Ahuja, G., 1996. Does it pay to be green? An empirical examination of the relationship between emission reduction and firm performance. Bus. Strateg. Environ. 5, 30–37.

Hatch, L.T., Fristrup, K.M., 2009. No barrier at the boundaries: implementing regional frameworks for noise management in protected natural areas. Mar. Ecol. Prog. Ser. 395, 223–244.

Hatch, L.T., Clark, C.W., Van Parijs, S.M., Frankel, A.S., Ponirakis, D.W., 2012. Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. Conserv. Biol. 26, 983–994.

Hildebrand, J.A., 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser. 395.

Jameson, S.C., Tupper, M.H., Ridley, J.M., 2002. The three screen doors: can marine "protected" areas be effective? Mar. Pollut. Bull. 44, 1177–1183.

Leaper, R., Renilson, M.R., 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. Trans. RINA 154 Available from http://www.ifaw.org/sites/default/files/Reducing%20Underwater%20Noise%20Pollutions%20for%20Large%20Commercial%20Vessels.pdf.

Lusseau, D., Bain, D.E., Williams, R., Smith, J.C., 2009. Vessel traffic disrupts the foraging behavior of southern resident killer whales *Orcinus orca*. Endanger. Species Res. 6, 211–221.

Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. Nature 405, 243–253.

McCook, L.J., Ayling, T., Cappo, M., Choat, J.H., Evans, R.D., De Freitas, D.M., Heupel, M., Hughes, T.P., Jones, G.P., Mapstone, B., 2010. Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. Proc. Natl. Acad. Sci. 107, 18278–18285.

McKenna, M., Katz, S., Wiggins, S., Ross, D., Hildebrand, J., 2012. A quieting ocean: unintended consequence of a fluctuating economy. J. Acoust. Soc. Am. 132, EL169–EL175.

Miller, P.J.O., Johnson, M.P., Madsen, P.T., Biassoni, N., Quero, M., Tyack, P.L., 2009. Using at-sea experiments to study the effects of airguns on the foraging behavior of sperm whales in the Gulf of Mexico. Deep-Sea Res. I Oceanogr. Res. Pap. 56, 1168–1181.

National Marine Fisheries Service, 2008. Recovery Plan for Southern Resident Killer Whales (*Orcinus orca*). National Marine Fisheries Service, Northwest Region, Seattle, WA, USA, p. 251.

Popper, A.N., Hawkins, A., 2011. The effects of noise on aquatic life. Advances in Experimental Medicine and Biology vol. 730. Springer (695 pp.).

Richardson, J.W., Greene, C., Jr, R., Malme, C.I., Thomson, D.H., 1995. Marine Mammals and Noise. Academic Press, San Diego (576 pp.).

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K., Kraus, S.D., 2012. Evidence that ship noise increases stress in right whales. Proc. R. Soc. B Biol. Sci. 279, 2363–2368.

Shyu, H.-J., Hillson, R., 2006. A software workbench for estimating the effects of cumulative sound exposure in marine mammals. IEEE J. Ocean. Eng. 31, 8–21.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., Popper, A.N., 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol. Evol. 25, 419–427.

Sloan, N., 2002. History and application of the wilderness concept in marine conservation. Conserv. Biol. 16, 294–305.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., 2007. Marine mammal noise exposure criteria: initial scientific recommendations. Aquat. Mamm. 33, 411–521.

Taylor, E.B., Pinkus, S., 2013. The effects of lead agency, nongovernmental organizations, and recovery team membership on the identification of critical habitat for species at risk: insights from the Canadian experience. Environ. Rev. 21, 93–102.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., Rasmussen, P., 2009. Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)). J. Acoust. Soc. Am. 126, 11.

Wale, M.A., Simpson, S.D., Radford, A.N., 2013. Noise negatively affects foraging and antipredator behaviour in shore crabs. Anim. Behav. 86, 111–118.

Weilgart, L., 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85, 1091–1116.

Williams, R., O'Hara, P., 2010. Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. J. Cetac. Res. Manage. 11, 1–8.

Williams, R., Lusseau, D., Hammond, P.S., 2006. Estimating relative energetic costs of human disturbance to killer whales (*Orcinus orca*). Biol. Conserv. 133, 301–311.

Williams, R., Ashe, E., O'Hara, P.D., 2011a. Marine mammals and debris in coastal waters of British Columbia, Canada. Mar. Pollut. Bull. 62, 1303–1316.

Williams, R., Krkosek, M., Ashe, E., Branch, T.A., Clark, S., Hammond, P.S., Hoyt, E., Noren, D.P., Rosen, D., Winship, A., 2011b. Competing conservation objectives for predators and prey: estimating killer whale prey requirements for Chinook salmon. PLoS One 6, e26738.

Williams, R., Clark, C.W., Ponirakis, D., Ashe, E., 2014a. Acoustic quality of critical habitats for three threatened whale populations. Anim. Conserv. 17, 174–185.

Williams, R., Erbe, C., Ashe, E., Beerman, A., Smith, J., 2014b. Severity of killer whale behavioral responses to ship noise: a dose-response study. Mar. Pollut. Bull. 79, 254–260.

Williams, R., Grand, J., Hooker, S.K., Buckland, S.T., Reeves, R.R., Rojas-Bracho, L., Sandilands, D., Kaschner, K., 2014c. Prioritizing global marine mammal habitats using density maps in place of range maps. Ecography 37, 212–220.

Wright, A.J., Deak, T., Parsons, E., 2011. Size matters: Management of stress responses and chronic stress in beaked whales and other marine mammals may require larger exclusion zones. Marine Pollution Bulletin 63, 5–9.

Zacharias, M.A., Gregr, E.J., 2005. Sensitivity and vulnerability in marine environments: an approach to identifying vulnerable marine areas. Conserv. Biol. 19, 86–97.

Please cite this article as: Williams, R., et al., Quiet(er) marine protected areas, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.09.012