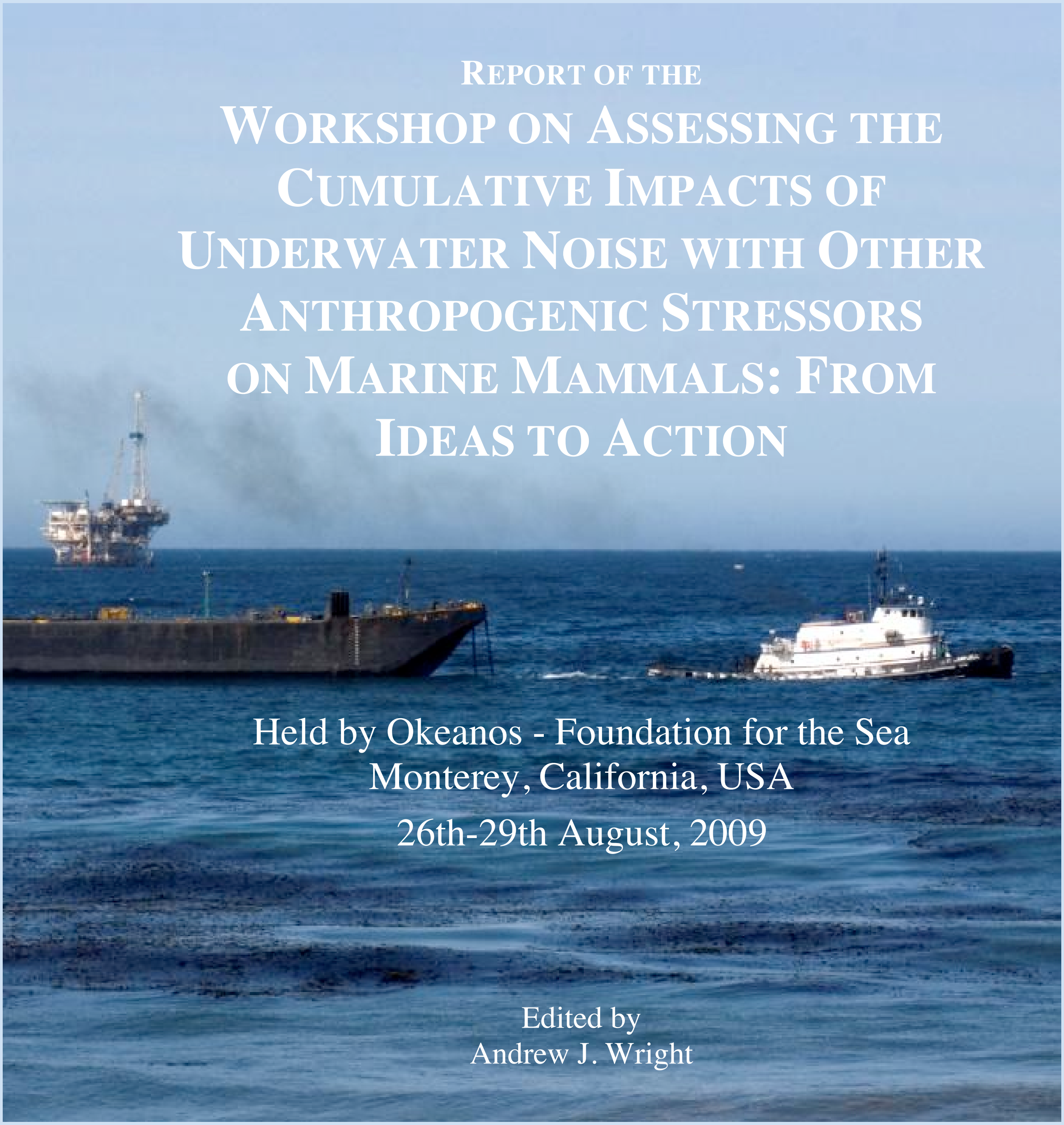

REPORT OF THE

WORKSHOP ON ASSESSING THE CUMULATIVE IMPACTS OF UNDERWATER NOISE WITH OTHER ANTHROPOGENIC STRESSORS ON MARINE MAMMALS: FROM IDEAS TO ACTION

Held by Okeanos - Foundation for the Sea
Monterey, California, USA

26th-29th August, 2009

Edited by
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Cover photo courtesy of the Michael H Smith, project coordinator, Gray Whales Count; 211 W Gutierrez St., Studio 8, Santa Barbara, CA 93101. USA. http://www.graywhalescount.org/

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Prologue

By Dieter Paulmann

As part of our ongoing work on the impacts of anthropogenic (human-made) noise on marine mammals, Okeanos – Stiftung für das Meer (Foundation for the Sea), has held a number of international, multi-disciplinary workshops to investigate and address various aspects of the issue. These workshops have produced discussions that have been both ground-breaking and bridge-building. Scientists from a diversity of disciplines (ranging from biologists to engineers) and policy makers have reached out to each other and advanced not only the science, but established valuable connections and also expanded the range of possible management mechanisms available to address underwater noise.

One important theme to emerge over the course of these workshops is that noise does not act in a vacuum. It affects species that are already facing a variety of other anthropogenic pressures, including contaminants, fisheries and, of course, climate change. Noise can also interact with these stressors in ways that may endanger them further. Appropriate management of cumulative stressors has been lacking partly because many legal systems act on a project-by-project basis. By the same token, scientists are only just beginning to investigate how stressors interact to affect individuals and ultimately populations. The issue is complicated further with respect to the management of cumulative impacts in marine mammal populations as data for these inaccessible animals are limited in any case.

Seeking to find a route forward to more appropriate and comprehensive management techniques for assessing cumulative impacts of noise and other stressors in marine mammals, Okeanos held another workshop in Monterey, California, from 26-29 August, 2009, to investigate the possibilities. Participants were carefully selected from disciplines as diverse as bioacoustics, management practice and network theory, and focus was placed upon free-flowing discussions, as this has proven highly successful in previous meetings. Specifically, participants were asked to consider three approaches to the problem: how currently available tools for regionally mapping anthropogenic pressures on the environment could be applied to the management of species; how the reported consequences of exposure to these pressures in marine mammals and their known interactions on an individual could be modelled; and how population modelling could best include cumulative impact assessment. Promisingly, participants felt that the three approaches could all be fulfilled in at least two data-rich populations – southern resident killer whales and North Atlantic right whales – and that the examples produced by this effort could then be used to inform management decisions for less-studied species, perhaps based on information about exposure to noise and other stressors alone.

What follows is a report of these discussions, in an unconventional form. The participants of the workshop felt that they had a unique opportunity to contribute their combined expertise through timely comments to the new U.S. Interagency Ocean Policy Task Force[1] and by offering suggestions on marine spatial planning, one of the options under discussion that could substantially advance the management of cumulative impacts. The Task Force is, at time of writing, working to construct a new National Policy for the Oceans, Coasts, and the Great Lakes.

[1] On June 12, 2009, President Obama sent a memorandum to the heads of executive departments and federal agencies establishing an Interagency Ocean Policy Task Force, led by the White House Council on Environmental Quality. The Task Force is charged with developing a recommendation for a national policy that ensures protection, maintenance, and restoration of oceans, our coasts and the Great Lakes.

To that end, participants drafted three documents, each addressing one of the three approaches that were explored at the workshop. The first document investigates options for incorporating noise in currently ongoing efforts to map the extent of human impact on the oceans. The second paper considers the possibilities for modelling how these various impacts may act upon populations of marine mammals in combination. The last document describes the potential for modelling how the multiple stressors might act in combination cumulatively, synergistically and antagonistically within an individual.

These background documents were used in support of two letters, also signed by many of the participants. The first was a letter to President Obama (the Task Force were sent a copy) calling for the inclusion of undersea noise in the new National Oceans Policy, while broadly supporting the initiative. It noted that reducing sources of underwater noise can quickly improve the matter as it dissipates relatively quickly, unlike contaminants that will persist in the environment for some time. The letter also pointed out that many measures to substantially address the problem of underwater noise are available now, and that moving forward with these option would provide marine life the best chance at surviving less tractable threats, such as climate change. The second letter was sent to the Task Force directly and summarised the plan developed at the workshop for moving towards a more comprehensive assessment of cumulative impacts. The three discussion papers included in this report were attached to this letter.

To allow wide dissemination of the information contained within these documents, they are written in simple language to the extent possible. It is hoped that, although they are particularly adapted to the current process within the U.S., they will be of interest to a wide, international audience. Similarly, many caveats and much of the fine detail often found in the wider literature have also been left out. These documents should thus be seen as an introduction to the issue of cumulative impacts of noise with other stressors on marine mammals, as well as an exploration of potential solutions. It is hoped that these discussions and recommendations will provide interested parties a firm starting point upon which they can build their knowledge.

In addition to the letters and discussion papers, this report also includes lists of participants and their presentations, the latter with abstracts.

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7th October 2009 Letter to President Obama

Participants of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action
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7th October, 2009

President Barack Obama
The White House
1600 Pennsylvania Avenue NW
Washington, DC 20500

Dear President Obama:

We write to urge you to address anthropogenic ocean noise, a growing threat to whales and other marine life, in your new National Oceans Policy.

We applaud the recognition of the threats facing ocean health detailed in your June 12th Presidential Memorandum and welcome your initiative to develop timely strategies to halt and reverse damage to the marine environment. One threat not highlighted, and one we believe is largely curable, is the rising level of noise in the sea, which amplifies the problems already faced by ocean life.

The ocean is a world of sound. Animals such as whales, dolphins, and fish depend on hearing for communicating, foraging, finding mates, detecting predators, and maintaining family and social groups. Human activity is rapidly altering the ocean's natural acoustic habitats. Industrial and commercial underwater noise propagates over enormous distances, affecting millions of square miles of ocean. For example, background noise at the same low frequencies vital to many marine species has increased 100-fold in some locations over the last 50 years. This growing fog of noise is shrinking the perceptual world of whales and other marine life, undermining their ability to "see" with sound. Chronic noise exposure is a recently recognized, largely hidden threat that can reduce long-term survival rates, while exposure to loud noise can result in injury, and even death in certain circumstances. Today few places in the world's oceans remain free of noises from human activities.

An international, multi-disciplinary group of scientists and resource managers gathered in Monterey, California, in August 2009, to discuss ways to manage the cumulative impacts of noise and other threats to whales and other marine life. We, the undersigned participants of this workshop, believe that reducing ocean noise is an achievable goal that will help marine life cope with less tractable threats such as climate change.

Unlike other ocean contaminants, noise does not remain in the environment for very long after the source is removed (although some effects may linger), and it is often produced unintentionally.

Most major noise sources, including propeller noise from large commercial ships and seismic pulses used in oil and gas exploration, can be reduced and still produce the public benefits desired. This can be achieved through operational measures and the application of technologies that are currently, or very soon to be, commercially available. Many noise sources can also be effectively mitigated through marine spatial planning. Federally mandated reductions will help fulfill agency obligations under the Endangered Species Act, Marine Mammal Protection Act, and other statutes, and expedite the recovery of endangered and threatened species.

Therefore we urge you to ensure, as an element of the new National Oceans Policy, that no net increase in ambient noise occurs in U. S. coastal waters and that a schedule be established to realize substantial reductions in ocean noise by 2020.

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24th November 2009 Letter the Interagency Ocean Policy Task Force

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24th November 2009

Ms. Nancy Sutley
Chair, Council on Environmental Quality
Chair, Interagency Ocean Policy Task Force
The White House
1600 Pennsylvania Ave., N.W.
Washington, DC 20500

Dear Chairwoman Sutley and Members of the Interagency Ocean Policy Task Force:

We write to advise you of the results of an international, multi-disciplinary workshop held in Monterey Bay, California, earlier this year, on the cumulative impacts of ocean noise and other threats to marine life. We, the undersigned participants of the workshop, believe our work bears upon the framework you are developing for coastal and marine spatial planning, and we wish to offer guidance and tools to support your important efforts.

As you know, human activities are altering the world's oceans at an unprecedented magnitude and speed. Ocean acidification and climate change are likely to have widespread, adverse impacts on marine food webs. These impacts will further disrupt ecosystems already stressed by pollution, invasive species, overfishing, noise, and the destruction of sea-floor habitats, posing a grave threat not only to ocean health, but also to human welfare. As we noted in our October 7 letter to President Obama (attached here), we believe that reducing ocean noise is an achievable goal that will strengthen the resiliency of marine life to less tractable threats.

In Monterey, we began to develop a novel set of tools for assessing the cumulative effects of human activities, including undersea noise from all sources, on cetaceans. (Details of this emerging methodology are provided in the attached supporting documents.) In summary, the necessary data and techniques are available to produce regional maps representing the distribution and intensity of noise in the oceans. These can be combined with other maps currently available for fishing, offshore development, contaminant levels, and other threats to ecosystem health, to determine overall exposure of populations of animals. For well-studied species, the information can be incorporated into population models to provide meaningful advice concerning the cumulative impacts of multiple stressors. Findings from both these maps and models can be applied to other data-poor species. While we focused on cetaceans, many of these techniques can be applied to other species groups and ecosystems, and all of these tools are directly relevant to regional marine spatial planning.

Furthermore, we believe that noise, which is essentially a form of habitat destruction, can be effectively mitigated through marine spatial planning in the same way as other impacts related to human activities. The available scientific information supports action to mitigate impacts in areas with particularly high levels of ocean noise, as well as to cap noise levels in important habitat, such as whale feeding and calving areas. Such reductions in noise will help fulfill agency obligations under the Endangered Species Act, Marine Mammal Protection Act, and other statutes, and expedite the recovery of endangered and threatened species.

Marine spatial planning could also be applied to great effect in areas of rapidly increasing human use. For example, expanding activity in the Arctic – particularly from shipping, seismic exploration, and fishing – threatens to acoustically urbanize what was only recently a near-pristine environment, where the calls of endangered bowhead and beluga whales traveled across hundreds or even thousands of miles of icy ocean.

We therefore urge you to include ocean noise in the framework for coastal and marine spatial planning and in associated guidelines for cumulative impact assessment. We also ask that you recommend setting a cap on ocean noise in substantial portions of the Arctic and in important marine habitat in US waters, as well as upon the high seas, preserving the biological integrity of these areas for the continued health of ocean ecosystems and the well-being of the people who depend upon them. Finally, in support of your efforts, we offer our ongoing work on threat mapping and cumulative impact assessment, as described above.

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Enclosures:
1) October 7 letter from the Participants of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action to President Obama
2) Kappel, C., Alter, E., Brewer, P., Deak, T., Erbe, C., Fristrup, K., Harrison, J., Hatch, L., Hildebrand, J. & Kroeker, K.J. 2009. Mapping Cumulative Threats to Cetaceans from Ocean Noise and Other Stressors. *Report of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action.*
3) Cooke, J., Bode, M., Clark, C., Crowder, L., Green, J., Loseto, L., Mangel, M., Munns, W., Ramasco, J.J., Reeves, R., Satterthwaite, W.H., Suydam, R., Taylor, B., Weilgart, L., Wright, A.J. 2009 Modeling the Population Effects of Cumulative Impacts. *Report of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action.*
4) Wright, A.J., Bode, M., Loseto, L., Ramasco, J.J., Munns, W., Deak, T. & Kroeker, K.J. 2009. A Model of Cumulative Impacts on an Individual Marine Mammal. *Report of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action.*

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Ken Salazar, Secretary of Interior
Dr. Jane Lubchenco, Undersecretary for Oceans and Atmosphere, NOAA Administrator
Lisa P. Jackson, Administrator of EPA
Sen. Maria Cantwell, Chair, Oceans Subcommittee, Senate Commerce Committee
Sen. Olympia Snowe, Ranking Member, Oceans Subcommittee, Senate Commerce Committee
Rep. Madeleine Bordallo, Chair, Insular Affairs, Oceans and Wildlife Subcommittee, House Natural Resources Committee
Rep. Henry Brown, Jr., Ranking Member, Insular Affairs, Oceans and Wildlife Subcommittee, House Natural Resources Committee

Mapping Cumulative Threats to Cetaceans from Ocean Noise and Other Stressors

Carrie Kappel, Elizabeth Alter, Peter Brewer, Terrence Deak, Christine Erbe,
Kurt Fristrup, Jolie Harrison, Leila Hatch, John Hildebrand, Kristy Jean Kroeker

1. Framework

Spatio-temporal management of noise and other stressors is increasingly recognized as a critical strategy for mitigating cumulative impacts[1] on marine species, including cetaceans (whales and dolphins). This strategy requires 1) identification, assessment, and mapping of quantitative information on both habitat distributions and anthropogenic threats, and 2) synthesis of these datasets to produce vulnerability maps (Agardy et al. 2007). Though data on noise-producing sources exist for many regions of the oceans, these data have never been synthesized with the goal of deriving comprehensive annual or seasonal estimates of cumulative noise exposure, or integrated with exposure maps for other anthropogenic stressors.

Consequently, we aimed to:

1. Develop robust methods for cumulatively mapping annual or seasonal anthropogenic noise exposure from a full suite of diverse sources.
2. Derive methods for integrating spatial mapping of anthropogenic stressors with quantitative vulnerability assessments for cetacean species.
3. Develop one or several regional case studies for both (1) and (2).

Below we describe progress toward these goals and outline an approach to meeting them in future work.

Recent approaches to mapping cumulative impacts of human activities on marine ecosystems (e.g., Halpern et al. 2008; Halpern et al. 2009) provide a useful template for accomplishing these objectives. Specific aspects of this approach that could be applied to the problem of cumulative noise include implementation of a framework for weighting and summation of maps of the distribution and intensity of diverse stressors; the design and use of expert surveys; and organization of threats by activity (e.g. seismic exploration, dredging). Halpern et al. (2008) have produced a global map of annual cumulative impacts from human activities including fishing, climate change, pollution, and other stressors. At the regional scale, a research team at the National Center for Ecological Analysis and Synthesis (NCEAS) has completed an assessment of cumulative anthropogenic threats for the California Current Ecosystem (Halpern et al. 2009) and is undertaking a similar project for the state and federal waters off of Massachusetts. These projects have not previously included anthropogenic noise as a data layer. Developing a map of noise sources and impacts that could be directly integrated with these efforts would be of great utility for managers and regulators.

An important additional consideration specific to noise is the problem of combining data from noise sources characterized by different frequencies, duration, duty cycle[2] and loudness. Participants agreed that a weighting and integration scheme should be developed to produce a noise pollution index that can be used to compare across noise sources with very different characteristics. Differences in temporal signatures are also important: while averaging impacts on an annual basis will make sense for some noise sources, incorporating seasonal signatures may be more appropriate for others.

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[1] Cumulative impacts are the total suite of impacts arising from two or more threats acting in combination upon a population. They do not necessarily have to occur at the same time or even in the same location to present a cumulative challenge to the population.

[2] Duty cycle is the portion of time during which the noise-making source is operated.

In addition, two general classes of noise-producing activities have very different impacts at the biological level. Chronic or continuous noise sources (such as shipping) can result in masking of sounds produced for communication, foraging or navigation, reducing habitat value indefinitely in areas of high use. Acute noise sources, such as explosions, which have higher peak noise levels, but usually more localized and short term use, can cause disturbance and result in injury and/or death in certain circumstances[3]. Noise data falling into these two categories should be compiled into two separate data layers during the analysis and mapping (though the two layers could easily be integrated into one noise layer in a final analysis). Chronic noise should be measured relative to ambient sound in the oceans, which differs regionally and seasonally. Therefore, data on ambient sound are needed at the same spatial and temporal scale as chronic noise data.

2. Classifying and determining data sources for noise-producing activities

Noise sources were classified by human activity, grouping activities that were deemed to have similar noise signatures in terms of frequency and duration. In some cases broadly defined activities produce multiple kinds of noise, and these noise components must be treated under different categories. For example, trawling produces both vessel noise and noise associated with the bottom trawl itself: the vessel noise is captured in Small and mid-size vessels and the trawl noise in Mobile bottom gear. Similarly, naval training exercises may involve vessel noise, active sonar and explosions.

We identified the following categories of prevalent sources of noise:

1. Shipping;
2. Small and mid-sized vessels (including fishing, recreational, whale-watching, law enforcement, and research vessels);
3. Seismic airguns;
4. Ice breakers;
5. Military sonar;
6. Industrial construction (including dynamic positioning, drilling, pile driving and thruster use in constructing coastal and energy infrastructure (including renewable and nonrenewable energy sources);
7. Explosions (including military, dynamite fishing and rig decommissioning);
8. Mobile bottom gear (trawling and dredging); and
9. Acoustic harassment devices used in aquaculture and other operations.

We discussed how quantitative data on these various noise-producing activities might be obtained at both regional (using Massachusetts Bay as a focal area) and global scales. For each noise source, potential sources of data for the spatial and temporal extent of the activity and the noise signature (sound profile) were identified. Table 1 summarizes these potential data sources.

3. Vulnerability measures

We next considered how to develop quantitative vulnerability assessments for cetaceans that could be integrated with spatial maps of noise and other stressors. We discussed the utility of analyzing stressors both for individual species (when data allows) and for species groups based on hearing or noise sensitivity; taxonomy (e.g. beaked whales); management considerations (e.g. threatened or

[3] As a further note, propagation of sound underwater changes the characteristics of highly repetitive, loud, low-frequency-dominant acute sources, such that they become less discrete temporally and could, at some distance from the source, mask communication signals produced by low-frequency active marine animals, (i.e. effectively becoming a chronic source).

endangered species); or behavioral characteristics related to foraging, migration, and other behaviors.

Drawing on the Millennium Ecosystem Assessment's definition, the group defined vulnerability as having three components: exposure, sensitivity and resilience. Exposure determines the probability that a species or group of species will encounter a given stressor. Sensitivity determines how likely the species or group is to be affected negatively by that stressor. Coping strategies such as avoidance behavior can limit exposure to stressors, but do not necessarily reduce the adverse health consequences of stressors. Finally resilience refers to the ability of the individual or group of individuals to thrive in the face of stressors and/or rebound following stressor exposure. This recovery could have both short and long term components: recovery time may measure either the time required for a return to normal physiological levels and behavior, represented by full recuperation of the individual (hours to weeks), or for population recovery, which may take years.

We concluded that, due to data limitations, expert surveys would be necessary to evaluate species- or group-specific vulnerabilities to noise and other stressors. The framework and the methods for expert elicitation we discussed build on those of Halpern et al. (2007) and Teck et al. (in press). In this framework, experts would assess the vulnerability of a particular species or group of species to each noise class, or possibly to the two broad layers of noise classes (chronic versus acute), using a set of vulnerability measures. These vulnerability measures would then be weighted and combined into an overall vulnerability score. Scores can be averaged across all threats to give an average vulnerability rank per species or group, or averaged across species or groups to rank threats. These vulnerability scores are then used to build overall cumulative impact scores.

To map cumulative impacts, three data inputs are required: distribution and intensity of the stressors, distribution and density of the species or group (here modeled using habitat suitability maps), and the vulnerability scores described above. Methods and approaches for mapping stressors other than noise are described in Halpern et al. (2008; 2009). An approach to modeling cumulative noise is described above, and potential sources of data are reported in Table 1. Predicted cetacean densities (in the absence of stressors) would come from habitat suitability or predicted density models when available and deemed reliable (e.g., Barlow et al. 2009). These models use the relationship between observed animal densities with in situ and/or remotely sensed oceanographic conditions across multiple years of survey data to predict average or future distributions.

With these data in hand, cumulative impact would be calculated for each map pixel and threat/species combination by multiplying across predicted density, threat intensity, and vulnerability of species to that threat. A species-specific cumulative impact score could then be derived by summing across threats; likewise, overall cumulative impact scores could be derived by first averaging across species and then summing across threats. The output of these calculations is a set of maps of cumulative impact, for individual species, groups of species, and for all, or subsets of, stressors. Together these maps and associated analyses can help scientists and managers to understand the spatial distribution of threats, which species are most vulnerable to cumulative impacts and where, and which stressors contribute most to cumulative impacts.

A broad suite of factors influencing species- or group-specific vulnerability to particular stressors was discussed for potential inclusion in vulnerability assessments. These included density of population; residence time/mobility/behavioral response; frequency of stressor exposure relative to response time; predictability of stressor; avoidability; controllability; aversiveness; magnitude of stress response; and index of reproduction. Predictability and controllability of a stressor are key factors in rodent experimental systems (Maier and Watkins 2005). In addition, laboratory results have shown that repeated exposure to stressors that are similar in type often leads to substantial habituation to that threat, while repeated exposure to very different stressors is associated with sensitized outcomes (Weinberg et al. 2009). The magnitude of the stress response can be used as a predictor of certain adverse health outcomes. Consequently, repeated exposure to unpredictable, inescapable threats arising from categorically distinct sources (chemical threats versus more psychological threats such as noise, for example) would be expected to have the greatest cumulative impact, physiologically, on exposed individuals (Deak 2007).

After considering this array of factors and the original Halpern et al. (2007) vulnerability framework, we decided to build the cumulative impact score from the following:

1. Spatial extent of impact (of a single event);
2. Frequency of impact (single event);
3. Trophic impact (whether predators and/or prey of a species are also affected);
4. Population impact (for example, percent change in abundance, reproductive output or another measure of severity of effect on demographic parameters – see Cooke et al. 2009); and
5. Recovery time (behavioral and physiological) of an exposed individual.

Per the Millennium Ecosystem Assessment definition of vulnerability, spatial extent and frequency of impact describe the risk of exposure to a stressor. The last three describe species- or group-specific sensitivity and resilience to a particular stressor at the community, population and individual levels.

The current approach assumes that these five factors combine linearly to give a measure of vulnerability, and similarly that all stressors combine additively (Halpern et al. 2007, Halpern et al. 2008, Teck et al. in press). However, we know that some stressors interact to produce synergistic or antagonistic effects (those which are greater or smaller than what one would expect from simply summing the stressors). Ultimately it will be desirable to incorporate some measure of synergistic effects of multiple stressors, either within the vulnerability assessment or the cumulative impact model itself.

4. Species-specific considerations

Producing species-specific vulnerability maps using the process outlined above requires mapping of species distributions. The working group noted that in the case of species distributions (as opposed to the spatial distribution of ecosystems), distributions of threats and species distributions may be negatively correlated if animals are actively avoiding certain areas where stressors are concentrated. For this reason, when building cumulative impact maps, it may be preferable to use predictive maps of habitat suitability in addition to or in place of density maps built from observations. It should be noted, however, that predictive density or habitat suitability maps are not necessarily free of the influence of stressors on species distributions, because they are built based on relatively recent observations of species distribution and density, which may have been affected by human activities. For some species for which very few data exist, it may be necessary to use expert knowledge to build predictive habitat suitability indices. Another alternative would be to produce species-specific cumulative risk maps, without respect to the species' actual or predicted distributions. These maps would show the potential risk to the species in terms of cumulative impacts, for all locations across a study region. Finally, it was noted that survey data could potentially be used post-hoc to test correlations between actual (as opposed to predicted) distributions and noise exposure. Such analyses would need to be done very carefully though, as many factors other than noise exposure contribute to determining distributions.

5. Integration with population models

This mapping framework can eventually be combined with the population modeling framework (Cooke et al. 2009) in a variety of ways. First, the outputs of population models can provide quantitative information to supplement or replace expert judgment on the population impact vulnerability measure (and potentially others). Second, spatially explicit population models can be used to map vulnerability to each stressor at each location and time (e.g., breeding and feeding seasons). This would generate temporal and spatial vulnerability fields for each species with respect to each stressor. These vulnerability fields can then be used as a spatial weighting factor in the cumulative impact model, as described above. Finally, cumulative risk maps generated through the mapping analysis may serve as inputs to a spatially explicit individual or agent-based simulation.

6. Next steps

These methods will be best developed and tested through focused case studies. Given the availability of existing data on human activities, noise sources, and a vulnerable cetacean population (the North Atlantic right whale), Massachusetts Bay represents an ideal initial case study. Mapping of cumulative impacts of human activities is ongoing (NCEAS), as is noise monitoring and modeling (Stellwagen Bank National Marine Sanctuary). As noted in the population modeling document, the population of North Atlantic right whales is well-studied, making it suitable for detailed population modeling. Finally, there is a recognized need for an approach to quantifying cumulative impacts to this population.

Additional case studies could concentrate on Southern resident killer whales in the Puget Sound area or baleen whales in the Southern California Bight. Either of these case studies could build from published work on the cumulative impacts of human activities within the California Current (Halpern et al. 2009), extensive data on cetacean populations, predictive habitat maps for cetaceans, and ongoing noise monitoring and modeling.

Finally, the framework outlined above could be applied at the global scale to produce a global map of cumulative risks to cetaceans from human activities, building on the global map of Halpern et al. (2008) by incorporating, among other stressors, a comprehensive data layer on the distribution and relative intensity of anthropogenic noise.

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Table 1. Potential data sources for noise-producing activities.

	Subcategory	Chronic vs acute	Temporal aspects	Source of spatial data	Source of acoustic characterization data	Comments
Shipping	Large, ocean-going	Chronic	Annual averaging okay for metric (no seasonal component)	AIS (coastal) and HITS (pelagic) data	Generic sound profile data for a large ship plus propagated noise field, e.g. Scrimger & Heitmeyer, JASA 1991.	
Ice breakers		Chronic	Seasonal	Canadians keep track of ice breakers in Arctic; Antarctic - use base locations	Christine Erbe can provide information	
Small to mid-sized vessels	Fishing	Chronic	Seasonal	MA: NMFS and MA DMF; Global, CA: spatial fishing data from Halpern et al. 2008, 2009	Generic sound profile data for small/mid-sized vessels	
	Recreational	Chronic	Seasonal	Port or harbor size as a proxy for source and diffuse away from port. Number of boat licences (not boat driver licences) from county office.	Generic sound profile data for small/mid-sized vessels	Could Google Earth be used to count boats in harbor? Diffusive path may be linear along coast rather than radiating from port. Majority of boats stay within a few nm from harbor.
	Whale-watching	Chronic	Seasonal	Average across a localized area of regional activity based on number of boats or number of operator licences	Generic sound profile data for small/mid-sized vessels. Christine Erbe could provide data.	May need to consider correction to source level to reflect the fact that noise is not distributed randomly with respect to animals.
	Law enforcement	Chronic	No seasonal component		Generic sound profile data for small/mid-sized vessels	
	Research	Chronic	Seasonal		Generic sound profile data for small/mid-sized vessels	

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	Subcategory	Chronic vs acute	Temporal aspects	Source of spatial data	Source of acoustic characterization data	Comments
	Support vessels for construction/ maintenance	Chronic	No seasonal component		Generic sound profile data for small/mid-sized vessels	
Seismic exploration		Chronic	Seasonal in some regions (Arctic)	Global database of seismic vessels by region (World Geophysical News): # vessels/mo	Use acoustic signature of "average" industry vessel ; signatures of seismic arrays from Christine Erbe	
Military sonar	Mid Frequency Acoustic	Acute	No seasonal component	Hours of use of 53C (NOAA permitting)	Navy propagation models	
	Low Frequency Acoustic	Acute	No seasonal component	Extrapolate from pattern of historical use	Navy propagation models	
Explosions	Military	Acute	No seasonal component	NOAA permitting has data on ordinances used per exercise		No propagation model probably needed
	Dynamite fishing	Acute	No seasonal component	Hildebrand map for Indian Ocean		
	Rig de-commissioning	Acute	No seasonal component			
Mobile bottom gear	Trawling	Chronic	Seasonal	Use data from Halpern et al. from logbook reports/NMFS information for MA	Acoustic signature can come from Leila Hatch, could then be translated into global context	
Aquaculture	Acoustic harrassment	Acute	No seasonal component	MA and CA: Halpern et al. 2009 data from Google Earth combined with town data	Acoustic signature from manufacturer	
Construction/ industrial activites	Liquefied Natural Gas	Chronic	No seasonal component	Permitting agency -- Army Corps?		

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Subcategory	Chronic vs acute	Temporal aspects	Source of spatial data	Source of acoustic characterization data	Comments
Wind energy	Chronic	No seasonal component	State permitting/coastal planning. CA - wind E potential map; MA - Ocean Mgt Plan wind E areas	Generic sound profile data for turbines	
Tidal energy	Chronic	No seasonal component	State permitting/coastal planning. MA - Ocean Mgt Plan proposed tidal energy locations		
Wave energy	Chronic	No seasonal component	State permitting/coastal planning. CA - wave energy potential map		
Dynamic positioning	Chronic	No seasonal component			
Land-based construction	Chronic	No seasonal component	NOAA Environmental Sensitivity Index (hardened shoreline).		
Drilling (fixed and mobile)	Acute	No seasonal component	NOAA oil & gas permitting; World Geophysical News		
Pile-driving	Acute	No seasonal component	Presence of large harbors/ports and assume some level of periodic pile driving.	Christine Erbe can provide sound characteristics.	Use mean spectrum and attach some information on duty cycle. Keep track of peak levels in addition to averaging out.
Dredging	Acute	No seasonal component	Presence of large harbors/ports and assume some level of dredging		

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Modeling the Population Effects of Cumulative Impacts

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1. Summary

While the excessive hunting of the 18th-20th centuries has been brought largely under control, marine mammals − whales, dolphins, porpoises, pinnipeds and sirenians − now face a widening range of threats or stressors that together could jeopardize the survival of populations: entrapment and entanglement in fishing gear; collisions with vessels; noise from shipping, seismic surveys, sonar and other sources; toxic contaminants; ecological changes associated with climate change, fishing and pollution; and various other types of habitat alteration and degradation.

Assessment and management approaches for marine mammals have focused to date on direct mortalities or removals. These approaches need to be extended to cover sublethal effects, when individuals are not always killed (or otherwise removed from populations) immediately, but their health and condition is compromised, leading to reduced rates of individual survival, growth and reproduction. The survival of marine mammal populations depends on whether the cumulative impact of these threats or stressors can be contained within bounds that the populations can sustain. Otherwise, populations will decline, and species will disappear from parts of their current range, or even entirely.

Approaches to the management of cumulative impacts[1] on marine mammal population will require, among other inputs, results from population modeling that incorporates sublethal effects into survival and reproductive rates. Such modeling can yield population projections under different scenarios of threat levels and management action, and/or it can estimate levels of cumulative impact that are and are not consistent with population recovery or survival. This document outlines an approach to developing such models and proposes two case studies: North Atlantic right whales in the western Atlantic and “southern resident” killer whales in the eastern North Pacific.

2. Introduction

The days when species after species of whales and seals were hunted to the brink of extinction are over, but in the 21st century marine mammals − whales, dolphins, porpoises, pinnipeds and sirenians − face a range of threats that together could threaten the survival of populations: entrapment and entanglement in fishing gear; collisions with vessels; noise from shipping, seismic surveys, sonar and other activities; toxic contaminants; ecological changes associated with climate change, fishing, and pollution; and various other types of habitat alteration and degradation.

The challenge is that the effect of each single adverse factor may be hard to detect but the cumulative impacts may be enough to cause the disappearance of some species from part or all of their range.

While some threats, such as vessel collisions and entanglements, are known to kill marine mammals outright, quantification of the number of deaths, especially at the global scale, is still very approximate. The impacts of more subtle stressors, such as noise, are only now beginning to be understood. Noise can cause deaths directly in special circumstances, such as when mass strandings of beaked whales are linked to the use of military mid-frequency sonar. However, sublethal effects,

[1] Cumulative impacts, in this case, are the total suite of impacts arising from two or more threats acting in combination upon a population. They do not necessarily have to occur at the same time or even in the same location to present a cumulative challenge to the population.

such as exclusion from key habitat or reduction in the range of feeding- or mating-related communication between whales, have only recently been elucidated. The potential population-level impacts of these sublethal effects have yet to be quantified.

The amount of baseline demographic data available on populations varies greatly. In some well-studied populations, such as right whales in the western North Atlantic and "southern resident" killer whales (in Washington State and British Columbia), almost every individual is known, while for most populations of beaked whales, a family of whales that seems particularly vulnerable to acoustic threats, and many other populations of cetaceans, little is known about population abundance and structure.

Gaining a full understanding of the cumulative impact of all major stressors on the survival and reproductive rates of a marine mammal population is inherently difficult even with the kind of long-term, intensive research that to date has been conducted for only a few populations. We simply do not have the luxury of first finding out everything we would like to know about a species or population and the impacts of the stressors that they are exposed to, and only then beginning to design and implement strategies to reduce or mitigate the impacts. Taking that approach would almost certainly allow species to disappear from heavily impacted regions before the exact relationships between causes and effects are understood.

Instead, we need to act on the basis of what we know or can responsibly infer − erring, where uncertainty makes it necessary, on the side of precaution − while at the same time ensuring that directed research improves understanding of key relationships and enables management and mitigation strategies to be improved in the light of new knowledge. In particular, we need to use our knowledge of the better-studied populations to guide the determination of "allowable" exposure levels in the management of other species and populations for which data are sparse. Given the large data gaps that exist, these levels will inevitably depend on a substantial amount of inference, calibrated where possible to fit the data that we have.

The concept of PBR (Potential Biological Removal) has been of great utility in managing the levels of anthropogenic mortality of cetaceans in US waters in conformity with the Marine Mammal Protection Act (MMPA). The PBR formula provides quantitative target ceilings for human-caused direct mortality (hunting, fatal entanglements, fatal ship collisions) for both data-rich and data-poor marine mammal populations, the latter through the use of reasonable default values for unknown population parameters.

Application of the PBR formula ensures that a red flag is raised for populations subject to potentially unsustainable removals, and provides a target towards which take reduction teams can work. The PBR takes explicit account of uncertainty in that the precision of population estimates, as well as their point values, enter the formula. The Revised Management Procedure (RMP) of the International Whaling Commission (IWC) is based on a similar approach.

A challenge is to extend the PBR concept to include sublethal effects, i.e., those that do not involve immediate, observable mortality, but which over time reduce survival and reproductive rates. The goal is to develop a means to specify maximum acceptable levels of cumulative impact that serve as targets or thresholds for management strategies, or provide a red flag for populations where the cumulative impact exceeds the threshold. To make this possible, we need to develop and implement ways to express the different effects − lethal and sublethal – in a common currency so that they can be added, taking account of synergies where these can be expected to occur. Maximum Cumulative Impact (MCI) would become a threshold to be promoted at the international and national level, and at the appropriate regional level for marine mammal populations whose range spans the waters of two or more countries.

The MCI concept could be used to develop specific Cumulative Impact Management Plans for populations, or it could be incorporated into the Recovery Plans developed under the MMPA, or the Conservation Plans currently being considered by the IWC, ACCOBAMS and other multilateral bodies.

This document outlines the population modeling component of the directed research needed to improve our understanding of the demographic impacts of cumulative stressors, with the ultimate goal of contributing to the development of appropriate management and mitigation targets or thresholds.

3. List of threats

The following threats or stressors contribute to the cumulative impact and should be considered in the modeling of cumulative impacts on a population, even though not all of these stressors will be significant or applicable for all populations. The list is not exhaustive.

- Vessel interactions:
  - direct mortality and serious injuries from collisions;
  - disturbance, including from research and whale watching vessels.
- Entrapments and entanglements – direct mortality and serious injuries.
- Noise:
  - direct mortality or acoustic injury (in special cases);
  - chronic stress responses, with physiological and psychological effects;
  - habitat exclusion (spatial);
  - disturbance to feeding (time lost, reduced energy intake, increased energy use);
  - obscuring sounds important for:
    - foraging;
    - breeding;
    - predator avoidance.
- Deliberate removals, e.g., by hunting and live-capture (need to be taken into account in population projections).
- Contaminants, including oil spills:
  - direct (sublethal and occasionally lethal) physiological effects including immunological health;
  - effects on fertility.
- Nutritional and health effects of habitat change resulting from:
  - commercial fishing;
  - pollution;
  - other factors, such as exposure to novel diseases or increased competition that may result from changing habitat;
  - climate change.

Even though there can be considerable uncertainty about the numbers involved, direct mortality is in principle expressible in terms of the numbers of individuals removed from the population (broken down by age class and sex as appropriate). The challenge is to quantify sublethal effects in demographic terms.

For populations whose range includes US waters, a useful step would be the inclusion, in the Stock Assessment Reports (SARs) mandated by the MMPA, of details of human activities believed to harass or injure marine mammals, that are occurring (or have occurred) in the habitat of each population. The agencies that prepare these reports (National Marine Fisheries Service and the Fish and Wildlife Service) are also responsible for authorizing such activities.

4. Aims and approaches for modeling population effects of cumulative impacts

The aims of modeling the cumulative impacts on populations include to:

- provide a framework for estimating the population-level impacts of exposures to different stressors;
- identify the populations most at risk;
- assess possible interactions of different impacts;
- determine targets or thresholds for mitigation strategies for these populations;
- develop an approach for expressing different impacts in a common currency and thereby contribute to the development of a MCI management threshold; and
- help to identify the priorities for obtaining data on stressors and populations, in terms of both the kinds of data most needed, and the areas and species of highest priority.

Approaches to modeling cumulative impacts at the population level involve several linked stages:

1. Identification of the nature and sources of threats, and mapping of stressor levels. This will typically involve mapping, *inter alia*:
   a. noise levels by frequency, duty cycle, seasonality and type of source;
   b. fishing gear deployment by type of gear;
   c. vessel traffic by size and type of vessel;
   d. levels of major contaminants based on estimated deposition patterns from point sources, atmospheric and riverine transport, etc.;
   e. indices of water quality, and occurrence of red tides and other ecotoxic events.

2. Estimation of the level of exposure of each population to each stressor based on the distribution of each population by time of year and population component. Mapping of the distribution of marine mammals will typically involve both directly relevant data (e.g., from surveys) and inferences from habitat suitability mapping to cover less well-surveyed areas.

3. Incorporation of direct mortalities into the demographic model in the obvious way (but taking account into account the sex and age composition of the mortality because the different components of a population can be disproportionately affected).

4. Characterization of the responses, both behavioral and physiological, to sublethal threats (singly and in combination), and estimation of dose-response relationships. Where relevant, also determination of the energy cost of responses, in terms of reduced caloric intake and/or increased energy expenditure (e.g., reduced feeding time or efficiency caused by noise disturbance).

5. Integration of the different types of sublethal response into one or more common condition factors, to which demographic parameters can be related.

6. Estimation of the demographic consequences of reduced condition, in terms of the following parameters:
   a. calving/pupping rate;
   b. calf/pup survival;
   c. adult survival; and
   d. age at first reproduction.

Changes in some demographic parameters are easier to detect than others. For example, calving rates can often be measured from direct calf counts or from calving intervals of known mothers. Changes in survival rate are harder to detect, requiring many years of data, but small changes near the threshold of detection can represent the difference between a viable and non-viable population. In general, it is not safe or appropriate to assume that the harder-to-measure parameters will remain constant in the face of variations in the more easily measurable parameters. Use of general life history models to infer relationships between demographic parameters can be explored.

5. Types of data on marine mammal populations

The kinds of data that are or can be collected from marine mammal populations include:
- animal density (from surveys, supplemented with habitat suitability mapping);
- population size and structure (from surveys or from photographic or genetic identification);
- distribution and migration (from surveys and tracking data);
- visible body condition (e.g., degree of emaciation or obvious injury);
- physiological condition from biopsies (e.g., biochemical stress indicators, contaminant levels);
- reproduction (e.g., calving intervals, pup counts);
- mortality (direct observations including necropsies);
- survival rates (from longitudinal studies of individuals); and
- behavioral responses to threats.

Population models can be fit to each of these kinds of data in distinct ways. Because data on most populations are scarce, it is important that population models are able to make full use of the limited data that are available.

6. Population models

The design of population models that address cumulative impacts is to a large extent determined by the following requirements:
- incorporate lethal and sublethal effects in a consistent way, for example through a generalized condition factor;
- assimilate the available population and demographic data of different kinds, and fill data gaps;
- allow for normal demographic stochasticity (especially for small populations) and natural environmental variability;
- integrate multiple sources of uncertainty and express outcomes in probabilistic terms; and
- provide demographic projections for different scenarios of threats and mitigation.

Taken together, these requirements tend to dictate the following characteristics of the models:
- spatially explicit, to allow for incorporation of the spatial distribution of the different threats and population occurrence under various threat and mitigation scenarios to be incorporated;
- seasonally explicit, because migration patterns of most marine mammal populations lead to differential exposure to the various threats during different parts of the lifecycle (feeding, migration, breeding);
- individually-based, to allow for variation in condition of individuals within the population, to make use of data on individuals (for the better-studied populations), and to facilitate incorporation of potential interactions in threat-impact pathways;
- allow for random variation, at both the individual level (demographic stochasticity) and the population level (environmental variability); and
- partly or fully Bayesian, to allow for uncertainty in assumptions and inferred parameters (but with appropriate sensitivity analyses conducted to determine the sensitivity of the conclusions to prior assumptions).

For larger populations, demographically-structured bulk models provide an alternative to individually based models, but can become unwieldy as the number of threat factors and consequent subdivisions of the population into different states of health or vitality increases.

An example of the internal structure of such a model is outlined in Wright et al. (2009). The results of such a model can be expressed in several different ways, depending on the management questions to be addressed, such as:

- population projections under different scenarios of stressor levels and mitigation; and
- estimation of the maximum cumulative impact that would be consistent with population recovery or persistence.

The models can be used to assess the sensitivity and resilience of populations to specific threats or stressors. The sensitivity is the impact on the population, expressed for example in terms of the effect on population growth or decline rate of a unit increase in stressor level. The resilience of the population can be expressed in terms of the predicted recovery time following reduction of a stressor by a specified amount. Along with exposure, sensitivity and resilience are component factors of what is usually referred to as the vulnerability of a population to a specific stressor.

In addition, the models can be used to construct temporal and spatial vulnerability fields for each species with respect to each stressor. For each geographic location and time of year, the local vulnerability to a stressor is a function of the relative occurrence of each population component at that location and time, multiplied by the sensitivity (in terms of demographic impact) of those individuals to a unit change in stressor level. The latter is in turn a function of habitat usage at the given time and place (e.g. feeding, nursing, migration). The constructed vulnerability fields can be used as input into mapping exercises that generate maps of cumulative impact by location and season, and maps of the relative importance of reducing stressors as a function of season and location. This will in turn be an important input into marine spatial planning (MSP) processes.

7. Case studies

The most effective way to develop a population modeling approach for cumulative threats is to start with specific cases. The cases should have the following characteristics:

- individuals are subject to multiple stressors, which in combination threaten the population; and
- data-rich (both in terms of the populations themselves and the stressors they are exposed to).

Based on these criteria the following case studies are recommended:

North Atlantic right whales in the western North Atlantic.
The population is well studied; the majority of individuals are known; photo-id, genetic and other data have been collected for over 20 years; the data time series is long enough to estimate demographic parameters with high precision. The reproductive rate is low and variable. The population is believed to be at a small fraction of historical abundance and is recovering only slowly or not at all. The main known threats are vessel collisions, entanglements in fishing gear, and noise (which has been shown to mask communications relevant to feeding). Food availability may be subject to natural decadal climatic variations producing regular nutritional challenges that reduce reproduction during these periods of lower food availability. This pattern would be exacerbated in some climate change scenarios. A Recovery Plan (last updated 2004) has been drawn up by the US National Marine Fisheries Service (NMFS); it considers all known threats, but does not specify a mechanism for assessing and addressing cumulative impacts.

"Southern resident" killer whales in the eastern North Pacific.
The population has been well-studied for 30 years; all living individuals are believed known, as are most individuals that have died since research began. The reproductive history and parentage of individuals is also known. The population inhabits the inshore waterways of Washington State and southern British Columbia from spring to autumn, and ventures as far as central California in winter.

The social structure and feeding habits are well studied. It appears to be genetically isolated from other killer whale populations. Threats include interactions with commercial shipping, ferries, whale watching, research and recreational vessels (noise, disturbance and collisions); reduction of food resources (Chinook salmon); and contaminants (including PCBs and PBDEs). The population is also potentially vulnerable to major oil spills in its feeding habitat should these occur. A Recovery Plan under the US MMPA and a Recovery Strategy under the Canadian Species at Risk Act (SARA) were each published in 2008.

The anthropogenic stressors that potentially affect each of these populations are listed in Tables 1 and 2 along with the population parameters that are liable to be affected by each stressor.

The results of the two case studies can be both of direct use in the conservation of the studied populations, and also contribute to the development of techniques and impact reduction targets for application to less well studied populations and locations. The success of the case studies will depend critically on the support and contribution of those experts most closely involved in the study and management of these populations.

Further case studies can be added later. The application of these approaches to Arctic species such as bowhead whales and beluga will represent a particular challenge, as we may see not merely incremental changes relative to the previous state of the environment, but a radically new habitat. The retreat of sea ice may open up the Arctic to greatly increased levels of shipping, seismic surveys and industrial activity with associated noise and other impacts.

Stressor	Survivorship	Feeding effectiveness / growth	Calving rate / interval	Distribution changes
Ship Strikes	–	–?	0	0
Whale Watching / Scientists	0	–?	0	0
Entrapment and Entanglement in Fishing Gear	–	–	0	0
Habitat Degradation	0	0	0	-?
Noise	0	–	–?	-?
Contaminants	–?	0	–?	0
Underwater Explosives	–	0	0	0
Climate and Ecosystem Change	+/–	+/–	+/–?	+/–?
Commercial Exploitation	0	0	0	0
Genetic / Inbreeding Effects	–?	0	–?	0

Table 1. Threats facing North Atlantic right whales. Stressors were originally drawn from the Recovery Plan for the North Atlantic Right Whale (NMFS 2005). Table entries reflect initial thoughts about the direction of impact that participants believed to be represented in the literature at the workshop: - = negative effect; + = positive effect; 0 = no significant effect. ? = indicates a limited availability of precise data in this particular population or species, although the participants still believe an effect is likely to be present.

Stressor	Survivorship	Feeding effectiveness / growth	Calving rate / interval	Distribution changes
Overfishing / Habitat (inc. hatcheries)	–	–	–	–
Environmental Contaminants	–	–?	–	0
Whale Watching	–?	–	0	–?
Oil Spills	–	–?	–	–?
Alternative Energy Projects	–?	?	0	?
Disease	–?	?	–?	0
Research	–?	–?	0	0
Social Structure Issues	– (c)	–	–	–
Other Noise	–?	–	–?	–?
Genetic / Inbreeding Effects	–?	0	–?	0

Table 2. Threats facing Southern Resident killer whales. Stressors were originally drawn from the Recovery Plan for Southern Resident Killer Whales (NMFS 2008). Table entries reflect initial thoughts about the direction of impact that participants believed to be represented in the literature at the workshop: - = negative effect; + = positive effect; 0 = no significant effect. ? = indicates a limited availability of precise data in this particular population or species, although the participants still believe an effect is likely to be present. (c) indicates the effect is thought to be primarily a concern for calves.

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A Model of Cumulative Impacts on an Individual Marine Mammal

Andrew J. Wright, Michael Bode, Lisa Loseto, Jose J. Ramasco,
Wayne Munns, Terrence Deak, Kristy Jean Kroeker

1. Introduction

Marine mammal species confront a set of stressors[1] that may be tolerable in isolation, but cumulatively impact population viability (i.e., through effects on survival and reproduction). These stressors range from persistent organic pollutants and bycatch, to recently acknowledged acoustic disturbances. While conservation concerns and regulatory authority are manifested primarily at the population scale, our understanding of the impacts of particular stressors is predominantly described at an individual level – a scale that has proven more amenable to experimentation. An individual-based population model can act as a bridge between our understanding of individuals and our interest in population demographics. A small expert group of workshop participants began to develop a model of the cumulative impacts of anthropogenic activities on individual marine mammals. This model describes various stressors that may affect the survival and reproduction of an individual, focusing particularly on the potential interactions between such stressors. Even at this early, conceptual stage, it could help inform development of more realistic population models for assessing the impacts of multiple stressors on populations, as well as simulate effects of different intervention measures.

2. Model development

The group began this exercise by listing the stressors and impacted biological processes that would eventually become the basic elements of an individual marine mammal cumulative impact model. First, we identified ten serious ***stressors*** marine mammals face (the blue boxes in Fig. 1). Then, we created a list of stressor-associated ***health effects*** to marine mammals for each of these stressors, which included both physiological and behavioral impacts/effects (the health effects for those stressors that remain in the model are listed in Table 1). Next, we grouped the comprehensive list of consequences into nine larger categories that we called ***individual attributes***[2] (the red ovals in Fig. 1). The individual attributes are each representative of a broad health state, function or process within an individual. For example, we considered a ship-strike injury to be a form of "Physical Injury" – a change that makes daily life more difficult in general. A set of other impacts, including acoustic trauma and non-lethal predator attacks, were also grouped under the umbrella, "Physical Injury".[3]

[1] 'Stressor,' as it is used here, is not intended to insinuate that the anthropogenic activity or natural (although anthropogenically altered) challenge is producing a full stress response within the individual. It only indicates that the individual is presented with that particular challenge.

[2] It should be noted that 'Climate Change' and 'Habitat Loss' were originally included in the model as additional stressors, but we realized that these mostly impact marine mammals – and particularly cetaceans, such as our two likely case study populations (see Cooke et al., 2009) – through other mechanisms that were included here (e.g., 'Reduction in Prey Abundance'). They were therefore removed from the list in the interests of simplicity. Similarly, 'Death' was originally included as a consequence of several of the stressors, but was removed as it is instead an end-point for the model and can be thus included in any of the processes or attributes.

[3] We acknowledge that some effects are not included in this model. We have attempted to catch all the major influences, but fully expect the model to develop further as we begin to incorporate numerical values. For example, we have not included any ways that individual attributes might feed back to influence the way that stressors might affect them (e.g., when animals metabolize their fat stores, they may release contaminants locked within those stores into the blood stream, essentially increasing their dosage). Similarly, possible multi-generational impacts are not included in this conceptual model, such as the direct influence of a reduction in time spent parenting, perhaps to increase time available for foraging, on the stress reactivity of an affected offspring. However, in this case, the multi-generational effects go beyond the capabilities of this conceptual model and would need to be included in wider individual-based population models.

After substantial discussion, it was decided that the health impacts of the stressors to be included in the conceptual model would be restricted at this time to readily identifiable changes in the physiology and behavior of marine mammals that have been reported in the literature. Problems with measurement of traditional physiological metrics of the stress response (corticosteroids, catecholamines, heart rate, blood pressure, etc) or attribution of psychological distress in marine mammals mean that such impacts have not been studied in detail to date and therefore these effects do not meet the reported criteria. With this in mind, the focus group recognized the two key components of individual consequences that are not represented in the model below, although we believe that there is enough data available in other species that they could be included through the use of scientifically supported assumptions. First, there are a variety of stress-related pathologies (increased general anxiety, post-traumatic stress, etc) that probably have a significant impact on how future stressors are evaluated by, but that cannot be adequately quantified in, marine mammals. Second, prolonged exposure to substantial stressors is often accompanied by periods of recuperation, during which an organism's behavior is severely disrupted from normal, and that are crucial in driving physiological (and potentially psychological) recovery from prior insults. Though omission of these two factors represents limitations to the conceptual model, it seems imperative to incorporate these concepts in future model development.

Stressor	**Health Effects**
Bycatch	Injury and potentially death.
Contaminants: Hg	Neurotoxic, leading to issues with learning, vision, motor skills. (NOTE: several forms capable of bioaccumulation and biomagnifications rendering high trophic level and long lived species at greater risk)
Contaminants: Non-PBTs*	Disorientation through narcotic effects, liver toxicity and death. (NOTE: include industrial and urban waste such as oil spills, sewage, pharmaceuticals that are typically metabolized by vertebrates yet may compromise food quality and quantity)
Contaminants: PBTs*	Disruption of endocrine (hypothal, thyroid), immune (possibly also growth) and reproductive systems (hormone disruption via xeno-estrogens). (NOTE PBTs are also carcinogenic and might also alter food availability if it makes prey sick. The quality of this food will also be inherently compromised).
Continuous (chronic) sound	Hearing loss (disorientation and possibly injury?), Reduction in energy budget, prey availability and reproduction through masking, obscuring, coping and avoidance. Noise from ships has been both suggested (by acoustical studies) to increase and decrease the risk of ship strikes.
Impulsive / tonal (acute) noise	Increase in harassment and disturbance (including alert & stress response), hearing damage (disorientation and possibly injury), potentially non-aural injury and death. Also displacement from habitat is possible (for them or their prey), which can reduce prey availability. May also increase bycatch
Increased Predation	Increase in harassment and disturbance (including alert & stress response), injury, and death
Pathogens	(Potentially increased as a consequence of climate change.) Decrease in reproduction and energy budget, a compromised immune system, injury, and death
Reduced prey availability	(Including through habitat loss and/or increase competition, perhaps as a result of climate change.) Decrease in energy budget
Ship strike	Injury and potentially death.

Table 1. Stressors and health effects. *PBT = persistent, bioaccumulative, toxic.

The final step was to propose connections between these 19 "nodes" (10 stressors and 9 individual attributes) through a flow diagram. Links drawn with red arrows reflect the immediate or direct consequences of stressors for an individual (see Table 1.). For example, increases in the numbers of predators lead to a heightened risk of harassment or injury to individuals (and also death), prompting red arrows linking the stressor "Increased Predation" with the individual attributes of "Physical Injury" and "Harassment / Disturbance".

Causal links between the various stressors themselves were designated using blue arrows. For example, "Continuous (Chronic) Noise" may lead to an effective reduction in prey availability since it can render hunting more difficult ("Reduction in Prey Availability"). Analogously, causal links between the individual attributes, where impacts on one aspect of an individual's health can, in turn, have important consequences on another, were included using green arrows. For example, "Physical Injury" will likely lead to a reduction in food intake, decreasing an individual's "Energy Budget" (i.e., the energy available to the individual for movement, growth and reproduction, etc.), in the same way, perhaps, as a reduction in prey availability. This conceptual model (Fig. 1) was ultimately presented to all Workshop participants at the meeting. Although it has been revised slightly since, all participants have been able to review the changes.

Participants believe that the model offers a new way to think about the possible combinations of stressors to an individual that can produce synergistic or antagonistic consequences. They also agreed that the model might form the basis of an individual-based cumulative impact model for populations of marine mammals.

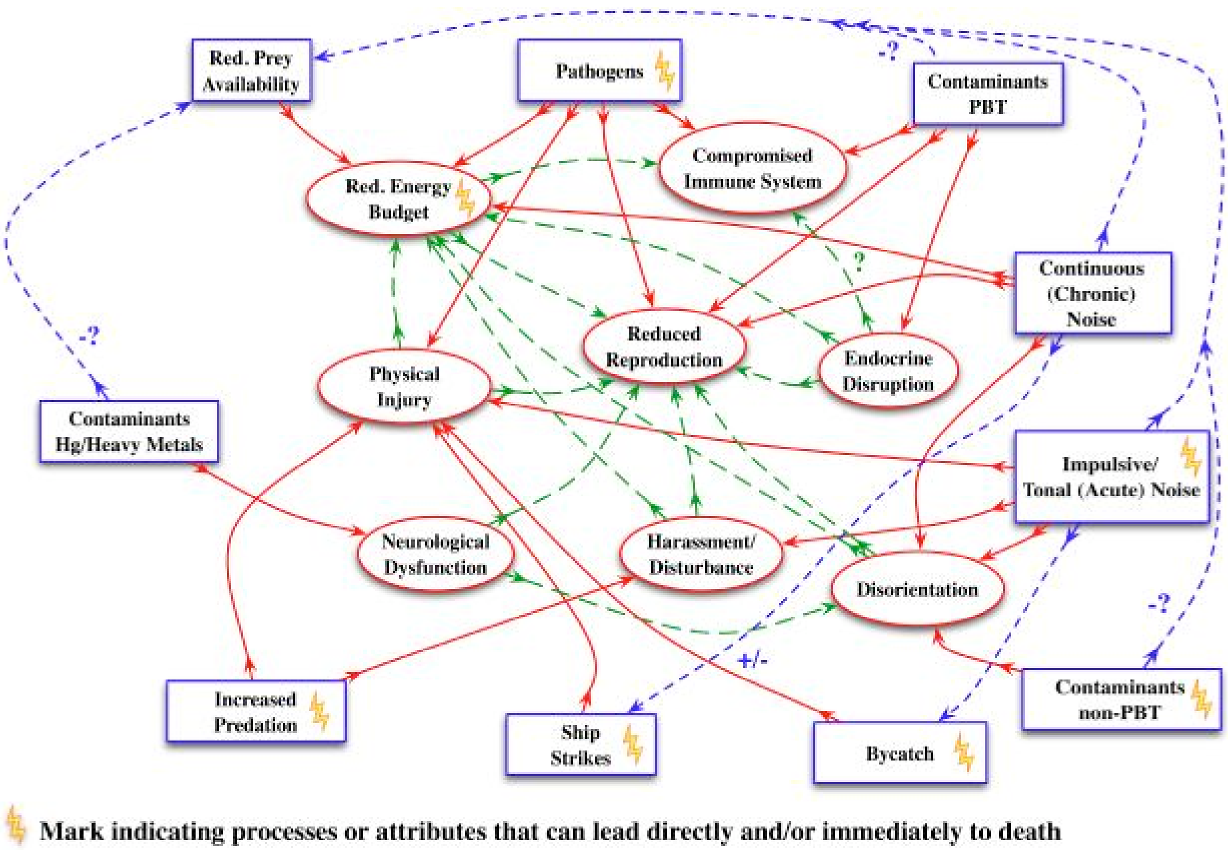

Figure 1. The Cumulative Impacts Conceptual Model

3. Next steps

The original members of the small group would like to develop this model further as follows:

1) The model's nodes (i.e., stressors and individual attributes) and links (i.e., paths of action and interaction) will be revised and refined to improve the model's value as a conceptual tool for the consideration of cumulative impacts.
2) Numerical values (or ranges) will be assigned to all the various model components as far as possible.
3) Expert opinion will be combined with a (species specific) sensitivity analysis to determine at least the appropriate level of magnitude for values to be assigned to outstanding components.
4) The products of this additive model will be compared with the data available on synergistic, additive and antagonistic interactions between stressors, to determine the reliability of the model and to update links as appropriate.
5) The model itself (even conceptually) could then be used by managers to identify probable cumulative impacts as part of their management of multiple stressors to a species or population.
6) The model, if suitably reliable, might become part of the wider effort by Workshop participants to investigate cumulative impacts on certain data-rich case study populations of marine mammals through the development and analysis of an individual-based model. These case studies will then be used to guide policy makers and (potentially) develop more generalized models that can be applied more widely. Such models may need to be focused mostly on determining when cumulative exposures can become problematic for a population due to the lack of available appropriate data for the majority of marine mammal species.

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Okeanos had invited an environmental economist to attend (and present in Session 9, see Abstracts below), but they had to pull out just one month before the workshop. We were not able to find a replacement at such short notice. We did not receive an abstract and so participants were not able to consider such things within their deliberations. Instead, we simply acknowledge that this area may have methodology that could be adapted for application to cumulative impact/effect assessment.

Similarly, Okeanos invited Fisheries and Oceans (DFO), Canada, to send a representative from their regulatory offices, given the discussions of current methods for assessing cumulative impacts and the anticipated focus on the Arctic. Our invitation was ultimately declined.

Presentation Abstracts

1. Introduction

1.1 Including noise in evaluating the cumulative impacts of human activities on marine mammal species: a roadmap to the Okeanos workshop

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Human activities generate sound in the marine environment for explicit purposes (e.g., mapping or exploration), and as an incidental byproduct of industrial activities (e.g., construction or transportation). The legislative basis for most undersea noise regulation in US waters focuses on the protection and recovery of particular species (e.g. the Marine Mammal Protection Act [MMPA] and Endangered Species Act [ESA]). The regulatory processes that implement this legislation (authorization to injure or harass marine mammals and evaluation of noise impacts to endangered species) rely heavily on estimating the number of individuals that will be exposed to specified noise levels. These estimates incorporate knowledge or assumptions regarding the sound source characteristics, propagation conditions, and the location and movements of individual animals. Such analyses face significant challenges in accounting for cumulative impacts to individuals and populations over temporal and spatial scales pertinent to most protected or listed marine animals and many types of underwater noise (Hatch and Fristrup in press). In addition, software packages designed primarily to calculate accrued exposure to focal animals do not reflect relationships between different focal species (such as different whale species), between focal and non-focal species (such as marine mammals and their prey) or other indirect effects of noise exposure resulting from interspecific interactions (*ibid*). Finally, these modeling techniques do not address possible synergism or additive effects experienced by individuals exposed to noise as well as other environmental stressors. Thus, impact assessments based on these analyses are often insufficient to meet mandates imposed by the ESA and MMPA, as well as those of the National Environmental Policy Act which require the National Oceanic and Atmospheric Administration (NOAA) to take into account cumulative impacts to protected or listed species and their habitats when authorizing acoustic harassment and when evaluating noise impacts.

There have been significant efforts over the past five years to develop more comprehensive analytical frameworks for evaluating noise impacts to marine mammals. In 2004, a committee convened by the National Research Council of the US National Academies held a public workshop to discuss methodologies for determining when noise causes biologically significant effects to marine mammals (NRC 2005). Workshop participation helped formulate a conceptual model, called the Population Consequences of Acoustic Disturbance [PCAD] model, to trace acoustic disturbance through the life history of a marine mammal and then to determine the consequences for the population (*ibid*). Also in 2004, the International Whaling Commission Scientific Committee's Workshop on Habitat Degradation developed a general framework for modeling the links between environmental stressors that degrade cetacean habitat (including noise) and population effects (IWC 2006, Figure 3). New analytical methodologies for estimating the cumulative exposure of marine animals to noise have recently been applied to address a variety of mitigation and/or monitoring contexts (see Erbe & King 2009, Clark et al. in press, NOAA 2009).

Recommendations to expand analytical frameworks to better assess cumulative noise impacts have often stressed the need for management frameworks to expand in parallel. The concept of Potential Biological Removal (PBR) (Taylor et al. 2000) as developed by scientists at NOAA Fisheries, and the concept of the revised management procedure (RMS) (Cooke 1994) as developed by scientists associated with the International Whaling Commission both provide methods for integrating scientific uncertainty into marine mammal management decisions. To apply the PBR concept to address cumulative impacts to populations and species more effectively, the 2005 NRC committee recommended including all sources of mortality, injury and behavioral disturbance (including noise) in threshold determinations, rather than focusing on fishing-associated impacts in isolation (NRC 2005). Similar recommendations have been made to ensure that RMS threshold extraction levels remain conservative in the face of significant uncertainty resulting from complex multi-stressor and multi-species interactions (IWC 2006).

Finally, area-based management tools have been suggested for the purpose of assessing and addressing human-induced underwater noise more holistically in places designated to be of national concern (Hatch and Fristrup in press). By focusing on management of all living and non-living resources within a local area, marine protected areas (MPAs), such as US National Marine Sanctuaries, can serve as "sentinel sites" for evaluating acoustic impacts on an ecosystem rather than species-specific basis. As many nations consider an expanded role for marine spatial planning to address increasing urbanization in coastal and outer shelf waters, MPAs are poised to play a valuable role in developing tools to evaluate the impacts of noise and other human-induced stressors within a diversity of local marine environments.

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2. Marine mammals and noise: A review of available information on impacts of noise on marine mammals

2.1 An overview of the importance of sound for marine mammals and the variety of anthropogenic underwater noise sources

Lindy Weilgart

Marine mammals, particularly cetaceans (dolphins, porpoises, and whales), use sound for all aspects of their life, including reproduction, feeding, communication, navigation, hazard avoidance, and otherwise sensing their environment. Hearing is their primary sense, as sound travels very efficiently underwater (hundreds of kilometers), whereas vision is limited to only tens of meters. Some cetaceans use active biosonar, emitting sound pulses to "see" with sound, but all marine mammals probably depend to a large degree on listening (passive detection) for the sounds their prey, predators, conspecifics, and environment make. Sometimes sounds of great importance can be very faint, so that even small increases in underwater noise can make the difference between detecting a predator, prey, or navigational hazard in time, or not. Some cetaceans are primarily solitary and widely scattered. In blue and fin whales, for instance, females probably must rely on finding mates by the loud, low frequency sounds males make. Such calls can theoretically travel almost across ocean basins, at least in the absence of appreciable human-made noise. Cetacean vocalizations are thought to be used for purposes such as to coordinate movements and maintain contact between group members, to repel mating competitors and attract mates, to identify group membership, etc. Mating songs probably also allow females to assess the quality of potential mates. Echoes from the ice may help whales found in polar waters navigate through open leads safely. Similarly, whales likely use acoustic cues, such as echoes from ocean bottom features or surf noise, to find their way during long migrations. It is unknown to what degree sound quality is important, or whether in some circumstances it is enough merely to detect the presence or absence of a sound. Undoubtedly, though, some information which may be critical, is lost in conditions of higher underwater noise. Thus, it is safe to assume that anthropogenic ocean noise is a threat to marine mammals, especially cetaceans.

Manmade underwater noise is principally caused by shipping, seismic surveys by the petroleum industry to find undersea deposits of oil and gas, and naval sonar. Other sources include underwater explosions, construction, drilling, pile driving, icebreakers, oceanographic experiments, acoustic harassment devices (e.g. to repel seals from aquaculture facilities), and recreational boating. These noise sources vary in characteristics such as loudness, pitch, duration, rise times, directionality, duty cycle, etc. Cetaceans also vary in how they react to even the same noise source, depending on the species, age, sex, prior experience, and context. Noise impacts may be long- or short-term, and could primarily affect the individual or population, although these distinctions are very difficult to discern in cetaceans, given how little is known of most populations. Acute noise impacts are those where noise exposure quickly results in fatal strandings or deaths at sea, or immediate hearing damage. Chronic noise impacts include "masking" or the obscuring of important signals, such as from the incessant hum of shipping traffic. Hearing damage may also occur from chronic underwater noise. Both acute and chronic impacts can be serious, and can cause population-level effects.

2.2 The potential impacts from chronic noise and methods for measuring the potential long-term impacts from multiple non-pulsed sources, including assessment of variability in noise fields over space and time

Christopher W. Clark

In the domain of marine mammals, this topic, although seemingly intuitive and obvious, is not well defined or constrained by standard terminology, methodologies, or knowledge. There is little to no precedent as to the scientific processes for quantifying and evaluating "potential impacts from chronic noise." Therefore, such discussions often begin with an imbalance of attitudes. expectations, and expertise, and, most importantly, a lack of consensus as to a way forward. Notice that the word potential has been inserted to qualify the word impacts. Recognize that there is no clear scientific definition of "non-pulsed sources." Understand that measuring and mapping noise over scales appropriate for marine mammals is extraordinarily difficult and has rarely been attempted. Accept the fact that many of you reading this do not have hands-on experience studying whales or measuring sound underwater. Thus, it is important to set one's frame of mind with a fair amount of cognitive flexibility and begin with as much of an open mind as possible when it comes to thinking about chronic noise and marine mammals. We are at the beginning of a journey with only a rather crude map and without necessarily a consensus as to where exactly we're going, why we're going there, how we're going to get there and what we're going to find once we arrive. But the river is flowing, we're in it and so we must prepare for what is happening and for what lies ahead.

In this presentation I will focus on the issue of "potential impacts from chronic noise" as it relates to free-ranging, baleen whales because I believe this is the group likely at greatest potential risk from chronic exposure from anthropogenic sound. My working mode is to use the biology of the animals to set specifications and to constrain uncertainty. At the same time I try to establish a paradigm and an algorithm that can be applied to other groups of marine mammals. Baleen whales are extraordinarily well adapted for listening to and producing sounds in the low-frequency band (<1000Hz). Therefore the spatial and temporal scales of concern are as great as many tens of thousands of square miles and many decades. "Non-pulsed sources" are those sources that generate sound for at least as long as the whales' own sounds (e.g., 1-2 s) or the sounds of biological importance (e.g., predators, ocean upwelling).

One of the most likely chronic impacts from noise, and the one I will focus on here, is that of acoustic masking of communication sounds, first articulated by Roger Payne and Doug Webb in 1971 for blue and fin whales. Communication masking is the loss of communication space as a result of sound added to the ambient noise environment. Communication space is the space over which animals communicate, and the communication masking metric is referenced to the communication space under ocean noise conditions prior to human activities that generate noise in the ocean, referred to as ancient ambient. Vessel noise is the primary anthropogenic source of sound added to the ocean's low-frequency environment, but other sources include those from such things as seismic exploration, construction and active sonars.

Here I present a model, informed by empirical data, to quantify the effect of vessel noise on acoustic communication space for three species of baleen whales: fin, humpback and right whales. Acoustic data are from long-term acoustic monitoring systems sampling the low-frequency band throughout ocean areas of 400 – 10,000 nmi2 for periods of months to years. Resultant acoustic data were analyzed to map, quantify and describe the spatio-temporal variability of the acoustic habitat over ecologically meaningful scales for the three species. Species-specific 3rd octave frequency bands were used for right whale contact calls and fin and humpback whale songs. Ship GIS movements and source characteristics were documented using the U.S. Coast Guard's Automatic Information System (AIS) and seafloor acoustic recorders, respectively. Results quantify the extent to which multiple sources of sound in the ocean cumulatively influence the ambient noise environment throughout an area within which and over time periods when whales are known to be acoustically active. By this procedure, we define acoustic communication space as part of both an individual animal's and a population's ecological habitat. By altering this communication space, anthropogenic activities have the potential to impact such basic biological activities as mating, foraging, or migrating. In some habitats with high levels of vessel noise, the predicted area over which animals can communicate is routinely reduced to a small proportion (< 20%) of what it would be under ancient ambient conditions. When considered from a large-scale and behavioral ecology perspective, reduction in acoustic habitat, as measured in terms of the proportional loss of communication space, likely represents a significant cost for species to which acoustic communication is biological critical.

2.3 Acute impacts of noise and a summary of methods currently applied to sum impacts from repeated exposure to impulsive sources

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Decibels are the standard shorthand for describing acoustic intensity and sound pressure level, but may lead to misunderstanding when applied as bioacoustic metrics. Acoustic power and source transmission energy are alternate metrics with intuitive appeal. Acoustic power, calculated from the acoustic intensity, multiplied by the emitted solid angle, yields units of Watts. Likewise, the energy per source transmission, given by multiplying acoustic power by the duration of the transmission, yields units of Joules. For continuous (or quasi-continuous) signals, the standard procedure is to measure the root-mean-square (RMS) of the signal. However, this presents problems for short duration (impulsive) signals where the duration of the signal being measured is an important parameter. In these cases it may be more appropriate to measure the peak-to-peak signal, rather than RMS. Bandwidth is another important component of how the signal is described, typically in a narrow-band for ambient noise and broad-band for discrete sources. The characteristics of acute anthropogenic noise sources in terms of these metrics will be discussed.

3. Interactions of noise and other threats to marine mammals

3.1 Cumulative and synergistic impacts of natural and anthropogenic stressors: lessons from the lab

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All species face a diverse range of threats that stem from their ecological niche. These threats most commonly arise in the form of natural stressors such as predator exposure, food/nutrient deprivation, social stress associated with the development and/or maintenance of social hierarchies and territoriality. For the most part, species-specific and threat-specific strategies have evolved at both the physiological and behavioral level to minimize the impact of these natural threats, thereby optimizing survival and reproduction. Industrialization of human society over the past 200 years, however, has brought forth an entirely new set of threats, referred to as anthropogenic stressors, which expand both the quantity and quality of challenges that wildlife face in their daily life. Examples of some anthropogenic stressors include (but are not limited to) extreme noise and vibration, habitat destruction and the accompanying loss of food/shelter, exposure to chemical pollutants, toxins and toxicants. The influence of anthropogenic stressors is felt by all species, yet nowhere are these effects more prominent than in marine mammals. Though there is some agreement that the uptick in anthropogenic stressors has led to rapid and deliberate adaptation among affected species, the cumulative and synergistic impact of chronic stress exposure (arising from both natural and anthropogenic sources) on the physiology and behavior of wildlife can be difficult, if not impossible, to predict.

Recent advances in stress physiology may provide significant insight into the expected outcomes of anthropogenic stressors. The two main stress responsive systems are the sympathetic nervous system (SNS) and the Hypothalamic-Pituitary-Adrenal (HPA) axis. These classic stress-responsive systems have been highly conserved across vertebrate species and in many ways represent a general response to nearly all threats. More recent advances suggest that activation of inflammatory signaling pathways in response to stress challenges play a key role in orchestration of the stress response, and provide a crucial link between stressor exposure and the development of stress-related pathology. Importantly, stress-dependent activation of inflammatory signaling pathways (i) occurs across a wide range of endocrine glands and bodily organs; (ii) does not depend on the presence of any apparent antigen or infection; and (iii) may occur as a final point of convergence for intense, or categorically distinct, stress challenges. These findings may implicate inflammatory signaling factors as more appropriate biomarkers for stress-related pathology (than the classic stress responsive systems), and identify inflammation as a potential target for ameliorating adverse health consequences of stressor exposure. Given the role that inflammatory signaling pathways play coordination of host immune responses to pathogens (bacteria, viruses, parasites, etc) and foreign antigens (chemical toxicants, pullutants, etc), the likelihood of synergistic – or competitive – interactions between true immunological challenges and psychological threats abound. Indeed, such interactions are well-precedented in the biomedical literature, yet the form of such interactions (sensitization, cross-sensitization, etc) remain difficult to predict. In this talk, we will provide a theoretical framework that may be useful for predicting adverse consequences of stress.

3.2 Multi-stressor interactions in the Arctic

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Arctic marine mammals have adapted to a marine environment in which sea ice dominates the seascape and its food web. Some Arctic marine mammals are ice-obligate and require sea ice for survival (e.g. ringed seals), while others feed in the seasonal productive ice-edge zones. In this way, the climate change-related loss of sea ice poses a real and dramatic risk to such marine mammals. Change in sea ice dynamics will directly impact marine mammals by altering their habitat, as well as have indirect effects to food web productivity that may alter prey quality and quantity. A reduction in sea ice will also have a multitude of indirect impacts on other stressors that already exist in the Arctic marine environment. Arctic marine mammals have been exposed to environmental contaminants and disturbance related to human/industrial activities in the Arctic and elsewhere. Although the Arctic is far removed from industrial and urban pollution typical of mid latitudes; contaminant levels in Arctic marine mammals are relatively high due to the ability of some contaminants to undergo long range transport. Of particular concern are persistent organic pollutants (POPs) that include the endocrine-disrupting PCBs, and the metal mercury, a neurotoxin. Local sources of contaminants such as hydrocarbons may soon become a concern with increased industrial activity in the north. The opening of the Northwest Passage will attract shipping vessels as it offers a shorter route between the Atlantic and Pacific than through the Panama Canal. This will increase noise and disturbance in the water column, and may cause habitat displacement if (when) ice breakers are used. Shipping activity will also increase with the oil and gas exploration, development and advancement throughout the North. Oil and gas exploration techniques employ acoustic means, specifically seismic exploration (e.g. dynamite, air guns) to locate hydrocarbon sources. Given the anticipated increase in demand of oil and gas, and the increased accessibility to the Arctic, there is little doubt that the Arctic will become busier, noisier, and more contaminated. The extent to which these stressors represent a real threat to Arctic marine mammal populations will depend in large on our ability to understand habitat needs in a changing world. Human/industrial activity, climate change and contaminant exposure have synergies in occurrence and prevalence, we will present the current knowledge on them and evaluate their impacts on Arctic marine mammal health.

3.3 Ocean acidification and the increasing transparency of the ocean to low frequency sound

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pH dependent species involving dissolved borate and carbonate ions affect the absorption of sound in seawater so that as the ocean becomes more acidic it becomes more transparent to low frequency (~10 kHz and below) sound. The effect is quite large; a decline in pH of only 0.3 causes a 40% decrease in the intrinsic sound absorption coefficient (α, dB/km). The fossil fuel CO_2 invasion of the ocean is now lowering pH, and reasonable projections based upon conservative IPCC scenarios show that an anthropogenic change in surface ocean pH of -0.3 will likely occur by mid-century. Since acoustic properties are measured on a logarithmic scale then, neglecting other losses, sound at frequencies important for marine mammals and for naval and industrial interests will travel some 70% further than today. The military and environmental consequences of these changes have yet to be fully evaluated.

The physical basis for this effect is well known: if a sound wave encounters a molecule such as borate ion that can be "squeezed" into a lower volume state a resonance can occur so that sound energy is lost and the molecule then returns to its normal state. Ocean acousticians recognized this pH-sound linkage in the early 1970s but connection to global change and environmental science is in its infancy. Changes in pH in the deep sound channel will be large due to the combination of the fossil fuel CO_2 invasion, and additional change from decreasing O_2/rising respiratory CO_2 from physical climate change, and the acoustic consequences may be felt over thousands of miles.

It is important to recognize that the intrinsic chemical effect described here is a very small component of overall sound loss in the ocean, and that losses from physical scattering and absorption at the ocean surface and sea floor far exceed these terms. The pH effect is significant only at long range, and sound intensity drops off very quickly with distance.

For approximate scale in the 57 Hz antipodal sound transmission of the Heard Island experiment the volume attenuation over 18-Mm (megameters) is 5 dB for the Atlantic and 3 db for the Pacific with its lower pH. Nonetheless it is these terms that are changing due to mankind's activities while other terms remain constant. The effect is significant at low frequencies and the ubiquitous anthropogenic 60Hz and 50Hz signals clearly fall into this category.

This effect may be both troubling and useful, and wisdom will be called for in addressing these issues. Marine animals at mid-water depths now face a basic challenge to life from declining O_2 and rising CO_2 levels, much as would humans in a submarine or space craft. Models predict a very large expansion of ocean dead zones at depths which correlate well with the sound channel. Thus the ocean sound channel will increasingly become a depth zone depleted in marine life with its associated bio-acoustic properties, and increasingly chemically transparent to sound. There are few ways to efficiently document such changes taking place over large length scales and alert a skeptical world. Long range acoustic probing of ocean sound absorption offers one uniquely integrative approach and recent work shows that this is very possible.

4. Noise in cumulative impact assessment: Political frameworks and legal standards and tools

4.1 Noise in cumulative impact assessments for NMFS ESA species/populations: regulatory mandates and methods used in ESA Biological Opinions, with ideas for improvements

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The U.S. Endangered Species Act of 1973 (as amended) is one of the two primary authorities available to the U.S. government for protecting marine mammals from the adverse effects of human activities. Specifically, section 7(a)(2) of the Endangered Species Act of 1973 (ESA) requires every agency of the U.S. government, with very few exceptions, to insure that any action they authorize, fund or otherwise carry out is not likely to jeopardize the continued existence of any listed species or result in the destruction or adverse modification of critical habitat that has been designated for those species. To comply with this section of the ESA, Federal agencies must "consult" with the National Marine Fisheries Service and the Fish and Wildlife Service (the Services) on actions that may affect threatened or endangered species marine mammals or critical habitat that has been designated for those species.

As a result of this legal requirement, NMFS personnel consult with the U.S. Navy on its training activities; with the Minerals Management Service on oil and gas leasing and seismic exploration on the Outer Continental Shelf of the U.S.; with the National Science Foundation on seismic surveys they fund; with the U.S. Department of Transportation on construction projects that involve pile-driving; among many other categories and kinds of activities. Although the assessment framework NMFS uses to conduct these consultations does not separately consider "cumulative impacts" of these activities (as that term is usually construed for impact assessments), NMFS personnel are required to consider accumulations of effects, interactions, synergisms, and antagonistic effects in their assessments.

NMFS begins its assessments by identifying the physical, chemical, and biotic stressors that would be associated with an action. NMFS personnel then estimate the number of exposure events that are likely to involve endangered or threatened species and designated critical habitat and the circumstances of that exposure. NMFS personnel then assess the probable responses of endangered or threatened individuals to a single exposure event or a series of exposure events, given their exposure to the same or other stressors prior to or contemporaneous with a particular exposure event. NMFS then assessing the probable consequences of those responses on the expected lifetime reproductive success (the current and expected future reproductive success) of the individuals that are expected to be exposed to one or more stressor. If NMFS personnel conclude that one or more individuals are likely to experience reductions in reproductive success, they then assess the probable consequences of those reductions on the viability of the population(s) those individuals represent and conclude by assessing the consequences of any reductions in the viability of one or more populations on the "species" those populations comprise (the ESA defines "species" to include taxonomic species, sub-species, and distinct population segments of vertebrate species). See the attached background document for more detail on this assessment framework and its treatment of cumulative impacts.

NMFS personnel face several obstacles when they try to use this framework to assess the cumulative impacts of anthropogenic noise and other stressors on endangered or threatened marine mammals. The most important obstacle results from the limited number of studies of whether free-ranging animals respond differently to exposure events involving a single stressor versus exposure events involving multiple stressors and, if so, the differences in those responses. Although the concept of canonical cost proposed by McNamara and Houston (1986), which are reductions in an animal's expected future reproductive success that would occur when an animal engages in suboptimal behavioral acts, provides a currency for assessing cumulative impacts of anthropogenic noise and other stressors on endangered or threatened marine mammals, attempts to convert this concept into a method that can be used to estimate future effects remain elusive.

4.2 Noise in Cumulative impact assessments for NMFS MMPA species/populations: regulatory mandates and methods used in addressing threats to marine mammals, with ideas for improvements

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The U.S. Marine Mammal Protection Act of 1972 (as amended; MMPA) is one of the two primary authorities available to the U.S. government for protecting marine mammals from the adverse effects of human activities. Specifically, the MMPA prohibits the "take" of marine mammals or those activities that "harass, hunt, capture, or kill or attempt to harass, hunt, capture or kill a marine mammal." However, in several specific circumstances, NMFS can authorize the "take" of marine mammals in one of two ways: by issuing a permit for scientific research and enhancement or by issuing an authorization if the "take" is incidental to activities that would be legal in other respects.

To issue an authorization for incidental "take" of marine mammals, NMFS must make certain that (1) the total "take" will have a negligible impact on the species or stock of marine mammal and (2) will not have an unmitigable adverse impact on their availability for subsistence uses. Authorization and permits NMFS issues identify permissible methods of "take" and means of effecting the least adverse impact practicable on marine mammals and their habitat and specifies monitoring and reporting measures that recipients of these authorization or permits must satisfy.

The framework NMFS uses to assess the effects of MMPA authorizations or permits do not specifically consider the cumulative impacts of activities covered in authorizations or permits. However, NMFS must satisfy the requirements of the U.S. National Environmental Policy Act before it can issue MMPA authorizations or permits, which require explicitly require NMFS to consider the cumulative impacts of any "take" it authorizes. Those cumulative impact analyses are constrained by the limited scientific information available on the effects of interactions, synergisms, and antagonisms among the various physical, chemical, and biotic stressors and stress regimes found in the environment of free-ranging marine mammals.

4.3 Assessing cumulative impact and risk – approaches at the U.S. Environmental Protection Agency[1]

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The U.S. Environmental Protection Agency (EPA) has a mission and regulatory mandate to protect human health and the environment. EPA's primary role is to implement environmental laws by developing and enforcing national regulation. Cogent to the goals of this workshop, key environmental laws that EPA administers include the Clean Water Act, the Clean Air Act, and the

[1] This abstract has not been subjected to Agency-level review, and therefore do not necessary reflect the views of the U.S. EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Marine Protection, Research and Sanctuaries Act.[2,3] EPA also has a unique responsibility in the National Environmental Policy Act (NEPA) process, in that under the Clean Air Act, it is required to review and publicly comment on the environmental impacts of major federal actions. EPA's regulatory mission is supported by the research conducted by its Office of Research and Development.

In the late 1980s and early 1990s, EPA regulatory programs began adopting risk assessment as a primary decision informing tool for evaluating the potential impacts of anthropogenic stressors on humans and the environment. Ecological risk assessment is a process for evaluating the likelihood that adverse ecological effects will occur or are occurring as a result of exposure to one or more stressors (U.S. EPA 1992, 1998). It is intended to be a general, organizing process for science-based evaluations of the environmental consequences of human activity. Its concepts and approaches can be applied to problems involving any environmental stressor and the attributes of any species, community, or ecological system or process (the "assessment endpoint" in risk assessment parlance). As practiced historically by EPA (see Suter et al. 2003 for a history of ecological risk assessment), however, ecological risk assessment has been used for regulatory purposes primarily to inform decisions pertaining to the management of chemicals, and usually for single chemicals in isolation or classes of chemicals that act similarly. Further, the majority of past ecological risk assessments have focused on survival, reproduction or individual growth of organisms as their primary measures of effect. Such practices served EPA well in informing the actions that led to control of overt problems of chemical pollution.

Environmental policy and management goals in EPA regulatory programs are evolving. Ecological emphasis is shifting toward protection of populations, habitats, and whole ecosystems in the context of multiple stressors and their cumulative impacts. Parallel evolution is occurring with respect to human health risks. With these changes comes the need for more sophisticated risk assessment planning and methods, ones that can account for environmental complexity and realistic context more effectively than can single-stressor, single-endpoint approaches. Assessments that consider the cumulative risks of multiple stressors provide the arrays of information needed to support the objectives of regulatory, resource management and conservation more comprehensively than do traditional single-stressor impact and risk assessments.

Many specific definitions of *cumulative impact or risk assessment* exist, but all reflect the notion of explicitly considering the aggregate impacts of multiple important agents or stressors on the endpoint or receptor of concern through time. In 2003, EPA released its *Framework for Cumulative Risk Assessment* (U.S. EPA 2003) to articulate an analytic-deliberative process and considerations for performing cumulative risk assessments (CRA) within the Agency. As with EPA's *Framework for Ecological Risk Assessment* (U.S. EPA 1992) before it, this process is intended to be applicable to broad array of environmental problems, and informative to a variety of environmental decisions, including those associated with NEPA. The basic steps of CRA (mirroring those of ecological risk assessment) are: 1) Planning, Scoping and Problem Formulation, within which the risk problem is defined and the assessment is planned; 2) Analysis, primarily an analytic process evaluating the risk problem at hand; and 3) Interpretation and Risk Characterization, focused on integration and interpretation of the results of the Analysis phase. Although CRA as framed by the *Framework* is oriented primarily toward human risk, its approach and considerations can serve as models for

[2] Although EPA has responsibilities under the Endangered Species Act, management of that Act is primarily the responsibility of the U.S. Fish and Wildlife Service.

[3] EPA, under the Noise Control Act of 1972, had promulgated regulations that set maximum noise limits on a number of household, industrial and vehicular sources to protect against adverse effects on humans. However, primary responsibility for regulating noise was shifted to state and local governments in the early 1980s. Although the Noise Control Act and the Quiet Communities Act of 1978 were not rescinded by Congress and remain in effect today, they essentially are unfunded.

assessing cumulative risk to nonhuman receptors and populations, including marine mammals. EPA has begun a process of developing more explicit guidance for performing cumulative risk assessments, which is intended to be vetted and released in the near future.

Importantly, the CRA *Framework* identifies a number of research and development needs that address gaps in the knowledge and methodology required to perform CRA effectively. Included are methods for understanding the timing of exposure to stressors and its relationship to effects, methods for understanding how multiple stressors and their mechanisms of effect interact to result in risk, and methods for combining different types of risk. Such deficiencies in the science supporting CRA surely will affect our ability to assess the cumulative risk of noise and other stressors to marine mammal populations. However, because protection of populations necessarily requires appreciation of the contributions of multiple stressors to risk, increasing emphasis by EPA's Office of Research and Development and other organizations on development of tools to assess population-level risk to wildlife and aquatic life (e.g., U.S. EPA 2004, Munns 2004; also see Barnthouse et al. 2007) should continue to address these deficiencies.

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4.4 Assessing and managing noise in National Parks: lessons for metric and threshold design

Kurt Fristrup

The U. S. National Park System derives its resource management authority from legislation with forceful conservation priorities. The purpose of NPS is "to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations (Organic Act of 1916, P. L. 64-235)." This conservation mandate was reinforced by subsequent legislation (General Authorities Act of 1976, P. L. 94-458; The Redwoods Act of 1978, P. L 95-250). NPS management is founded on the principle that conservation will predominate when there is a conflict between resource protection and visitor use (NPS Management Policies, "MP2006").

The Grand Canyon National Park Enlargement Act of 1975 (P. L. 93-620) explicitly recognized "natural quiet as a value or resource in its own right to be protected from significant adverse effect." In addition, the Wilderness Act of 1964 (P. L. 88-577) calls for the enduring preservation of areas with "a community of life untrammeled by man" and "outstanding opportunities for solitude." Accordingly, MP2006 states that unreasonable interference with the "the atmosphere of peace and tranquility, or the natural soundscape maintained in wilderness and natural, historic, or commemorative locations within the park" constitutes an unacceptable impact. The acoustical environment is protected as a physical resource, like water and air quality. It is also protected due to its value for ecosystem function and visitor experience. "The natural ambient sound level—that is, the environment of sound that exists in the absence of human-caused noise—is the baseline condition, and the standard against which current conditions in a soundscape will be measured and evaluated (MP2006, 8.2.3)."

NPS uses three metrics that reference natural ambient levels: audibility to attentive human listeners, loss of alerting distance, and loss of listening area. The latter two metrics distinguish between conditions in which hearing serves to warn animals of hazards or to cue them to opportunities (e. g. the footfalls of potential predators or prey, respectively). Metrics that document changes in the physical environment, without reference to animal hearing systems, are in development.

NPS marine resources include more than 12,000 km2 of ocean and Great Lakes waters and 8,000 km of shoreline. Glacier Bay NP has monitored noise from cruise ship vessels for several years, and is in the process of developing underwater noise management standards. However, national protocols for underwater acoustical monitoring and noise management have not been established.

NPS efforts to preserve outstanding acoustical conditions have been persistently opposed by other U. S. agencies that have decades of practice managing noise in relation to hearing loss, interference with conversational speech, interruption of sleep, and annoyance. These acute impacts should be rare in national park units, but they are thresholds that must be routinely exceeded before other agencies consider management action. Concerns about precedents, defense of past practices, preservation of established routines: all of these present substantial obstacles to acknowledging affirmative obligations to protect acoustical resources.

5. Quantification of cumulative exposure

5.1 Spatio-temporal aspects of threats in the Arctic relative to marine mammal habitat and distribution

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The Arctic is changing rapidly. The most visible change in the marine environment is the dramatic reduction in the extent of sea ice during the summer. Other environmental changes are also occurring, such as decreased amount of multi-year ice, changes in phenology, and increased coastal erosion. The biological environment is also changing. For example, marine mammals rarely seen in the Arctic are occurring there more regularly. There are likely many other changes of which we are not aware. The reduction in sea ice coverage, thinner sea ice, increased cost of oil, and greater human interest in the Arctic have resulted in plans for increased human activity. That activity includes: oil and gas exploration and development, mining, commercial shipping, science (including mapping of continental shelves), tourism, fishing, and military activities.

My knowledge and experience are mostly focused on the Beaufort and Chukchi seas, adjacent to Alaska, but I also provide a less thorough overview of human activities in other portions of the Arctic.

Russia is looking to the Arctic for its "socio-economic stability and security". There are several main components to their interest in the Arctic, to develop and transport hydrocarbon resources and commercial shipping through the Northern Sea Route. Mining for metals and coal is also underway. It is likely that Russia will also rebuild their military presence and capability in the Arctic. Norway is developing natural gas fields in the Barents Sea and continues commercial fishing. Greenland is involved in mining, especially for rare metals, exploration for hydrocarbons, and commercial fishing. In Canada, there is increased interest in mining and exploration and development for oil and gas, especially in eastern Beaufort Sea. Commercial shipping through the Northwest Passage is also a possibility. Science and tourism are also increasing. In the U.S. Arctic, Alaska is experiencing increased oil and gas exploration and development, mining, science, and tourism. Shipping and commercial fishing are also activities for which planning is underway.

The timing of these human activities varies. Seismic exploration in offshore areas occurs primarily during the open water months of summer, while exploratory drilling and development can occur throughout the year. Transport of materials from mining operations, science, tourism, and commercial fishing occurs primarily during summer.

The diversity of marine mammals in the Arctic is relatively low. Key species of cetaceans include bowhead, gray, beluga whales and narwhals. Key species of pinnipeds include: bearded, ringed, hooded, ribbon, and harp seals. Some of these species occur in the Arctic primarily in the summer months while others are present year round. There are potential direct impacts to marine mammals from greater levels of anthropogenic sounds, oil spills, ship strikes, and commercial fishing. There are also potential impacts to other marine organisms, habitats, and to the people that live in the Arctic. Understanding the direct impacts from one industrial operation or one activity has many challenges. The Arctic is a difficult place to work. Additionally, there is limited baseline information in many cases. Understanding direct and indirect cumulative impacts is exceedingly difficult yet becoming more important as the environment changes and as human activities increase. Separating impacts from environmental change versus anthropogenic activities will be especially difficult. Additional data are needed on how marine mammals use arctic environments, their population sizes for many species, and habitat models at various scales. Models are needed to predict impacts from both a changing environment and increasing human activities.

5.2 Worldwide threats to marine mammals, ranked in significance and considered in relation to distribution, exposure, and overlap with noise

Randall R. Reeves

Perceptions of threats to marine mammals have changed markedly since the late 1960s and early 1970s, when direct and deliberate off-take[1] (by whaling, sealing, etc.) was by far the principal concern. As the commercial exploitation of seals and whales was scaled down in response to international protest campaigns and policy changes, the emphasis shifted during the 1980s toward incidental removals in fisheries ("bycatch") (Hofman, 1995), which is still widely regarded as the greatest immediate threat to many species and populations (Read, 2008). An extreme imbalance has existed, and continues to exist, between the extent to which threats (individual, much less cumulative) are investigated, understood, and addressed in North America-Europe-Australia-New Zealand vs. in the rest of the world. Recent extinction of the baiji is clear evidence, although the ongoing decline of monk seals in southern Europe and Hawaii should be borne in mind.

In attempting to rank "significance" of various threats,[2] the following criteria are proposed as potentially relevant: (1) degree of certainty regarding cause and effect, (2) immediacy, (3) severity (e.g., in terms of lethal vs. sublethal, acute vs. chronic, and the conservation status of affected taxa

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[1] Here meant to include most removals from the wild.

[2] In the present context, a threat is to the persistence of the species or population, not necessarily to the survival or welfare of the individual marine mammal.

[critically endangered, common and widespread, etc.]), (4) reach of the threat (i.e., how widespread or geographically extensive it is), (5) spatial range of species or populations affected, and (6) feasibility of mitigation[3]. Threats to marine mammal species and populations at the global level include, in addition to off-take: toxic contamination (which may affect the animals themselves or their food, or both; this threat includes biotoxins, petroleum products, and a variety of manmade toxins); disease; effects of small population size; death or serious injury from vessel strikes; reduction of or damage to the food base (e.g., due to fishing or other perturbation); and disturbance caused by noise [e.g., seismic profiling, shipping, military sonar], chasing, or spatial displacement [e.g., by aquaculture facilities, windfarms, port development, intensive harbor usage]. Unlike terrestrial organisms and some other groups of marine animals, the marine mammals are not generally threatened by invasive species[4] or habitat fragmentation, degradation, and loss, although habitat alteration is a major threat to manatees, seals, and dolphins living in running freshwater systems, estuaries, and very near-shore marine waters (e.g., Reeves et al., 2000; Smith and Jefferson, 2002).

Some threats, such as ocean acidification and climate change, are pervasive, insidious, complex, and difficult to characterize, quantify, or track in relation to individual species or species groups. Their effects are often indirect. For example, climate change will likely “alter the exposure levels of marine mammals to a variety of toxicants through … changes in distribution of harmful algal blooms…, changes in long-range atmospheric and oceanographic transport (including interactions with sea ice), biotransport, changes in feeding ecology, increased and altered runoff, and increased human involvement in the Arctic” (Burek et al. 2008, p. S130). The aggregate negative effects of climate change could ultimately dwarf those of all other threats, combined, on some species (e.g., polar bear, walrus, ice seals, arid-region river dolphins).

The recent attempt by Schipper et al. (2008) to analyze and map global mammalian diversity, threats, and knowledge (based on IUCN Red List assessments) provides a possible starting point for integrating multiple categories of information to identify hotspots of risk. Their study found that nearly 80% of marine mammal species are threatened by “accidental mortality” (including bycatch and ship strikes), 60% by “pollution” (defined to include noise as well as chemical toxicants), and about half by “harvesting.” Particularly striking is that nearly 45% of marine mammals are classified as either Near Threatened or Data Deficient, meaning the proportion of threatened species (Critically Endangered, Endangered, or Vulnerable) could be considerably higher than the current estimate of about 23%. A broadly similar but much more focused and detailed study of the marine mammals alone might be informative. It would be desirable if such a study were to incorporate, among other things, finer-scaled GIS mapping of threats (e.g., with exposure to noise and to chemical contaminants considered separately) and species data (e.g., with at least some species broken down into subspecies or populations with differing status and distribution).

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[3] Inclusion of this criterion needs careful consideration in the context of cumulative impacts. In many instances, infeasibility of mitigation would likely *increase* a threat’s significance.
[4] Here meaning specifically alien species introduced to an area through human agency, and not species moving on their own into “new” areas as environmental conditions change.

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5.3 Determining and mapping cumulative exposures in the marine environment

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The management and conservation of the world's oceans require spatial data on the distribution and intensity of human activities and their cumulative impacts on marine ecosystems and species. We developed an ecosystem-specific and scale-independent spatial model to synthesize 17 global datasets of anthropogenic drivers of ecosystem change for 20 marine ecosystems (Halpern *et al.* 2008). Our analysis indicates that no area is unaffected by human influence and that a large fraction (41%) is strongly affected by multiple drivers. However, areas of relatively minimal human impact remain, particularly near the poles, but also in other locations scattered across the globe. The analytical process and resulting maps provide flexible tools for regional and global efforts to allocate conservation resources, implement ecosystem-based management, and inform marine spatial planning. We have also applied these same methods to the Northwest Hawaiian Islands (14 human activities and 10 ecozones; Selkoe *et al.* 2009) and to the California Current, using more comprehensive and higher-quality data for 25 human activities and 19 marine ecosystems (Halpern *et al.* 2009). The latter analysis indicates where protection and threat mitigation are most needed in the California Current and reveals that coastal ecosystems near high human population density and the continental shelves off Oregon and Washington are the most heavily impacted, climate change is the top threat, and impacts from multiple threats are ubiquitous. Remarkably, these results were highly spatially correlated with global results for this region ($R^2 = 0.92$), suggesting that the global model provides guidance to areas without local data or resources to conduct similar regional-scale analyses.

While this framework has yet to be applied to cumulative effects on species or populations, it is designed to be flexible and transferrable. We discuss here the potential to apply it to assessing marine cetaceans' cumulative exposures to anthropogenic impacts. There are several important differences when applying the framework to species rather than ecosystems. More empirical data and models may be available with which to judge relative vulnerability of populations to individual impacts, reducing our reliance on expert judgment to calibrate vulnerability weights used in the cumulative impact model (see Halpern *et al.* 2007). Second, our spatial snapshot approach may be insufficient; we need new methods for accumulating impacts in time as well as space. Finally, spatiotemporal dynamics of migratory populations will be critical to determining exposures. Transferrable methods include using expert judgment to fill data gaps, using ecological vulnerability measures to standardize scoring of vulnerability, and applying our cumulative impact GIS model. Mapping of many important stressors (and habitats, which may be helpful in mapping cetacean distributions) has already been completed at the global scale and in more detail for particular regions. A starting point for applying this framework to cetacean cumulative impacts is to develop seasonal snapshot maps of cumulative impacts for populations in their breeding and foraging areas and along key migratory corridors. Doing so would allow us to begin to visualize the seascape of threats to cetaceans and to think about them in the context of broader ecosystem impacts.

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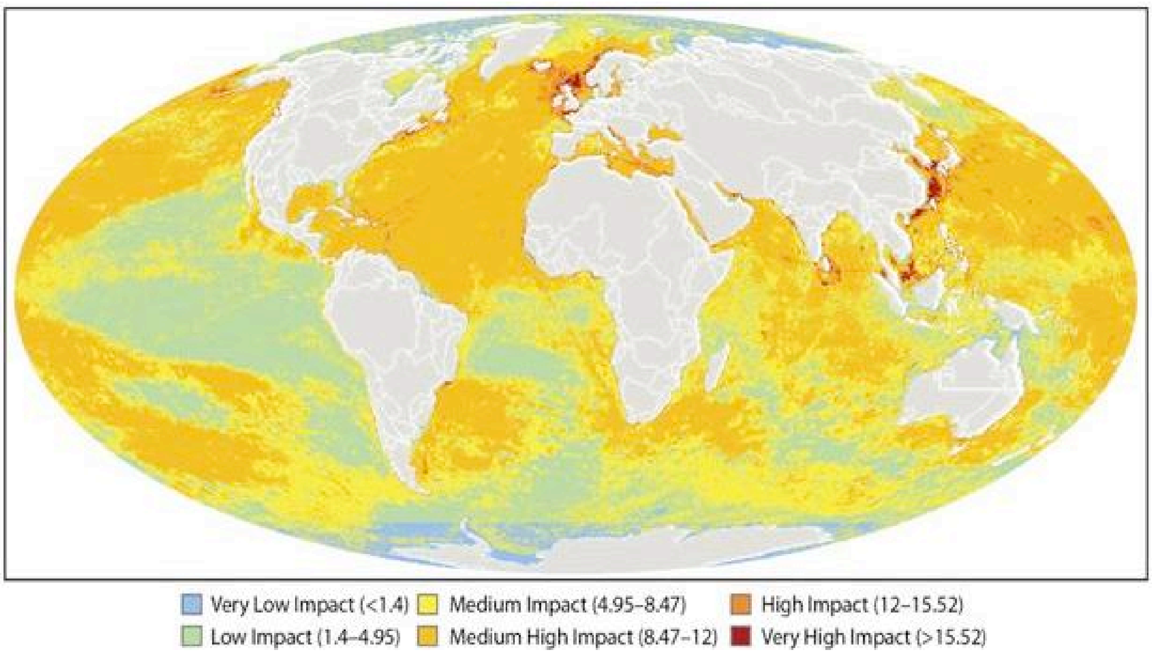

Figure 1. Global map of cumulative effects on marine ecosystems from Halpern *et al*. 2008. White lines on the continents represent watershed boundaries from which land-based effects were derived.

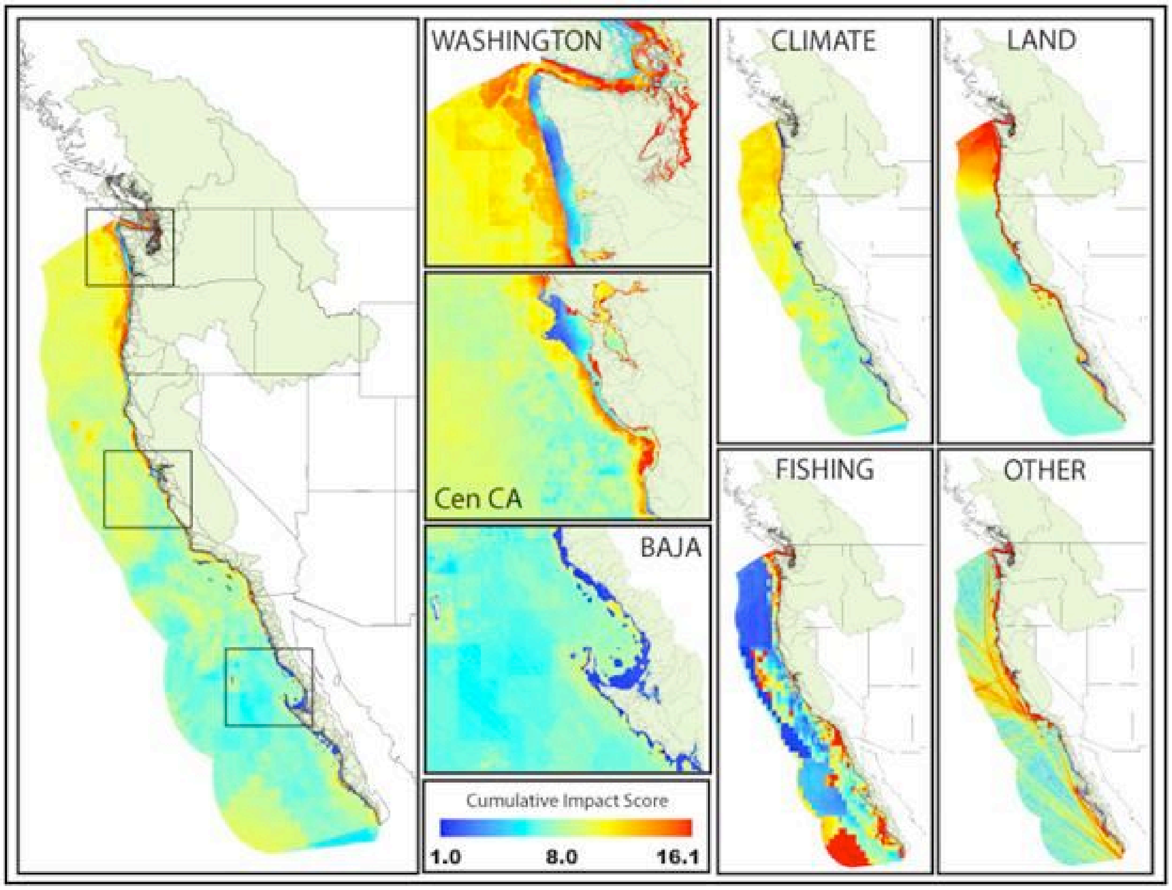

Figure 2. Cumulative impact map of 25 different human activities on 19 different marine ecosystems within the California Current with close-up views of three regions (Washington State, central California, and central Baja California), and impact partitioned into four sets of human activities of particular interest: climate change (n =3 layers), land-based sources of stress (n = 9 layers), all types of fishing (n = 6 layers), and other ocean-based commercial activities (n = 7 layers). Puget Sound is the reticulated bay in Washington, San Francisco Bay is the large bay in Central California, and Tijuana is at the Mexican border with California. From Halpern *et al*. 2009.

5.4 Modeling cumulative sound exposure over large areas, multiple sources and long durations

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A software tool is presented for mapping cumulative sound exposure levels from multiple, moving, pulsed or continuous sound sources over large areas and long durations. The tool is illustrated for the example of a marine seismic survey. There were 5,000 shots spread out over 400 km^2 of coral reef. The survey took six weeks. Animals of concern were resident fish who were not expected to leave the reef but who had been shown to 'simply' hide amongst the coral for the full duration of a seismic survey elsewhere. The goal was to produce a map of cumulative received sound exposure levels at the reef from the entire survey. The challenge was to account for all the different sound propagation paths from 5,000 source locations to a fine grid of receiver locations.

Solution:
1. Place an evenly-spaced receiver grid over the area.

2. Extract bathymetry profiles for all shot-receiver pairs.
3. Cluster bathymetry profiles with a self-organizing neural net.
4. Model transmission loss along all cluster centroids.
5. Extrapolate transmission loss for all other shot-receiver pairs.
5. Integrate energy at all receivers over all shots (=integration over time and area).

Options:
In the presented example, bathymetry was the single most important factor affecting sound propagation. Bathymetry varied from being very steep on the outsides of the reef to very flat in the reef centre. Large coral outcrops existed all over the reef, sometimes reaching the water surface and stripping energy at high frequencies. Geology (geoacoustic parameters of the seafloor) and sound speed profiles of the water column did not vary substantially over the reef. In other environments, where the geology or water properties are not homogeneous, environmental provinces should be defined and the model run for each province separately.

Applicability:
The tool is useful for moving sources or for very large numbers of sources where an integration in area (over all source locations) is necessary. If only a few stationary sources exist, it will be easier to model sound propagation once for each source and to integrate over time. The tool is useful to assess impact on marine species that are confined to the area modeled (i.e. they don't flee the area), e.g. fish at a coral reef, dugong confined inside a bay etc. The tool produces a sound exposure map, which can be overlain with habitat maps to estimate the percentage of habitat that receives certain threshold levels.

A full article on this model with all references can be found at:

Erbe, C., and A.R. King (2009) "Modeling cumulative sound exposure around marine seismic surveys", *Journal of the Acoustical Society of America* 125(4): 2443-2451.

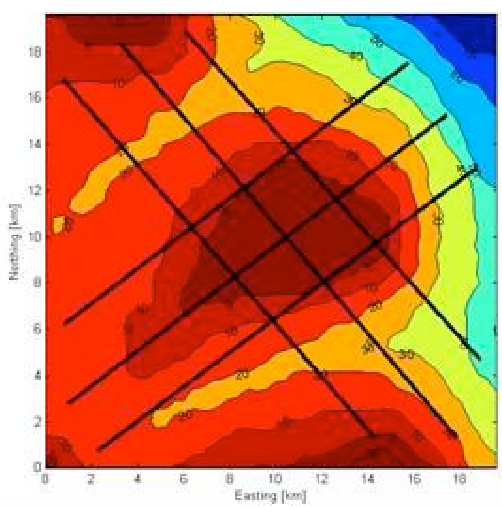

Fig.1: Coral reef of 20km x 20km size.

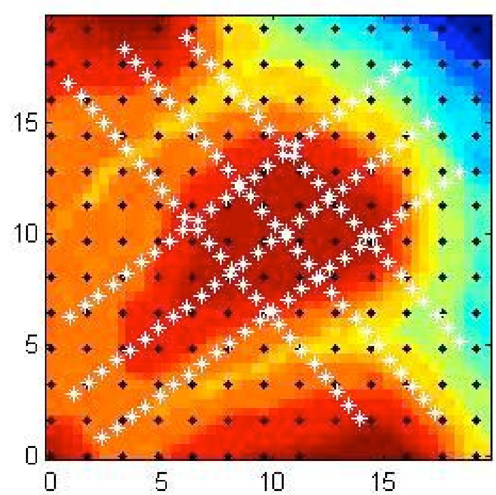

Fig.2: Every 32nd shot (white) + a coarse receiver grid (black).

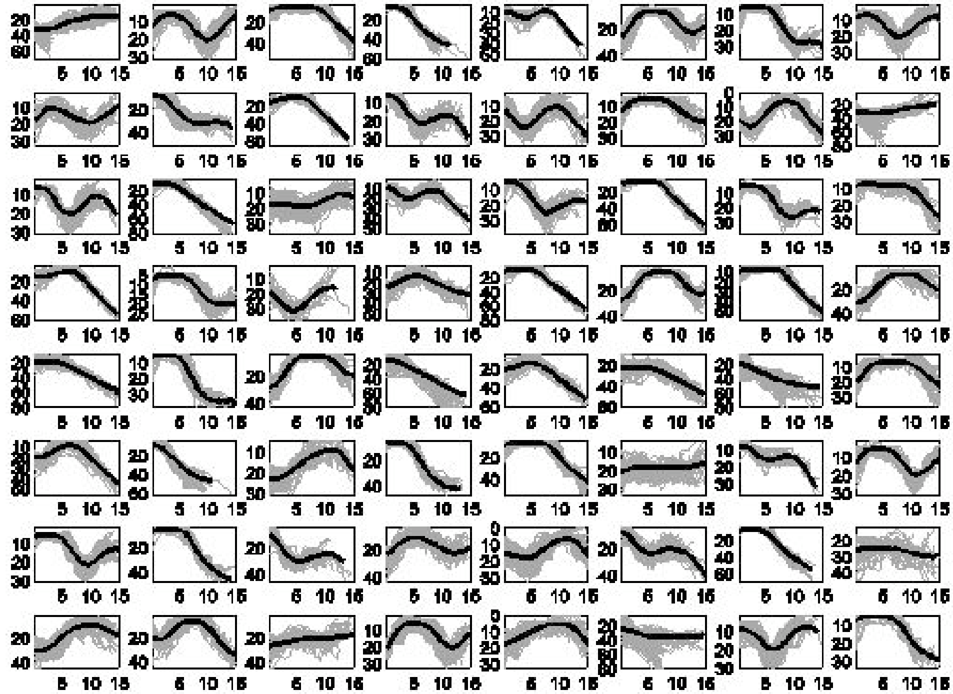

Fig.3: 64 clusters of bathymetries (x: range, y: depth [m]) connecting all shots with all receivers. Centroids in black.

Category	Area receiving this level [km^2]	% of total reef area
SEL > 190 dB re 1 μPa^{2}s	5.80	1.54 %
SEL > 195 dB re 1 μPa^{2}s	2.72	0.72 %
SEL > 200 dB re 1 μPa^{2}s	0.48	0.13 %

Table 1: Total ensonified areas of this reef.

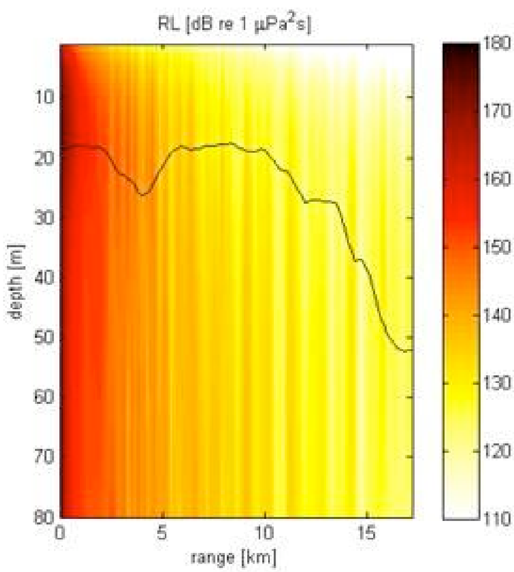

Fig.4: Sound propagation along 1 centroid.

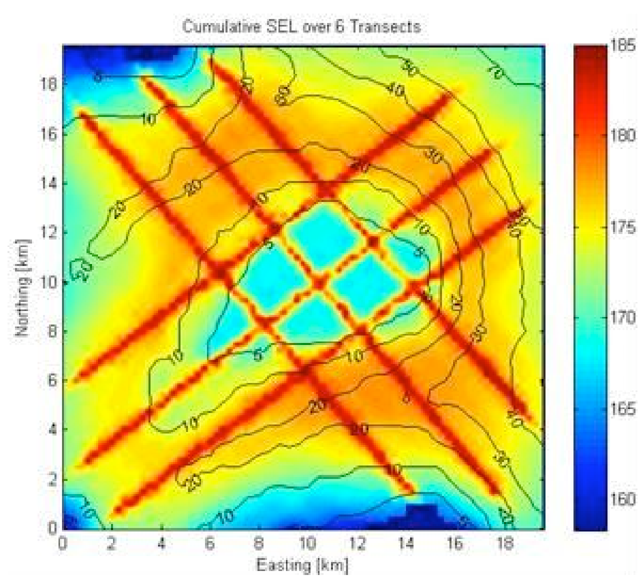

Fig.5: Total SEL from entire survey over whole reef.

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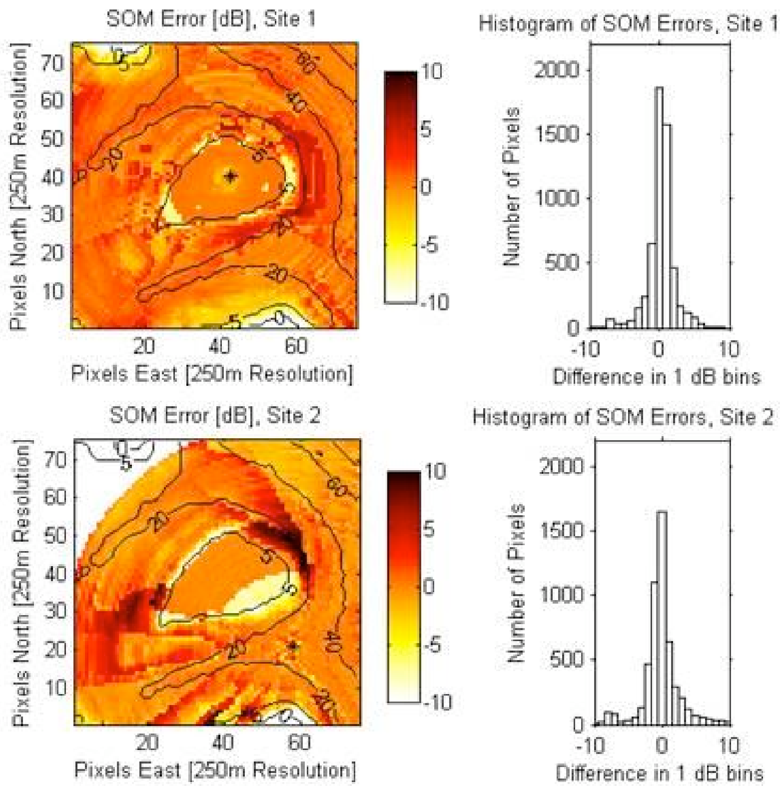

Fig.6: Error of the algorithm compared to modeling each source individually. Error is largest where bathymetry changes rapidly. Mean error: -1 ± 3 dB re 1 $\mu Pa^2 s$.

6. Quantification of cumulative impacts

6.1 Assessment of cumulative effects in the Canadian Arctic

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Introduction

Assessment of cumulative effects is a required component of the environmental assessment for most large project applications in Northern Canada. This brief note provides an overview of:

- regulatory requirements
- a regional overview of current human activities
- typical approaches used in current assessments
- strengths of current approaches
- challenges in improving cumulative effects assessment

Regulatory Requirements

Environmental reviews and approvals for Projects under federal jurisdictions are set out in the Canadian Environmental Assessment Act (CEA Act). The requirement for assessment of cumulative effects in the environment is set out in Section 16(1) of the CEA Act; specifically:
16. (1) Every screening or comprehensive study of a project and every mediation or assessment by a review panel shall include a consideration of the following factors:

- *the environmental effects of the project, including the environmental effects of malfunctions or accidents that may occur in connection with the project and any cumulative environmental effects that are likely to result from the project in combination with other projects or activities that have been or will be carried out;*
- *the significance of the effects referred to in paragraph (a);*

Additional direction on assessment of cumulative effects under the CEA Act is provided in the Cumulative Effects Assessment Practitioner's Guide (Hegmann et al. 1999).

Within northern Canada, the requirement for environmental assessment is entrenched the land claim agreements for the Inuvialuit Settlement Region (ISR) and Nunavut. In the ISR, environmental assessments must meet the requirements of the CEA Act, as well as the requirements of the Inuvialuit (see below). Within Nunavut, the Nunavut Land Claims Agreement (NLCA) supersedes the CEA Act; environmental assessments must meet the requirements of the Nunavut Impact review Board (see below). The CEA Act would only apply if the physical components of a Project and/or the environmental effects of a Project were to cross the boundary between a provincial or territorial jurisdiction; or extend beyond the NSA into federal jurisdiction, including international issues.

The Inuvialuit Final Agreement (IFA) was signed in 1984 between the Committee for the Original People's Entitlement (COPE) (representing the Inuvialuit of the Inuvialuit Settlement Region) and the Government of Canada. Section 11 of the IFA establishes a formal Environmental Impact Screening and Review Process for proposed projects. Two separate and distinct bodies may be involved in the review of a project proposal:
- the Environmental Impact Screening Committee (EISC)
- the Environmental Impact Review Board (EIRB)

These bodies have assessed a number of offshore projects, mainly in relation to the oil and gas industry. The requirement for cumulative effects assessment is defined in the Operating Guidelines and Procedures for the EISC (EISC 2004); specifically:
"Developers are expected to identify and assess the cumulative effects of the proposed development and other activities in the area. Depending on the development, the assessment of cumulative effects may be qualitative rather than quantitative."

The guidelines are currently being revised. Based on the draft revisions, cumulative effects are defined as "A change to the environment that is caused by a human action in combination with other past, present and reasonably foreseeable actions; and, a cumulative effect on Inuvialuit harvesting as a change to present or future harvesting opportunities caused by a human action in combination with other past, present and reasonably foreseeable actions" (EISC 2009). Additional guidance on assessment of cumulative effects is provided in EISC and EIRB (2002).

The Nunavut Land Claims Agreement (NLCA) was signed in May 1993 between the Tungavik Federation of Nunavut (representing the Inuit of the Nunavut Settlement Area, then part of the Northwest Territories) and the Government of Canada, subject to the Constitution Act of 1982. The Nunavut Impact Review Board (NIRB) is responsible for screening project proposals and, if so determined, review of project proposals within the NSA. Reviews are conducted pursuant to Article 12 of the NLCA, and must take into account both ecosystem and social-economic effects of a project.

The requirement for assessment of cumulative effects is outlined in by NIRB (2006); specifically:
"The assessment of impacts on the biophysical and socio-economic environment that results from the incremental effects of a development when added to other past, present, and Reasonably

Foreseeable Future Developments, regardless of what agency or person undertakes such other developments. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time."

To date, NIRB has assessed marine aspects for several projects, primarily involving shipping associated with mines, extension of roads or port development.

Regional Overview of Current Human Activities

The Inuvialuit Settlement Area includes all of the Mackenzie River Delta, the Canadian Beaufort Sea and some of the high arctic islands in Canada. Under the IFA, the Inuvialuit have title to lands, as well as rights to financial compensation, rights to harvesting of wildlife and fish, and wildlife compensation.

Human activities in the marine areas of the ISR include nearshore and offshore seismic and exploration drilling, supply shipping for northern communities, limited volumes of other shipping traffic (cruise ships and defence), aircraft overflights, and traditional harvesting. The oil and gas industry has been active in the ISR since the early 1960s, with offshore activity reaching the highest levels during the 1970s-1980s. To date, 86 offshore exploration wells have been completed in the offshore. No production has occurred to date.

The Territory of Nunavut spans most of the high arctic islands in Canada, as well as the land area between Hudson Bay in the west and the Northwest Territories (and the ISR) in the east. The Nunavut Settlement Area, as specified in the NLCA, includes the entire land base within Nunavut, as well as marine areas out to the 12-mile territorial limit or, in the case of the east coast of Baffin Island, the outer landfast ice zone. Under the NLCA, the Tungavik Federation of Nunavut (TFN) have title to approximately 350,000 square kilometres of land, of which 35,250 square kilometres include mineral (sub-surface) rights.

Human activities in the nearshore and offshore are similar to those described for the ISR, but also have included regular annual shipping of ore and products from several mining projects on the arctic islands and Nunavut mainland. Offshore oil and gas primary activity in Nunavut occurred primarily during the 1970s, with most activity occurring in the high arctic islands. Oil was produced from the Benthorn well and shipped to eastern Canada from 1985 through to 1997.

Typical Approaches used in Current Assessments

Based on input from Inuvialuit and Inuit, regulators, and management agencies, assessments for marine mammals typically have focused on Valued Environmental Components (VECs) such as bowhead whale, beluga whale, polar bear and narwhal (Nunavut only). Effects from routine project activities that have been considered include:

- underwater noise resulting in physical harm (this effect is usually screened from detailed assessment due to low probability of occurrence)
- behavioural responses to underwater noise and use of summer habitat in the Canadian Beaufort (e.g., changes in feeding, migration and nursing)
- mortality risk (vessel strikes)
- combined effects of above

Assessments have also considered accidents or malfunctions and cumulative effects.

Assessment of cumulative effects first typically consider each different effect separately, and generally involve the following tasks:

1. Screening of how each individual effect may interact cumulatively with similar effects from other human activities and projects (past, present and foreseeable future)
2. Development of an activity and project inclusion list for the geographic scope of the assessment. Some assessments qualitatively discuss similar effects in other parts of the VEC's range
3. Scoping of assessment in terms of issues of concerns, spatial and temporal boundaries, terms or definitions for characterizing effects (e.g., scope, magnitude, duration, frequency, reversibility), and identification of thresholds for determination of significance
4. Description of mechanism(s) through which the cumulative effect(s) may occur
5. Identification of mitigation by proponent and regional initiatives
6. Assessment of cumulative effect (often based on spatial analyses with consideration of seasonal or inter-annual aspects), and characterization of these effects (as noted above)
7. Determination of significance with reference to:

- Significance of the cumulative effect from all sources
- Contribution of Project to the cumulative effect

Significance is typically related back to the sustainability of the designated population unit (e.g., Bering-Chukchi-Beaufort bowhead population; eastern Beaufort Sea (EBS) beluga population).

Once all of the individual effects are assessed, some assessors have attempted to qualitatively discuss how combined cumulative effects may affect the sustainability of the designated population unit. For example, how might changes in habitat use, mortality and/or contaminants in the food chain interact and cumulatively affect the overall sustainability of the population unit. This may include a discussion of pressures on a VEC in others areas of its annual range, and overall health and status of the population unit for the VEC when it enters and exits the geographic scope of the cumulative effects assessment.

Strengths of the Current Approach

The regulatory system in the ISR has been operational for over two decades, while the current regulatory system in Nunavut has been operational for approximately a decade. While the regulatory requirements and current approaches do focus the assessment of cumulative effects on specific projects and interactions of these projects with other activities and projects, the current approaches do have a number of strengths. These include:

- Involvement of aboriginal people and stakeholders throughout the regulatory and assessment process and project implementation. Both the IFA and NLCA include specific requirements for community engagement in scoping of assessments, planning of field research, and review of assessments.
- Strong focus by Inuvialuit and Inuit on species or species groups that are of high interest to them, including species of concern and harvested species. Marine mammals and individual species are consistently given a high profile.
- Both the IFA and NLCA include direction that traditional knowledge must be given equal weight to western science in environmental assessments and resource management decisions. Traditional knowledge, in practice, is strongly based on a holistic view of the environment. Accordingly, Aboriginal people often raise concerns about the overall effects of a project on the VEC and the environment that supports the VEC.
- Strong involvement of Aboriginal people in the decision making process. Both the EISC and the EIRB in the ISR and the NIRB in Nunavut require equal or majority participation by Aboriginal people. Aboriginal people also have strong representation on wildlife management and resource management organizations.

- All regulatory boards have the ability to seek input from adjacent jurisdictions. For example, the Inuvialuit have considered input from the Inupiat and Gwich'in in Alaska. Both the IFA and the NLCA have provisions for involvement of adjacent territories and provinces.
- The northern regulatory bodies can attach condition to approvals, including:
  - changes to project design or operations
  - additional mitigation and environmental protection planning
  - requirements for additional field studies or follow-up monitoring
- Northern regulatory boards do refer to past environmental effects monitoring (e.g., effects of underwater noise on marine mammals, effects of water-based drilling muds) when formulating their decisions on projects.

Challenges in Improving Cumulative Effects Assessment

Assessment of cumulative effects on marine mammals is a complex challenge that requires consideration of a broad range of potential effects on a population unit throughout its annual range, as well as consideration of multiple stressors within the geographic scope of a specific assessment. Some of the challenges faced by practitioners include:
- Jurisdictional, regulatory and practical considerations often limit the assessment to a specific geographic area (i.e., the ISR, Nunavut).
- Estimating the effects on a VEC from other stressors throughout the annual range of a population unit. For example, when a cumulative effects assessment is limited to a defined geographic area by the factors noted above, how can the status of a mobile species such as bowhead whale or beluga whale be established when they enter and exit arctic Canadian waters?
- Practitioners may have to identify a broad range of existing activities and projects that will or may result in similar effects to the project under consideration. Obtaining information on the spatial and temporal aspects of past and present projects is difficult, particularly with respect to unregulated activities and development. It is also challenging to accurately forecast what activities and projects may occur in the future, and especially difficult to quantify the spatial and temporal nature of effects from these future projects. There is also considerable debate over how far in to the future an assessment should be extended.
- Defining the appropriate population unit. For a specific area or region, are subpopulations, matrilines or other population units most suitable as a basis for the assessment?
- Understanding the effect mechanism(s). Some effects mechanisms are not yet well understood. For example, how do observed or predicted behavioural responses to underwater noise affect the health of individual animals and, in turn, how do these changes affect the long-term sustainability of the population unit under consideration.
- Quantifying individual cumulative effects. What are preferred methods and measurable parameters for assessing specific effects on a VEC and quantifying these effects in terms of scope, magnitude, duration, frequency, etc.?
- Considering cumulative project effects in the context of climate change. Given the rapid changes in ice cover in the Arctic, how are these changes detrimentally or positively affecting marine mammals, and how might these changes interact with other effects of human development and associated activities?
- Qualifying or quantifying the combined cumulative effect on a VEC (i.e., how do we deal with additive and synergistic effects).
- Confirming project effect and cumulative effect predictions. While some information was obtained during past periods of industrial activity, additional effort is needed to monitor responses of marine mammals and other marine biota to specific types of industrial and other human activity to better understand effect mechanisms and better quantify species responses to individual or multiple stressors.

- Developing and verifying thresholds for specific effects or suites of effects. Few, if any, thresholds exist for individual or cumulative effects on marine mammals. For example, what are appropriate acoustic thresholds for marine mammals in arctic regions (e.g., are recommendations by Southall et al. (2008) applicable to species in the Canadian arctic and, if so, how?).
- Confirming the effectiveness of mitigation and management. Industry and government agencies have developed and implemented different approaches to better manage or mitigate project and cumulative effects on marine mammals. How can we best assess if these measures are effective in minimizing an effect or suite of effects to marine mammals?

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6.2 *Cumulative impact assessment in Canada: A critique*[5]

Lorne Greig

This paper touches on the legislative framework for cumulative impact assessment (CIA) in Canada, current practices that limit the utility of CIA, and key needs for redeploying CIA in a meaningful way. In much of the legislation and literature, the term cumulative effects assessment (CEA) is used rather than CIA. With regard to the interpretation of "effects" this may be a critical distinction.

Legislative Framework

Environmental assessment (EA) in Canada is mandated provincially, territorially and federally by a variety of legislative instruments. Some provinces explicitly require consideration of cumulative effects (CEs) in their legislation while others do not. Assessment of cumulative effects is required only by British Columbia, Alberta and Quebec, Yukon, Northwest Territories (NWT, Mackenzie Valley Resource Management Act, by the Inuvialuit Settlement Agreement, and the Nunavut Land Claims Agreement. Federally, explicit consideration of cumulative effects is required by the Canadian Environmental Assessment Act (*the Act*). Regarding management of Canada's marine waters, the Oceans Act provides for designation of Marine Protected Areas, and prohibition of some classes of activities within them. It does not otherwise provide specific management powers, but extends other Canadian laws (federal and provincial) into Canada's territorial sea. Management of marine cumulative effects requires extraordinary governmental collaboration and co-operation.

[5] Prepared for Okeanos Foundation Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action. Monterey California. August 2009.

Central Problems with CEA Practice

What we are concerned about with CIA is the consequence of the totality of pressures that act on a valued ecosystem component (VEC). Duinker and Greig (2006) identify six key problems with CEA practice in Canada:

1) Application of CEA in Project EA,
2) Focus on project approval,
3) Separation of CEs from project specific impacts,
4) Interpretations of cumulative effects,
5) A lack of understanding of ecologic thresholds, and
6) Consideration of future developments.

The application of CEA within project EA is problematic as CEA and EA are rooted in fundamentally different perspectives. CEA must be done from the perspective of the VECs we are concerned about (a VEC-centric view Figure 1), while EA typically takes a project-centric approach (Figure 2).

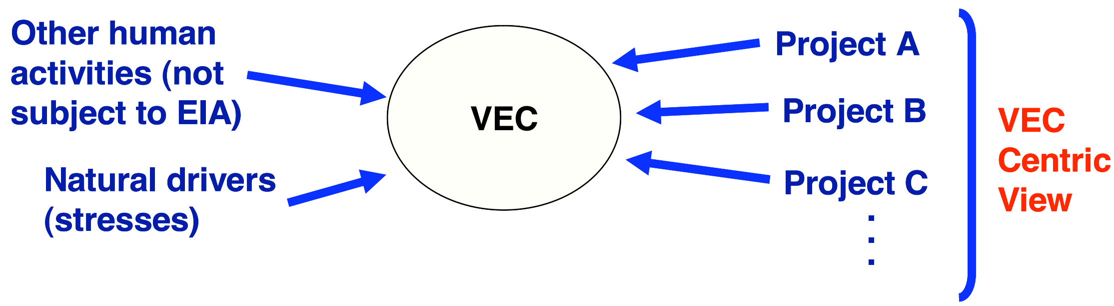

Figure 1: Analytical view required for CEA.

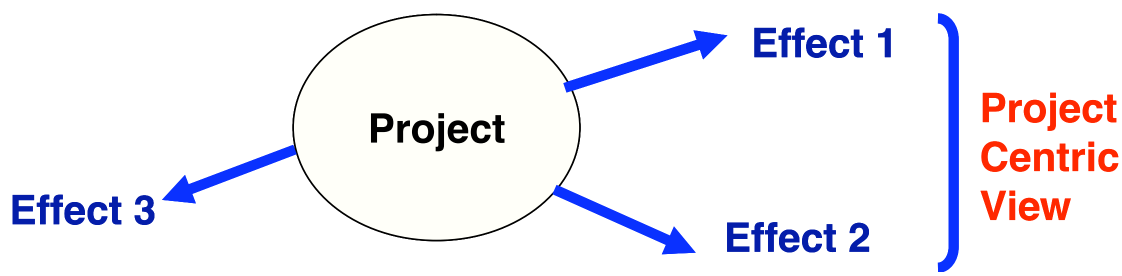

Figure 2: Analytical view typically taken in project EA.

Give this dichotomy, project EA is an inappropriate frame for CEA. In practice, CEAs prepared under the Act tend to be done as a separate add on to the EA, are frequently qualitative and tend to be severely limited by their interpretation of CEs.

The Act defines CEs only implicitly in its requirement that project assessments consider CEs that "are likely to result from the project in combination with other projects or activities that have been or will be carried out". Despite some good guidance, proponents are left to interpret this language. Common interpretations are that CEs occur (only) in some interaction with other projects. Decision trees are often used to establish when CEs occur (Figure 3). With this approach, a project that imposed direct mortality and another that reduced habitat would not be considered jointly to cause CEs, nor would two that both imposed noise pollution on marine mammals but which occurred at different times or in different locations. This is a totally inadequate interpretation of the concept of CEs.

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Thus the search for "cumulative effects" becomes a diversion that is not helpful in the search for meaningful conclusions about the consequence of cumulative pressure on resources. Instead CEA in Canada needs to be refocused as an analysis of the ecological sustainability of VECs under the totality of natural drivers and human pressures.

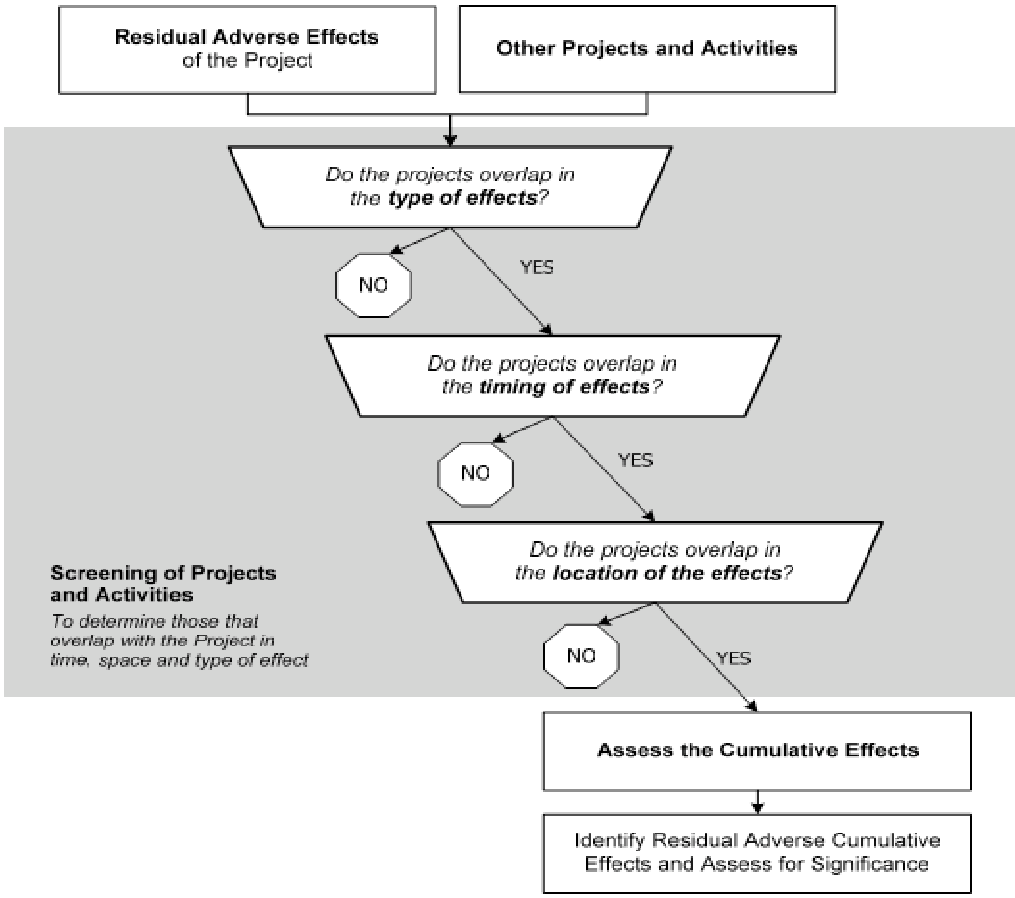

Figure 3: An example of a cumulative effects decision tree (Golder Associates Ltd., 2008).

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6.3 Calculating synergistic and antagonistic impacts: lessons for the marine environment

Kristy Kroeker

Determining the cumulative effects of multiple stressors requires a conceptual model of how individual stressor effects can accumulate. In the simplest scenario, one can use an additive model for which the null hypothesis predicts the combined effect of two stressors is the algebraic summation of the singular effects. Cumulative effects are then categorized as additive, synergistic, or antagonistic based on their relation to the predicted additive response (Folt et al. 1999). The designation of interactive effect types is highlighted in figure 1 (excerpted from Crain et al. 2008).

In the most common case, when both stressors have a negative effect on the response variable (Fig. 1A), the cumulative effect would be designated additive if the response to multiple stressors is the summation of responses to the singular stressor treatments. If the response is significantly less than the predicted additive response (i.e. the cumulative effect is greater than the sum of the singular treatment effects), it is designated synergistic. If the response is greater than predicted additive response (i.e, the cumulative effect is less than the sum of the singular treatment effects), it is designated antagonistic. The interpretation of additive, synergistic, or antagonistic cumulative effects will vary depending on the direction of the responses to singular treatments. In addition to this example of a stressor negatively impacting the response variable (Fig. 1A), the singular stressors may both increase the response variable (Fig. 1C), or one stressor increases the response variable while the other stressor decreases it (Fig. 1B; Crain et al. 2008).

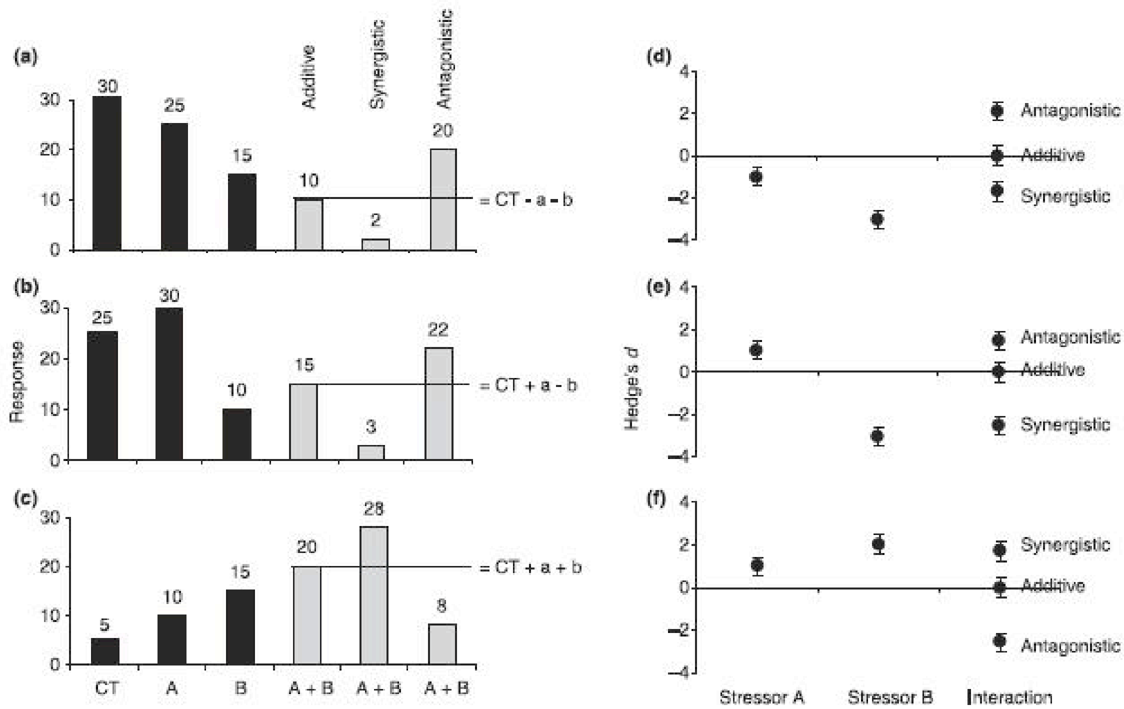

Figure 1 Conceptual approach to interpreting interaction types from population or community response data presented in factorial studies (a–c) and corresponding individual and interactive effect sizes measured with Hedge's *d* (d–f) before combining across studies using meta-analysis. Treatments in factorial studies include control (CT), with stressor A (A), with stressor B (B), and with both stressors (A + B). Interaction types (additive, synergistic and antagonistic) vary depending on A + B response and are illustrated here for stressors that have double negative (a and d), opposing (b and e), and double positive (c and f) main effects on the response variable of interest.

In practice, cumulative effects are determined by calculating an interactive effect-size index. Two common effect-size indices are Hedges *d* (Hedges and Olkin 1985, Fig 1D-F) and the response ratio (Hedges et al. 1999, Darling et al. 2008). Significant interactive effects (i.e., synergistic or antagonistic effects) are those in which the chosen confidence interval of the given effect size does not overlap the pre-determined value of an additive effect size (Fig. D-F). Effect-size indices from individual studies can then be combined using meta-analysis in order to summarize results across multiple studies (Hedges and Olkin 1985).

Two other models of cumulative effects have been described: multiplicative, where the combined effects are expected to be the product of the individual stressors' effects; and comparative, where one stressor primarily drives the response (Folt et al. 1999). An additive model is often used to categorize the cumulative effects of multiple anthropogenic stressors because the null hypothesis is the simplest combination of effects from which we can test for deviations. Additionally, an additive model underlies the ANOVA framework used in factorial experiments, comparable analyses and applications (Halpern et al. 2008, Crain et al. 2008, Darling et al. 2008).

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7. Quantifying Cumulative Risk to Populations

7.1 *Managing marine mammal populations in the U.S.*

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The Potential Biological Removal (PBR) management system was created to manage direct mortalities in fisheries, which was the primary threat to marine mammals in U.S. waters in the 1990s. Review of why and how this transparent system was developed provides an example of a process that uses a minimal amount of data, directly incorporates uncertainty and relies on quantitative objectives. Since new threats have developed (including ocean noise), data obtained for the PBR system were used to address the question: "For what proportion of stocks could we detect precipitous declines (50% decline in 15 years assuming a = 0.05)?" The statistical power to detect such a decline is near zero for beaked whales, which was not surprising. However, a power of only 30% to detect such a decline for large whales was a surprise and is a sobering value for assessing cumulative effects of numerous potentially small indirect effects. Risk assessment for demographically independent populations often relies on estimates of trends in abundance. Given the poor ability to detect precipitous declines using traditional statistical significance criteria, an alternative method using Bayesian methods is given to provoke discussion of possible extensions to a PBR-like approach that consider more than direct human-caused mortality.

7.2 Managing cumulative impacts and uncertainty

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Uncertainty is an ever-present concern when managing wild populations (Williams 2001; Hauser *et al*. 2007). When considering the impacts of underwater noise on marine mammals – a group of species with long generation times, difficult to observe lifestyles, and highly-evolved behavioral responses – this uncertainty is greatly amplified. Some aspects of this management question are understood, for example, the physical processes of underwater sound generation and propagation. There is also no doubt that on an individual level, certain forms of noise have been shown to cause considerable physiological and behavioral stress (Jepson *et al*. 2003; Morton & Symonds 2004). However, estimating the cumulative impact of anthropogenic noise on a population of marine mammals depends on a suite of highly uncertain factors. It is unclear precisely how most types of noise injure or alter the behaviour of marine mammals. Further, researchers cannot confidently predict the consequences of these immediate, individual-scale impacts on long-term population-scale attributes, such as demographic structure or growth rates (NRC 2005). The practicalities of management further complicate the treatment of uncertainty in two important ways. First, the research resources available to reduce this multi-faceted uncertainty are very limited, particularly compared to the prohibitive costs of gathering data on appropriate spatial and temporal scales. Second, much of the potentially threatening anthropogenic noise is generated by critical economic and political forces, including international trade, geophysical exploration, and the military (NRC 2003). Political institutions may need to be particularly confident that a given activity is having biologically significant effects before they will implement constraints. The required level of confidence required to instigate changes may therefore depend on the threatening process.

In such complex ecosystems, decision-making can only be efficient and transparent with the support of quantitative models that explicitly incorporate uncertainty (Wintle 2007). Decision-theory approaches to uncertain management problems have become best-practice for conservation in the terrestrial environment (e.g., Margules & Pressey 2000), but many are actually extensions of innovations that originated in fisheries management (e.g., Clark 1990). I will discuss two important aspects of management in uncertain conservation systems. The first is the range of methods available for coherently incorporating uncertainty into ecological models and decision-support tools. A suite of different approaches exist for this purpose, each of which is appropriate when different amounts of information are available, ranging from parameterized risk through to severe uncertainty (Regan *et al*. 2005). The second issue is located at the interface between ecology and management: how should the decision-focus of management influence our attitudes towards uncertainty. In contrast to ecological research, conservation management is primarily concerned with making efficient decisions. Understanding ecological processes, and accurately predicting future dynamics, are only important insofar as they improve management objectives. When the focus is shifted from science to decision-making, our attitude towards uncertainty is fundamentally altered. Some level of uncertainty is not just tolerated by conservation, it is actually optimal. Additional research will not necessarily improve outcomes, if it requires the investment of resources and time that could be invested in management actions (Grantham *et al*. 2009*a,b*). The best focus for research may not necessarily be the most uncertain aspects in the ecosystem, nor the most sensitive. Instead, research attention should be decided by the highly variable costs of different ecosystem components, and by the expected impact of reduced uncertainty on manager's decisions (Baxter *et al*. 2006).

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7.3 Determining population risks under cumulative threats

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Marine mammal populations are subject to an increasing range of anthropogenic threats throughout their range. Two key issues in managing these threats and their impacts are: (i) the empirical detection and measurement of effects of single or cumulative adverse factors on marine mammal populations; and (ii) the prediction and estimation of the expected population consequences of different future levels of specific adverse factors. The two issues are related, because generally one relies on the detection of impacts in at least some cases in order to quantify by analogy (albeit with low precision) the possible impacts of comparable factors on the same or other populations.

The prospects for determining the effects on populations of single or cumulative threats depend strongly on the nature of the expected impact and the kind of population monitoring that is in place or could be implemented.

The kinds of impact that, depending on the threat, need to be detected and measured, include:
(i) immediate: mortality events in close temporal and spatial proximity to the causal event;
(ii) short-term: extra mortality or diminished reproduction in the same or following year to the causal event;
(iii) medium or long-term reduction in survival or reproductive rate.

The kinds of monitoring that are or can be implemented include: monitoring levels of population abundance; monitoring of distribution; direct observation of mortality; indirect estimation of mortality from survival analyses; observation of reproductive success from direct counts of calves/pups or from calving/pupping intervals; observation of physical or biochemical indicators of body condition or pathology.

The feasibility or utility of each kind of monitoring, expressed in terms of precision information gained for a given level of research effort, depends on the characteristics of the species and population. Tables can be constructed for each species showing the power to detect different kinds of impact from each type of monitoring.

Reduction in abundance at the population level, and indirect evidence of enhanced mortality from survival analyses, can typically only be detected after a considerable period and when the reduction has become severe; the power to link the change to a specific cause is low. Provided the causal factors are sufficiently variable and their effect is immediate or short-term, direct observations of mortality, reproduction and body condition factors offer greater power to detect and identify certain kinds of impact.

As a worked example of the approach, this analysis is applied to the Critically Endangered western population of gray whales (*Eschrichtius robustus*) which is subject to threats from petroleum-related operations, including seismic surveys, in the prime feeding habitat for mothers and calves, by-catch in fishing nets on its migration route, and possible additional adverse factors on its still undiscovered breeding grounds.

Where there are grounds for concern about the impact of a potentially adverse factor that is being introduced into the marine environment, it is essential that appropriate monitoring programmes for the potentially affected marine mammal populations, tailored both to the characteristics of the populations and to the nature of the threats, are implemented at an early stage. Otherwise, impacts may go undetected for a long period until severe damage to the population has been inflicted.

8. Quantifying Cumulative Risk to Ecosystems

8.1 Tools for large scale (ecosystem-based) and long-term (evolutionary) environmental risk assessment in the marine environment

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Even after the potential physiological impacts of an environmental change on individuals have been identified, scaling these impacts up temporally (to evolutionary time periods) and spatially (to the ecosystem level) remains a challenging task. We lay out a conceptual framework within which established effects of environmental conditions on individual physiology can be scaled up to make broader predictions. Models can link changes in individual physiology to predictions about individual behavior, which interact with natural selection to create changes in distribution and abundance in space and time. We describe these linkages and the prediction of impacts at multiple scales, using examples drawn from work by our lab group and collaborators. By showing examples of these tools in action, we hope to provide guidance for applying this framework to the marine noise problem. For example, noise pollution might affect the distance at which foraging marine mammals can detect their prey, which would be predicted to reduce encounter rates, and the magnitude of this effect can be modeled on a mechanistic basis (Gerritsen and Strickler 1977). According to classic rate-maximizing models of diet choice (Mangel 1996, Mangel and Wolf 2006), this may lead to a broader diet. More sophisticated state-dependent behavioral models (Clark and Mangel 2000, Cresswell et al. 2008, Satterthwaite et al. 2009) may additionally predict changes in time budgets, energy allocation, and total consumption; and provide a means to link these changes to reproductive success. These changes in diets and reproductive success can be used to predict trends in population size using demographic models (Caswell 2001, Finkelstein et al. 2008, Wiedenmann et al. 2008) and to predict changes in community composition using ecosystem models (Christensen and Walters 2004, Aydin et al. 2007). Changes in community composition may feed back to the individual and population level by changing prey availability and thus potentially altering consumption, diet choice, and reproductive success (Mangel and Wolf 2006).

To achieve stakeholder buy-in, model predictions should be presented with some measure of associated uncertainty, and alternative models should be allowed to compete (Wolf and Mangel 2008). With complicated models of this sort, traditional statistical approaches can be inappropriate to apply and/or difficult to interpret. Numerous promising alternatives are available. Simple sensitivity analyses (Satterthwaite et al. 2009) are computationally straightforward means of summarizing the effects of uncertainty in key variables within a given model structure. When comparing how well multiple model formulations can explain existing data, information-theoretic model comparison tools (Burnham and Anderson 2002) provide an established framework for trading off the increased fit made possible by a more complicated model against the associated risk of increased bias. Bayesian statistics (McCarthy 2007) provide a tool for making use of existing prior knowledge, combining the information gained through multiple studies, and making probabilistic statements that can incorporate multiple sources of uncertainty.

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8.2 Implementing ecosystem-based management via marine spatial planning: Reducing cumulative impacts on marine mammals

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Marine mammals once dominated ocean ecosystems now increasingly dominated by human activities. Here I briefly review the role of marine mammals in the structure and functioning of marine ecosystems, the declining influence of marine mammals on marine food webs, and the role of cumulative impacts on their functional role in these systems. We understand the vital rates that influence the health of marine mammal populations, but we understand little about the vital rates of a healthy marine ecosystem. What role do marine mammals now play in marine ecosystems? What role would we like them to play? How do we transition from where we are now to where we would like to be? In response to such specific problems, the scientific community has called for a transition from traditional population-level management to ecosystem-based management. The way to implement marine ecosystem-based management is likely to include marine spatial planning. In this talk, I will provide an overview of the MSP process with special reference to reducing conflicts between marine mammals and human activities.

9. Potential new tools in the management of cumulative impacts in marine mammals

9.1 Network theory and its potential for use in understanding and managing cumulative and synergistic impacts

Jose Javier Ramasco

Networks have recently shown to be useful tools for understanding and characterizing complex systems. Systems that can be analyzed using network models (called 'graphs') include the following examples: the description of social groups; the study of Internet; and the spread of disease. The basic elements of the system, such as people, animals, populations, etc, can be represented as nodes and their relations as links. The spreading of a disease, information or contaminant thus follows the subtract (i.e., the flow follows the structure of contacts dictated by the network connections) established by the graph, while social processes such as group fission or fusion correspond to the dynamical aspects of the network (see for instance Albert02, Newman03, Pastor04, Dunne06, Barrat08).

The application of complex networks to social systems has a long tradition, going back a little more than half a century (Freeman 04). Some of these results can be extrapolated to communities of social animals and their dynamics. Complex networks have been also employed to describe food-webs and food-chains, which are important for describing how some pollutants such as heavy metals propagate in the ecosystem. They are also essential to model infectious disease propagation. In my presentation, I will summarize previous results and will aim to propose topics and examples that could be of interests for the study of anthropogenic impacts on marine mammals. The hope is to facilitate future interdisciplinary collaborations.

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