Report of the Workshop on Acoustic Masking and Whale Population Dynamics

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1. CONVENOR'S OPENING REMARKS AND TERMS OF REFERENCE

Williams welcomed the participants to the Workshop on Acoustic Masking and Whale Population Dynamics, held at the Golf Hotel, Bled, Slovenia, 4-5 June 2016.

Williams reviewed the Terms of Reference for the Workshop:

(1) provide an update on progress made on 'masking sound', with emphasis on noise from shipping;
(2) provide overview of the Population Consequences of Disturbance (PCoD) framework; and
(3) explore ways that the PCoD and similar frameworks could be modified to predict the population consequences of acoustic masking to cetaceans.

2. ELECTION OF CHAIR

Suydam was elected as Chair.

3. APPOINTMENT OF RAPPORTEURS

Cholewiak, Leaper and New were appointed as rapporteurs.

4. ADOPTION OF AGENDA

The Agenda was adopted as given in Annex A.

5. AVAILABLE DOCUMENTS

The documents available to the Workshop were identified as SC/J16/SNAM01-SNAM03. They are listed in Annex C.

6. INTRODUCTION AND BACKGROUND

All marine mammals produce and use sound in all of their major life functions. Of all the possible impacts of noise, masking is perhaps the most pervasive. Masking is the interference of noise with hearing. Acoustic habitats[2] have been defined as the aggregate sound field from multiple sources compiled at spatial and temporal scales consistent with the ecology of marine mammals (Clark *et al.*, 2009; Moore *et al.*, 2012). From the perspective of acoustic habitats, higher levels of noise reduce a cetacean's listening and communication space such that individuals and populations lose opportunities to effectively engage in basic life functions.

Additionally, from the acoustic habitat perspective, the impacts of increased ocean noise are chronic rather than acute, large rather than small scale, and occur across multiple species, with some populations likely losing large portions (>50%) of their acoustic habitats for many months of the year over many years. Although the population consequences from such broad-scale habitat loss are very difficult to estimate, the Workshop agreed that existing levels of ocean noise are chronic and the expected impacts to acoustic habitats from masking most likely have population consequences.

Since the IWC/IQOE International Quiet Ocean Experiment Workshop on Predicting Soundfields – Global Soundscape Modelling to inform Management of Cetaceans and Anthropogenic Noise, held in Leiden, Netherlands in April 2014 (Boyd *et al.*, 2011) there has been considerable progress on addressing the problem of masking from anthropogenic noise. For the purposes of this Workshop, masking was defined as both the process and the amount by which the threshold of hearing of one sound is raised by the presence of another (Erbe *et al.*, 2016). Progress includes advances in modeling, measurement and visualisation tools; increased understanding of uncertainties in model input parameter values; recognition of the role of behavioural context (e.g. foraging, mating, migrating) for estimating impact on cetaceans (Ellison *et al.*, 2012); and examples of population-level consequences. Given cetacean dependence on listening to and producing sounds for survival, it is important to expand the specific issue of acoustic masking impact into the broader topic of acoustic habitats.

The Workshop noted recent work by the US National Oceanic and Atmospheric Administration (NOAA) to develop an Ocean Noise Strategy Roadmap (ONSR), which aims to broaden the agency's approach to ocean noise management to include an evaluation of impacts to acoustic habitats (Hatch *et al.*, 2016). Details of the ONSR, including illustrative implementation case studies, are available online[3].

7. CONSIDERATION OF PREVIOUS RECOMMENDATIONS FROM IWC SCIENTIFIC COMMITTEE

The Committee has been discussing the impacts of noise since 2004 (IWC, 2005), including seismic surveys in 2005 (IWC, 2006), and specifically considering noise from shipping in 2008 (IWC, 2009). The latter followed a workshop held in Hamburg in 2008 (Wright and Okeanos Foundation for the Sea, 2008) which had wide participation including shipping operators, designers and builders. That workshop agreed on a simple target for reducing shipping noise by half within ten years. This target was endorsed by the IWC Scientific Committee which further strongly recommended in 2010 that:

(1) the goal of noise reduction from shipping set in 2008 (i.e. 3 dB in 10 years; 10 dB in 30 years in the 10-300 Hz band) be actively pursued;
(2) new and retro-fit designs to reduce noise from ship propulsion be advanced within the goals of the International Maritime Organization (IMO), when- and where-ever practicable; and
(3) the IWC and IMO continue to work collaboratively to advance the goal of worldwide reduction of noise from commercial shipping when- and where-ever practicable including reporting progress on noise measurements and implementing noise reduction measures.

[1]Presented to the Scientific Committee meeting as SC/66b/Rep10.
[2]The term 'acoustic environment' refers to ocean noise levels, independent of any organism. The term 'acoustic habitat' implies the perspective of a listener. See Annex B for a Glossary of Terms.
[3]*http://cetsound.noaa.gov/road-map.*

The IMO has recognised the problem of underwater noise pollution from shipping and agreed that scientific uncertainty as to the effects of noise should not preclude efforts towards developing quieting technologies for commercial ships. The IMO went on to establish a correspondence group, including participation from members of the IWC Scientific Committee, to develop non-mandatory technical guidelines for reducing ship noise. These were agreed in 2014 (MEPC.1/Circ.833). In addition, the IMO Marine Environment Protection Committee (MEPC) had recommended that member states should encourage a review of their merchant fleets in order to identify the vessels that would benefit most from efficiency-improving technologies, which would also be likely to reduce underwater noise output. The IMO correspondence group also noted that quieting a relatively few of the loudest ships is a potential way to efficiently reduce the overall contribution of shipping noise to the global ocean noise budget.

The IWC Scientific Committee further agreed in 2014 that increased efforts should be made to avoid, minimise and mitigate the adverse effects of anthropogenic noise on cetaceans. In particular, the Committee recommended that IWC Member Governments should promote and facilitate the adoption, by industry, of noise-reducing technologies, including shipping noise.

The Commission has been developing stronger links with the IMO and continues to have observer status with the IMO. There was a meeting between the Secretariats in January 2016 to discuss a range of issues including underwater noise. There was some discussion of ways in which outputs from the Workshop could assist in the Commission's collaboration with the IMO.

7.1 Identify the scientific work needed, and ways the outputs from the Workshop can contribute, to progress on the goal endorsed by the Scientific Committee in 2010 of reducing noise from shipping (i.e. 3dB in 10 years; 10dB in 30 years in the 10-300Hz band)

Recognising that the IMO has already asked its Member States to review their merchant fleets, the Workshop identified a number of recent extensive data sets (for instance, approaches to Boston off the east coast of the US and approaches to ports off the west coast of the US) with source characteristics of individual vessels (e.g. source level, spectral characteristics, sound radiation characteristics), which could be used to identify the noisiest vessels. Therefore, the Workshop **recommended** that ship source characteristic data be evaluated to identify the noisiest ships and quantify their relative contribution to overall ocean noise. The Workshop further **recommended** that those ships that contribute disproportionately to ocean noise be considered a priority for replacement or application of ship-quieting technologies.

The Workshop noted that the 17 Sustainable Development Goals agreed in August 2015 by the 193 member nations of the United Nations[4], included a strong commitment to the world's oceans under Goal 14, including the following targets:

- by 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution; and
- by 2020, conserve at least 10% of coastal and marine areas, consistent with national and international law and based on the best available scientific information.

The Workshop **agreed** that addressing ocean noise was essential to meet these targets.

7.2 Identify potential outputs of the Workshop relevant to the Commission's collaboration with the IMO

The Workshop **recommended** that the Commission develop a paper for submission to the IMO MEPC, providing an update of recent information, available since the IMO guidelines were adopted in 2014, related to the extent and impacts of underwater noise from shipping. The paper should address questions raised at the IMO including an overview of the relative contribution of shipping to the ocean noise budget compared to other sources and an evaluation of the potential benefits of applying different noise reduction strategies across global shipping fleets.

8. NOISE MEASUREMENTS AND MODELLING RELEVANT TO MASKING

8.1 Measurements of ambient noise and sound mapping

The Commission, International Quiet Ocean Experiment (IQOE), NOAA, ONRG (Office of Naval Research Global), TNO (the Netherlands Organization for Applied Scientific Research) and Netherlands Ministry of Infrastructure and the Environment hosted a two-day workshop in April 2014 in Leiden, Netherlands, on Predicting Sound fields: Global Soundscape Modelling to Inform Management of Cetaceans and Anthropogenic Noise. The motivation for this Workshop was a need by decision makers to characterise, monitor and manage chronic anthropogenic noise for which soundscape modelling and mapping tools would be useful. Twenty-six participants from 11 countries evaluated existing sound mapping approaches and identified data gaps and research needs. Targets of a proposed two-year work plan, possibly focussing on a couple of case studies, included: a registry of anthropogenic operations by geographic region, an inventory of sound signatures of anthropogenic activities, a growing database of ambient noise recordings, standardised recording and data analysis paradigms, agreed modelling parameters, model validation, and visualisation tools that could predict noise footprints and cumulative noise maps, as well as quickly compare alternative operational scenarios.

The Workshop discussed the recommendations from the IWC/IQOE Workshop - which had all been endorsed by the Committee in 2014 – and also those arising from subsequent discussions by the Committee (IWC, 2015).

The Workshop further elaborated on these recommendations to provide examples of how the recommendations might be implemented, and the activities that would be required to do so (Table 1). The Workshop **endorsed** the recommendations listed in Table 1.

8.2 Measurements of noise characteristics of individual vessels

Leaper presented information on the noise characteristics of individual vessels. There is a need for a simple metric for the overall contribution of individual vessels. This can be considered as the 'acoustic footprint' of that vessel. A simple metric characterising the acoustic footprint can be used to address questions about the relative contribution of different vessels. For example, what is the relative effect of replacing several smaller vessels with one larger, potentially louder, one? Leaper *et al.* (2009; 2014) used the simple two dimensional area estimated to be ensonified to a certain received level to represent the acoustic footprint. This allowed an estimate of the relative contribution of different

[4]*http://www.un.org/sustainabledevelopment/oceans/.*

Table 1

Recommendation examples and effort required combined from the IWC/IQOE Workshop in 2014 and this current Workshop.

Recommendation	Example	Level of effort required
1. Noise generation		
1.1. Compile a log/registry of what noise sources operate where and when	Ship Automatic Identification System data, licensed activities generating intense sounds such as seismic surveys, and offshore pile driving.	Bookkeeping, no research need but has proven challenging. Within Europe, states are developing registries of noise generating activities to meet requirements of the Marine Strategy Framework Directive.
1.2. Compile inventory of: (a) sound source signatures; and (b) parameters that affect signatures	(a) Source levels and spectra and spectrograms, beam patterns; (b) as a function of vessel speed, draught, etc.	Some data collection left to do, in particular on parameters affecting signatures. Some desktop work/data compilation, some research.
1.3. Identify noisiest sources/vessels	What are the noisiest ships that could most benefit from application of noise quieting?	Data collection, data mining.
1.4. Create an inventory of ambient noise	Statistical distribution of noise levels, on various time scales.	Some data collection necessary in specific areas, otherwise data mining.
2. Noise modelling and prediction		
2.1. Create inventory of parameters that affect sound propagation	Sound speed profile in the water and seafloor, absorption.	There are databases on bathymetry and ocean parameters with large-scale coverage and detailed info in specific areas; depending on area might need to do additional data mining or collection.
2.2. Model noise levels on a variety of time, space and spectral scales	Need high resolution model for short-term, localised monitoring; low-res for ocean-basin scale.	Data mining, slow processing exercise.
2.3. Quantify uncertainty and accuracy; validation	Validate existing models (some available as share-ware) with spot measurements, or model against model.	Data mining and processing exercise.

Note: 1.1, 1.2, 1.4, 2.1, 2.2, 2.3 were recommendations made by the IWC/IQOE 2014 workshop; 1.3 are recommendations from the current Workshop.

vessels to the overall acoustic footprint of the fleet and an evaluation of change as a result of slow steaming practices. This definition of footprint is a simple generalisation that does allow comparisons to be made taking account that shipping is truly global, with individual vessels transiting through many different whale habitats and propagation environments. The results were sensitive to different assumptions about propagation but indicated that the noisiest 10% of vessels may contribute between around 48% and 88% of the total acoustic footprint. Based on a review of the general relationship between source level and speed, the results suggested substantial noise reduction associated with slow steaming. For example, for a typical container ship travelling at 25 knots, the total acoustic footprint would be reduced to 21% for slow steaming at 20 knots.

In discussion, it was noted that studies such as Leaper *et al.* (2014) and Veirs *et al.* (2016) provide support for identifying priorities for replacement or application of quieting technologies to accomplish the recommendations to reduce ocean noise contributions by shipping. In addition, it was noted that the relationship between source level and speed was not the same for all vessels. The Workshop **encouraged** further studies to generate a better understanding of the source level to speed relationship for a range of vessel types.

The Workshop also **recommended** the use of Automatic Identification System (AIS) and source characteristic data to relate shipping density data to estimated loss of acoustic habitat from shipping noise in regions where acoustic impacts may be particularly severe but measurements of noise levels are not available.

9. MASKING METRICS

Reyes presented information (SC/J16/SNAM02) on the potential acoustic masking of Commerson's dolphins (*Cephalorhynchus commersonii*) from ship noise in shallow waters off the Argentine Patagonian coast. Broadband acoustic recordings for different types of vessels were obtained in two coastal areas of southern Patagonia Argentina (Bahía San Julián and Ría Deseado) where Commerson's dolphins are the target of dolphin watching and are also exposed to other vessel noise coming from recreational, fishing and freighter vessels. Commerson's dolphins are small dolphins that produce mostly narrow-band high-frequency (NBHF) clicks with all the energy above 100kHz for echolocation and communication. Recently, Reyes *et al.* (2016) described that this species in Bahía San Julián produces whistles and broadband clicks with frequency content well below 100kHz down to 4kHz. Whistles may be used for parental communication between the mother-calf pairs of Commerson's dolphins, while broad-band clicks may be suitable for communication among adults. Ship noise recordings were quantified as received third-octave levels (RTOLs) at the time of closest point of approach. The potential decrease in acoustic space for Commerson's dolphins in the presence of vessel noise was estimated following Hermannsen *et al.* (2014) for third-octave bands of 1, 10 and 125kHz. The first band was centered at 1kHz, which is in the lower frequency range of harbour porpoise hearing, which was assumed as the best proxy for Commerson's dolphins' hearing capabilities. The second band was centered at 10kHz, which is the upper limit indicated for the noise contribution of ship activity according to the Wenz curves, and in a frequency band where porpoises have a relatively good hearing and Commerson's dolphins produce whistles in Bahía San Julián. The third band was centered at 125kHz, which is the frequency range where porpoises have their most sensitive hearing and where Commerson's dolphins produce clicks for echolocation and communication. Ship noise from a range of different vessel types substantially elevated median ambient noise levels across the entire recording band from 200Hz to 200kHz at ranges between 10 and 500m. Vessel noise is able to reduce acoustic space by 90% within a distance of 500m in the third-octave bands of 1 and 10kHz. The increase in ambient noise levels at the frequency band of 10kHz has the potential of masking whistles, affecting communication between mother and calf. Besides, assuming a maximum communication range between mother and calf of 500m using NBHF clicks, as has been estimated for porpoises, ship noise levels at the third-octave band of

Table 2
Recommendations for further research on masking parameters.

Recommendation	Example	Level of effort required
1. Compile inventory of parameters relevant to masking.	Audiograms, critical ratios, critical bandwidths, temporal integration, etc.	Experiments, data collection, research
2. Need better understanding of masking release mechanisms (Erbe *et al.*, 2016).	Spatial release from masking, co-modulation masking release, Lombard effect.	Research
3. Undertake research on signal-to-noise ratio required for signal detection, discrimination, recognition, comfortable communication.	A higher signal excess is required to 'make sense' of a signal (Erbe *et al.*, 2016).	Research

125kHz may decrease the range for communication by 50% up to a maximum of 67%, and the range of echolocation at a maximum of 74% at distances between 1 and 100m. Additionally, the increase in background noise levels at the 125kHz band may mask broad-band clicks produced by Commerson's dolphins in Bahía San Julián. These results show that several types of vessels increase ambient noise levels not only at low frequencies but also at medium and high frequencies, where toothed whale hearing seems to be most sensitive, and thus vessel noise should be considered over a broad frequency range when assessing noise effects on Commerson's dolphins and other small cetaceans. Even though acoustic masking may be a short-term effect caused by a single exposure, cumulative impacts of repeated short-term exposures may produce long-term effects such as reducing fitness of the animals.

The Workshop thanked Reyes for presenting the new data on Commerson's dolphins. In discussion, it was recognised that concerns surrounding masking have primarily focused on low-frequency sounds. However, the Workshop noted the need to consider the effect of high frequencies on species such as small dolphins, which are sensitive in this range. The Workshop **encouraged** further work to articulate where this potential loss of acoustic habitat imposes itself on the life functions of these small dolphin species. They highlighted the need to consider different taxonomic levels and acoustic clades when considering the effects of sound on marine mammal species.

9.1 Review of masking in cetaceans

Erbe presented information compiled from her recent review paper on masking (Erbe *et al.*, 2016). Masking is defined as both the process and the amount by which the threshold of hearing of one sound is raised by the presence of another. The Power Spectrum Model of Masking assumes the auditory system consists of a series of overlapping bandpass filters; a listener attends to the filter that encompasses the signal, or has the highest signal-to-noise ratio (SNR); there exists a critical SNR (the critical ratio), below which the signal is masked. Masking and critical ratios have been measured with several captive marine mammals in various listening tasks, showing that the Power Spectrum Model often effectively predicts masking, in particular when the signal is of tonal character and the noise is broadband and continuous. Other natural scenarios, however, are more difficult to assess and model, e.g. when the noise has temporal gaps, as in pulsed noise from pile driving and seismic airgun arrays, and strongly amplitude-modulated ship noise, or when signal and noise are spatially separated, arriving at the listener from different directions. The spectro-temporal characteristics of noise can change as noise propagates through the ocean (e.g. the brief broadband pulses from seismic airguns can turn into extended frequency-modulated sounds), meaning that the masking potential, the type of signals it affects, and the species that might be impacted change with range from the source. Many questions remain before masking can effectively be incorporated into the management of specific anthropogenic operations. While there is confidence in the ability to predict whether a (tonal) signal is detectable in many types of noise, there are no data on signal discrimination, recognition or comfortable communication in any marine mammal. Based on information from terrestrial animals and humans, it is known that significantly higher SNRs are needed for successful communication.

There are many marine mammal species for which even the most basic information on hearing capabilities is non-existent. Masking studies with realistic signals (e.g. communication or echolocation sounds) and realistic noise are needed, and studies are needed to investigate natural masking release phenomena. Last but not least Erbe highlighted that the biological significance of masking, or 'How much is too much?' is not yet fully understood.

The Workshop thanked Erbe for this review of work on masking.

It was noted that the conversation surrounding acoustic habitat loss has been focused around the ability of cetaceans to detect the calls of conspecifics, environmental signals and echolocation. In discussion, the Workshop highlighted that detection of an acoustic signal does not mean an individual will be able to recognise the content of the signal, even in cetaceans, for which some species may change their behaviour (e.g. Lombard effect) in response to the changing acoustic environment. Studying these thresholds between detection and recognition will prove challenging, as it is not currently possible to duplicate many sound sources of interest (e.g. seismic airguns) in a captive setting.

The Workshop **recognised** that other complications can arise when attempting to determine the exact mechanisms by which acoustic disturbance can impact a marine mammal species. Furthermore, received levels do not necessarily predict an individual's response to sound, but may be dependent on the individual's behavioural context. For example, an individual faced with multiple 'small' stressors, such as whale-watching vessels, may not react to what might normally be considered the larger disturbance (e.g., a nearby container ship) because of the more proximate source of disturbance. This may also lead to other indirect effects, such as an increased risk of ship strikes due to the individual's distraction and highlights the need to consider the different impacts of various vessel types and the relationship between disturbance, distance and duration.

The Workshop **recommended** the activities listed in Table 2 as further avenues of research needed to better quantify the factors underlying masking.

9.2 Masking and loss of communication space in baleen whales

Clark presented a review of communication space in baleen whales, whereby each species occupies different acoustic spaces depending on the characteristics and functions of their sounds, and showed how various anthropogenic sounds overlap with those spaces. Within this framework, an acoustic space is defined by the dimensions of the frequency band in which the sound occurs, the distance over which the sound operates (communication range for cetaceans *vs* range over which noise propagates), and the duration of the sound. For low-frequency specialists such as baleen whales, for which experimental audiometric data are lacking, there are data supporting the conclusion that auditory thresholds are driven by ambient noise levels and can be used to estimate how vessel noise reduces communication space (e.g. masking). After showing several examples of acoustic communication in whales (Clark *et al.*, 2009; Williams *et al.*, 2014), examples were provided demonstrating the dynamics and scales over which ship noise and seismic airgun impulses influence the acoustic environment and North Atlantic right whale acoustic habitat. It was emphasised that the mechanisms for calculating the dynamics of lost acoustic environment are well established and should now be considered as 'commodities'. Although there are uncertainties (e.g. environmental factors for computing transmission loss), the limiting factors in estimating lost acoustic space, masking, or acoustic habitat loss are primarily driven by biological uncertainties (e.g. animal distribution, density, behavioural context, auditory sensitivity). The essential question, thus, becomes how do changes in the acoustic environment from anthropogenic sound sources translate into acoustic habitat loss for particular species, reduced opportunities for essential life functions, and possible impacts at population levels?

The Workshop thanked Clark for this presentation on loss of communication space.

The Workshop discussed the importance of identifying places and populations where acoustic habitat modelling should be applied. Comparison of different regions, such as the North and South Atlantic were considered potentially valuable, although this raised the question of appropriate scales from a biological and management perspective.

Additionally, a potential confounding variable is climate change, the effects of which will likely be cumulative and complex, introducing multiple new stressors into the system. The Workshop **recommended** reducing the most tractable stressors, such as anthropogenic noise as a way to increase populations' resilience and improve their future prospects.

When considering multiple stressors, the differences between the use of the terminology 'aggregate' and 'cumulative' threats were discussed, with emphasis on properly distinguishing between these terms. The term 'aggregate' threats was used to refer to multiple sources of the same type of threat (e.g. noise from various sources), while the term 'cumulative' threats was used to refer to a variety of stressor types (e.g. toxins, noise, reduction in prey base, climate change).

It was noted that communicating the threat of acoustic habitat loss to the general public and policy-makers is a difficult task. The Workshop **recommended** the continued development of clear and concise statements and visually compelling communication tools, such as those presented by Clark, to convey the importance and impact of anthropogenic noise in the oceans.

10. INTEGRATING MASKING INTO STATISTICAL MODELS OF WHALE POPULATION DYNAMICS

10.1 PCoD and related models

New gave a presentation on the evolution of a family of statistical models of anthropogenic disturbance and their application to several marine mammal populations. When considering the increasing levels of anthropogenic noise in the world's oceans, cetacean populations are of particular concern because of their known susceptibility to sound and reliance on it for communication and feeding. As a result, a National Research Council working group (NRC, 2005) had attempted to address the issue by outlining a conceptual framework, known as the Population Consequences of Acoustic Disturbance (PCAD), which linked changes in behaviour to population effects via 'life functions'. At the time, the NRC working group estimated that the scientific community was 10 years from being able to apply the PCAD framework to any marine species. However, advances in statistical tools and computational power enabled the first test of the PCAD framework to begin in 2009.

Four marine species were chosen for the initial application of the PCAD framework; elephant seals (*Mirounga* sp.; New *et al.*, 2014; Schick *et al.*, 2013b), coastal bottlenose dolphins (*Tursiops* sp.; New *et al.*, 2013b; Pirotta *et al.*, 2014), North Atlantic right whales (*Eubalaena glacialis*; Schick *et al.*, 2013a), and beaked whales (family *Ziphiidae*) New *et al.*, 2013a). These case studies led researchers to expand the framework to include multiple forms of disturbance, both anthropogenic and environmental, and physiological effects in addition to behavioural ones. These generalisations resulted in the framework being renamed the Population Consequences of Disturbance, PCoD (New *et al.*, 2014). Additional developments included the ability to distinguish between disturbances that have acute, immediate effects on vital rates (e.g. survival or fecundity) and disturbances that have a chronic effect on vital rates through individual health. In this model, health (defined as internal factors that impact an individual's fitness), then becomes the main route by which indirect effects on individual vital rates take place (New *et al.*, 2014). Given some knowledge of the population and the proportion impacted by disturbance, the changes in vital rates can be linked to population effects, thus connecting changes in individuals to changes in the population. This last link, between vital rates and population effects, is arguably one of the best studied in ecology (Caswell, 2001).

Masking is not a disturbance, nor is it a behavioural or physiological response in and of itself. Instead, the ensonification of the oceans can lead to masking, which can result in either physical impairment or behavioural change through changes in foraging or call behaviour. It is these potential changes that may then result in an effect on individual health, vital rates and then population dynamics.

While the application of the PCoD framework has been successful, it has its limitations. Primary among these is that there are few other marine mammal populations that have been as intensively studied as those listed above, resulting in a lack of appropriate datasets for many species of conservation and management concern. This has led to the development of two alternative approaches to the PCoD framework (Table 3). Both alternatives circumvent the need to understand the impacts of changes in behaviour and physiology on health and the link between health and vital rates, as this is most often the largest data gap. The first approach, known as 'PCoD-lite', uses published relationships from the literature to draw the connections between the effects of disturbance on behaviour and physiology, and how these changes impact vital rates. For example, with killer whales (*Orcinus orca*), disturbance from boats is known to alter behavioural budgets, reducing the time spent foraging (Williams *et al.*, 2006). In addition, the index of Chinook salmon (*Oncorhynchus tshawytscha*) abundance is known to be correlated with killer whale survival (Ford *et al.*, 2009).

Table 3

Definitions for the various PCAD/PCoD modeling frameworks.

PCAD	The original 2005 NRC framework (NRC, 2005).
PCoD	Data are available to parameterise all the transfer functions (e.g. the equations describing the link between disturbance and behavioural change, vital rates and population dynamics) in the framework (New *et al.*, 2014).
PCoD-lite	Data are not available to parameterise the transfer functions between behavioural and physiological changes and an individual's health. Instead, the transfer functions between these changes and vital rates are informed from the scientific literature.
Interim PCoD	Data are not available and there is no information in the scientific literature for some of the transfer functions in the framework (e.g. the amount of disturbance an individual can tolerate before there is a change in behaviour). Expert elicitation is used to inform these transfer functions, but only until empirical data are available (King *et al.*, 2015).

In a worst-case scenario, the killer whales would be unable to compensate for the time lost foraging, making that change in behaviour equivalent to a proportional decrease in the availability of Chinook salmon (i.e. the index). Therefore, a change in behaviour could be linked to a vital rate, which could then be used to determine the effects on the population dynamics (Williams *et al.*, 2016).

The second approach to addressing data limitations in the PCoD framework is the use of expert elicitation and is known as interim PCoD. In this case, knowledge is elicited from experts regarding parameter values that might otherwise be obtained through field research and analysis (King *et al.*, 2015). The field of conservation uses this sort of expert judgement routinely, but efforts to incorporate expert judgement are often lacking in structure (Elith *et al.*, 2013) and dominated by cognitive biases and heuristics (McBride and Burgman, 2011). Expert elicitation is a formalised process to obtaining the needed knowledge and uses structured approaches to improve the process (Estévez *et al.*, 2013; Hayes *et al.*, 2007), resulting in more robust and unbiased estimates. In the context of PCoD, elicited values may include vital rates like survival, but can also be estimates of parameters such as the number of days of disturbance required to impact an individual's vital rates, or perhaps their energy reserves. The interim PCoD approach has been used to assess the effect of off-shore wind farm construction on harbour porpoise (*Phocoena phocoena*) in the North Sea (King *et al.*, 2015), as well as the exposure of bottlenose dolphin populations to anthropogenic disturbances in the Moray Firth, Scotland (Lusseau *et al.*, 2011). The use of the term 'interim' is important, because the approach is not meant to replace scientific research, but rather to be used as a temporary measure, allowing management and conservation decisions to be made while empirical data are collected.

The Workshop thanked New for the detailed presentation of the PCAD and PCoD modeling frameworks. The Workshop noted that masking has not been integrated into any PCAD, PCoD, PCoD-lite or Interim PCoD models conducted to date. The Workshop **recommended** efforts be made to expand these statistical frameworks to predict the population consequences of masking. The Workshop further **recommended** research to quantify the relationship between reduction in acoustic space and prey intake.

The Workshop discussed the use of expert elicitation for quantitative variables in the Interim PCoD models. The Workshop recognised that eliciting expert opinion may be the only way to generate model inputs in certain cases, but expressed concern that expert elicitation can sometimes be misinterpreted. It was noted by some that decisions come with costs, and the costs of making the wrong decision could be high. Some members of the Workshop expressed concern that expert opinion can include strong biases depending on which experts are included or excluded.

After discussion of noise and cumulative effects, the Workshop noted that, due to the lack of information on whether cumulative effects are additive or multiplicative, the PCoD model currently requires simplifying assumptions about background levels of disturbance, and have been developed to explore the consequences of varying levels of a single disturbance variable. New noted that the PCoD working group is developing new models incorporating cumulative noise exposure and multiple anthropogenic stressors.

10.2 Population viability analyses incorporating noise

Lacy presented SC/J16/SNAM03, along with an introduction to the use of Population Viability Analyses in the conservation and management of wildlife populations. Population Viability Analysis (PVA) is a class of scientific techniques that uses demographic modelling to assess risks to wildlife populations and evaluate the likely efficacy of protection, recovery, or restoration options (Beissinger and McCullough, 2002; Shaffer, 1990; Sjögren-Gulve and Ebenhard, 2000). PVA can extend standard demographic projections (Caswell, 2001) in several important ways: (1) the impacts of forces external to the population (e.g. changing habitat quality, extent, and configuration; interactions with other species in the community; impacts of disease or contaminants; harvest, incidental killing, or other direct human impacts) on the demographic rates can be explicitly considered and evaluated; (2) the cumulative impacts of multiple threats to a population can be examined, allowing tests of the relative importance of each threat individually and as possibly synergistic or offsetting interactions; and (3) uncertainty in the population trajectory caused by intrinsic (e.g. demographic stochasticity, limitations in local mate availability or other density dependent feedbacks, inbreeding impacts) and extrinsic (e.g. environmental variation, occasional catastrophes) stochastic factors can be explicitly modeled, usually through the use of simulations.

The Vortex population model (Lacy, 2000; Lacy and Pollak, 2014) is an individual-based simulation for PVA that might be suitable for assessing the impacts of anthropogenic noise on cetacean populations. Vortex models the details of demographic process (e.g. sexual maturation, mate acquisition, inter-birth intervals, calf survival, survival of later age classes, reproductive senescence) and projects population trajectories as the aggregate fates of the simulated individuals. The software has the flexibility to specify the probability of each demographic event being a function of individual (e.g. sex, age, body condition, genetics), population (e.g. density, age structure), or external variables (e.g. habitat quality, contaminants, prey availability, disturbance). The flexibility of the Vortex model allows for consideration of several aspects of population dynamics that are observed in some cetaceans but not normally included in wildlife population models, such as long dependency of calves on dams, reproductive senescence long before the maximum life span, and pod structure that determines breeding opportunities and limits dispersal. Vortex has been used to assess threats to hundreds of species, including cetaceans such as killer whales (Lacy *et al*., 2015; Taylor and Plater, 2001) and bottlenose dolphins (Lacy and Wells, 2009; Manlik *et al*., 2016). Vortex simulations have been confirmed to produce population trajectories that are consistent with monitored wildlife populations (Brook *et al*., 2000b) and with other population models (Brook *et al*., 2000a). The overall structure of the program was published in Lacy (2000), and the compiled program and documentation are distributed freely at *http://www.vortex10.org/Vortex10.aspx*.

In order to model the impacts of noise (or any stress) on populations in Vortex, the impacts of noise on one or more demographic rate(s) must be specified. Ideally, these functional relationships would be obtained from studies on the populations of interest, but otherwise they might be assumed to be similar to relationships measured on related species, elicited from expert opinions based on understanding of the ecology of the species, or specified as hypotheses to be explored in terms of the possible impacts and the concordance of population trajectories generated by the model with survey trends. Inevitably, there will be considerable uncertainty around the values of many of the parameters entered into a PVA. Therefore, sensitivity testing of the impacts of alternative values on the population trends is an important part of PVA. Such tests can be carried out by running scenarios with different parameter values or by sampling, in each iteration of the simulation, each parameter value from a distribution describing our uncertainty in that rate. The variability in the population fates generated by the simulation can then be partitioned into that caused by the uncertainty in the basic demography of the species, uncertainty in the levels of threatening processes impacting the populations, and uncertainty in the demographic responses to those threats.

The above PVA approach was used to examine the expected threats to the southern resident killer whale (SRKW) population in the northeastern Pacific Ocean. Initially, the modeling focused on assessing the likely impacts of a proposed oil shipping terminal, caused by increased noise disturbance, frequency of boat strikes, chronic pollution from PCBs and oil, and likelihood of major oil spills. These threats were assessed individually and as cumulative impacts on top of a currently depleted base of the whales' preferred prey (Chinook salmon), with expected further declines in Chinook projected with climate change (Lacy *et al*., 2015). The mechanisms through which these changes would impact population demography could be estimated and quantified with available data on the relationships of birth rate and mortality to prey abundance (Vélez-Espino *et al*., 2014; Ward *et al*., 2009), the rate of bioaccumulation of PCBs in blubber and the effects of maternal PCB loads on calf survival (adapted from Hall *et al*., 2012), the projected frequency and extent of oil spills, and the number of deaths due to boat strikes. Moreover, data were available on the reduction in time spent feeding when killer whales were in the presence of boats, and it was assumed that such disturbance by boat noise could be directly translated into a parallel reduction in feeding efficiency that would be equivalent to a reduction in prey availability, consequently reducing birth rate and survival. In this population, the projected impact of increased boat noise caused greater reduction in population growth than did the predicted impacts of increased boat strikes, pollution, or occasional large oils spills. The cumulative impact of all the expected effects of the increased oil shipping traffic was more than two times worse than any one impact. However, the projected effects of the reduced prey base due to climate change was greater still than the impacts of the vessel traffic, and any effects of increased shipping on killer whales could be offset by improvements to the Chinook stocks. Increasing the availability of Chinook salmon to whales may be accomplished through altered management of the fishery, spawning habitat restoration, or reduction of anthropogenic disturbance to improve foraging efficiency.

These analyses have been extended in SC/J16/SNAM03 to examine what improvements in demography would be required for this killer whale population to reach one stated recovery goal of 2.3% annual growth, and what reductions in anthropogenic threats would be required to achieve the necessary demographic improvements. It was found that the recovery target could not be reached through mitigation of any one factor alone, although efforts to increase salmon stocks would generate the greatest benefit to southern resident killer whales. To reach the recovery target through Chinook recovery alone, Chinook stocks would have to reach levels that have not been observed at any point in the last 40 years. The PVA identified that the recovery target could be reached by mitigating threats in combination. A 50% reduction in noise disturbance and a 25% increase in the Chinook abundance would be sufficient. Increases in Chinook abundance above levels that have been observed over the last four decades would allow the SRKW population to grow at rates beyond the 2.3% recovery target.

The above analyses focused on a population that is very well studied, with 40 years of detailed demographic data, assessments of demographic consequences of changing prey availability over time, and measurements of the reduction in feeding behaviour caused by boat noise. Such data are rare. However, the same approach might be used to explore possible noise (and other) impacts on population projections, with the understanding that the results will indicate relative impacts of threats only to the extent that the sparse data, proxy species, or expert opinion provide plausible estimates of key demographic parameters, magnitude of threats, and relationships between threats and demographic consequences. Even with such limitations, sensitivity testing can help to clarify what is known and is not known, document what assumptions and hypotheses are made with respect to the threats, quantify the effect of uncertainty of parameter values on our uncertainty of outcomes, identify research priorities to reduce the more influential uncertainties, identify species characteristics that increase vulnerability, and test the relative benefits of management actions. As an initial test of applying the methodology to cases with much less demographic and threat data, Lacy and colleagues compared PVA models for four oceanic dolphin species with different demography. Impacts of noise, depleted prey, and chronic pollution were drawn from studies of coastal odontocete populations as proxies. Recognising that the relative impacts in the model were fully dependent on the as yet unknown severities of the threats to these populations, as well as the very uncertain descriptions of baseline demographic rates, across the ranges that we tested the damage done by reduced prey availability, contaminants, and noise disturbance were comparable. The oceanic bottlenose dolphins, with the highest estimated population growth (due to longest potential longevity and highest birth rates) could tolerate the highest levels of threats, but were still brought down to about zero population growth at the highest levels tested for any one threat. Pacific white-sided dolphins, with lower estimated birth rates, were shifted from slow but positive to negative growth by any of the threats. The shorter-lived long-beaked and short-beaked common dolphins had lowest baseline population growth rates, and were most severely impacted by the threats considered in the PVA.

The case studies illustrated that population modelling tools already exist to explore the likely population-level consequences of threats such as noise disturbance. The few well-studied populations presented offered evidence of serious impacts of noise on cetacean populations, mediated through reductions in feeding efficiency and consequent reductions in fecundity and survival. The effects of anthropogenic noise on the populations compound other threats, and together can be sufficient to cause population declines. In most cases, necessary data are lacking to quantitatively describe the relationships of noise to individual behaviour and demography, and consequently to population-level impacts. At this time, data are lacking on a sufficiently large and diverse array of cetacean species to allow confident extrapolations of quantitative effects across species, or definitive statements about which species would be most vulnerable to the effects of changes to their acoustic habitats.

The Workshop thanked Lacy for his presentation.

Some members of the Workshop expressed concern that despite the best scientific efforts to understand the consequences of environmental stressors on population viability, in some cases by the time the research is completed, the populations under study may already be suffering irreversible decline. However, the Workshop noted that PVA can be used to identify populations that may be most resilient to external stressors, and therefore prioritise population protection where it would be most effective.

It was noted that much of the scientific development is hindered by lack of guidance from policy-makers on the level of risk that might be considered acceptable (Williams *et al.*, 2016). It was noted that a key strength of a PVA is to model the likely outcome of both continued habitat degradation and habitat restoration that would result from management actions. By communicating the population consequences of alternative management actions (including no action), PVA is an effective tool for communicating the risk and benefit of alternative management options to stakeholders, managers and policy-makers.

The Workshop noted that the PCoD and PVA tools provide complementary approaches for understanding the influence of different environmental stressors on population dynamics, and emphasised that although data may be lacking for all of the links in the models, they are still extremely useful for organising the way scientists think about threats. The Workshop **agreed** that these tools hold great promise for dealing with the issues of masking and aggregate/cumulative effects.

The Workshop also noted that some stressors may act through multiple pathways, which have not been incorporated into any of the PCoD or PVA models presented to date. For example, masking may lead to a reduction in foraging efficiency as well as loss of mating opportunities.

The Workshop **emphasised** the importance of matching the application of models to management and conservation needs, and noted that these models provide an opportunity for researchers to work with policy makers and managers to document ways of reducing the effects of noise. The Workshop also **stressed** the importance of recognising that unknown threats cannot be quantified in models, and therefore identification of all relevant threats that may affect population dynamics is extremely important.

In order to integrate changes in acoustic habitat into statistical models of whale population dynamics, the Workshop **recommended** the following tasks:

- generate and provide the best estimates of all aspects of a model (e.g. functional links, parameters, sound field maps) along with associated measures of uncertainty;
- develop model structures and outputs to address pertinent management questions about impacts of anthropogenic noise and the effectiveness of mitigation to reduce ocean noise; and
- use these models as an heuristic tool to help researchers define their thinking, construct hypotheses and explore uncertainty in ways that may not be possible through field studies alone.

The Workshop noted that, given current knowledge, the best way to model population consequences of loss of acoustic habitat is through reduction in foraging opportunities or caloric intake. This approach hinges on two critical links: one between noise and prey intake; and another between prey intake and demography. Prey-demography links are available (or could be derived) for several well-studied marine mammal populations summarised in Williams *et al.* (2016), but fewer data exist to quantify effects of acoustic habitat changes on prey intake. In particular, data to quantify the link between acoustic habitat and prey intake do not yet exist for most baleen whale species. To prioritise future work, the Workshop **recommended** the identification of two sets of priority cetacean case study species or populations. One set could be selected based on urgent conservation needs (e.g. central Baltic harbour porpoise). Another set of data-rich case studies could be selected to form 'archetype' populations that would be useful to refine and improve population models. The Workshop noted that results from future studies on tractable populations may have to be extrapolated to those populations of high conservation priority for which there do not exist sufficient data for direct application of these models. The Workshop **recommended** that fully parameterised models from archetype case studies be evaluated for their potential for extrapolation to other species and habitats.

11. DISCUSSION AND SUMMARY

The Workshop **agreed** that there is now compelling evidence that chronic anthropogenic noise is having an effect on the marine acoustic environment in many regions (Clark *et al.*, 2009; Hatch *et al.*, 2016; Moore *et al.*, 2012), and **recognised** emerging evidence that compromised acoustic habitat can affect some cetacean populations adversely (SC/J16/SNAM03; King *et al.*, 2015). Given cetacean dependence on listening to and producing sounds for their survival, the Workshop **recommended** increased research and management consideration of the importance of acoustic habitat in cetacean conservation efforts.

Workshop participants noted the inherent difficulty of drawing causal linkages between loss of acoustic habitat and adverse effects on cetacean populations, and **agreed** that the lack of scientific certainty should not hinder management actions to reduce ocean noise. The Workshop **recommended** that member nations undertake management efforts to keep quiet areas quiet and make noisy areas quieter (Williams *et al.*, 2015).

The Workshop reiterated its **recommendation** that ships that contribute disproportionately to ocean noise levels be considered a priority for replacement or application of ship quieting technologies.

Noise is one of many stressors in the environment in which cetaceans live. Therefore, the Workshop **recommended** that noise be explicitly considered as part of a suite of cumulative effects in models being developed for cetacean conservation and management efforts. In addition, the Workshop **recommended** that noise impact models should consider single noise stressors, aggregate noise stressors, and the combination with other non-acoustic stressors.

The Workshop noted efforts already being undertaken to evaluate the impacts of loss of acoustic habitat on foraging, but **recommended** that similar research be initiated to look at other impacts of noise on other life functions (e.g. breeding). Specifically, the Workshop **recommended** research that demonstrates the linkages between masking of sounds/loss of acoustic habitat and the affect on other life functions, similar to what has been done with the examples presented on foraging.

Recognising new commitments by both the Convention on Biological Diversity (Aichi Targets 7 and 11) and under the United Nations Sustainable Development Goals (Goal 14), including that governments around the world have committed to protect 10% (36 million square kilometers) of the world's oceans by 2020, the Workshop **recommended** that nations integrate consideration of ocean noise into such efforts.

Recognising the efforts of the IUCN Joint Species Survival Commission/World Commission on Protected Areas Task Force on Marine Mammal Protected Areas, the Workshop **recommended** that efforts to identify and protect Important Marine Mammal Areas should integrate information on anthropogenic noise into site selection and management, and where possible, reduce ocean noise levels in the Important Marine Mammal Areas.

12. ADOPTION OF REPORT

The Workshop thanked the Chair, Convener, Speakers and Rapporteurs for their hard work. The report was adopted at 16:00 on 6 June 2016.

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Annex A

Agenda

1. Convenor's opening remarks and Terms of Reference
2. Election of Chair
3. Appointment of rapporteurs
4. Adoption of agenda
5. Available documents
6. Introduction and Background
7. Consideration of previous recommendations from IWC Scientific Committee
   - 7.1 Identify the scientific work needed, and ways the outputs from the workshop can contribute, to progress on the goal endorsed by the Committee in 2008 of reducing noise from shipping (i.e., 3dB in 10 years; 10dB in 30 years in the 10-300Hz band)
   - 7.2 Identify potential outputs of the Workshop relevant to the Commission's collaboration with IMO
8. Noise measurements and modelling relevant to masking
   - 8.1 Measurements of ambient noise and sound mapping
     - 8.1.1 Outcomes of 2014 IWC/IQOE Workshop on regional and ocean-basin scale underwater sound field mapping techniques
   - 8.2 Measurements of noise characteristics of individual vessels
     - 8.2.1 Developing a definition of 'acoustic footprint'
     - 8.2.2 Relating potential masking impacts to source levels of individual ships to support evaluation and prioritisation of application of quieting technologies
9. Masking metrics
   - 9.1 Review of masking in cetaceans (Erbe)
   - 9.2 Masking and loss of communication space in baleen whales (Clark)
10. Integrating masking into statistical models of whale population dynamics
    - 10.1 PCoD and related models (New)
    - 10.2 Population viability analyses incorporating noise (Lacy)
11. Discussion/wrap-up

Annex B

Glossary of Terms

Acoustic Environment: sound levels in the marine environment, including all natural and anthropogenic sounds, independent of any organism.

Acoustic Habitat: the aggregate sound field from multiple sources compiled at spatial and temporal scales consistent with the ecology of marine mammals; implies the perspective of a listener.

Acoustic Space: the dimensions of the frequency band in which the sound occurs, the distance over which the sound operates (communication range for cetaceans vs. range over which noise propagates), and the duration of the sound.

Aggregate Threats: the combination of multiple sources of the same type of threat (e.g. noise from various sources).

Communication Space: the volume of space surrounding an individual, within which acoustic communication with conspecifics may occur (adapted from Clark *et al.*, 2009).

Cumulative Threats: the combination of a multiple stressors from a variety of stressor types (e.g. toxins, noise, reduction in prey base, climate change).

Masking: interference of noise with hearing; or, more specifically, both the process and the amount by which the threshold of hearing of one sound is raised by the presence of another (Erbe *et al.*, 2016).

SNR: signal-to-noise ratio.

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Annex C

List of Documents

SC/J16/SNAM

1. Draft agenda (23 May 2016)
2. Reyes Reyes, V., Hevia, M., Hildebrand, J., Iñíguez, M., Tossenberger, V. and Melcón, M. Potential acoustic masking of Commerson's dolphins (*Cephalorhynchus commersonii*) from ship noise in shallow waters of the Argentine Patagonian coast.
3. Lacy, B., Clark, C., MacDuffee, M. and Paquet, P. Ranking the relative importance of multiple anthropogenic threats to endangered killer whales to inform effective recovery plans.