Report of the Workshop on Cumulative Effects, 23 and 24 April 2018

Members: Hall (chair); Atkinson, Avellan, Avila, Barreto, Cholewiak, Cipriano, Cooke, Coscarella, Cosentino, De la Mare, Demaster, Domit, Donovan, Forestell, Fortuna, Freitas, Gulland, Hubbell, Kitakado, Lundquist, Marcondes, McKinlay, New, Noren, Palka, Parsons, Rojas-Bracho, Ridoux, Ritter, Rose, Rowles, Scheidat, Schwacke, Segueira, Simmonds, Slooten, Suydam, L. Thomas, P. Thomas, Urban, Weinrich, Ylitalo

1. Convenor's opening remarks and Terms of Reference

The workshop on Cumulative Effects was held in Bled, Slovenia, on 23rd and 24th April, 2018. It was chaired by Hall. Ylitalo and Cippriano were appointed as rapporteurs and Hall thanked them for the invaluable contribution to the workshop.

Hall welcomed the workshop participants, thanked them for attending the meeting and looked forward to a lively and wide-ranging discussion on how the impact of cumulative effects on cetacean populations could be investigated and potentially progressed with the support of the IWC subcommittee on Environmental Concerns. It was agreed at IWC/SC/67a that a workshop on this topic would provide an important contribution to the initiatives currently being undertaken in other fora, and would be a particularly timely activity following the recent publication of the U.S. National Academies of Sciences, Engineering and Medicine report on "Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals" (National Academies of Sciences, Engineering, and Medicine, 2017). This topic is important to IWC through its concern about the effect of environmental change on cetaceans, particularly noted in IWC Resolutions 1998-5 and 2007-7. It also follows on from an IWC workshop on Habitat Degradation that was hosted by the University of Siena in 2004 (IWC, 2006).

Introduction

Hall opened the workshop by briefly summarising the report of the IWC Habitat Degradation workshop (IWC, 2006). Although the emphasis of the 2004 workshop was on the impact of deterioration in cetacean habitat rather than explicitly on cumulative effects, there was much overlap between the focus and objectives of that workshop; which were to (1) develop frameworks and approaches that could be taken to understand the impact of habitat degradation on cetaceans, both at the individual and population levels (2) consider case studies in relation to the species and populations to which the frameworks could be applied; (3) help assess current understanding of cetacean critical habitat and evaluate issues such as habitat quality indices; and (4) review methodological considerations including modelling approaches.

The objectives of the current workshop were similarly broad and were to:

(1) Summarise the methods available for assessing cumulative effects of multiple stressors on cetaceans (both individual and population);

(2) Discuss and review those methods and frameworks;

(3) Identify case studies on specific species and populations (identifying their pros and cons) to which the frameworks, or components of the frameworks, could be applied;

(4) Develop criteria required for robust case studies;

(5) Recommend the means and ways of progressing this work and communicating the importance of recognising the potential impact of multiple stressors on cetaceans to a wider audience.

Methods available for assessing cumulative effects of multiple stressors on cetaceans

L. Thomas gave a summary of the findings of the “Approaches to understanding the cumulative effects of stressors on marine mammals” reported by National Academies of Sciences, Engineering, and Medicine (2017), of which he and Schwacke, also present at the workshop, were National Academies of Sciences (NAS) committee members responsible for undertaking this work. The remit of that work was to (a) review scientific understanding of cumulative effects, (b) to assess theoretical and field methods used to estimate the effects of anthropogenic stressors, and (c) to identify new approaches to improve these assessments. The NAS committee distinguished between cumulative risk (combined risk from exposure to multiple stressors) and aggregate risk (combined risk from exposure to one single stressor from multiple sources or pathways). Both are of relevance to cumulative effects assessments. A major concern behind such assessments is the possibility of synergistic interaction – i.e., cases where the effect of multiple stressors is greater than the sum of the effects of the stressors applied independently. However, as is well recognized in toxicological studies, such cases can arise simply because the dose-response function is non-linear. Although no experimental studies on interactions between multiple stressors have been undertaken for marine mammals, the NAS committee reviewed meta-analyses of laboratory and small-scale studies on other animals and plants. They found no strong patterns that would enable generalities to be made about when to expect interactions between stressors, except one: if stressors act along the same causal pathway then interaction may be more likely.

Given the considerable scientific uncertainties, the NAS committee created a flowchart to enable managers to determine when possible interactions may be of concern when considering permitting a new anthropogenic stressor or change in existing stressor (Figure 1). They also created a conceptual framework for considering cumulative effects, the so-called PCoMS model (Population Consequences of Multiple Stressors, Figure 2). This builds upon the earlier PCoD (Population Consequence of Disturbance) model (King *et al*. 2015). The framework assumes that stressors cause physiological and behavioural responses in exposed animals; these responses may have direct, acute effects on demographic parameters (survival and reproduction) or may have chronic effects by affecting animal health. Individual effects on demographic parameters may lead to population consequences depending on the number and level of animals affected, and on population processes such as density dependent responses. A key concept is that animal health acts as a buffer, integrating the short-term responses to stressors and affecting the longer term demographic parameters. Health may be quantified in several ways (see Figure 2). Lastly, given the considerable scientific uncertainty around cumulative effects assessment, the NAS committee recommended a dual approach to dealing with the possibility of ecological surprises: relatively inexpensive population surveillance to detect major unexpected declines combined with monitoring of early-warning indicators of population-level responses, if such indicators can be found.

In discussion, the Workshop participants noted the importance of understanding the definitions for the various terms used in the cumulative effect models presented and summarised above. For example, ecological drivers such as climate change would not be considered a stressor whereas a reduction in food and increases in temperature resulting from climate change, would be considered as stressors. The terminology used is therefore defined in a glossary which is given in Appendix 1 and this is consistent with the terms used in the U.S. National Academies of Sciences report.

The Workshop noted that multiple levels of responses could be included in the models including physiological and behavioural responses and that responses to stressors could differ across species. Transgenerational effects were not explicitly considered in the NAS models but the Workshop noted the need to include these effects in specific cases. There was also some discussion regarding the use of qualitative assessments, which are often proposed approaches for assessing cumulative effects of multiple stressors, *in lieu* of other options. However, it was suggested that these qualitative approaches are no substitute for real data collection for a quantitative approach. Although response scales were also considered by the NAS committee, it was most concerned with measurable behavioural and physiological responses. The Workshop also recognised the difficulties in collecting response measurements and noted that the collection of baseline information is critical, particularly prior to the introduction of a novel activity that would introduce an additional stressor into cetacean habitat.

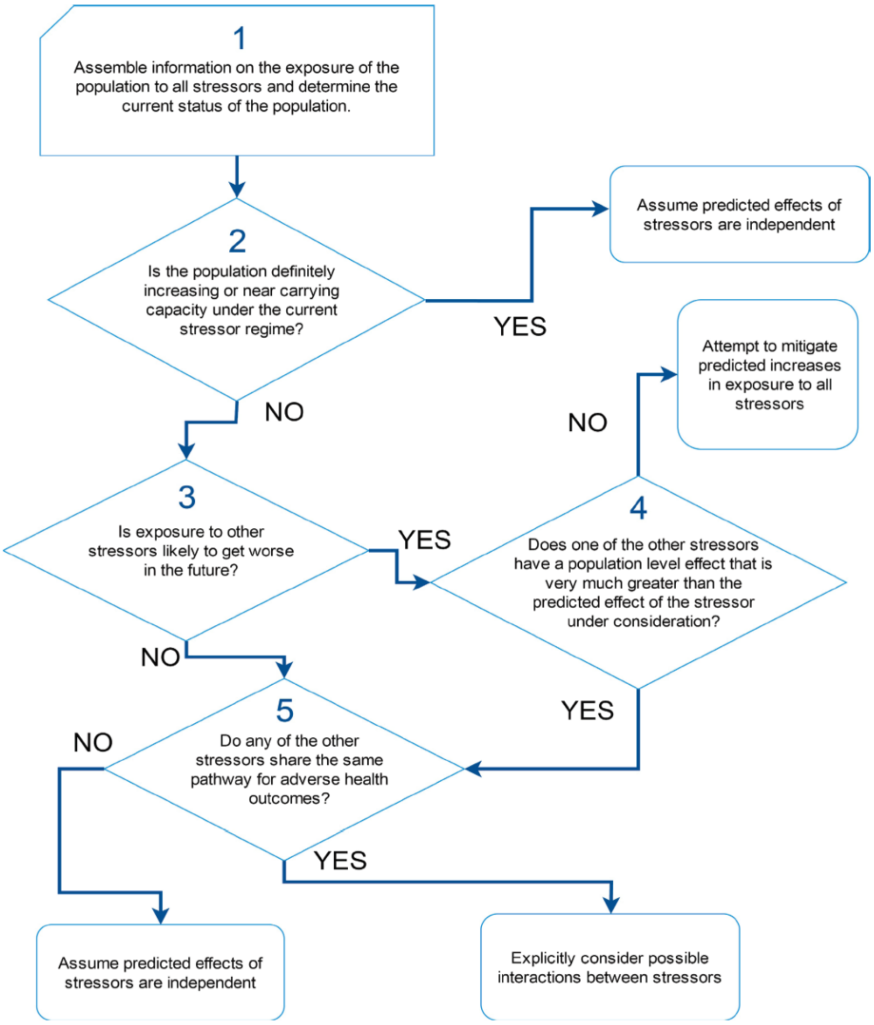

Figure 1. A decision tree for identifying situations where studies of the possible interactions between stressors should be given a high priority when considering the effect of a focal stressor on a population. (Reproduced with permission from National Academies of Sciences, Engineering, and Medicine 2017).

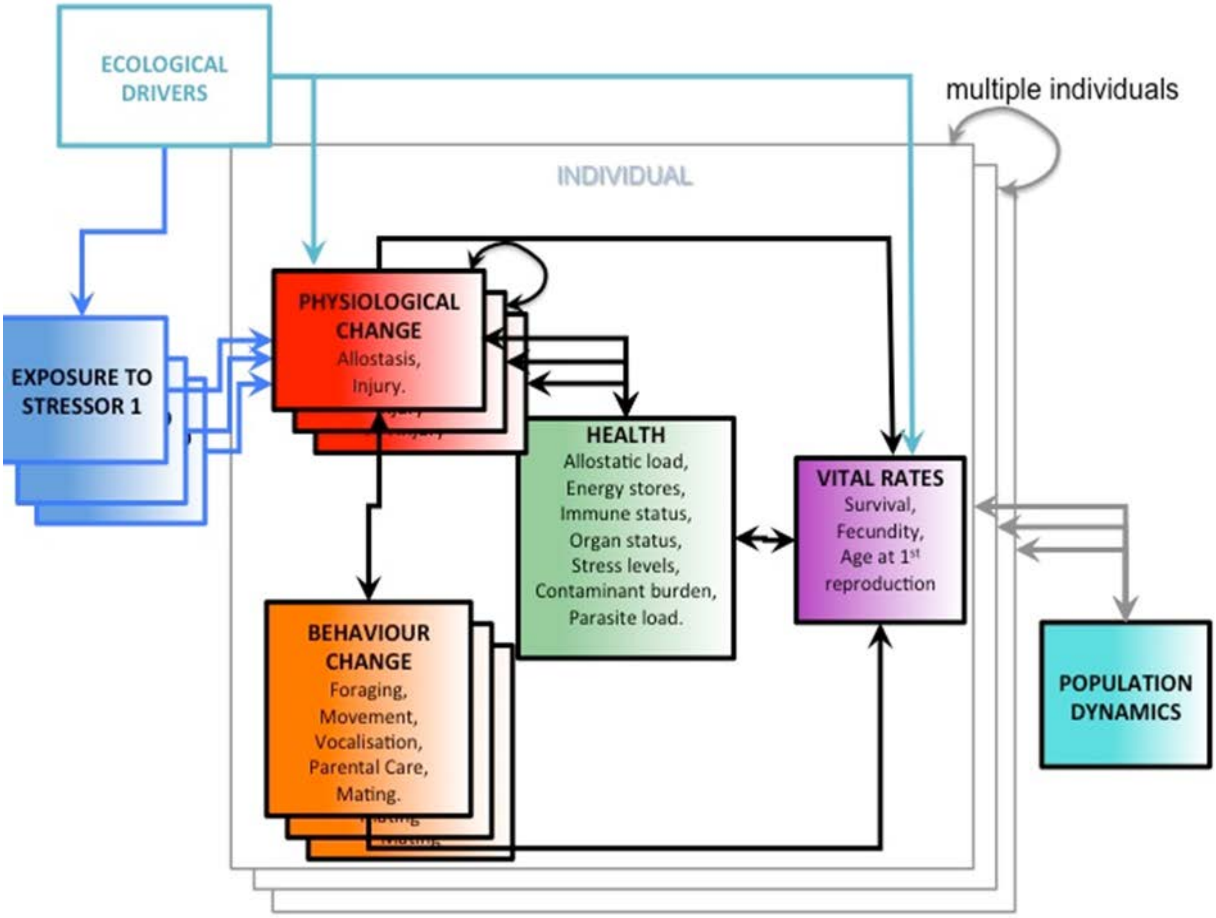

Figure 2. The Population Consequences of Multiple Stressors (PCoMS) framework. Each compartment (bold box) in the framework represents one or more quantities (variables) that evolve over time. Compartments are connected by arrows that represent causal flows (also called “transfer functions”. Stressors affect multiple individuals (indicated by the stack of light boxes), causing population-level consequences (Reproduced with permission from National Academies of Sciences, Engineering, and Medicine 2017).

This led to a discussion on dose-reduction experiments in which effects might be observed following the decline in a single stressor. One example discussed was a study that reported reduced ship traffic and vessel noise in the Bay of Fundy, Canada after 11 September 2001 and decreased levels of stress-related faecal hormones in North Atlantic right whales during the same time frame (Rolland *et al*. 2012). However, it was recognised that there are limitations to these studies and opportunities for them to be applied to situations where multiple stressors are impacting cetacean populations are likely to be limited.

Modelling the population consequences of exposure to multiple stressors

L. Thomas gave a second talk covering in more detail modelling approaches to assessing cumulative effects. The presentation focussed on the PCoD and PCoMS frameworks, and the cases in which the former has been implemented to date. These cases have largely focussed on body condition and energetics as the basis to quantify individual health. In cases where data are available, these are used to construct detailed data-based models, often focussed on modelling individual energy budgets in either a stochastic or deterministic framework. In more data-poor situations, formal expert elicitation has been used to parameterize the overall PCoD model, or in some cases to bypass the health component by proceeding to directly elicit putative relationships between stressor dose and ecological response. Although considerable progress has been made in formulating PCoD models, PCoMS represents a much more challenging problem that will require considerable effort to approach.

The Workshop discussed this approach in more detail and agreed that collecting population monitoring data and health measures for cetaceans are likely to be the components of the model in which advances towards understanding cumulative effects could be made. An example was the 1999-2000 gray whale unusual mortality event that occurred along the west coast of North America, in which observations of strandings indicated that something was happening to individuals in the population, prior to the population level effects being detected. Although both population dynamics and health assessments are equally subject to imprecision, development of new methodologies for population assessments (e.g. environmental or eDNA, unmanned aerial vehicles (UAV) and passive acoustic monitoring approaches) and health measures (e.g. hormone measurements in faeces or blow and body condition determined through aerial photogrammetry) will improve data precision. The Workshop suggested that efforts should be directed towards the further development of both of these assessments (health and population) to reduce uncertainty in the risk models. But the Workshop recognised that population abundance assessments, particularly for cetaceans are typically relatively imprecise and are primarily used to detected large scale changes in abundance over time. Without associated health assessments, it is difficult to determine the mechanism(s) behind any detected declines, which are often only observed sometime after the onset of the cause or causes. Thus, it was emphasised that monitoring health parameters rather than focussing on population abundance and trend monitoring.

Furthermore, the Workshop noted that for understanding exposure impacts and determining the most appropriate metrics, animal movements (e.g. 'residents' in exposure zone are exposed for a long period of time compared to animals that move through the zone and have a much shorter period of exposure) must be included.

Health assessments and multiple stressors: challenges and opportunities

The need to more comprehensively assess the health of cetaceans is now widely recognised as a key component in making headway towards understanding cumulative effects of multiple stressors. Hall described a conceptual model for understanding the multiple risk factors involved in the occurrence of a given disease that was developed by Rothman in the 1970s (Rothman, 1976) in the field of human and veterinary epidemiology, the “causal pie” model. Rothman defines risk factors (i.e. different disease-causing stressors) as individual or “component” causes. Outcomes (that can be a specified disease or it can simply be all-cause mortality) result from the occurrence of a number of “sufficient” causes, pathways through which the disease comprising multiple component causes may occur. Thus each sufficient cause is a causal pie comprising a number component causes (i.e. risk factors or stressors, Figure 3). Several different causal pies may exist for the same outcome. If, and only if, all component causes of a sufficient cause are present, i.e. the completion of a causal pie, does the disease or outcome occur. The effect of each individual component cause hence depends on the presence of the other component causes that constitute a given causal pie. There is therefore no limit to the number of component causes.

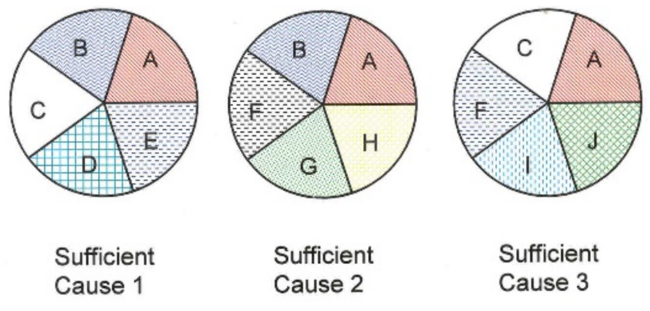

Figure 3. Rothman’s causal pie model. Three sufficient causes are illustrated, all resulting in the same disease or outcome. The sufficient causes are made up of different component causes.

The model can also assist in understanding interactions between component causes. For example, in Figure 3, if G was a substance that did not exist then no disease would occur through sufficient cause 2 as the causal pie would not be complete. In this case component causes B and F would be biologically independent because they act through different pathways (sufficient causes 1 and 3). However, if G was then created, the disease could then also occur through sufficient cause 2 and since component causes B and F are also present in sufficient cause 2 they would interact. Component causes can be exposures of any kind, biotic or abiotic, intrinsic or extrinsic. Wensink *et al.* (2014) investigated the applicability of this model to ecological and evolutionary biology and illustrated the concept in relation to how component causes may accumulate through an animal's life course. Vital rates might be improving during an animal's life but causal pies of morbidity (disease) and death are being filled in during maturation and ageing making the distance to death shorter. The time at which component causes, i.e. the addition of stressors occur, will influence the likelihood that a given sufficient cause will be complete. So the causal pie model can assist in determining when and why exposures, risk factors, or stressors (component causes) have an effect. Component causes can also influence when other component causes have an effect.

One study design that is widely used in human and veterinary epidemiology to investigate the causes of a disease is the case control study. Hall then outlined how case control studies can be used to estimate an effect measure in causational epidemiological studies. The most robust method for understanding the relative risk of a disease is achieved by following individuals in a population that have been 'exposed' or 'unexposed' to the stressors of interest over time, to determine the occurrence of disease in each group (known as a prospective cohort study). The incidence rates for each group are calculated as the number of incident cases divided by the population at risk (or animal-time at risk). The relative risk (or incidence rate ratio) is then calculated as the ratio of the incidence rate in the exposed divided by the rate in the unexposed. It is important to specify the time period at risk because if you are looking at all-cause death then the longer the time at risk is, the more similar the incidence (of death) will be among the exposed and unexposed (if the time is long enough, the risk of death will be 100% in both groups resulting in a relative risk=1). However, this is generally only a viable option in a very limited number of cases for cetaceans where individuals can be consistently followed over time to determine exactly when disease or death occurred. But another option is to use a case-control approach. In this study design, individuals who have developed the disease (cases) and individuals without the disease (controls), are identified. The previous exposure to the stressors for each case and control is then identified. The case group is composed only of individuals known to have the disease or outcome and the control group is ideally drawn from the population that gave rise to the cases. The odds of exposure between cases and controls is then calculated and the ratio of the odds is calculated as the odds in the exposed divided by the unexposed. Odds ratios > 1 indicate the likelihood of disease is higher in the exposed, but the associated 95% confidence intervals must be considered when interpreting the results.

There is extensive literature in the medical field on this approach and it has drawbacks (DiPietro *et al.*, 2010; Szeker *et al.* 2017). The odds ratio is a good approximation of the relative risk when the outcome is infrequent and becomes less reliable as the outcome becomes more common. In addition, the exposure of interest must precede the disease, something which may not be reliably determined for all stressors of interest. However, it has the potential to be applied to the problem of understanding the effect of multiple stressors on cetaceans, particularly as dead stranded animals can be used if the exposures or stressors of interest can be identified. An example of where this approach has been applied in cetaceans is a study in which the risk of infectious disease mortality following exposure to contaminants in harbour porpoise was investigated (Hall *et al*. 2006).

In addition, Hall presented a summary of the individual based model (IBM) approach (Effects of pollutants on cetacean populations) (Hall *et al.* 2018; Carlsen *et al*. 2004; Stow and Carpenter 1994) that has been developed under the IWC Pollution 2020 initiative and how it might have some application for investigating the population consequences of exposure to multiple stressors, particularly those affecting immune function. This model quantifies the effects of PCBs on potential population growth rate, using maternal contaminant concentrations to modify calf survival and disease resistance. The states (live/dead, age, parturition, and contaminant concentration) of individuals are simulated through time. Because IBM models incorporate stochasticity, multiple simulations produce a range of potential growth rates from which confidence intervals may be calculated. We refer to the growth rates as “potential” because there is no attempt to incorporate density dependence into the model. The model simulates the fate of individual female dolphins, using published fecundity and survivorship data for case study populations. The model also simulates the accumulation of PCBs through transplacental transfer, suckling, and prey and loss of PCBs through female lactation (depuration). Maternal PCB concentrations then affect calf survival and disease resistance in a dose-dependent manner. Published information from laboratory animal models with associated uncertainty, was used to provide an estimated concentration-response function, due to the absence of data for cetaceans. The model can then be run under various scenarios of exposure to infectious diseases, the estimated impact on the population of a viral epidemic and the time to recovery explored. It is conceivable that if data on the cumulative effect of stressors (synergistic or antagonistic effects) which act on immune function (such as contaminants and biotoxins) were available, this could also be incorporated into the model. This data could also be from surrogate model species or from *in vitro* studies, in the absence of cetacean-specific concentration-response functions.

The Workshop thanked Hall for providing this summary.

Review of cumulative effect modelling approaches and frameworks

Health measures

The Workshop discussed the advantages and disadvantages of the modelling approaches and frameworks, and how they can be applied to studies of cetaceans. Health measures, including our ability to assess the magnitude of the stress response that could be used in cumulative effects models were discussed by the Workshop. Participants acknowledged that the term ‘stress-levels’ is often used in relation to the response of animals and humans to various risk factors or situations but that it is widely used without a full understanding of its meaning. Animals increase circulating ‘stress hormones’ such as the glucocorticoids, particularly cortisol as well as catecholamines following a stimulus. These responses are entirely normal and whilst they may indicate the presence of a stressor or a stressful situation, the animal is responding as it should in order to cope with the perceived danger. However, the health of the animal is in jeopardy when this endocrine response is inappropriately enhanced or reduced. The Workshop noted that stress response has several different arms - neurological (e.g. behavioural avoidance), cellular responses (e.g. indicators of oxidative stress) as well as the endocrine response, recognising that evaluating baseline data are essential before these additional stress response measures can be interpreted. However, instant response measures such as cortisol concentrations may be impossible to interpret without substantial context information. It was suggested that a review of stress responses from the cellular, neurological and endocrine perspectives and how they relate to marine mammals was needed and this was discussed.

Other health measures, such as body condition, may be more directly valuable but we need to understand the relationship between body condition indicators and population response measures, particularly changes in vital rates. And whilst it may seem that body condition is relatively easy to assess, in practice it is very difficult to accurately measure energy stores in cetaceans.

Vital rates

The Workshop noted that care is needed when defining reproduction, as pregnancy is not the same measure as the number of live births. For the suggested modelling approaches, 'successful reproduction' is generally defined as the number of offspring living to age one, as was seen to be the most useful measure. Adult survival estimates are often also needed but changes in overall survival rates can be very difficult to measure. Individual growth rates and energy balance or budgets are probably also linked to reproductive success rates, but the models at this stage only include observable rather than unobservable state changes.

Study designs

Reference populations for cumulative effect studies that differ in only a few exposures of interest (e.g. similar habitats with fewer vessels) might allow for valuable comparative studies.

The Workshop also discussed and considered the 'expert elicitation' approach, in which the synthesis of opinions of subject experts is utilised where there is insufficient data or when such data is unobtainable at the time an assessment is required. Expert elicitation is essentially a scientific consensus method that quantifies uncertainty and is an interim approach. Clearly background documentation is necessary for the experts involved in this approach, as is information on who was invited to participate, who participated and who declined. Although the Workshop noted that expert elicitation approach is not ideal, it does have value for filling in knowledge gaps in situations where decisions are needed quickly, as well as providing guidance on the potential use of data to address a particular problem. The Workshop noted that taking a precautionary management approach is another alternative to the expert elicitation, noting that this still essentially relies on opinion regarding where the level of precaution should be set.

Ecosystem modelling

The Workshop received summaries of two relevant work streams being carried out by members of the IWC sub-committee on Ecosystem Modelling.

Long-term environmental variability on whale populations

Cooke summarised the framework (developed by Cooke, 2007) for incorporating environmental variation into models of the net recruitment rate of baleen whales. Drawing from last year's report of the Ecological Modelling sub-committee Cooke described how they were investigating the effect of environmental variability on recovering populations of baleen whales (also drawing on earlier studies under MSYR working group). These modelling efforts projected population recovery trends using deterministic and stochastic-influenced models, for a range of assumptions, including no, medium, or long-term variability, and low, medium, and high-quality habitats. In early years, there were no differences between the stochastic and deterministic models. However, more fluctuations were observed in the future as baleen whale populations continue to recover. These models were also able to explore the effects of disturbance where they either reduce the amount of time spent feeding and where they reduce the effective reproductive rate. The Workshop thanked Cooke for his valuable input and noted that a dramatic decline in a population may be due to historic environmental changes which could occur at any time.

Individual-based energetic models

De la Mare described a modelling class library that links environmental characteristics relating to prey availability to population characteristics through the modelling of individual animals on daily or longer time steps. The model was originally developed to link rates of increase observed in depleted populations of baleen whales to characteristics in yield curves. In particular the model allows for density dependence to occur not only in births, but also in age-specific mortality and for the covariance in the demographic parameters to arise, all as emergent properties of the model. The model uses individual animal models with a detailed energy budget to determine reproductive success, growth and mortality in an environment where food has a patchy spatial distribution. The details of this model can be found in SC67b/EM07. All the major processes of the animal's seasonal activities are modelled including migration, breeding, and feeding. Their location and movement are specified by latitude, longitude, and velocity. Animals must search for food and look for new food patches when local food abundance falls due to the effects of local intra-specific competition. Animals accumulate long-term memories about locations where they can forage at specific times over multiple seasons, but with a forgetting coefficient to discount older memories. Complete forgetting occurs when the discounted memory falls below a threshold. The same structure could also be used to accumulate aversive memories relating to stressors. The model uses an environment with spatial grid structure that allows flexible modelling of spatial characteristics of prey through recursion, i.e. a cell on any level of a spatial grid can itself contain a finer scale grid. Each cell can have an arbitrary number of data values and parameters and could include information on local stressors. A cell address is fully resolved by any latitude and longitude that it contains, and the smallest cell containing a given location is automatically selected. The model includes options to model individual feeding dives (SC67b/ForInfo/28) and searching behaviour (SC/67b/EM04) to locate individual prey schools.

De la Mare noted that the model is coded in standard C++ and is available on request to interested researchers. The Workshop participants thanked De la Mare for his input and appreciated that this approach would be potentially very constructive for assessing cumulative effects of multiple stressors.

The Workshop discussed the complexities involved in measuring energetics in cetaceans due to variability in space (e.g., depth, migration range) and time (e.g., seasonality changes). Blubber mass and thickness has been used widely used as a measure of body condition for cetaceans. But more recently other techniques have been explored such as deploying telemetry tags to measure animal density and buoyancy (Miller *et al*. 2004), determine protein biomarkers and adipocyte size in blubber biopsy samples (Kershaw *et al*. 2018; Castrillon *et al*. 2017) and photogrammetry (Durban *et al*. 2015).

In addition, the prey field is well defined in the De la Mare energetic model whose dynamics is highly adjustable, and the scale of which can be refined in the energetics models. De la Mare noted that the type of feeder (e.g., specialist, generalist), as well as the effect of competition for animals that share the same environment, can be included in the model.

Transgenerational, epigenetic effects could also incorporated into the De la Mare energetic model and this led to a discussion among the participants on the importance and potential impact of these effects. It was concluded that in some instances these transgenerational effects (e.g. on lower growth rates in subsequent generations where nutritional limitations were imposed in the previous generation) could be significant and consideration should be given to their impacts.

Case studies

A presentation of an assessment of the global threats to cetaceans, as well as four potential case studies for understanding the impact of cumulative effects were presented to the Workshop.

Avila presented a summary of her recent paper entitled “Current global risks to marine mammals: taking stock of the threats” (Avila et al. 2018). Based on a literature review of more than 3000 papers over 4 years, the authors geo-referenced and encoded available information from more than 1780 papers on marine mammal threats into a database, which is also available to the scientific community. Threats to 121 marine mammal species that occurred globally between 1991 and 2016 were included. From the database a series of risk maps were developed, linking information about species-specific vulnerabilities to large-scale species distributions, thus providing an assessment of how threat levels for marine mammals vary in space. Risk areas were produced based on binary (presence/absence) range maps using the core habitat. Risk severity was quantified with respect to 1) number of species affected per cell, 2) proportion of affected species per cell of the total marine species present per cell, 3) number of threats documented per cell. The results show that almost all studied marine mammal species, 98% (119 species), were documented to be affected by at least one threat. Bottlenose dolphin (*Tursiops truncatus*) was the species with the largest range of diversity of threats. Incidental catch affected the most species (112 species), followed by pollution (99 species), direct harvesting (89 species) and traffic-related impacts (86 species). Risk areas were identified for 51% of marine mammal core habitat. The majority of local marine mammal communities are at high-risk in 47% of world coastal-waters. Higher risk areas were located mainly in temperate and polar coastal waters and in enclosed seas. However, risk areas differed by threat types and taxa. The risk maps presented in this study are based on documented threats and species requirements and are a more nuanced approach which could be a starting point for systematic and comprehensive global research and conservation efforts.

In addition, Avila presented unpublished results of the documented effect or outcome of the threats. Death and diseases/health problems were the major effect of the documented threats on the marine mammals between 1991 and 2016.

The Workshop thanked Avila for presenting information on a global mapping tool to visualize hot spots for cumulative effects for cetaceans.

Bottlenose dolphins in the United States and the United Kingdom

The common bottlenose dolphin (*Tursiops truncatus*) was proposed as a model species that could be highly amenable for studying the nature of cumulative effect interactions. A significant amount of information is currently available on baseline demographics and vital rates for *Tursiops*, and much has been documented regarding stressor effects and the health status of inshore stocks, particularly along the southeast U.S. and Scottish east coasts. There are over 40 Bay, Sound, and Estuary (BSE) *Tursiops* stocks, managed as separate units by NOAA/NMFS, along the U.S. Gulf of Mexico and Atlantic coast. Many of these stocks have been the focus of health assessment, stressor exposure and effects assessments, and photographic monitoring studies over the several decades. The health assessment studies have included temporary capture for hands-on sampling, comprehensive veterinary examination, blood and tissue analysis, and satellite and/or VHF tag attachment. Aside from having extensive baseline health information, including established reference ranges for a suite of health parameters (e.g. normal ranges of blood values and body mass index), the BSE stocks have well characterized reproductive and age-specific survival rates [e.g., (Kellar et al. 2017, Schwacke et al. 2017, Lane et al. 2015, Wells et al. 2014, Wells and Scott 1990]. In addition, BSE *Tursiops* remain in the inshore waters year-round, which can simplify stressor exposure assessments and facilitate photographic follow-up monitoring for longitudinal studies of effects. The multiple, independent stocks within the BSE habitats make *Tursiops* conducive for epidemiological study, allowing for populations with varying degrees of exposure to stressors to be compared.

Three specific BSE stocks are considered particularly good candidates for assessing cumulative effects. The first of these is the Southern Georgia Estuary System (SGES) stock, which has been followed since 2004 to assess the exposure and associated health effects of chemical contaminants. The SGES habitat has been highly polluted with persistent contaminants, and these dolphins have been found to have some of the highest tissue concentrations of polychlorinated biphenyls (PCBs) ever reported for marine species (Balmer et al. 2011, Kucklick et al. 2011). The PCB exposure is associated with disruption of thyroid hormones and suppressed immune function in the SGES stock (Schwacke et al. 2012), and

PCBs are well-established to cause immune suppression in other marine mammal species (Ross et al. 1995, Ross et al. 1996). Another risk for this stock is its potential exposure to morbillivirus. Health assessments of SGES dolphins conducted in 2015 determined that at least some members of the stock were previously exposed to the deadly virus (Rowles et al. unpublished). Morbillivirus was determined to be the cause of a massive Unusual Mortality Event (UME) in 2013-2015, in which over 1800 dolphins stranded along the U.S. Atlantic coast (http://www.nmfs.noaa.gov/pr/health/mmume/midatldolphins2013.html). Morbillivirus infection, when not fatal, has been associated with long-term immune perturbations and chronic disease. The co-exposure to morbillivirus and high levels of PCBs, both of which are known to affect a common immune effects pathway, suggests a higher likelihood for effect interaction potentially leading to a synergistic and thus more severe impact on the population. The remaining two *Tursiops* stocks of interest are within the Gulf of Mexico. One, the Barataria Bay stock, was heavily impacted by the *Deepwater Horizon* oil spill, which has led to chronic disease conditions (e.g., immune perturbations, altered adrenal/stress response, and lung injury) and reproductive impairment (Kellar et al. 2017, Smith et al. 2017). Additional ongoing stressors in Barataria Bay include fishery entanglement and fluctuations in salinity, and more extreme and prolonged decreases in salinity are anticipated in future years with planned ecosystem restoration efforts. This low-salinity stress on top of the ongoing chronic oil-related disease conditions will certainly hinder the recovery of the population, and potentially lead to synergistic effects on population health through interactions in the hypothalamus-pituitary-adrenal (HPA) pathway.

In contrast, injuries following the *Deepwater Horizon* oil spill were not documented for the St. Andrew Bay stock (along the Florida Panhandle), but this stock is being impacted by other environmental stressors which also have the potential for HPA pathway interactions. High concentrations of DDT, a persistent pesticide, have been found in the St. Andrew Bay dolphins; metabolites of DDT are known to be toxic to the adrenal gland and can lead to impaired adrenal hormone response and thus inappropriate or inadequate response to stress events. In addition, a high prevalence of human interaction (i.e., provisioning) has been documented in this stock, raising the question of how these multiple stressors may interact through the HPA pathway.

Other populations of bottlenose dolphins which could be of interest for furthering our understanding of cumulative effects include those in the East coast of Scotland. Hall summarised the information available for this population which includes long-term abundance estimates (over the last ~20 years) as well as estimates of vital rates. Potential stressors in this region include noise and vessel interactions, pollution, pathogen exposure from sewage outfalls and exposure to biotoxins including domoic acid and saxitoxins.

Southern resident killer whales

Noren presented information on southern resident killer whales (SRKW), a group of resident type (fish eating) killer whales that inhabit the Northeast Pacific Ocean. The SRKW distinct population segment (DPS) is comprised of three matrilineal pods (J, K, L). This population occurs in waters off the United States of America and Canada, ranging from the central California coast (Monterey Bay) to southeast Alaska. The core critical habitat of SRKWs (April-Oct) includes coastal waters off Washington (USA) and the inland straights of Washington (USA) and British Columbia (Canada). Beginning in the late 1960s, a live-capture fishery removed killer whales for display at marine parks, resulting in an immediate steep population decline. Live captures of SRKWs ended in the early 1970s, and since that time the population experienced several periods of growth and decline. From 1996 to 2001, the population was reduced to 80 whales. Because of this decline and other factors, the Southern Resident killer whale DPS was listed as Endangered under both the U.S. Endangered Species Act (ESA) and the Canadian Species at Risk Act (SARA).

Individuals are highly tractable to study because there is an annual photo ID survey, which was initiated in the early 1970’s. As such, all births, deaths, and maternal relationships since that time are known. The total number of individuals (76 individual SRKWs as of Sept. 2017), survival rates (by age and sex class), and female fecundity (by age) are lower (Ward et al. 2013, 2016) in SRKWs compared to other resident populations in the Northeast Pacific Ocean (e.g., Northern Resident killer whales and Southeast Alaska resident killer whales). There is some evidence (fecal hormones, aerial photogrammetric images) that SRKWs have a high rate of pregnancy loss, including the loss of calves during late term gestation/early post-partum. The primary stressors facing SRKWs are lack of sufficient prey (quantity and/or quality), disturbance from vessels and sound, and exposure to chemical contaminants (e.g., persistent organic pollutants, POPs).

Southern Resident killer whales primarily consume salmon, particularly Chinook. Several salmon stocks in the region are depleted and listed under the U.S. ESA. The size of individuals in some stocks have also decreased over recent decades (Ohlberger et al. 2018). Vital rates (survival and fecundity) of both Northern and Southern Resident killer whales are related to indices of Chinook abundance (Ward et al. 2009). SRKWs compete with fisheries and other predators, particularly increasing populations of pinnipeds (Chasco et al. 2017 a, b). Finally, POP concentrations (measured in SRKW feces) may be higher when prey abundance is low (Lundin et al. 2016).

SRKWs are exposed to high levels of vessel noise and disturbance from shipping traffic, ferries, private boaters, and a large commercial fleet of whale watch boats from Canada and the US. During the summer months SRKWs can be followed by private and commercial whale watchers for nearly 12 hours per day. Changes in respiration rate, swim speed, and path directedness have been observed when boats are within 400 m (Williams et al. 2009). Rates of surface active behaviors (SABs) increase in response to close approaches and the number of vessels present within 400 m (Noren et al. 2009, Williams et al. 2009). Call amplitude (loudness) increases with increasing background noise, which increases with the number of vessels present within 1000 m (Holt et al. 2009). The metabolic cost of most of these short-term behavioural responses, measured through modelling and experiments on trained bottlenose dolphins, are relatively low, but do increase with intensity and/or repetition (Holt et al. 2015; Noren et al. 2012, 2013, 2017 a, b). The reduction of foraging behavior and increase in travel when boats are within 400 m (Lusseau et al. 2009) is likely to be a greater impact to SRKW, particularly because the number of hours spent foraging can significantly decrease when SRKWs are exposed to vessels for 12 hours (Noren et al. 2017 b). Vessel presence may increase stress hormones during periods of low prey availability (Ayres et al. 2012).

Relative concentrations of persistent organic pollutants vary by pod and individual (Krahn et al. 2007, 2009). Differences between pods reflect differences in habitat use patterns. As yet, no empirical studies to assess effects of POPs on reproduction and health have been conducted, but that is an area of concern, given the lower survival and reproductive rates for SRKWs. Preliminary results from a study on trained killer whales to assess POP transfer from females to their calves suggest that the highest contaminant concentrations are transferred in milk during the first few months post-partum, which is a concern, given that neonate mammals are still developing after birth.

Given the multiple risks facing Southern Resident killer whales, this population is an excellent case study for cumulative effects. Several killer whale populations (resident and transient killer whales) residing in the Northeast Pacific Ocean could be used as comparative populations to tease apart the relative impacts of risk factors facing Southern Resident killer whales. Trained bottlenose dolphins and killer whales could also be used to collect relevant physiological data to better understand physiological impacts of stressors.

Gulf of Mexico sperm whales

Garrison presented information on the northern Gulf of Mexico (GoMex) sperm whale population that has been the focus of environmental impact assessments and related studies since the late 1990s. The sperm whale is only cetacean species in the GoMex listed under the U.S. Endangered Species Act, and therefore the primary focus of this research has been supporting environmental assessments related to the potential impacts of energy exploration and extraction activities. In particular, the Bureau of Offshore Energy Management (BOEM, formerly Minerals Management Service) has supported several studies directed at understanding the response of sperm whales to exposure to seismic airgun activity (e.g., SWSS, Jochens 2008). Additional studies have focused on sperm whale prey resources and the habitats and spatial distribution of sperm whale in the Southeastern Gulf of Mexico (SEFSC, unpublished data). Most recently, a Population Consequences of Disturbance (PCoD) model has been developed for GoMex sperm whales that quantifies the behavioural and energetic effects of exposure to sound from seismic airguns (Farmer et al. in review). The PCoD study included the development of a detailed bioenergetics model (Farmer et al. 2018). Given the management requirements for understanding the influence of anthropogenic stressors on sperm whale population dynamics and the work done to date on behavioural and bioenergetic responses to exposure to sound, the GoMex sperm whale population may be a tractable study species to explore applications of the PCoMS approach.

Information on GoMex sperm whale abundance and spatial distribution has been collected since the late 1980s. Abundance estimates have primarily been developed from vessel-based visual line transect surveys. To date, the estimates used in MMPA stock assessment reports have not been corrected for the probability of detection on the trackline and thus are known to be negatively biased. The most reliable abundance estimates based upon survey data from 1996-2001, 2003-2004, and 2009 range between 763 animals (CV = 0.38) and 1,665 animals (CV = 0.20). The estimate for 2009 was substantially lower than that from 2003-2004, though the difference was not statistically significant. A recent abundance estimate derived from a spatial density model, averaged over all available survey data, and including corrections for detection probability was 2,138 (Roberts et al. 2016). Additional vessel data collected during the summers of 2018 and 2019 will provide updated abundance estimates and will be followed by a more robust analysis of temporal trends in abundance. There is a lack of information on the degree to which sperm whales in the northern GoMex utilise habitats of the southern Gulf outside of U.S. waters.

Sperm whale habitat use and spatial distribution are key considerations in evaluating the exposure of GoMex sperm whales to anthropogenic stressors. Spatial density modelling conducted by the SEFSC evaluated seasonal and spatial patterns in sperm whale density from recent survey data. There was a bimodal relationship with bathymetric slope whereby there were high densities of sperm whales in areas with high values for slope (i.e., along the shelf break), a gap in distribution, and then high densities in areas with lower slope (i.e., in deeper waters of the central Gulf). In addition, sperm whales demonstrated a strong association with mesoscale circulation features and regions with water flows tending to transport primary production from the continental shelf into deep waters and along the outer edges of eddies. These are regions where upwelling may be expected to occur driving high concentrations of mesopelagic secondary production. In general, the spatial density models predict high densities of sperm whales both along the shelf break from the Mississippi River delta into the western Gulf and in deep waters of the central Gulf. These spatial patterns are consistent with movement patterns of sperm whales tagged with telemetry tags during both the SWSS project (Jochens et al. 2008) and Natural Resource Damage Assessment studies conducted during 2010-2013 (Bruce Mate, Oregon State University, unpublished data) indicating distinctions between sperm whales that prefer “shallow” versus “deep” habitats. In addition, there is an area of high sperm whale density in the southeastern Gulf north of the Dry Tortugas. Telemetry tag studies and some genetic and photo-identification analyses suggest that sperm whales in this region may be distinct from those of the northern GoMex, and their range may include Mexican waters of the Campache Bank and the Florida east (Atlantic) coast. This apparent complexity in population structure and/or habitat use may result in sub-groups of sperm whales with differential exposure to various stressors.

The GoMex is one of the most highly industrialised bodies of water in the world and, as a result, sperm whales occupying the region are exposed to a broad suite of anthropogenic and natural stressors. The primary industrial activity is oil and gas extraction that is focused on the continental shelf and inner continental slope of the western GoMex. This includes oil platforms, pipelines, and high levels of vessel activity associated with servicing of this infrastructure. To a large extent, these activities overlap with regions of high sperm whale density along the shelf-break and inner continental slope. The eastern Gulf and deeper waters of the central Gulf are largely free from oil extraction activities.

Another key stressor for this population was exposure to oil from the *Deepwater Horizon* oil spill in 2010. Sperm whales were observed during the spill close to the wellhead and in the areas with the highest concentration of surface oiling. The footprint of the most intense oil exposure included deep waters of the north-central Gulf. Based upon this footprint, it was estimated that approximately 16% of the sperm whale population was exposed to surface oil and was expected to experience injury including reductions in both survival and reproductive success. In addition, recent studies have suggested the possibility of large-scale depletion of potential prey resources as a long-term secondary effect of the *Deepwater Horizon* oil spill. It remains to be seen if this is an additional, as yet unquantified, stressor for sperm whales.
A broad suite of additional stressors may influence sperm whale population dynamics, in particular the possibility of disease events, a large region of hypoxia in the central Gulf, and the potential transport of pollutants into the oceanic waters of the GoMex through inputs from the Mississippi River. The high level of industrial activity also results in very high levels of pervasive low frequency noise due primarily to vessel traffic and seismic exploration. While it is unlikely that sperm whales have the same sensitivity to low frequency sound that baleen whales may have, it is unknown whether or not chronic increases in noise levels interfere with sperm whale feeding and communication.

The available information on sperm whale behavioural responses, bioenergetics, and population dynamics has been recently integrated into a PCoD model focused on the influence of exposure to sound from airguns (Farmer et al. in review). The primary mechanism for impacts to the sperm whale population is through a behavioural response whereby animals suspend foraging activity in the presence of airgun noise. The model explicitly included the degree of overlap between sperm whales and the degree of airgun activity in different regions of the Gulf. The cessation of feeding may lead to depletion of metabolic reserves, reduction in the energy available for calving and lactation, and perhaps a starvation response and elevated mortality (Farmer *et al*. 2018). These responses at the level of individuals were integrated into a population model that also accounted for the reductions in survival and reproduction for the portion of the population exposed to *Deepwater Horizon* oil. The key uncertainty in this model is the degree of behavioural response to sound exposure. There is a dearth of available data to characterise this response and a broad range of values are reported in the literature. In addition, the underlying bioenergetics model relies upon data from other regions, and it is possible that GoMex sperm whales have chronically low levels of energetic reserves due to the long term and increasing exposure to industrial activities over the last 50-70 years. Identifying and addressing these key uncertainties through additional data collection will be essential for improving the current PCoD approach.

The GoMex sperm whale is a viable candidate in which to explore the development of a PCoMS approach that includes the effects of interactions between multiple stressors on population dynamics. Relative to other deep-diving cetaceans (e.g., beaked whales), there is a relatively rich collection of data on abundance, spatial distribution, behavioural responses, bioenergetics, and physiology. In addition, analogies may be drawn between bottlenose dolphins exposed to *Deepwater Horizon* oil and sperm whales experiencing similar exposure. For example, quantification of the intensity and duration of lung diseases or adrenal effects in bottlenose dolphins may be used to characterize potential impacts on sperm whales that could intensify the energetic costs associated with cessation of feeding or food limitation. The primary challenge for implementing the PCoMS approach will be developing and applying tools to assess the health and metabolic status of free-swimming sperm whales. Tools such as photogrammetric analysis of body condition, sampling and analysis of biopsy tissue samples, and sampling and analysis of fecal or breath samples hold some promise for improving health assessment. Ideally, the current models could be evaluated for sensitivity to key parameters, and field studies could be implemented to collect data that would reduce bias and uncertainty in those parameters. In addition, the differential exposure of different sperm whale groups to different suites of stressors may provide an opportunity to test hypotheses regarding interaction effects within the PCoMS framework. There are significant management and conservation drivers that may lend both urgency and resources to addressing these key data gaps over the next 3-5 years.

Cook Inlet belugas

Rowles provided an overview on the Cook Inlet beluga population that was proposed as one of the case studies that would be useful to examine interactions of cumulative effects. The recent North Atlantic Marine Mammal Commission (NAMMCO) Global Assessment of beluga populations and the recent PCoD modelling workshop for the Cook Inlet beluga population provide information on both status, potential comparison populations, and an approach to evaluate noise which would inform the study of cumulative effects interactions. Cook Inlet belugas are one of 5 recognised beluga populations in the U.S. and reside within Cook Inlet, Alaska. Historically, the population was subject to unregulated commercial, sport, and subsistence hunting. A steep decline in the population during the mid-1990s coincided with a period of large-scale, unregulated subsistence hunting. In 1999, a moratorium promulgated through regulation was implemented on Cook Inlet beluga whale harvests limiting subsistence hunts to those conducted under cooperative agreements between NMFS and affected Alaska Native organisations. There has been a zero quota since 2006. The corrected annual abundance estimates for 1994-2016 are shown in Figure 4. From 1999 to 2016, the rate of decline was 0.4% (SE = 6%) per year, with a 73% probability that the growth rate is negative, while the 10-year trend (2006-2016) is -0.5% per year (with a 76% probability the population is declining) (Shelden et al. 2017). In addition to the decline in abundance, there has been a contraction of habitat use to the upper portion of Cook Inlet. The area of habitat used has decreased by 75% from 7,226 sq km in 1978-79 to 1,787 sq. km in 2009–14 (Shelden et al. 2015). The 2009-16 range was estimated to be only 29% of the range observed in 1978-79, a slight increase from 25% for the period 2009-14 (Shelden et al. 2017). Through examinations of carcass, growth curves have been developed using evaluation of GLGs of teeth with total carcass length and timing of reproduction from identification of fetuses, calves, and neonates. Based on these studies, breeding is most likely occurring in May and calving is primarily occurring from June through August. There remain data gaps relative to the assessment of the population, however new studies are underway to fill some of those gaps (reference new table).

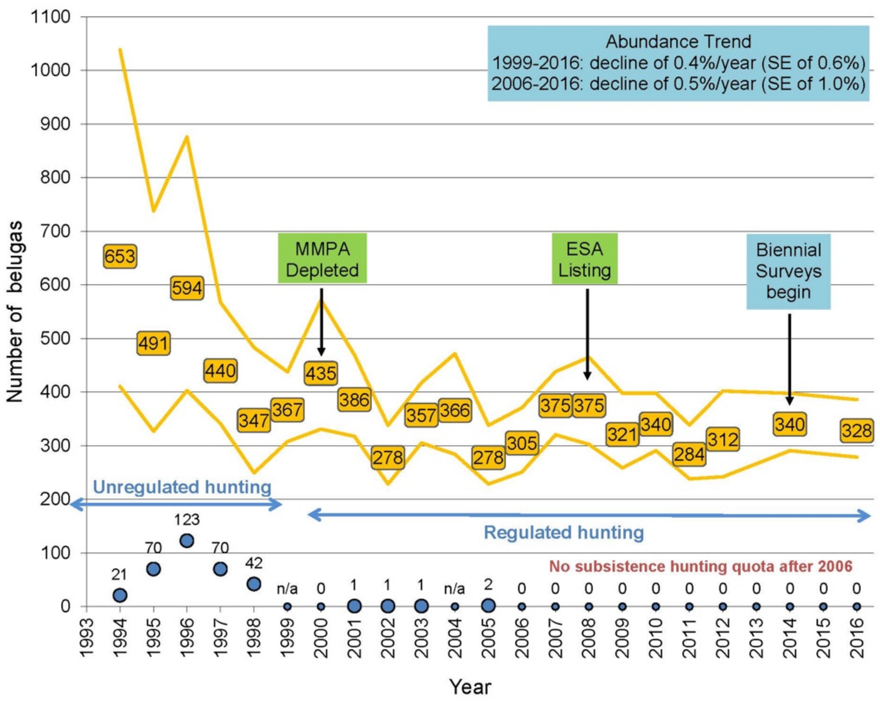

Figure 4. The corrected annual abundance estimates of Cook Inlet beluga for 1994-2016.

The decline of the Cook Inlet beluga stock has been well documented (Hobbs et al. 2015). While the early cause of the decline is most likely the unrestricted hunting, the factor(s) preventing recovery of this stock since that time are unclear. There has been a zero quota since 2006 and the role of commercial fisheries is likely to be very low. The threats that may be affecting this population were discussed and ranked in the Recovery Plan for the Cook Inlet Beluga Whale (NMFS 2016). Threats that were ranked as high include cumulative effects of multiple stressors, catastrophic events, and noise; disease (i.e., pathogens, harmful algal blooms); medium includes habitat loss or degradation, prey reduction, and unauthorised take; and low includes pollution, predation and subsistence harvest. Of continued concern is the reduction in habitat use and the high concentration of the population in the same area at the same time, which increases the risk of large catastrophic events (e.g., oil spill, harmful algal blooms, infectious disease outbreak) affecting a large portion of population. Recent passive acoustic monitoring studies provide further evidence that noise is a high priority threat for this population (Castellote et al. 2016, Small et al. 2017). These studies demonstrated that a variety of noises have exposures of greater than an hour and for several sound sources, the proportion of time with sound exposures exceeding 120 dB, the current threshold for behaviourial harassment for cetaceans, was high (Castellote et al. 2016). This population, therefore, provides an excellent case study or model population for future research into the impacts and interactions of multiple stressors. The St. Lawrence beluga population provides a comparison population for evaluation and collaboration between U.S. and Canadian researchers are already underway.

The participants thanked all the presenters of the case studies for their excellent overviews and noted the importance of information on cumulative effects for each of these populations. The Workshop recognised the value of highlighting these cases that could be used in future cumulative effects assessments and collectively identified (Tables 1 and 2) of all the potentially beneficial case study species and populations where research on multiple stressors and the nature of their interactions, could be conducted. This was conducted at two levels. The first was to list ***only*** those examples where it was recognised the multiple stressors and cumulative effects (i.e. where antagonistic or synergist effects were likely, rather than impacts being additive) were potentially important.

Where are cumulative effects potentially important?	Relevant data available?	Pathogens	Biotoxins	Chemical Pollution	Noise	Prey quantity/ quality	Human Interactions (e.g. dolphin or whale watching)	Ship / vessel strike	Entanglement	Bycatch (lethal and non-lethal)
Possible potential case study species and / or populations										
North Atlantic Right Whales	High	x	x		x	x		x	x	x
Beluga Cook Inlet	High	x	x	x	x	x				
Beluga St Lawrence Estuary	High	x	x	x		x	x	x	x	x
Southern Resident Killer Whales	High			x	x	x	x	x		
Bottlenose dolphins (GoM)	High	x	x	x	x	x	x		x	x
Harbour porpoise (N Sea)	High	x	x	x	x					x
Bottlenose dolphins (Georgia)	High	x		x		x	x		x	x
Franciscana	High	x		x	x	x			x	x
Western gray whales	High									
Bottlenose dolphins (Black Sea?)	Low		x	x						x
Sperm Whales (GoM)	Low/Medium			x	x	x		x		
Bryde's whales (GoM)	Low/Medium			x	x	x		x		
Bottlenose dolphins (North Sea)	Low/Medium		x	x	x					
Bottlenose dolphins (Southern Brazil)	High	x		x	x			x	x	x
Bottlenose dolphins (Northern Gulf of California)	Low			x	x					x
Guiana Dolphin (South and Southeast Brazil)	Medium	x	x	x	x			x	x	x
Harbour porpoise (West Scotland)	Medium		x	x	x					
Bottlenose dolphin (Carribean Panama)	High	x	x	x	x		x	x	x	
Bottlenose dolphins (Madeira)	High			x	x	x	x	x		x
Short finned pilot whales (Madeira)	High			x	x	x	x	x		
Bottlenose dolphins (Fjordland NZ)	Low?						x			

Table 1. Case study populations and species that could be used to investigate the cumulative effect of various stressors.

Recommendations

Recognising IWC's ongoing interest in environmental changes on cetacean populations and identifying the need to better understand the impact of cumulative effects on cetaceans, it was noted that there is considerable uncertainty in this field and a continuing need to provide assessments and management advice with current state of knowledge.

The Workshop recommended that:

1. Case studies be further developed, particularly focussing on how stressors interact to affect cetacean health and how that relates to vital rates.
2. Methods to assess health be developed across species and populations for which similar and sufficient data sources are available (see Table 1). The primary focus should be on populations for which it is believed there is most chance of success i.e. those for which good information is available on both cetaceans and potential stressors over a reasonable time period, recognising that overall there are few cetacean populations studied with sufficiently broad sampling programmes covering sufficiently long-time frames.
4. Biomarkers of health be developed for use in the field, particularly using 'omics approaches and new technologies, recognising that new techniques need to be applicable to free-swimming cetaceans. In addition, methods for investigating interactions between stressors should be developed, (for example utilising the potential of *in vitro* exposure-response studies).
5. The key data gaps in assessing the nature of the interactions between stressors be addressed, focussing primarily on those that may act through the same physiological pathways.
6. Nevertheless, consideration needs to be given to developing a widely applicable approach for providing precautionary advice for populations in which cumulative effects are of concern. For those where there is immediate concern, where possible, action should be taken to mitigate any recognisable adverse effects.
7. Develop ways of communicating current knowledge about multiple stressors and their potential for cumulative effects to a wider audience particularly conservation managers, policy makers and other stakeholders.
8. Monitor the progress of cumulative effects studies in the Environmental Concerns Sub-committee.

9. Ways of progressing cumulative effects studies in conjunction with other similar initiatives should be explored, recognising that implementing these studies requires considerable resources due to their long-term and complex nature.

The Workshop thanked Hall for chairing the Workshop and looked forward to the advancement of assessing the impacts of cumulative effects to cetaceans.

References

Avila, I.C., Kaschner, K. and Dormann, C.F., 2018. Current global risks to marine mammals: Taking stock of the threats. *Biol. Conserv.* 221: 44–58.

Ayres, K.L., Booth, R.K., Hempelmann, J., Koski, K., Emmons, C.K., Baird, R.W., Balcomb-Bartok, K., Hanson, M.B., Ford, M.J. and Wasser, S.K. 2012. Distinguishing the impacts of inadequate prey and vessel traffic on an endangered killer whale (*Orcinus orca*) population. *PLoS ONE* 7(6): e36842.

Balmer, B.C., Schwacke, L.H., Wells, R.S., George, R.C., Hoguet, J., Kucklick, J.R., Lane, S.M., Martinez, A., McLennan, W.A., Rosel, P.E., Rowles, T.K., Sparks, K., Speakman, T., Zolman, E.S., and Pabst, D.A. 2011. Relationship between persistent organic pollutants (POPs) and ranging patterns in common bottlenose dolphins (*Tursiops truncatus*) from coastal Georgia, USA. *Sci. Total Environ*. 409: 2094–101.

Castellote, M., Thayre, B., Mahoney, M., Mondragon, J., Schmale, C. and Small, R.J. 2016. Anthropogenic noise in Cook Inlet beluga habitat: sources, acoustic characteristics, and frequency of occurrence. Alaska Department of Fish and Game, Final Wildlife Research Report, ADF&G/DWC/WRR-2016-4, Juneau. https://alaskafisheries.noaa.gov/sites/default/files/anthropogenic-noise-cib-habitat-2016.pdf.

Castrillon, J., Huston, W. & Nash, S.B. 2017. The blubber adipocyte index: A nondestructive biomarker of adiposity in humpback whales (*Megaptera novaeangliae*). *Ecol Evol*, **7**, 5131-5139.

Chasco, B., Kaplan, I.C., Thomas, A., Acevedo-Gutierrez, A., Noren. D.P., Ford, M.J., Hanson, M.B., Scordino, J., Jeffries, S.J., Pearson, S., Marshall, K.N. and Ward, E.J. 2017a. Estimates of Chinook salmon consumption in Washington State inland waters by four marine mammal predators from 1970-2015. *Can. J. Fish. Aquat. Sci*. 74: 1173–1194.

Chasco, B.E., Kaplan, I.C., Thomas, A.C., Acevedo-Gutierrez, A., Noren, D.P., Ford, M.J., Hanson, M.B., Scordino, J.J., Jeffries, S.J., Marshall, K.N., Shelton, A.O., Matkin, C., Burke, B.J. and Ward, E.J. 2017b. Competing tradeoffs between increasing marine mammal predation and fisheries harvest of Chinook salmon. Sci. Rep.-UK 7: 15439. doi:10.1038/s41598-017–14984–8.

DiPietro, N.A. 2010. Methods in epidemiology: observational study designs. *Pharmacotherapy*, **30**, 973-984.

Durban, J.W., Moore, M.J., Chiang, G., Hickmott, L.S., Bocconcelli, A., Howes, G., Bahamonde, P.A., Perryman, W.L. & LeRoi, D.J. 2016. Photogrammetry of blue whales with an unmanned hexacopter. Mar. Mam. Sci., 32, 1510-1515.

Hobbs, R.C., Shelden, K.E.W., Rugh, D.J., Sims, C.L. and Waite, J.M. 2015. Estimated abundance and trend in aerial counts of beluga whales (*Delphinapterus leucas*) in Cook Inlet, Alaska, 1994-2012. *Mar. Fish. Rev*. 77(1): 11–31. (doi: 10.7755/MFR.77.1.2).

Holt, M.M., Noren, D.P., Veirs, V., Emmons, C. and Veirs, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *J. Acoust. Soc. Am. Express Letters* 125: EL27–EL32.

Holt, M.M., Noren D.P., Dunkin, R.C. and Williams, T.M. 2015. Vocal performance affects metabolic rate in dolphins: implications for animals communicating in noisy environments. *J. Exp. Biol*. 218: 1647–1654.

International Whaling Commission. 2006. Report of the IWC Scientific Committee Workshop on Habitat Degradation, 12-15 November 2004, Siena, Italy. *J. Cetacean Res. Manage. (Suppl.)* 8:313–35.

Kellar, N.M., Speakman, T.R., Smith, C.R., Lane, S.M., Balmer, B.C., Trego, M.L., Catelani, K.N., Robbins, M.N., Allen, C.D., Wells, R.S., Zolman, E.S., Rowles, T.K. and Schwacke, L.H. 2017. Low reproductive success rates of common bottlenose dolphins *Tursiops truncatus* in the northern Gulf of Mexico following the Deepwater Horizon disaster (2010-2015). *Endang. Species Res*. 33: 143–58.

Kershaw, J.L., Botting, C.H., Brownlow, A. & Hall, A.J. 2018. Not just fat: investigating the proteome of cetacean blubber tissue. *Conservation Physiology*, **6**, 15.

King, S.L., Schick, R.S., Donovan, C., Booth, C.G., Burgman, M., Thomas, L. & Harwood, J. 2015. An interim framework for assessing the population consequences of disturbance. *Methods in Ecology and Evolution*, **6**, 1150-1158.

Krahn, M.M., Hanson, M.B., Baird, R.W., Boyer, R.H., Burrows, D.G., Emmons, C.K., Ford, J.K., Jones, L.L, Noren, D.P., Ross, P.S., Schorr, G.S. and Collier. T.K. 2007. Persistent organic pollutants and stable isotopes in biopsy samples (2004/2006) from Southern Resident killer whales. *Mar. Pollut. Bull*. 54(12): 1903–11.

Krahn, M.M., Hanson, M.B., Schorr, G.S., Emmons, C.K., Burrows, D.G., Bolton, J.L., Baird, R.W. and Ylitalo, G.M. 2009. Effects of age, sex and reproductive status on persistent organic pollutant concentrations in “Southern Resident” killer whales. *Mar. Pollut. Bull.* 58(10): 1522–29.

Kucklick, J., Schwacke, L., Wells, R., Hohn, A., Guichard, A., Yordy, J., Hansen, L., Zolman, E., Wilson, R., Litz, J., Nowacek, D., Rowles, T., Pugh, R., Balmer, B., Sinclair, C. and Rosel, P. 2011. Bottlenose dolphins as indicators of persistent organic pollutants in the Western North Atlantic Ocean and Northern Gulf of Mexico. *Environ. Sci. Technol.* 45: 4270–77.

Jochens, A.E. 2006. Sperm whale seismic study in the Gulf of Mexico: Synthesis report. US Dept. of Interior, Minerals Management Service, Gulf of Mexico OCS Region.

Lane, S.M., Smith, C.R., Mitchell, J., Balmer, B.C., Barry, K.P., McDonald, T., Mori, C.S., Rosel, P.E., Rowles, T.K., Speakman, T.R., Townsend, F.I., Tumlin, M.C., Wells, R.S., Zolman, E.S. and Schwacke, L.H. 2015. Reproductive outcome and survival of common bottlenose dolphins sampled in Barataria Bay, Louisiana, USA, following the Deepwater Horizon oil spill. *Proc. R. Soc. B* 282(1818):20151944.

Lundin, J.I., Ylitalo, G.M., Booth, R.K., Anulacion, B., Hempelmann, J.A.,Parsons, K.M., Giles, D.A., Seely, E.A., Hanson, M.B., Emmons, C.K. and Wasser, S.K. 2017. Modulation in persistent organic pollutant concentration and profile by prey availability and reproductive status in Southern Resident killer whale scat samples. *Environ. Sci. Technol*. 50 (12): 6506–16.

Lusseau, D., Bain, D.E., Williams, R. and Smith, J.C. 2009. Vessel traffic disrupts the foraging behavior of Southern Resident killer whales *Orcinus orca*. *Endang. Species Res* 6: 211–21.

Miller, P.J.O., Johnson, M.P., Tyack, P.L. & Terray, E.A. (2004) Swimming gaits, passive drag and buoyancy of diving sperm whales *Physeter macrocephalus*. *Journal of Experimental Biology*, **207**, 1953-1967.

National Academies of Sciences, Engineering, and Medicine 2017. Approaches to understanding the cumulative effects of stressors on marine mammals. National Academies Press.

National Marine Fisheries Service (NMFS). 2016. Recovery Plan for the Cook Inlet beluga whale (*Delphinapterus leucas*). National Marine Fisheries Service, Alaska Region, Protected Resources Division, Juneau, AK. https://repository.library.noaa.gov/view/noaa/15979.

Noren, D.P., Johnson, A.H., Rehder, D. and Larson A. 2009. Close approaches by vessels elicit surface active behaviors by Southern Resident killer whales. *Endang. Species Res*. 8: 179-92.

Noren, D.P., Dunkin, R.C., Williams, T.M. and Holt, M.M. 2012. Energetic cost of behaviors performed in response to vessel disturbance: one link in the population consequences of acoustic disturbance model. In: Hawkins, A. and Popper, A.N. (Eds.) *The Effects of Noise on Aquatic Life*, pp. 427-30.

Noren, D.P., Holt, M.M., Dunkin, R.C. and Williams, T.M. 2013. The metabolic cost of communicative sound production in bottlenose dolphins (*Tursiops truncatus*). *J. Exp. Biol*. 216: 1624-29.

Noren, D.P., Holt, M.M., Dunkin, R.C. and Williams, T.M. 2017a. Echolocation is cheap for some mammals: Dolphins conserve oxygen while producing high-intensity clicks. *J. Exp. Mar. Biol. Ecol*. 495: 103-09.

Noren, D.P., Holt, M.M, Dunkin, R.C., Thometz, N.M. and Williams, T.M. 2017b. Comparative and cumulative energetic costs of odontocete responses to anthropogenic disturbance. Proceedings of Meetings on Acoustics 27, 040011. doi:10.1121/2.0000357.

Ohlberger, J., Ward, E.J., Schindler, D.E. and Lewis, B. 2018. Demographic changes in Chinook salmon across the Northeast Pacific Ocean. *Fish Fish*. doi: 10.1111/faf.12272

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K. and Kraus, S.D. 2012. Evidence that ship noise increases stress in right whales. *Proc. R. Soc. B* 279(1737): 2363-68.

Ross, P., de Swart, R.D., Reijnders, P., van Loveren, H.V., Vos, J. and Osterhaus, A. 1995. Contaminant-related suppression of delayed-type hypersensitivity and antibody responses in harbor seals fed herring from the Baltic Sea. *Environ. Health Persp*. 103: 162-67.

Ross, P., De Swart, R., Addison, R., Van Loveren, H., Vos, J. and Osterhaus, A. 1996. Contaminant-induced immunotoxicity in harbour seals: wildlife at risk? *Toxicology* 112: 157-69.

Schwacke, L.H., Zolman, E.S., Balmer, B.C., De Guise, S., George, R.C., Hoguet, J., Hohn, A.A., Kucklick, J.R., Lamb, S., Levin, M., Litz, J.A., McFee, W.E., Place, N.J., Townsend, F.I., Wells, R.S. and Rowles, T.K. 2012. Anaemia, hypothyroidism and immune suppression associated with polychlorinated biphenyl exposure in bottlenose dolphins (*Tursiops truncatus*). *Proc. R. Soc. B* 279: 48-57.

Schwacke, L.H., Thomas, L., Wells, R.S., McFee, W.E., Hohn, A.A., Mullin, K.D., Zolman, E.S., Quigley, B.M., Rowles, T.K. and Schwacke, J.H. 2017. Quantifying injury to common bottlenose dolphins from the *Deepwater Horizon* oil spill using an age-, sex- and class-structured population model. *Endang. Species Res*. 33: 265-79.

Shelden, K.E.W., Goetz, K.T., Rugh, D.J., Calkins, D.G., Mahoney, B.A. and Hobbs, R.C. 2015. Spatiotemporal changes in beluga whale, *Delphinapterus leucas*, distribution: results from aerial surveys (19772014), opportunistic sightings (1975-2014), and satellite tagging (1999-2003) in Cook Inlet, Alaska. Mar. Fish. Rev. 77(2):1-31 + appendices. DOI: dx.doi.org/10.7755/MFR.77.2.1.

Shelden, K.E.W., Hobbs, R.C., Sims, C.L., Vate Brattström, L., Mocklin, J.A., Boyd, C. and Mahoney, B.A. 2017. Aerial surveys, abundance, and distribution of beluga whales (*Delphinapterus leucas*) in Cook Inlet, Alaska, June 2016. AFSC Processed Rep. 2017-09, 62 p. Available at http://www.afsc.noaa.gov/Publications/ProcRpt/PR2017-09.pdf

Small, R.J., Brost, B., Hooten, M., Castellote, M. and Mondragon, J. 2017. Potential for spatial displacement of Cook Inlet beluga whales by anthropogenic noise in critical habitat. *Endang. Species Res.* 32: 43-57.

Smith, C.R., Rowles, T.K., Hart, L.B., Townsend, F.I., Wells, R.S., Zolman, E.S., Balmer, B.C., Quigley, B., Ivančić M., McKercher, W., Tumlin, M.C., Mullin, K.D., Adams, J.D., Wu, Q., McFee, W., Collier, T.K. and Schwacke, L.H. 2017. Slow recovery of Barataria Bay dolphin health following the *Deepwater Horizon* oil spill (2013-2014), with evidence of persistent lung disease and impaired stress response. *Endang. Species Res*. 33: 127-42.

Szeker, S., Fogarassy, G. & Vathy-Fogarassy, A. (2017) Comparison of Control Group Generating Methods. *Study Health Technol Inform*, **236**, 311-318.

Ward, E.J., Holmes, E.E. and Balcomb, K.C. 2009. Quantifying the effects of prey abundance on killer whale reproduction. *J. Appl. Ecol.* 46(3): 632-40.

Ward, E.J., Ford, M.J., Kope, R.G., Ford, J.K., Velez-Espino, A., Parken, C.K., LaVoy, L., Hanson, M.B. and Balcomb, K.C. 2013. Estimating the impacts of Chinook salmon abundance and prey removal by ocean fishing on Southern Resident killer whale population dynamics. U.S. Dept. of Commerce, NOAA Technical Memorandum, NMFS-NWFSC-123, 71 p.

Ward, E.J.**,** Dahlheim, M.E., Waite, J.M., Emmons, C.K., Marshall, K.N., Chasco, B.E. and Balcomb, K.C. 2016. Long distance migration of prey synchronizes demographic rates of top predators across broad spatial scales. *Ecosphere* 7(2): e01276.

Wells, R.S., Scott, M.D. 1990. Estimating bottlenose dolphin population parameters from individual identification and capture-release techniques. In: Hammond, P.S., Mizroch, S.A., Donovan, G.P. (eds.) Individual Recognition of Cetaceans: Use of Photo-identification and other techniques to estimate population parameters. Cambridge, UK: International Whaling Commission.

Wells, R., Smith, C., Sweeney, J., Townsend, F., Fauquier, D., Stone, R., Langan, J., Schwacke, L. and Rowles, T. 2014. Fetal survival of common bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay, Florida. *Aquat. Mamm.* 40: 252-59.

Williams, R., Bain, D.E., Smith, J.C. and Lusseau, D. 2009. Effects of vessels on behaviour patterns of individual Southern Resident killer whales *Orcinus orca*. *Endang. Species Res*. 6: 199–209.

Appendix 1

Glossary of Terms

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Acute Effect – The severe, often lethal, effect of a stressor on an individual that occurs rapidly and is of short duration (see also Chronic Effect).

Acute Exposure – Exposure to a stressor that occurs for a single, discrete period of time (see also Chronic Exposure and Intermittent Exposure).

Adaptive Management – A systematic approach for improving resource management by learning from management outcomes.

Additive Stressor Effect – The combined effect of two or more stressors is considered additive when the shape of the dose–response function of either stressor does not change in the presence of the other stressor (see also Antagonistic Stressor Interaction, Interactions Among Stressors, Stressor, and Synergistic Stressor Interactions).

Adverse Outcome Pathways – A structured representation of biological events leading to adverse effects that is often considered in risk assessments.

Aggregate Exposure – The combined exposure to one stressor from multiple sources or pathways integrated over a defined relevant period: a day, season, year, or lifetime.

Allostatic Load – An organism's cumulative physiological degradation resulting from exposure to stressors, as well as from heightened activity of physiological systems or changes in metabolism.

Antagonistic Stressor Interaction – The interaction of two or more stressors is considered antagonistic if the resulting effects are less than the sum of the effects of the individual stressors (see also Additive Stressor Effect, Stressor, and Synergistic Stressor Interactions).

Bias – The difference between a true population parameter and the expected value of the estimate of that parameter (see also Precision).

Chronic Effect – A stressor effect that does not immediately result in death or reproductive failure, but persists or is irreversible, and may influence long-term survival or reproductive success.

Chronic Exposure – Ongoing or continuously occurring exposure to a stressor (see also Acute Exposure and Intermittent Exposure).

Cumulative Risk – The combined risk from exposures to multiple stressors integrated over a defined relevant period: a day, season, year, or lifetime.

Direct Effects – When considering the influences and interactions among species, and between species and their abiotic environment, direct effects are the proximate impacts that one species or factor has on another species or factor without the effect occurring via an intervening species or factor.

Dose – The magnitude or amount of a stressor that is directly experienced or ingested, inhaled, or absorbed by an animal, ideally measured by a dosimeter on the animal.

Dose–Response Relationship – The relationship between the amount of exposure (dose) to a stressor and the resulting changes in behaviour, physiology, or health (response).

Driver – A biotic or abiotic feature of the environment that affects populations directly and/or indirectly by changing exposure to a single (or multiple) extrinsic stressor.

Ecological Driver – A biotic or abiotic feature of the environment that affects multiple components of an ecosystem directly and/or indirectly by changing exposure to a suite of extrinsic stressors. Ecological drivers may operate on multiple species at varying trophic levels and may affect multiple ecosystems.

Exposure – Contact with or experience of a stressor, ideally measured in the environment near the animal.

Extrinsic Stressor – A factor in an animal's external environment that creates stress in the animal (see also Intrinsic Stressor and Stressor).

Health – The ability of an organism to adapt and self-manage.

Homeostasis – The tendency of the physiological systems of an organism to maintain internal stability in response to stimulus that might disturb its normal condition or function.

Indirect Effects – Interactions between species or between species and the abiotic environment that occur through one or more intervening species or abiotic factor.

Interactions Among Stressors – Interactions occur when the presence of one stressor changes the shape of the dose–response function of the other stressor (see also Additive Stressor Effect).

Intermittent Exposure – Exposure to a stressor that occurs intermittently, repeatedly, or in cycles (see also Acute Exposure and Chronic Exposure).

Intrinsic Stressor – An internal factor or stimulus that results in a significant change to an animal's homeostatic set point. Short-term internal stresses that evoke physiological responses occurring daily to maintain an organism near its homeostatic set points *are not* considered stressors, but natural aspects of an individual's life cycle (e.g., lactation, migration and fasting) that result in significant changes to homeostasis are considered stressors (see also Extrinsic Stressor and Stressor).

Oxidative Stress – Stress to an organism caused by a disturbance in the balance of prooxidants and antioxidants.

Recovery – Restoration of normal function after withdrawal of a stressor.

Stressor – Any causal factor or stimulus, occurring in either the animal's internal or external environment, that challenges homeostasis of the animal.

Synergistic Stressor Interactions – The interaction of two or more stressors is considered synergistic if the resulting effects are more than that of the sum of the effects of the individual stressors (see also Additive Stressor Effect, Antagonistic Stressor Interaction, and Stressor).