Final Report of Marine Species Monitoring for the Population Consequences of Disturbance (MSM4PCoD):

An Integrated Approach to robustly monitoring marine mammal populations

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Report Code:	SMRUC-LMR-2026-007
Date:	Thursday, 26 February 2026

This report is to be cited as: Booth, C.G., Ryder, M., Chudzinska, M., Jacobson, E., Harwood, J., Hin, V., Quinn, M. and Thomas L. 2026. Marine Species Monitoring for the Population Consequences of Disturbance (MSM4PCoD): an integrated approach to robustly monitoring marine mammal populations - Final Report to Living Marine Resources. Report number SMRUC-LMR-2026-007 (unpublished).

Contents

Figures

Tables

1 Executive Summary

The overall objective of the 'MSM4PCoD' project is to review data collected as part of the US Navy Marine Species Monitoring (MSM) program to determine if these efforts can inform future Population Consequences of Disturbance (PCoD) analyses, in addition to exploring possible recommendations for future development. Below we describe the process and findings of the project (section 1.1) and describe the recommendations for the MSM program (section 1.2).

1.1 Project Summary

In 2020, a scoping phase was held with Navy stakeholders (see Appendix 1) to discuss and potentially further define the scope of the 'MSM4PCoD' project, in addition to reviewing the monitoring objectives and efforts to date under the MSM program. As part of this scoping phase, review meetings and a scoping workshop were held in which participants worked to focus the scope of the project and agree upon next steps to ensure the project would support Navy needs.

Parameters were discussed including identifying geographic areas in which previous Navy monitoring had been carried out, and which species within these areas were priorities. It was subsequently agreed that the MSM review would be focused on the Atlantic Fleet Training and Testing (AFTT) and Hawaii Southern California Training and Testing (HSTT) areas.

There are four core elements of the 'MSM4PCoD' project:

1. To carry out a review of the applicable current and historical MSM projects for priority areas and species, and to compile this information into a reference database. For each project the following information was compiled; methods used, species sampled, and effort / sample sizes obtained for different species/method combinations. The aim of compiling this information is to gain a clearer understanding of the monitoring effort that has been conducted over the past 20 years of the MSM program.
2. To use bioenergetic models to identify early warning sign metrics that can be monitored using established or novel monitoring methods. The outputs of this task also inform power analyses in the project.
3. To carry out power analyses to assess the power of monitoring programs using classical, single datastream approaches such as visual line transect survey only or passive acoustic monitoring (PAM) only. Subsequently, to assess how integrated approaches can harness the utility of the data collection under the MSM program to support the ultimate objective of PCoD – to detect population change.
4. To use the outputs of elements 1-3 to summarize how the MSM program can support PCoD analyses and detect population changes.

Databases of Atlantic and Pacific MSM projects were completed and updated through to the end of 2023. Each database contained a tab for each data type and included data columns specific to the data collection method used during that project. For example, acoustic data collection details included type of PAM device, number of detections and recording hours. A series of case studies were prepared which summarized the different data streams collected in Southern California (SOCAL), Hawaii and Hatteras regions. One such case study focused on Cuvier's beaked whale in in the SOCAL region as a case study for bioenergetic modelling and power analysis, and the details of which are discussed below.

To identify metrics of population change, we adapted the Hin et al. (2023)'s Cuvier's beaked whale energetic population model to analyze how animals might respond in a bioenergetic sense under varying environmental conditions. The goal was to identify the early warning signs of population change and consider which of the indicators could reliably be monitored using established or emerging monitoring techniques. Based on multiple model assumptions, it was concluded that two ratios ('calves to adults observed' and 'immature to mature animals') were appropriate indicators to be monitored. A key finding was also that the population recovery (i.e., how long a difference in these metrics can be detected) depends on assumptions about the effect of disturbance, the quality of the environment and the strength of density dependence in this ecological system. An Integrated Population Model (IPM) simulation tool was used to investigate how data should be collected to better detect declines. This approach can combine data on demographic parameters and population indices to estimate the parameters of a single underlying population model.

In conclusion, this particular case study simulated a hypothetical metapopulation based on Cuvier's beaked whales in the SOCAL region, with the eventual goal of building a framework that could be adapted for species, region or scenario. Using the information collated in the review of the MSM program's effort on Cuvier's beaked whales in the SOCAL region (and early warning signs from bioenergetic modelling), a series of simulation scenarios were designed to investigate what this simulation IPM would predict by combining effort streams.

These simulations highlighted that there was a significant increase in power generated from integrating datasets. In particular, including a calf: adult ratio was a key element driving the increase in power from these integrated approaches. The ratio was generated from photo-ID surveys in the simulation, but also could be derived from visual surveys and photogrammetry. It's important to stress that the model was a simulation. Future efforts using different declines, fitting different population models and increasing uncertainty around parameters could help to determine the robustness of this integrated approach. This would further test the value of such approaches to the Navy in support of compliance goals.

An integrated approach appears promising for improving the power to detect changes. This is a key element of the PCoD framework and has been largely ignored to date due to challenges using classic methods. This project suggests that the MSM program is well positioned to apply simulation case studies to predict power of a monitoring program to detect a change given different survey methods, effort and sample sizes (via simulation), as well as to estimate power using empirical data (i.e. building an IPM using data collected to date).

1.2 Recommendations from the MSM4PCoD project

The following recommendations were made regarding the future of the MSM studies and reporting on their effort and results , and were designed to help improve the utility of disparate studies across regions and species. Note that they are focused on the MSM program but could apply across all Navy programs or more broadly fitting in with other collation programs:

1.2.1 Reporting

- Reporting standardization: The presentation of data in technical reports and publications from the MSM program varied considerably. Summaries of survey effort and observations could be standardized. These differences in data reporting could be improved with the development of a reporting guidance document.

- Use of unique identifiers: As the data collected within each research program can often be used to answer more than one question, this information can be dispersed between technical reports, in addition to being incorporated into peer reviewed publications. This can make it difficult to identify duplicated reporting. In the future, it could therefore be beneficial to assign unique identifier codes to each survey or dataset.
- To maximize the utility of these datasets, it could be beneficial to develop an accessible storage system for the raw data collected under these research programs. This would require a protocol for the raw data requirements, and investment in a storage platform.
- Ensuring these webpages for studies are regularly updated and documented in a standardized format would help to showcase the efforts of the MSM program.

1.2.2 Inputs to PCoD & PCoMS frameworks

Further recommendations were made regarding how the effort expended to date could inform PCoD analyses. Depending on Navy needs, additional focus could be put on better understanding of behavioral and physiological responses to Navy sonar exposure and other noise-generating Navy activities (e.g., pile driving, explosions). Additionally, or alternatively, effort could be focused on the end point of PCoD, which is the robust assessment of changes in population dynamics (e.g. abundance or density) using demographics (and potentially health metrics like body condition) to improve the detection of population change. These recommendations were as follows:

- To maximize the utility of existing datasets given the estimation of >$100M invested in the past two decades on marine mammal research. Existing data can help provide the empirical basis for the estimation of multiple/aggregate exposures, estimating the probability of exposure, characterizing the effect of disturbance (e.g. changes in net energy intake). Extensive animal-borne tag datasets and PAM datasets could support such analyses.
- To expand PCoD and PCoMS analytical toolkits further as this evidence base evolves. This approach can also help ensure building capacity to advance these areas – a critical need for the next decade.
- To continue investing in PCoD and PCoMS modelling as these tools are extremely valuable in helping prioritise needs in support of acoustic effects and compliance. This kind of effort likely does not necessarily fall under the purview of the MSM program.

1.2.3 Monitoring for population change

Recommendations were made relating to how the ultimate objective of PCoD and PCoMS frameworks – the power to detect changes in populations (which can support negligible impact determination) are provided covering the following areas:

- With extensive PAM capabilities and existing data sets (both PAM and acoustic tags providing cue rates) – there is scope to understand the Navy's capabilities to estimate trends in PAM density estimates (PAM-DE) alone. Improving knowledge on the frequency and precision of the PAM-DE would be valuable to critically assess how frequently robust density estimates could be derived (i.e. monthly, quarterly, annually) for priority species. Such a project could leverage off other LMR projects.
- This study has identified metrics which could provide suitable early warning signs of population change. The simulation IPM approach highlighted the importance of including such early warning signs (in the form of demographic parameters) in driving overall power. Whilst

these methods are less novel, there is significant value in continuing to operate long term monitoring programs that provide these kinds of information.

- There is value in exploring how integrative modelling approaches (like IPM) could support Navy compliance objectives however, it is necessary first to ensure that the simulation IPM approach described in this study is robust. With further development, this can improve the utility of the IPM to assess different situations (e.g. ones in which a steady decline has occurred, or where a step change has occurred). Furthermore, expansion of IPMs to utilize different datasets as demonstrated in many other taxa (e.g., telemetry, prey habitats or productivity, population counts or indexes, strandings, capture-recapture) could lead to a powerful suite of tools to provide lines of evidence in Negligible Impact Determination (NID).

1.2.4 Supporting strategic Navy needs

Finally, the report concludes by considering some broader holistic recommendations regarding the pursuit of case studies and novel monitoring approaches which could help the Navy's monitoring.

On the topic of case studies to potentially pursue:

- A number of the priority species remain data poor within the scope of this MSM program and in some cases, this is due to a lack of availability of sufficient metadata to inform the levels of detections. Collecting additional data in such cases and/or Improving the quality and availability of metadata may correct this.
- In general, beaked whale species and short-finned pilot whales are the best studied of the priority species. Data from PAM studies from instrumented ranges and other PAM arrays are likely to have the potential to monitor for a wide range of species. However, the efficacy of such PAM efforts will be dependent on the current scale of detection, classification and localization (DCL) capabilities.
- There is value in considering sites with relatively little Navy activity (e.g. Jacksonville, Marianas) as reference sites, which would provide a baseline as activity ramps up.

With respect to novel monitoring approaches:

- Booth et al. (2017) summarized the current state of knowledge of the feasibility (i.e. how practical it is to utilize this survey method for a given species to provide useful metrics) and the utility (how many useful metrics can be estimated via this method for a given species group) of different novel monitoring approaches. Identifying where new or established technologies can be added into existing MSM projects might provide significant added value. Specifically, adding new survey capabilities where the survey infrastructure exists already means a cost-effective increase in what can be achieved by a given program.

2 Introduction

2.1 Assessing population change and the consequences of disturbance

Investigating the sublethal effects of disturbance and their consequences at a population-level remains a significant ecological challenge. It typically requires extensive baseline knowledge of life-history and demography for species of interest. However, for most marine mammal populations, this knowledge is currently lacking and it could take many years to fill these gaps. During this time, undetected population declines may occur. Commonly, marine mammal populations are monitored via surveys to determine their abundance or density. There are well established methods – such as line-transect surveys for cetaceans (e.g. Wade and Gerrodette 1993) or telemetry-corrected haulout counts for pinnipeds (e.g. Thompson and Harwood 1990) for estimating these parameters, but surveillance is typically expensive, particularly in the case of cetacean populations. They also tend to provide imprecise estimates, because marine mammal populations are often spread over wide areas and individuals are often submerged where they cannot be sighted. Consequently, monitoring programs based on these methods typically only have the power to detect large declines (Taylor et al. 2007, Jewell et al. 2012). Additionally, for long lived species, it can take a long time before changes in vital rates manifest themselves as changes in population size (Holmes & York 2003).

Therefore, there may be merit in monitoring demographic characteristics (such as the age- or stage-structure of the population) and indicators of individual health that can provide an early warning of population level effects and help to identify some of the drivers of changes (National Academies of Sciences Engineering and Medicine 2017, Booth et al. 2020)(Figure 1). Booth et al. (2017) and Booth et al. (2020) used existing Population Consequences of Disturbance (PCoD) models to determine that changes in certain demographic variables, such as the mother: calf ratio and proportion of immature animals, are strongly correlated with changes in abundance or population status. Therefore, such metrics, if monitored with high precision, can provide some early warning of future changes in abundance. However, the same analysis revealed that there was a high risk of false positives (i.e. predicting a decline when there is none) if these variables were used on their own as early warning indicators. The study noted that capture-recapture and photogrammetry were likely to be the most useful approaches for monitoring population demography. PCoD models also predict changes in individual health in declining population, and Booth et al. (2017) concluded that remote tissue sampling, photogrammetry and individual tracking (e.g. using telemetry) were likely to be the most useful approaches for monitoring health variables in baleen whales and deep-diving cetaceans.

Previously, Holmes and York (2003) used time-varying matrix models of Steller sea lion (*Eumatopias jubatus*) populations to determine whether age-structure information could be used to detect changes in survival, fecundity and population status. Incorporating the 'juvenile fraction' (akin to the proportion of immatures) along with count data improved their ability to detect changes in demographic parameters. More recently, Jacobson et al. (2020) demonstrated the value of integrating classical marine mammal survey data with other multiple datastreams in an Integrated Population Model (IPM) framework to improve estimates of population trend of Cook Inlet beluga whale (*Delphinapterus leucas*). Another approach is to incorporate relevant covariates to improve power to detect changes (e.g. Gimenez et al. 2006).

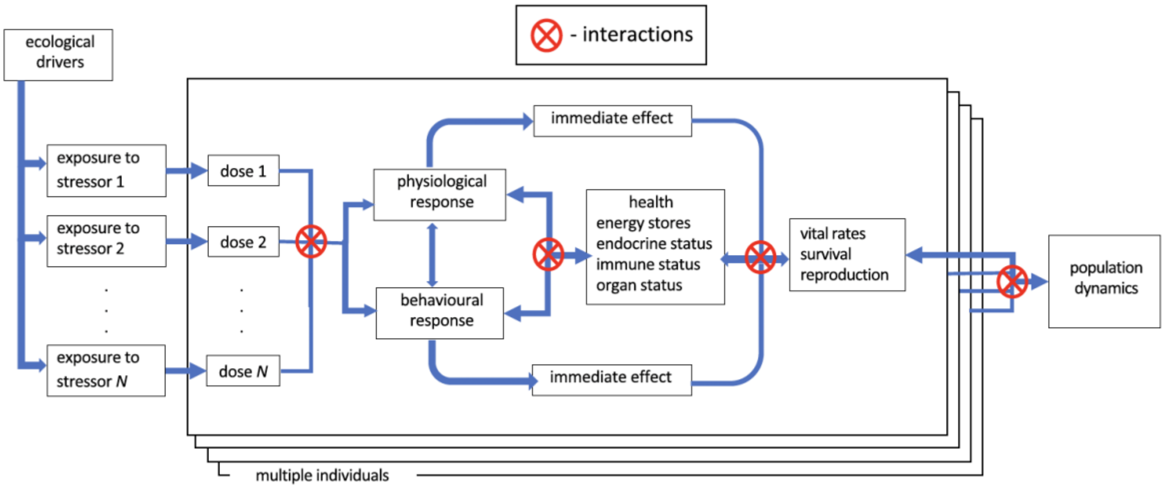

Figure 1 - Reproduced from Tyack et al (2022): "Population Consequences Of Multiple Stressors (PCOMS) conceptual model. The doses caused by exposure to stressors trigger responses that can either have an immediate effect on vital rates or can accumulate changes in health which affects vital rates. The effects of stressors on population dynamics are modelled by summing these effects across all individuals. Areas where interactions between stressors, responses and population effects can occur are indicated by red circles with an 'X' inside."

2.2 The Navy Marine Species Monitoring Program

Marine mammals in North America are protected by environmental legislation, including the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA). The marine operations conducted by the US Navy are also subject to these federal laws, and as such they are required to demonstrate regulatory compliance. The Marine Species Monitoring (MSM) program supports this compliance process by investment in the monitoring of marine mammals for baseline data collection, in addition to facilitating an understanding of the potential impacts of military activity such as underwater detonations and sonar training events.

The MSM program research studies can be categorized by the strategic monitoring goal, of which there are currently four main categories: Occurrence, Exposure, Response, and Consequences. These categories align with Population Consequences of Disturbance (PCoD) framework that is detailed in New et al. (2014). The PCoD framework determines that the 'Occurrence' and 'Exposure' categories focus on understanding the number of disturbed animals, while the 'Response' category highlights the changes to individual behavior and physiology that may occur due to a disturbance event. Research studies under the 'Consequences' category aim to understand how Occurrence, Exposure and Response interact to impact overall population dynamics. This could relate to the life stage distribution for a population, animal density within a given area, or the potential impacts on the total population size. Booth et al. (2017) and Booth et al. (2020) evaluated existing PCoD models to demonstrate that demographic information such as mother: calf ratios can be linked to population level changes, and therefore could represent an early warning of population declines.

2.3 MSM4PCoD Overall Scope & Objectives

The overall objective of the 'MSM4PCoD' project is to review the data collected as part of US Navy MSM program to see if these efforts can inform future PCoD analyses and explore possible recommendations for future development.

A scoping phase was held for this project in 2020 (see Appendix 1) with Navy stakeholders to review monitoring objectives and efforts to date, and to discuss and potentially refine the scope of the project. During review meetings and a scoping workshop, participants worked to focus the scope of the project and agree on next steps to ensure the project would support Navy needs. Parameters discussed included geographic regions for Navy monitoring and species within regions that were priorities. It was agreed to focus the MSM review on the Atlantic Fleet Training and Testing (AFTT) and Hawaii Southern California Training and Testing (HSTT) areas. The species prioritized in these regions are shown in Table 1.

Table 1 - List of priority species considered in this project following the scoping effort. All species are either captured as a 'deep diving species' or are ESA listed large whale (grey shading). * also ESA listed.

Species Name	Latin Name	Notes	Area
Blainville's Beaked Whale	*Mesoplodon densirostris*	Deep diving species	HSTT
Bryde's Whale	*Balaenoptera edeni*	ESA listed large whale	HSTT
Cuvier's Beaked Whale	*Ziphius cavirostris*	Deep diving species	AFTT & HSTT
False Killer Whale	*Pseudorca crassidens*	Deep diving species	HSTT
Fin whale	*Balaenoptera physalus*	ESA listed large whale	AFTT
Minke whale	*Balaenoptera acutorostrata*	ESA listed large whale	HSTT
Humpback Whale	*Megaptera novaeangliae*	ESA listed large whale	AFTT & HSTT
North Atlantic Right Whale	*Eubalaena glacialis*	ESA listed large whale	AFTT
Short-finned Pilot Whale	*Globicephala macrorhynchus*	Deep diving species	AFTT & HSTT
Sperm Whale*	*Physeter macrocephalus*	Deep diving species	AFTT

There are four core elements of the project:

1. A review of the applicable current and historical MSM projects for priority areas and species and compile information into a reference database. For each monitoring study, the methods employed, the species sampled, and the effort / sample sizes obtained for different species/method combinations will be compiled. This will result in a clearer understanding of the monitoring effort that has been conducted over the past 20 years of the MSM program.
2. Using bioenergetic models to identify early warning sign metrics that can be monitored using established or novel monitoring methods. The outputs of this task also inform power analyses in the project.
3. Power analyses to assess the power of monitoring programs using classical, single datastream approaches (e.g. visual line transect survey only or passive acoustic monitoring (PAM) only) and how integrated approaches can harness the utility of the data collection under the MSM program to support the ultimate objective of PCoD – to detect population change.
4. Using the outputs of parts 1-3 to summarize how the MSM program can support PCoD analyzes and detect population changes.

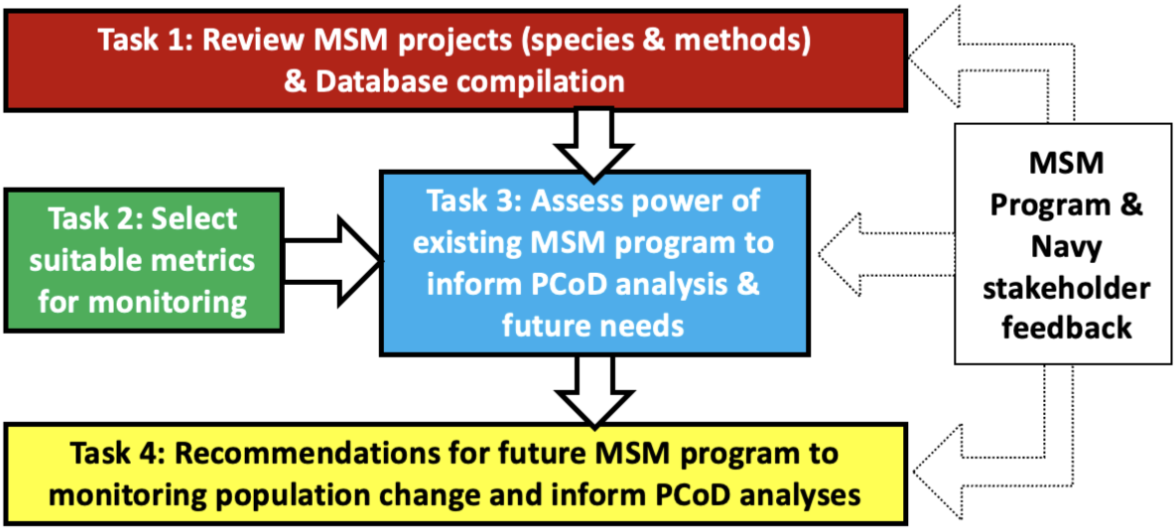

Figure 2 - MSM4PCOD Project Structure showing the four tasks summarized here.

2.4 Report Intention

This report summarizes the work completed under each of these four core elements and concludes with recommendations for how the MSM program could inform PCoD analyses. Two peer-reviewed manuscripts have been produced as part of this project. These are not presented in full , but are instead summarized to provide adequate foundational information where advances in knowledge therein drives the recommendations.

Section 3 summarizes the review of MSM effort for the AFTT and HSTT areas (for the priority species), and Section 4 focuses on the use of bioenergetic models to identify the early warning metrics that precede changes in abundance. This work has a particular focus on metrics that can be monitored using conventional or emerging techniques.

Section 5 explores the current state of knowledge of the power to detect population changes from single datastreams (e.g. PAM only) (section 5.1) and via integrated approaches (section 5.2). This is briefly summarized in Section 6 before recommendations for the MSM program and wider Navy stakeholders given the results of the above sections (Section 7).

3 Review of MSM program effort

3.1 Methods

Following the identification of the relevant studies, unique project codes were assigned that reference an acronym for the study name, the study region, and the year of data collection, in order to facilitate easy recognition, grouping and filtering. An initial high-level overview of the MSM publications revealed that each survey method would benefit from an individual database to ensure that as most information as possible could be captured from each report, reduce redundant data rows, and improve accessibility. This process was part of the development of comprehensive databases with appropriate column headings to capture the metadata available for each survey type. Two main databases were created in Microsoft Excel, to collate information from studies in the Pacific and Atlantic separately in order to ensure a user-friendly experience.

Following the development of the databases, the literature review focused on long term studies, using the research projects that can be found under the 'Atlantic Region: Current Projects' section under the Marine Species Monitoring website. At the time of data collation, not all studies were up to date within this section. As such, the 'Technical reports' section was then consolidated under the 'Reading room' heading within the MSM website. This section of the website provided more current reports and became the primary source of data collation for the remainder of the review. Under the Atlantic Fleet Training and Testing (AFTT) there were 15 research projects that focused on marine mammals in the North Atlantic. A preliminary review of these projects allowed for a subset of six research programs to be selected for further collation and analysis. Under these six research programs, approximately 150 technical reports and publications were reviewed. Surveys conducted under the MSM program in the North Atlantic can be differentiated by region, with most data collection efforts took place within Cape Hatteras, Jacksonville, Cherry Point, Norfolk Canyon and Camp Lejeune.

The Pacific monitoring program includes projects from a range of Training Areas, including the Hawaii-Southern California Training & Testing (HSTT), the Gulf Of Alaska Training Activities (GOA), Marianas Training and Testing (MITT), and the Northwest Training and Testing (NWTT). Within Task 1 of MSM4PCoD, research programs that conducted within the HSTT region and the NWTT were the main focus. There were 14 relevant research programs under the HSTT, including surveys from the Southern California (SOCAL) Range Complex, and the Hawaii Complex (PMRF). Within these 14 research programs, approximately 140 research publications and technical reports were reviewed. Not all reports contained relevant information to the review, but this review process was required to ensure that the summary database provided a synthesis that was as accurate as possible.

For each survey method, the database aimed to capture important information about the data collection efforts and included a summary value for the sample size of animals surveyed, detected, tagged and biopsied. The database also included information on the project PIs and their contact details, in addition to information surrounding the responsible research institute. Links are provided to direct the user to each report, should they wish to learn more about a specific research project or dataset. To ensure the maximum accessibility of these databases, a guidance document was created to improve user experience and support.

3.2 MSM Review Database - Summary

3.2.1 AFTT database

As each database has been partitioned by survey method, summary information on the available data has been condensed into tables in Appendix 1. These summaries demonstrate the differences in survey effort between regions within the Atlantic and Pacific, respectively. In the North Atlantic, Cape Hatteras represents the survey area with high levels of acoustic survey effort, spanning between 2009 to 2019. While most of this data was collected using High-frequency Acoustic Recording Package (HARP) devices, towed acoustic arrays and seagliders were also implemented. Additionally, over 200 tagged marine mammals were reported and over 100 biopsy samples were collected in the Cape Hatteras region.

Cherry Point and Jacksonville also reported high levels of acoustic effort over eight years of data collection. In the Jacksonville training area, there were no tagged animals reported, and biopsies were taken for species defined as non-priority within this review. Cherry Point was associated with high levels of both aerial and boat-based survey data, and 30 biopsies were taken, including priority species. The survey effort information provided in the Atlantic and Pacific databases was consulted to select three case study examples for further exploration, which helped to determine the feasibility of developing an IPM. The initial concept for the IPM within Task 3 was developed from this process. Cape Hatteras was selected as the case study example within the Atlantic (Figure 4), specifically focusing on short-finned pilot whales and Cuvier's beaked whales. At this time, Figure 4 allows for the visualization of overlapping survey effort but could be expanded in the future to incorporate an estimate of the sample size of acoustic detections and visual observations for these species. Using the data reported though publications on the MSM website, Cape Hatteras provided survey effort from acoustic recorders, visual survey data, telemetry data and demographic information through biopsies. It provides a clear example of a region that could be evaluated for a future IPM. This would require additional effort to obtain a more comprehensive understanding of the survey effort, either by accessing additional summary information on these datasets, or through discussions with the data holders.

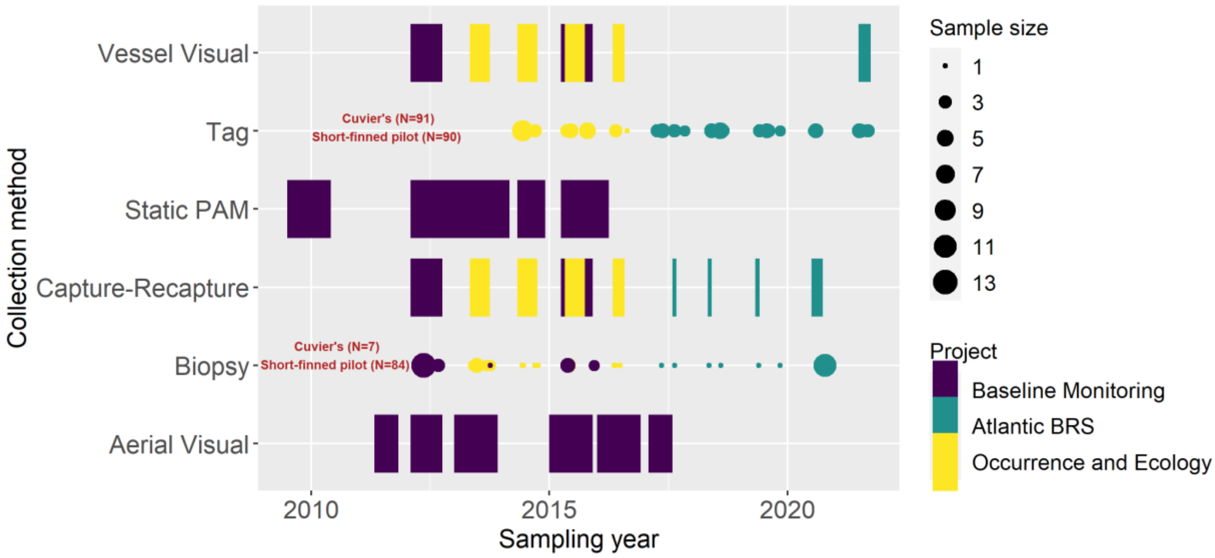

Figure 3 - The identified case study for Cape Hatteras, which demonstrates the data available for Cuvier's beaked whale and short-finned pilot whale.

Jacksonville potentially presents a useful site to consider due to the relative lack of Navy activity on site in recent years. Extensive data collection was carried out for the priority species between 2009 and 2018 (Figure 4). However, as metadata was not collated after 2018 there was a lack of the priority species being detected in reports after this point. As such, revisiting this dataset to understand what could be achieved via PAM on the USWTR range and the M3R program could be valuable.

Figure 4 - An overview of all MSM data collection the Jacksonville region (all priority species) from three different projects within the MSM program. This figure demonstrates the available data specifically for Cuvier's beaked whale, short-finned pilot whale, fin whale, humpback whale, North Atlantic right whale and sperm whale.

3.2.2 HSTT database

It was determined from the review that Cuvier's beaked whale within the SOAR region represented one of the best opportunities for exploring the possibly of combining data sources in an IPM. Figure 5demonstrates the extensive PAM dataset available, in combination with consistent visual survey efforts, interspersed with telemetry data and biopsy sampling. However, within the Pacific region, there was extensive survey effort across the navy training ranges. In addition to the specific surveys conducted on the SOAR range, the SOCAL region also had high levels of acoustic effort in addition to aerial and boat-based surveys, across sonobuoys, towed hydrophones, and HARP devices,. These datasets were collected between 2008 – 2022. Data collection in the Hawaii Range complex (HRC) was also considerable, with specific efforts conducted within the Pacific Missile Range Facility (PMRF) noted separately. Acoustic datasets were reported from as early as 2005, with the HRC acoustic surveys finishing in 2018, but with data collection in the PMRF specifically continuing through 2022. Fifty-nine satellite tags were deployed within the HRC, and another 19 at PMRF, collecting data on a range of species, including short-finned pilot whales and Blainville's beaked whales. In the HRC, 92 biopsy samples were taken between 2010 – 2021. Some of this data has been summarized within Figure 6 and this case study specifically relates to datasets within the HRC that focus on Short-finned pilot whales, Blainville's beaked whales, and false killer whales.

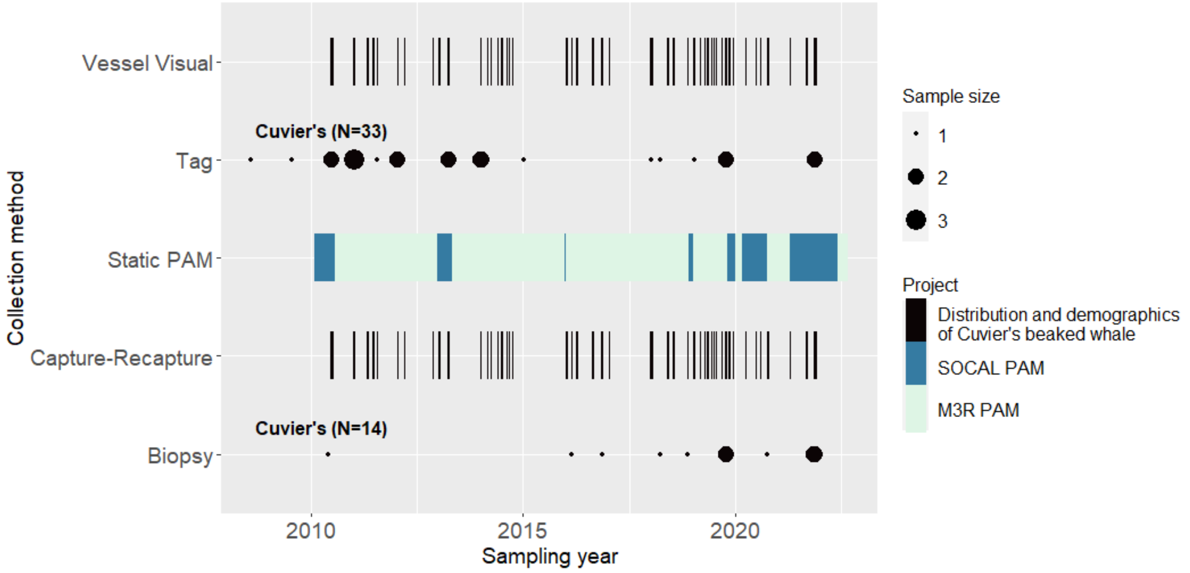

Figure 5 - An overview of the available data on Cuvier's beaked whale at SOCAL and SOAR, demonstrating the temporal overlap in datasets, over more than a decade.

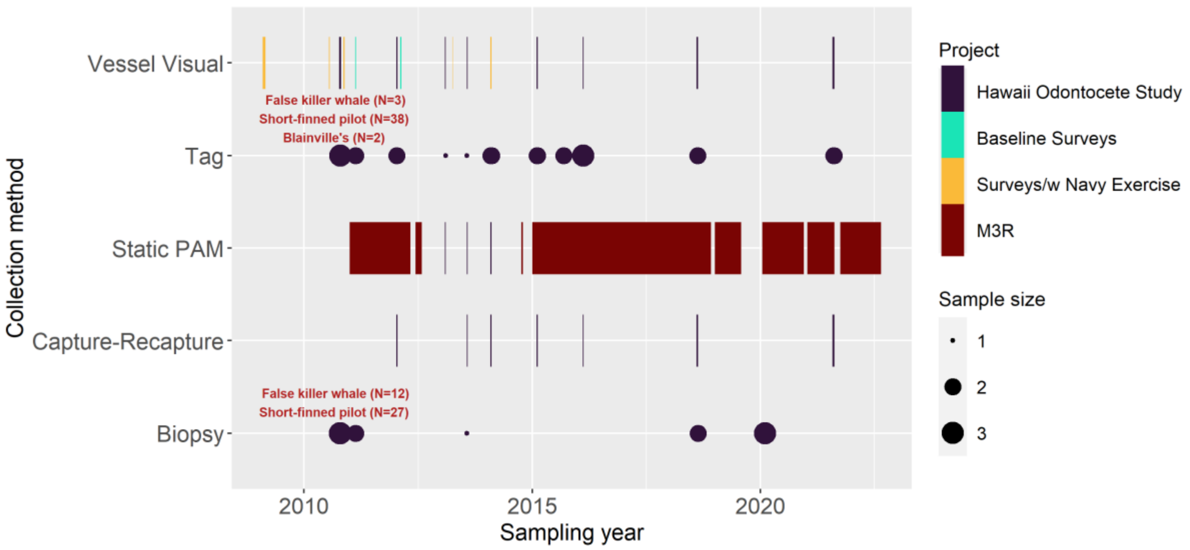

Figure 6 - An overview of the available data on priority species around Hawaii, from four different projects within the marine species monitoring program. This figure demonstrates the available data specifically for false killer whales, short-finned pilot whales, and Blainville's beaked whales.

4 Identify early warning metrics

4.1 Use of bioenergetic modelling for conservation

Disturbance has the potential to cause behavioral, physiological and health changes which can have subsequent effects on an individual's vital rates (i.e. their chances of reproducing or surviving) and ultimately affect population dynamics (Figure 1). The effects of disturbance on animals are widely considered to be mediated by two factors:

1. the state of the individual (e.g., life history stage (e.g. juvenile, adult), exposure history, body condition (a proxy for overall health)), and

2. the environment that the animals live in (e.g. prey resource availability).

In both of these cases, the most widespread effects are likely to be behavioral changes which can reduce food availability by displacing animals from important foraging grounds or by reducing their foraging time (e.g. Pirotta et al. 2014). Individual based dynamic bioenergetic models can be used to predict how reductions in individual food intake leads to changes in individual body condition and explore how such changes could affect that individual's vital rates. These models rely on insight from physiological and evolutionary theory to dictate how animals allocate energy to maximize fitness, by prioritizing survival over nonessential processes like growth and reproduction (Sibly et al. 2013). Because of their mechanistic underpinning, they have been widely used to investigate how natural and anthropogenic disturbance might affect individuals and populations of marine mammals (see Pirotta et al. (2018) and Pirotta et al. (2023)for reviews).

Individuals respond differently to disturbances, and responses are likely influenced by local resource availability and the individuals' energetic status (Gallagher et al. 2021). A benefit of these individual based bioenergetics models is that they can be used to take into account how an individual's energetic requirements vary during different life history stages (e.g. calves, juveniles and adults), in addition to the state of the environment the individual is in (e.g., different quality of environment, presence of predators). Therefore, these models provide a useful method to consider how disturbance can affect different life stages under different assumptions about the quality of the environment. It's important to note that animals in a good quality environment (or condition) are likely to be more resilient to lost foraging opportunities than those in a poor environment (or condition).

4.2 Estimating the effect of disturbance

The impact of disturbance on individuals will depend on several factors, two of which are:

1. The "**probability of disturbance**": a combination of the probability that an individual is exposed to a stressor ("**probability of exposure**") and the probability that it will respond to that exposure ("**probability of response**") and

2. The "**disturbance effect**": how long that individual ceases to feed as a result of its response if reduction in energy intake is the main effect of disturbance.

Little is known about the probability of disturbance and disturbance effect on beaked whales. Tagging studies of Cuvier's and Blainville's beaked whales have recorded behavioral responses to sonar that can lead to loss of foraging opportunities, including avoidance of the sonar source, cessation of foraging and prolonged interruption between deep foraging dives (DeRuiter et al. 2013, Falcone et al. 2017). Tagging of beaked whales (Cuvier's and Blainville's) showed that animals are likely to move away from the disturbance source, which reduces their probability of multiple exposure from the same source but at the same time, may displace animals from important foraging grounds. Joyce et al. (2019) showed that the majority of tagged whales were displaced 26 – 68 km after the onset of exposure and Tyack et al. (2011) showed 16 km displacement lasting 2-3 days. Studies by Falcone et al. (2017) and DeRuiter et al. (2013) showed that the duration of the time interval between deep dives (proxies for the duration of cessation of foraging) after exposure to sonar was between 3 and 8h. On the other hand, Schorr et al. (2020) showed that such deep dive intervals change very little after exposure and may even decrease in duration.

Estimation of these two factors (probability of disturbance and disturbance effect) is crucial to understand the effects of stressors on vital rates and ultimately population dynamics. This has been recently demonstrated by Chudzińska et al. (2024), who show that depending on the assumptions of these two parameters, the three vital rates (birth rate, offspring and adult survival) for the three marine mammal species (harbor porpoise, grey and harbor seal) may be very highly reduced or not affected at all (

Figure 7).

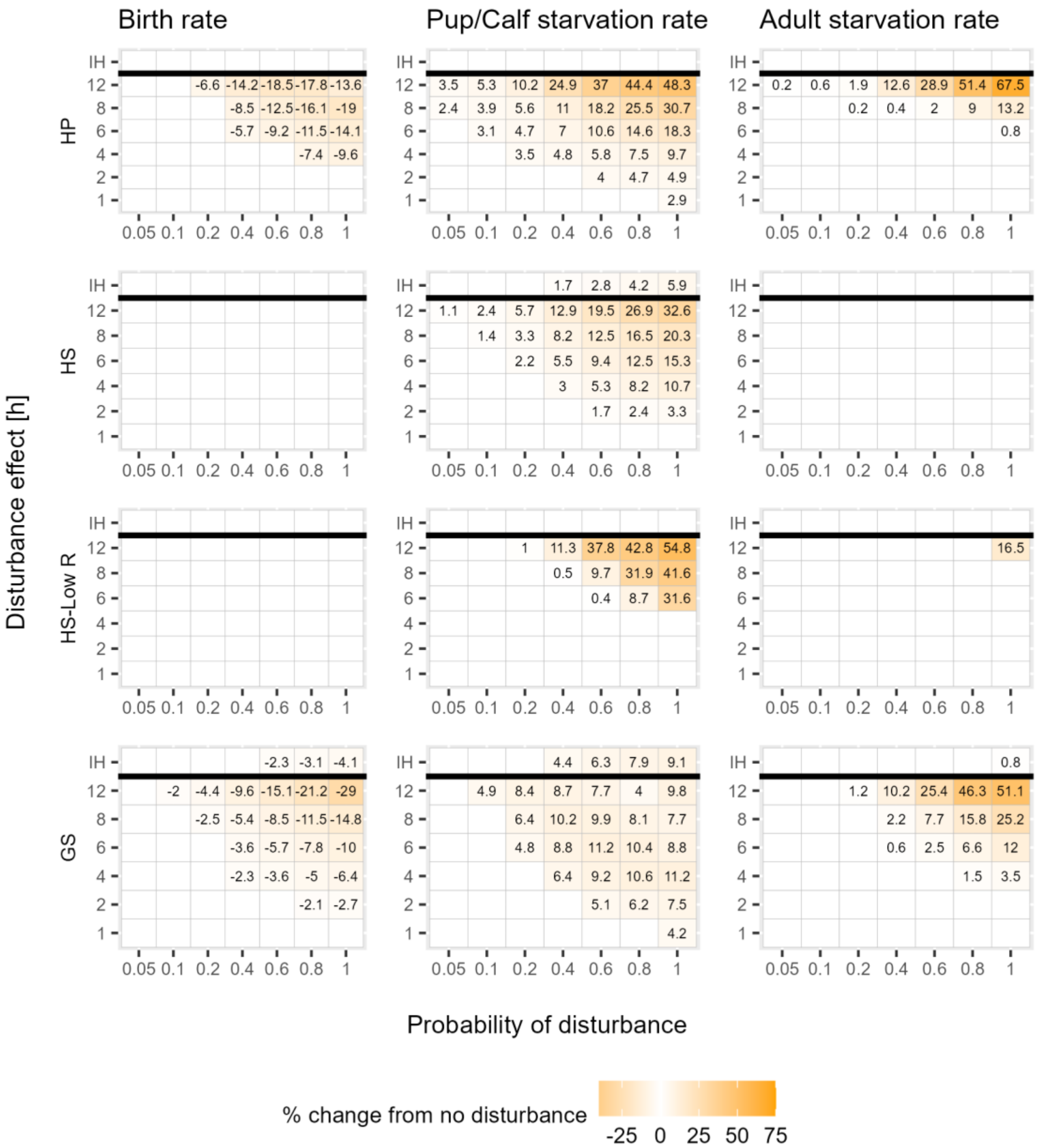

Figure 7 - Reproduced from Chudzińska et al. (2024). Percentage change from no disturbance in birth rate, pup/calf and adult starvation rate for different combinations of probability of disturbance and disturbance effect for the three studied species: 'HP' – harbor porpoise, 'HS' – harbor seal, 'HS-Low R' – harbor seal from a food-limited population, 'GS' –grey seal. The results of the individual heterogeneity (IH) analysis are shown as the top row of each panel (i.e. where disturbed animals showed a variable response in affected foraging (from -1 to -12 h with no foraging)). Empty cells

indicate that there was no significant change between undisturbed and disturbed simulations for a given combination of probability of disturbance and disturbance effect.

4.3 Monitoring demographic rates

As lactation is energetically the most demanding period in the life of female marine mammals (see review by McHuron et al. 2023), lactating females are particularly vulnerable to disturbance. As a result of exposure to stressors, lactating females may provide less milk to their offspring. This reduces the survival probability of offspring during the lactation phase, as well as after weaning. Indeed, several studies which used bioenergetic models to understand the effect of stressors on vital rates of marine mammals, indicated that pup/calves survival is the most affected vital rate, especially in the early exposure to the stressors (McHuron et al. 2018, Hin et al. 2019, Silva et al. 2020, Gallagher et al. 2021, Chudzińska et al. 2024). Extended exposure to stressors during lactation may also directly affect survival of the females, which has been showed for beaked whales by Hin et al. (2023). Mortality of adult males has not been demonstrated as the early change of this vital rate due to disturbance. Therefore, monitoring of demographic characteristics rather than population size or density may improve the ability to detect population effect of disturbance (see review by Booth et al. 2020). Candidate demographic rates to include in monitoring are the calf: female ratio and female body condition (e.g. Bradford et al. 2012). Booth et al. (2020) showed that monitoring a proportion of immature animals in the population, rather than calf: female ratio may give a stronger signal, but the latter may be more difficult to include in the monitoring scheme.

4.4 Aim of the bioenergetic simulations

The Hin et al. (2023) Cuvier’s beaked whale bioenergetic population model (see details in Section 4.5 below) was used to more closely investigate which demographic rates changed and in what order, in order to identify the early warning signs of population change. Those authors published a paper in 2023 highlighting the potential for decline in population density (based on strict assumptions). The Hin et al. (2023) model was adapted to allow variable investment in energy in growth, dependent on the quality of environment (meaning animals can prioritize and deprioritize growth as conditions vary, see details below). This improved the realism of the model and predictions about the effect of disturbance on individuals and populations.

The aim of this project was not to establish and test the most likely values of the probability of disturbance and the disturbance effect, but two scenarios were explored to ensure that our recommendations were not biased by one set of assumptions.

4.5 Bioenergetic model description

An adapted version of the bioenergetic population model for Cuvier’s beaked whale from Hin et al. (2023) was used within the bioenergetic simulations. A full description of the model is presented in the cited study however, a short overview of this model is presented below for context, along with an outline of how it was adapted for use in these simulations.

This individual-based population model follows multiple generations of male and female beaked whales and their prey base. Each modelled whale requires energy to meet the costs of metabolism and growth in body size. Female whales require additional energy for gestation (metabolic and growth costs of their fetus) and lactation. Energy is derived from prey feeding and all whales are assumed to feed from the same prey base. If energy derived from prey feeding is insufficient to meet the energetic costs of metabolism, growth and reproduction (pregnancy and lactation), whales then catabolize stored energy reserves. Consequently, energy reserves decrease if total energy expenditure exceeds total energy acquisition (negative net energy intake) and increases if the opposite is true (positive net energy intake). Ultimately, the ability of whales to grow, survive and reproduce (i.e. give birth to and wean a calf) is determined by prey density. Prey density increases via a productivity term and decreases from feeding by all whales in the population (prey depletion). The coupled dynamics between whales and their prey creates competition between individual whales for available prey. As prey density limits the energy available for growth, reproduction and survival, whale demographic rates are indirectly dependent on whale population density, through the depletion of prey.

The Hin et al. (2023) model was modified to include variable length at birth and variable growth in structural mass. Hin et al. (2023) assumed that length at birth was fixed, meaning that each female gives birth to a fetus of the same length regardless her own age or length. This implies that costs of pregnancy are relatively larger for smaller females, because of their lower capacity to store energy reserve. It is likely that smaller females will reduce fetal investment and, as a consequence, produce smaller calves. At least for minke whales, fetal length was shown to decrease with female body condition (Christiansen et al. 2014). To account for variable length at birth, fetal growth rate was assumed proportional to female length, using a proportionality constant equal to the ratio between the minimum length at birth of 250 cm (MacLeod 2005) and the reported length at maturity of 580 cm (Mead 1984). This resulted in a length at birth of 289 cm for calves of fully-grown females.

In addition, the structural growth rate of individuals was made a function of the net energy intake. This modification was made to account for the observation that it is energetically expensive to synthesize protein from stored energy reserves, which are mostly lipids (Lockyer et al. 1985, Lockyer 1993, Evans et al. 2003). In situations where energy intake is insufficient to cover all energetic demands (metabolism, growth, gestation, and lactation), a κ-fraction of the energy intake was assigned to fuel structural growth, and the $1-\kappa$ fraction was used to cover metabolism and lactation. For pregnant females, foetal growth costs were paid from the κ – fraction, while foetal metabolic costs were paid from the $1-\kappa$ fraction. If the κ- fraction of energy intake is insufficient to cover the structural growth costs of the female and any foetus, then these growth rates are reduced proportionately. Any deficit from the $1-\kappa$ fraction allocated to metabolism and lactation is covered from the reserves. This modification ensures that structural growth costs will not be paid from stored energy reserves. In addition, $\kappa = 0.1$ was adopted by default which implies that in situations with reduced energy intake, only 10% of the energy intake is assigned to structural growth.

The fetuses of pregnant females affected by repeated disturbance at the time when their lengths were below the minimum length at birth, would most likely not survive.

Besides these two modifications to the energetics models (length at birth and κ), the spatial configuration of the model was also simplified. Hin et al. (2023) modelled three spatial areas with varying habitat quality, exposure to stressor and movement rates between areas derived from satellite-tagged whales. However, these simulations only modelled a single area and all whales had the same probability of being exposed to the stressor.

All simulations were run using discrete time version of the Hin et al. (2023) model using the DEBPCoD R-package. Code is available upon request.

4.5.1 Simulation disturbance settings

We modelled a population corresponding to southern Pacific population of Cuvier's beaked whales estimated to ~4000 individuals (Barlow et al. 2022). We used time series of sonar activity days as presented in Joy et al. (2022) based on data provided by the US Navy on hourly detections of Navy sonar at SOAR. This time series resulted in ~ 177 of sonar days per year equally spread across a year.

We first ran the simulations for populations in the absence of disturbance for 100 years to establish baseline population metrics. We then repeated the same time series of sonar use for the following

100 years of simulations. On the day of sonar activity, each whale had 0.75 probability of being disturbed and when disturbed it would stop foraging for 12h. We ran 20 replicates of these 200 years simulations.

The following metrics were output for each year of the simulation (see Appendix 3 for a sample of other metrics explored):

- Calf to adult female ratio.
- Young (calf + juvenile) to all adult ratio.
- Reserve mass of females at the time of giving birth.

The main effect of disturbance on any of the above metrics is expected to happen soon after commencement of disturbance, as indicated by the results in Hin et al. (2023). We therefore presented the results as percentage change in a given metric between baseline simulations (first 100 years of simulations) and the first 20 years after the onset of sonar activity. The only exception to this presentation is for reserve mass, as here we presented the results for baseline ('pre-dist'), first 20 years of disturbance ('early-dist') and the subsequent 20 years of disturbance ('late-dist').

To understand how disturbance settings affect the results, an additional set of simulations were run which set disturbance (sonar activity) to take place ~300 days/year and that individuals would stop stop foraging for 8 h when disturbed. Each whale had a 0.40 probability of being disturbed on the day of disturbance. The probability of disturbance was derived from data on satellite tagged Cuvier's beaked whales which showed that only 40% of individuals the modelled population is within SOAR (Falcone et al. 2017, Hin et al. 2023).

Other demographic variables such as inter-birth intervals or age at first reproduction could be investigated, but these are very challenging to monitor.

4.6 Bioenergetic model simulation results

Disturbance resulted in a rapid population decline in the first 2 years after disturbance started. This decline was mainly driven by a decrease in number of calves. After the rapid decline, a steady increase towards a new carrying capacity was observed. This period is characterized by annual cycles in number of individuals. After ~ 30 years, the population reached a new stable level, and the cycles were less pronounced (Figure 8). However, it's important to consider that there are a large number of assumptions that underpin the current construction of the bioenergetic model. Despite using the best available information, Hin et al (2023) stated: *"Our study indicates that the magnitude of the population effect of non-lethal disturbance likely depends on a multitude of factors, such as the spatial distribution of prey resources, the type and strength of the behavioral response, baseline movement patterns and the intensity and temporal pattern of the stressor (MFAS-use in our case study). This underlines the importance of a multidisciplinary approach that integrates results from multiple lines of research into a single assessment framework (Pirotta et al., 2022). In particular, our study highlights that a good understanding of the dynamics and spatio-temporal variation in prey resources is critical, as this will determine the ability of individuals to compensate for the energetic losses due to disturbance.".* This is described further in section 7.

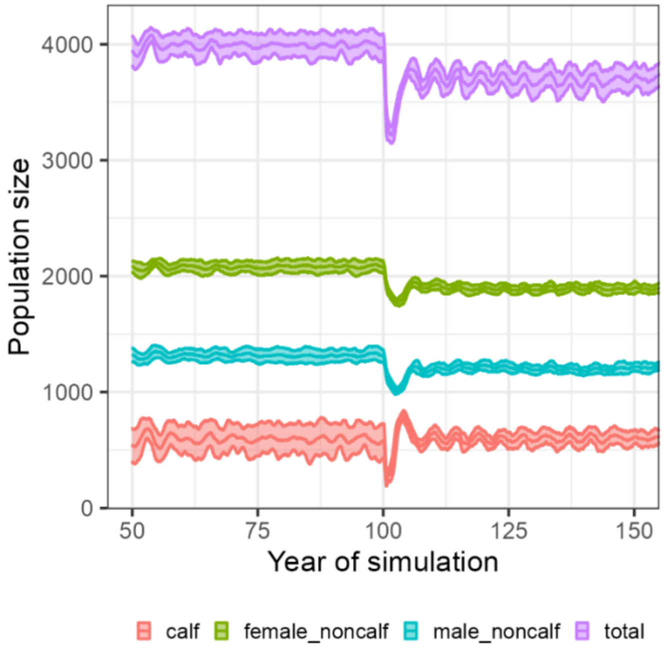

Figure 8. Changes in population size of Cuvier's beaked whales over years of simulations. Disturbance starts at the year 100 of the simulations.

Metrics involving the ratio between calves and other age classes showed the largest deviance from the baseline, especially soon after disturbance started. Figure 9 shows the changes in ratio between young (calves + juveniles), all adults and calves, and all adults. Out of these two demographic rates, young to all adults gave a more prolonged signal than ratio of calves to all adults, and the magnitude of effect was approximately similar between the two. Percentage change between baseline simulations (in the absence of disturbance) and first 20 years of disturbance and other metrics considered are shown in Appendix 3 (Figure 17). Ratio between adult male and females, and ratio of pregnant females and all females showed little changes in comparison to no disturbance time. There was no clear pattern in the order in which different demographic rates change and no distinct change in body condition of females as the result of disturbance was observed (Figure 10).

The same conclusions can be reached based on simulations that assume 300 days of sonar activity per year, 0.40 probability of disturbance, and cessation of foraging for 8h when disturbed (Figure 18). Although, the magnitude of change was lower in these simulations than further simulations assuming 177 days of sonar activity, 0.75 probability of disturbance, and cessation of foraging for 16h when disturbed.

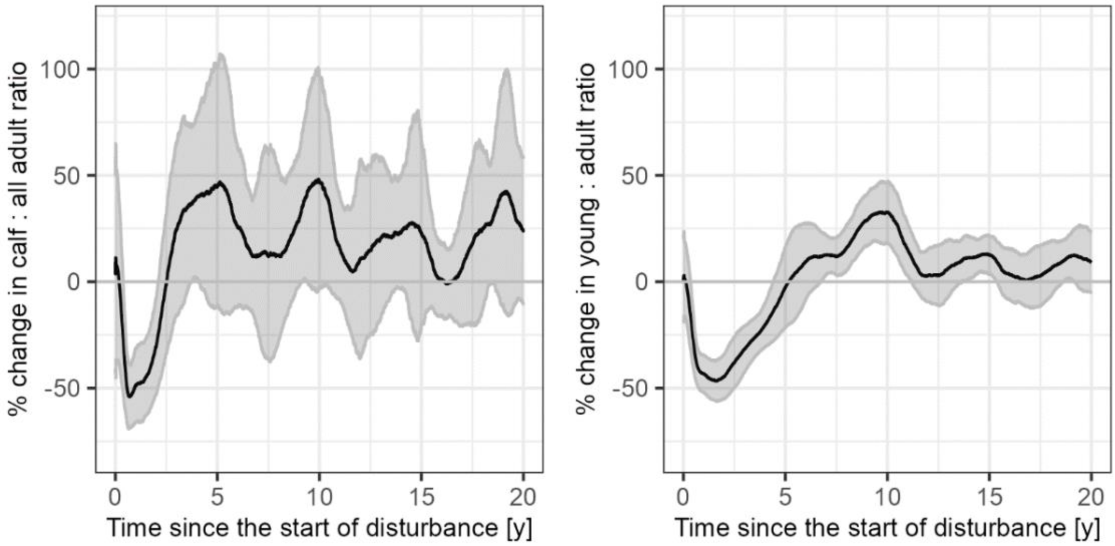

Figure 9. Percentage change of the most suitable metrics from baseline simulations in the absence of disturbance and first 20 years after disturbance started. Black lines indicate the mean of the 20 replicates of the simulations and the grey area shows standard deviations.

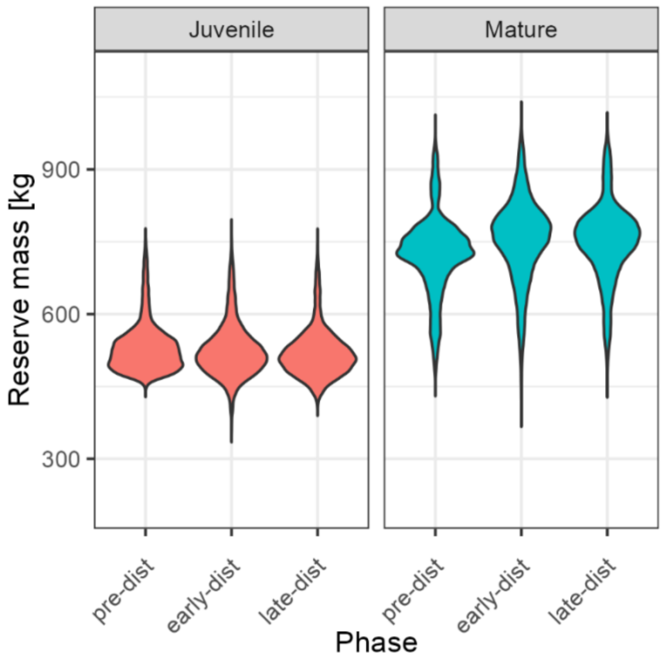

Figure 10. Distribution of body condition (total reserve mass, kg) of females at the time they give birth for the three time periods: 20 years before the disturbance happened ('pre-dist'), first 20 years of disturbance ('early-dist') and the following 20 years of disturbance ('late-dist') for the two female age classes: juveniles so first year breeders, and mature females.

4.7 Summary of early warning signs

The bioenergetic modelling identified a small number of early warning signs (demographic metrics) which changed in a consistent, cascading fashion when the population experienced repeated disturbance. The metrics which did change, changed very quickly after the disturbance was imposed on the population and subsequently provide candidate metrics to be considered for monitoring. After filtering according to which of these metrics could reliably be monitored using established or emerging monitoring techniques – the most appropriate metrics to be monitored were the ratio of calves to adults observed and the ratio of immature animals to mature animals (or ratio of 'young to all animals'), with the latter providing a stronger signal.

The magnitude of the effect (i.e. the effect size) after disturbance commences, is dependent on assumptions on the effect of disturbance (in terms of reduction in energy intake because of cessation of foraging), the presence and frequency of the stressor (i.e. sonar activity in SOAR) and the quality of the environment (which can affect the density dependent response of the simulated population).

The two simulated scenarios used here differed in terms of frequency of sonar activity, the probability of animals being disturbed and effect of disturbance, but do not allow us to distinguish which of these three aspects have the largest effect on the results. However, a good understanding of all of these three aspects is crucial for reliable estimate of the effect of disturbance on populations (e.g. Hin et al. 2023, Chudzińska et al. 2024). Further understanding the movement patterns of animals in an area of interest (which affects the probability of disturbance (sensu Chudzińska et al. (2024)) –

Figure 7) is needed to more robustly predict how disturbance affects different species.

The simulations in this analysis suggest that modelled demographic characteristics mainly change at the early stages of disturbance. However, there are a number of relatively simple assumptions in these models. As there is ample evidence that the marine environment is dynamic and animal responses to sonar exposure are variable (Adame et al. 2020; Bowen et al. 2002; Ellison et al. 2012; Harris et al. 2018; Southall et al. 2019; Tyack et al. 2022), it is important to understand how such models perform in a much more dynamic environment (that is likely reflective of reality) rather than a stable, controlled one.

If the prey environment, probability of disturbance, or effect of disturbance is in constant fluctuation this means that no stable baseline is reached, or recovery may not be so swift. Instead, this would suggest that suppressed population demography metrics may persist in the population for a long period, as observed in South American sea lions following harvest (see Figure 3 of Romero et al. 2017); authors stated: *"50 years after hunting cessation, the population still represents only 40% of its pre-exploitation abundance"*. As such, it remains uncertain as to whether real marine mammal populations (and their prey environments) are sufficiently stable to allow such fast population recovery. Romero et al. (2017) found demographic rates were depressed for decades after lethal impacts on the population but could not identify a clear explanation regarding why the population did not recover.

It is highly likely that the population demography (and density/abundance) will change as the frequency and strength of response of the stressors change and/or the population is exposed to multiple stressors. As such, we cannot be sure that there is only a narrow window to monitor for change, and there is merit in continuing to consider approaches to monitor for population changes. Adult: calf ratio is relatively easy to monitor (with sufficient effort) with the use of visual surveys and photo-ID. The ratio of young (calves and juveniles) to all adults may be harder to monitor (Booth et al. 2020) but can be achieved using photo-ID (a capture-recapture method) and photogrammetry.

5 Power to detect change

To understand the potential for population change, we need to consider information on long-term trends in population size and their demographic drivers. Statistical power analyses are fundamental for conducting scientific research to ensure sample sizes are sufficiently large to allow detection of an effect. There are a number of approaches that can be used to investigate (a) whether trends are occurring through time, and (b) whether there is sufficient statistical power to detect a biologically significant trend in the data (Steidl and Thomas 2001, Thomas et al. 2004). However, we are also interested in detecting sudden declines or increases to both better understand the natural variations (and their drivers) and also enable adaptive management or mitigation (e.g. Durant et al. 2011). Assessing statistical power is a way of determining whether the uncertainty associated with estimates in a time series dataset is low enough to be able to detect a biologically significant trend if one was present in the time series.

In a PCoD setting we are interested principally if whether MSM efforts to date have the power to inform PCoD analyses and to better understand what effort would be required for different species/method/variable combinations. MSM efforts have been conducted for the past 15 years and so by using the outputs of the MSM review (Section 3) and bioenergetics modelling (Section 4), here we explore power analyses using SOCAL and Cuvier's beaked whales as a case study.

5.1 Single data-stream power analysis

We carried out a series of power analyses of data collected using Passive Acoustic Monitoring or visual vessel-based survey data (using estimates of precision from Cuvier's beaked whales on SOCAL). These power analyses determined that either method has low power in isolation (i.e., when only a single datastream is used). Annual visual surveys alone would similarly require 40-80 years of data (all power estimates are affected by the precision around density estimates) (Figure 11). Using PAM alone, the power to detect a 1% annual decline required 43 years of monitoring (assuming a single density estimate generated each year and a coefficient of variation (CV) of 0.208) (Figure 12).

These single datastream power analyses highlight two well-established approaches by which the power of surveys can be improved. Firstly, improving the precision of the estimates (i.e., reducing the CV); Figure 11 shows how halving the CV can lead to detecting a change ~15 years earlier). Secondly, if sufficient data are available, producing multiple density estimates per year can similarly result in an improved ability to detect a given change. For example, doubling the number of estimates per year can lead to detecting the same decline ~6-8 years earlier (Figure 11 & Figure 12). If more estimates per year can be derived (e.g. quarterly or monthly) this can lead to a further increase in power to detect change. However, it is important that estimates can still be considered independent – this should be assessed statistically for each specific PAM or visual program.

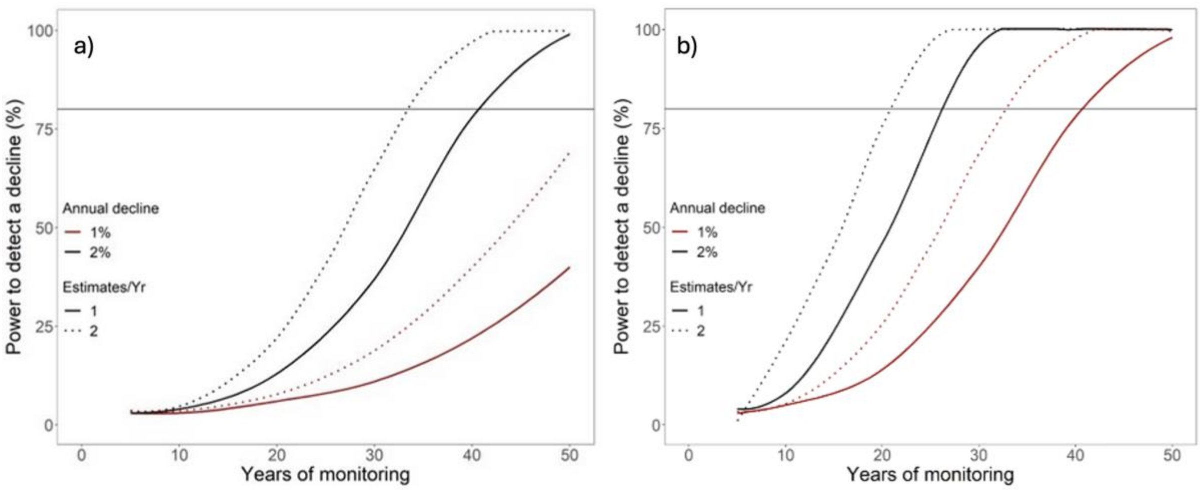

Figure 11 - The power of visual surveys to detect a decline in the Cuvier's beaked whale population in the California Coastal Ecosystem (alpha <0.05) with different levels of precision (a) survey CV = 0.67 and (b) survey CV = 0.29).

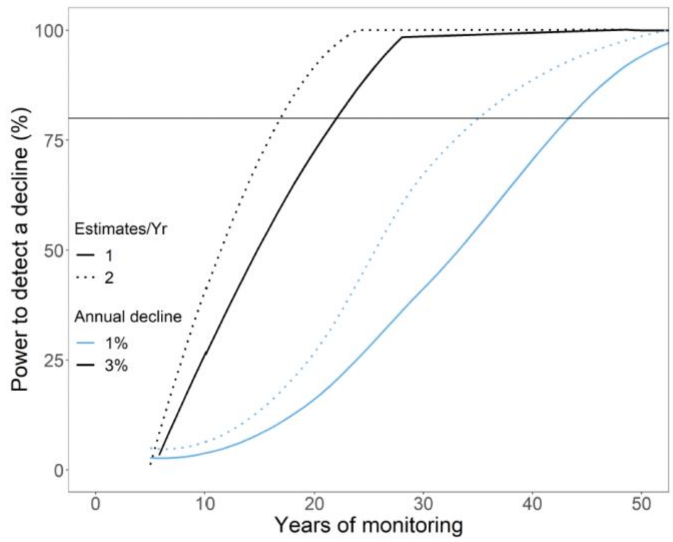

Figure 12 – Indicative power analysis of the power to detect a decline in Cuvier's beaked whale using Passive Acoustic Monitoring (using values emulating the hydrophone array from SOAR). Simulations based on 1 or 2 density estimates per year, and 1% or 3% annual declines. This simulation was based on having 5 localizing hydrophones within the array and alpha < 0.05.

5.2 Integrated approaches

The review of MSM approaches indicates that the Navy has collected many years of valuable data to achieve a variety of goals (section 3). The bioenergetic population modeling highlights that there are early warning signs of declines and that these are reflected not in density or abundance of animals, but in demographic rates like calf:adult ratio (section 4). The initial power analyses confirm that single datastream density estimates (combined to assess trends) do not have sufficient power to detect changes on meaningful management timelines under the MMPA or ESA (section 5.1).

As such, this suggests that, if we are to detect changes in abundance and trend in and around Navy ranges, it is necessary to consider alternative approaches. Therefore, we assessed if it was possible to combine datasets to maximize the ability to detect declines and investigated this via an Integrated Population Model (IPM) simulation tool. IPMs can combine data on demographic parameters and population indices to estimate the parameters of a single underlying population model. These models often achieve more precise parameter estimates as they generate increased statistical power than separate analyses. IPM approaches have been widely used in terrestrial and avian literature – and successfully in marine mammal literature more recently (see Zipkin and Saunders 2018 for a review).

5.2.1 Objective

Our goal was to investigate the statistical power to detect trends in marine mammal populations where disturbance and sampling may not be uniformly distributed. We investigated this question using a simulation tool. Briefly, the simulation included population simulation via an individual-based population model, data generation via simulated line-transect, capture-recapture, and passive acoustic surveys, and trend analysis via an integrated population model. As a case study, we simulated a hypothetical metapopulation loosely based on Cuvier's beaked whales *(Ziphius cavirostris)* in Southern California.

5.2.2 Methods

5.2.2.1 Population Simulation

The population simulation used a simple two-box structure, meant to emulate a metapopulation with two regions each containing a subpopulation. Each region was structured such that it had its own carrying capacity and internal dynamics, but animals could move between regions (explained below). This simulation differed from the model of Hin et al. (2023) in that life history parameters (including survival rates) were fixed rather than emergent properties of the model. The populations are assumed to have density-dependent fecundity. For simplicity, we assumed that the two regions are the same size (unitless) and start with the same carrying capacity.

We projected the population forward in time according to life-history parameters plus the disturbance scenario. In the model, the carrying capacities is set for each year and region, so that disturbance can be simulated in one or both regions. Realized fecundity and survival were simulated stochastically (i.e., via draws from binomial distributions). Individual animals were tracked over time and between regions (this is necessary for the mark-recapture simulation, explained below).

Density-dependent movement was programmed to occur in the simulation. That is, if the density of animals in one region was higher than the density of animals in the other region, some animals would move to the region with lower density. The simulation assumed that the animals do not correctly perceive the habitat quality, i.e., the density each year is perceived based on the carrying capacity in year 1, if carrying capacity changes, it is assumed that the animals are not aware of this. However, population dynamics (especially changes in fecundity) did respond to the new carrying capacity. This was designed to mimic an ecological trap. For the purposes of the case study, this design emulated the hypothesized scenario in Southern California, where disturbance due to Naval training and testing is considered to overlap with high-quality habitat.

Only juvenile animals were allowed to move between regions. The simulation includes a connectivity parameter that controls how much redistribution of animals occurred. The parameter took values between 0 and 1. When connectivity = 1, animals redistribute so that the densities in the two regions are equal. When 0 < connectivity < 1, "surplus" animals in one region will move to the other region.

For the case study, we simulated two scenarios: one where carrying capacity is constant across regions and time and one where carrying capacity decreases by 50% in one region but not the other.

5.2.2.2 Survey Simulation

We simulated four different types of data collection and analysis: photographic capture-recapture surveys for estimates of adult survival, small-boat visual surveys for estimates of the ratio of calves to adult animals, visual line-transect surveys for estimates of abundance, and fixed passive acoustic monitoring for estimates of abundance.

Photographic capture-recapture surveys were simulated to occur only in the disturbed region. Parameters of the simulation include survey years and capture probability. Because marks are acquired with age, only subadult and adult animals could be captured in the survey. In conjunction with the photographic capture-recapture surveys, we simulated data collection on the number of calves and adult animals present.

We simulated generic abundance estimation surveys given survey years and expected CV of the surveys. In the case study, this function was used to simulate both visual line-transect and passive acoustic surveys of animal abundance. For line-transect surveys, the expected CV was 0.6 (Moore and Barlow 2017) and surveys are simulated to occur every 5 years. For passive acoustic surveys, the expected CV was 0.356 (see section 5.1 of this study) and surveys are assumed to occur every year. Line-transect surveys were simulated at the metapopulation level while capture-recapture, calf ratio, and passive acoustic surveys were simulated at the subpopulation level in the disturbed area. Probability of capture was 0.2 in the majority of simulations (unless stated).

5.2.2.3 *Integrated Population Model*

We constructed a Bayesian state-space integrated population model to jointly analyze multiple simulated datasets. This model consists of a central population process model that is linked to observational submodels (Figure 13). The integrated population model is implemented in Nimble (de Valpine et al. 2017) and fit with MCMC. The IPM generates posterior estimates of population size for each year of the simulation. We fit a generalized linear model to each of the posterior timeseries, with an indicator variable for whether the year was before or after the onset of disturbance. In disturbance scenarios, for each model fit, if the indicator variable was significant, we counted that as a successful detection of a change in the population. The power of each scenario was calculated as the proportion of successes across all posterior samples.

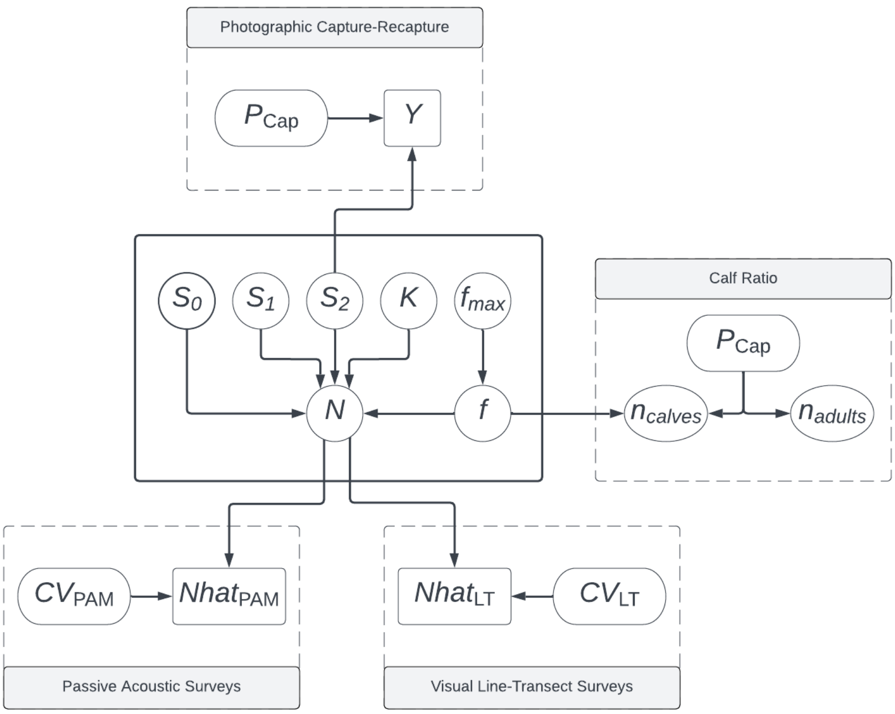

Figure 13 - Directed acyclic graph describing the integrated population model. The central box with a solid black border represents the matrix population model. The population size *N* is controlled by carrying capacity *K* along with life-history parameters including calf survival (S_0), juvenile survival (S_1), adult survival (S_2), and maximum fecundity (f_{max}). In the photographic capture-recapture observational submodel, adult survival S_2 is estimated along with the probability of

capturing animals. The calf ratio submodel uses the same probability of capture, but now calves and adults are enumerated, and the ratio is used to inform fecundity. The passive acoustic and visual line-transect observation submodels consist of imperfect estimation of the true population size ($Nhat_{PAM}$ and $Nhat_{LT}$) according to the CV of the survey (CV_{PAM} and CV_{LT}).

5.3 Power Analysis Simulations with IPM

A series of simulations were run using 15 years of surveys pre-change and 15 years post-change using annual PAM density estimates (CV = 0.35) and a visual survey density estimate (CV=0.6) (see Figure 14-Figure 16). The IPM (supported by yearly capture-recapture) outperforms PAM and less frequent visual line transect surveys markedly – with an eight-fold increase in power to detect a 1% annual decline (Figure 14). Improving the precision around the PAM and LT density estimates can improve the power of individual datastreams in the IPM (as described in section 5.1). This likely also improves the performance of the IPM.

The large increase in power is, in part, driven by the inclusion of an early warning sign metric (calf ratio). When trend is evaluated from an IPM simulation without the calf ratio metric, the power is markedly lower (a four-fold reduction in power (Figure 15). This difference in power is akin to detecting the 1% annual decline ~25 years earlier than using PAM only (c.f. Figure 12).

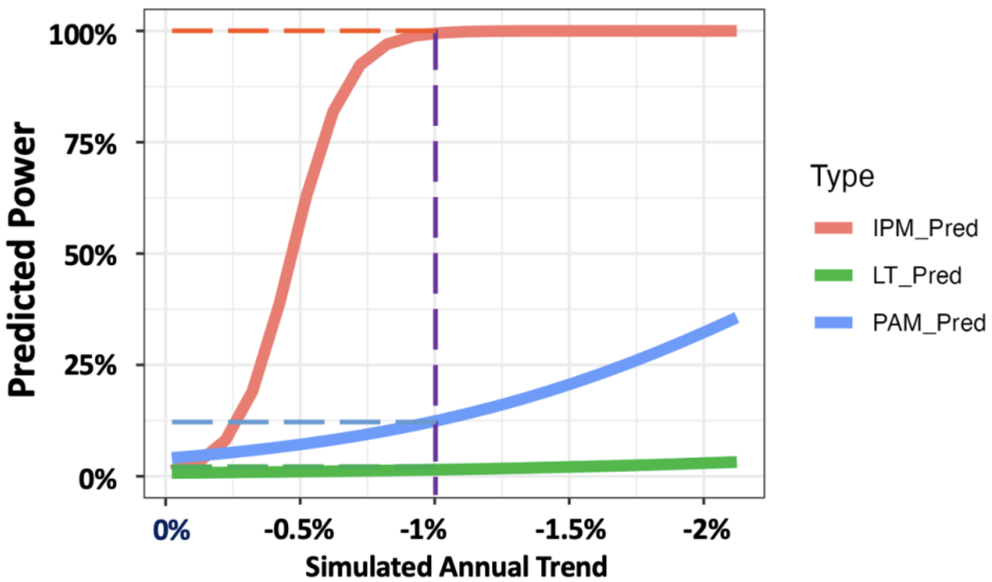

Figure 14 – Predicted power of visual line transect surveys (LT_pred), PAM (PAM_Pred) and combined (IPM_Pred). Calf:ratio information is provided from yearly capture-recapture (e.g. photo-identification) surveys. PAM CV = 0.35, LT CV = 0.6.

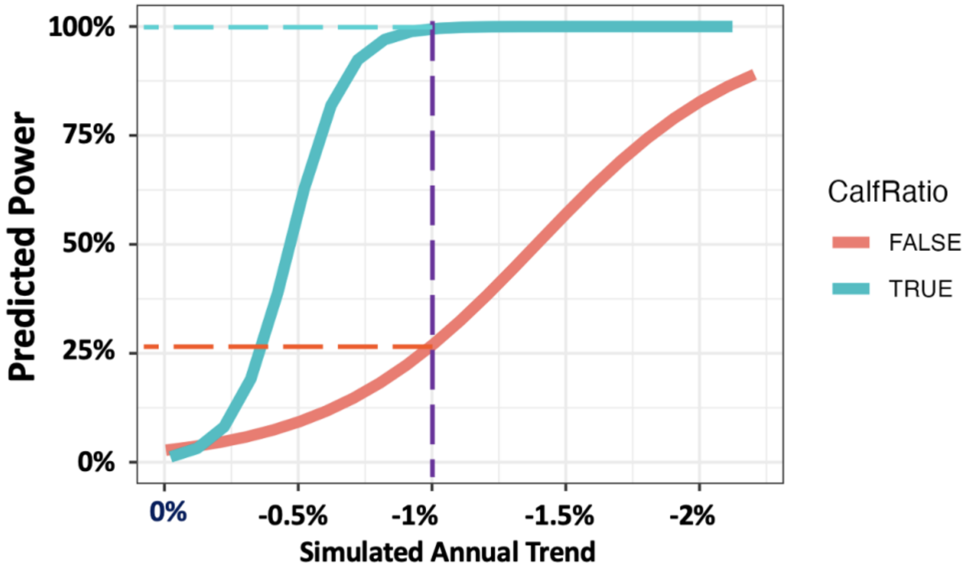

Figure 15 - Predicted power of the IPM for the same scenario with (TRUE) and without (FALSE) calf:ratio estimates being available.

Figure 16 shows the effect of varying the probability of capture (during capture-recapture surveys) when all other variables are held constant. It highlights that this variable can change the power by approximately 10%.

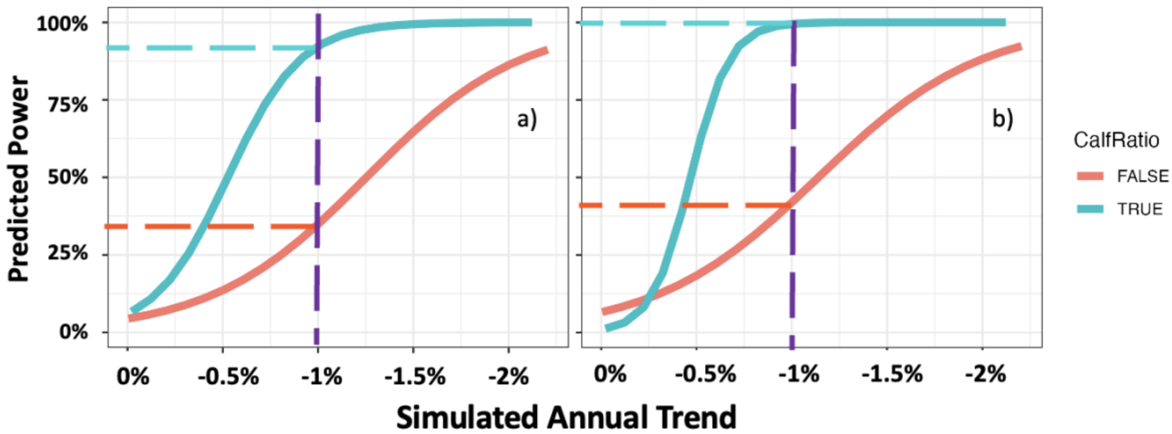

Figure 16 – Shows the same simulations as in Figure 15 with varying probability of capture values. Panel (a) shows the power when the probability of capture is 0.1 and (b) when the p(capture) is 0.4.

Note, simulations using only 5 years before and after the change were attempted – but there were insufficient data available in the simulations from which to derive power from visual survey (only 1 estimate) – as such it was only possible to assess the power from the IPM in such scenarios.

This highlights a limitation of the current framework and the type of decline being assessed. Other power calculations could be developed in future iterations of the model.

5.4 IPM Conclusions & Caveats

The IPM simulation results indicate that there is a significant increase in statistical power to detect trends in population size as a result of integrating different datastreams. This is partly driven by the inclusion of an early warning indicator metric like calf:adult ratio,but even when using simulations with low precision (moderate to high CVs), the increase in power from the IPM integration was significant.

It's important to stress the model is a simulation and therefore may be optimistic in its predictions. The current iteration of the model assumes that the model is correctly specified. This could be investigated in the future by fitting a different population model. Currently the model simulates a decline in carrying capacity across the entire study area, with perfect mixing across the study area, calves are always observed during surveys if present (and never mis-classified as juveniles). Additionally, some parameters are fixed (i.e. are not allowed to vary as they might in reality) – such as the survival rates for calves and juvenile which could lead to the model over-predicting power. Finally, the prior for adult survival is currently tightly constrained – in line with the best estimates of Curtis et al 2020.

In general, false positive rates for the IPM were low (<10%) and improved by inclusion of the calf ratio submodel. For example, in the scenario presented in Figure 17, when the simulated trend was 0 (i.e., no trend), the IPM incorrectly detected a trend 1% of the time, while for PAM data this was 4% and 1% for line-transect data alone. When calf ratio data was excluded, the IPM false positive rate rose to 7%. For line-transect and PAM data these rates varied across scenarios, indicating to us that stochasticity in the simulation was important. Future work could include running additional replicates of scenarios to better estimate false positive rates.

Our power metric was fairly crude in that we considered *any* detected change in trend to be an indication of success; in reality it will be important to consider what a biologically meaningful trend is, which will influence the resulting true and false positive rates. Similarly, real-world scenarios require different trade-offs of false positive and false negatives. In general, the precautionary principle suggests that we prioritize reductions in false negatives, which is what we have focused on here.

Future efforts should involve simulating different declines, fitting different population models (e.g., with different types of density dependence) and allowing for increased variation and uncertainty in life history parameters. This will help to determine how robust this integrated approach is – and the value of such approaches to the Navy – in support of compliance goals.

These points notwithstanding, such an integrated approach looks very promising as a means to improve power to detect changes (along with other improvements, including increasing the number of density estimates per year and improving precision).

This project suggests that the MSM program is likely well placed for further case studies for simulation to predict power of a program to detect a change given different survey modalities, effort and sample sizes (via simulation). Additionally, based on effort to date, there is scope to build an IPM using empirical data collected to date (e.g. Cuvier's in SOCAL) to estimate power of real-world surveys. We discuss the potential for this and other recommendations below.

6 Conclusions

This study has successfully reviewed the MSM program efforts over the past two decades, collated the meta-data and summarized the monitoring. We identified the areas with the most comprehensive monitoring efforts for the priority species identified. We improved the realism of bioenergetic models in estimating the early warning signs of population change and identified these characteristics which are most suitable for monitoring. We also identified the power of these monitoring studies, in isolation, to detect population changes – and demonstrate the potential of using integrated approaches to combine datastreams from the MSM (and other) monitoring. This potential could provide an extremely powerful tool in support of Navy compliance (e.g. by demonstrating power exists to detect a specific decline in Navy monitoring, but that no such decline has been observed). Additionally, once further developed, this simulation tool could drive targeted investment in the MSM program via predictions of the required effort (using different survey methodologies for given species and location) to detect a specific change.

7 Recommendations

This section of the report serves to both summarize the effort within the MSM4PCoD project, but also to outline recommendations that could be taken forward by Navy stakeholders. The focus is the MSM program, but we recognize the utility of this effort for distinct ONR, LMR and Fleet efforts.

A key takeaway from this study is that given the likely >$100M invested in the past two decades on marine mammal research funded by the Navy, major gains have been achieved by revisiting datasets (and these can be achieved at a fraction of the cost of further data collection). Such analyses in the past have yielded a high return on investment and can further target monitoring to allow prudent investment, as the evidence base and Navy priorities evolve.

The following sections span recommendations stemming from the review (section 3) and modelling elements (section 4 and 5). A first set of recommendations relate back to the structure of this study and how they can apply to the MSM program and wider Navy stakeholder needs (section 7.1-7.3). Section 7.4 provides more holistic perspectives and recommendations which might apply across training and testing areas, priority species and Navy funding needs.

Each distinct recommendation comes under a numbered heading which has a unique code to help with utility (e.g. 7.1.1, 7.1.2, etc.).

7.1 Review of MSM metadata

This review demonstrates the extensive efforts of the MSM program to evaluate baseline and response data for marine mammals under the four main groups: Occurrence, Exposure, Response, and Consequences. While there are few studies that currently consider the population level consequences under this program, the long term historial datasets that are presented within the review databases demonstrate their future potential. The considerations and recommendations proposed here would enhance the accessibility of the MSM reports, improve the feasibility of future meta-analysis, and further showcase the efforts of the U.S navy to demonstrate regulatory complaince.

7.1.1 Reporting standardization

During the development of the MSM Review, it was observed that the level of detail within the technical reports varied considerably. While technical reports are expected to differ due to analysis methods, the summaries of survey effort and observations could be standardized. These differences in data reporting could be improved with the development of a reporting guidance document or table template to be completed by the author. This could identify the important information that should be included within every technical and annual report. This could also specify the desired reporting metrics for each survey method; for example, acoustic surveys should include the number of hours of recordings for each deployment or survey, in addition to the number of classified detections for every identifiable species in each recording period.

Misalignment in reporting can also be observed through the disconnect between published results and described survey effort. Publications often report on observations from surveys that span across two years, but only describe the survey effort per single year. For example, between October 2021 – January 2022, there were 85 acoustic detections of Cuvier's beaked whale at SOAR. It is specified that in 2021, the acoustic survey effort was 4621 hours, and in 2022, to date the survey effort was 222 hours. This makes it difficult to align the number of detections or sightings with the amount of survey effort. Examples of this can be found in the M3R report from 2023 (Dolan et al., 2023). Future reporting could provide effort levels that are specifically related to the reported observation data.

7.1.2 Unique identifiers

As the data collected within each research program can often be used to answer more than one question, this information can be dispersed between technical reports, in addition to being incorporated into peer reviewed publications. This can make it difficult to identify duplicated reporting. One example of this would be two reports that include aerial surveys in the same area, in the same year. If the survey dates are listed slightly differently between these two reports, which they might be if the data had been subset, we might think that these are two separate surveys, where in fact they are reporting on the same dataset. This could lead to double counting or a misrepresentation of survey effort. In the future, it could therefore be beneficial to assign unique identifier codes to each survey or dataset. This information could be cited at the start of each technical report, to provide key information on the dataset that is being analyzed. If this data is to be digitally archived, the unique identifier could also incorporate a code to reference the location of the raw dataset.

7.1.3 Data repository

The quantity of data collected under the MSM program is extremely impressive. However, under the current reporting scheme, it is difficult to appreciate the full extent of these research efforts. The suggestions outlined above would assist in the streamlining of these reports and improve the comparability of the different research programs during each survey year. To maximize the utility of these datasets, it could be beneficial to develop an accessible storage system for the raw data collected under these research programs. This would require a protocol for the raw data formatting requirements, and investment in a storage platform. While the initial setup would be an investment in time and resources, this would ensure not only the reproducibility of results of these research programs, but also provide an opportunity for future research projects to build on existing data. In the long term, this could reduce the requirements for new data collection and provide an opportunity for collaborative research across research programs and survey methods.

In addition, within the scientific community there is increasing advocation for the submission of reproducible code and the associated datasets to ensure scientific integrity (Miyakawa, 2020; Powers et al., 2019). If the MSM program were to adopt this strategy, they would be aligned with best practice for ecological research and could help the MSM research programs to improve their strategy for publishing peer-reviewed literature.

7.1.4 Individual web links

Given the extensive effort that has been invested in monitoring under the MSM program, this information should be presented on the Marine Species Monitoring website. Some research programs have very detailed documentation of the relevant technical reports, associated publications, and recent project updates (the Atlantic Behavioural Response Study). This is not the case for all research programs within the marine species monitoring website. For example, the CalCOFI project does not contain any description of the project, progress, or results. This also occurs for the SOCAL PAM project. Ensuring these webpages are regularly updated and documented in a standardized format will help to showcase the efforts of the MSM program.

7.2 Inputs to PCOD model analyses

The PCoD framework (sensu Pirotta et al. 2018) details the inputs, process and outputs of how exposure to a stressor can cause physiological and/or behavioral responses – which translate to impacts on vital rates and population dynamics. A more complex framework is presented by Tyack et al. (2022) spanning the effects of multiple stressors (Figure 1).

It is clear from this review that extensive monitoring effort has been expended over the past two decades across a range of regions and species – employing a variety of monitoring methods. All of these datasets have high utility as elements in a PCoD assessment – either in support PCoD analyses (i.e. quantify inputs or process elements of the model) or in the ultimate goal of PCoD – to identify changes in population dynamics. Much of the MSM research up to 2018 approximately was more focused on characterizing the Occurrence and Exposure elements. These were characterized more by long-term PAM monitoring, and visual aerial and vessel-based surveys. In certain cases, dedicated capture-recapture approaches were also employed. From around 2018 onwards, more studies focused on improving understanding of behavioural and physiological responses to Navy exposure (and to inform baseline states). This period was characterized by increases in the use of animal borne telemetry and biopsy efforts.

Depending on Navy needs, additional focus could be put on better understanding of behavioural and physiological responses to Navy sonar exposure and other noise-generating Navy activities (e.g. pile driving, explosions). Additionally, or alternatively, effort could be focused on the end point of PCOD – the robust assessment of changes in population dynamics (e.g. abundance or density) using demographics (and potentially health metrics like body condition) to improve the detection of population change.

7.2.1 Maximize utility of existing datasets

The MSM program has collected many useful datasets with high utility to monitor different population indices. Section 7.3.3 details how these could be considered in an integrated modelling framework (building on the results in section 5). Here we focus on how MSM program outputs could be used as inputs to PCoD analyses.

The Navy has collected extensive datasets that can inform PCoD assessments. Significant investment in Behavioral Response Studies (BRS)can be used to improve PCoD modelling by providing the empirical basis for the estimation of multiple/aggregate exposures, estimating the probability of exposure, characterizing the effect of disturbance (e.g. changes in net energy intake). Extensive animal-borne tag datasets could support such analyses – to facilitate the linkages between BRS and PCoD research to support Navy compliance goals (Pirotta et al. 2022).

Explicitly, the telemetry data collected in the MSM program could be used to further assess the duration of responses, characterize typical behavior, the time required to return to baseline patterns (if disturbed), and of the ability of individuals to compensate for missed foraging time or alter energy requirements. A clear example of this is the data from the Atlantic BRS – which provide baseline and response data at multiple spatio-temporal scales that can help inform estimates of response duration and compensation abilities for some species. Any assessment of the ability of animals to recover from a response and compensate for missed foraging opportunities will also require a better understanding of prey availability and abundance.

Telemetry is also an important tool to help improve assessments of if individuals are repeatedly disturbed ,as they are likely to be more affected than individuals that are disturbed sporadically. A wide range of factors affect this “aggregate exposure” of individuals in a population, and this uncertainty has a strong influence on the estimated consequences of disturbance. There have been methodological advances in recent years (e.g., through the development of simulation movement models), assessing aggregate exposure remains challenging and predictions of aggregate exposure levels from simulation models require validation with empirical estimates. The extensive data collected via the MSM (and other Navy) program could help drive the development of a generic tool to estimate and validate population and individual levels of aggregate exposure using various input data sources (e.g., telemetry data, species density surfaces, data from surveys). Therefore, it could address a key sensitivity of population-level assessments.

Future research should consider how these diverse datasets could contribute to the further development of dose-response functions and focus on how to reconcile the response patterns observed via different approaches (e.g., response duration and severity from tag records vs range PAM detections). Hin et al (2023) utilized information from instrumented ranges to characterize disrupted foraging. Chudzinska et al (2024) highlights how critical it is to understand the effect of disturbance in driving PCoD analyses. The current gulf between the effect of disturbance estimated from instrumented ranges like SOAR or AUTEC and those derived from telemetry records (e.g. the longest inter-foraging-dive-interval observed in beaked whales is ~18h (Schorr, pers. comm.) which is less than the median response used in Hin et al (2023).

Whilst above we have focused on telemetry data, it’s important to highlight extensive PAM data could be used to characterize the many different types of BRS that have been carried out. With acoustic BRS methods advancing, exploring whether BRS-PCoD integration could be achieved with humpback whales utilizing data from PAM studies (e.g. ongoing data collection at PMRF).

7.2.2 Expand analytical toolkits to utilize existing datasets

A key takeaway from this project is the volume of effort expended to monitor marine mammal individuals and populations over the past 20 years. Whilst many reports and publications have been produced from these efforts, it is likely that the scientific community has only scratched the surface of what could be assessed utilizing these varied datasets (as described in section 7.2.1). Projects like DoubleMOCHA, tagtools, DENMOD and 3S (e.g. Miller et al. 2016) have developed advanced analytical methods that have improved our ability to make inferences from the outputs of significant Navy investment over the past 20 years.

We have highlighted that in many cases, MSM projects have been designed to answer different research topic areas such as occurrence of species, exposure and responses to Navy sonar. Future projects could be designed with specific analysis methods in mind to help facilitate Consequences projects. These might include the assessment of energetically relevant responses given specific questions and observation method***s*** *(e.g.,* PAM, satellite tags, DTAG, etc.; see Synthesis). More broadly, , continuing to support the development of tools which can advance the Navy compliance field (across density estimation, noise propagation, behavioral response and PCoD fields) and help build capacity to advance these areas across the field, is a critical need for the next decade. In addition to collecting relevant data and utilizing extensive existing datasets. Advancing tools and expanding capacity likely represents a strong and cost-effective return on investment to advance Navy priorities.

Ultimately, such datasets and analysis approaches might be helpful in supporting dose response functions for energetically significant takes (e.g. closer to a Southall 7 or 8). Navy compliance requires estimates of takes to support NEPA analyses. Current severity criteria consider a range of behavioural and physiological responses, but established noise criteria (i.e., fixed acoustic thresholds or dose-response functions) cover lower-level responses than those predicted to be relevant to populations by existing energetics PCoD models (i.e., marked increased energy expenditure or reduced intake such that vital rates are affected). Analysis of BRS data with a focus on responses that can lead to a substantial alteration of an individual's energy budget could help inform take estimates that are more reflective of long-term population consequences.

7.2.3 Continued development of PCOD or PCOMS models

This study adapted the Hin et al (2023) bioenergetic model to assess the early warning signs of population change. As noted in section 4.6 and 4.7 there are a number of assumptions that underpin the conclusions of Hin et al (2023) and sensitivities that affect how long changes in demographic parameters persist to be monitored (and provide power indicators of change). As such, it is important that models that inform recommendations themselves should also be further developed and tested for utility.

Additionally, this project highlighted that bioenergetic models can be limited in their utility to assess body condition. This is because the limited metric to link to body condition (in this version of the model) is via total reserve mass. The lack of a strong pattern in body condition has no value as a metric to be monitored as this runs counter to the studies showing the greatest utility of body condition as a health metric (and one that appears to drive vital rate outcomes in some species). It is more likely that the total reserve mass is not a suitable metric in beaked whales at least, or in the way the model is constructed. Clearly other body condition metrics like posterior blowhole depression (Joblon, et al 2014), body volume, body height to volume ratio or at specific locations along the body length (Aoki et al. 2021; Christiansen et al. 2020; Johnston, Rayment, and Dawson 2022; Raverty et al. 2020) – obtained from photo-ID or photogrammetry have significant value to PCoD analyses. This is likely both to help better parameterize models and as another early warning sign of change (Pirotta et al. 2024).

Furthermore, many papers detail the data needs and framework developments to improve bioenergetic modelling for PCoD applications (Keen et al. 2021; McHuron et al. 2022). Such needs also exist for other pathways to effect (e.g. effects on endocrine status, hormone status etc.).

This kind of effort likely does not necessarily fall under the purview of the MSM program – but it's important to consider that these tools guide the recommendations. As such it remains a critical need to revisit assumptions, test and further develop these models.

7.3 Monitoring for population change

7.3.1 Density estimation using instrumented ranges and PAM arrays.

Passive acoustic monitoring is the most widely used survey methodology within the MSM program. With instrumented ranges in both Atlantic and Pacific and other research PAM deployment locations throughout both regions – and ancillary data collection (e.g. acoustic tags providing cue rates) means there is likely ample data with which to estimate trends in PAM density estimates (PAM-DE) alone. What is uncertain is the frequency and precision of the PAM-DE. As such it would be valuable to critically assess how frequently robust density estimates could be derived (i.e. monthly, quarterly, annually) for priority species.

Given such approaches have been demonstrated for a range of marine mammal species, including on Navy ranges (Booth et al. 2017; Marques et al. 2011, 2013) – this seems like an obvious route to pursue. Additionally, because of the capital investment involvement in initiating such surveys, the cost of analysis to derive density estimates or the investigating what can be achieved with such datasets is likely to be comparatively low and provide a large return on investment (e.g. if high precision PAM-DE can be derived monthly or quarterly – there is a good chance of a high power to estimate trends).

Leveraging off of the outputs (and/or data collation) within the ACCURATE project may provide a very useful foundation from which to assess the feasibility of such an approach for different regions, ranges and species. Whilst we have focused on MSM efforts, it is valuable to consider other datasets that could be compiled and potentially integrated (e.g. CalCOFI, NMFS surveys).

Additionally, information from PAM surveys could be with visual survey data to confirm species detections (Thompson et al. 2015). Furthermore Jacobson et al. (2017), combined PAM with aerial visual surveys to define the detection area of PAM devices, in order to then estimate abundance in harbor porpoise. This kind of approach might be possible in Cape Hatteras, Jacksonville (USWTR) and SOCAL where PAM and visual surveys overlapped heavily. It might also be possible in the Hawaii region – though limited visual effort overlaps with extensive PAM data from the M3R project. In all cases an assessment would need to be of the full datasets (rather than metadata as assessed here) to establish the number of detections that are available (and therefore the best candidates for such an approach.

7.3.2 Long-term monitoring of early warning metrics

As stated above, the MSM program has generated multiple long-term datasets which in isolation might only have limited power (though this needs to be assessed – see section 7.3.1) – but when integrated – could provide a powerful foundation in support of Navy compliance goals (though see section 7.3.1).

This study has identified a small number of metrics which could provide suitable early warning signs of population change (though there may be more (see section 7.2.3)). The simulation IPM approach highlighted the importance of including such early warning signs (in the form of demographic parameters) in driving overall power (section 5.3) and this is consistent with other IPMs (Zipkin and Saunders 2018). This lends further evidence to the value of monitoring approaches that can measure these variables and to continuing those efforts. Booth et al (2020) identified that demographic parameters can be estimated during visual surveys and photo-ID surveys. In addition, both vertical and lateral (e.g. laser-) photogrammetry can provide size estimates of animals (Cheney et al. 2018) which can help estimate growth and early survival and if samples could help estimate the proportion of immature animals in a population (Vivier et al. 2023)(informed via assignment of individuals into stage structure) or, if the population life-history is well-understood, pregnancy rate (vertical photogrammetry only)(Christiansen et al. 2018).

Where possible, monitoring programs should be identified which can provide reference or control populations against which observed patterns can be compared (Baumann-Pickering et al. 2016; Trickey et al. 2022). Considering sites such as USWTR in Jacksonville (Figure 4) could be a useful baseline. Similarly, multidisciplinary studies which provide important contextual information (e.g. environmental quality – such as Benoit-Bird 2017) to help inform PCoD studies and establish (or dismiss) potential causes are extremely valuable (Boyd and Punt 2021).

7.3.3 Integrated approaches

7.3.3.1 How integrated modelling can advance Navy needs

Zipkin and Saunders, (2017) review the Integrated Population Modelling field and describe it succinctly as: *"Integrative modeling generally refers to the incorporation of multiple (1) data types on a single target population, (2) analytical models or methods, or (3) predictions from multiple theories into a model, thus 'integrating' several pieces of information into a single modeling framework. The combined analysis of all available information allows for an understanding of processes underlying ecological and demographic responses to environmental variability".* This study uses an integrated population model simulation tool to highlight how the Navy MSM program has collected data (and could continue to collect data) that could be integrated to support Navy compliance in Negligible Impact Determination. For example, with an adequate integrated approach, it could be possible to determine which MSM (and supporting) efforts would be likely to have the power to detect specific declines (e.g. a 1% or 2% annual decline for a specific species or population). If no such decline is detected, then this would support that a negligible (or no) impact has occurred.

Additionally, once a robust simulation IPM is updated for Cuvier's beaked whales, it could be used to explore different sampling regimes to inform more targeted monitoring and funding decisions. Specifically, the tool is capable to assessing the levels of effort, the frequency of effort (e.g. every year, alternate years etc.), and different levels of precision (i.e. CVs) which could be achieved for a given species, study region and survey approach. Understanding the combinations of monitoring efforts (and identification of other datastreams for integration – e.g. prey data, climate data) could allow the design of targeted monitoring programs for consequences (and focus funding decisions on return on investment). This might also be achieved by sensitivity analysis of different survey combinations.

Finally, as the framework is species agnostic, it would be possible to amend the existing simulation population model to be applied to other species to determine if different combinations of sampling approaches are fit for purpose.

Of course, to achieve this, it is necessary first to ensure that the simulation IPM approach described in this study is robust. Once this model has been further tested (see section 5.4) and different power analysis calculations included – this can improve the utility of the IPM to assess different situations (e.g. ones in which a steady decline has occurred, or where a step change has occurred).

It is important to consider the full utility of IPMs – in their ability to utilize data from many different data sources in submodels – for example data from telemetry, prey habitats or productivity data, population counts or indexes, strandings data, capture-recapture (Boyd and Punt 2021; Goethel et al. 2021; Piironen et al. 2023, Tinker et al. 2021) and these represent a powerful suite tools.

There are many examples of how different datastreams have been integrated using case studies from terrestrial and avian literature (though not necessarily using IPMs). We provide some examples below.

7.3.3.2 Photo-ID for demographic information

Capture-Recapture efforts, with sufficient effort, can estimate demographic parameters. Photo-identification has previously been combined with biopsy data to extract information on population structure from various marine mammal species, including Cuvier's beaked whale (Curtis et al. 2020). Obtaining information about the age structure and sex ratio of a population provides extra detail which may be used to inform a population model, and potentially reduce uncertainty in estimates of population size. One of the earliest examples of incorporating demographic information into a population model was on Stellar sea lions (Holmes and York 2003). Photographs were used to estimate the number of juveniles within the samples from animal size. An age-structured population model was then fit using pup, non-pup and juvenile fraction data. It was found that using juvenile fraction data for the detection of change in vital rates to be detected with 1 year, versus the 7 years required for population and new-born counts alone. While there are only a few marine mammal-specific examples of this type of integrated population model, simulated datasets also show support for the merging of multiple datastreams (including demographic information) to accurately detect trends within a population (Boyd and Punt 2021).

7.3.3.3 Telemetry and Capture-Recapture

Currently, few other studies have combined telemetry with capture recapture methods for marine mammals, with the exception of polar bears (Regehr et al. 2018). Despite this, an integrated approach using capture-Recapture and telemetry data is becoming more frequent in terrestrial mammals and bird literature. Murphy et al. (2019) incorporated telemetry information into a capture-recapture model, to inform the model of cryptic activity related to home range. Modelling sex as a partially identifying categorical covariate further improved the precision of population estimates. Recently, tagging of Cuvier's beaked whale in the Cape Hatteras region revealed that individuals occupy small core use areas, and are infrequently displaced from the region (Foley et al. 2021). Therefore, including home range could help inform a population model for this species, if a capture-recapture model were to be implemented. Capture-recapture studies in the terrestrial environment have recently supported the combined efforts of telemetry and photo-id, and it has been hypothesized that methods might be beneficial to localize the activity centre for mobile species (Whittington et al. 2018). This method has been shown to improve the precision of density estimates in other terrestrial mammals, for example in Florida Panthers (Sollmann et al. 2013).

Telemetry also has the potential to provide better estimates of the probability of capture for data derived from photo-ID studies (see Figure 16). This could increase the precision of estimates and therefore the overall power to detect trends of population change. Further, if sex and age can be estimated from a combination of photo-id and biopsy, perhaps this information could be incorporated as partially identifying categorical covariates.

7.3.3.4 Biopsy and population models with age/sex structure

Biopsy sampling can be used to obtain a wide range of information about an individual, but also about its population and genetic background. Within the navy reports, biopsy samples have been used to better understand population structure (age and sex ratios), as well as in some cases, looking at the genetic components of the individual to determine ecotypes. While the intention for this analysis is expressed, much of the results are not provided within annual reports. This could be the result of the time required to analyze samples, but also perhaps the results from analysis are held until a full report is ready to be published. Booth et al 2020 summarizes the potential for remote sampling in its application to MSM4PCoD, whereby biopsy can be used for sex and age ratios, and to better understand reproductive hormone levels (and other health markers). This information can be used to inform a population model where these parameters might otherwise be more generally estimated.

7.4 Supporting Navy needs

7.4.1 Which datasets from MSM program are most useful?

It is challenging to determine which MSM datasets are most useful as this is dependent on Navy needs and priorities – which evolved over the course of this project.

As described in section 7.2.1 and 7.3.1 there are extensive long-term PAM data both from instrumented ranges and more broadscale deployments. Investigating these PAM data to generate density estimates (where sufficient supporting data are available) would be extremely valuable. Such an exercise could make use of the outputs of the ACCURATE project (LMR Award N3943019C2176) to help generate density estimates for the best studied species.

Given the investment made in studies of beaked whales and their responses to Navy sonar, this group represents an obvious choice for case studies to inform the Response-Consequence elements (e.g. Pirotta et al. 2021). Data could be utilized from many past and current Navy projects to generate improve inputs to PCoD analyses (e.g. improved estimates of energy intake and expenditure in baseline and exposure scenarios and expansion of the Hin et al (2023)'s models for Cuvier's and Blainville's beaked whales could lead to more robust PCoD assessments (e.g., decoupling environment, energy intake and expenditure). See section 4.6.1, 4.7 and 7.2.3.

Extensive telemetry data have been collected alongside other survey modalities (AFTT: 268 satellite, time depth recorders and DTAGs; HSTT 250 tags deployed). Many such datasets could inform the questions detailed in section 7.2.1.

This project did not review in detail the uses of the biopsy or other remote sampling of marine mammals carried out by the MSM program. However, it's clear that extensive samples have been collected for many priority species (AFTT: a minimum 269 biopsies from nine species, HSTT: 184 biopsies across 10 species). If samples remain stored (i.e. have not been fully analyzed), then assessing what could be achieved (e.g. assessing hormone levels, pregnancy rates etc.) would be valuable.

7.4.2 Best case studies to pursue?

A number of the priority species remain data poor within the scope of this MSM program. In some cases, this is down to insufficient metadata being available to inform the levels of detections to inform what can be achieved. In general, beaked whale species, short-finned pilot whales are the best studied of the priority species. PAM studies from instrumented ranges and other PAM arrays are likely to have greater scope for a range of species – but will be dependent on the current scale of detection, classification and localization (DCL) capabilities.

If the findings of this initial study are confirmed and the IPM approach demonstrated herein proves to be robust and provides meaningful increase in power, then the best Navy case studies appear to be SOCAL (for Cuvier's beaked whale) and Hatteras (for Cuvier's beaked whale and short-finned pilot whale) – though the shift to BRS studies after 2018 in Cape Hatteras might require careful consideration of what datasets can inform density since 2009. In Hawaii, short-finned pilot whales appear to be the most data-rich species (though this is dependent on DCL capabilities within M3R).

There is value in considering sites with relatively little Navy activity could be valuable (e.g. Jacksonville, Marianas) or other reference sites to consider sites that could provide a baseline, as activity ramps up. Jacksonville potentially provides a good candidate with many datastreams collected through 2018 and given the USWTR and M3R, it could be valuable to understand species occurrence. In this study, data did not show up after 2018 due to a lack of the priority species being observed.

Contextual variables are of critical importance as they can dramatically improve the inferences that can be drawn (even those the focus is on understanding the effects of sonar). As such considering sites with long term and robust environmental monitoring could be valuable. If the Navy is a stressor for marine mammals – unlikely Navy is the only stressor and so long-term monitoring of a shifting baseline (e.g. CalCOFI or other similar programs) could provide valuable supporting information to improve inferences.

Ultimately, this is a topic that likely requires further discussion. In isolation, the best approach would be to re-assess priority needs and cross reference with the most data rich species.

7.4.3 What novel monitoring could be integrated into the MSM program?

There are likely many new avenues that could be pursued – which provide added value as inputs or a better understanding of process within PCoD and PCOMS models or to provide the critically needed early warning sign metrics which drive the power to detect change. Booth et al 2017 summarized the current state of knowledge of the feasibility (i.e. how practical it is to utilize this survey method for a given species to provide useful metrics) and the utility (how many useful metrics can be estimated via this method for a given species group). See Figure 5-15 of that report. The assessments remain relevant in 2024, though methods like photogrammetry have seen an increase in their application for monitoring body condition and demographic parameters 7.2.1.

Identifying where new or established technologies can be added into existing MSM projects might provide significant added value. Specifically, adding new survey capabilities where the survey infrastructure exists already means a cost-effective increase in what can be achieved by a given program. A good example of this is the inclusion of vertical or lateral laser-photogrammetry, or remote tissue sampling into an existing vessel-based effort could be valuable. The cost per sample would be moderate given the existing infrastructure in place. Similarly, in the future, as new technology develops and is validated (e.g. estimates of body condition remotely sampled and telemetered from tags, remote drone operations), these can be incorporated into appropriate monitoring efforts.

8 Acknowledgements

This project was funded under NAVFAC award N3943019C2175. Thanks to Eleanor Marwood for support in producing figures and to Rachael Sinclair for advice during the project. Final thanks to the LMRAC and other Navy stakeholders who guided this project from start to finish.

9 Literature Cited

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10 Appendix 1 – MSM4PCoD Scoping Summary

The intention of the MSM4PCoD Scoping workshop was to engage with relevant Navy stakeholders via a workshop to communicate the intent of 'MSM4PCOD', learn more about the MSM perspective and ultimately review and refine the scope of the main effort to ensure it was fit for LMR/MSM purposes. This was considered to be critical to the success of any future MSM4PCoD effort. Due to travel restrictions and ongoing COVID issues, the workshop was held online in a series of three meetings: mini-reviews of the Atlantic and Pacific (specifically Hawaii and SOCAL) MSM projects to date. Following these, a larger meeting was held with a wider range Navy stakeholders (and MSM project practitioners) to discuss and finalise the main project scope.

10.1 Scoping & Prioritization process

An introduction engagement meeting for the MSM4PCoD project was convened on the 22nd January 2020. This meeting was designed to allow gathering of initial feedback from Navy stakeholders about the MSM program and the best way to structure the scoping workshop. An introductory presentation was made by PI Booth (the presentation can be viewed

It was agreed that providing a review template would be helpful to the leads of the Atlantic, Hawaii and SOCAL programs – to allow for the key information to be collated.

Therefore SMRU Consulting drafted a Review Template and associated Guidance Note. The purpose of this initial data collection was to help identify the priority species at each Complex/OPAREA, get an overview of the survey method types used, and to obtain contact information and links to reports.

The information collated in this initial data collection will form the starting point for SMRU Consulting to create the full database on all MSM efforts (if Options are funded) in 2021 and 2022, which will include finer scale detail on effort and sample sizes etc obtained from the survey reports and available data.

The following documents were circulated to Joel Bell, Jessica Chen, Jessica Bredvik, Jene Nissen, Laura Busch, Chip Johnson and Julie Rivers during March 2020 with the following instructions:

- Review Template Guide - This Word document gives detailed instructions on how to complete the spreadsheet.
- Review Template – *"This Excel spreadsheet will need to be filled out for each major project (separate tabs) that is or has occurred in your monitoring region. Most important thing is to gather data on priority species or species that we have the most data for. "*
- MSM Effort Summary – *"This PowerPoint presentation will be for each monitoring region lead to present at the workshop. Include an intro slide on your region and then include the details requested in the "Case Study" slides for as many projects as you see fit."*

Following these mini-reviews by MSM personnel, two mini-review meetings were convened to discuss the projects and better understand stakeholder perspectives. Separate meetings were held for Atlantic and Pacific (focused on Hawaii and SOCAL) mini-review meetings on the 12th and 14th May 2020 respectively. These allowed us to obtain an overview of the monitoring projects that have been, and are currently being conducted, and to obtain a high-level insight into the methods that have been used and the species that have been studied. The information provided in the Review Templates and the presentations from the mini-review meetings are available for the Atlantic and Pacific and summarised in Table 2 and 3 respectively.

Following the mini-review meetings, a final Scoping Workshop was carried out on the 19th May 2020. The invited participants are shown in Appendix 1. The presentation slides from this workshop meeting are here. The structure was such that PI Booth led the discussions, both to summarise the main outcomes of the mini reviews (see Tables 4 and 5) and link those key outcomes into the wider scope of the larger MSM4PCoD project. MSM4PCoD Project Tasks Leads (Booth, Harwood and Thomas) presented an overview of their approaches for discussions and agreement with MSM stakeholders. Below we summarise the main outcomes of the meeting.

Table 2 - Summary of the projects detailed in the Atlantic Review Template. VAC = VACAPES, CHP = Cherry Point, JAX = Jacksonville. OERC? outlines which of 'Occurrence, Exposure, Response and Consequences are the focus of this study. VS = Visual surveys, PAM = Passive Acoustic Monitoring, IT = Individual Tracking (e.g. telemetry), RS = remote sampling (e.g. biopsy sampling), CR = capture recapture methods are employed (e.g. photo-identification). CBW = Cuvier's beaked whale, SFPW = Short finned pilot whale, SW = sperm whale, BW = blue whale, FW = fin whale, SeiW = Sei whale, HW = humpback whale, NARW = North Atlantic right whale, Oth = other marine mammal species.

	Region				Years															*Methods*					*Species*								
Study #	**VAC**	**CHP**	**JAX**	**GoM**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**OERC?**	**VS**	**PAM**	**IT**	**RS**	**CR**	**CBW**	**sfPW**	**SW**	**BW**	**FW**	**SeiW**	**HW**	**NARW**	***Oth***
1	x														X	X	X	X	R	x		X	x	x	x	x							*x*
2	x										X	X	X	X	X				O	x		X	x	x	x	x							*x*
3	x												X	X	X	X	X	X	O	x		X	x	x					x		x	x	*x*
4	x																X	X	R			X									x		
5	x													X	X	X	X		O	X		x	x	x	x	x	x		x	x			*x*
6	x														X	X	X	X	O			X											*x*
7	x	x	x									X	X	X	X	X	X		O			X										x	
8	x									X	X	X	X	X					R		X												*x*
9		x									X	X	X	X					O		X								x	x	x	x	*x*
10		x	x									X	X	X					R		X				x	x	x		x			x	
11A			x				X	X	X	X	X	X	X	X	X				O	X					x		x		x			x	*x*
11B		x			X	X	X	X	X										O	X					x		x		x			x	*x*
11C	x								X	X	X	X	X	X	X				O	X					x		x		x			x	*x*
11D	x												X	X	X	X	X		O	X					x		x		x			x	*x*
12A			x				X	X	X	X	X	X	X						O	X		x	x	x	x	x	x						*x*
12B	x						X		X	X	X	X	X						O	X		x	x	x	x	x	x						*x*
12C		x			X	X	X	X	X	X	X	X	X						O	X		x	x	x	x	x	x						*x*
12D		x*						X	X	X	X								O	X		x	x	x	x	x	x						*x*
13A			x				X	X	X	X	X	X	X	X	X	X	X	X	O		X				x			x	x	x		x	*x*
13B		x*			X	X	X	X	X	X	X								O		X				x			x	x	x		x	*x*
13C	x									X	X	X	X	X	X	X	X	X	O		X				x			x	x	x		x	*x*
13D	x											X	X	X	X	X	X	X	O		X				x			x	x	x		x	*x*
14	x									X	X	X	X						O	X	x										x		*x*

Table 3 - Summary of the projects detailed in the Hawaii/Southern California (SOCAL) Review Template. OERC? outlines which of 'Occurrence, Exposure, Response and Consequences are the focus of this study. VS = Visual surveys, PAM = Passive Acoustic Monitoring, IT = Individual Tracking (e.g. telemetry), RS = remote sampling (e.g. biopsy sampling), CR = capture recapture methods are employed (e.g. photo-identification). CBW = Cuvier's beaked whale, BBW = Blainville's beaked whale, oBW = other beaked whale species, SFPW = Short finned pilot whale, SW = sperm whale, MHW = melon-headed whale, PKW = Pygmy killer whale, FKW = False killer whale, BRyW = Bryde's whale, BW = blue whale, FW = fin whale, SEIW = Sei whale, HW = humpback whale, Oth = other marine mammal species.

	Region												Years											Methods												Species						
Study #	**SOCAL**	**HA**	**NW**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**OERC?**	**VIS**	**PAM**	**IT**	**RS**	**CR**	**CBW**	**BBW**	**oBW**	**SW**	**sfPW**	**MHW**	**PKW**	**FKW**	**HW**	**BRyW**	**FW**	**BW**	**SEIW**	***Oth***
PMRF tagging		X								**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	E	x		**X**	x	x	x	x		x		x	x	x						*x*
PMRF RL		X											**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	E		**X**	**X**							x	x		x						*x*
PMRF PAM		X		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	R		**X**				x	x		x					x	x	x	x	x	*x*
M3R		X											**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	R		**X**				**x**	**x**												
SOCAL_Zc	X							**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	O			**X**		X	**x**										x			
SOCAL_GFS	x																			**X**	**X**	**X**	O	X		**X**																*x*
SOCAL_Gliders	x	x																			**X**	**X**	O		**X**				x	x	x											*x*
SOCAL_PAM	x												**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	O		**X**				x	x	x								x	x		*x*
Mn_tagging	x	x	x															**X**	**X**	**X**	**X**	**X**	O			**X**	X	X									**x**		x	x		
SOCAL_BmBp_tag		x														**X**	**X**	**X**	**X**	**X**			O			**X**	X	X											x	x		*x*
CALCOFI	X								**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	O	**X**	**X**																	*x*
SOCAL_Aerial		x								**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**			O	**X**	**X**				x	x		x					x	x	x	x	x	*x*
HI_LOE	x	x										**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	O	**X**								x					x					*x*
HI_MonkSeal		x										**X**	**X**	**X**	**X**								O			**X**																*x*
HI_PAM		x									**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**			O		X				x	x		x	x	x	x	x	x		x	x	x	*x*
HI_Exe		x									**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**			E	**X**				X					x			x	x					*x*
HI_baseline_Vis		x							**X**	**X**	**X**	**X**	**X**	**X**									O	**X**	X	X	X	X	x	x	x	x	x		x	x	x		x	x	x	*x*
HI_baseline_Tag		x							**X**	**X**	**X**	**X**	**X**	**X**									O	**X**	X	X	X	X	x	x	x	x	x		x	x	x		x	x	x	*x*

Via the scoping meetings, it was agreed that the priority regions for the review task would include: VACAPES, Cherry Point and Jacksonville in the Atlantic, and Hawaii and SOCAL in the Pacific. Other regions such as Gulf of Mexico, Gulf of Maine, Northwest Training and Testing, Marianas Islands Training & Testing and Gulf of Alaska were currently identified as lower priority and therefore that theses regions would only be included in the review if time allows.

10.2 Conclusions

In summary, we agreed to focus the effort on (current) priority areas of the Atlantic (excluding the Gulf of Maine and Gulf of Mexico), Hawaii and SOCAL. For the Atlantic region it was agreed that the key priority species are: Cuvier's beaked whale, short-finned pilot whale and sperm whale and, if time allows then a secondary set of species could be included, including: humpback whales, fin whales and NA right whales. For the Pacific, the key species identified were Cuvier's beaked whales, Mesoplodon species, humpback whale, blackfish species and those species frequently detected on the PMRF PAM range (minke and Brydes whales).

It was also agreed, that the review would focus on MSM efforts, but where appropriate (and where time allowed) include other leveraged learning from other LMR funded efforts. In addition, considering new methods or techniques coming online from ONR or SERDP supported projects would be beneficial. An key example of where MSM and LMR supported projects could be utilised further, is the SOCAL Cuvier's beaked whale program and we will explore what might be achieved with such projects, in collaboration with the relevant PIs and data-holders.

10.3 MSM4PCoD Scoping Meetings Invitees

The table below outlines the personnel invited to partipate in the MSM4PCoD meetings between January and May 2020.

Table 4 – List of invitees to the four MSM4PCoD scoping meetings.

Name	Organisation
Andrea Balla-Holden	Marine Resources Program Manager Pacific
Anurag Kumar	LMR Program Manager, NAVFAC EXWC
Benjamin Colbert	Environmental Planner NAVSEA
Brittany Bartlett	NAVFAC Pacific
Chip Johnson	Natural and Marine Resource Program Manager Pacific
Christiana Salles	Marine Resource Specialist, NAVFAC Southwest
Corey Pressley Plakos	Naval Air Systems Command
Cormac Booth	SMRU Consulting
Dana Schrimpf	Marine Resources, NAVFAC Pacific
Daniel Engelhaupt	HDR Inc
Daniel Engelhaupt	HDR Inc
Danielle Jones	Marine Resources, NAVFAC Atlantic
Danielle Kitchen	Chief of Naval Operations
Deanna Rees	Marine/Wildlife Biologist (NAVFAC)
Eiren Jacobsen	Centre for Research into Ecological & Environmental Modelling
Emily Hague	SMRU Consulting
Gregory Sanders	Environmental Specialist at US Navy
Jacqueline Bort	Marine Mammal Compliance and Mitigation Program

Jamie Gormley	Marine Resources Specialist
Jene Nissen	Environ. Readiness, U.S. Fleet Forces
Jessica Aschettino	HDR Inc
Jessica Bredvik	NAVFAC Southwest
Jessica Chen	Marine Resources, NAVFAC Pacific
Joel Bell	Marine Resources, NAVFAC Atlantic
Julie Rivers	US Pacific Fleet Terrestrial and Marine Resources Program Manager
Kristin Ampela	HDR Inc
Laura Busch	U.S. Fleet Forces Command Action Officer and Marine Resources Oversight
Len Thomas	Centre for Research into Ecological & Environmental Modelling
Mandy Shoemaker	LMR Deputy Program Manager, NAVFAC EXWC
Mark Cotter	HDR Inc
Mark Deakos	HDR Inc
Michael Richlen	HDR Inc
Michael Weise	ONR Marine Mammal & Biology Program
Nancy Dimarzo	NUWC M3R
Rachael Sinclair	SMRU Consulting
Stephanie Watwood	NUWC M3R

11 Appendix 2 – MSM Review

11.1 Links to MSM review databases and supporting information

- Guidance document for the Atlantic and Pacific databases
- MSM4PCoD Atlantic and Pacific databases
- Helpfile on how to use MSM databases to generate case study gantt-style plots document, it contains links to the necessary data inputs and R code file.
- Papers produced by MSM4PCoD project

11.2 Atlantic region data summaries

11.2.1 Passive Acoustic Monitoring

Region	Date range	Priority species detected	Types of acoustic devices deployed
Cape Hatteras	2009 - 2019	Cuvier's beaked whale, Short-finned pilot whale, Sperm whale, Fin whale, Humpback whale, North Atlantic right whale	HARP, towed acoustic arrays, seaglider
Jacksonville	2009 - 2017	Cuvier's beaked whale, Short-finned pilot whale, Fin whale, Humpback whale, North Atlantic right whale, Sperm whale	MARUs, towed array, HARP,
Camp Lejeune	2010-2011	Bottlenose dolphin	CPODs
Cherrypoint	2007 - 2015	Cuvier's beaked whale, Short-finned pilot whale, Fin whale, Humpback whale, North Atlantic right whale, Sperm whale	MARUs, towed array, HARP,
Norfolk Canyon	2014 - 2019	Cuvier's beaked whale, Fin whale, Humpback whale, Sperm whale	HARP

11.2.2 Visual surveys

Region	Date range	Species sighted	Survey Type
Cape Hatteras	2011 - 2017	Short-finned pilot whale, Cuvier's beaked whale, Sperm whale, Fin whale, Humpback whale	Aerial
Cape Hatteras	2009 - 2021	Short-finned pilot whale, Cuvier's beaked whale, Sperm whale, Fin whale	Boat
Cherrypoint	2007 - 2011	Short-finned pilot whale, Sperm whale, Fin whale, Humpback whale	Aerial
Cherrypoint	2007 - 2015	Short-finned pilot whale	Boat
Norfolk Canyon	2016 - 2019	Short-finned pilot whale, Cuvier's beaked whale, North Atlantic right whale, fin whale, Humpback whale, Sperm whale	Aerial
Jacksonville	2009 - 2017	Short-finned pilot whale, North Atlantic right whale, Sperm whale, Humpback whale	Aerial
Jacksonville	2009 - 2015	Short-finned pilot whale, North Atlantic right whale	Boat
Chesapeake	2016	North Atlantic right whale, humpback whale, Fin whale	Aerial
VACAPES Complex	2015 - 2021	Short-finned pilot whale, Cuvier's beaked whale, Fin whale, Humpback whale, Sperm whale, North Atlantic right whale	Boat
Camp Lejeune	2010	No priority species listed	Boat

11.2.3 Telemetry

Region	Date Range	Species tagged	Number of tags deployed	Tag types
Cape Hatteras	2014 - 2021	Cuvier's beaked whale, Short-finned pilot whale, Sperm whale, other non-priority species	202	Satellite tags, DTAGs
VACAPES complex	2017 - 2021	Fin whale, Humpback whale, North Atlantic right whale, Sperm whale	66	Satellite tags, DTAGs

11.2.4 Biopsy

Region	Date Range	Species biopsied	Number of biopsies taken
Cape Hatteras	2012 - 2020	Cuvier's beaked whale, Short finned pilot whale, Sperm whale, Fin whale, non-priority species	117
Jacksonville	2012 - 2015	No priority species biopsied	82
Cherrypoint	2010 - 2013	Cuvier's beaked whale, Short finned pilot whale, non-priority species	30
VACAPES Complex	2017 - 2021	Fin whale, Sperm whale, Humpback whale	40

11.3 Pacific region data summaries

11.3.1 Passive Acoustic Monitoring

Region	Date range	Priority species detected	Types of acoustic devices deployed
PMRF	2009 - 2022	Blainville's beaked whale, pilot whale spp, Minke whale, False killer whale, Cross Seamount, Cuvier's beaked whale, Short-finned pilot whales	Seafloor hydrophones, towed hydrophones (minimal)

Hawaii Range Complex	2005 - 2018	Short-finned pilot whale, Cuvier's beaked whale, False killer whale, Blainville's beaked whale, Sowerby's bealed whale, Gervais beaked whale, Deraniyagala's beaked whale, Humpback whale, non-priority species	Fixed hydrophones, HARP, EARs, PAM glider, towed hydrophones
SOCAL	2008 – 2022	Cuvier's beaked whale, Humpback whale, beaked whale spp, Baird's beaked whale, non-priority species	Sonobuoys, Towed hydrophone, HARP
SOAR	2010 - 2021	Cuvier's beaked whale, Humpback whale, Short-finned pilot whale	Seafloor hydrophones

11.3.2 Visual surveys

Region	**Date range**	**Survey Type**	**Species sighted**	**Survey Type**
Hawaii Range Complex	2008 - 2016	Aerial	Short-finned pilot whale, False killer whale, Mesoplodon spp, non-priority species	Aerial
Hawaii Range Complex	2009 - 2021	Boat	Blainville's beaked whale, False killer whale, Short-finned pilot whale, Humpback whale, Bryde's whale, non-priority species.	Boat
PMRF	2014	Boat	Short-finned pilot whale, False killer whale, non-priority species.	Boat
SOCAL	2008 - 2013	Aerial	Cuvier's beaked whale, Bryde's beaked whale, Humpback whale, non-priority species	Aerial
SOCAL	2004 - 2019	Boat	Cuvier's beaked whale, Baird's beaked whale, False killer whale, Humpback whale, Short-finned pilot whale, Killer whale, non-priority species.	Boat
SOAR	2010-2021	Boat	Cuvier's beaked whale, Humpback whale, Killer whale, non-priority species	Boat

11.3.3 Telemetry

Region	**Date Range**	**Species tagged**	**Number of tags deployed**	**Tag types**
Hawaii Range Complex	2010 - 2021	Short-finned pilot whale, False killer whale, Blainville's beaked whale, non-priority species	59	Satellite tags, satellite/ depth tags
PMRF	2011 - 2016	Short - finned pilot whale, False killer whale, Blainville's beaked whale, non-priority species	19	Satellite, satellite/depth tags
SOAR	2008 - 2021	Cuvier's beaked whale, Baird's beaked whale, Killer whale, False killer whale	51	Satellite tags, LIMPET tags, Archival tags
Northwest Training Range	2014 - 2019	Humpback whale, non-priority species	121	Satellite tags, satellite/ depth tags

11.3.4 Biopsy

Region	**Date Range**	**Species biopsied**	**Number of biopsies taken**

Hawaii Range Complex	2010 - 2019	Short- finned pilot whale, False killer whale, Humpback whale, non-priority species	92
Northwest Training Range	2014 - 2018	Humpback whale, non-priority species	42
SOAR	2011 - 2021	Cuvier's beaked whale, Killer whale, non-priority species	50

12 Appendix 3 – Bioenergetics model figures

12.1 Other metrics

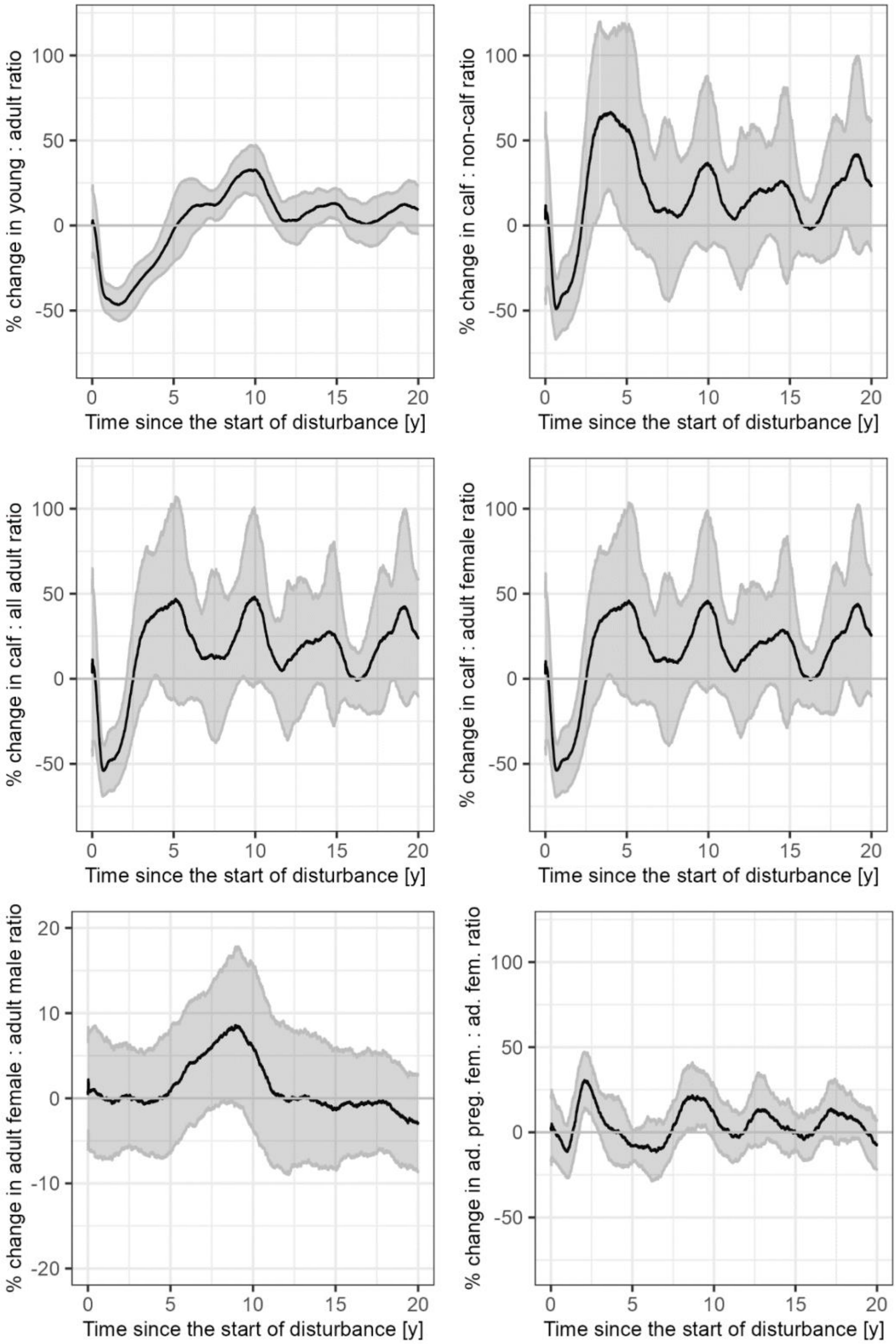

Figure 17. Percentage change of the six metrics from baseline simulations in the absence of disturbance and first 20 years after disturbance started. Black lines indicate mean of the 20 replicates of the simulations and the grey area shows standard deviations. Note that y axis differs in between the panels.

12.2 Different disturbance patterns

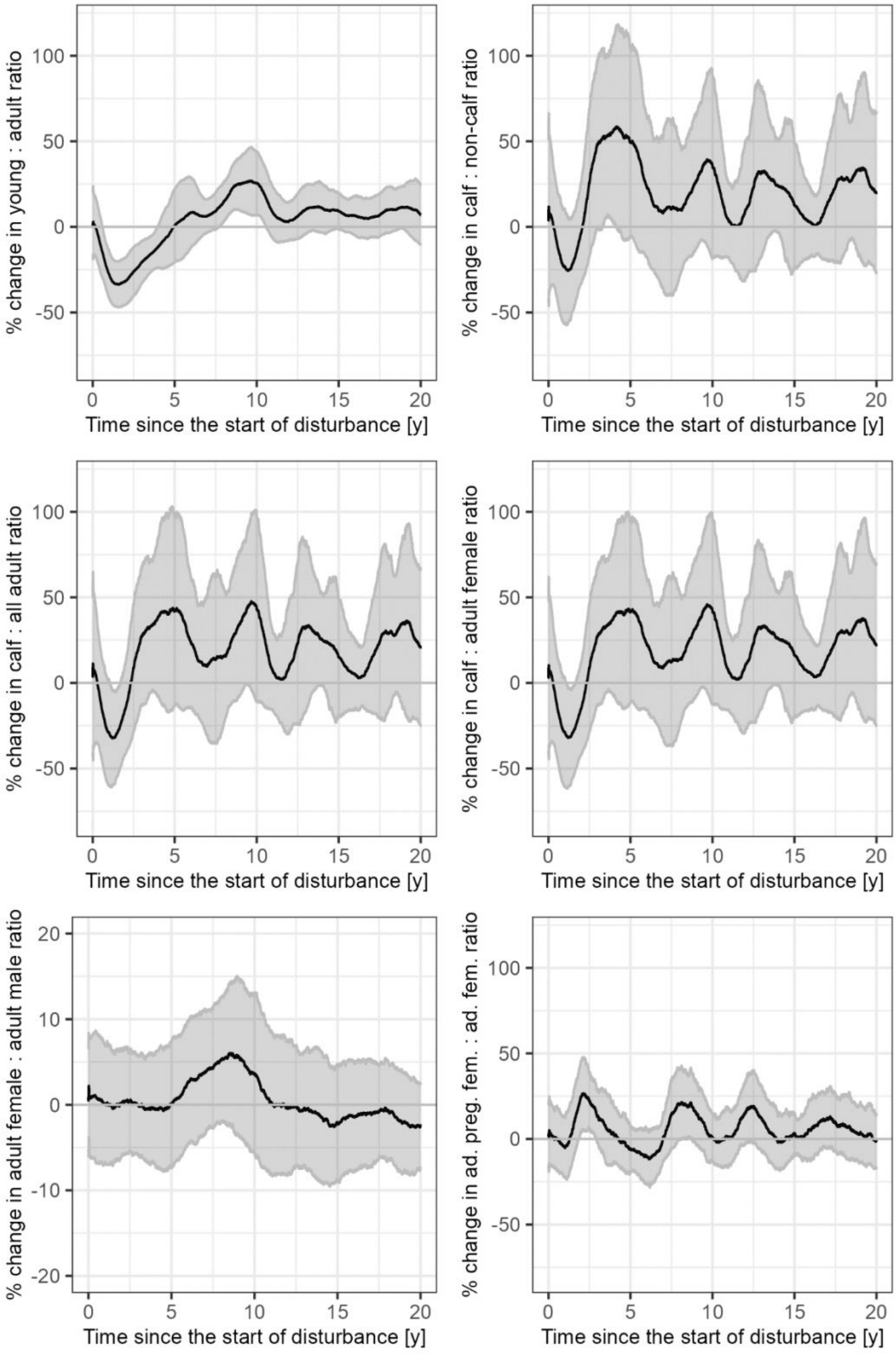

Figure 18. Percentage change of the six metrics from baseline simulations in the absence of disturbance and first 20 years after disturbance started for the set of simulations assuming 300 days of sonar activity per year. Black lines indicate mean of the 20 replicates of the simulations and the grey area shows standard deviations. Note that y axis differs in between the panels.