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Review

Data collection and analysis methods to evaluate potential impacts of seismic surveys and other marine industrial activities on baleen whales

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ABSTRACT

Offshore surveying from seismic airgun arrays and other intense types of industrial development introduce substantial underwater noise, with potentially serious consequences for marine life. We describe an adaptive spectrum of data collection and analytical methods to evaluate the type, magnitude, and complexity of disturbance associated with industrial activities. Scientists and managers have often been mired in a cycle of mitigation and monitoring plans and data collection schemes that focus solely on the prevention of significant but generally rare instances of injury or death. Increased focus is needed on achieving a refined understanding of the sub-injurious but vastly more common impacts of disturbance on energetics, reproduction, and survivorship at population levels. Approaches that apply and adapt earlier knowledge and integrate tools tuned to exposed species, exposure type, and situational context can provide more insightful understanding of likely effects to inform effective monitoring, and mitigation. Such approaches require multi-disciplinary measurement technologies and individual/population-level statistical models to demonstrate how various types and levels of acute and chronic anthropogenic noise affect marine life. Standardized biological data (e.g., distribution, animal tracking, behavior) should be collected within structured, prioritized, and integrated methodological and analytical frameworks before, during, and after noise-generating activities. This paper sets forth an 'ideal' approach for planning, collecting data, and conducting analyses to test for effects of noise on baleen whales. The approach can range from simple to complex, depending on the context. Further, we discuss and recommend methods for analyzing sampling data using currently available tools and guidelines, including behavioral response severity metrics, acoustic criteria, and bioenergetic and population effects models.

1. Introduction

Offshore energy exploration and development has become frequent in many areas of the globe over the past half-century (e.g., for the extraction, storage, and transport of hydrocarbons). Many of the associated activities, such as seismic surveying, are likely to continue

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(Bröker, 2019), for hydrocarbons as well as other sources of energy (e.g., various forms of kinetic energy; Wiser et al., 2021).[1] Marine seismic surveys employ intense sound sources, commonly with compressed air guns, to investigate and characterize marine substrata for geological research or energy development (Hildebrand 2009). These surveys have known or potential impacts on marine life, from whales to plankton (e.g., Blackwell et al., 2015; McCauley et al., 2017; Southall et al., 2021). Awareness of these risks has led competing resource users (for example, subsistence communities that depend on access to healthy and abundant living marine life) to demand efforts be made by industry to prevent, monitor, and mitigate harm. Governments have required companies to conduct environmental impact studies, and regulatory agencies establish rules for how, when, and where marine seismic surveys occur (Nowacek and Southall, 2016). While seismic surveys for oil and gas development are currently among the most intense sources of intentional anthropogenic sound routinely used in the ocean, other marine activities (e.g., wind energy development, geophysical research, vessel traffic, onshore coastal developments, military sonar) also use acoustic sources that create noise that can impact marine life (Hildebrand 2009). For this paper we primarily consider approaches to measure and mitigate the potential impacts of seismic surveys, including those used in scientific programs, but also consider some other industrial sources and contexts.

Scientific research on the hearing and acoustic communicative behavior of marine mammals and how they may be negatively affected by anthropogenic noise has expanded greatly since the mid-20th century (Southall et al., 2007; 2019a, 2021). The range of potential effects of noise on marine mammals is well established and impacts can include a host of observable behavioral responses (e.g., Southall et al., 2021), interference with communication (i.e., masking; Clark et al., 2009; Hatch et al., 2012), physiological stress responses (e.g., Rolland et al., 2012; Atkinson and Dierauf, 2018; Lemos et al., 2022), temporary, or (less commonly) permanent hearing loss (Southall et al., 2007; 2019a), or even more rarely, stranding and mortality (Filadelfo et al., 2009). Given the focus here on baleen whales, it is notable that while there are estimates of hearing range and relative sensitivity from studies of auditory structures and mechanics (e.g., Parks et al., 2007; Tubelli et al., 2012; Cranford and Krysl, 2015), no direct measurements have yet been made of the hearing sensitivities or auditory impacts on hearing of any baleen whale species. This is an acknowledged limitation that calls for a cautious approach in estimating such effects in noise criteria, particularly for endangered species (see Southall et al., 2019a). Such criteria have guided local, national, and regional guidelines for preventing direct injury from sound exposure. They should continue to be used as guidance for adaptive monitoring and mitigation as they are based on relatively precautionary interpretations of the potential for impacts, including auditory damage, until they are informed by direct measurements.

Behavioral disturbance has been a focus of monitoring and mitigation during potentially disturbing activities, and scientists have become adept at collecting substantial quantities of exposure and response data (see: Southall et al., 2007; 2016, 2021; Gailey et al., 2016, 2022a). Research linking observed behavioral responses, or changes in behavior, to long-term population trends has evolved significantly in recent years (e.g., Pirotta et al., 2015, 2018; Keen et al., 2021). The 'severity' of behavioral responses or changes is thus increasingly seen as an important measure of the consequences of disturbance. Southall et al. (2021) established three categories of behavioral changes – those affecting feeding, reproduction, and survival. Specifically, they described a spectrum of behavioral changes associated with these life functions that can be used to measure and assess responses, along with a detailed set of acoustic exposure and response variables with which to report and aggregate the data (See Appendix I). They also note the strong context-dependency of behavioral response evident in many species, notably baleen whales, which can have substantial mediating effects on the probability of response (see: Ellison et al., 2012, 2018; Southall et al., 2016). Not only are noise levels associated with exposure important, but so are many biological parameters including behavioral state and exposure history of the animals. Contextual features of the noise and environment are also important such as the relative movement of noise sources relative to exposed animals, regularity of occurrence of noise, physical features (e.g., water depth, bottom type, thermal structure) of the exposed area. Finally, Southall et al. (2021) also identified a comprehensive suite of noise metrics that should be reported (see Table 1).

A key consideration in how data on disturbance are collected, analyzed, and interpreted in terms of predictive relationships and ultimate consequences relates to the unit of analysis (individual, group, or population) and the temporal and spatial scale over which disturbance is assessed. Shorter-term studies of acute exposures, such as behavioral response studies (BRSs) where there is experimental control, have the advantage of known exposure conditions and observable responses of varying degrees of severity, often assessed with severity scales such as the vital-rate paradigm (Southall et al., 2016, 2021). Longer-term population-level studies have the benefit of tracking parameters at broad spatial and temporal scales, but they lack the fine-scale resolution of exposure and response typically used in analyses of probabilistic predictive relationships (exposure-response functions). While we currently have more explicit means of evaluating and predicting responses at the individual, short-term level, extensive new and ongoing research is increasing the ability to evaluate longer-term responses and possibly interacting stressors at population levels (NASEM, 2017; Pirotta et al., 2022).

It has long been recognized that sound production is important to baleen whales and that human noise can interfere with their acoustic communication (Payne and Webb, 1971). Baleen whales predominantly produce and are thus presumed to be attuned to low frequencies (e.g., below 1000 Hz). Much research effort has been directed at understanding how they are affected by and respond to low-frequency underwater noise produced by human activities with a view to developing effective mitigation measures where needed. Baleen whales are adapted to live in a naturally noisy environment with sounds from waves, rain, earthquakes, and myriad biological sounds, and not all anthropogenic underwater noise will necessarily have negative consequences. The type and probability of impacts depend on characteristics of the noise, the environmental and biological context in which it is produced, and how it interacts in time, space, frequency spectrum, and other characteristics of the receiving animals (Ellison et al., 2012; Southall, 2017; Southall et al., 2021). Much of the relevant research has consisted of field measurements of primarily behavioral and masking impacts on three species in three regions where offshore energy development has expanded rapidly: bowhead whales (*Balaena mysticetus*) off Alaska and in northern Canada, gray whales (*Eschrichtius robustus*) in the Russian Far East, and humpback whales (*Megaptera novaeangliae*) off Australia. We focus primarily on these three exemplars and on lessons learned from associated studies of disturbance and mitigation, with selected examples from other cetacean species.

[1] We acknowledge and welcome the roadmap toward net zero (in terms of carbon pollution) provided by the International Energy Agency (IEA, 2021). Our intention is not to weaken in any way the case for a rapid cutting back on exploration for hydrocarbon deposits and a fair, inclusive, and unwavering global transition to renewable energy as envisioned by the IEA. However, we also recognize that geotechnical surveys to optimize the exploitation of hydrocarbon reservoirs already under production and for other offshore endeavors (e.g., site profiling for alternative energy facilities, seafloor mapping, tectonic research) will remain for the forseeable future as will activities like pile-driving for windfarm installation. We must not ignore the need to apply best monitoring and mitigation practices to such processes, many of which involve the introduction of intense noise energy into the ocean.

Table 1
Recommended biological and acoustic exposure measurement approaches for variable spatial and temporal scales.

Spatial and Temporal Scales	Level of Effort and Complexity	Biological Measurements – Baseline Data and Behavioral Response		Acoustic Exposure Measurements and Analytical Methods	
		Methods	Data types and analyses	Acute (source-specific) measurements	Aggregate acoustic fields and ambient noise
Shorter-term; finer scale	*Simple*	Vessel- or shore-based visual observations (near noise source, short periods Before-during-after (BDA) exposure, observational)	Presence-absence data; Distribution scan sample data; Focal animal observations	Single sensor PAM deployment; Source-specific SPL-only data (near noise source, during operation)	Single sensor PAM deployment; Broad-band SPL-only noise source and ambient sound data (near noise source, short periods BDA during operation)
	Complex	Integrated visual observations (multiple platforms, including aerial UAV); PAM; eDNA Archival tag deployments; biopsy sampling (all near noise source, short periods BDA, observational or experimental)	Individual and/or group presence, distribution, density and movement; Behavioral state and changes BDA exposure; Integrated behavioral and physiological response metrics	Multi-sensor PAM deployments; SPL, SEL, kurtosis, other derived metrics of noise source; (near source, during source operation)	Multi-sensor PAM deployments; SPL, SEL, kurtosis and other derived metrics of noise source and ambient sound data (broadly distributed, short periods BDA source operation)
Longer-term; broader scale	*Simple*	Sequential visual sampling observations (vessel-, shore-based); Small array PAM deployments; Small number medium- to long-term telemetry tags (Geographic area around noise source, selected periods BDA, observational)	Presence-absence data over longer periods; Density estimates Distribution scan sample data; Repeated focal group observations over broader scales; Longer-term individual movement, behavioral state	Small array PAM deployments; Source-specific SPL-only data (area around noise source, selected periods BDA source)	Small array PAM deployments; Broad-band SPL-only noise source and ambient sound data (area around source, selected periods BDA source)
	Complex	Sequential, integrated visual sampling observations (vessel-, shore-based, aerial); Large array PAM deployments including control areas; Many medium- to long-term telemetry tags; Ecosystem/prey data collection (geographic area broader than effects range of noise source, selected periods BDA including non-disturbance years, observational or experimental)	Presence-absence and density over longer periods in disturbed and undisturbed areas; Repeated distribution scan sample data; Repeated focal group observations over broader scales and undisturbed areas; Ecosystem driver metrics: Large sample size, longer-term individual movement, behavioral states	Large array PAM deployments including control areas; SPL, SEL, kurtosis, other derived metrics of noise source; (geographic area broader than seffects range of ource, selected periods BDA including non-disturbance years)	Large array PAM deployments including control areas; SPL, SEL, kurtosis and other derived metrics of noise source and ambient sound data (geographic area broader than effects range of source, selected periods BDA including non-disturbance years)

1.1. Observations on disturbance and mitigation from key species

Bowhead whales live in Arctic and sub-Arctic waters and some populations are subject to limited hunting for subsistence by Indigenous peoples in Russia, the United States, Canada, and Greenland, with hunting regulated (except in Canada) under the 1946 International Convention for the Regulation of Whaling. Their severe depletion by commercial whaling up to the early 20th century, together with the strong advocacy by hunting communities to protect their hunts, spurred U.S. and Canadian regulators to force oil and gas companies to invest heavily in acoustic and other behavioral research on bowheads (e.g., Stafford and Clark, 2021). This work has been ongoing for decades and has resulted in some of the most insightful and comprehensive studies of, for example, the impact of seismic surveys on the behavior of whales (e.g., Blackwell et al., 2015; Robertson et al., 2016; Würsig and Koski, 2021).

Gray whales were widely distributed and abundant on both sides of the North Pacific Ocean prior to being depleted by commercial whaling, primarily up to the early 20th century (Henderson, 1972; Weller et al., 2002). Their numbers in the western Pacific remain low (Cooke, 2019; Reeves et al., 2022; Gailey et al., 2022a) but the eastern population has made a strong recovery since legal protection from commercial whaling was established by the International Whaling Commission (IWC) in 1946 (Durban et al., 2015; Stewart and Weller, 2021). The rapid development of the offshore oil and gas industry on the northeastern Sakhalin Island shelf of Russia, which began in the late 1990s, elicited a global outcry from conservationists because of its proximity to the only presently known summer and autumn feeding areas of gray whales in the western Pacific, which are generally referred to as "western" gray whales (Reeves et al., 2005). Studies of western gray whales have provided several examples that can help frame this paper as the whales spend time feeding near Sakhalin, meaning that some of the data collection and analytical methods that are not feasible for offshore locations (e.g., theodolite tracking from shore stations) can be applied on the island (e.g., Gailey et al., 2007, 2016, 2022a, 2022b; Muir et al., 2015a,b). Gray whales undertake one of the longest annual migrations of any mammal, traveling some 15,000–20,000 km round trip. During the summer and fall, most of the eastern North Pacific population feeds in the northern Bering and southern Chukchi seas, but some whales forage in waters off Southeast Alaska, British Columbia, Washington, Oregon and northern California. Feeding gray whales are usually alone or in small group in dispersed aggregations of higher numbers of whales.

Humpback whales in the Southern Hemisphere were greatly reduced by commercial whaling but have made a strong recovery since they were accorded legal protection from commercial whaling in the 1960s (Allen, 1980). They migrate along both the east and west coasts of Australia and have been studied extensively, including a recent large-scale program known as the Behavioral Response of Humpback Whales to Seismic

Surveys (BRAHSS). This study tested the responses of individual humpbacks as they migrated along the east coast of Australia, and it employed robust modern methodology (Cato et al., 2016; Dunlop et al. 2016, 2017), which can be used by researchers working in similar situations as a good guide. The effects of seismic surveys on humpback whales during a different phase of their life history (i.e., singing, possibly to mediate social interactions; Cholewiak et al., 2018) have also been studied in a population off Angola (Cerchio et al., 2014). This latter study did not sample and track individual whales as the animals were in open water far from shore. Differences in methods appropriate for different circumstances (e.g., life cycle phase: feeding, breeding, migrating; or location: offshore, inshore) are discussed in this paper.

For feeding baleen whales exposed to offshore industrial exploration and development, examples are available showing how the results of data collection and analysis can be used to guide Monitoring and Mitigation Program (MMP) design. Most humpback and gray whales spend the winter months in low-latitude breeding/calving grounds, although some animals stay in high-latitude waters throughout the year (Charif et al., 2001). The reasons for making the trip to low-latitude waters for calving and the early stages of calf rearing and, presumably, breeding have been debated (Corkeron and Connor, 1999; Clapham, 2001), but these typically warmer and often shallower waters are preferred by females with their young calves. Gray whales, humpback whales, and right whales (*Eubalaena* spp.) normally do not feed other than opportunistically in the areas where calving and early stages of calf rearing occur. Whether they feed or not, these areas where very young whales occur and where, presumably, mating also occurs are important as they host these critical life history functions. The behavior of the whales on these breeding/calving grounds can be quite different than the behavior on feeding grounds; the data collection methods can be similar, but the repertoire of behavior to be sampled will differ. It should be noted that bowhead whales generally do not follow the same pattern as the other species mentioned above (George et al., 2021).

2. Monitoring and Mitigation Programs

The application of MMPs, with varied levels of complexity and integration, has become a standard practice in many jurisdictions for operators wishing to carry out marine seismic surveys of any kind in or near environmentally sensitive areas (e.g., Johnson et al., 2007; Bröker et al., 2015; Nowacek and Southall, 2016; Aerts et al., 2022; Gailey et al., 2022a; b). MMPs usually need to be set within multiple frameworks – scientific, regulatory, and monitoring/risk assessment, with consideration of long-term effects. The basic questions to be addressed are simple: (i) are the noise-producing activities causing significant harm or disturbance to whales (and the ecosystem as a whole), and (ii) is the applied mitigation adequate? Three categories of potential impacts (indicators) are often used to assess whether individuals (and ultimately populations) are harmed or disturbed. This includes consideration of specific impacts, including: hearing damage/injury; non-auditory impacts (e.g., release of stress hormones) and behavioral effects (including masking) of variable severity. Where the fauna of the area is poorly known, then the first step in MMPs should be to establish which species are present and how they are using the area (e.g., for feeding, reproduction, migration) and the seasonal pattern of occurrence (e.g., year-round or in certain months only – Table 1, Fig. 1). This may support temporal mitigation where activities are conducted when key species are not present. The initial mitigation components are expected to provide a means of allowing the industry to accomplish essential work while at the same time ensuring that negative impacts on whales (and some other fauna) are ideally avoided or at least minimized. Monitoring components of MMPs are expected to collect data to enable improved understanding of how and to what extent survey activities may injure or disturb whales. Mitigation measures such as shut-down or power-down zones have been applied, although multiple authors have argued such approaches may be less effective than viable methods to reduce overall noise footprints through quieting technologies (e.g., Simmonds et al., 2014; Leaper et al., 2015; Wright and Cosentino, 2015).

While designed for dual purposes, MMPs vary widely in their design,

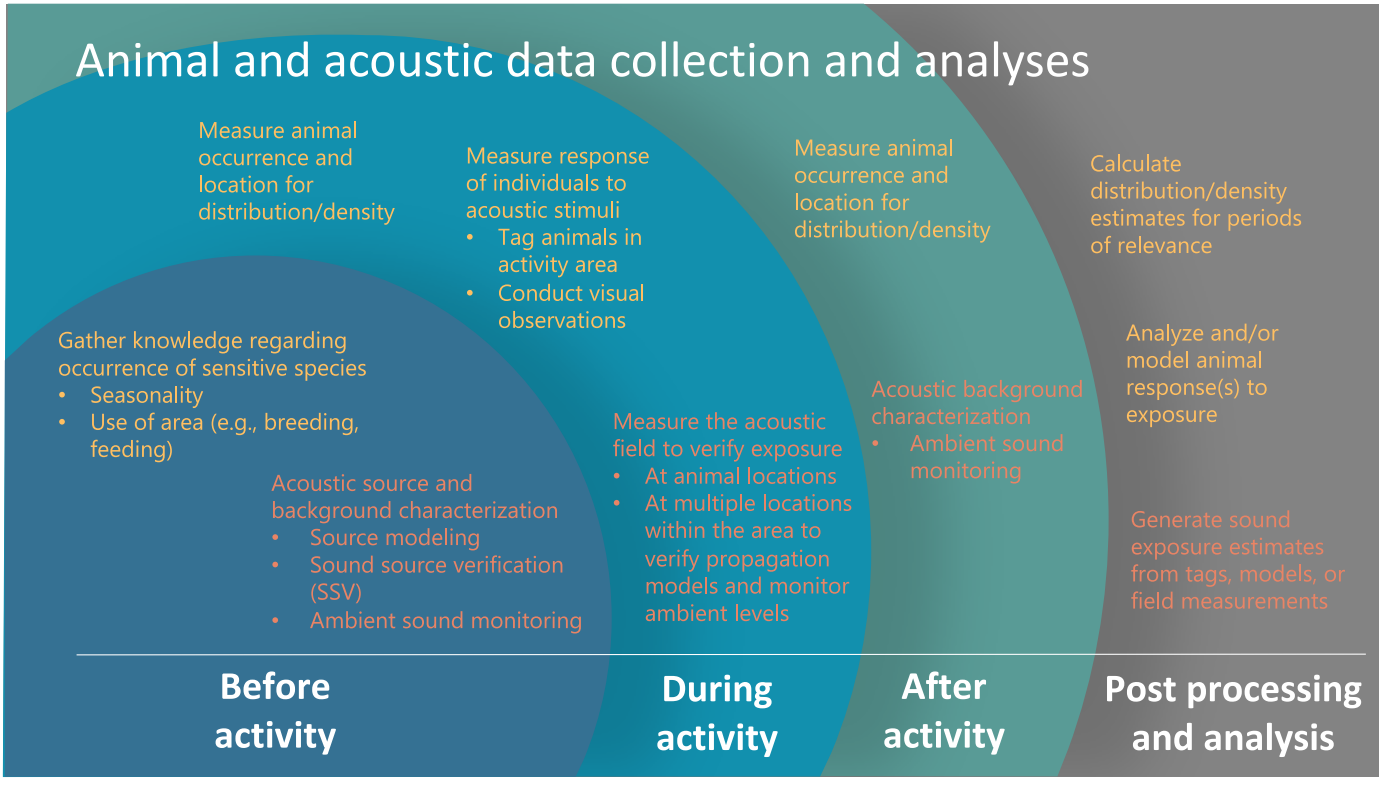

Fig. 1. Recommended strategic approaches for data collection and analysis in different phases of industrial activity.

and in practice, the primary focus on mitigation can sometimes come at the expense of monitoring. However, monitoring is critical as it helps determine whether there has been an impact and whether mitigation measures are or aren't effective. Importantly, it also provides a basis for learning how to mitigate future impacts more effectively. For responsible marine energy companies as well as regulators, a major aim is to learn from experience, leading to more effective MMPs. The data collected as part of a MMP must be deliberately and rigorously collected so that quantities such as rates (e.g., of feeding bouts or attempts, courtship interactions) and densities (individuals present per unit of area) can be calculated and, wherever possible, using methods that are consistent across surveys to allow data pooling and/or comparison of results. An example of mitigation and monitoring and how the two interact is the use of marine mammal observers (MMOs) to watch for animals entering an exclusion area or a 'shutdown zone' in the waters immediately surrounding an operating airgun array or other sound source. Such zones are usually envisaged primarily to prevent hearing injury, so if whales are seen in or near this zone, the source is temporarily shut down; this reflects the mitigation function. Monitoring whales' behavior outside this zone and/or their response during the acoustic stimulus (e.g., firing of the airguns) or after a shutdown can inform future MMP design. For example, do whales outside the exclusion zone exhibit normal or disturbed behavioral patterns? This thus reflects the monitoring function but also feeds back into the mitigation function.

Data collection and analytical tools available to better understand impacts have increased. Bioenergetic models, for example, have been developed to explore potential short- and long-term impacts on several species, including baleen whales (e.g., Villegas-Amtmann et al., 2015), and the collection of data relevant to such models (including their validation) has become an explicit objective of some MMPs. Empirical examples of multivariate analyses of the effects of individual seismic surveys on whale distribution and behavior are available (e.g., Gailey et al., 2007, 2016, 2022b; Dunlop et al., 2016; Schwartz et al 2022a,b). While recognizing that consistent methodological approaches are desirable, it is also evident that each survey or development operation is unique in purpose, scale, design, environmental context, technical capabilities of operators and analysts, biota at risk of being harmed, and other factors. Therefore, there is value in having a set of basic principles and adaptive monitoring approaches that can be tuned to different situational contexts to guide data collection and analyses (see Van Parijs et al., 2021).

Learning and building from earlier approaches to reduce impacts from industrial development on baleen whales through effective multidisciplinary MMP planning and execution, is the essential focus of this paper. It is in some ways an update and expansion of a previous article by many of the same authors describing "responsible practices" for seismic survey MMPs (Nowacek et al., 2013) and is also informed by recent related contributions (e.g., Southall et al., 2019, 2021; Keen et al., 2021; Pirotta et al., 2021). It provides practical guidance for integrating sampling and analysis of data and metadata in strategic ways to meet specific objectives (e.g., regulatory compliance, scientific, and/or conservation objectives).

3. Data collection and analysis methods for measuring and detecting animal responses to noise over multiple time and space scales and levels of complexity

To address aspects of monitoring and mitigation in a straightforward, practically effective manner, we differentiate two main data streams: animal-centric factors and noise source (soundscape) data. We describe the types of data to collect, when and how to collect those data, possible methods to analyze the data, and how to apply the results, with the understanding that each marine activity can, and often does, take place in unique circumstances that require case-specific protocols. An overarching goal is to promote methods that yield results comparable to existing data that can be consistently and rigorously analyzed with existing tools. We recognize that innovation in both data collection and analysis methods will continue, and our effort here is not to restrict that but to identify the need for comparable data to allow analyses of both short- and long-term effects and trends.

We advocate for an adaptive approach to data collection that relates to both biological and acoustic data that may span either short- or long-term deployments and may range from relatively simple and straightforward to increasingly complex and multidisciplinary (Table 1; Fig. 1). Factors to examine include: status of potentially affected population of each species; proportion of the population(s) that might be affected; life cycle stage (e.g. migration, breeding/calving, feeding); sound source output parameters; length of exposure; regularity exposure (e.g. one-off, intermittent, common); ease of mitigation; potential for monitoring; legal framework; and whether the animals are exposed elsewhere in their range or by more than one operation within the same area.

A comparatively simple approach may suffice where the overall risk is assessed to be low, for instance where scenario aspects of the exposure scenarios are well known, whales use of the area is low, and local populations are stable or increasing. Conversely, a more precautionary, rigorous, longer-term, and more complex approach may be required where the animals likely to be disturbed are doing poorly from a conservation perspective, extensive uncertainty exists, or the acoustic sources to be deployed are relatively uncommon. Many legal frameworks go beyond considering "population-level" impacts alone and require that animal welfare concerns be considered. Therefore, lack of evidence of a decline in whale numbers doesn't necessarily lead to the conclusion that mitigation measures can be relaxed (Risch et al., 2021).

Knowledge of the animals' previous exposure to noise is important, particularly where there is considerable uncertainty and/or novelty in industrial development activities. Data cannot be considered to represent the 'before' period if another disturbing activity was occurring closely overlapping in time and space. The 'before' period needs to be long enough to collect sufficient distribution and behavioral data to understand pre-exposure parameters and variability, tuned to the exposure scenario and species involved. Obtaining robust information on the demographic parameters of whale populations, with an ability to detect changes, may take years of monitoring, which may be impractical. In such cases, reasonably precautionary approaches using existing data from long-term studies in representative species (Keen et al., 2021) may be used. The 'during' period of the seismic survey should include the entire time of active surveying (i.e., the exposure period). The relatively short 'quiet' intervals (e.g., for line turns) are not considered to be 'after' but instead part of what is, in effect, an intermittent exposure regime. The 'after' period should not be seen as an optional extra. It is critical to allow collection of appropriate post-exposure data on density, distribution, and behavior for comparison with the pre- and during-survey data as well as maintaining an ability to detect effects that occur late in the exposure period or even after it has ended. The after-survey period should be at least as long as the pre-survey period.

3.1. Animal demographic and life-history data

This section is organized around specific aspects of a species natural history traits: feeding, reproduction (socializing, calving, mating), migration and survival (normally simplified as 'juvenile' and 'adult' survival). Obtaining reliable estimates of suitable parameters requires an understanding of the structure of the population (and the relationship of the animals that use the affected area to the total population) and some require a much longer time-series than others (e.g., parameters associated with feeding rate vs reproduction or survival, Table 1); often, monitoring of a larger area than simply the area of the noise-producing operation is required to evaluate population-level effects. Collection of data on each of these parameter types is not mutually exclusive and do we not imply that any one is more or less important than another – this will depend on the objectives of the MMP. However, the relative

importance may well depend on the given context (e.g., humpback whales in low-latitude mating/calving grounds are believed to rarely engage in feeding activity). Organizing baleen whale data streams in accordance with life history stages to evaluate potential impacts enables researchers to focus on the stream or streams that are most important for the specific context.

Particularly considering their lengthy life spans, demographic studies of baleen whale populations require data collected over at least several years to yield insights into the characteristics and conservation status of the population(s) present. If there are effective ongoing studies in the area, it is preferable to support or augment these rather than to start a new, independent study program. Consolidating and mobilizing the requisite expertise can take time and advantage should be taken of existing capacity rather than starting afresh.

Where there are recognized data gaps in the existing program(s) that would preclude essential aspects of risk assessment (e.g., life history, population structure and trends, response probabilities for specific kinds of exposure), especially for species of conservation concern, the industry operators should conduct or support studies that strategically enhance or complement existing data. For example, if previous and ongoing research has been limited (for logistical or other reasons) to only a portion of the whale population's range, such as near-shore waters, consideration should be given to investing newly available resources (personnel, vessels, equipment) in another portion of the range, such as offshore waters, to broaden and deepen the knowledge base. In all cases, close collaboration with knowledgeable local experts is highly desirable.[2] Moreover, it is essential that industry operators make the data collected openly available to the public and other researchers (see: van Parijs et al., 2021).

Depending upon the context in terms of potential disturbance intensity, conservation status of the exposed whale population, source novelty, and understanding of the exposure context, monitoring should begin up to several years prior to the proposed activity. Multidisciplinary teams that have expertise in formulating adaptive, strategic MMPs may bring considerable knowledge from other contexts. It is advisable early in planning, and especially before planning field surveys, however, to consult with local researchers, other marine operators, and any users of the area who may have relevant knowledge. Surveys should be conducted according to established protocols, particularly regarding the recording of sighting and effort data. The design and protocols of the surveys should be reviewed by an independent expert sufficiently in advance to allow any required modifications. Hammond et al. (2021) provide a review of methods to estimate density and abundance using distance sampling with vessel and boat surveys, as well as mark-recapture techniques using known individuals. The former approach is useful to obtain an initial idea of the overall population structure and density if carried out at the same time of the year and in the same area as the projected operations. The latter approach, which estimates the number of animals 'using' an area over time, may be more appropriate where they are possible than the former.

It is important to establish whether the locally occurring whales are resident, or a discrete group of individuals that visit the area seasonally. To determine this, it is necessary to identify and catalogue the animals, to see whether the same individuals are present in successive years. For species with easily distinguishable body markings, individuals can be identified photographically. Decisions as to whether moderately "invasive" research methods such as the collection of skin and blubber biopsies or the application of non-implantable tags are incorporated into the monitoring program should be made with care and consideration, ensuring the objectives are clearly articulated and maximum scientific value is derived. Tissue samples, in addition to allowing identification of individuals and their sex, are valuable to investigate population differentiation, measure levels of certain chemical pollutants, and inform trophic studies. They are also increasingly being used to estimate age and hormone levels (e.g., cortisol levels as a relative indicator of physiological stress).

Knowing the age and sex composition of the affected population is important, especially where there are conservation concerns. In the case of gray whales off Sakhalin Island, for example, it was important to identify and locate areas where mother-calf pairs are present and determine their proximity to noisy activities, including seismic surveys and pile driving. There was a concern that noise would have a disproportionate impact on mature females and calves, who are vital to the reproductive capacity of the population. Gray whales at Sakhalin have been studied since the mid-1990s using photo-identification, and more recently biopsy sampling (see: Reeves et al., 2022). It is important to obtain as much information as possible, including the timing of mother-calf linkages (e.g., genetically or by standardized field observation methods including photogrammetric measures of body dimensions, such as total length and girth). Experienced observers are essential for reliable species identification as well as for discriminating among sex and age classes (e.g., mother-calf pairs).

It is unlikely that data collection within the operational area alone will reveal clear evidence of a population-level impacts attributable to disturbance from seismic surveys or other industrial activities, unless that operational area includes a large proportion of the population(s) concerned (Forney et al., 2017). Together with other studies conducted in comparable situations, the results may also contribute to understanding the circumstances under which whale populations can persist, or not, in the proximity of noise-generating industrial activities. The permitting of such activities often requires that mitigation measures are taken, and those measures generally need to be accompanied by monitoring animals as they are being exposed, which ideally inform whether the mitigation measures are effective. Once incorporated into a legal framework, such measures are difficult to change, even if the evidentiary basis for establishing them was weak. This is evident, for instance, in the fact that step-function thresholds based on expert opinion rather than direct measurements derived to manage behavioral and hearing impacts early in the U.S. regulatory processes (HESS, 1999) have long persisted in decision-making despite extensive contravening empirical data supporting different thresholds and approaches using probabilistic risk functions (see: Southall et al., 2019a,b, 2021).

3.2. *Acoustic data – characterizing exposure*

3.2.1. *Acoustic source data collection*

Unlike animal data such as whale density and behavior, the distribution of sound in the water column is governed by precise physical laws that enable (at least in principle) the spatial mapping of acoustic levels from knowledge of the properties of the propagation medium (which includes the water and the sea bottom) and of the source(s). Even when acoustic monitoring is performed continuously at multiple locations during an activity, spatial interpolation of sound levels between measurement points can only be performed if the sources and propagation are known (Table 1; Fig. 1). Hence the requirement to be able to estimate the spectral (intensity as a function of frequency) and directional characteristics of a sound source such as an airgun array, which is usually needed for planning and regulatory purposes well in advance of device deployment, and thus must be/should be? Measurable *in situ*.

Source modeling software such as NUCLEUS (PGS) and AASM (JASCO Applied Sciences) can be used to estimate the far-field point-source-equivalent properties of airgun arrays from their design specifications, enabling the simulation of acoustic fields and ranges of potential effects on marine mammals according to various criteria (Goertz et al., 2013; MacGillivray 2006). The most widespread use of pre-operation source modeling is to estimate the distance from a seismic survey source at which marine mammals may be injured or disturbed. In some jurisdictions such estimated ranges must be specified in permit

[2] For a good example of such a program please see: http://www.north-slope.org/departments/wildlife-management/nsb-shell-baseline-studies-program/.

applications as a 'shutdown radius' specific to a certain source and operational area (other jurisdictions rely on default radii for safety zones). Initially, safety radii were based on mean-square sound pressure level (SPL) threshold dependent on a single pulse of the source, but following Southall et al. (2007) a progressive shift took place toward using cumulative criteria. These include sound exposure level (SEL) accrued over numerous pulses, requiring in some cases the simulation and summing of tens to hundreds of estimated pulse levels along seismic survey lines. More recently, the still simplistic paradigm of a static receiver exposed to the pulses from a moving source has being superseded in many instances by the use of individual-based models of movement and exposure. Safety radii are estimated from the nearest approach and cumulative exposure received by thousands of simulated animals or 'animats' moving realistically through the modeled sound field from source locations according to rules mimicking the species of interest.

Regulatory bodies of various geopolitical locales may regard with differing levels of confidence the methodology by which a safety zone is estimated pre-operationally, especially because more advanced approaches entail elaborate parameterization and consequently there is wider latitude in the answer (i.e., greater uncertainty, or lack of precision). An estimated radius based on a straightforward metric is liable to be met with greater trust, especially if the assumptions on which it is based lead to a precautionary value. Nonetheless, as both the understanding of animal physiology and behavior and the technological ability to simulate more complex exposure scenarios evolve, our view is that methods of estimation based on the best available science and reasonable precautionary factors should be adopted – since unwarranted overrepresentation of effect ranges can be as harmful to the animals as underrepresentation by causing unnecessary disruption which ultimately leads to longer duration of the operations and greater net time of exposure to harmful levels of noise.

In some applications, safety radii may be proposed by the applicant through bespoke modeling rather than prescribed from fixed rules including static and uniform exposure 'radii'. Regulators may then request that within a statutory window of a few days from start of the survey, the estimate be validated by a sound source verification (SSV) acoustic measurement, and that the safety distance based on measurement replace the pre-operation estimate. This validation pertains solely to the accuracy of the sound source and propagation modeling; for advanced estimation methods in which animal motion is also considered, the related assumptions would remain such. For the execution of the SSV a good-practice approach is to deploy a minimum of three bottom-moored autonomous recorders aligned perpendicularly to a seismic survey line to be acquired at or near the beginning of the operation (e.g., Quijano et al., 2018). If the bottom depth over the survey region varies, the early line should lie in a deeper region. The planar offset distances from the line for the recorders should follow a geometric progression (for example 500 m, 1 km, 2 km) with the middle distance matching the estimated safety radius from pre-operation modeling, to provide a meaningful interpolation dataset to adjust the model if necessary. Further, the positioning of the measurement traverse downline from the start point should be at least twice the offset of the farthest recorder so that the accumulation of the exposure levels includes every pulse relevant to the total. These guidelines should ensure a meaningful acquisition and reliable adjustment of the estimates under most conditions. Finally, we would note that in instances where SSVs are not mandated by the regulatory agencies, we consider it a conscientious and advisable practice to perform an SSV of some degree of complexity unless the propagation properties of the region and the specific source array configuration are directly known to be accurately rendered by the models.

3.2.2. *Measuring the acoustic field: what data to collect (or model) and how to analyze*

The relatively new concept of 'acoustic habitat', as introduced and developed by Clark et al. (2009), Moore et al. (2012), Hatch et al. (2012), and others, emphasizes the potential consequences for baleen whales of the cumulative and chronic loss of acoustic communication space because of masking by anthropogenic noise. This is a concern for all baleen whales in areas where they need to maintain conspecific communication. Dredging, construction, and pipe-laying activities often associated with marine industrial development add to underwater noise levels and can have the effect of degrading the quality of, if not completely eliminating, feeding habitat (Reeves et al., 2005 [ISRP report]). Several different analyses are commonly used, including levels in or at designated areas, e.g., feeding areas (e.g., Hatch et al., 2016) and changes in soundscape from a host of industrial sources and reverberation (e.g., Ireland et al., 2016).

To determine whether an industrial activity has the potential to impact an individual or group of animals, knowledge of the levels and types of noise expected to reach the location of the animal(s) is essential. This should include 'scenario' assessments to consider different mitigation strategies to estimate overall exposure at individual and population levels based on differential spatial and temporal timing of survey element operations. Furthermore, many MMPs specify predetermined levels of acceptable noise in areas where animals are likely to occur. Acoustic monitoring is therefore necessary during, and strongly advisable before and after, the industrial activity (Table 1, Fig. 1). Monitoring during activities focuses on the region around the source of industrial noise where acoustic impacts are possible, i.e., the area where industrial noise and animal presence overlap. Noise characteristics are ideally measured at locations of the whales, though combinations of measurement and modeling can be effective and are often necessary due to the large areas over which animals and, thus, impacts may occur (Racca et al., 2015; Rutenko et al., 2022a, 2022b). The levels at which impacts on aquatic animals are expected to occur depend on the noise type (such as pulsed or continuous) and species or hearing group, and regulation criteria vary by jurisdiction. For impact criteria that are based on cumulative metrics, whether for pulsed or continuous signals, allowable noise levels are dependent on the amount of time over which the animal will be exposed to them.

In general, the boundaries of the monitored area are determined by combining data on the boundaries of the noise exposure zone as determined from acoustic modeling with the areas of the probability of whale sighting. When planning production activities near an aggregation area of a whale population of concern (such as a threatened or legally protected species), it is even more important to carry out extended monitoring before starting work to create density maps of species distribution. In cases where a succession of multiple years of observation data are available, longer time series may be used to estimate more reliable density kernels (see for example Muir et al., 2015b). These maps are then used in tailoring the monitoring scheme to ensure that acoustic exposure remains at permissible levels in areas of high animal density.

Reliable sound propagation modeling can be achieved with relatively few measured or estimated key parameters, including bathymetry, temperature, and salinity profiles of the water column at the season of the activity, and geoacoustic properties of the sea bottom. However, validation measurements at a few reference locations are highly recommended to ground truth estimates and increase precision. Quantities such as kurtosis and pulse duration or rise time, which depend on the temporal structure of the acoustic signal, can be modeled in principle using computation intensive full-waveform methods but may be obtained more practically through simpler differential reference to measured values (Rutenko et al., 2022b). Estimating the changes in kurtosis and rise time of transient signals as they expand through the medium is key to understanding when these features may be dulled by propagation effects to the extent that the signal no longer should be considered pulsed.

Acoustic data-processing methods depend primarily on the type of dominant noise received, pulsed or continuous. To analyze pulsed underwater noise, it is necessary to use data-processing algorithms that

enable the isolation of individual pulses even in the presence of confounding features such as precursor waves or multipath arrivals, so that the peak and the sound exposure levels of each pulse can be estimated. Standard spectral data-processing methods are used to analyze continuous underwater noise. Validated, free-access software packages for calculating noise characteristics are becoming readily available (e.g., MANTA[3]) or other comparable and capable software packages.

During the design and deployment of acoustic monitoring devices, local current and tidal patterns should be carefully considered, particularly for shallow-water deployments. High speed currents (e.g., related to due to variable tidal patterns) lead to non-laminar streamline of bottom hydrophones from which arise potentially high levels of non-acoustic noise. Engineering approaches to overcome this issue can include hydrophones deployed from drifting (untethered) recorders (e.g., Wilson et al., 2014) or shielded from pseudo sound by special coverings (e.g., Vedenev et al., 2023). Where conditions still introduce flow-related noise, the infrasound part of spectra for data collected at high current speeds should be either filtered or simply ignored as born by non-acoustic phenomena.

When conducting real-time monitoring, especially with a limited-capacity telemetry connection such as a satellite uplink, the station's on-board computer calculates and transmits the minimum data set necessary for monitoring the noise level. A typical on-board processing specification might have the following form.

a) For non-impulsive noise, an integral noise level is calculated in the 2 Hz to 2 kHz bandwidth with an average of 3 min and the spectrum in 1/3 octave bands (ANSI/ASA S1. 1-2013, 2013) for a frequency bandwidth of 2 Hz–16 kHz with a 3-min average. These partially averaged noise characteristics are transmitted by radio or satellite to the analysis site, where they are further averaged and compared with the permissible thresholds.
b) For impulse noise, the peak sound pressure level (PK) and the sound exposure level (SEL) from the individual impulses are calculated. The values averaged over a 3-min interval are transmitted in real time to the analysis site for ground-referencing of model-predicted values or direct comparison with permissible thresholds.

Acoustic levels at the location(s) of focal animals, which allows a more direct test of exposure impacts on behavior or distribution, can be difficult to obtain but important for understanding the potential for disturbance. Numerical modeling, if properly parametrized and ideally corroborated by ground-referencing to a set of fixed measurement points, has the potential to provide a form of "virtual acoustic tagging" of tracked animals that avoids the sample limitations, complexity, and disturbance risk of applying conventional tags. Emerging technologies for autonomous vehicles that can operate as near-silent acoustic monitoring platforms readily relocatable to the vicinity of monitored animals (with evident precautions to avoid interference) promise a new level of spatial sampling possibilities. Compact-sized uncrewed surface vehicles (USVs) and autonomous underwater vehicles (AUVs, primarily gliders) have considerable range and can tow small arrays enabling directional location of sound sources. Singularly powerful is the application of uncrewed aerial vehicles (UAVs, commonly known as drones) to localized acoustic sampling, as certain models can land on the water and deploy a suspended hydrophone while free floating – thus causing no acoustic disturbance to animals nearby. This technique has been shown capable of correlating the vocal behavior of gray whales with their visual behavior by using two drones, one camera-equipped and overflying the area and the other carrying a hydrophone to the vicinity of whales engaged in social activities (Frouin-Mouy et al., 2020).

Evidence from many dedicated experiments as well as monitoring studies have showed that acoustic received level (RL) is not always the sole or best predictor of response/impact, but can be an important contributor (Southall et al., 2016, 2021). With the often-large number of data streams, both acoustic and non-acoustic, collected as part of a comprehensive monitoring program, a relatively complex analysis is often warranted to explore changes in one or more of the measured variables with respect to the experimental phase (i.e., before, during, after). Some type of multivariate analysis (MVA) is often required to tease out specific effects, including relationships between those measured variables (Muir et al., 2016; Gailey et al., 2016).

3.3. Measuring behavioral responses to disturbance

3.3.1. Discrete, individual-animal behavioral responses

The last several decades have seen exponential increases in technology and methods to measure behavioral responses of whales. Earlier methods that evaluated the observed behavior of whales without identifying them individually (e.g., Richardson et al., 1986, 1999) have been adapted to include repeated sightings of individuals identified from photographs using distinctive markings. Advanced methods include whale-attached archival tag sensors to measure increasingly complex aspects of movement and behavior (e.g., Johnson and Tyack 2003; Goldbogen et al., 2013). New methods for some species have integrated traditional visual sampling and theodolite methods with passive acoustic and autonomous aerial photogrammetry methods to sample responses where individuals cannot be easily tagged (Durban et al., 2022). Observational studies of whales under operational conditions in field settings have provided insight into exposure and response in realistic conditions (e.g., Gailey et al., 2007, 2016). Different approaches using experimental methods have been applied in studies of free-ranging animals and various sound types with increasingly complex and realistic exposures that are known and controlled (see: Southall et al., 2016; Dunlop et al., 2016).

Behavioral responses of many blue whales to military sonar and other mid-frequency sounds were quantified using controlled exposure experiments (CEEs) in a series of studies off southern California (Southall et al., 2012, 2019b; Goldbogen et al., 2013; Friedlaender et al., 2016; DeRuiter et al., 2017). These experimental studies involved simulations of U.S. Navy SQS-53C systems that had been implicated in cetacean strandings. The combined results demonstrated significant behavioral responses of blue whales to tactical sonar and pseudorandom noise (PRN) of similar frequency and exposure level across many individuals. Further, the results illustrated several context dependencies in behavioral responses, as noted by Ellison et al. (2012), including strong influences of individual behavioral state at the time of exposure as well as influences of prey distribution and density. DeRuiter et al. (2017) demonstrated behavioral state switching greater probabilities for blue whales to either cease or fail to initiate deep-feeding behavior during sonar exposure. Southall et al. (2019b) used quantitative statistical methods and expert elicitation with structured severity scales to document behavioral responses in some but not all individuals and to document the contextual factors (namely subject behavioral state) driving differences in response probability and type. Collectively these studies showed generally that blue whales respond to controlled noise exposures in different ways, and that a suite of contextual factors influence response probability. Such observations clearly amplify the need for the consideration and quantification of such environmental, noise exposure, and animal contextual factors in MMPs, the extent and complexity of which is necessitated by the relative perceived risk of operations to given species in given areas.

3.3.2. Group behavioral responses

Some of the earliest systematic measurements of marine mammal behavioral responses to noise focused on bowhead whales and seismic airgun surveys. Studies using observational methods found statistically significant behavioral responses of groups of bowhead whales in some

[3] MANTA (Making Ambient Noise Trends Accessible) https://bitbucket.org/CLO-BRP/manta-wiki/wiki/Home.

conditions, including avoidance of sound sources and changes in respiration and movement patterns (Reeves et al., 1984; Richardson et al., 1985, 1986, 1999; Ljungblad et al., 1988). The behavioral context of exposure and specifically the behavioral state of whales at the time of exposure to seismic survey noise appears to strongly influence the probability of response, particularly avoidance. Aerial observations of groups of feeding bowhead whales exposed to seismic airgun sounds (single airgun and full-scale surveys) indicated minor changes in swimming and respiration at received levels of ~120–140 dB re: 1 μPa (RMS), but whales generally did not avoid operations at ranges greater than 6 km where received levels approached and exceeded 160 dB (Richardson et al., 1986). Conversely, migrating bowhead whales observed in aerial surveys were almost entirely displaced from an area of 20 km or more radius around seismic survey operations, corresponding to received noise levels in the 120–130 dB re: 1 μPa (RMS) and higher range (Richardson et al., 1999). Observations of whales in the same area during periods without seismic survey noise indicated regular transit patterns.

Malme et al. (1988) summarized the results of controlled exposure experiments with feeding and migrating gray whales. Observed responses by the whales to playbacks of drillship noise (continuous stationary source) led those authors to conclude that more than half of the whales would avoid the area at received levels of 120 dB re 1 μPa or higher. They concluded that 163 dB was the received level at which the pulsed noise from a single moving airgun would cause 10% of gray whales to interrupt their feeding activity while an average peak pressure level of 173 dB would probably cause 50% of the whales to interrupt their feeding. Malme et al. interpreted their limited data as indicating that the 'acoustic sensitivity' of feeding gray whales was 'not greatly different' from that of migrating gray whales.

Although there is no direct evidence of long-term displacement or other behavioral disruption of groups of feeding gray whales by noise, evidence of short-term displacement from prime feeding habitat and short-term changes in behavior were documented in some contexts during large-scale seismic surveys off Sakhalin Island (Yazvenko et al., 2007; Muir et al., 2015a, 2016; Gailey et al., 2007, 2016, 2022a, 2022b). Gray whale responses to cumulative vessel traffic and disturbance over the long term (more than a decade) have been examined. On the wintering grounds, gray whales abandoned one of their calving and calf-rearing lagoons in Mexico (Laguna Guerrero Negro) for about a decade (1957–1967), when salt barges were using the lagoon channel and it was being dredged repeatedly (Gard, 1974). Toward the end of the 1960s, barge and dredging activity abated, and whales began to again utilize during later surveys (Bryant, 1984). This classic example demonstrates strong displacement effect of 'disturbance' (likely from, among other things, noise), but the reoccupation of the lagoon perhaps implies a certain degree of resilience.

3.3.3. *Population-level demographic changes observed over long time periods*

Organisms are subject to numerous stressors that influence their ability to reproduce and survive. At the population level, parameters related to reproduction and survival are integrated and reflected in a population's abundance trajectory. Baleen whales are long-lived, and their dynamics are accordingly slow, making detection of significant changes in individual parameters (that are themselves difficult to estimate robustly) or the ultimate (integrated) parameter of abundance difficult to characterize and quantify except over decades. Despite the difficulties discussed below predictive modeling is required to address complex conservation issues and to evaluate potential mitigation strategies. At the same time, it is noted that reductions in noise output levels or other relatively simple mitigation actions are likely to have positive outcomes even in the absence of complete knowledge of population trajectory and should be prioritized where possible (see: Leaper et al., 2015; Risch et al., 2021).

The Scientific Committee of the International Whaling Commission (IWC) has invested considerable effort in simulation modeling of the impacts of human-induced stressors on baleen whale populations, especially direct removals such as catches, bycatches and vessel strikes (e.g., see Punt and Donovan, 2007 and references therein). Such modeling tends to rely on the availability of regular estimates of population abundance (and uncertainty) and a good knowledge of direct removals. They do not assume good knowledge of reproductive and survival parameters but rather investigate robustness to assumptions about these (including variations over time that might reflect anthropogenic stress) and a wide variety of other factors including model uncertainty, uncertainty about population structure (differentiation), changes in carrying capacity as a proxy for environmental change, and periodic 'catastrophes' such as reduction in a population by one third (without specifying the cause of the reduction). Thus, they do not imply, nor are they presented as, 'truth' but rather serve to illustrate the importance of considering all plausible scenarios. A key component is validation of operating models to ensure that they do not conflict with empirical data (e.g., abundance, removal histories). The models are used primarily to evaluate the effectiveness of various management strategies in a conservative (risk-averse) manner and simulate populations over time periods that changes to be detected, typically 100 years from present. We do not discuss this approach in detail here, but simply to note that information from populations that have been assessed in such a manner could prove valuable in evaluating relative risk to other kinds of disturbance (aside from direct removals).

Of perhaps greater relevance are targeted simulations based largely at the individual level to predict population dynamics. Individual-based models are particularly applicable to populations with long multiyear datasets on known individuals – typically using photo-identification techniques and/or genetic data. These allow for the development of complex age- and sex-structured individual-based models using empirical data. Good examples of methods and studies include extensive work on gray whales off Sakhalin (discussed above) and North Atlantic right whales (e.g., see Pace et al., 2017), although those studies are notable in the intensity of effort expended given extensive available resources to study those populations. Such models can be used to assess population dynamics empirically for years before and after the presence of stressor (s) in question (e.g., seismic surveys) or to investigate hypothetical future scenarios with assumptions about potential impact(s) on reproductive and/or survival parameters. For this to be useful in terms of providing advice on noisy operations, it will usually be necessary to apply the latter approach and to use, at least to some degree, comparative data from elsewhere since the operational area of a single operator rarely coincides with the entirety (or even a large proportion) of a population being present. One such instance, however, is the case of Sakhalin (see key studies discussed above) where individual identification data from the mid-1990s to recent years has allowed for investigation of certain parameters for years following operations (e.g., offshore platform construction, seismic surveys).

With migratory species such as baleen whales, detected changes in demography or life history parameters are clearly difficult to attribute to single activities because animals are generally subject to multiple stressors (e.g., Quintana-Rizzo et al., 2021). This needs to be recognized by regulators and operators from the outset. The latter may contend their activities alone are not responsible for (or cannot be *proven* to be responsible, which makes the bar very high) any observed problems at a population level and therefore they should be allowed to continue their operations unchanged, unless and until other stressors have been dealt with. This is where the issues of risk assessment, risk tolerance and the precautionary principle (or approach) arise, and those who set policies and implement regulations must make conservation value judgments

and choose priorities (on behalf of the governments or societies they represent).[4]

New, more complex (in terms of numbers of parameters and assumptions) population modeling approaches have been developed to try to assess the impacts of multiple and concurrent stressors on the vital rates of wild populations (e.g., see Booth et al., 2020; Christiansen et al., 2020; Currie et al., 2021). Such tools can be used to forecast population trajectories under different assumptions (e.g., additional management actions implemented, increased anthropogenic pressure, climate change, etc.) and include decision trees and simulation-based analyses such as population viability analyses (PVA) (Strindberg and O'Brien, 2012; Lacy et al., 2017). Such methods incorporate the combined effects of stochastic processes (e.g., demographic, environmental and genetic variability) and deterministic processes (e.g., overexploitation, disturbance, habitat degradation) to simulate population dynamics and assess extinction risk (Himes Boor, 2014). In addition, frameworks have been developed to quantify the Population Consequences of Multiple Stressors (PCoMS) and assess conservation implications of exposure of wildlife to multiple stressors (Pirotta et al., 2019, 2022). These are valuable attempts to provide quantitative scientific advice concerning management and mitigation, as well as to highlight where research should be focused to reduce uncertainty. A key challenge to any such complex modeling exercise is validation of the operating models used – the more complex the models, with more parameters and associated assumptions, the more difficulties arise. Inevitably, implementation of both PVA and PCoMS requires large volumes of multi-year data, which requires considerable funding. Few studies have successfully employed such methodologies using empirical data (Lacy et al., 2017; Senigaglia 2020) and even where this has been attempted, considerable uncertainty remains.

In summary, responsible management requires consideration at some level of all stressors facing the population(s) concerned, not just the operation that may be the focus of a particular MMP. Predictive population modeling is an important component of this, as are reasonable, simple approaches such as limiting the noise energy used to what is required. The degree to which it is important in the context of individual 'noisy' operations depends on examination of many factors used to determine whether the situation is 'simple' (modeling is probably not necessary) or 'complex' (see above) and on the availability of sufficient data. Uncertainty can be a limiting factor in either scenario, but gap analyses in such models can inform future MMPs.

4. Conclusions and recommendations

4.1. Scales of application and frameworks of integration

The aim here was to convey the value of having a set of adaptive principles and approaches to serve as guidance in biological and noise-source data collection and analysis, both for effective MMP planning and execution and to advance scientific knowledge (see: Fig. 2). As MMPs will be developed and applied within very different environmental, operational, and species contexts, we propose that those conducting them strategically select from the distinct but overlapping monitoring and mitigation frameworks described. Approaches should be tuned to the exposure conditions, exposed population characteristics, and the requisite levels of spatial, temporal, and methodological complexity. To that end, we identified methods for data collection and analysis that can feed information into any framework, including scientific, regulatory, and monitoring/risk assessment processes.

The responses of individuals to noise from industrial processes are important to measure as they can provide detailed evidence of any disturbance(s). These individual responses can be analyzed in a univariate manner or combined across animals and response types in models, providing a synthesis view of how that species or population responds to a particular stimulus and, importantly, how such response(s) translate into population consequences that may affect conservation status (Table 1). Analyzing responses 'by individual' can be quite revealing, so long as there are sufficient control or non-exposure data for comparison. Determining individual response type and magnitude can be a step toward reaching overall conclusions about response and, thus, identifying appropriate management and mitigation actions.

Group responses (e.g., a feeding aggregation) can also be informative with respect to impacts of marine industrial activities. Charting the movements and behavior of multiple animals before, during, and after an activity can provide insight into, for example, displacement from an important area (e.g., a feeding or breeding ground, Fig. 1; Fig. 2). Displacement is often cited as an indicator of disturbance, though it is also important to understand the alternatives animals may or may not have to avoid or move away from a source of disturbance (cf., Forney et al., 2017). Individual and group-level assessments are based primarily on data collected at around the time of the industrial activity. If data from long-term collection efforts are available (Table 1), then one may be able to evaluate population-level demographic changes associated with industrial processes. Such evaluations depend primarily on modeling (e.g., Pirotta et al., 2019), though some empirical studies have also been reported (e.g., Senigaglia 2020).

4.2. Acoustic source data collection

An important and increasingly standardized set of measurements relates to the acoustic characterization of the sound source at variable ranges. Initially this included sound pressure measurements (e.g., RMS, peak sound pressure levels) for single receivers relatively near sources to measure the radiated noise spectrum, duty cycle, and received levels with which to estimate source levels. Such measurements may remain appropriate for simple characterizations or verifications of known sound sources to meet mandated mitigation requirements (e.g., shut-down criteria based on received level estimates). However, increasingly sophisticated approaches, including vertical or horizontal arrays of receivers, provide the ability to characterize variability in complex sound fields in three dimensions and these approaches have been increasingly applied. Such measurements can document changes in noise spectra and other relevant parameters such as kurtosis that describe how relatively impulsive noises are and is relevant to the application of auditory exposure criteria (see Martin et al., 2019; Southall et al., 2021). Additionally, accumulation of metrics over time, including sound exposure level, is being characterized in more sophisticated noise source characterizations. Finally, and likely relevant for low-frequency animals including baleen whales, particle motion measurements to characterize non-pressure-based aspects of radiated noise that may impact the animals' ability to localize noise sources. Such measurements are common in studies of other taxa for which particle motion is a fundamental aspect of detecting and responding to noise sources (e.g., Vedenev et al., 2023) and should be increasingly integrated into more sophisticated measurements for baleen whales.

It is important to measure the ambient noise conditions, both those typically occurring within the area of noise disturbance as well as the contributions made by all aspects the operation to longer-term noise conditions. As noted in Table 1, these include relatively short-term and single-element metrics of ambient noise, but for larger, longer-term projects or those occurring in potentially highly sensitive areas, more extensive, sustained, multi-recorder systems are appropriate. Such measurements should include non-exposure periods prior to operations, non-operational periods during activities (e.g., seismic-survey line turns), and ideally ambient noise measurements after operations. These approaches are increasingly possible given the expansion and increasing standardization of noise soundscape metrics to provide a more holistic

[4] These issues are considered in a large body of literature. See, for example: https://www.iisd.org/system/files/2020-10/still-one-earth-precautionary-principle.pdf.

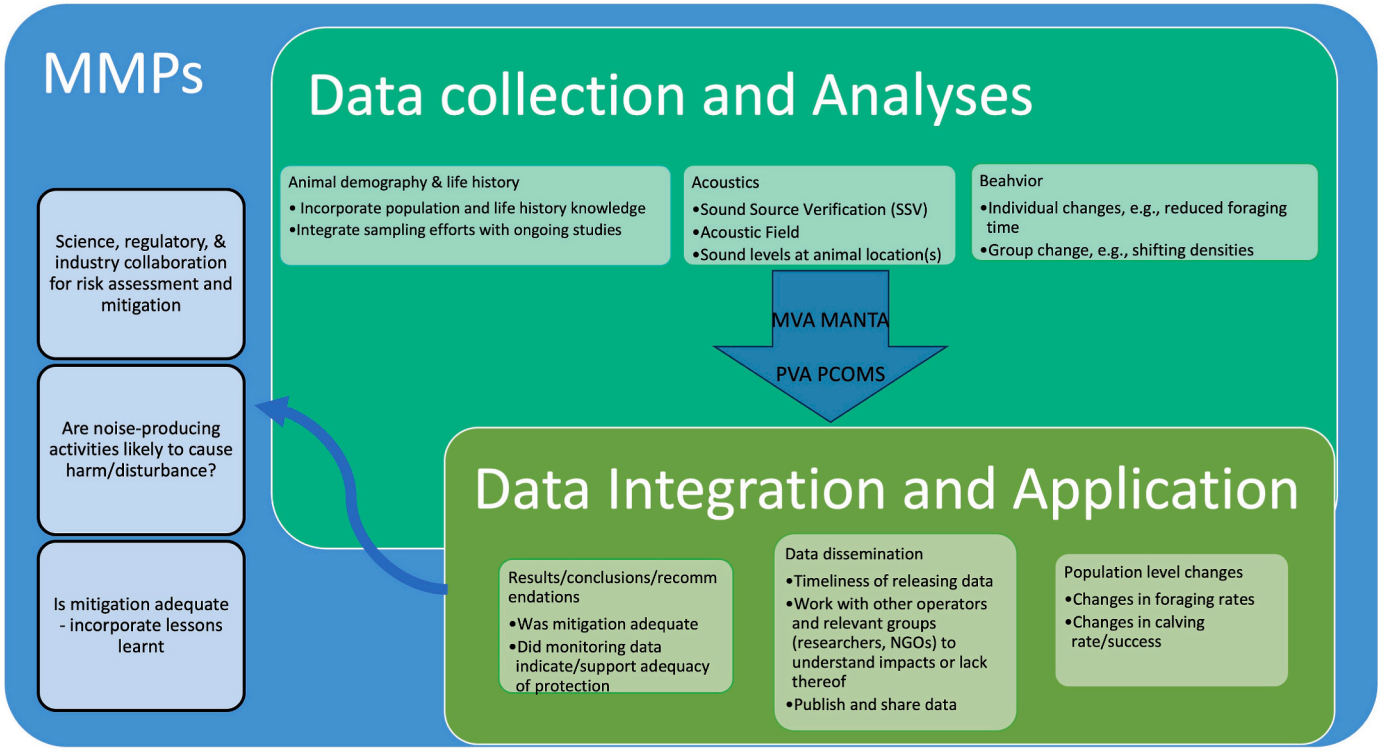

Fig. 2. Strategic data collection, analysis, integration, and application to inform responsible monitoring and mitigation programs (MMPs).

view of environmental, biological, and anthropogenic noise contributions to the ambient noise over time in a region (McKenna et al., 2021). The relative sophistication and effort, including spatial extent of recorder deployments, should be seen as scalable and adaptive based on many of factors including the type of noise source, its novelty to the deployment area, other known or potential stressors in the area, conservation status of species present, duration of deployment, and other factors.

Estimation of expected cumulative and maximum exposure conditions should become a standardized part of the early planning stages for the most intensive noise-producing activities, the aim being to ensure a science-based assessment of potential impacts before irreversible operational decisions are made. Future advice on offshore industrial activities should account for expected total impacts, how these compare with estimates of maximum acceptable impact, and what this implies for mitigation measures to be taken. While one operator is not obliged to integrate its MMP with those of other nearby operators, there is merit in developing recommendations for measures that would, in principle, be suitable for universal adoption. This would accord with the level-playing-field principle and provide output of wider utility.

4.3. Synthesis

Uncertainty is a common feature of any field sampling effort regardless of the framework although this can vary widely. The methods of sampling and analysis proposed here are geared toward reducing the uncertainty at all stages of MMP implementation, whilst recognizing that uncertainty always needs to be quantified and considered when developing robust MMPs.

A clear requirement from MMPs is the collection and especially the prompt analysis, sharing, and interpretation of new data to streamline and improve the effectiveness of future mitigation efforts. Empirical findings from MMP implementation can help shape and validate modeling approaches, which in turn often make possible more efficient, less costly means of acquiring information needed by industry while at the same time reducing risks. In many if not most cases, a properly implemented MMP, with defining principles and results that are openly shared through peer-reviewed publication and/or other means of dissemination and data access, can be expected to produce benefits well beyond the context of the project for which the MMP was designed. Regionally, the information obtained from one company's MMP can and should be applied in the drafting of others in the area (e.g., Gulf of Mexico, Sakhalin shelf). We advocate for both transparency from industry to be both self-motivated and required. The permission for industrial development and extraction carries with it a responsibility to ensure that data related to any potentially affected biota be made public in a timely manner. This can go a long way toward engendering public trust that good faith efforts are being made to protect the animals and to document and mitigate possible impacts (also see Van Parijs et al., 2021).

On a global scale, the observed responses of a species to given types and degrees of disturbance can and should be used to update guidelines and protocols to manage similar activities and protect this and related species in other parts of the world. For example, if one program documents the responsiveness of whales to a disturbance while they are foraging (e.g., the level of noise exposure that elicits a response from the animals is determined), then this result can be communicated to other operators, managers, and regulatory bodies. During the siting and design stages of development or exploration activities that have the potential to disturb baleen whales, a systematic assessment of the exposure context, knowledge available, and regulatory requirements should be undertaken sufficiently ahead of time to design an informed, strategic, transparent, and effective MMP.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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