Nowhere to go: noise impact assessments for marine mammal populations with high site fidelity

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ABSTRACT: As awareness of the effects of anthropogenic noise on marine mammals has grown, research has broadened from evaluating physiological responses, including injury and mortality, to considering effects on behavior and acoustic communication. Most mitigation efforts attempt to minimize injury by enabling animals to move away as noise levels are increased gradually. Recent experiences demonstrate that this approach is inadequate or even counterproductive for small, localized marine mammal populations, for which displacement of animals may itself cause harm. Seismic surveys within the ranges of harbor porpoise *Phocoena phocoena* in California and Māui dolphin *Cephalorhynchus hectori maui* in New Zealand highlight the need to explicitly consider biological risks posed by displacement during survey planning, monitoring, and mitigation. Consequences of displacement are poorly understood, but likely include increased stress and reduced foraging success, with associated effects on survival and reproduction. In some cases, such as the Critically Endangered Māui dolphin, displacement by seismic activities risks exposing the remaining 55 dolphins to bycatch in nearby fisheries. Similar concerns about military and industrial activities exist for island-associated species such as melon-headed whales *Peponocephala electra* in Hawai'i; shelf-break associated species such as Cuvier's beaked whales *Ziphius cavirostris* off the US Atlantic coast, and whales foraging in coastal habitats, such as the Critically Endangered western gray whale *Eschrichtius robustus*. We present an expanded framework for considering disturbance effects that acknowledges scientific uncertainty, providing managers and operators a more robust means of assessing and avoiding potential harm associated with both displacement and direct effects of intense anthropogenic noise exposure.

KEY WORDS: Anthropogenic noise · Marine mammals · Impact assessment · Mitigation · Monitoring · Small populations

INTRODUCTION

The potential for anthropogenic noise to negatively affect marine life has been acknowledged as a regulatory, scientific, and conservation issue for decades (e.g. Richardson et al. 1995, Southall et al. 2007) and it remains a timely issue (e.g. NMFS 2016). In this paper we follow the distinction of Aguilar de Soto et al. (2016), in which a sound is considered to be 'noise' if it has the potential to mask or interfere with natural

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auditory signal processing, or if it may cause harmful behavioral or physiological responses. Marine mammals use and rely on sound for critical life functions, including communication for mating, feeding, avoiding predators, and general spatial orientation. Although marine mammals have evolved to tolerate loud natural noise while utilizing acoustic signals for key biological functions, anthropogenic noise is a very recent, generally increasing, and near ubiquitous phenomenon in many areas of the ocean (see Hildebrand 2009). Negative impacts have been documented, including mortality events for some species (e.g. Filadelfo et al. 2009). More commonly, behavioral disturbance affects important activities such as feeding or reproductive behavior across a range of species and environments (e.g. Southall et al. 2007, 2016 (this Theme Section), Nowacek et al. 2007, Blair et al. 2016).

Early regulatory approaches to this issue were rudimentary (e.g. NOAA 1998), but more recent approaches, such as the application and evolution of the Southall et al. (2007) noise exposure criteria, have become increasingly complex (e.g. European Union 2008, 2014, NOAA 2013, Finneran 2015, Tougaard et al. 2015, NMFS 2016). The scientific basis for assessing direct impacts of noise, especially on cetaceans, has improved significantly, but there is growing recognition that sub-lethal effects are likely to be relatively widespread and may have a greater impact than direct physical injury. Such effects may include animals leaving biologically important habitat or auditory masking of sounds associated with communication, predator detection, or navigation (see recent review by Gomez et al. 2016). Depending on the duration and spatial scale of noise exposure (see Costa et al. 2016), sub-lethal effects could be either acute (generally short-term and associated with a specific activity) or chronic (longer-term and associated with many overlapping activities). Lack of observed response does not imply absence of fitness costs, such as physiological stress and reduced reproduction, survival or feeding success (e.g. Wright et al. 2007, 2011, Aguilar de Soto & Kight 2016). Apparent tolerance of disturbance may have population-level impacts that are less obvious and difficult to document with conventional methodologies, particularly for animals with high degrees of site fidelity (e.g. Beale & Monaghan 2004, Bejder et al. 2009).

Conventional means of mitigating negative impacts typically include a range of visual and acoustic monitoring techniques with associated rules for suspending intense acoustic emissions (e.g. NOAA 2013, Nowacek et al. 2013, 2015). Such mitigation

strategies generally aim to reduce the likelihood of intense exposures resulting in physical injury, assuming that measures such as gradually increasing the noise level ('ramping-up') or shutting down operations will enable animals to move away from the noise source and avoid physical harm. The effectiveness of these mitigation techniques is poorly known, and repeated ramp-up and shutdown may actually increase the cumulative energy output into the environment. Additionally, the proportion of animals within an impact zone that can be detected using planned monitoring methods is rarely quantified *a priori*. However, the probability of detecting cetaceans is very rarely 100 %, because weather, distance to observation platform, behavior, and survey methodology affect the likelihood of seeing animals that are present. Even during dedicated scientific surveys with rigorous protocols (e.g. operations during daylight hours, in good sighting conditions, and using a highly trained team of observers with 25× binoculars), detection probabilities are often much less than 100 % (e.g. Heide-Jørgensen et al. 2005, Barlow & Gisiner 2006, Hammond et al. 2013, Barlow 2015). In contrast, many noise-generating marine activities (e.g. seismic surveys, military sonar operations, high power multi-beam echosounder operations) operate day and night, in poor weather, and with only 1 or 2 on-board observers searching by unaided eye or with handheld binoculars. If animals are not detected, mitigation measures that trigger operational changes (e.g. reduced power levels, suspension of activities) cannot take place. For these reasons, it is increasingly recognized, and in some cases a legal requirement, that the spatial and temporal overlap between noise-generating activities and marine mammals should be minimized or avoided (e.g. Nowacek et al. 2015).

When avoiding spatiotemporal overlap is not possible, mitigation that reduces the likelihood of direct physical injury from intense anthropogenic noise is important and has been the primary focus of regulation. However, conventional mitigation approaches are fundamentally inadequate for species with very high site fidelity, particularly those with very small local populations. Animals typically favor particular areas because of their importance for survival (e.g. feeding or breeding), and leaving may have significant costs to fitness (reduced foraging success, increased predation risk, increased exposure to other anthropogenic threats). Consequently, animals may be highly motivated to remain in an area despite negative impacts (Rolland et al. 2012). Their lack of response may be incorrectly interpreted as a lack of

disturbance or impact rather than a lack of alternatives because of physiological or biological constraints (Beale & Monaghan 2004). We present 5 case studies to illustrate the above concerns, focusing on small, localized populations of several diverse cetacean species in both coastal and offshore habitats. We present a comprehensive framework for assessing impacts associated with animal displacement, and illustrate how this framework can be applied even when direct data are lacking. Lastly, we consider alternate strategies for evaluating, monitoring, and mitigating potential impacts of anthropogenic noise in these conditions. All of these issues have clear management implications for protected and endangered species, both in the scenarios depicted and in similar situations with other localized populations.

CASE STUDIES

Case 1: Harbor porpoises off central California, USA

The harbor porpoise *Phocoena phocoena* is distributed in temperate, shallow waters of the northern hemisphere. The National Oceanic and Atmospheric Administration (NOAA) currently recognizes several stocks of harbor porpoise off the US West Coast, including the southernmost population in the eastern North Pacific, the 'Morro Bay stock' (Chivers et al. 2002, Carretta et al. 2016). This population of about 2000 to 3000 porpoises (Carretta et al. 2009, Forney et al. 2014) is found within a narrow continental shelf (<200 m) habitat spanning about 265 km of coastline (Fig. 1). Along the central California coast, harbor porpoises have been subjected to a variety of anthropogenic impacts, including substantial bycatch in coastal set gillnet fisheries from 1969 to 2002 (Barlow & Forney 1994, Julian & Beeson 1998, Forney et al. 2001, 2014). The Morro Bay harbor porpoise stock is not listed as threatened or endangered under the US Endangered Species Act (ESA), nor is it considered a strategic stock under the US Marine Mammal Protection Act (MMPA) (Carretta et al. 2016).

Harbor porpoises use echolocation for foraging, navigation, communication, and spatial orientation (Verfuß et al. 2005, Clausen et al. 2011, Linnenschmidt et al. 2013). They are highly sensitive to a wide variety of anthropogenic sounds and have been documented to avoid areas with vessel traffic, acoustic warning or harassment devices ('pingers'), seismic surveys, and pile-driving (e.g. Polacheck & Thorpe 1990, Tougaard et al. 2009, Pirotta et al. 2014, Dyndo
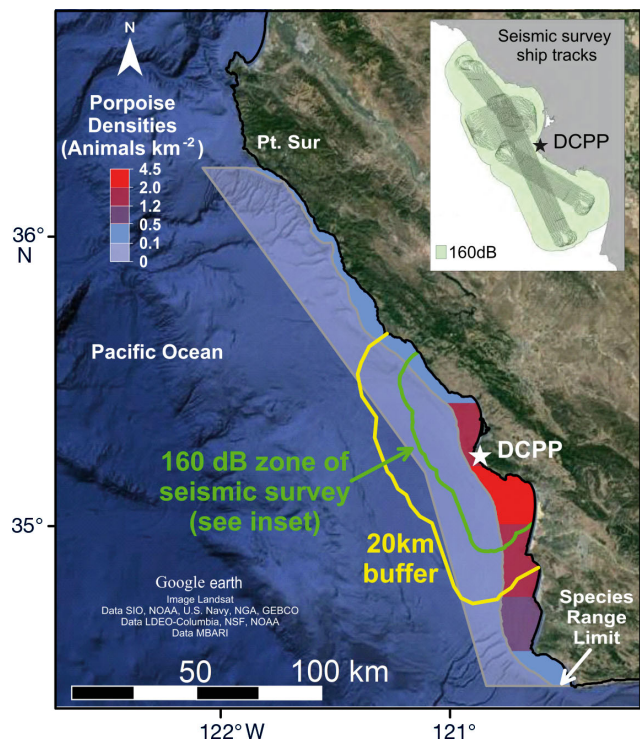

Fig. 1. Geographic range and densities (animals km^{-2}) of the Morro Bay harbor porpoise stock, and area of operation for the originally proposed seismic survey near the nuclear Diablo Canyon Power Plant (DCPP) on the central Californian coast. Densities are based on aerial line-transect surveys (Carretta et al. 2009). Green line shows the spatial footprint of the 160 dB RMS received level zone for the originally proposed seismic survey, and the yellow line is a 20-km buffer around this footprint. The 20-km buffer is intended to illustrate the distance at which harbor porpoise have been displaced in European studies (e.g. Dähne et al. 2013, Thompson et al. 2013). Inset shows seismic survey vessel tracks and 160 dB zone (modified from California State Lands Commission 2012, Appendix H)

et al. 2015, Kyhn et al. 2015). Harbor porpoises also appear to be susceptible to auditory injuries at much lower levels than other studied cetaceans (Lucke et al. 2009, Tougaard et al. 2015). Short- to moderate-duration (hours to many days) displacement of harbor porpoises over scales of 10 to 50 km has been well-documented in areas with offshore wind turbines (Koschinski et al. 2003), pile-driving operations (Carstensen et al. 2006, Tougaard et al. 2009, Dähne et al. 2013), and seismic surveys (Lucke et al. 2009, Thompson et al. 2013, Pirotta et al. 2014). The impacts of such displacement on harbor porpoises are likely to depend on the duration of the displacement and the quality of alternate available habitat, including considerations of prey availability and exposure to other risks, such as predation or bycatch in net

fisheries (Southall et al. 2007, Wright et al. 2007). Harbor porpoises are small-bodied and must forage frequently to meet their high daily metabolic demands (Yasui & Gaskin 1986, Read & Westgate 1997, Reed et al. 2000, Lockyer 2007). Energetic shortfalls caused by reduced prey availability in suboptimal foraging areas could rapidly deplete their reserves, so displacement of porpoises for weeks or months is expected to have adverse health consequences.

During 2012, a seismic survey was planned off the central California coast near the nuclear Diablo Canyon Power Plant (DCPP) to assess the structure of offshore geologic fault lines. The original footprint included 4 geographic boxes within shallow (10 to 200 m) waters, to be surveyed using 3D seismic survey methods. The entire project was scheduled to last 82 d, including 41 d of 24-h operations using 18 air guns that would fire simultaneously every 15 to 20 s. An environmental impact report (EIR) (California State Lands Commission 2012) identified an 'Exclusion Zone' and a 'Safety Zone' around the seismic survey vessel in which noise levels were expected to exceed nominal 180 and 160 dB re 1 µPa-m (RMS) levels, respectively. These were the applicable regulatory thresholds at that time for injury ('Level A' harassment under the MMPA) or disturbance ('Level B' harassment), following the noise exposure criteria developed by Southall et al. (2007). The combined 160 dB zone (green line in Fig. 1) covered an area of 1820 km^2, encompassing about two-thirds of the range of the Morro Bay harbor porpoise population and including most of the core habitat where porpoise densities are greatest (Fig. 1). The EIR concluded that 'significant and unavoidable' adverse impacts (Table 1) were expected for the Morro Bay harbor porpoise population, and nearly the entire population was expected to experience disturbance during the course of the 82-d project. The estimated direct harbor porpoise injuries or deaths (23) exceeded the total allowable anthropogenic takes, i.e. the 'potential biological removal' (PBR) (Taylor et al. 2000) of 15 for this population. Further, the well-known sensitivity of harbor porpoise to much lower noise levels than the nominal 160 dB RMS threshold meant that the true area of disturbance almost certainly included the entire stock range.

Morro Bay harbor porpoises have had no prior exposure to similar seismic surveys, and their responses are unknown. If animals remained in the impact zones, they would be exposed for weeks to noise levels known to impair harbor porpoise hearing in short-term experiments (e.g. Lucke et al. 2009, Kastelein et al. 2012). Alternatively, if porpoises avoided

Table 1. Environmental impact report assessment of significant and unavoidable noise-related impacts to the Morro Bay harbor porpoise population (from California State Lands Commission 2012, Section 4 and Appendix H)

Noise-related impacts
• Apparent sensitivity to sounds of various types would likely result in avoidance behavior
• Greater potential for avoidance behavior at large ranges
• Avoidance of important habitat may still occur
• Individual animals may be exposed up to 26 times over the course of the survey
• Population is resident species, and high-density within project area
• Likelihood of impacts resulting from individual and prey disturbance due to acoustic stress would be high
• Project would cause significant interference in porpoise movement and result in an adverse effect due to a reduction in core habitat

the seismic survey area and moved tens of kilometers, as documented in other areas (see above), this would force them out of their core habitat, either south of the species' range, offshore into deep waters, or into areas of low porpoise density, where the habitat is presumably sub-optimal because of reduced prey availability or other ecological factors (Fig. 1). Such displacement would likely reduce foraging success and expose the animals to physiological stress or other threats. Thus, harbor porpoises could be exposed to significant harm, whether they left the seismic survey area, or not.

The seismic-survey monitoring plan included shipboard visual observations by protected species observers (PSOs), passive acoustic monitoring for marine mammals, and aerial surveys before and after the seismic survey. These measures were based on established guidelines for high energy seismic surveys (High Energy Seismic Survey Team 1999), which were, however, recognized as outdated in the EIR. Such guidelines are commonly used when planning seismic surveys, regardless of their effectiveness for a particular circumstance (Wright & Cosentino 2015). Key proposed mitigation measures included avoiding areas of high (observed) marine mammal density, ramp-up of air gun activity, and shutdown if marine mammals were observed within the Exclusion Zone. The primary focus of these measures was to detect animals in the required 180 dB RMS Exclusion Zone to allow initiation of mitigation measures that would avoid 'Level A' injury. Secondarily, the measures were intended to document the

number of animals within the 160 dB RMS Safety Zone that were exposed to Level B harassment to ensure this did not exceed permitted levels. The plan relied on shipboard PSOs for detecting animals within the Exclusion Zone (about 1 km around the seismic survey vessel) and aerial surveys for detection of animals within a broader area extending up to 13.8 km around the survey tracks.

The proposed aerial surveys had several significant limitations. Surveys were to be flown at or above 328 m (1000 ft), because lower-altitude overflights required a separate permitting process that had not been initiated. However, this altitude is too high to reliably detect small-bodied harbor porpoises. Further, transects were spaced 4 km apart to achieve a stated goal of 'full coverage', implicitly assuming that all animals within a 2-km strip on each side of the aircraft would be detected. This assumption is directly at odds with published literature on aerial surveys showing that detection probabilities drop off rapidly within a few hundred meters of the transect line, even for large whales (e.g. Forney et al. 1995, 2014). Finally, the maximum probability of detection of harbor porpoises (directly on the transect line, during good weather conditions, using skilled observers) has been estimated to be only about 29%, because of porpoise diving behavior and the high speed of the aircraft (Laake et al. 1997). Detection probabilities are further reduced by wind or cloud cover (Forney et al. 1991, Heide-Jørgensen et al. 1993), a frequent occurrence within the central California study area.

Under US Federal law, the National Marine Fisheries Service (NMFS) may authorize the incidental injury or harassment of small numbers of marine mammals if the impact on the population is determined to be negligible. Clearly, the expected impacts from the proposed seismic survey could not meet this criterion, so the temporal and spatial scope of the project was scaled back to include only one of the original 4 seismic survey boxes within the first year. This reduced footprint involved a shorter period of 14 to 18 d of seismic survey operations, including 10 to 11 d of 24-h air gun operations. NMFS also required modification of the monitoring and mitigation plan, to address 2 key problems: (1) an extremely low probability of detecting harbor porpoises within the Exclusion and Safety Zones and (2) the inability to detect long-range displacement of porpoises, i.e. out to 20–40 km, as documented in European studies (Dähne et al. 2013, Thompson et al. 2013). The new plan included replicated 'before, during, after' low-altitude (198 m; 650 ft) aerial surveys, a network of passive acoustic monitoring instruments, and beach surveys to detect any stranded animals. The primary goals were to establish baselines of porpoise distribution and stranding rates, allow detection of any dramatic shifts in distribution or behavior during the seismic surveys, and document any strandings potentially related to the seismic survey quickly enough for the seismic survey operations to be suspended. Significant challenges related to weather, access to beaches along the rugged coastline, and natural variability in porpoise distribution were recognized, but unavoidable.

Ultimately, the California Coastal Commission denied approval for the project over concerns about adverse impacts to multiple aspects of the coastal environment (California Coastal Commission 2012). Therefore, the effectiveness of the modified proposed monitoring and mitigation measures was never evaluated. However, had the survey occurred, it is likely that only severe, broad-scale impacts (e.g. displacement of a large number of porpoises, multiple strandings) would have been detected, despite the fact that these severe and potentially population-level impacts were not requested in the permit application and would not have been authorized. Further, the modified monitoring program was added very late in the permitting and planning process, so it was limited to what could be done (given that all the revised planning had to take place in a matter of weeks), rather than what should have been done to allow optimal detection, monitoring, and mitigation of harm to porpoises using complementary methods.

Case 2: Māui dolphins off New Zealand

Hector's dolphin *Cephalorhynchus hectori* is endemic to New Zealand and is listed as Endangered nationally (Baker et al. 2010) and by the International Union for Conservation of Nature (IUCN) (Reeves et al. 2013a). The North Island subspecies *C. hectori maui*, known as Māui dolphin, is Critically Endangered (Baker et al. 2010, Reeves et al. 2013b) and listed as 'facing an extremely high risk of extinction' on the basis of very small population size, existing impacts, and the rate of population decline. In 1970, the population of Māui dolphins was estimated at 1729 individuals (CV 51%) (Slooten & Dawson 2010). This had declined to an estimated 111 individuals by 2004 (CV 44%) (Slooten et al. 2006) and to 55 individuals (1 yr and older) in 2010 (CV 9%) (Hamner et al. 2012). Māui dolphins are found within a very limited range off the west coast of New Zealand's North Island (Fig. 2). This is a high-energy shore, open to
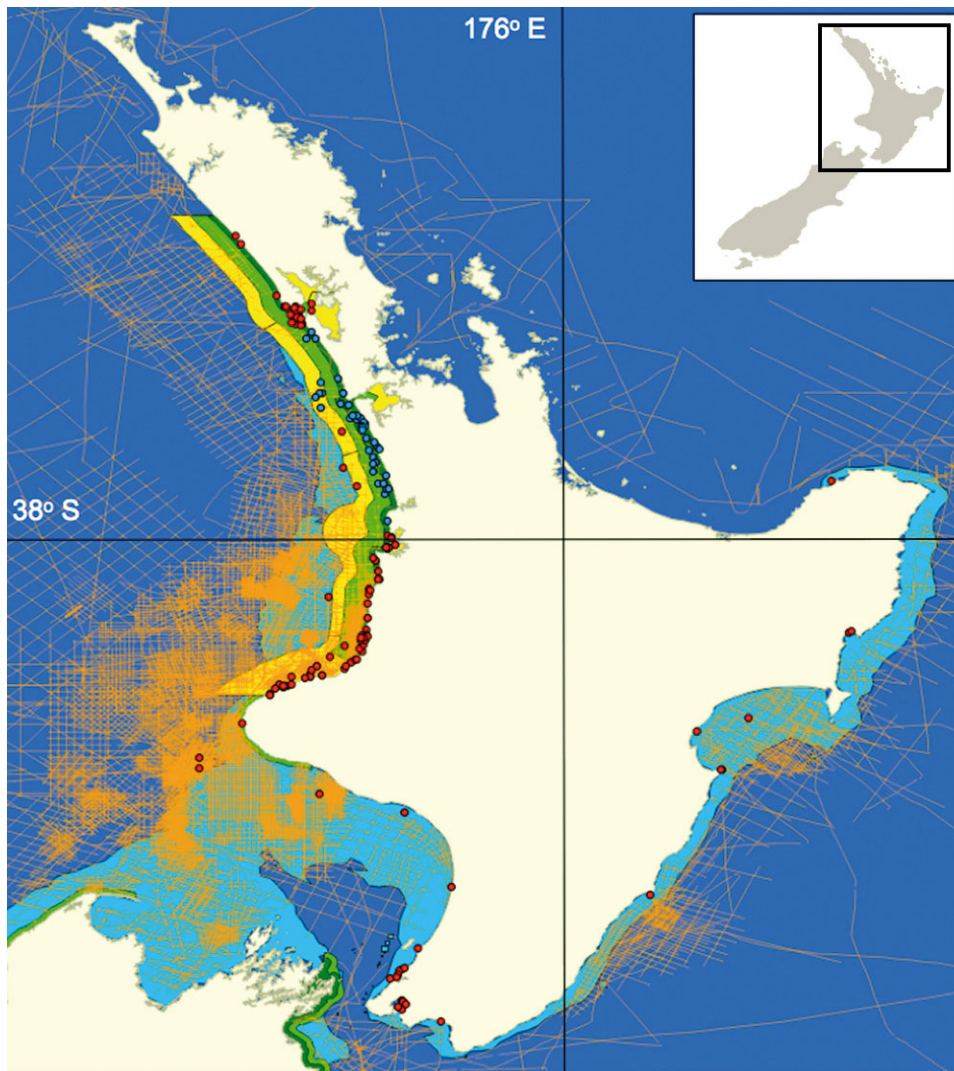
Fig. 2. Distribution of Māui dolphins on the coast of North Island, New Zealand, based on (•) research sightings and (•) public sightings. Yellow area: Marine Mammal Sanctuary protecting the species' primary distribution range on the west coast; light green area: extent of gillnet ban; dark green area: extent of area where both gillnets and trawling are banned; orange lines: recent seismic surveys; light blue: shallow water (<100 m); dark blue: deep water (>100 m)

prevailing southwesterly swells from the Tasman Sea. Although data are limited, habitat use by Māui dolphins appears similar to that of Hector's dolphins, including a stronger preference for harbors and other inshore habitat during summer than in winter (e.g. Rayment et al. 2011, Dawson et al. 2013).

The acoustic environment of Māui dolphins has not been studied, but includes vessel traffic, in particular fishing and cargo vessels, with relatively intensive traffic in some parts of the habitat (e.g. Manukau Harbor, New Plymouth, south Taranaki and Cook Strait). Māui dolphins make narrow-band high-frequency (NBHF) clicks centered on 125 kHz that are indistinguishable from those made by Hector's dolphins (Dawson & Thorpe 1990, Kyhn et al. 2009). Like Hector's dolphins and other NBHF species (sensu Madsen et al. 2005) all their sounds appear to be click-based and largely ultrasonic. The clicks are used in contexts that indicate echolocation (e.g. investigating novel objects) and are probably also used for communication (Dawson 1991).

The Threat Management Plan for Hector's dolphins and the expert panel report for Māui dolphins both identify bycatch in gillnet and trawl fisheries as the most important threat (Department of Conservation 2007, Currey et al. 2012). Impacts from mining and oil exploration (including noise, pollution, and habitat degradation) are listed as the second most serious threat (Currey et al. 2012). Nevertheless, there has been ongoing, intensive seismic survey activity on the boundary of and within Māui dolphin habitat (Fig. 2). These different types of threats may act in a cumulative and potentially synergistic way. For example, fishing impacts have been partially managed, with gillnets banned in about 19% of Māui dolphin habitat and both trawling and gillnetting

banned in 5% (IWC 2015) (Fig. 2). However, if seismic surveys cause Māui dolphins to leave these protected zones, even for short periods, they will be exposed to a greater risk of injury or death in fishing nets — already their number one conservation threat.

New Zealand has guidelines for seismic surveys that include requirements for soft starts (ramp-up) and at least 1 PSO to alert crew to any marine mammals detected within specified radii of concern (Table 2). If animals are detected within the 1 to 1.5 km zone of concern, the PSO requests that the crew of the vessel stop the air guns. This requires that PSOs can reliably detect animals within the zone of concern, but detection probabilities for Māui dolphins are likely very low. To illustrate this, consider that during dedicated scientific marine mammal surveys with a team of 3 trained observers using 25× and 7× binoculars, only about 40 to 50% of small dolphins/porpoises (most similar to Māui dolphins) on the transect line were detected in moderate weather conditions (sea state 3 on the Beaufort scale), dropping to 20% in rough seas (Beaufort 5) (Barlow 2015). Detection probabilities continue to decline as the distance between animals and the survey platform increases, making small dolphins such as Māui dolphins very difficult to detect beyond a few hundred meters (Dawson et al. 2004, Slooten et al. 2004). During seismic surveys with 1 to 2 observers searching with unaided eye or 7× binoculars, only a small fraction of the animals present will be detected (Barlow & Gisiner 2006, Weilgart 2014, Leaper et al. 2015). This fraction will decrease in poor weather and approach zero at night.

Passive acoustic monitoring (PAM) methods may be used to augment visual detections, but they depend on dolphins vocalizing and being detected, localized, and correctly identified to species or other

Table 2. Delayed start and shut down guidelines for seismic surveys in New Zealand. Levels indicate the total combined operational capacity of the acoustic source used. Distances are detection radii

	Delayed start	Shut down
Level 1 seismic survey >427 in^3 (>7 l)		
Species of concern with calf	1.5 km	1.5 km
Species of concern	1.0 km	1.0 km
Other marine mammals	200 m	
Level 2 seismic survey 151–426 in^3 (2.5–6.99 l)		
Species of concern with calf	1.0 km	1.0 km
Species of concern	600 m	600 m
Other marine mammals	200 m	

taxon of interest. In addition to spreading losses (typically between $10 \times \log R$ and $20 \times \log R$, where R is range), high frequency sounds suffer very high absorption in water (ca. 53dB km^{-1} at 130 kHz; Malme 1995). For this reason, high-frequency echolocation clicks can only be detected at close range (much less than 1 km). Acoustic detection is also dependent on the orientation of the animals to the hydrophone (Goodson & Sturtivant 1996).

Petroleum industry representatives have publicly acknowledged that 1 or 2 PSOs and/or PAM cannot detect all marine mammals within a radius of 1 to 1.5 km around the seismic survey vessel (e.g. Hughes 2015). The shutdown criteria, however, rely on the ability to correctly detect, identify, and determine whether a calf is present for each marine mammal sighting within a radius of 1.5 km around the vessel and the air gun array (which may be several kilometers behind the vessel). Clearly, this approach is unrealistic and ineffective.

Case 3: Kohala resident stock of melon-headed whales off Hawai'i Island, USA

The melon-headed whale *Peponocephala electra* is a poorly-known delphinid that typically inhabits open-ocean waters throughout the tropics and approaches shore only around oceanic islands (Brownell et al. 2009, Aschettino et al. 2012). In Hawaiian waters, where melon-headed whales can be found relatively close to shore (Baird et al. 2015), directed research on this species has been underway since 2002, using a combination of photo-identification, genetic sampling, and tagging (Aschettino et al. 2012, Woodworth et al. 2012, Baird et al. 2013, Kaplan et al. 2014, Baird 2016). Although rarely encountered, melon-headed whales are the most gregarious odontocete in Hawaiian waters, with average group sizes of about 250 individuals, and a maximum group size of 800 individuals (Barlow 2006, Baird et al. 2013).

NOAA recognizes 2 distinct populations of melon-headed whales in Hawaiian waters (Carretta et al. 2016). The Hawaiian Islands stock, estimated to include about 8600 individuals (Bradford et al. 2017), is primarily found in waters deeper than 1000 m and ranges among the islands and offshore into waters beyond the US Exclusive Economic Zone (Aschettino et al. 2012, Woodworth et al. 2012). In contrast, the Kohala resident stock appears to occur only in relatively shallow waters off the west and north side of Hawai'i Island (Fig. 3) (Carretta et al. 2016) — one of the smallest known ranges of any cetacean stock in
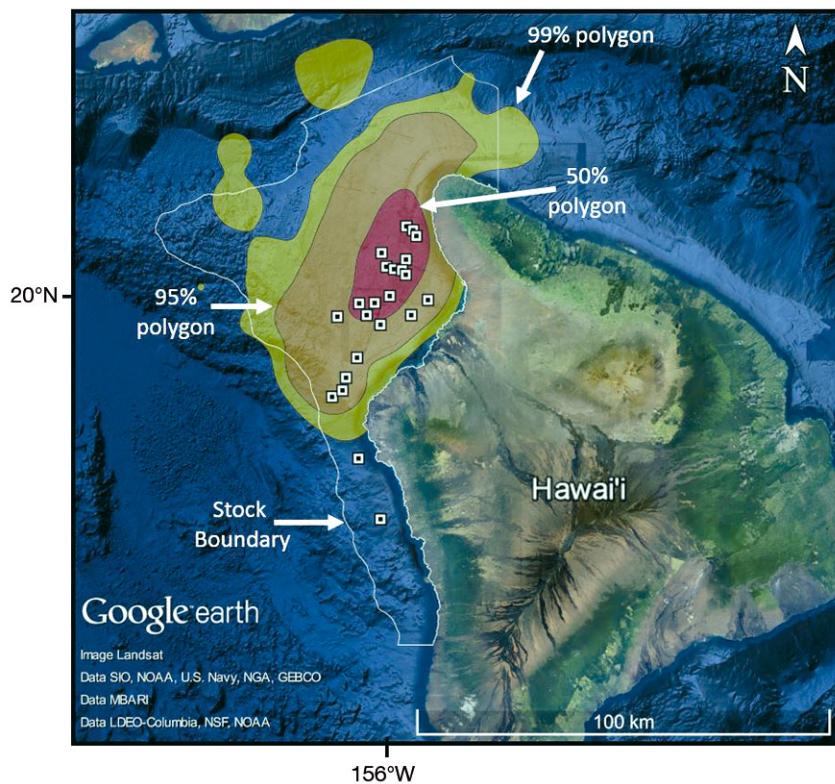
Fig. 3. Sightings (white squares, n = 23) and 50, 95, and 99% kernel density utilization distributions from satellite-tagged melon-headed whales (n = 8 individuals, 1175 locations) confirmed to be part of the Kohala resident stock, which occurs in shallow waters off the west and north side of Hawai'i Island. The white line shows the stock boundary (Carretta et al. 2016)

Hawaiian waters — and is estimated at 447 individuals (CV = 0.12) (Aschettino 2010). Estimated group sizes for the Kohala resident stock (50 to 550 individuals, median 210; R. Baird unpubl. data), suggest that all or most of the individuals in the Kohala resident stock are sometimes found together in a single group.

Information on the range of the Kohala resident stock comes from sightings of photo-identified individuals between 2005 and 2015, and from satellite tags deployed on 8 individuals, from 5 different groups, between 2008 and 2015 (see Baird et al. 2013, 2015). Satellite tag data are of limited duration (8 to 26 d, median 13 d), but span 6 months (January, June, August, September, October, and December). In all years, tagged whales remained off the north and northwest side of the island, an area designated as a 'Biologically Important Area' (Baird et al. 2015), with occasional excursions into the deepest parts of the 'Alenuihāhā Channel between Hawai'i Island and Maui. An estimate of the core range (the area within the 50% polygon from a kernel density analysis of locations from satellite tags) is only 411 km^2,

and the area within the 95% polygon is 1960 km^2 (Fig. 3; R. Baird unpubl. data). This area is a relatively shallow (<1000 m) plateau, and the median depths of locations of satellite-tagged individuals ranged from 437 to 810 m (R. Baird unpubl. data).

Prevailing winds in the main Hawaiian Islands are east or northeast trade winds. In contrast to the northeastern coast of Hawai'i Island, where another broad plateau exists, the Kohala resident stock area experiences less swell and has somewhat calmer conditions that may be conducive to early morning and daytime resting. Melon-headed whales primarily rest, socialize and travel during the day, and forage at night (Brownell et al. 2009, Baird 2016). The species is vocally active, producing a variety of whistles and clicks (Frankel & Yin 2010, Kaplan et al. 2014). As in other delphinids, clicks are used in echolocation, and whistles are likely important for communication, maintaining group cohesion and facilitating social interactions.

Melon-headed whales are known to be susceptible to high intensity anthropogenic noise (Brownell et al. 2008). The first record of melon-headed whales in Hawai'i was a group of animals being driven into Hilo Bay in 1841 by native Hawaiians 'making a great noise, to drive the fish in; and finally succeeded in forcing many of them into shoal water', where many were slaughtered (Wilkes 1845, p. 221). In July 2004, mid-frequency active sonar was 'a plausible, if not likely, contributing factor' in the near-mass stranding of a group of 150 to 200 melon-headed whales in Hanalei Bay, on the north side of Kaua'i, coincident with a multi-national Rim-of-the-Pacific (RIMPAC) naval training exercise being undertaken nearby (Southall et al. 2006, p. 2). In 2008 in Madagascar, about 100 melon-headed whales moved into a narrow lagoon system and eventually stranded, with 'the most plausible and likely behavioral trigger for the animals' determined to be a high-power multi-beam echosounder system being operated by a survey vessel (Southall et al. 2013, p. 4).

Mid-frequency (1 to 10 kHz) active sonar (MFAS) is used by the US Navy throughout Hawaiian waters, sometimes including areas off Hawai'i Island and

within the range of Kohala resident melon-headed whales; however, information on temporal and spatial patterns of MFAS use is not publically available. During the 2006, 2014, and 2016 RIMPAC exercises, multiple naval vessels were observed within the Kohala resident population's range, and MFAS use was documented in the area during the 2014 and 2016 RIMPAC exercises (R. Baird unpubl. data). Given the limited range of the Kohala resident population, such MFAS activities may ensonify their entire habitat. The Kohala resident population's small size and potential to occur in a single group adjacent to these activities places them at particular risk from this source of anthropogenic noise. The most obvious risk is a mass stranding of a large proportion of the population, but displacement (considered 'Level B' harassment under the MMPA) of whales to the south or east could also lead to adverse effects, because the habitats in those areas are notably different. To the south, along the west coast of Hawai'i Island, the narrow shelf quickly reaches depths over 3000 m. To the east, the windward coast of Hawai'i Island has similar water depths but is much more exposed to trade winds and swells. In either of these 2 habitats, foraging or daytime resting and socializing may be disrupted, with unknown consequences to individuals or populations.

Despite their proximity to shore and nearby harbors, there is relatively little monitoring of the Kohala population, and population trends have not been examined. Given the low number of encounters with melon-headed whales each year, it will be difficult to assess whether there are individual-level adverse effects from MFAS exposure in these relatively concentrated and biologically important areas and, if so, what population-level consequences might result.

Case 4: Cuvier's beaked whales off Cape Hatteras, USA

Cuvier's beaked whales *Ziphius cavirostris* have a cosmopolitan distribution in the world's oceans and are the most widespread species of beaked whale. In the northwestern Atlantic, the species ranges from Nova Scotia to the Caribbean, with sightings occurring primarily along the continental shelf edge and continental slope waters (Waring et al. 2015). NOAA currently recognizes a single stock of Cuvier's beaked whales in the entire northwestern Atlantic, although the stock assessment report notes that 'stock structure in the North Atlantic is unknown' (Waring et al. 2015). The size of this stock has been estimated as 6532 individuals (CV 0.32), but this estimate does not correct for availability bias, which is likely to be substantial because of the species' deep-diving capability (Barlow 2015, Waring et al. 2015). Cuvier's beaked whales are not taken frequently as fisheries bycatch and are not listed as threatened or endangered under the ESA, nor is this population considered a strategic stock under the MMPA.

One particularly important area for Cuvier's beaked whales in the northwestern Atlantic is The Point, a small area approximately 50 km east of Cape Hatteras, where the Gulf Stream flows over the shelf break before veering to the northeast (Fig. 4). Nine satellite-tagged individuals were followed for up to 2 months and demonstrated remarkable fidelity to this area (Fig. 4) (Baird et al. 2016). Photo-identification studies of well-marked individuals suggest that this site fidelity extends over seasons and years (A. Read unpubl.). Aerial surveys have also revealed year-round residency of Cuvier's beaked whales in this region (McLellan et al. 2015).

Until recently, our knowledge of Cuvier's beaked whales was derived almost entirely from observations of strandings. Beaked whales (predominately but not exclusively Cuvier's beaked whales) have been involved in atypical mass stranding events associated with MFAS training operations in many locations in the Northern Hemisphere (Brownell et al. 2004, Cox et al. 2006, Filadelfo et al. 2009, Podestà et al. 2016). Given these observations and fairly extensive recent research involving 4 beaked whale species, including Cuvier's beaked whales, those species tested appear to be particularly sensitive and vulnerable to certain types of acoustic disturbance relative to most other marine mammal species (see Southall et al. 2016). Due to concerns over the vulnerability of beaked whales to acoustic disturbance, several research programs have been developed, providing new insights into the diving behavior and movements of these cryptic species. For example, studies using satellite-linked dive recorders have revealed that Cuvier's beaked whales are the most extreme mammalian divers, capable of reaching depths of almost 3000 m and remaining submerged for more than 2 h (Schorr et al. 2014). Records from digital acoustic tags indicate that Cuvier's beaked whales produce regular echolocation clicks and foraging buzzes during deep dives, but are generally silent in the upper 500 m of the water column (Tyack et al. 2006). Individual whales react strongly to experimental exposure to simulated MFAS at relatively low received levels, by stopping foraging and moving away from the sound source for extended periods
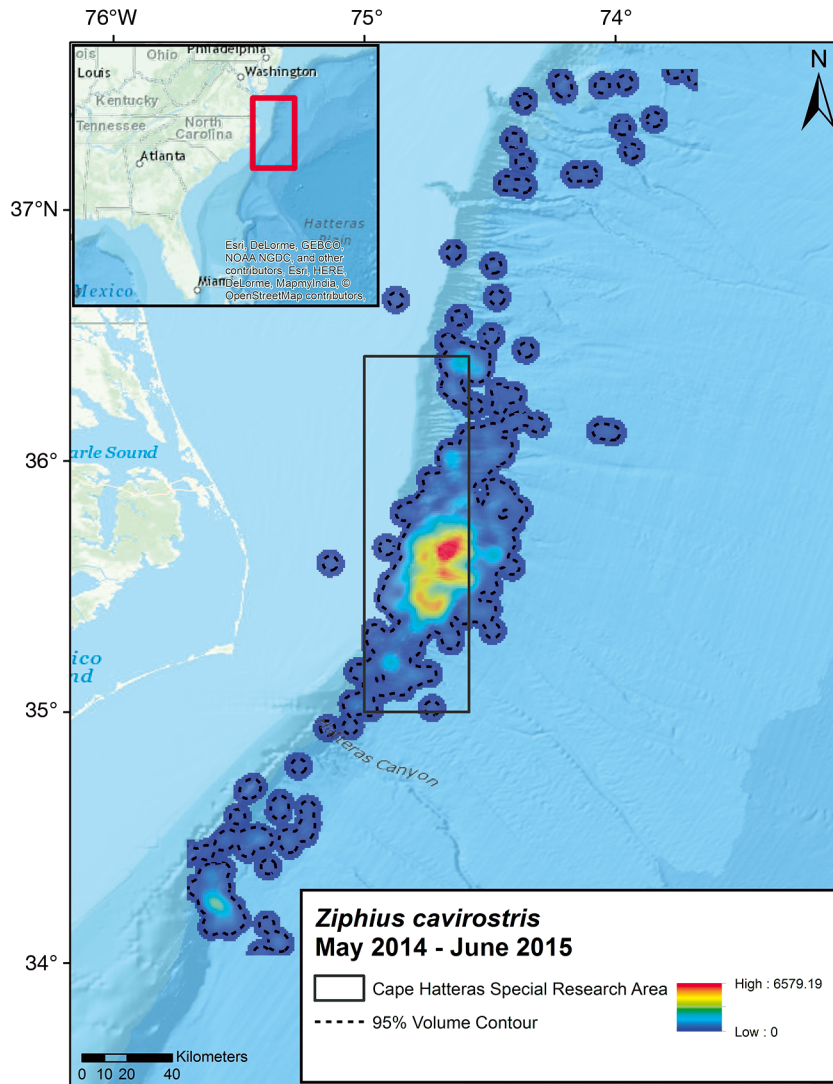
Fig. 4. Relative density of Cuvier's beaked whales at The Point (northwestern Atlantic, off Cape Hatteras, North Carolina, USA) based on kernel density analysis of the movements of 9 satellite-tagged individuals in 2014 and 2015 (Baird et al. 2016)

by Congress to conduct a Programmatic Environmental Impact Statement (PEIS) to evaluate the environmental effects of geological and geophysical (G&G) activities in the Atlantic Outer Continental Shelf region. The PEIS (BOEM 2014) describes impacts of air gun surveys on many aspects of the environment, including marine mammal populations, which are protected by the MMPA and, in the case of listed species, the ESA.

Using existing regulatory standards, the 'preferred alternative' in the PEIS (BOEM 2014) estimated that up to 541 Cuvier's beaked whales would be exposed to sound levels causing injuries (Level A harassment). In addition, up to 53 042 behavioral (Level B) harassment events, including repeated exposures of individual whales, would be expected. The PEIS emphasizes that these are 'conservative' upper limits that do not take many mitigation measures, such as visual observation and passive acoustic monitoring, into account (BOEM 2014). However, as noted by Barlow & Gisiner (2006), 'the effectiveness of all mitigation methods that are currently in use has not been established for beaked whales.' Beaked whales pose a particular challenge to the use of such mitigation measures because of their cryptic surfacing behavior and silence while near the surface. Dedicated scientific surveys that employ a team of highly trained observers and high-powered binoculars can detect only about 10 to 40% of Cuvier's beaked whales on the transect line, depending on sea states (Barlow 2015). Detection probabilities further decrease rapidly with distance from the vessel, such that only a small fraction of animals close to the ship can be seen under most realistic field conditions. As described above, PSOs aboard seismic survey vessels have lower detection rates, so their monitoring is clearly not effective for detecting beaked whales exposed to harm.

Following the expiration of the moratorium on oil and gas development in the Atlantic, 11 G&G companies filed applications with BOEM to conduct surveys, all but one using air gun surveys. At the time of
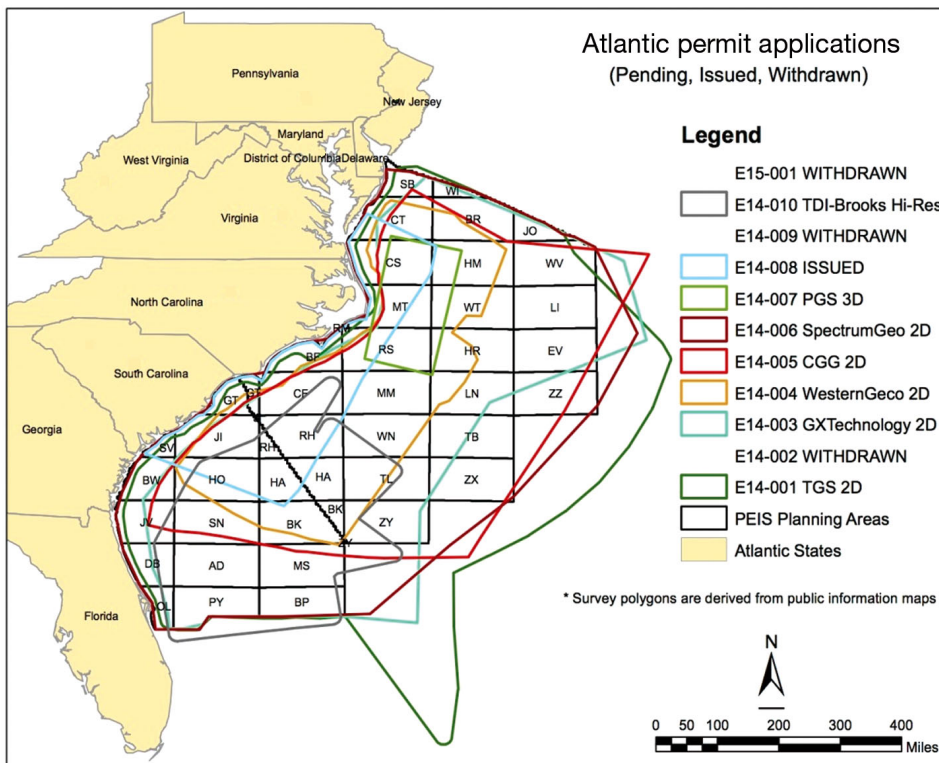
(DeRuiter et al. 2013). Such responses, if evoked on a frequent basis, could result in significant fitness costs to individual whales, as a result of lost foraging opportunities and the energetic costs of such movements. The abundance of this species has declined during the past 25 yr along the US West Coast (Moore & Barlow 2013), and routine exposure to MFAS over the past 50 yr in this region is one of several possible contributors to this decline.

A moratorium on oil and gas development along the Atlantic coast of the USA was established by Presidential directive in 1990 (BOEM 2014). The moratorium expired in 2008, and in 2010 the Bureau of Ocean Energy Management (BOEM) was directed

Fig. 5. Spatial extent of permit applications to the Bureau of Ocean Energy Management from Geological and Geophysical companies to explore for oil and gas deposits in the Outer Continental Shelf region of the Atlantic. PEIS: Programmatic Environmental Impact Statement; two character codes identify individual PEIS planning areas. (Modified from www.boem.gov/Atlantic-G-and-G-permitting/#permitting, accessed October 2016)

writing in 2016, 3 permit applications had been withdrawn, one expired, and the remaining 7 were still active. Six out of the 7 active permits included The Point, an area of particular interest for oil and gas development (Fig. 5). Although the moratorium on oil and gas leases was renewed by President Obama in March 2016, oil and gas exploration activities (e.g. seismic surveys) may still be authorized for potential future development. Failure to consider effects of both noise exposure and displacement of Cuvier's beaked whales from their habitat in this region could lead to more severe biological consequences than 'Level B harassment' (as defined under US law), because (1) not all animals that can be injured are likely to be detected, and (2) displacement out of their population range may adversely affect foraging rates, reproduction or the health of Cuvier's beaked whales.

Case 5: Western Pacific gray whales

The western Pacific gray whale subpopulation is classified as Critically Endangered by IUCN and endangered under the ESA. These whales were hunted to such low numbers that, by the mid-20th century, some researchers believed they were extinct (Bowen

1974). They were rediscovered in the 1970s (Brownell & Chun 1977), and the Sakhalin feeding aggregation of the western Pacific gray whale was estimated in 2015 to contain 175 (95% CI 158 to 193) animals aged 1 yr and over (Cooke et al. 2015). The International Whaling Commission (IWC) and the IUCN have each expressed serious concern about the status of this subpopulation and have called for urgent measures to be taken to help ensure its protection and recovery. Two of the primary identified threats to this subpopulation include entanglements in fishing gear and impacts of oil and gas development.

There is some evidence of mixing between eastern and western gray whale subpopulations, including satellite-tagged whales feeding off Sakhalin and migrating back to the west coast of North America (Mate et al. 2015). However, incidental catches of western Pacific gray whales continue to be documented in coastal net fisheries, particularly off Japan within their traditional migratory route (Weller et al. 2002, Kato et al. 2010), supporting the existence of a distinct, yet quite small, subpopulation of western gray whales. Projections from population assessments suggest that, if the documented level of net-related mortality continues, there is a high probability that the subpopulation will decline to extinction

(Cooke et al. 2015). Analysis of scarring on western Pacific gray whales found that 18.7 % (n = 28) of 150 individuals identified between 1994 and 2005 had been previously entangled in fishing gear (Bradford et al. 2009). Nothing is known about bycatch in Korean and Chinese waters, but mortality is possible in these fisheries. The subset of western Pacific gray whales that migrate back to the eastern Pacific in winter are also at risk from ship strike and entanglement during their migration along the US West Coast (Carretta et al. 2016).

The development of the major oil and gas reserves along the eastern continental shelf of Sakhalin Island in the mid-1990s introduced new threats to the survival of the subpopulation (Weller et al. 2002, Reeves et al. 2005). Potential adverse impacts include (1) behavioral disturbance; (2) negative effects on hearing (including masking and temporary threshold shifts) from underwater noise associated with seismic surveys, platform operations, pipeline dredging, and ship and air traffic; (3) direct interactions between whales and an oil spill or other waterborne chemicals, ships, and possible entanglements in cables or lines; and (4) habitat changes related to seafloor modifications associated with dredging and sand pumping activities that may adversely impact gray whale prey (for a complete review see Reeves et al. 2005). The cumulative impacts of oil and gas development in this summer/fall foraging ground are a concern, because whales rely on this area for most of their annual food intake (Weller et al. 1999). Photo-identification studies between 1994 and 2014 show high levels of inter-annual site fidelity to this foraging area (Weller et al. 2008a,b, Burdin & Sychenko 2014), particularly for reproductive females that feed in the area during all phases (i.e. while pregnant, lactating, and resting) of their reproductive cycle (Brownell & Weller 2002, Weller et al. 2002, 2003).

During the summer of 2001, 3D seismic surveys were conducted from 17 August to 9 September in prime gray whale foraging habitat (Odoptu) off Sakhalin Island (Johnson et al. 2007). Systematic observations of whales in relation to operational condition (i.e. pre-seismic, seismic, post-seismic) showed that a significantly lower number of individuals and groups were seen during seismic surveys, compared to pre- and post-seismic conditions (Weller et al. 2006, Johnson et al. 2007). This indicates a potential for harm caused by displacement of this endangered subpopulation from foraging areas (Weller et al. 2006). In another study, Yazvenko et al. (2007a,b) examined an 'overall feeding index' (the frequency of mud plumes at the surface) and concluded that bottom feeding activity of gray whales was not significantly affected by the seismic survey; however, foraging success and prey type were not determined so this interpretation could not be confirmed. During a 2008 seismic survey and an on-land pile driving project, the near-shore distribution of gray whales decreased by nearly 40 % compared to 2007, and the number of whales using the offshore feeding area more than doubled (Cooke et al. 2015). The IUCN Western Gray Whale Advisory Panel concluded that 'the precautionary approach is to act on the assumption that the shift in distribution evident in 2008 was caused by anthropogenic disturbance, and that it will have negative implications for feeding success and ultimately reproductive success' (IUCN 2009, p. 22).

Despite extensive research and mitigation efforts focused on reducing the spatial and temporal overlap between gray whales and oil and gas activities (Nowacek et al. 2013, Bröker et al. 2015, Racca et al. 2015), there are clear and present issues of concern for this subpopulation. Feeding areas are being heavily and regularly impacted by both seismic surveys and oil and gas development. Industrial activities on the continental shelf of this region have steadily increased in the past 15 yr and are scheduled to expand at a rapid pace. Whales that migrate to the eastern Pacific during winter months may also be exposed to seismic surveys and other anthropogenic sound sources along their seasonal migratory routes along Alaska and the US West Coast (Mate et al. 2015). Failure to consider impacts of both noise exposure for animals that remain on very concentrated feeding areas despite disturbance, and potentially similar or worse consequences of displacement for animals that leave could adversely impact the recovery of the endangered western gray whale subpopulation.

CHANGE IN PARADIGM

The above case studies illustrate that the current paradigm for avoiding death or injury of marine mammals from anthropogenic noise fails to adequately consider the effectiveness of monitoring and mitigation, and the biological costs of displacement from important habitats. The primary goal of mitigation has been to reduce the risk of direct physical injuries to animals exposed to anthropogenic noise. Mitigation measures (e.g. ramp-up, suspension of activities when animals are detected) rely on the assumption that animals will be able to move away

and in doing so will not be harmed. Although some legal statutes, such as the ESA for endangered species, require consideration of displacement effects along with direct injuries, many other legal statutes do not (e.g. under the MMPA, displacement is generally considered to be 'Level B' harassment, a relatively minor behavioral disruption without potential to injure the marine mammal). The prevailing management paradigms implicitly or explicitly assume that displacement effects are less harmful than direct injuries, particularly when detailed data on displacement effects for a given species are lacking or uncertain. However, displacement can also be a source of significant harm (including injury or death), particularly for small, resident populations that may have 'nowhere to go' and for which the costs of leaving their habitat may be severe.

Species that respond to noise by avoiding an area are unlikely to be observed using traditional methods (PSOs and PAM), because animals may react at distances well beyond the potential detection range, in some cases up to tens of kilometers from the sound source (e.g. Southall et al. 2007, Dähne et al. 2013, Thompson et al. 2013). Hence even very strong reactions would be unobserved, and visual or acoustic monitoring from a seismic survey vessel must be considered biased towards species that are relatively tolerant of seismic noise. Further, the full range of pathways by which such disruption can cause harm is rarely considered explicitly, because there are so many unknowns about individual and population-level consequences of disturbance (Gill et al. 1996, King et al. 2015, Costa et al. 2016). Responses and effects can vary markedly among species, geographic areas, and populations with varying levels of past exposure to anthropogenic noise. Naïve populations may have a greater response than habituated populations (Heide-Jørgensen et al. 2013, Thompson et al. 2013). The availability of alternate nearby high-quality habitat without other threats (e.g. bycatch, predation) is also a major consideration when evaluating potential harm. If

animals are strongly motivated to stay in an area because of its biological importance, this does not mean there are no deleterious effects on their physiology (Gill et al. 2001, Beale & Monaghan 2004, Wright et al. 2007, Aguilar de Soto & Kight 2016, Gomez et al. 2016)

A more comprehensive paradigm for assessing impacts of anthropogenic noise (or other activities) on marine mammals needs to include explicit consideration of all potential pathways of harm, including adverse impacts resulting from both close-range exposure and displacement away from the sound source. Both types of responses can lead to reduced foraging success, increased stress, disruption of important social and reproductive functions, and decreased survival or reproductive success through a variety of pathways (Fig. 6). Permanent and temporary threshold shifts have often been the primary consideration for regulatory measures and are more likely for animals that may be reluctant to leave an area, but stress (Rolland et al. 2012), effects of acoustic 'masking' (Todd et al. 1996, Clark et al. 2009, Nielsen et al. 2012, Gomez et al. 2016) and displacement (e.g. Dähne et al. 2013, Thompson et al. 2013) are increasingly recognized as important impacts that need to
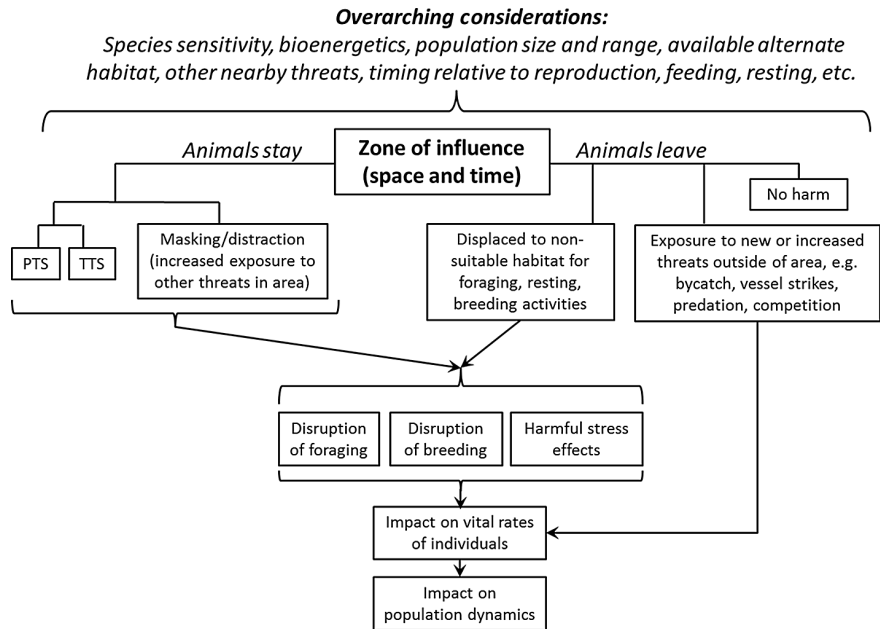

Fig. 6. Expanded framework for assessing potential impacts of anthropogenic activities on marine mammals. For small marine mammal populations with high site fidelity, the pathways at the right of the figure are, in many cases, the principle source of harm. Although data are limited for many of these pathways, they can nonetheless be assessed conceptually based on basic biological principles or qualitative considerations. If mechanisms of harm are conceptually plausible (e.g. bycatch in nearby areas, loss of foraging habitat), then they cannot be ignored in assessments of potential impacts. PTS: permanent threshold shift; TTS: temporary threshold shift. See Box 1 for examples of overarching considerations

be considered explicitly. Although data may be lacking on the precise magnitude of species-specific responses, qualitative assessments can be performed and are essential for providing sound management advice. Also, they can help identify whether additional mitigation measures or research may be required to resolve key questions of uncertainty for proposed activities.

The specific details of each case will differ, as assessments under the expanded framework in Fig. 6 must also consider overarching species-specific and case-specific factors (Box 1). These may include the need for daily food intake or resting (Yasui & Gaskin 1986, White & Seymour 2003, Tyne et al. 2015), the biological role of acoustic communication that may be masked or disrupted (Clark et al. 2009, Wright & Cosentino 2015, Gomez et al. 2016), or the presence of other threats nearby (Wright et al. 2007, Slooten 2013). Some of these considerations can be evaluated based on established biological science, such as the relationship between metabolic rate and mammalian body size (Kleiber 1932, White & Seymour 2003). Others can be approximated based on patterns observed in similar populations, species or taxa (e.g. sensitivity of harbor porpoises to noise wherever they have been studied; vulnerability of small cetaceans to gillnet bycatch). Where information is lacking, targeted research conducted well in advance of proposed noise-generating activities may resolve key questions, such as the responses of individuals in a given population to novel stimuli (Southall et al. 2012, 2016, DeRuiter et al. 2013). Such studies can be expensive and require time to achieve sufficient sample sizes, as behavior is highly variable among individuals, but they are essential for understanding the mechanisms of harm to marine mammals. Research and monitoring programs must also consider statistical power, to ensure that sufficient data are collected to be able to detect meaningful environmental effects (on all exposed species) while allowing for natural variation in animal distribution, behavior, and biological processes. In this context, endangered species present a dilemma; only large effects are likely to be detectable, even though very small effects can be biologically meaningful. Thus, a fundamentally important aspect of any robust assessment of the effects of disturbance

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Box 1. Overarching considerations for assessing impacts of anthropogenic noise on small populations with high site fidelity

Population-specific factors
Population size and uncertainty therein
Population status (e.g. threatened, endangered)
Population range and habitat
Behavioral state (e.g. reproduction, feeding, resting)
Species sensitivity to sound (causing disturbance and/or injury)
Species stress-responses
Species susceptibility to mass strandings
Required food intake to meet metabolic needs

Environmental factors
Proportion of population's habitat exposed to sound
Duration of proposed sound exposure
Propagation of proposed sound within the habitat (e.g. shallow vs. deep)
Amount and quality of alternate habitat available for displaced animals
Sensitivity of prey species to anthropogenic noise
Other anthropogenic threats (e.g. fishery bycatch, vessel traffic)
Natural threats (predator density, inter-specific aggression)

Monitoring and mitigation factors
Effectiveness of monitoring (% of individuals detected)
Effectiveness of mitigation actions if animals are present

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is advanced planning and monitoring, including sufficient sampling to understand the baseline state of populations and the natural variation therein. This may require years of advanced and adaptive research.

In some cases, questions about the effectiveness of mitigation measures can be addressed more quickly via targeted experiments, such as those routinely conducted to assess the effectiveness of scientific research surveys at detecting marine mammals (e.g. Laake et al. 1997) or via project-specific simulations (Leaper et al. 2015, Costa et al. 2016). The extensive body of research on line-transect abundance estimation includes a variety of methods for assessing the proportion of animals missed because of diving behavior, weather conditions, vessel attraction or avoidance, and as a function of distance from the observation platform (e.g. Turnock & Quinn 1991, Buckland et al. 2001, Barlow et al. 2011, Barlow 2015). This information on detection efficiency is critical for understanding the true impacts of activities, because animals that are not detected cannot be protected from harmful activities. Managers cannot make informed decisions on whether to approve or disapprove potentially harmful activities unless they are

given an accurate estimate of the effectiveness of the proposed monitoring and mitigation measures for all exposed species.

APPLYING THE EXPANDED FRAMEWORK

Below we provide examples from the first 4 case studies above to illustrate how the expanded framework represented by Fig. 6 can improve assessments of potential impacts to small populations with high site fidelity, or at least identify the data and information required before a proper assessment can be made. These case studies illustrate how managers can make informed decisions even when specific data are lacking, rather than overlooking or implicitly ignoring effects that cannot be estimated precisely, as has often been the case under the existing paradigm. For the western gray whale case study, we note that some of the more recent studies and monitoring and mitigation efforts have begun to consider and implement some of the kinds of recommendations put forward here, e.g. advanced planning, reducing spatiotemporal overlap, collecting baseline data, and integrating multiple monitoring techniques (Nowacek et al. 2013, Bröker et al. 2015).

Central California harbor porpoises

Temporary hearing damage has been documented in harbor porpoises at equivalent sound exposure levels below the nominal 160 and 180 dB re 1 µPa RMS levels predicted to result in behavioral disturbance and injury, respectively (Lucke et al. 2009, Kastelein et al. 2012, 2015). The 160 dB level, in particular, extends far beyond the area that can effectively be surveyed visually by PSOs and using real-time passive acoustic methods. This suggests that the left side of the flowchart in Fig. 6 ('animals stay') is likely to lead to undetected harm because many animals will be missed. At a minimum, monitoring and mitigation measures must be carefully designed to achieve sufficiently high harbor porpoise detection probabilities to allow effective mitigation. Impact assessments must also recognize that even the best design will still miss animals that may be present and harmed (e.g. at night). The number of animals potentially harmed without being observed should be accounted for when assessing impacts on a given population.

If porpoises leave the area of seismic survey noise (right side of flowchart in Fig. 6), it is clear that addi-

tional pathways of harm exist, although the nature and severity of harm depends in part on displacement distance and in part on the availability of alternate suitable habitat. The sensitivity of the Morro Bay population of harbor porpoises to anthropogenic impulse sound sources has not been studied directly, but there is considerable evidence from studies of harbor porpoises elsewhere that displacement on the order of 20 to 40 km is common. In a study of harbor porpoise responses to a 10-d seismic survey off northeast Scotland, Thompson et al. (2013) documented temporary displacement of animals within 10 to 40 km of the source. Harbor porpoises exposed to longer-term pile-driving activities from wind farm construction within their habitats in European waters were displaced by at least 20 km during the monitored construction periods (Carstensen et al. 2006, Tougaard et al. 2009, Dähne et al. 2013). In one follow-up study, porpoise densities had not returned to pre-pile-driving levels within the affected area after many years (Teilmann & Carstensen 2012). Naïve populations, such as the Morro Bay harbor porpoise, are likely to exhibit more pronounced responses (Carstensen et al. 2006, Tougaard et al. 2009, Dähne et al. 2013, Thompson et al. 2013).

In the absence of population-specific information, these studies of other populations form the best available science from which to assess impacts. For example, if one assumes a displacement distance of 20 km, at the smaller end of the above range (yellow line in Fig. 1), the original seismic survey design would have excluded the Morro Bay harbor porpoise population from nearly all of its primary foraging habitat, with animals pushed either offshore into deeper waters, southward beyond the species' eastern Pacific range, or northward into an extremely narrow shelf region along the Big Sur coastline, where few porpoises have been seen on aerial surveys (Forney et al. 2014). Any of these options would reduce foraging success for the duration of the displacement, and could increase other risks such as predation, inter-specific aggression (Cotter et al. 2012, Wilkin et al. 2012, Jacobson et al. 2015), bycatch, or harmful stress effects. Harbor porpoises must consume about 5% of their body mass daily to meet metabolic requirements (Yasui & Gaskin 1986, Read & Westgate 1997, Lockyer 2007). Shortfalls caused by reduced prey availability in suboptimal foraging areas can rapidly deplete the reserves of such a small-bodied animal, adversely impacting health, reproduction and survival.

Based on these basic biological principles—and without the absolute need for population-specific

data—the best available science indicates that disruption of foraging activity for days to weeks can be expected to adversely impact the health and survival of harbor porpoises. For the Morro Bay harbor porpoise population, even the reduced duration and geographic extent of the modified seismic survey had the potential to cause significant harm to a large proportion of the population, regardless of whether the porpoises stayed (and were subject to auditory injury and stress) or left the area (and were displaced from their foraging habitat). This underscores the need for multi-year advanced planning that includes (1) explicit considerations of porpoise displacement effects; (2) multi-year studies to establish a baseline of porpoise behavior and distribution from which changes of a biologically important magnitude can be detected with acceptable statistical power during a seismic survey; and (3) short-term experiments to assess the sensitivity and range of responses of Morro Bay porpoises to novel acoustic stimuli. These steps are necessary to allow effects to be assessed accurately and monitoring plans to be designed effectively. The key to an effective plan is that it must reliably allow the detection of porpoises at risk of harm, from both exposure or displacement, and it must quickly implement proven, real-time mitigation measures to prevent such harm. If this cannot be achieved, then precautionary planning must consider avoiding or modifying the activity to ensure no harm occurs.

Māui dolphins off New Zealand

Māui dolphins are in a similar situation, where harm can take place through direct injury (if dolphins stay in the immediate area of seismic survey operations), via disruption of important behavioral activities such as feeding or social interactions, or through displacement to other areas with a greater risk of bycatch. Direct injury or disruption of important behaviors by seismic surveys can only be mitigated effectively if detection probabilities for the monitoring methods used are quantitatively determined to be close to 100%. Otherwise, if a monitoring plan can only detect e.g. 25% of the animals present and exposed to harm, then for every animal detected, 3 animals would go undetected and thus be harmed. Clearly, this is not defensible for a Critically Endangered population of 55 dolphins. The very low probability of detecting Māui dolphins means that mitigation by means of exclusion zones is not effective. Seismic surveys are likely to pose an even greater

threat through displacement, because any Māui dolphins leaving the protected area in their primary habitat are at greater risk of bycatch in adjacent areas with active gillnet and trawl fisheries. Māui dolphins are Critically Endangered because of extensive past bycatch, and bycatch remains the most serious threat to their survival.

The PBR for Māui dolphins has been estimated to be 1 dolphin death every 10 to 23 yr (Currey et al. 2012). Approximately 27 of the 55 individuals in the population are expected to be female, and about half of these (i.e. 14 individuals) of breeding age (Slooten et al. 2006). Females breed every 2 to 4 yr, and the maximum population growth rate is estimated at 1.8% yr^{-1} (Slooten & Lad 1991). Hence the death or injury of a single breeding female from this population, or any reduction in reproductive rate (e.g. due to reduced feeding success) would substantially increase extinction risk and delay any recovery of Māui dolphin. A single death or injury would be very difficult to detect, but could have serious biological consequences. Reductions in feeding success or reproductive rate would be even more difficult to detect. An assessment of impacts of seismic surveys to this population is, therefore, incomplete unless it considers the harm caused by displacement into areas with greater bycatch risk as part of the overall impact of the ongoing seismic surveys.

Proper mitigation of impacts is only possible once all potential threats are fully recognized, so targeted studies may be required to address unknowns, e.g. to characterize the extent of Māui or Hector's dolphin responses (e.g. displacement distances) to nearby noise sources. When threats are known, successful mitigation must consider the full (cumulative) suite of risks to Māui dolphins, ideally as part of the approval and permitting process (e.g. requiring the elimination of gillnets from the surrounding areas for the duration of the seismic survey to avoid bycatch). By considering all pathways to harm explicitly within the expanded framework of Fig. 6, it becomes self-evident that displacement cannot be considered a minor disruption to behavior, but rather itself a source of harm. Until these threats can be fully assessed and mitigated reliably, a precautionary approach would prohibit high-intensity seismic exploration within and adjacent to Māui dolphin habitat. Alternative, lower-impact methods of acquiring geophysical data include technologies that use vibration, a controlled electromagnetic source, low-impact seismic arrays, 'suppressor' devices, 'silencer' devices and/or the use of a sound source on the sea floor (e.g. Deffenbaugh 2002, Weilgart 2010, NOAA et al. 2011).

Kohala resident stock of melon-headed whales

This population is found only in a small shelf area on the west side of the Hawai'i Island, directly adjacent to a US Navy Operational Range within the Alenuihāhā Channel. The entire population can at times be found together in a single large group, and this species clearly appears to be particularly sensitive to MFAS and other forms of sonar, based on previous stranding events. The restricted range of this population limits options for individuals to move away in response to sonar. Thus there is non-trivial potential for harm to this population on both sides of Fig. 6. If they stay, they may expose themselves to a mass stranding risk that could affect the entire population. If they move into non-primary habitat, there will be likely consequences for foraging success, resting, and socializing. Again, these risks need to be explicitly evaluated in order to assess the costs and benefits of various actions, such as the elimination of sonar activities in areas near the Kohala population of melon-headed whales, conducting research on population-level responses to sonar-type sounds, or allowing activities to take place at the risk of losing an entire population of a protected marine mammal.

Cuvier's beaked whales

It is unclear what effects repeated air-gun surveys would have on the Cuvier's beaked whales that inhabit The Point, because we know so little about this species' response to seismic surveys, particularly in areas where animals have not previously been exposed to such noise. However, disturbance from seismic surveys and associated exploration (and drilling activities if oil and gas reserves are discovered) could last for years. And, as noted above, this species is known to be particularly sensitive to other sources of anthropogenic noise. Thus, pathways of harm exist whether animals stay and experience direct injury or disruption of key behaviors, or leave and are potentially displaced from their localized slope foraging habitat. However, standard mitigation and monitoring methods are not suited for detecting and assessing the impacts of behavioral responses of beaked whales to air gun surveys. Furthermore, the stock-wide assessment surveys conducted by NMFS are too coarse in both time and space to detect even the most severe effects, such as complete abandonment of their habitat. The potential physiological consequences of such displacement are even less well understood.

A combination of approaches will be necessary to evaluate the potential effects of air-gun surveys on this resident group of beaked whales. First, we need to understand more about the population structure of Cuvier's beaked whales in the northwestern Atlantic, so that we can determine whether the whales that inhabit The Point constitute a separate population or are part of a larger meta-population. This is particularly important, given the evidence of site fidelity for individuals, as it suggests there may be distinct smaller populations within the area. A dedicated research program employing satellite telemetry, photo-identification and molecular genetics could resolve this question. Second, as noted by Barlow & Gisiner (2006), controlled exposure experiments, which measure the behavioral responses of animals to sound sources, hold great potential for understanding the response of beaked whales to specific anthropogenic noises and for designing appropriate, species-specific mitigation strategies. Such approaches have proved extremely powerful for understanding the behavioral response of this species and other beaked whales to MFAS in other areas (e.g. DeRuiter et al. 2013). Finally, monitoring and mitigation plans need to include technologies and methods that are effective for detecting and minimizing impacts to Cuvier's beaked whales and other species that are known to be sensitive to noise.

SUMMARY

The above case studies illustrate a range of impacts that are poorly understood and particularly severe for small populations of marine mammals exhibiting high site fidelity. Such populations occur in both coastal and pelagic habitats and include both endangered species for which the entire population is included as well as localized stocks of species occurring elsewhere. In these and other cases where biological resources that are strongly associated with a particular place are so important to the health and viability of a population, we argue that a fundamentally new paradigm is needed to effectively and responsibly evaluate the effects of disturbance. Elements of the paradigm developed here must explicitly consider the different kinds of challenges animals may face by either remaining in the area and tolerating disturbance or injury, or leaving the area and coping with associated secondary effects. Long-term cumulative impacts are of major importance, but we will almost certainly only detect such impacts after many years of extensive population monitoring and, in most cases, only if the impacts are very severe.

Laws in the USA (e.g. ESA and MMPA) and in other countries provide tools for minimizing harm to marine mammals from anthropogenic noise, but often we are not asking the right questions to assess impacts properly. The expanded conceptual framework proposed here (Fig. 6) ensures that all relevant impact pathways are considered, recognizing that animals can be harmed even if they are not seen, and that displacement is not necessarily a minor behavioral disruption but rather itself a potential source of significant harm. Mitigation and monitoring plans should explicitly include estimation of cetacean detection probabilities, to ensure that as many animals as possible are detected and that true risks of harming animals that may never be seen are understood.

Small, localized populations are especially vulnerable, as they may literally have nowhere to go without experiencing harm. Effective and responsible mitigation of disturbance within important habitats for such species requires substantial advance planning, multi-year baseline studies, and well-designed monitoring and mitigation, as well as a new way of thinking about how effects may manifest themselves in animals that choose to either tolerate or avoid disturbance.

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