



Seal Bomb Noise as a Potential Threat to Monterey Bay Harbor Porpoise

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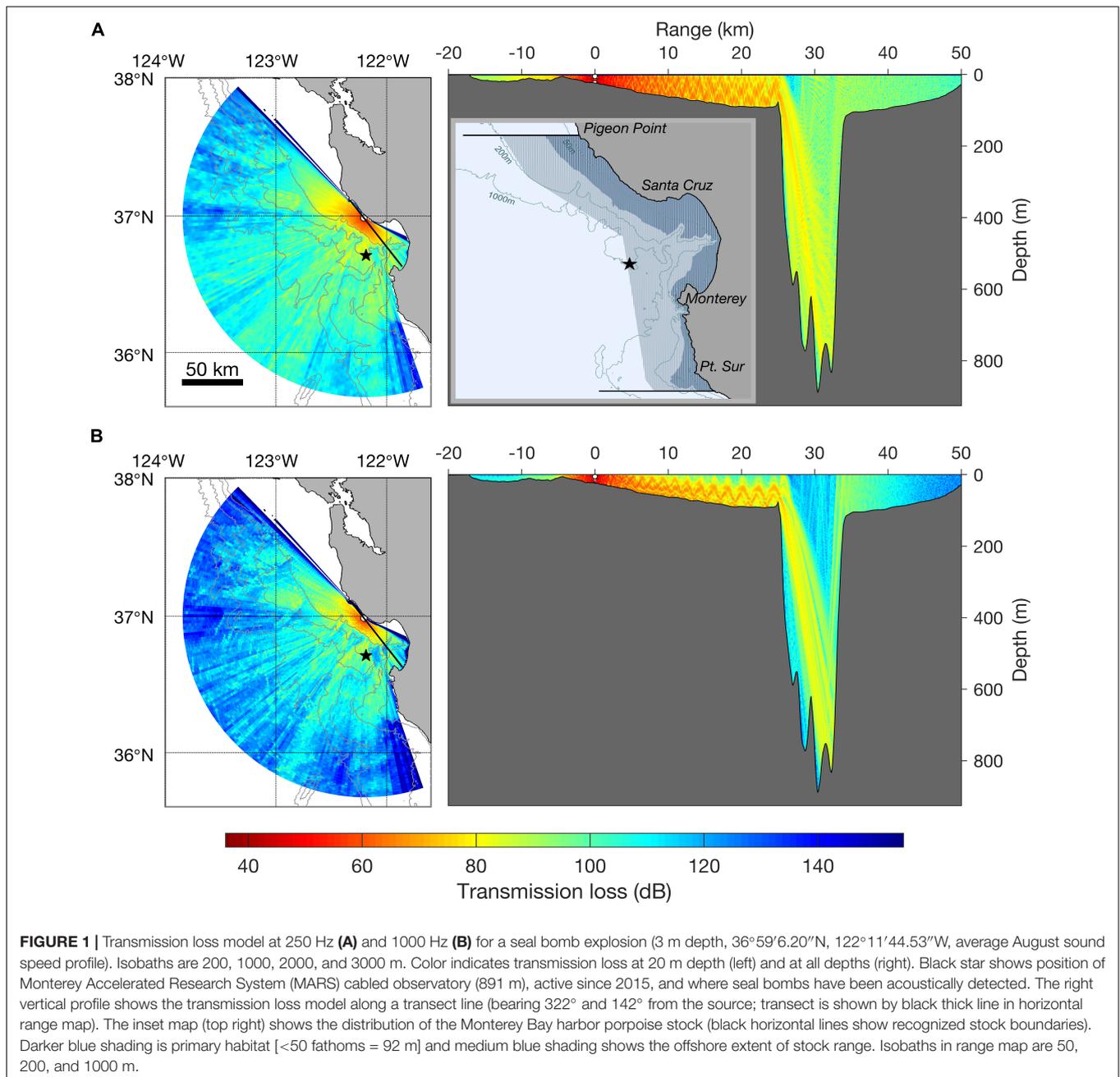
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Anthropogenic noise is a known threat to marine mammals. Decades of research have shown that harbor porpoises are particularly sensitive to anthropogenic noise, and geographic displacement is a common impact from noise exposure. Small, localized populations may be particularly vulnerable to impacts associated with displacement, as animals that are excluded from their primary habitat may have reduced foraging success and survival, or be exposed to increased threats of predation or bycatch. Seal bombs are underwater explosives used in purse seine fisheries to deter marine mammals during fishery operations. Pinnipeds are believed to be the primary target for seal bomb use, however there may be indirect impacts on harbor porpoises. Active purse seine fishing using seal bombs in the greater Monterey Bay area may, at times, span the entire range of the Monterey Bay harbor porpoise stock, which may lead to negative impacts for this population. In this contribution, we review anthropogenic noise as a threat to harbor porpoises, with a focus on the potential for impacts from seal bomb noise exposure in the Monterey Bay region.

Keywords: harbor porpoise, seal bombs, noise, acoustic deterrents, fishery interactions, displacement, Monterey Bay

ANTHROPOGENIC NOISE AS A THREAT

Anthropogenic noise has been recognized as a threat to marine mammals for decades, making it a central issue for their conservation and management (Tougaard et al., 2015; National Marine Fisheries Service, 2016; Southall et al., 2019). For many marine mammals, hearing is the primary sensory modality, important for navigation, foraging, predator avoidance, and communication (Tyack, 1986). Noise can be considered as any sound that has the potential to interfere with normal functioning of auditory processes or cause harmful behavioral or physiological responses. Potential impacts of noise include interruption of essential behaviors (Wisniewska et al., 2018), masking



signals of interest (e.g., the sounds of predators, conspecifics or prey) (Hermannsen et al., 2014), displacement from crucial habitat (Carstensen et al., 2006), direct physical injury including temporary or permanent hearing loss (Ketten et al., 2004; Finneran, 2015), and in extreme cases, death (Filadelfo et al., 2009). Strategies to mitigate noise impacts act to allow animals to avoid a noise source; however, there is growing concern that interruption of important behavior or displacement from crucial habitat may pose serious, population-level threats (Nowacek et al., 2007; Nabe-Nielsen et al., 2014, 2018; Forney et al., 2017).

Noise impacts may be particularly severe for small populations of acoustically sensitive marine mammals such as the harbor

porpoise (*Phocoena phocoena*). Along the United States west coast, five populations (“stocks”) of harbor porpoises are currently recognized under the Marine Mammal Protection Act, including the “Monterey Bay Stock” (Figure 1; Carretta et al., 2019) which ranges from just south of Point Sur to Pigeon Point, California. This is also a valuable region for squid and anchovy fisheries (California Department of Fish and Wildlife, 2019), which commonly use explosives called “seal bombs” to deter pinnipeds from catch or gear. Hence, there may be potential indirect impacts to harbor porpoises. In this review, we focus on the Monterey Bay harbor porpoise stock to evaluate potential impacts of seal bomb use in local fisheries and to

identify assessment needs with respect to noise exposure from these explosives.

HARBOR PORPOISE RESPONSE TO NOISE

Throughout their global distribution, harbor porpoises are known to be particularly sensitive to acoustic disturbance. The range of best hearing for harbor porpoises extends from 4 to 150 kHz, making them members of a “Very High-Frequency (VHF)” hearing group (Kastelein et al., 2010; Southall et al., 2019). They use narrow-band high-frequency echolocation signals for navigation, foraging and communication (Verfuß et al., 2009; Clausen et al., 2011). Harbor porpoises and other VHF species have a relatively stiff basilar membrane (Ketten, 2000); this, along with metabolic processes in the inner ear, may lead to lower thresholds for hearing loss in porpoises compared to other odontocetes (Lucke et al., 2009; Southall et al., 2019). Beyond hearing loss, harbor porpoises are highly responsive to noise, and numerous studies have documented short and long-term displacements at various spatial scales (10s of m to 10s of km) when porpoises are exposed to diverse sounds including pile-driving (Tougaard et al., 2009), seismic surveys (Thompson et al., 2013), ship noise (Dyndo et al., 2015; Wisniewska et al., 2018), acoustic warning devices (“pingers”) placed on fishing nets (Carlström et al., 2009), and non-explosive acoustic harassment devices originally designed to deter pinnipeds (Brandt et al., 2013). Displacement from important habitat can be especially risky for small, localized populations of harbor porpoises, due to the increased stress, reduced foraging success and potential follow-on impacts to their survival and reproduction (Forney et al., 2017).

EASTERN PACIFIC HARBOR PORPOISE DISTRIBUTION AND LIFE HISTORY

Along the west coast of North America, harbor porpoises inhabit temperate, nearshore habitats from Point Conception, California (34° 33'N, 120° 39'W) to Alaska, although fine-scale population structure has been identified through pollutant ratio studies (Calambokidis and Barlow, 1991) and genetic analyses (Chivers et al., 2002, 2007). The limited distribution, non-migratory nature, and small population size of some of these stocks (e.g., Morro Bay, Monterey Bay) make them particularly vulnerable to localized impacts (Forney et al., 2014, 2017). The range of the Monterey Bay harbor porpoise population is primarily confined to water depths less than 200 m (less than 30 km offshore), and extends 100 km from north to south (Forney et al., 2014). Limited information is available on the life history of Monterey Bay harbor porpoises, but they are known to calve during late spring and early summer (May–June; Sekiguchi, 1987). Their diet is seasonally variable, largely consisting of anchovies during spring through fall months, and market squid in winter months (Dorfman, 1990). From 1969 to 2002, the major threat to the Monterey Bay harbor porpoise

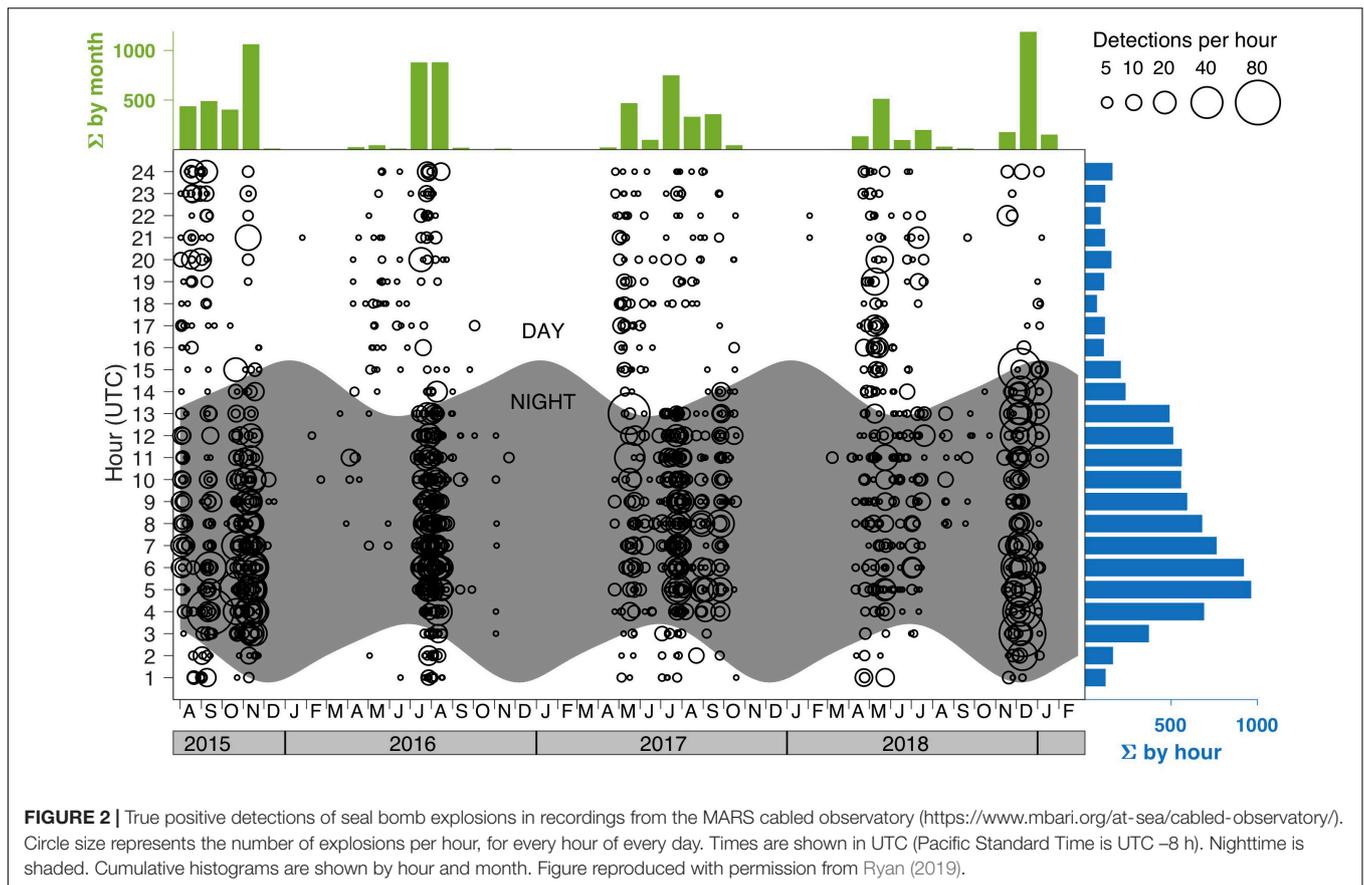
population was bycatch in coastal set gillnet fisheries; a ban on gillnets inshore of 60 fathoms in this region eliminated this threat in 2002 (Barlow and Forney, 1994; Forney et al., 2001, 2014; Carretta et al., 2019). Recently, noise exposure associated with explosive acoustic deterrents used in fisheries has been recognized as a potential threat to cetaceans off California (Wiggins et al., 2019).

SEAL BOMBS IN UNITED STATES WEST COAST FISHERIES

Seal bombs are hand-thrown pyrotechnic devices designed to explode underwater to deter marine mammals during fishery operations. The underwater explosion of a seal bomb with 2.33 g of flash powder has an estimated zero-to-peak source level (SL) of 234 dB re 1 μ Pa at 1 m, and estimated source sound exposure level (SEL) of 203 dB re 1 μ Pa²s at 1 m when integrated over a 100-ms time window, which approximates the integration time of mammalian ears and includes multiple bubble pulses associated with underwater explosions (Madsen, 2005; Tougaard et al., 2015; Wiggins et al., 2019). The frequency content of seal bomb explosions has not been reported in peer-reviewed literature, but examples show broadband energy reaching above 10 kHz, and the majority below 2 kHz (Awbrey and Thomas, 1986; Ryan et al., 2016; Meyer-Loebbecke et al., 2017). Seal bomb impulse pressure is estimated at 208 Pa s, but different manufacturers of seal bombs may use varying amounts (2–6 g) of flash powder which will affect the peak pressure of the explosion (Wiggins et al., 2019). The variation in the composition of seal bombs used in United States West coast fisheries is not known. The described seal bomb explosions may rise above background noise over distances of 10s of km; however, the environment (i.e., temperature profile, bathymetry) has a significant effect on sound propagation (Wiggins et al., 2019).

The primary concerns associated with the use of seal bombs include physical injuries estimated for close ranges (<4 m; Myrick et al., 1990), and auditory injuries and behavioral disturbances at longer ranges (Finneran, 2015; Wiggins et al., 2019). Smaller species of marine mammals are at greater risk for blast injuries (Ketten et al., 2004), and evidence of traumatic injuries to California sea lions (*Zalophus californianus*) from intra-oral explosions has been documented (Kerr and Scorse, 2018). Further, reports of dead fish in the vicinity of seal bomb explosions indicate various taxa may be at risk (National Marine Fisheries Service, 2008).

Research into the effectiveness of deterrents for pinnipeds is ongoing, but there have been few reports on the effectiveness of seal bombs. Multiple experiments have shown seal bombs as unreliable or ineffective deterrents for pinnipeds because animals eventually learn to tolerate the noise, however none of the published studies have been peer-reviewed (Geiger and Jeffries, 1986; Harvey and Mate, 1986; DeAngelis et al., 2008; Brown et al., 2009; Scordino, 2010). More research has been directed toward other acoustic deterrent devices, although there is considerable variation in the perceived effectiveness (Graham et al., 2009; Götz and Janik, 2013, 2015; Benjamins et al., 2018). When animals



are strongly motivated by easily accessible, abundant, high-quality food, habituation to deterrents commonly occurs and depredation will continue unless the animal's motivation can be satisfied by a suitable alternative (Schakner and Blumstein, 2013). However, with few clear options to address depredation, some United States west coast fisheries continue to use seal bombs to deter pinnipeds from their catch (Brown and Santoro, 2019), and may inadvertently be attracting pinnipeds through the “dinner bell effect” (Richardson et al., 2013).

Since 2005, seal bomb explosions have been documented at listening stations along the United States west coast, including Southern California (Meyer-Loebbecke et al., 2016), Monterey Bay (Ryan et al., 2016; Ryan, 2019), the Washington coast and Gulf of Alaska (Wiggins et al., 2017). Seal bomb use within Monterey Bay exhibits seasonal and diel patterns and can be pervasive at certain times, with up to 88 explosions per hour, 335 per day, and 1188 explosions per month (Figure 2) (Ryan, 2019). Monterey Bay has a complex bathymetry, with the continental shelf intersected by a deep submarine canyon. Simple models (e.g., spherical or cylindrical spreading) are not sufficient to estimate acoustic propagation here. We estimated the propagation from seal bomb noise using a physics-based propagation loss model as described in Margolina et al. (2018). Our transmission loss model (TL; Figure 1) is based on an explosion about 1 mile offshore of Davenport, CA (36°59'6.20"N, 122°11'44.53"W) based on the

source characterization in Wiggins et al. (2019), and an average sound speed profile for the month of August, when seal bomb detections were prevalent during 2015–2018 (Figure 2). Seal bomb explosion energy propagates throughout Monterey Bay (Figure 1) in an area of known importance to harbor porpoises (Calambokidis et al., 2015), exposing this restricted population to impacts associated with noise exposure.

POTENTIAL IMPACTS ON HARBOR PORPOISE FROM SEAL BOMBS

Noise-Induced Threshold Shift

Hearing loss from noise, also known as noise-induced threshold shifts (TS), can be temporary (TTS) or permanent (PTS), depending on the ability of the auditory system to recover once the sound has stopped. In marine mammal studies, TTS onset is usually defined as TS of 6 dB or greater measured shortly (1–4 min) after stopping the exposure (Southall et al., 2019). The short duration and high amplitude of impulsive sounds can create a greater risk of direct, mechanical (as opposed to metabolic) damage to the inner ear compared to non-impulsive sounds (Henderson and Hamernick, 1986). The repetition rate of a sound can also influence the magnitude of TTS when hearing does not recover completely within inter-pulse intervals (Finneran and Carder, 2010; Kastelein et al., 2014a). This means

that while a single pulse may not induce TTS, the cumulative effects of repeated exposure may cause TTS. Ideally, the acoustic energy over time, including over multiple exposures (i.e., the cumulative SEL), along with the zero-to-peak SPL, should be used to determine noise exposure – see review in Southall et al. (2019). The onset of PTS in marine mammals has not been documented experimentally; however, based on studies on other mammals, zero-to-peak SPL and SEL criteria estimate PTS onset 6 and 15 dB above the respective TTS-onsets (Henderson and Hamernick, 1986; Southall et al., 2019).

For harbor porpoises, TTS onset has been measured for a variety of impulsive sound sources (Lucke et al., 2009; Kastelein et al., 2012, 2014b, 2015). Exposure limits for TTS at different frequencies show a similar shape to the porpoise audiogram, suggesting broadband SEL alone is not a good predictor for all frequencies and that frequency weighting is necessary to compare TTS thresholds of different sound sources (Tougaard et al., 2015). However, published records of VHF-weighted SELs of seal bombs are lacking. Among the stimuli studied for harbor porpoises, pile driving and seismic airguns are most similar to seal bombs due to their high-intensity, broadband impulses with strong low-frequency components (Hermannsen et al., 2015; Kastelein et al., 2016). Thresholds for TTS and PTS in “Very High-Frequency” odontocetes including harbor porpoises, have been based on studies of these stimuli (Southall et al., 2019).

Using the TTS and PTS thresholds defined by Southall et al. (2019), and the TL model for Monterey Bay (Figure 1), we estimate that harbor porpoises may be exposed to noise levels that cause TTS and PTS at ranges out to 650 and 150 m from the explosion, respectively (Table 1). In our estimates, when considering zero-to-peak SPL thresholds, we use TL at 250 Hz, as the bulk of energy in seal bomb noise is contained below this frequency (Awbrey and Thomas, 1986). When applying time-integrated thresholds, such as SEL, we use TL at 1000 Hz, because

harbor porpoise hearing is more sensitive at higher frequencies (Kastelein et al., 2010). Neither TL model incorporates the time dispersion effects which will dissipate the peak energy of the waveform as it propagates (Urick, 1983), nor do they consider cumulative effects of multiple explosions or multiple sources.

Playback experiments using pile driving and airgun pulses show porpoise hearing loss at low frequencies (4 and 8 kHz; Kastelein et al., 2015, 2017), although experiments with tonal sounds show TTS at increasing frequencies above the exposure frequency as signal SPL increases (Kastelein et al., 2014a). It is unclear how TTS or PTS at low frequencies will impact the ultimate fitness of harbor porpoises, but impacts on their ability to forage, navigate and communicate will likely be negligible because there is no overlap with the high-frequency content of their echolocation clicks and communication signals (115–135 kHz; Clausen et al., 2011). However, whistles produced by North Pacific mammal-eating killer whales (Riesch and Deecke, 2011) fall directly in the range of observed harbor porpoise hearing loss from impulsive noise, which could impact their ability to detect potential predators.

The spatial distribution and rate of seal bomb explosions may be important contributing factors to the risk of noise-induced TS from cumulative sound exposure (Kastelein et al., 2016). Assuming the local TL model for seal bomb noise in Monterey Bay (Figure 1) and an equal energy model [i.e., TTS threshold of a cumulative SEL from multiple exposures is the same as a single-pulse TTS threshold – but see Kastelein et al. (2014a) regarding variation in TTS thresholds for different inter-pulse intervals], one can estimate that a porpoise would experience TTS from exposure to 2 explosions at 1 km, or 6 explosions at 2 km. To date the maximum seal bomb detection rate in Monterey Bay is 88 per hour (Ryan, 2019), which means a porpoise would have to remain within 2 km of the source for about 4 min to suffer TTS. In reality, porpoises will likely start moving away upon hearing

TABLE 1 | Estimated ranges of impacts from seal bomb noise exposure based on received level (RL) metrics reported in the literature and the seal bomb transmission loss (TL) model for Monterey Bay.

	RL Metric	Threshold or Response Level	Seal bomb SL (at 1 m)	250 Hz		1000 Hz		References
				TL (dB)	Max distance (km)	TL (dB)	Max distance (km)	
TTS	p_{0-pk}	196 dB re 1 μ Pa	234 dB re 1 μ Pa	38	0.65			Southall et al., 2019
	SEL	164 dB re 1 μ Pa ² s	203 dB re 1 μ Pa ² s			39	0.3	Lucke et al., 2009
PTS	p_{0-pk}	202 dB re 1 μ Pa	234 dB re 1 μ Pa	32	0.15			Southall et al., 2019
Avoidance	SPL _{RMS}	145 dB re 1 μ Pa ²	226 dB re 1 μ Pa			81	118	Bain and Williams, 2006
	SEL	145–151 dB re 1 μ Pa ² s	203 dB re 1 μ Pa ² s			52–58	2–9	Thompson et al., 2013
	$L_{eq-fast}$ *	130 dB re 1 μ Pa	210 dB re 1 μ Pa			80	116	Tougaard et al., 2015
	SEL	139–152 dB re 1 μ Pa ² s	203 dB re 1 μ Pa ² s			51–64	2–17	Dähne et al., 2013
	SEL	143 dB re 1 μ Pa ² s	203 dB re 1 μ Pa ² s			60	11	Brandt et al., 2018
Reduced foraging	SEL	130–158 dB re 1 μ Pa ² s	203 dB re 1 μ Pa ² s			45–73	1–64	Sarnocińska et al., 2020
	SEL	130 dB re 1 μ Pa ² s	203 dB re 1 μ Pa ² s			73	64	Pirotta et al., 2014

Seal bomb source level (SL) is from Wiggins et al. (2019). Table is arranged so columns represent the order in the equation: $RL = SL - TL$. Thresholds (or Response Levels for behavioral responses) are based on the best available data, are unweighted for VHF hearing, and may change with more research. TL at 250 Hz is used for thresholds based on zero-to-peak SPL (p_{0-pk}) and TL at 1000 Hz is used for time-integrated thresholds such as SEL, SPL_{RMS} and $L_{eq-fast}$. *See Tougaard et al. (2015) for discussion of $L_{eq-fast}$.

the first impulse, and this movement can alter the risk for TTS (Aarts et al., 2016).

Behavioral Response

To date there have been no investigations into the response of harbor porpoises to seal bomb noise, however behavioral response studies on impulsive, low-frequency noise during pile driving associated with windfarm construction (Tougaard et al., 2009, 2015; Dähne et al., 2013; Graham et al., 2019), seismic airguns (Bain and Williams, 2006; Thompson et al., 2013), and other explosions (Von Benda-Beckmann et al., 2015) may provide valuable insight into response levels.

A variety of sound level metrics and behavioral response thresholds have been reported from studies of harbor porpoises exposed to low-frequency, impulsive stimuli (Table 1). While many authors report responses to airgun or pile driving noise at distances >10 km (Bain and Williams, 2006; Carstensen et al., 2006; Tougaard et al., 2009; Dähne et al., 2013; Brandt et al., 2018; Sarnocińska et al., 2020), the environment will significantly impact sound propagation, so here we focus on estimating a maximum response distance based on reported received sound levels. As above, we use the TL model for Monterey Bay (Figure 1) to calculate the maximum ranges at which harbor porpoises could experience levels equal to the response thresholds reported in the literature when the sound source is a single seal bomb explosion. We estimate a potential range of disturbance up to 64 km, but responses at ranges as long as 118 km cannot be excluded (Table 1). The maximum estimated range of response reported here does not consider scenarios of cumulative exposure to multiple explosions, or from multiple sources.

There is considerable variation in the estimated ranges over which Monterey Bay harbor porpoises will respond to seal bomb noise (1–118 km) based on studies of pile driving and airgun noise exposure (Table 1). However, considering the overlap of harbor porpoises with purse seine fisheries within Monterey Bay (California Department of Fish and Wildlife, 2019) and the expected seal bomb noise propagation, it is possible that harbor porpoises are exposed to noise from seal bomb explosions throughout much or all of their preferred habitat (Figure 1). The extent of impacts from noise-induced displacement will depend on displacement duration, quality of alternative habitat, and exposure to other risks such as predators or bycatch (Nabe-Nielsen et al., 2014, 2018).

Harbor porpoises have high-metabolic demands (Kastelein et al., 2018; Rojano-Doñate et al., 2018), so reduced foraging effort due to disturbance or displacement to suboptimal foraging areas for prolonged periods may have negative impacts on their ultimate fitness. Harbor porpoises have been shown to stop foraging due to noise exposure from shipping (Wisniewska et al., 2018) and seismic surveys (Pirodda et al., 2014), and even modest levels of anthropogenic disturbance may have severe consequences for their survival and reproduction if lost feeding opportunities cannot be energetically compensated for (Wisniewska et al., 2016).

Foraging success of harbor porpoises around Denmark is particularly critical in spring and summer to thicken blubber

layers, which support high energy demands from pregnancy and cold temperatures during winter months (Kastelein et al., 2018). In Monterey Bay, harbor porpoises prey on seasonally abundant anchovy and market squid (Dorfman, 1990), thus seal bomb noise from both daytime (anchovy) and nighttime (squid) fishing may be detrimental to foraging success. With large interannual variation in seasonal timing, fishery explosion activity can be elevated between April and December (Figure 2), impacting spring-summer lactation and winter pregnancy periods. Recent bioenergetics-based models, which consider the species' life history and local habitat to assess population consequences of sub-lethal behavioral effects, can guide conservation and management strategies (Nabe-Nielsen et al., 2018).

REDUCING IMPACTS

The potential for injury and other negative impacts of seal bombs was a concern for dolphins in the Eastern Tropical Pacific tuna fishery in the 1980s until their use was outlawed in 1990 (Cassano et al., 1990; Myrick et al., 1990), but the impacts of seal bombs in other fisheries have not been discussed until recently (Götz and Janik, 2013; Meyer-Loebbecke et al., 2016; Ryan, 2019). The Monterey Bay National Marine Sanctuary advisory council has made formal recommendations to increase monitoring of sound over time, to catalog current uses of seal bombs, and to convene collaborative groups of diverse stakeholders with the goal of minimizing seal bomb use and developing effective alternative deterrents (Monterey Bay National Marine Sanctuary Advisory Council, 2017).

Under the Marine Mammal Protection Act, the National Marine Fisheries Service uses quantitative thresholds to consider multiple types of acoustic impacts including: PTS, TTS, and for explosives, direct injuries to lungs and gastrointestinal tracts (National Marine Fisheries Service, 2018). These quantitative thresholds may not encompass important behavioral responses, as there is growing evidence that the energetic costs associated with displacement can be detrimental to cetaceans, particularly for populations with high degrees of site fidelity (e.g., Bejder et al., 2009; Forney et al., 2017; Southall et al., 2019). In a 2015 workshop exploring non-lethal deterrents used in fisheries, there was general agreement that management strategies should be defined based on the most sensitive species in an area (Long et al., 2015). To the best of our knowledge, the most acoustically sensitive marine mammal species that resides year-round in Monterey Bay is the harbor porpoise.

Particularly within the Monterey Bay National Marine Sanctuary, it is imperative that potential harmful side effects of human activities are assessed and either shown to be benign, or modified to ensure other species are not negatively impacted. This is especially important for commercially valuable fisheries that support local communities. As we move toward ecosystem-based management, there is a critical need for collaboration among fishermen, researchers and resource managers to develop, analyze, and implement strategies that protect the ecosystem while supporting the use of natural resources.

AUTHOR CONTRIBUTIONS

AS, KF, SR, JR, JJ, and AD devised the initial plan for a mini-review. TM ran the transmission loss model for a seal bomb explosion in local conditions of Monterey Bay. JR, YZ, AK, and SB-P contributed information on seal bomb detections along the US west coast. AS wrote the first draft of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Conflict of Interest: AS was employed by the company Ocean Associates, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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