Explosive Deterrents "Seal Bombs" in Fisheries and their Effects on Small Cetaceans in Southern California

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List of Abbreviations

ADD	Acoustic deterrent device
AHD	Acoustic harassment device
CPA	Closest point of approach
CPF	Coastal pelagic fish
dB	Decibel
DPD	Detection positive days
DPH	Detection positive hours
DPM	Detection positive minutes
EPD	Explosion positive day
GAM	Generalized additive model
HARP	High-frequency acoustic recording package
HMS	Highly migratory species
Hz	Hertz
kHz	Kilohertz
ms	Millisecond
µPa	Micro-Pascal
PAM	Passive acoustic monitoring
PTS	Permanent threshold shift
PWSD	Pacific white-sided dolphin
rms	Rout-mean-square
RD	Risso's dolphin
SCB	Southern California Bight
SSR	Sea surface reflection
SEL	Sound exposure level
SEL_{cum}	Cumulative sound exposure level
SL	Source level
SPL	Sound pressure level
TL	Transmission loss
TTS	Temporary threshold shift

Summary

In Southern California, commercially produced explosive deterrents, commonly known as “seal bombs”, are used to protect fishing gear and catch from pinniped predation. Common U.S. made seal bombs usually contain about 2.3 g of an explosive flash powder mixture, with a waterproof fuse at one end and weighted with sand or silica at the other end to sink and explode approximately up to 4 m below the water surface. In 1990 their use was banned for the tuna purse-seine fishery where they have been used to catch fish while their general use as a pinniped deterrent is still legal and unregulated. Using passive acoustic monitoring data collected between 2005 and 2016 at 21 sites within the Southern California Bight and near Monterey Bay, it was shown that about 94% of explosions occurred at nighttime and at many nearshore sites high explosion counts were detected, up to 2,800/day. Due to similar spatio-temporal patterns and a strong correlation with market squid landings (*Doryteuthis opalescens*) at many sites, most recorded explosions likely come from seal bombs being used by the California market squid purse-seine fishery. To determine source levels of seal bombs, an experiment offshore off San Diego was conducted in which > 500 seal bombs were deployed and exploded underwater in different distances to a floating hydrophone system resulting in a peak source pressure level of 234 dB re 1 µPa and a sound exposure source level of 203 dB re 1 µPa^{2}s. Taken those values as a basis, a local transmission loss model for seal bombs in Monterey Bay revealed that harbor porpoises (*Phocoena phocoena*) would experience permanent and temporary threshold shifts at ranges out to 150 and 650 m from a seal bomb explosion, respectively. A temporary threshold shift from cumulative exposure of 6 seal bomb explosions was estimated to occur within 2 km range. The passive acoustic monitoring data also revealed that Risso’s dolphins (*Grampus griseus*) were exposed to seal bomb noise for > 30 % of the hours they spent around certain sites, with mean received cumulative sound exposure levels of 160-170 dB 1 µPa^{2}s and thus great potential for hearing damage and other physiological effects. Whereas Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) showed much less overlap and seemed to avoid the noise, at least during times of high noise. Risso’s dolphins prey heavily on squids, sharing the same main target with the fishery using seal bombs, while Pacific white-sided dolphins are more opportunistic feeders, which can explain the different overlap and effects. The results of this dissertation aim to support the implementation of regulations to protect cetaceans and other taxa from being harmed by seal bomb noise.

Zusammenfassung

In Südkalifornien werden kommerziell hergestellte, explosive Vergrämungsmittel, sogenannte „seal bombs“, verwendet, um die Fischereiausrüstung und den Fang vor Fraß durch Robben zu schützen. Übliche, in den USA hergestellte seal bombs bestehen aus 2,3 g eines explosiven Blitzpulvergemisches, mit einer wasserdichten Lunte am einen und Sand bzw. Silica als Gewicht am anderen Ende, damit sie auf bis zu 4 m Wassertiefe sinken und explodieren. 1990 wurde ihr Gebrauch in der Ringwadenfischerei für Thunfische verboten, wo sie genutzt wurden, um zu fischen, wobei ihre Verwendung zur Vergrämung von Robben weiterhin legal ist und gesetzlich nicht reguliert wird. Mithilfe von Daten eines passiv akustischen Monitorings zwischen 2005 und 2016 an 21 Standorten in der Südkalifornischen Bucht und in der Nähe von Monterey Bay konnte gezeigt werden, dass ca. 94 % aller Explosionen nachts stattfanden und dass an vielen küstennahen Stationen hohe Explosionsanzahlen von bis zu 2.800/Tag detektiert wurden. Aufgrund eines ähnlichen räumlich-zeitlichen Vorkommens und einer hohen Korrelation mit Anlandungen von Tintenfischen der Art *Doryteuthis opalescens* an vielen Stationen, stammen die meisten Explosionen wahrscheinlich von seal bombs, die von der kommerziellen Ringwadenfischerei für diese Tiere verwendet werden. Um Quellpegel von seal bombs zu bestimmen, wurde ein Experiment auf See vor der Küste San Diegos durchgeführt, bei dem > 500 seal bombs in verschiedenen Abständen zu einem schwimmenden Hydrophon-System zur Explosion gebracht wurden. Daraus resultierend wurde ein Quellspitzenschalldruckpegel von 234 dB re 1 µPa und ein Quellschallereignispegel von 203 dB re 1 µPa^{2}s ermittelt. Basierend auf diesen Werten, hat ein lokales Transmissionsdämpfungsmodell für Monterey Bay ergeben, dass Schweinswale (*Phocoena phocoena*) eine dauerhafte bzw. temporäre Hörschwellenverschiebung durch seal bombs je in 150 bzw. 650 m erleiden würden. Eine temporäre Hörschwellenverschiebung durch kumulative Belastung von 6 Explosionen wird schätzungsweise in einem Radius von 2 km hervorgerufen. Die Daten des passiv akustischen Monitorings zeigten ebenfalls auf, dass Rundkopfdelfine *(Grampus griseus*) während mehr als 30 % der Stunden, welche sie in der Umgebung bestimmter Stationen verbrachten, Lärm durch seal bombs ausgesetzt waren. Pazifische Weißseitendelfine (*Lagenorhynchus obliquidens*) zeigten hingegen eine geringere Überlappung und schienen den Lärm, zumindest während Zeiten starken Lärms, zu meiden. Rundkopfdelfine ernähren sich vor allem von Tintenfischen, womit sie und

diejenige Fischerei, die seal bombs verwendet, dieselbe Beute haben. Pazifische Weißseitendelfine sind hingegen eher opportunistische Jäger, was die verschiedenen Überlappungen und Effekte erklären kann. Die Ergebnisse dieser Doktorarbeit sollen dazu beitragen, Regularien zu implementieren, um Wale und andere Arten vor Schädigung durch seal bombs zu schützen.

General Introduction

Ambient noise in the marine environment results from both natural and anthropogenic sources. Natural sound is caused by geological or meteorological processes, like earthquakes, rainfall, and waves, or has biological origins, like communicating animals (Hildebrand 2009; Pijanowski et al. 2011). Anthropogenic noise, from shipping, pile-driving, seismic exploration, sonar operations, acoustic deterrents, or explosions has strongly increased in terms of power and pervasiveness and has increased worldwide ocean ambient sound levels within the last century (Richardson et al. 1995). In the Southern California Bight (SCB), which is home to a diverse array of marine species and habitats, low-frequency ship noise has increased average ambient noise levels by about 2–3 dB per decade since the 1960s (Andrew et al. 2002; McDonald et al. 2006). While low-frequency ship noise affects both basin-wide and regional areas, other man-made noise sources, such as naval sonar, acoustic deterrents and explosives, can have strong local impacts on marine life (Hildebrand, 2009).

Effects of noise on cetaceans

In the SCB and surrounding waters, at least thirty species of cetaceans and other marine mammals, like pinnipeds and sea otters, as well as four species of sea turtles can be found (Leatherwood et al. 1982). Especially cetaceans depend on hearing as their primary sensory mode. Odontocetes, or toothed whales, use high-frequency echolocation to orientate as well to track and capture prey, while mysticetes, or baleen whales, use long-range, low-frequency acoustic communication for mating and socializing (Au 2000; Au and Hastings 2008). Negative effects of anthropogenic noise on and the according responses by cetaceans depend on a variety of factors: 1. Sound characteristics, like sound type (e.g., impulsive, or non-impulsive), source and received level, peak frequency and bandwidth and exposure duration, 2. animal characteristics, like species (having different hearing ranges), sex, age, individual experience, physiological state, or motivation (Southall et al. 2007, 2019; Weilgart 2007). Accordingly, responses to noise can be behavioral, acoustic and/or physiological, which can have effects on individual and up to population level (Nowacek et al. 2007).

Behavioral responses include, e.g., displacement, avoidance, or attraction as well as changes in diving, foraging, resting or other behavior (Weilgart 2007). Strong avoidance reactions were found in several baleen and toothed whale species in response to naval sonar, for instance. Within controlled exposure experiments, killer whales (*Orcinus orca*), for example, avoided an area for several hours and responded with a prolonged cessation of feeding and vocal behavior, the strongest reaction was a calf getting separated from its mother in response to sonar (Miller et al. 2012). Within a similar experimental setup, a minke (*Balaenoptera acutorostrata*) and a bottlenose whale (*Hyperoodon ampullatus*) responded with high-speed, long-term area avoidance and cessation of feeding (Sivle et al. 2015). Blue whales (*Balaenoptera musculus*) responded with cessation of feeding in high depths or increased swimming speed to mid-frequency military sonar (Goldbogen et al. 2013). DeRuiter et al. (2013) showed that Cuvier's beaked whales (*Ziphius cavirostris*) swam rapidly away and prolonged dive duration also in response to sonar. Strong, temporary avoidance reactions were also observed in harbor porpoises (*Phocoena phocoena*) during impulsive pile-driving as part of the construction phase of several offshore wind farms in the North Sea. Dähne et al. (2013) reported avoidance in up to 10 km and more in the first German offshore wind farm "alpha ventus". Benhemma-Le Gall et al. (2021) detected porpoise avoidance in up to 12 km distance in response to pile-driving and in up to 4 km in response to construction vessel noise at two Scottish offshore wind farms. Wisniewska et al. (2018) reported bottom diving and interrupted foraging behavior leading to fewer prey capture attempts of harbor porpoises in response to high vessel noise. The cost of these avoidance and behavioral reactions resulting in lower intake of prey and energetic loss due to enhanced swim speed or change of diving behavior, may, if they occur often enough, have significant effects on health and fitness of individuals and populations (New et al. 2013).

Acoustic responses include changes in amplitude, frequency, duration, or timing of vocalizations to account for masking of biologically important sounds by noise (Tyack and Janik 2013). Blue whales, for instance, were found to consistently call more often during days with seismic exploration, presumably to compensate for elevated ambient noise levels (Di Iorio and Clark 2009). North and South Atlantic right whales (*Eubalaena glacialis* and *australis*) produce calls with a higher frequency and at lower rates in response to masking from low-frequency ship noise (Parks and Clark2007), even on a long-term basis. Also, bottlenose dolphins (*Tursiops truncatus*) adjust frequencies of their whistles in response to vessel and other noise (Papale et al. 2015; Gospi´c and Picciulin 2016; Ginkel et al. 2017). Increasing the amplitude or intensity of vocalizations is known as Lombard effect (Zollinger and Brumm 2011) and has been described for different cetacean species. Using passive acoustics, humpback whales (*Megapetra novaeangliae*) were shown to increase source levels (SL) of their songs by 0.5 dB per 1 dB increase in background noise levels (Guazzo et al. 2020), while others found higher increases of 0.9 dB per 1 dB increase of noise (Dunlop et al. 2014). The same was found for killer whales (Holt and Noren 2009), minke whales (Helble et al. 2020), right whales (Parks et al. 2011) and bowhead whales (*Balaena mysticetus*) (Thode et al. 2020), for example. The costs of such vocal compensation mechanisms are difficult to estimate, but could include energetic costs for increasing vocal intensity, degraded communication among animals or stress (Holt et al. 2015).

Physiological responses include, e.g., tissue damage, hearing damage, like temporary or permanent shifts of auditory thresholds (TTS and PTS), releases of stress hormones and changes in metabolism, heart and respiration rates (Nowacek et al. 2007). Most studies on physiological effects are limited to hearing studies conducted with small odontocetes in captivity. In harbor porpoises, e.g., TTS was observed after a single air gun pulse with a sound exposure level (SEL) of 164 dB dB re 1µPa^{2}s with recovery after approximately 55 hours (Lucke et al. 2009). Repetitive exposure to playbacks of pile-driving strikes (> 2,700 strikes/h) with single strike SELs of ~145 dB re 1µPa^{2}s also resulted in TTS of a harbor porpoise, pointing out the effect of exposure duration (Kastelein et al. 2016). Belugas and bottlenose dolphins experienced TTS in response to playbacks of mid-frequency active sonar (Mooney et al. 2009; Schlundt et al. 2000). Naval sonar has been shown to be lethal for several species, especially beaked whales, as they can lead to mass strandings (e.g., Balcomb and Claridge 2001). The most extreme source of noise are detonations, which can lead to internal bleeding, embolism, disruption of tissues and cells and hearing damage, even at greater distances depending on charge weight (Koschinski 2012). In 2019, mines from World War II were cleared by blasting by the military within a marine protected area in Germany with 24 harbor porpoises found dead afterwards, multiple of them with blast injuries as cause of death (Siebert et al. 2022). Physiological responses to noise other than hearing damage are not well documented for marine mammals. A beluga whale (*Delphinapterus leucas*) showed a neural-immune response, with enhanced levels of stress hormones, such as dopamine, norepinephrine and epinephrine, after suffering from a TTS due to seismic air gun noise (Romano et al. 2004), while killer whales respiration rate changed in response to shipping noise (Williams et al. 2014). In another study, a beluga exhibited increased heart rate due to exposure to mid-frequency sonar (Lyamin et al. 2011) and right whales were shown to have increased levels of stress-related hormone metabolites when exposed to ship noise (Rolland et al. 2012).

If noise levels are high or duration of exposure is prolonged, effects are mostly a combination of the described responses, which is important to consider for assessing full impact, as well as cumulative effects caused by multiple stressors in the marine environment.

Effects of noise on other marine taxa

Besides cetaceans, noise represents a serious threat for other marine animals as well and effects have been described for taxa up and down the food chain, from pinnipeds to different fish species as well as invertebrates, from cephalopods to zooplankton. Although other taxa are not the focus of this dissertation, a summary with some examples of the variety of responses to noise is given in the following. TTS in response to simulated pile-driving noise was experienced by harbor seals (*Phoca vitulina*), but only after prolonged exposure (Kastelein et al. 2018). During pile-driving at an offshore windfarm in England they showed strong avoidance, with a decrease in abundance of 20-80 % in up to 25 km distance (Russel et al. 2016). However, recovery in both studies occurred quickly. Caged green (*Chelonia mydas*) and loggerhead sea turtles (*Caretta caretta*) displayed an alarm response in about 2 km and avoidance reactions in about 1 km distance to an approaching air-gun (McCauley et al. 2000). However, studies on effects of noise on sea turtles are rare (Popper et al. 2014). Teleost fish don’t have an outer or middle ear, but an inner ear with main hearing through the otolith end organs, receiving both particle motion and acoustic pressure when close to gas-filled structures, like the swim bladder (Popper and Fay 2011). E.g., pink snapper (*Pagrus auratus*) suffered from long-term physical damage of the sensory cells of the inner ear due to air gun noise (McCauley et al. 2003). However, effects of noise are highly variable depending on species. Pile-driving can lead to stress responses, like enhanced oxygen uptake in juvenile European seabass (*Dicentrarchus labrax*; Spiga et al. 2017), or even severe barotrauma after prolonged exposure in striped bass (*Morone saxatilis*; Casper et al. 2013).

Most invertebrates “hear” by detecting the particle motion component of a sound field through the sensory organs’ statocysts (André et al. 2016). Studies have shown that anthropogenic noise can physically harm and change the behavior of squid. In Jones et al. (2020) longfin inshore squids (*Doryteuthis pealeii*) showed increased alarm responses such as escape and firing ink sacs in response to noise. Near seismic surveys, strandings of *Architeuthis dux* (giant squid) have been reported (Guerra et al. 2004) and Solé et al. (2013) described statocyst lesions in four squid species from the Mediterranean after exposure to low-frequency noise (*Sepia officinalis*, *O. vulgaris*, *Loligo vulgaris* and *Illex condietii*). Blue mussels (*Mytilus edulis*) increased clearance rates in response to pile-driving noise, which was interpretated as a stress response (Spiga et al. 2016). Palinurid rock lobsters (*Jasus edwardsii*) showed impaired righting reflexes and damage to the sensory hairs of the statocyst after exposure to air-gun noise; recovery did not occur after one year (Day et al. 2019). McCauley et al. (2017) showed that the abundance of zooplankton in Australian waters decreased by 50 % in response to simulated air-gun noise in up to 1.2 km distance, with negative effects mainly for small copepods.

Acoustic deterrents in fisheries

Sources of noise have changed little within the last decades, but noise from pile-driving of offshore wind farms as well novel acoustic deterrent (ADD) and harassment devices (AHD) represent a noteworthy addition (Nowacek et al. 2007). Noise-generating ADD and AHD are used within fisheries and aquaculture to minimize interactions with marine mammals that prey on the catch or stock, damage fishing gear or become fatally entangled in nets as by-catch (Jefferson and Curry 1996; Shapiro et al. 2009; Schakner and Blumstein 2013). They are also used for mitigation purposes, e.g., to deter marine mammals outside a zone of potential hearing damage prior to pile-driving or detonations (e.g., Dähne et al. 2017; McGarry et al. 2020). These high-frequency acoustic alarms are mainly differentiated by source level with ADD, like pingers, having lower (<150 dB re 1 µPa) and AHD, like seal scarer, with higher power (> 180 dB re 1 µPa) (Dawson et al. 2013). While pingers are often deployed on passive fishing gear such as gill or drift nets to prevent cetacean by-catch, seal scarers are classically used to keep pinnipeds away from static structures such as fish farms, for instance (Nowacek et al. 2007; Dawson et al. 2013).

Despite their positive effects to reduce by-catch for several cetacean species (Barlow and Cameron 2003; Dawson et al. 2013; Mangel et al. 2013), they also have been shown to cause habituation (Cox et al. 2001) or "dinner bell" effects (Carretta and Barlow 2011) in some cases, large-scale noise exposure, and habitat exclusion for target and non-target species (Götz and Janik 2013). Even TTS may be induced by deterrents, which has been shown for harbor porpoises and seal scarers (Schaffeld et al. 2019; Findlay et al. 2021). Especially AHD have the potential to cause marine mammal displacement over distances of multiple kilometers and far beyond the intended or needed deterrence distance. Strong avoidance reactions in response to seal scarers have been shown for harbor porpoises being deterred in varying degree, but up to 12 km distance (Brandt et al. 2013; Mikkelsen et al. 2017; Dähne et al. 2017). Permanent or repeated exclusion of animals from critical habitat and the corresponding costs are therefore of great concern when it comes to the use of acoustic deterrents, which need to be carefully weighed against potential benefits.

Seal bombs and other explosive deterrents

A special case of AHD used in fisheries is the use of small charges of explosives. Two main types of explosive deterrents can be differentiated: so-called **cracker shells** and **seal bombs** or seal control devices. Cracker shells, which are fired from a pistol and detonate in air or at the water surface, usually produce less energy than seal bombs (Awbrey and Thomas 1987). The more commonly used seal bombs consist of 2–6 g (depending on type and fabrication origin) of explosive flash powder mixture (mostly with potassium perchlorate as an oxidizer, pyro-aluminum powder and sulfur fuel as a fire starter) in a sealed cardboard tube. Fitted to the tube is an 8-second waterproof fuse at one end. The tube is weighted with sand or silica at the other end so that it will sink and explode approximately 1–4 m below the water surface. Common U.S. made seal bombs usually contain about 2.3 g explosive charge mixture and are similar to M-80 firecrackers (Myrick et al. 1990a).

Both types of explosive deterrents have been used in California fisheries, an important sector of Southern California's economy, to keep pinnipeds, like California sea lions (*Zalophus californianus*) and Pacific harbor seals (*Phoca vitulina richardsii*; Beeson and Hanan 1996; Scordino 2010) away from fishing activities. Recently, they have also been used in combination with vessel hazing to prevent California and Steller sea lions

(*Eumetopias jubatus*) from feeding on endangered salmon species in the Colombia River (Brown et al. 2008, 2013). Most studies or reports, which describe the effectiveness of explosives as deterrents, have low data coverage, are solely based on interviews with fishermen and/or are non-peer reviewed. As an overall result, explosive deterrents appeared effective initially, but to be ineffective in the long-term. Pinnipeds were deterred for at least a short period of time, but it was common for habituation to occur and pinnipeds learned to avoid or tolerate the noise (e.g., Geiger and Jeffries 1987; Scholl and Hanan 1987; Brown et al. 2013). They were also ineffective in keeping cetacean species away from fishing activities or preventing entanglement of killer whales (Dahlheim 1988) and harbor porpoises (Hall et al. 2002). However, studies on explosive deterrents as a noise pollutant or on their behavioral and physiological effects on marine mammals are either absent or very scares.

Seal bombs have been used in the yellowfin tuna purse-seine fishery since at least the 1970s to catch schooling fish, and since the 1980s to control the swimming behavior of dolphins and catch the tuna following them (so called "porpoise fishing"). Cassano et al. (1990) reported no significant effect of seal bomb use on dolphin mortality during this type of procedure, but Myrick et al. (1990b) tested a variety of seal bombs and determined, based on extrapolated impulse pressures and tests with dolphin carcasses, that seal bombs can cause severe to moderate injury (tissue damage) to dolphins when detonated within a 0–4 m distance. Due to these potentially adverse effects, a complete ban of seal bombs for the tuna purse-seine fishery was declared in March 1990 (55 Federal Register 11588), while their general use as a pinniped deterrent is still legal. Kerr & Scorse (2018) described the lethal injuries of two sea lions that were found by staff of the Marine Mammal Center in Monterey Bay, which were most likely caused by seal bombs, questioning their legal use.

The issue of seal bombs as a potential threat for marine wildlife has been largely overlooked since their ban from the tuna fishery, until Baumann-Pickering et al. (2013) published a first report on very high numbers of explosions recorded via passive acoustic monitoring (PAM) in the SCB, pointing out the connection to purse-seine fisheries. Afterwards, the issue moved back into the focus of scientists, journalists, and authorities in California. This dissertation has its origin within the above-mentioned report and aims to fill into a broad knowledge gap on the current use of seal bombs in fisheries as well as their effects on cetaceans in Southern California by using PAM.

Passive acoustic monitoring

The disadvantages of traditional visual observations from ships or airplanes of cetaceans are that they only represent a snapshot in time and can only be conducted during daylight hours and relatively good weather conditions. Cetaceans spend most of their time underwater and can only be observed once they are close to the surface. The results are therefore often highly variable (Mellinger et al. 2007). Acoustic monitoring, however, does not have these restrictions, but is sometimes more limited in terms of spatial coverage, while detection radii depending on species-specific features of the produced sounds, e.g., frequency bandwidth, SL, directionality, or the vocal behavior of the animal (Mellinger et al. 2007, Zimmer 2011). Additionally, information on some specific behaviors, on exact group size or the presence of calves can often not be obtained. Within the last decade though, considerable progress in estimating abundance, densities, or population size of cetaceans by the means of acoustic monitoring has been made (Marques et al. 2013; Amundin et al. 2022).

Acoustic monitoring can be either active or passive. During active acoustics sound is transmitted while information is drawn from the returning echo, which is often used, e.g., for analysis on densities and distribution of zooplankton, fish, or the deep scattering layer (Mellinger et al. 2007). Active acoustic methods have also been used to detect cetaceans and analyze their occurrence in connection to prey fields (Benoit-Bird et al. 2019). More commonly used for cetacean research are passive acoustics capturing all kinds of sounds from the surrounding environment. PAM can either happen by the means of mobile or static acoustic sensors. In the first case hydrophones have been fixed to gliders, are towed from ships, are floating (e.g., sonobuoys) or are integrated into tags, e.g., DTAGs which can record movement and diving patterns as well as acoustics signals (Johnson and Tyack 2003; Klinck et al. 2015; Todd et al. 2015). Mobile methods have the advantage that they can cover larger areas and can be more easily combined with visual observations or behavioral data. During static PAM, autonomous recorders, like High-frequency acoustic recording packages (HARPs; Wiggins and Hildebrand 2007, 2016) used for this dissertation, are left in place and moored to the seafloor, with the actual sensor deployed a few meters above the seafloor using cables or ropes and buoys. The advantage here is that recording can span over much longer time spans, e.g., multiple months or sometimes even a year at a time, also in remote places, like far offshore, in the deep-sea or in polar regions, and that this method is quite cost-effective (Mellinger et al. 2007; Todd et al. 2015; Zimmer 2011). Additionally, they are non-invasive and there is little interference with the animal’s natural behavior (Zimmer 2011). Depending on storage capacity and sampling duration recording can either be continuous or duty-cycled, with pre-defined on and off periods.

Static PAM is widely used with more than 40 different instrument types of fixed autonomous acoustic recording devices in use for marine mammal research worldwide (Sousa-Lima et al. 2013). Data from static PAM can be used for a wide range of different purposes; to analyze diel patterns, seasonal occurrence or distribution ranges of species, spectral features of calls, whistles, and clicks, to estimate the abundance of species, analyze behaviors (e.g., by detection of feeding buzzes or mating calls) or to track animals by using hydrophone arrays or multi-channel hydrophones and using time-of-arrival differences for localization (Mellinger et al. 2007; Zimmer 2011). It is also essential for analyzing effects of underwater noise on cetaceans (Todd et al. 2015; Zimmer 2011), especially behavioral and acoustic responses, with the advantage that noise types and levels as well as cetacean reactions (e.g., decreased acoustic activity) can be recorded by the same instrument. Sometimes, unexpected findings are discovered within recordings, which was the case with the high numbers of explosions, the subject of this dissertation, recorded by HARPs in Southern California, which were originally deployed to monitor occurrence of cetaceans and effects of navy sonar.

Aims of Chapters

Chapter 1

To develop and evaluate sustainable management and mitigation measures for the protection of the marine environment and to assess impacts on different taxa and species, detailed information on the origin, extent and occurrence of a potential threat needs to be determined. Chapter 1 therefore aims to provide detailed insights into (1) the spatio-temporal occurrence, distribution, counts and sound exposure levels (SELs); (2) long-term trends; and (3) the origin of underwater explosions, recorded at

21 long-term passive acoustic monitoring (PAM) sites distributed throughout two important commercial fishing areas, the Southern California Bight (SCB) and Monterey Bay, California, United States of America. We hypothesized that most underwater explosions originate from seal bombs used within purse-seine fisheries (Baumann-Pickering et al. 2013). To test this hypothesis, we compared and investigated potential similarities in spatial and temporal patterns as well as correlation of recorded explosions and reported landings and receipts of three major commercial purse-seine fleets in California for (1) market squid, (2) coastal pelagic fish (4 species) and (3) highly migratory species (5 species).

The results of chapter 1 are presented in a published paper “Long-term patterns of noise from underwater explosions and their relation to fisheries in Southern California” (Krumpel et al. 2021).

Chapter 2

Infliction of hearing damage, such as temporary (TTS) or permanent threshold shift (PTS), and behavioral responses especially of protected marine mammals (e.g., Southall et al. 2007, 2019) are primary concerns with the use of seal bombs. To successfully manage and mitigate noise effects of seal bombs, providing the corresponding acoustical metrics are of great importance. Therefore, chapter 2 aims to provide (1) seal bomb sound source (source level, SEL etc.) and (2) propagation characterization. To determine these metrics an experiment offshore of San Diego, CA, USA was conducted, in which seal bombs were deployed and exploded underwater in different distances to a floating hydrophone system. The results were also used for comparison with TTS/PTS thresholds of different marine mammal hearing groups (NMFS, 2018).

The results of chapter 2 are presented in a published paper “Seal bomb explosion sound source characterization” (Wiggins et al. 2021).

Chapter 3

Harbor porpoises have been shown to be particularly sensitive to anthropogenic noise (Dähne et al. 2013; Wisiniewska et al. 2018 etc.) and their TTS threshold has been measured for different impulse sounds (e.g., Lucke et al. 2009; Kastelein et al. 2016). The harbor porpoise stock in Monterey Bay might be particularly vulnerable to local impacts as it is limited in distribution, is non-migratory and the population is small

(Forney et al. 2017). Monterey Bay is an important fishing area, where seal bomb use has been shown (Ryan 2019; Krumpel et al. 2021). Therefore, chapter 3 aims to assess potential impacts of seal bomb noise on harbor porpoises by (1) reviewing anthropogenic noise effects on harbor porpoises, (2) estimating seal bomb noise propagation in Monterey Bay via a local transmission loss model and (3) calculating distances for PTS and TTS onsets and behavioral responses of harbor porpoise in reaction to seal bomb noise based on results from the experiment described in chapter 2.

The results of chapter 3 are presented in a published review paper "Seal bomb noise as a potential threat to Monterey Bay harbor porpoise" (Simonis et al. 2020).

Chapter 4

Responses to anthropogenic noise by cetaceans depend on a variety of factors; one of them is the motivation of an animal to be in a certain area exposed to noise e.g., for feeding, mating, socializing, migrating, or resting (Weilgart 2007). In chapter 1, seal bomb explosions have been shown to mostly occur at night, a time when various cetacean species focus their foraging effort, in the SCB e.g., Risso's and Pacific white-sided dolphins (Soldevilla et al. 2010a, b). Chapter 4 aims to describe (1) the general acoustic activity and diel patterns of the two dolphin species throughout the SCB, (2) investigate if areas of seal bomb use and fisheries overlap with dolphin foraging habitat and (3) assess the extent of noise exposure and (4) effects of seal bomb noise on their acoustic behavior. Risso's dolphins feed heavily on squid (e.g., Cockcraft et al. 1993), in the SCB especially on market and jumbo squid, while Pacific white-sided dolphins are more opportunistic feeders (e.g., Stroud et al. 1981). Therefore, we hypothesized that habitat overlap is more pronounced for Risso's dolphins and effects of seal bomb noise differ between the two species, because Risso's dolphins might not leave a crucial foraging area. To test these hypotheses, we compared the occurrence of dolphins, seal bombs and market squid landings as well as the influence of explosions counts and cumulative SEL on dolphin acoustic activity at 12 PAM sites within the SCB.
The results of chapter 4 are presented in a manuscript "Opposite effects of seal bomb noise on two dolphin species in Southern California", which is prepared for submission (Krumpel et al., in prep.).

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Chapter 1: Long-term Patterns of Noise from Underwater Explosions and their Relation to Fisheries in Southern California

This paper was published in Frontiers in Marine Science (section Marine Conservation and Sustainability) in 2021. The study was designed by my advisor Dr. Simone Baumann-Pickering and me. I was responsible for signal detection of explosions, data analysis and interpretation. I also wrote the manuscript. Signal detection was also carried out by Jennifer Trickey and other lab members prior to the beginning of my PhD. Dr. Simone Baumann-Pickering designed the automated explosion detector. Computation for extracting signal characteristics was conducted by Dr. Kaitlin Frasier, Fairlie Reese (as part of her summer internship, that I supervised) and me.

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Long-Term Patterns of Noise From Underwater Explosions and Their Relation to Fisheries in Southern California

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Acoustic deterrents can reduce marine mammal interactions with fisheries and aquacultures, but they contribute to an increasing level of underwater noise. In Southern California, commercially produced explosive deterrents, commonly known as "seal bombs," are used to protect fishing gear and catch from pinniped predation, which can cause extensive economic losses for the fishing community. Passive acoustic monitoring data collected between 2005 and 2016 at multiple sites within the Southern California Bight and near Monterey Bay revealed high numbers of these small-charge underwater explosions, long-term, spatio-temporal patterns in their occurrence, and their relation to different commercial purse-seine fishing sectors. The vast majority of explosions occurred at nighttime and at many nearshore sites high explosion counts were detected, up to 2,800/day. Received sound exposure levels of up to 189 dB re 1 μPa^2-s indicate the potential for negative effects on marine life, especially in combination with the persistence of recurring explosions during periods of peak occurrence. Due to the highly significant correlation and similar spatio-temporal patterns of market squid landings and explosion occurrence at many sites, we conclude that the majority of the recorded explosions come from seal bombs being used by the California market squid purse-seine fishery. Additionally, seal bomb use declined over the years of the study, potentially due to a combination of reduced availability of market squid driven by warm water events in California and regulation enforcement. This study is the first to provide results on the distribution and origin of underwater explosions off Southern California, but there is a substantial need for further research on seal bomb use in more recent years and their effects on marine life, as well as for establishing environmental regulations on their use as a deterrent.

Keywords: underwater explosions, seal bombs, acoustic deterrence, purse-seine fisheries, market squid, Southern California (United States)

INTRODUCTION

The increased occurrence, power, and pervasiveness of anthropogenic noise sources in the ocean has increased ambient sound levels (Richardson et al., 1995; Hildebrand, 2009). Low-frequency ship noise has increased average ambient noise levels recorded in the Southern California Bight by about 2–3 dB per decade since the 1960s (Andrew et al., 2002; McDonald et al., 2006; Haren, 2007). While low-frequency ship noise affects both basin-wide and regional areas, other underwater noise sources, such as sonar, acoustic deterrents and explosives, can have strong local impacts on marine life (Hildebrand, 2009). It is important to determine acoustic impacts of all potentially harmful noise sources, to support well-informed and sustainable management decisions and mitigation policies for the marine environment.

Within fisheries and aquaculture, noise-generating acoustic deterrents are used to minimize interactions with marine mammals that prey on the catch or stock, damage fishing gear or become fatally entangled in nets as bycatch, and cause extensive economic losses for the fishing industry (Jefferson and Curry, 1996; Shapiro et al., 2009; Schakner and Blumstein, 2013). However, acoustic deterrents also have been shown to cause habituation or "dinner bell" effects, large-scale noise exposure, and potential habitat exclusion for target and non-target species (Götz and Janik, 2013). Commercial fisheries are an important sector of Southern California's economy and there is potential for adverse effects from interactions with the area's two most abundant pinniped species: California sea lions (*Zalophus californianus*) and Pacific harbor seals (*Phoca vitulina richardsii*; Beeson and Hanan, 1996; Scordino, 2010). A variety of deterrents have been used to keep these species away from fishing operations and areas.

One type of deterrent uses small charges of chemical explosives. Common types of explosive deterrents are cracker shells and seal bombs. Cracker shells, which are fired from a pistol and detonate in air or at the water surface, usually produce less energy than seal bombs (Awbrey and Thomas, 1987). More commonly used are seal bombs, or seal control devices, which consist of 2–6 g (depending on type and fabrication origin) of explosive flash powder mixture (mostly with potassium perchlorate as an oxidizer, pyro-aluminum powder and sulfur fuel as a fire starter) in a sealed cardboard tube. Fitted to the tube is an 8-s waterproof fuse at one end. The tube is weighted with sand or silica at the other end so that it will sink and explode approximately 1–4 m below the water surface (Myrick et al., 1990a). Common United States made seal bombs usually contain about 2.3 g explosive charge mixture and are similar to M-80 firecrackers. They are assumed to produce at least 80% of the pressure of an equivalent charge of Trinitrotoluene (TNT; Myrick et al., 1990a). In general, explosions are relatively broadband in frequency, with most sound energy in the low-frequency range of <1 kHz. Awbrey and Thomas (1987) reported seal bombs to produce a flash of light and a 30 ms impulse resulting in sound exposure levels of 190 dB re 1 μPa^2-s @ 1 m. Wiggins et al. (2021) recently conducted a field experiment with seal bombs and calculated a peak source pressure level of 234 dB re 1 μPa m and a sound exposure source level of 203 dB re 1 μPa^2 m^2 s over a 100 ms window.

Seal bomb use in fisheries seems to be mostly concentrated along the North American west coast (this study; Ryan et al., 2016; Wiggins et al., 2017; Simonis et al., 2020). Few studies or even brief references on their use in other areas exist [South Africa: Shaughnessy et al. (1981), Tasmania: Pemberton and Shaughnessy (1993), New-Zealand: Visser (2000) and Kemper et al. (2003)]. Within United States fisheries, the limited amount of published studies referring to seal bombs show that they have been used in a variety of different fishing sectors, including the king mackerel troll fishery (Zollett and Read, 2006), yellowfin tuna (*Thunnus albacares*) purse-seine fishery (Cassano et al., 1990), various salmon fisheries, and the steelhead trout fishery (Jefferson and Curry, 1996). Seal bombs have been used in the yellowfin tuna purse-seine fishery since at least the 1970s to catch schooling fish, and since the 1980s to control the swimming behavior of dolphins and catch the tuna following them (so called "porpoise fishing"). Cassano et al. (1990) reported no significant effect of seal bomb use on dolphin mortality during this type of procedure, but Myrick et al. (1990b) tested a variety of seal bombs and determined, based on extrapolated impulse pressures and tests with dolphin carcasses, that seal bombs can cause severe to moderate injury (tissue damage) to dolphins when detonated within a 0–4 m distance. A human swimmer was accidentally killed by a similar device when it was detonated 0.3 m away (Hirsch and Ommaya, 1972). Kerr and Scorse (2018) described the lethal injuries of two sea lions that were found by staff of the Marine Mammal Center in Monterey Bay, which were most likely caused by seal bombs. Additionally, a recent review on seal bombs pointed out the potential threat they pose to Monterey Bay harbor porpoises regarding not only hearing damage but also behavioral effects like displacement or disturbance which possibly result in reduced foraging effort and success (Simonis et al., 2020).

Due to these adverse effects, a complete ban of seal bombs for the tuna purse-seine fishery was declared in March 1990 (55 Federal Register 11588) and in 1995 NOAA proposed to prohibit the selective use of seal bombs for deterring cetaceans, but not pinnipeds (NOAA, 1995). The Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) has enforced the regulations of the Safe Explosives Act on seal bombs and similar pest control devices since May 2011. As a reaction to this law enforcement, groups such as the Alaska Trollers Association, which represents salmon fishermen in Southeast Alaska, called out for an exemption for the commercial fishing community because seal bombs were an important tool for fishermen and represented the most effective, non-lethal deterrent for sea lions (Alaska Trollers Association, 2012). However, while explosive deterrents appear effective initially, scientific studies have shown them to be ineffective in the long-term. While pinnipeds were sometimes deterred for at least a short period of time, it was common for habituation to occur and the pinnipeds learned to avoid or tolerate the noise [seals and sea lions: Geiger and Jeffries (1987), Scholl and Hanan (1987), South African fur seals: Shaughnessy et al. (1981), and Australian fur seals: Pemberton and Shaughnessy (1993)]. Seal bombs were also ineffective at keeping cetacean species away from fishing activities or preventing entanglement for killer whales (Dahlheim, 1988) and harbor porpoises (Hall et al., 2002). More recent pinniped deterrence programs, to prevent sea lions from feeding on endangered salmon species, included a combination of vessel hazing and explosives (Brown et al., 2008, 2013). Jefferson and Curry (1996) provide a review summarizing the effectiveness of explosive and other harassment devices. For most of these studies, the underlying data came from interviews with fishermen or data coverage was low. However, the overall conclusion was that explosives are not very helpful for deterring pinnipeds or increasing catch success.

Since the 1990s the issue of seal bombs has been largely overlooked. When explosions have been discussed in the literature, the focus has been on explosions with a much higher charge weight (several kilograms) compared to that of explosive deterrents (a few grams; Hubbs and Rechnitzer, 1952; Saila et al., 1993; Todd et al., 1996; Finneran et al., 2000; Fox et al., 2003; Woodman et al., 2003; Fox and Caldwell, 2006; Govoni et al., 2008; Viada et al., 2008; Dos Santos et al., 2010; Koschinski, 2012; Buckstaff et al., 2013). But with increasing awareness of the impact of anthropogenic sounds on marine life (Popper and Hawkins, 2012; Shannon et al., 2015; Williams et al., 2015), seal bombs have more recently moved back into scientific and public focus (e.g., Baumann-Pickering et al., 2013; Kerr and Scorse, 2018; Simonis et al., 2020). In August 2020, NOAA officially proposed Guidelines for Safely Deterring Marine Mammals (NOAA, 2020) which regulate the use of seal bombs as marine mammal deterrents (these guidelines don't have jurisdiction if seal bombs are being used for other fishing practices besides deterrence). However, no long-term studies on the spatio-temporal distribution of seal bomb use in fisheries or their large-scale contribution to noise pollution in the marine environment have been conducted. To provide insight on the use of seal bombs in fisheries, we evaluated long-term passive acoustic monitoring (PAM) recordings from 2005 to 2016 offshore of California, an area of extraordinary importance for commercial fisheries. The aims of this study were to: (1) investigate the spatio-temporal occurrence, distribution, counts and received sound exposure levels of recorded seal bomb explosions within two important commercial fishing areas, the Southern California Bight and Monterey Bay; (2) analyze long-term trends of explosion occurrence and compare the past and recent state of seal bomb use; (3) assess if and how timing and locations of commercial fishery landings from economically important purse-seine fishing sectors and the occurrence of recorded explosions correlate on different temporal scales.

MATERIALS AND METHODS

Acoustic Recordings

Between 2005 and 2016, autonomous High-Frequency Acoustic Recording Packages (HARPs; Wiggins and Hildebrand, 2007) collected long-term passive acoustic data at 20 different sites offshore of California: 19 within the Southern California Bight and one close to the Monterey Bay area (**Figure 1**). Additionally, acoustic data were recorded between 2015 and 2016 at the MARS (Monterey Accelerated Research System) cabled observatory in Monterey Bay (Ryan et al., 2016). Recorders were all bottom-moored at average seafloor depths between 260 and 1,380 m (**Supplementary Table 1**).

High-frequency acoustic recording packages are calibrated acoustic recording instruments that have a hydrophone suspended 10 m above the seafloor, are capable of continuous recording up to 160 kHz and are usually deployed for several months up to a year (Wiggins and Hildebrand, 2007, 2016). For this study, HARPs were all set to a sampling frequency of either 200 or 320 kHz with 16-bit quantization (effective bandwidth 10 Hz to 100 or 160 kHz, respectively). Each HARP was equipped with a two-stage hydrophone to cover the broad frequency range. The low-frequency stage (10 Hz to 2 kHz or 25 kHz) was comprised of a bundle of six cylindrical elements (AQ-1, Teledyne Benthos Inc., North Falmouth, MA, United States), while the high-frequency stage (2 or 25 to 100 kHz) used a single spherical element (typically ITC-1042, International Transducer Corporation, Santa Barbara, CA, United States). These sensors were connected to a custom-built preamplifier and low-pass filter circuit board (see Wiggins and Hildebrand, 2007). The calibrated system response was applied to the recordings during data analysis. The MARS cabled observatory was equipped with an icListen Smart hydrophone (Ocean Sonics Ltd., Great Village, NS, Canada), used a sampling frequency of 256 kHz (effective bandwidth 10 Hz–128 kHz) and 24-bit quantization. The manufacturer provided hydrophone calibration.

Individual deployment durations varied from a few weeks to several months while recording schedules were either continuous (87.5% of 208 analyzed deployments in total) or duty cycled (26 deployments, with 5 min of recordings occurring at 7–25 min intervals; **Figure 2**). To prevent overestimation of explosion counts, we decided on a conservative estimation of explosion counts for statistical analyses by not correcting for differences in duty cycles using a linear normalization scheme because explosions are individual events and are not continuous over time. This likely resulted in underestimating explosion counts at certain sites and times. However, only for calculation of maximum explosion counts per day, corrected values were shown additionally underneath **Table 1** (but not used to categorize sites regarding explosion intensity) to highlight the potential extent of noise pollution. The total amount of analyzed data varied between sites, from about 4 months to over 7 years per site. In this study, the cumulative amount of data for all sites exceeds 47.5 years (17,370 days; **Figure 2** and **Supplementary Table 1**). The varying recording effort between sites over the years of this study potentially affects the explanatory power of spatial comparisons between sites, as a site where recordings are only available during peak fishing years (e.g., site Q) is difficult to compare to a site where only more recent data (e.g., sites LJP and M1) were analyzed. Again, to prevent overestimation of explosion noise, we did not sum up explosion counts over multiple sites, as there may have been double counts of some explosions if the same explosion signal was recorded at different sites that were recording simultaneously.

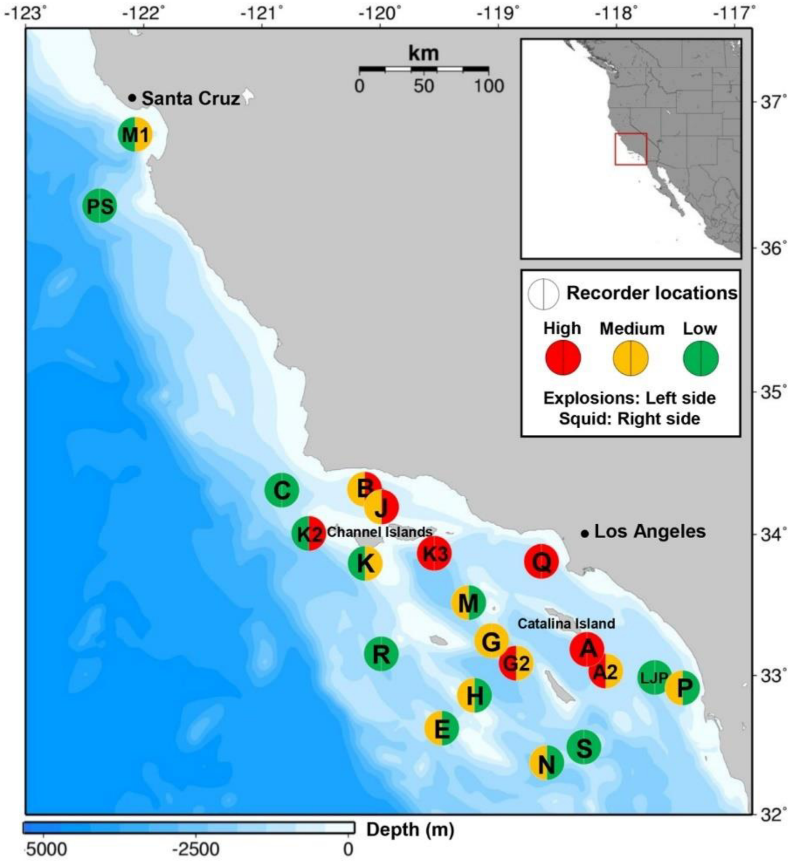

FIGURE 1 | Locations of 21 passive acoustic monitoring sites (circles) deployed between 2005 and 2016 in the Southern California Bight and the Monterey Bay area with high (red), medium (orange) or low (green) explosion occurrence (left side of circle) and market squid landings (right side of circle). For definition of high, medium and low categories for explosions see **Table 2**. Squid landings were labeled as high, medium or low according to the average daily landings (high > 100,000 lbs, medium 25,000–100,000 lbs, low <25,000 lbs) reported within a 50 km radius and during recording period of the corresponding recording site. Map generated using Maptool. 2002. SEATURTLE.ORG, Inc. http://www.seaturtle.org/maptool/ (2018/08/08).

Explosion Detections and Metrics

All recordings were decimated by a factor of 20 to create an effective acoustic bandwidth from 10 Hz to 5 or 8 kHz (for 200 or 320 kHz sampled HARP data, respectively) and from 10 Hz to 6.4 kHz (for 256 kHz sampled MARS hydrophone data). Effort was directed toward finding explosions, which included seal bombs, military explosions and other explosive events. High explosive detonations are characterized by a sharp onset, a shock wave rising toward a large peak almost instantaneously, followed by a reverberant decay (Cole, 1948). The flash powder in seal bombs deflagrates and does not detonate like high explosives, but overall, they show a similar impulsive signature (Wiggins et al., 2021).

Individual explosion signals (**Supplementary Figure 1**) were automatically detected using a MATLAB-based (Mathworks, Natick, MA, United States) matched filter detector algorithm. It cross-correlated the envelope (Hilbert transform; Au, 1993) of the template explosion signal (for waveform of template explosion see **Supplementary Figure 2A**), which is a filtered composite set of recorded example explosions, with the envelope of 75 s recording segments to capture similarities. The cross-correlation was squared to "sharpen" peaks of explosion detections. The time series was digitally filtered with a 10th order Butterworth band-pass filter, with a band-pass between 200 Hz and 2 kHz. The low frequency cutoff was set to minimize the influence from noise from sources such as boats and weather; the high frequency cutoff minimizes interferences with sources such as mid-frequency sonar and odontocete whistles. Once the correlation coefficient exceeded the specified threshold (above the median cross-correlation calculated over each 75 s segment to detect explosions within, e.g., noise from shipping) the time series waveform containing the potential explosion signal was inspected more closely. Consecutive explosions had to have a minimum time difference of 0.5 s to be detected as separate signals. For each detection period, a Hilbert envelope with a floating smoothing window of 300 samples was calculated while explosion signal start and end times were extracted based on a 2 dB above the average envelope threshold. Signal duration and noise before and after the

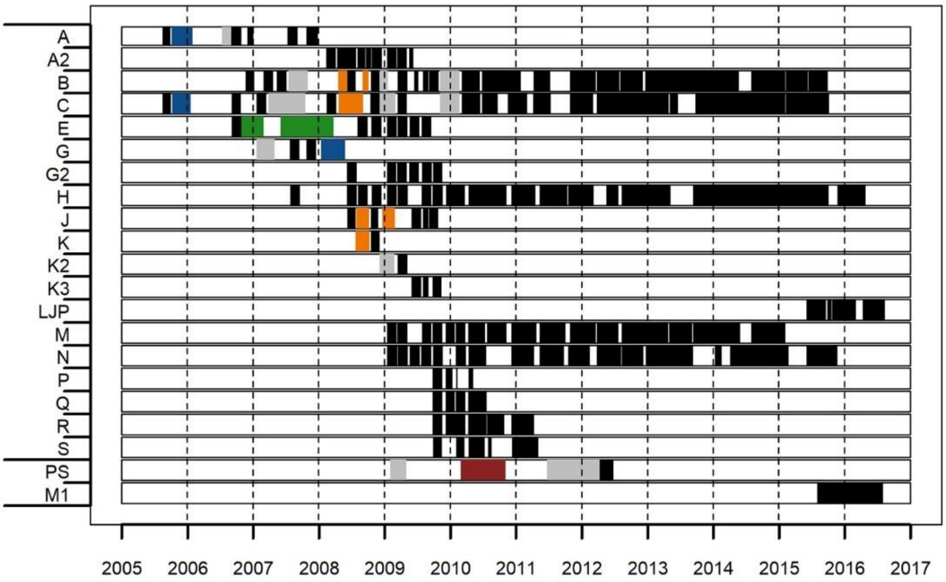

FIGURE 2 | Overview of acoustic recording periods with explosion analysis effort per site between 2005 and 2016; the first 19 sites (A–S) are from the Southern California Bight, the last two sites (PS and M1) are from the Monterey Bay area. Black (continuous recordings) and colored areas (duty-cycled recordings; recording duration (min)/recording interval (min): orange = 5/7, gray = 5/10, blue = 5/15, green = 5/20, red = 5/25) represent times of explosion analysis effort.

signal (based on peak-peak and root-mean-square (rms) received levels) were computed and used to eliminate false detections. The potential explosion was classified as a false detection and deleted if (a) the signal duration was shorter than 0.03 s or longer than 0.55 s, (b) the dB difference between the signal and the time before the signal for peak-peak and rms received levels were less than 3 and 1 dB, respectively, or (c) the dB difference between the signal and the time after the signal were less than 4 and 1.5 dB, respectively. These thresholds were empirically established based on the histogram distribution of manually verified true and false detections. Additionally, as HARP data contain self-noise every 75 s from disk writing, those periods, of up to several seconds with specific narrowband spectral features, were excluded from the detection algorithm. The detector output was saved into a log file containing information on start and end times, durations and received level differences of explosions and surrounding noise.

The detector algorithm was designed to produce a limited number of false-negative detections in exchange for a high number of false-positive detections (>85% false-positive detection rate for all detected potential explosion signals). Therefore, each automated detection was manually reviewed and verified by trained analysts. To do so efficiently, a MATLAB-based custom graphical user interface (GUI) was used (Helble et al., 2012), which displays time-condensed spectrograms of the detections, provides tools to listen to them (adjustable band-passed audio) and to make a verification decision (accept as true or reject as false-positive detections; for example see **Supplementary Figure 2B**). The GUI reads in the explosion detector log files as well as the corresponding decimated (factor of 20) .wav files. Afterward, metadata of all positive detections were stored in the Tethys metadata database (Roch et al., 2016).

The sound exposure level (SEL) was calculated for each detected explosion signal using custom MATLAB scripts. For impulse signals, such as explosions, the SEL, calculated by integrating the sum-of-square pressures over the duration of the pulse, is more appropriate than peak or root-mean-squared sound pressure levels, because it accounts for the total energy in the signal, not just the pressure amplitude (Wiggins et al., 2021). For SEL calculation the undecimated and unfiltered raw data were taken as a basis. The time series was then digitally filtered with a 50 Hz high-pass elliptical filter and decimated by a factor of 10. Calculated SEL values are received, not source values, from explosions with unknown distance to the hydrophones and are therefore influenced by various distance and surrounding noise effects.

Commercial Fishery Data

Information on California commercial fishery landings, which are fish and shellfish caught, landed, sold and subsequently reported at California harbors, were provided by the California Department of Fish and Wildlife (CDFW) for target species caught with purse-seine, drum-seine, lampara, half ring and other encircling nets. Only target species caught with these gears were chosen for analyses as (a) they usually belong to the largest volume fisheries in California and (b) information from fishing agencies and fishing experts indicated their use of explosive deterrents. For this analysis, a target species was defined as the species that made up greater than or equal to 50% of the weight recorded on a landing receipt. If the landing was a 50/50% split of two different species, the landing would have two target species (0.09% of the dataset), but if the landing was 51/49% of two different species, the landing would have only one target species.

TABLE 1 | Overview of (A) explosion counts and SEL and (B) fishery landings for the monitoring sites across all years.

Site	(A) Explosions										(B) Fishery landings		
	Category	% EPD	Counts (percentiles/EPD)			Max. count	% day	% night	Med. SEL (dB)	Max. SEL (dB)	Squid (lbs)	CPF (lbs)	HMS (lbs)
			25	Median	75								
Southern California Bight													
G2	High	77.0	28	96	366	2,798	3.5	96.5	151	167	66,000	22,000	2,000
Q		81.0	8	62	432	2,041	3.4	96.6	153	171	227,000	66,000	0
A		80.9	10	38	189	1,169*	5.0	95.0	156	177	164,000	135,000	400
A2		78.5	7	29	123	1,186	7.2	92.8	168	182	75,000	137,000	4,000
K3		50.0	19	277	830	1,815	4.5	95.5	153	177	367,000	5,000	200
M	Medium	36.7	4	37	181	1,493	7.7	92.3	141	175	17,000	1,000	40
B		35.8	7	33	117	2,153	6.1	93.9	148	172	113,000	4,000	400
H		55.9	7	32	128	2,620	4.4	95.6	146	187	400	600	1,000
J		39.5	3	27	260	1,770*	3.7	96.3	159	179	144,000	3,000	1,000
E		32.2	2	6	29	1,122	4.7	95.3	142	177	0	600	1,000
G		40.8	2	11	54	667*	3.9	96.1	148	177	41,000	41,000	1,000
P		73.1	3	7	28	594	15.2	84.8	150	174	1,000	40	0
N		35.2	2	5	32	559	11.2	88.8	138	189	10,000	800	1,000
S	Low	35.6	5	12	40	338	53.8	46.2	147	187	21,000	1,000	0
LJP		57.8	3	7	14	206	59.7	40.3	-	-	0	0	0
R		15.0	1	3	12	893	9.9	90.1	139	169	300	0	0
C		6.0	4	14	48	238	9.8	90.2	146	179	11,000	70	10
K2		7.9	3	7	31	81*	0.4	99.6	141	179	132,000	500	100
K		0	0	0	0	0	NA	NA	NA	NA	87,000	1,000	900
Monterey Bay area													
M1	Low	31.6	3	9	38	279	19.5	80.5	-	-	53,000	76,000	0
PS		16.7	3	10	25	191*	17.9	82.1	148	164	6,000	3,000	0

(A): Percentage of Explosion Positive Days (EPD), median explosion counts per EPD (with 25th and 75th percentile), maximum explosion counts during 1 day (based on these metrics, sites were assigned into three different categories: high, medium or low explosion occurrence), percentage of day- and nighttime explosion occurrence, median and maximum received values for sound exposure level (SEL) in dB re: 1 μPa^2*-s.*

(B): Rounded average daily fishery landings in pounds (lbs) for market squid, coastal pelagic fish (CPF) and highly migratory species (HMS) with catch origin within 50 km radius and during recording period of the corresponding HARP site (rounding to tens for values <100, to hundreds for 100–1,000, to thousands for >1,000).

**Maximum explosion counts during 1 day with duty cycle correction: A = 3,483, G = 722, J = 2,125, K2 = 162, PS = 382.*

In addition, mixed landings where no single species accounted for greater than 50% of the landing were excluded from the analyses (0.3% of the dataset).

California Department of Fish and Wildlife fishery data included monthly and daily amounts of landings (weight in pounds) and number of landing receipts (number of times a target species was landed) for each purse-seine target species per fishing block (catch origin) for the years 2005 until 2015. Fishing blocks are a grid of rectangular areas within the Exclusive Economic Zone off California and are used to report catch locations on CDFW landing receipts to describe a general location for fishing activity. Their relatively large size, of approximately 11 × 9 nautical miles (except for blocks along coastlines), allow fishermen to keep their specific fishing sites private. The distances between the center of each fishing block and each of the 21 hydrophone sites were calculated, and only landing and receipt data from fishing blocks with up to a maximum distance of 50 km and within the recording period of the HARP sites were included for subsequent statistical analyses and comparisons with acoustic explosion data. Simonis et al. (2020) calculated a transmission loss model for seal bomb noise (at 250 Hz) in California waters; the results show that seal bomb noise is still detectable in 50 km distance. Recreational fisheries were not included as (a) exact catch reports are only legally required for a handful of species and commercial passenger fishing vessels (recreational fishing effort is estimated within the California Recreational Fisheries Survey based on field sampling and telephone surveys) and (b) seal bombs are mostly used by commercial fishermen.

For the correlation analyses and/or comparisons with temporal and spatial explosion patterns, commercial landing and receipt data for ten purse-seine target species were divided into three fishery sections according to the fleets they were caught by: (1) market squid, (2) coastal pelagic fish (CPF), and (3) highly migratory species (HMS). Five of these 10 species are considered coastal pelagic species and represent the largest purse-seine fisheries in California, both in terms of landings volume and value (CDFW landing receipts, 2005–2015). Additionally, these fisheries primarily operate in Southern California and, to a lesser extent, in Central California (Hackett et al., 2009) and are therefore concentrated in our study area. Within this group, market squid (*Doryteuthis opalescens*) represents the number one fishery in the state, with 11,216 landing receipts for 2005–2015 in total (CDFW landing receipts, 2005–2015). In 2010, for the California commercial market squid fishery permits for 81 market squid vessels (large purse-seine vessels), 25 brail vessels (brail gear) and 53 light boats (used to attract but not catch squid) were issued (California Department of Fish and Wildlife, 2021). The other four coastal pelagic species, Northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax caerulea*), Pacific mackerel (*Scomber japonicus*) and Pacific jack mackerel (*Trachurus symmetricus*), had 8,972 landing receipts for 2005 to 2015 in total and will be referred to as coastal pelagic fish (CPF). For CPF, the main fleet consisted of about 65 participants using primarily purse-seine gear. However, many of the vessels fishing for CPF also fished for market squid and vice versa, when available, or when there were market orders for certain species. The remaining five purse-seine target species, which were considered for this study, are highly migratory species (HMS): Pacific bonito (*Sarda lineolata*), albacore tuna (*Thunnus alalunga*), Pacific bluefin tuna (*Thunnus orientalis*), skipjack tuna (*Katsuwonus pelamis*), and yellowfin tuna (*Thunnus albacares*). These HMS species represented the third largest group of fish caught with purse-seine gear in California. Although there were fewer landing receipts of HMS species from 2005 to 2015 than for market squid and CPF (251; CDFW landing receipts, 2005–2015), they were selected for analyses because of the use of seal bombs by the tuna purse-seine fishery in the past (Cassano et al., 1990).

Statistical Analyses

All statistical analyses were done using R 4.0.3 (R Core Team, 2020). For each site, the percentage of explosion positive days (% EPD) over the respective recording period was calculated to describe the degree of explosion persistence. A day was explosion positive if a minimum of one explosion was recorded on that day. Median and maximum explosion counts per EPD were calculated to describe the intensity of explosion occurrence. These metrics were chosen to account for the high degree of variability within the data. Based on these three metrics, each site was assigned to one of three categories: high, medium or low explosion occurrence (**Table 2**). Classification in one of the categories required at least two out of the three metrics to fall into that category.

Explosion counts were examined for diel patterns. For each site, daily sunrise and sunset data were obtained from the National Oceanic and Atmospheric Administration Earth System Research Laboratory website (NOAA solar calculator). Each detected explosion was assigned to either a day- or nighttime period, separated by apparent sunset and sunrise times. A Kruskal-Wallis test was used to examine whether differences were significant between day and night. As fishery landings and receipt data were only available per day, no diel pattern was examined. Weekday and annual patterns of explosion occurrence and fishery landings were analyzed and compared for significant differences using a pairwise Wilcoxon rank sum test with *p*-value correction method after Benjamini and Hochberg (1995). For non-parametric tests the R package zoo (v1.8-9; Zeileis et al., 2021) was used. For analysis of weekday patterns it is important to note that fishery data represents the weight of fish landed at California ports per day, although the day it was actually caught can vary because catches are not always reported the same day (especially on Sundays). Particularly for fisheries operating at night, fish were often caught the day before they were landed.

TABLE 2 | Category metrics and threshold values for classification of sites regarding explosion occurrence.

Metric	Category		
	High	Medium	Low
% EPD	>75%	25–75%	<25%
Median/EPD	>50	25–50	<25
Daily maximum	>1,000	500–1,000	<500

Seasonal patterns of explosions and fisheries were analyzed *via* generalized additive modeling (GAM) testing calendar week (as proxy for seasonal development) as predictor (with cyclic cubic smooth function) and year and site as categorical factors. Data sampled within an ecological context, like fishery data, e.g., is often characterized by a large proportion of zeros together with a right skewed distribution and some extreme values, which was also the case here. We accounted for this by selecting a compound-gamma distribution model, a member of the Tweedie family, which are specifically appropriate to handle zero-inflation especially under variable sampling effort by site (Lecomte et al., 2013). A logit link function was used. We simplified the GAM structure through a bottom-up, stepwise procedure, selecting the best model with the minimum Akaike Information Criterion (AIC) that retained significant predictors. Basic residual plots were used for model validation. We did not correct for temporal autocorrelation of the predictor variable in the GAM, as we mainly examined the effects of calendar week, as proxy for seasonal pattern, which itself is depicted by the autocorrelation within the data, and we did not evaluate the effect of any environmental parameters. Important packages in R were mgcv (v.1.8-36; Wood, 2021) for GAM and statmod (v.1.4.36; Smyth et al., 2021) to calculate parameters of Tweedie distributional family.

At five of the 21 stations (sites B, C, H, M, and N) almost 7 years of continuous data were analyzed, collected from January 2009 until September-December 2015 (except site M, until January 2015). Data from these long-term sites were included in a trend analysis for explosion and fishery activities using the Theil-Sen linear regression method for non-parametric data (Sen, 1968). The Theil-Sen method is robust to outliers and is based on Kendall's rank correlation. Strong seasonal patterns decrease the statistical power for detecting a trend, as they add more variability to the data. Therefore, Seasonal-Trend-Decomposition using LOESS (STL) was applied on the data before the trend analysis was conducted (Cleveland et al., 1990). STL uses a sequence of smoothing fits on localized data subsets to decompose the timeseries and to generate distinct seasonal, trend and remainder (residual) components. The seasonal component was then removed to de-seasonalize the data (Nunifu and Fu, 2019). The data from the five sites were combined to account for an overall trend development throughout the Southern California Bight. The median change of slope (and slope uncertainties) per year was used to compare the extent of trends. This trend analysis was conducted using the openair R package (v.2.8-3; Carslaw and Ropkins, 2012).

To analyze the correlation between explosion occurrence and fishing activity, we also conducted a Theil-Sen regression analysis using the R package mblm (v0.12.1; Komsta, 2019). A Daniels trend test based on Spearman rank correlation coefficient (rho) was conducted as a rank statistic using the package ggpubr (v.0.4.0; Kassambara, 2020). Rho was evaluated based on the guidelines of Cohen (1988). Correlation analyses were applied for explosion counts per week and the weekly amounts of landing receipts for the three defined fishing sectors for each site and for all sites combined. Landing receipts, instead of landings in pounds, were included in correlation analyses, as they represent a proxy for the presence of active fishing vessels potentially using seal bombs in the area. Weeks without fishing activity were excluded from the model, to focus on the analysis of the relationship of the particular fishing sector and explosion occurrence.

RESULTS

Explosion Counts and Sound Exposure Levels

Explosions were detected at all but one (site K) of the 21 monitored sites, resulting in a total of 707,738 explosion signals (actual recorded explosions, without normalized counts for duty cycle correction) detected on a total of 6,307 recording days (36.3% EPD). EPD per site varied from 6.0 to 81.0%. Median and maximum explosion counts per EPD ranged from 3 to 277 and 81 to 2,798, respectively (**Table 1**). Based on these metrics, five sites were categorized as high, eight as medium and eight as low regarding explosion occurrence. The timeseries of daily explosion counts (and squid landings) for all sites can be found in the supplement (**Supplementary Figures 3–5**). Median and maximum SEL ranged from 138 to 167 dB re: 1 μPa^2-s and 164 to 189 dB re: 1 μPa^2-s, respectively (**Table 1** and **Figure 3**).

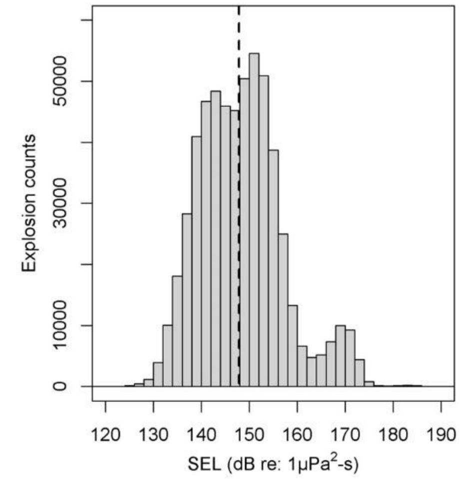

FIGURE 3 | Frequency and distribution of the explosions received sound exposure level (SEL) in dB re: 1 μPa^2-s with median (dashed line). Received values are likely influenced by effects of the unknown distance to the source and surrounding noise. SEL values show a small additional peak at around 170 dB indicating signals were above the clipping level of the hydrophone. Decreasing detections between 130 and 140 dB may result from variable signal detectability, e.g., depending on site/bathymetry.

Spatial Explosion and Fishery Landing Patterns

High explosion counts were identified at five nearshore sites (**Figure 1** and **Table 1**): within Santa Monica Bay (site Q), around Santa Cruz Island (Channel Islands National Marine Sanctuary, site K3), at Santa Catalina Island (sites A and A2) and at San Clemente Island (site G2). They accounted for 34.4% of the total recorded explosions, but only for 8.5% of the total recording days. At these sites, median daily explosions varied between 29 and 277, while maximum values of up to 1,170–2,800 explosions per day were detected and 50–81% of the days were EPD (**Table 1**). Median SEL were highest here as well (151–167 dB re: 1 μPa^2-s), except for site J (159 dB re: 1 μPa^2-s), categorized as "medium" explosion counts. Other near-shore sites [around Santa Cruz Island (site J), Santa Barbara Island (site M) or within the Santa Barbara Channel (site B)] had overall medium explosion counts, but explosion counts were high within certain seasons, especially during winter 2008/2009 and fall 2009 (**Supplementary Figure 4**).

Explosion counts at offshore sites were either low (sites R, S, and PS) or medium (sites H, E, and N). But one offshore site at Tanner Bank (site H) showed high explosion counts over multiple seasons between 2009 and 2012 (up to 2,600 per day). Low or medium counts were also detected at the southern nearshore sites close to the San Diego coast (sites LJP and P). Site M1, within the Monterey Bay National Marine Sanctuary, had low explosion counts, although the recordings at site M1 started much later than in the Southern California Bight, making large-scale regional comparisons difficult (**Figure 1** and **Table 1**). At the north-western most sites in the Southern California Bight, such as Point Conception or the western part of the Channel Islands (site C, K2, and K) explosion occurrence was low as well.

The highest amounts of squid landings were reported for fishing blocks around nearshore sites, primarily around the Channel Islands (sites J, K, K2, and K3), within Santa Monica Bay (site Q), around Santa Catalina Island (sites A and A2) and within the Santa Barbara Channel (site B). Few squid were caught around the southern nearshore sites close to the San Diego coast (sites LJP and P) and around offshore sites (E, H, PS, and R; **Table 1** and **Supplementary Figures 3–5**). CPF landings were highest around Santa Catalina Island (sites A and A2), followed by other nearshore sites in Monterey Bay (site M1), within Santa Monica Bay (site Q) and around San Clemente Island (sites G and G2). At all other sites, CPF landings were comparatively low. HMS landings were rare compared to the other two purse-seine fisheries. They were mostly caught around nearshore sites, like A2, G, G2, and J, but also at some offshore sites, like E, H, and N (**Table 1**).

Diel Explosion Pattern

The majority of explosions (93.9%) were recorded at night. In the Southern California Bight, the percentage of total nighttime explosions varied between 84.8 and 99.6% at 17 sites. At two southern sites, LJP and S, the pattern was different; 53.8–59.7% of all explosions occurred during the day, but both sites had only low explosion counts. At the two sites in the Monterey Bay area, 80.6–82.1% of all explosions were detected during the night (**Table 1**). At 18 sites, explosion occurrence differed significantly between day- and nighttime (Kruskal-Wallis-Test $p < 0.001$). At three sites it was not significant (LJP $p = 0.866$, P $p = 0.627$, R $p = 0.134$). Overall, most explosions were recorded within the time between 22:00 and 00:59 (**Figure 4**). Per hour, 10.7-12.2% of all daily explosions were assigned to each of these three hour-bins. Before and after, hourly explosion counts were decreasing gradually. Explosion counts were lowest between 09:00 and 17:00 with 0.2–0.3% of all daily explosions occurring within each of these hours.

Weekly Explosion and Fishery Landing Patterns

Explosion counts showed a clear weekly pattern (**Figure 5A**), with counts peaking between Mondays and Thursdays (each day with 17.9–21.8% of total explosions), decreasing on Fridays (10.0%), being almost absent on Saturdays (1.4%), and then increasing again on Sundays (10.9%). In total, there were no significant differences in daily explosion occurrence from Monday to Wednesday (pairwise Wilcoxon rank sum test, $p = 0.38–0.98$). Fridays and Sundays did not differ from each other ($p = 0.21$) and were significantly lower than all the other working days ($p < 0.001$). Explosion counts on Saturdays were significantly lower than on all the other days ($p < 0.001$). This pattern with

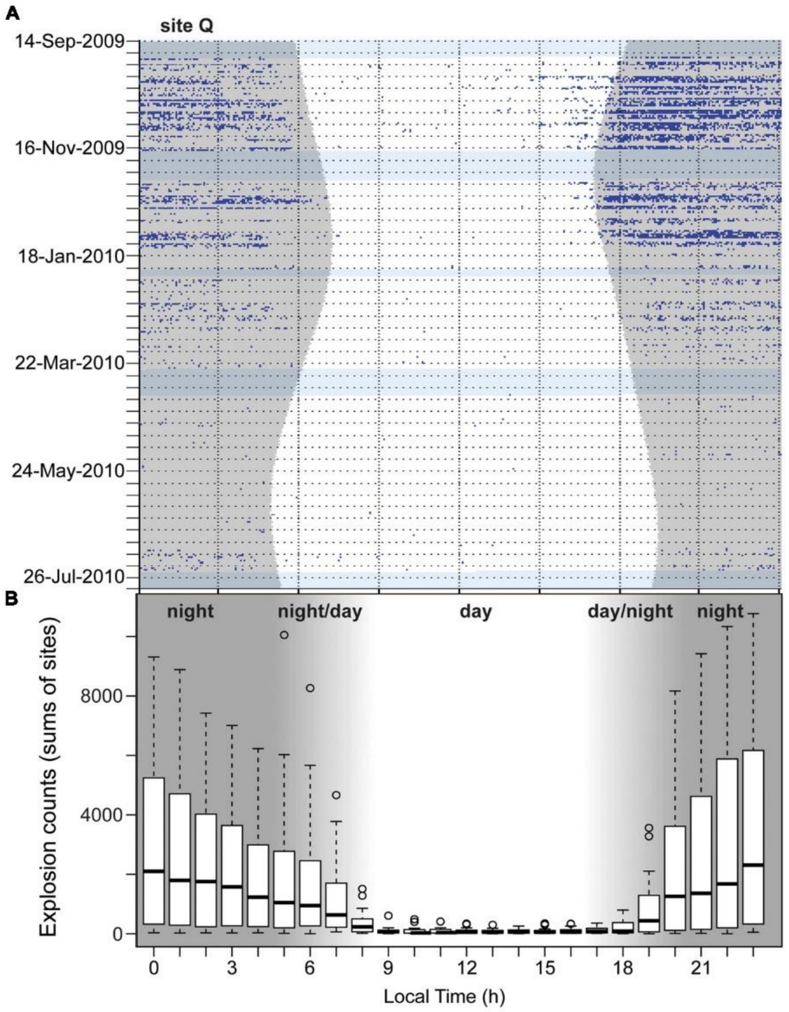

FIGURE 4 | (A) Diel presence of explosions (blue dots) in one minute bins from September 24th, 2009 to July 21st, 2010 at site Q with high explosion counts. Gray hourglass shading denotes nighttime and light blue horizontal shading denotes periods with no recording effort. **(B)** Boxplot of explosion counts (sums per site) per hour of the day (dark-gray areas: nighttime, white: daytime, light-gray: day- or nighttime depending on season) at all sites.

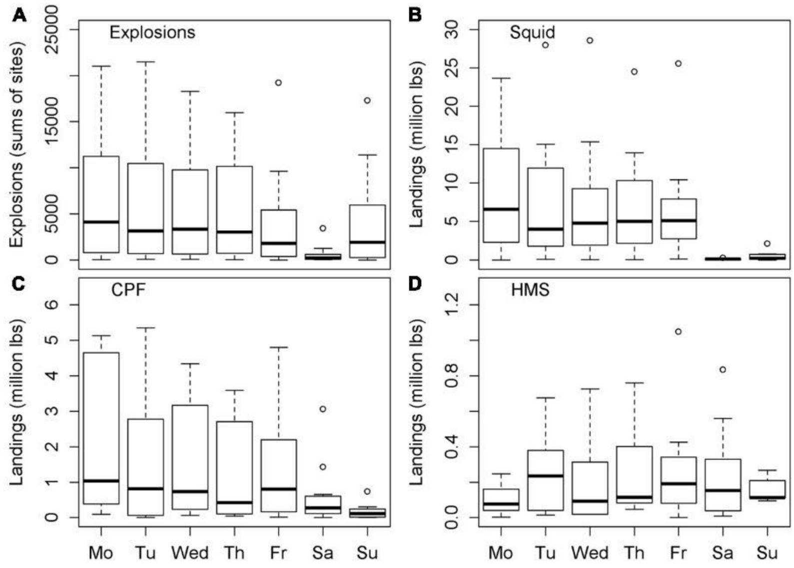

FIGURE 5 | Boxplot of **(A)** explosion counts, **(B)** reported market squid, **(C)** coastal pelagic fish (CPF), and **(D)** highly migratory species (HMS) landings in million lbs per weekday based on sums per site.

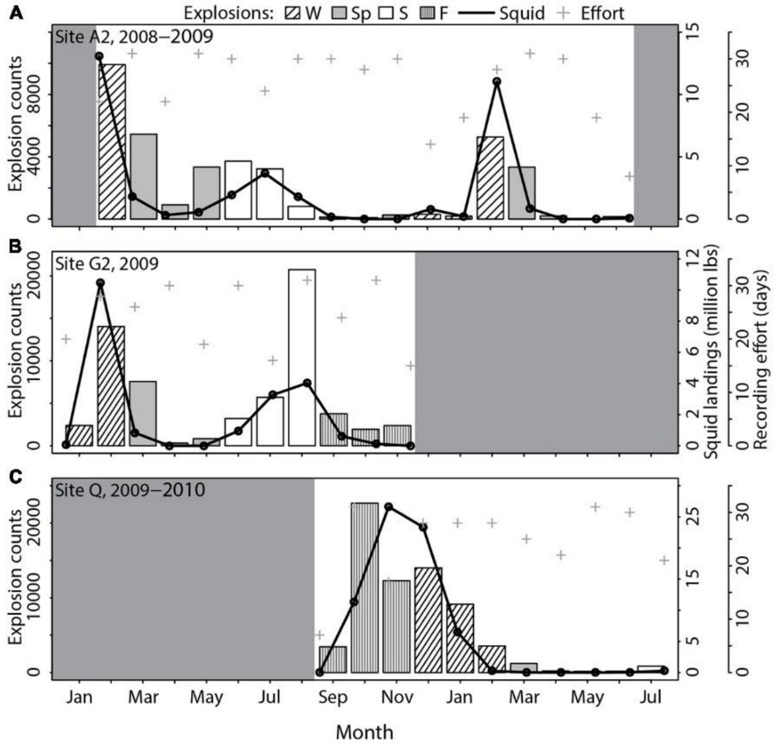

FIGURE 6 | Explosion counts [bars: Winter (W) = black inclined stripes, spring (Sp) = gray, summer (S) = white, fall (F) = gray vertical stripes], market squid landings within a 50 km radius around the site (black line) and days with recording effort (gray cross) per month for **(A)** site A2, **(B)** site G2, and **(C)** site Q. Other fisheries are not shown as no overlapping seasonal pattern with explosions was found.

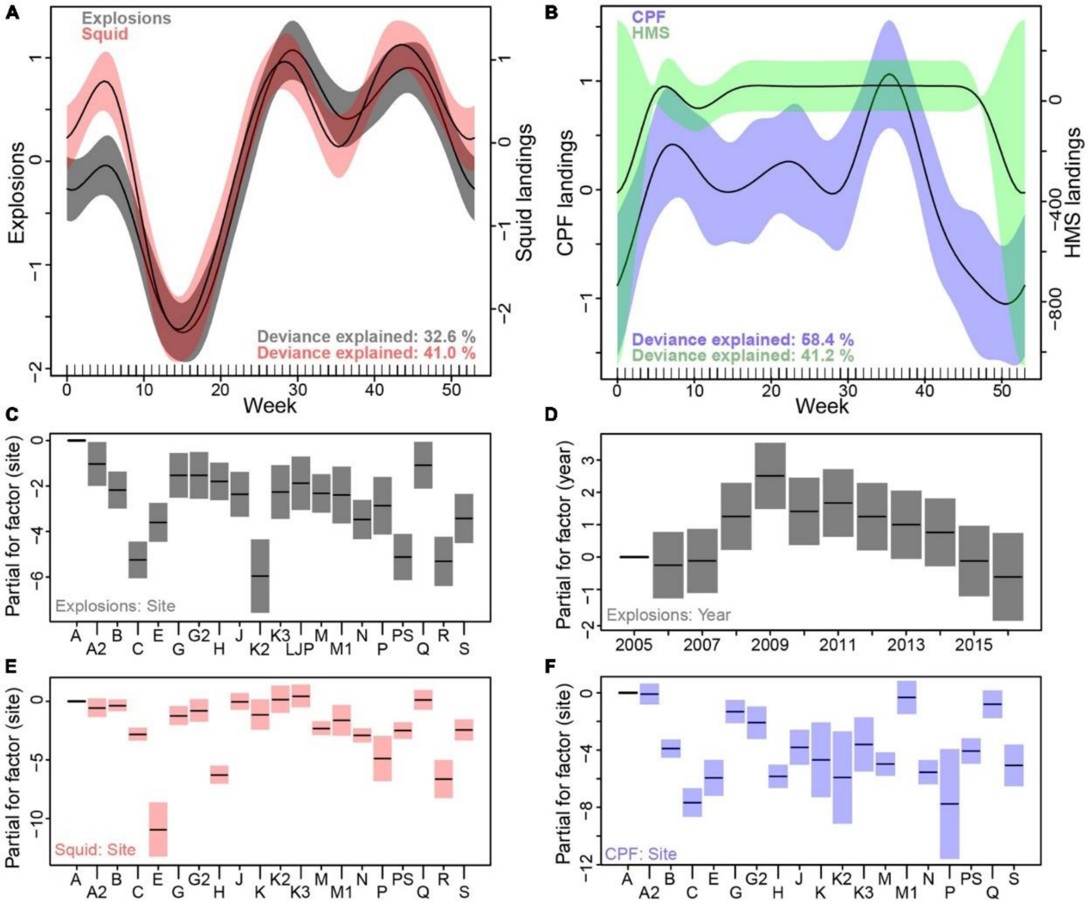

FIGURE 7 | Generalized additive modeling (GAM) results for seasonal patterns of explosions and fisheries with calendar week as predictor (cyclic cubic smooth function) and site and year as factors using a Tweedie (compound Poisson-gamma) distribution. **(A)** Smooth terms for the influence of week on explosion counts (gray) and squid landings (red) and **(B)** for CPF (lilac) and HMS landings (green), **(C)** partial effect of factor site and **(D)** of factor year on explosion counts (gray), **(E)** of factor site on squid landings (red) and **(F)** of factor site on CPF landings (lilac).

very low explosion counts on Saturdays (0–3.6% of explosions per site) was visible at all sites, except for LJP (11.6%), where no weekly pattern was observed at all.

A clear weekly pattern was also observed for reported squid and CPF landings (**Figures 5B,C**), with highest landings between Mondays and Fridays and almost no landings (significantly lower; $p < 0.001$) on weekends. HMS landings were rare compared to squid and CPF landings. Between 2005 and 2015 catches were made on only 125 days within the vicinity and the recording period of the HARP sites and thus, no clear weekly pattern was detected (**Figure 5D**).

Seasonal Explosion and Fishery Landing Patterns

Overall recording effort was evenly distributed over all seasons. In total, most explosions were recorded in fall (38.6% of all explosions), followed by winter and summer (27.0 and 26.4%, respectively), and were lowest during spring (7.9%). However, this pattern was not reflected at every site and the only pattern that was consistent over almost all sites (except for site A2 and G2) was low explosion counts during spring. The highest values were detected in fall, summer and/or winter depending on the site (**Supplementary Table 2**). For example, at site A2 close to Catalina Island explosion counts were lowest in fall. Highest values were detected much later in February and were still elevated during spring (**Figure 6A**). At site G2 near San Clemente Island explosion occurrence was much higher in summer and winter than it was in fall, but values also decreased in spring (**Figure 6B**). At site Q in Santa Monica Bay the highest explosion counts were detected in fall (98.2% EPD, median explosions/EPD 640) with the highest monthly counts of all sites with over 22,650 explosions recorded in October (**Figure 6C**). Afterward counts were still high but steadily decreased over the course of the winter, until they reached lowest values in spring, especially in April and May.

A GAM revealed highly significant effects of calendar week on explosion occurrence and fishery landings (**Figures 7A,B** and

Supplementary Table 3). Site was a significant predictor for explosions, squid and CPF landings (**Figures 7C,E,F**), but not for HMS. The inclusion of year only improved the explosion model (**Figure 7D**). Peaks in overall explosion occurrence were found during summer, fall and, less pronounced, in winter, whereas a strong decrease was found in spring. Squid landings showed a very similar overall seasonal pattern, while CPF landings were lowest in winter and HMS landings showed no clear seasonal pattern.

Annual Explosion and Fishery Landing Patterns and Trend Analysis

For the sites with concurrent long-term recordings (B, C, H, M, and N), the period of January 2009 until September–December 2015 was analyzed for annual patterns and trend (site M only until January 2015).

Overall explosion occurrence for the five combined sites was significantly highest in 2009 and decreased until it reached its significantly lowest level in 2015 (pairwise Wilcoxon rank sum test; $p < 0.001$). High maximum daily counts of over 1,000 explosions were only present from 2009 until 2012. From 2010 to 2013, explosion counts were not significantly different ($p = 0.52–0.83$), but after 2013 counts were significantly lower each following year ($p < 0.001$ for both 2014 and 2015). Squid landings (fishing blocks within a 50-km radius around the five long-term recording sites) were highest in 2009 and successively decreased until 2012. In 2013 squid landings increased before decreasing again in 2014 and 2015. CPF and HMS landings did not show any comparable annual patterns (**Table 3**).

A trend analysis based on de-seasonalized Theil-Sen linear regression estimates revealed a significant negative trend for explosions and a significant negative trend for squid landings, while CPF and HMS landings did not experience any significant linear trend. The median change of slope per year was higher for explosions than it was for squid landings, indicating a stronger decline for explosions compared to squid landings within 50 km around the five recording sites (**Table 3** and **Figures 8A,B**).

Regression Analysis for Explosions and Fishery Landing Receipts

The Theil-Sen regression model and Daniel's trend test for explosion counts and squid landing receipts per week, combined for all sites, were both significant ($p < 0.0001$) with a high correlation coefficient rho of 0.58 (**Figure 9**). Per site (**Supplementary Table 4**), strong and significant correlations of explosions and squid landing receipts were found for all sites categorized as "high" (A, A2, G2, K3, and Q) regarding explosion occurrence (rho = 0.66–0.88, $p < 0.001$), but correlations were also present at some sites categorized as "medium" (B, J, and M; rho = 0.34–0.46, $p < 0.01–0.001$) and "low" (C and M1; rho = 0.53–0.76, $p < 0.01–0.001$). For all other sites, including all offshore sites, like E, H, N, R, and S, etc., no correlation was found, or squid landings were so rare that the analysis could not be conducted. There was no significant correlation for explosions and CPF landing receipts in total (rho = −0.07 with $p = 0.28$) or at individual sites. For sites A, A2, G, G2, and K3 the results of the Theil-Sen regression were significant, but Daniel's trend test did not show significant results; rho was low and also negative for three of these sites. For HMS landing receipts and explosions overall, no correlation was found (rho = 0.1 with $p = 0.53$). Per site, only the two offshore sites E and H showed significant results for the Theil-Sen regression ($p < 0.001$) and at the same time

TABLE 3 | Overview of metrics for annual patterns (A) and trend (B) for explosions and fishery landings at the five long-term monitoring sites B, C, H, M, and N combined.

	Explosions					Fishery landings		
			(A) Overview per year					
Year	**% EPD**	**Percentiles/EPD**			**Daily Max./site**	**Squid**	**CPF**	**HMS**
		25	**Median**	**75**				
2009	48.8	5	35	211	2,620	48,000	2,000	2,000
2010	36.6	7	34	105	1,391	32,000	2,000	10
2011	37.2	3	30	187	1,294	26,000	300	40
2012	38.7	5	26	101	1,508	16,000	800	0
2013	39.4	4	17	68	760	36,000	300	50
2014	25.6	3	16	57	611	17,000	800	1,000
2015	18.6	3	9	35	389	19,000	4,000	300
			(B) Trend analysis using Theil-Sen estimates (median with 95% CI)					
					Explosions	**Squid**	**CPF**	**HMS**
Δ slope in %/year					−14.8*** (−17.6, −11.4)	−9.7** (−13.9, −3.7)	0.1^{x} (−5.0, 10.0)	0^{x} (0, 0)

*(A) % of Explosion Positive Days (EPD), median explosion counts per EPD (with 25 and 75 percentiles), maximum daily explosion counts (maximum at a single site) and rounded average daily fishery landings (lbs) with catch origin within 50 km radius per year (rounding to tens for values <100, to hundreds for 100–1,000, to thousands for >1,000). (B) Results of trend analysis based on Theil-Sen estimates for explosions and fishery landings with median change of slope in % per year (with 95% confidence intervals) and significance level (***<0.001, **<0.01, ^{x} not significant).*

meaningful values for rho (0.55–0.57), although they were not significant (p = 0.06–0.11).

DISCUSSION

Southern California, especially its National Marine Sanctuaries, is home to a diverse array of marine species and habitats. At least thirty species of cetaceans and other marine mammals, like pinnipeds and sea otters, as well as four species of sea turtles are found in the region (Leatherwood et al., 1982). The distribution of these animals is closely linked to the region's high level of biological production (Munger et al., 2009), which subsequently dictates the distribution of fisheries and, therefore, seal bomb use.

This study is the first to provide long-term results on the distribution, intensity and origin of underwater explosions that occur in Southern California waters. The information provided here can help to assess their influence on marine life as a noise pollutant, the scale of their use in this region, and to identify potential areas of concern. Comparisons of explosion patterns with commercial fishery data have revealed a correlation with the market squid fishery (**Figure 9** and **Supplementary Table 4**). We will discuss known squid fishing practices in California and compare them to our results for the various spatial and temporal patterns of explosions and squid landings. The CPF and HMS fisheries will not be described in depth as no significant correlation was found with the occurrence of explosions.

Explosions as Noise Pollutant

Research on anthropogenic noise off Southern California has mainly focused on shipping and military sonar operations (Croll et al., 2001; McDonald et al., 2006, 2008; McKenna, 2011; Melcón et al., 2012; DeRuiter et al., 2013; Goldbogen et al., 2013; Houser et al., 2013), as these were thought to be the most significant noise sources. Our results suggest that, at least during peak seasons and years, there has been extensive and persistent noise from underwater explosions related to commercial fishing activities. Underwater explosions represent a relevant anthropogenic noise source off Southern California as they were detected on more than one third of all recording days and were also detected in the vicinity, or inside of, the Channel Islands and Monterey Bay National Marine Sanctuaries. Especially around nearshore sites (those close to Santa Cruz, Santa Catalina or San Clemente Island and Santa Monica Bay) high explosion counts of up to 2,800/day were detected and maximum SEL of up to 189 dB re 1 μPa^2-s were recorded (**Table 1** and **Figure 3**). Nighttime noise from explosions may also be particularly relevant for marine ecosystems, as this is the time when deep scattering layers rise and various dolphin species focus their foraging effort (for the Southern California Bight, e.g., Soldevilla et al., 2010; Simonis et al., 2017).

Possible impacts from noise include death, physical injury of the auditory systems [Permanent or Temporary Threshold Shift (PTS or TTS)], masking of biologically important sounds, alteration of behavior and habitat exclusion (e.g., Southall et al., 2007). The National Marine Fisheries Service (2018) estimated received acoustic threshold levels for PTS onsets for different marine mammal hearing groups. For impulsive sounds, a dual metric using peak sound pressure level (SPL_{peak}) and weighted 24 h-cumulative SEL was used. In a recent experiment using seal bombs, source levels exceeded all these thresholds (Wiggins et al., 2021), except for the SEL threshold for otariid pinnipeds. Although weighted and un-weighted, as well as cumulative and non-cumulative, metrics cannot be compared one to one, they are still a reasonable indication for the risk seal bombs pose to marine mammals. The maximum SELs (unweighted, non-cumulative) of 164–189 dB re 1 μPa^2-s per site, recorded within this study (**Table 1**), partly exceed PTS and TTS thresholds for cetaceans as well as for phocid pinnipeds (National Marine Fisheries Service, 2018). Simonis et al. (2020) estimated, based on a local transmission loss model for seal bombs in Monterey Bay, that harbor porpoises would experience a TTS from cumulative exposure of two seal bomb explosions within 1 km or six explosions within 2 km. Taking maximum values of explosion occurrence at high count sites from this study into account, on average, explosions happened multiple times per minute during the night, meaning that nearby porpoises would potentially not have been able to flee before experiencing hearing damage. In Germany, e.g., federal regulations exist for impulsive pile-driving so that a SEL (also unweighted, non-cumulative) threshold of 160 dB re 1 μPa^2-s cannot be exceeded, in order to protect endangered harbor porpoises from TTS (Deutsches Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2013). In this study, median SELs close to and above 160 dB re 1 μPa^2-s were recorded at site A2 near Catalina Island and site J within the Channel Islands National Marine Sanctuary. These sites were classified as "high" and "medium" (but with times of high explosion occurrence for the latter case) regarding explosion occurrence, meaning there is the potential for additive or cumulative effects. Moreover, for explosions which have happened very close to the recording site, recorded signals likely have been clipped and actual received SEL were higher, which is indicated by the second smaller peak of received SEL in **Figure 3** (the hydrophones clipping level is ∼167 dB SPL). Additionally, since most of the energy of explosions lies within the low-frequency range, the sound can travel great distances and effects on marine mammal behavior might be far more wide-ranging than just physical harm. Other repetitive, low-frequency, impulsive sounds, like air gun blasts or pile-driving strikes, are known to disturb the behavior of marine mammals (e.g., Gordon et al., 2003; Stone and Tasker, 2006; Lucke et al., 2009; Di Iorio and Clark, 2010; Castellote et al., 2012; Dähne et al., 2013).

The focus so far has been on potential effects on marine mammals, as they are known to be particularly sensitive to noise and are, at least in the case of pinnipeds, the main target of seal bomb use. But other marine organisms, down the food chain, are likely to be affected as well; for example, sea turtles, fish (Popper et al., 2014), lobsters (Day et al., 2019), and zooplankton (McCauley et al., 2017). The possible impact of seal bombs on squid species should also be considered, since this study has revealed a positive correlation between explosions and the market squid fishery. Squid have statocysts (otoliths) and are able to "hear" by detecting the particle motion component of a sound field (Mooney et al., 2010). When exposed

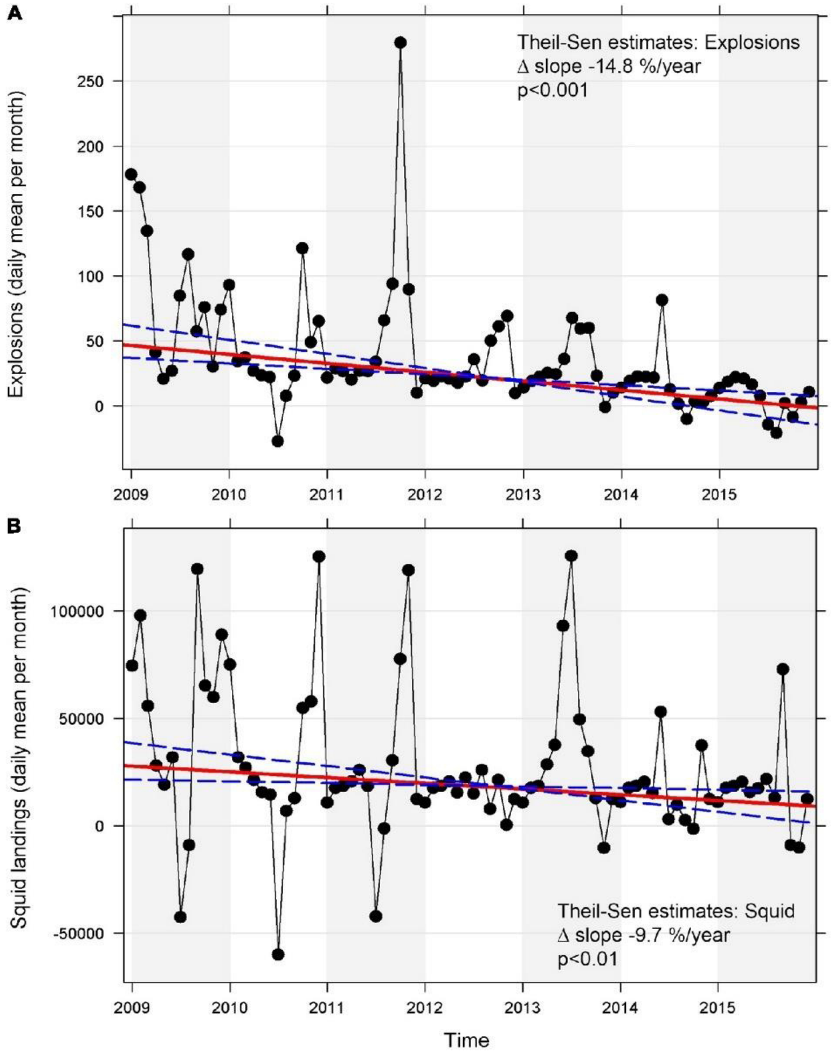

FIGURE 8 | Trend analysis of mean daily values per month using a Theil-Sen regression model for **(A)** explosions and **(B)** squid landings at five long-term sites (B, C, H, M, and N) off Southern California between 2009 and 2015 (red line: regression line, blue dashed line: 95% confidence intervals). A Seasonal-Trend-Decomposition using LOESS (STL) was applied to de-seasonalize the data first to account for the strong seasonality. The removal of the seasonal component occasionally resulted in theoretical negative values and peaks within the trend analysis as a product of the remaining trend and residual components.

to anthropogenic noise, different squid species have shown increased alarm responses such as escape and firing ink sacs [using simulated noise for *Sepiotheutis lessoniana* and *Octupus vulgaris*: Hu et al. (2009), for *Doryteuthis pealeii*: Jones et al. (2020)]. For example, McCauley and Fewtrell (2008) reported that some squid reacted to simulated air gun noise by initially swimming faster but then slowing and lying motionless near the surface. Near seismic surveys, strandings of *Architeuthis dux* (giant squid) have been reported (Guerra et al., 2004) and Solé et al. (2013) described statocyst lesions in four squid species from the Mediterranean after exposure to low-frequency noise (*Sepia officinalis*, *O. vulgaris*, *Loligo vulgaris,* and *Illex condietii*). These studies show that anthropogenic noise can physically harm and change the behavior of squid, and further research is needed to determine how seal bombs may be impacting squid off Southern California.

Origin of Explosions and Correlation With Fisheries

Explosive deterrents pose a risk to marine life – determining their origin, as well as how and why they are being used, is a necessary step in ensuring they are properly regulated and managed. Our results suggest that most of the recorded explosions come from seal bombs, or similar explosive deterrent devices, being used by the California market squid fishery. However, we cannot rule out that some explosions have sources other than fisheries. The signal detector applied for this study is based on template explosion

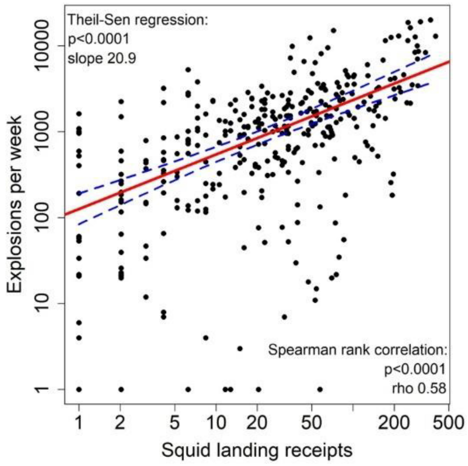

FIGURE 9 | Theil-Sen regression model of explosion counts and market squid landing receipts per week (based on weekly sums of all sites; weeks without squid fishing activity were excluded from the model) with log-scaled axes (red line: regression line, blue dashed line: 95% confidence intervals).

signals and each signal was manually verified. A mix-up with other signals resembling explosions is unlikely, but potential sources of similar signals are discussed below. Off Southern California, explosions can occur during naval training exercises, but they are not used in high numbers and typically occur during the day (Baumann-Pickering et al., 2013), whereas almost 94% of all explosions recorded in this study occurred at night (**Figure 4**). There are acoustic similarities between seismic air gun blasts and explosion signals (Guerra et al., 2011), but to our knowledge, no industrial seismic exploration has ever been conducted in California waters. Additionally, air gun blasts are usually executed in a specific periodic sequence, which was not seen within our recordings. Mining operations at a rock quarry at Catalina Island could have produced impulsive signals but blasting almost solely at night seems unlikely. Gunshot calls of North Pacific right whales (*Eubalaena japonica*) are short, impulsive, broadband (10 Hz to 2 kHz) signals (Rone et al., 2012). They are the rarest of all baleen species and their main distribution range in United States waters lies within the Gulf of Alaska and the Bering Sea; sightings in California waters are rare exceptions (Gendron et al., 1999). Therefore, seal bombs (or similar devices) remain the most likely source for the explosions detected in this study.

Explosions and squid landings were both highest at nearshore sites and lowest offshore (**Figure 1** and **Table 1**). Average SELs above or close to 160 dB re 1 μPa^2-s were recorded at some of these nearshore sites as well (sites A2 and J), indicating that explosions were occurring close to the recording site. Market squids inhabit coastal, pelagic zones from Alaska to Baja California and spawn in nearshore, shallow and sandy habitats in Central and Southern California at the end of their lifespan (Vojkovich, 1998). In Southern California, squid fishing activity is concentrated around Santa Catalina Island and the Channel Islands (Santa Rosa, Santa Cruz, and Anacapa Island; Maxwell et al., 2004); locations where high explosion counts were detected. Squid fishing is prohibited within the Channel Islands Marine Protected Areas. Whenever possible, the squid vessels will operate close to Los Angeles port, where they will land and sell their catch. The mainland sides of Catalina Island and Santa Monica Bay are closed for the use of purse-seine gear and so brail vessels are used instead (California Department of Fish and Wildlife, 2020).

There were some exceptions to the spatial pattern of highest squid landings and explosion activity in nearshore and lowest values in offshore areas. At island-associated sites K and K2, high landings of squid were reported, but few or no explosions were recorded. However, this may have been because recording effort was low at these sites (about 4 months per site, but each at least partly within squid fishing season). Although explosion counts were generally lower at offshore sites, site H, located near Tanner Bank, had high explosion counts over several seasons. Almost no squid fishing was reported within fishing blocks around site H. Since we also saw low CPF and HMS landings in this area, it is possible that a different fishery, outside the purse-seine sector, is the main source for explosions around site H. Another potential explanation is that the explosions occurred at a different location but the oceanographic and bathymetric characteristics around site H contributed to basin-wide propagation of the signal's low-frequency component. This theory is supported by the fact that explosions at site H showed a similar seasonal pattern to explosions and squid landings at other sites. Further analyses of other fishery landings and larger radii for included fishing blocks, as well as sound-propagation modeling taking bathymetric characteristics into account, are required to better understand acoustic detection near Tanner Bank.

We found clear patterns in seal bomb occurrence over various temporal scales. Almost 94% of explosions were detected at night (**Table 1** and **Figure 4**), which indicates their use in a night-time fishery. Simonis et al. (2020) described diel patterns for explosions recorded at the MARS cabled observatory in Monterey Bay during 2015–2018, where the majority of explosions also happened at night. Market squids are usually caught at night with purse-seine, drum-seine or brail vessels assisted by light boats, which use high-intensity lights to attract the spawning squids toward the sea surface, where they are more easily encircled with large nets (California Department of Fish and Game, 2005). Whether sardines and other CPF species are caught during the day or at night depends on the region (Kaltenberg and Benoit-Bird, 2009; Krutzikowsky and Smith, 2012; Lynn et al., 2014). Fishing for HMS (bonito and tuna) is generally possible during day and night (Walker et al., 2010; Hall and Roman, 2013).

Total numbers of explosions were reduced on Fridays and Sundays and were almost absent on Saturdays (**Figure 5**). This pattern seems to reflect the closures that occur in the squid fishery. There is a weekend closure for the commercial market squid fishery from the United States-Mexico border to the California-Oregon border between Friday noon and Sunday noon each week to allow a period of 48 h of uninterrupted spawning (California Department of Fish and Game, 2005). This weekend closure results in reduced landings on weekends. For squid caught on Sunday evenings, after the closure, it is common to not be landed until Monday. The CPF fishery showed a similar weekly pattern to the squid fishery, with decreased landings on the weekend. Many fishermen for squid and sardines are the same and can use their nets to catch either. Sweetnam (2010) reported that in 2008, during times when both fisheries were active, daily landings of sardines were minimal on weekends. Fishing for market squid is much more profitable, and so it affects the CPF fishing sectors. All fisheries depend on market demand: market squid have a higher volume and value and so, if the processors have to reduce staff on weekends due to the market squid closure, it might result in reduced demand for sardines on weekends as well.

Although peaks in occurrence varied by site, explosions were typically lowest in spring (**Figures 6**, **7** and **Supplementary Table 2**). This seasonal pattern is similar to that of market squid landings. In California, the market squid fishery is managed through a state-based management plan. The fishing season runs from 1 April through 31 March the following year with a seasonal catch limitation of 118,000 tons and a subsequent fishing closure after those limits are reached until the end of the season (California Department of Fish and Game, 2005). There are two distinct market squid fisheries in California: one in the Southern California Bight, where most fishing occurs between mid-fall and late winter, and one in Monterey Bay, where the fishery usually spans from late spring to early fall (California Department of Fish and Wildlife, 2020). Accordingly, Simonis et al. (2020) also reported a strong seasonality with peaks in explosion occurrence in Monterey Bay in 2015–2018 mostly during the summer months, but for some years also in late spring and fall.

We considered the ability of fishermen to deploy the large number of explosives detected at some sites. Taking landing receipts per day as a proxy for the number of vessels operating in an area into account, we calculated that on average, per site with "high" explosion occurrence, each vessel may have been responsible for 20–100 explosions per night (assuming an average night duration in Southern California), which is about 2–8 explosions per hour from each vessel. As an example, on the day with maximum recorded explosion counts of 2,800 (February 23, 2009 at site G2) 27 squid landing receipts were issued for that area. This resulted in an average of eight explosions per vessel per hour over the course of the night (night-length was 12.75 h for that day). This assumes that every squid vessel (but no vessels from other fishing sectors) used seal bombs and that they were used evenly throughout the night, which both may not be true (e.g., seal bomb usage could be concentrated during certain actions, like hauling the nets). Even so, when considering the number of potential vessels involved, the number of seal bombs used per squid vessel appears to be feasible. However, exceptionally high rates of confirmed explosions on short time scales (up to ~400 explosions per hour) attest to the high level of use that can occur sometimes.

The correlation between explosions and squid landings/receipts, as well as the spatial and temporal overlap of explosions and known squid fishing practices, leads us to conclude that the major source of seal bombs detected in this study is the market squid fishery. However, as not all sites showed significant correlations, there is likely another fishery, not analyzed in this study, which uses explosive deterrents. Additionally, it is possible that seal bombs are used to some extent during CPF fishing as well, as fishermen for market squid and CPF are often one and the same. Though this does not seem to be a main source compared to squid fishing over our study period and sites, as no significant correlation was found (**Supplementary Table 4**). However, CPF fishing seemed to be mostly concentrated around Catalina Island and Santa Monica Bay/San Pedro; sites which were not sampled on a long-term basis.

Sea lions in California prey on squids and CPF (Weise and Harvey, 2008); both fisheries as well as sea lions are concentrated in coastal areas. However, correlations with explosion occurrence only found for squid indicate the possibility that seal bombs are also being used for other reasons beside pinniped deterrence within the squid fishery.

Interannual Variation of Explosions and Fisheries

Explosion counts in the Southern California Bight decreased from 2009 to 2015 with lowest values in 2014 and 2015. Squid landings also decreased around the five sites with long-term recordings, again particularly in 2014 and 2015, although an overall decreasing trend was not as pronounced as it was for explosions (**Table 3** and **Figure 8**). Yearly fluctuations in landings indicate that changes occurred in the commercial fishing industry, which likely impacted seal bombs usage, too.

In 2011, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) began enforcing the regulations of the Safe Explosives Act, making the purchase and handling of seal bombs more difficult for the fishing community (27 Code of Federal Regulations, Part 555, Subpart D, G, and K[1]). The increased paperwork for permits and reports, as well as specific storage regulations (which may be difficult to implement on fishing vessels), likely made seal bombs a less attractive resource.

Additionally, during the period of this study, there were environmental variations that could have impacted the use of seal bombs: a warm water "blob" between 2013 and 2016 (Gentemann et al., 2017) and El Niño events in 2009/2010 and 2015/2016, which affected the market squid fishery. The market squid fishery is one of the biggest and most important fisheries in California in terms of volume and value: most years it is the number one fishery in the state (California Department of Fish and Game, 2012; California Department of Fish and Wildlife, 2014, 2015). However, market squids are very sensitive to rising ocean temperatures, such as during El Niño events, and so the fishery tends to fluctuate along with environmental variation. Historically, overall squid landings decreased during El Niño and later recovered during La Niña

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[1] https://www.atf.gov/explosives/explosives-pest-control-device-requirements (2020/06/25).

phases (Pacific Fishery Management Council, 2019). During the El Niño of 1997/98, the squid fishery disappeared completely around the Channel Islands (Jackson and Domeier, 2003) and the El Niño of 2015/2016 resulted in greatly reduced squid landings as well (California Department of Fish and Wildlife, 2015). The underlying mechanism for this is not yet completely understood but is most likely linked to reduced food availability (krill species) for juvenile squid during times of reduced upwelling (Perretti and Sedarat, 2016). The warming from the "blob" together with early El Niño signals, also affected the geographic distribution of the squid fishery during our study period (Pacific Fishery Management Council, 2019). During the 2014/2015 season, the fishery moved northward resulting in a peak in squid landings off Central California and, for the first time in recent history, squid catches were reported even further north off Eureka, California (California Department of Fish and Wildlife, 2014; Ryley and Protasio, 2015).

The decrease in seal bomb explosions over the years, especially in 2014 and 2015, can be partly explained by the decline in squid landings due to the 2015/2016 El Niño and the warm "blob" event and the resulting geographic shift. Although there was an El Niño in 2009/2010 as well, landings and explosion counts were high in 2009. However, this event was not as strong as the 2015/2016 El Niño and it was characterized by an unusually fast phase transition (Kim et al., 2011). The 2015/2016 El Niño, on the other hand, was one of the most powerful of such events observed, comparable to the 1997/1998 event (Rupic et al., 2018).

Because the decline in explosions was more pronounced than the decline in squid landings, it is likely that other factors, like enforced ATF regulations, have contributed to the decreased use of seal bombs in more recent years as well. However, of the five sites analyzed for long-term trends, high squid landing amounts were only reported around site B (**Figure 1**) and the extent of the overall trend for squid landings in the Southern California Bight might be somewhat different. For example, for the CPF fishery, landings decreased strongly between 2009 and 2015 in the Southern California Bight (California Department of Fish and Wildlife, 2015), which is not reflected in landings around the five long-term sites, because they were low for CPF landings.

Even though detections of explosions decreased over the course of this study, it is possible that their use has since increased again once the squid fishery recovered from the El Niño. However, Simonis et al. (2020) did not report increasing counts of explosions in Monterey Bay between 2015 and 2018/2019.

Conclusion and Outlook

This study aims to improve understanding of where and when seal bombs are being utilized and of their likely impact on marine life, so that their future use can be better regulated. Until recently, the few published studies on the use of seal bombs have typically been from the 1990s or earlier, have often not been peer-reviewed, and primarily deal with the effectiveness of seal bombs as a marine mammal deterrent, not as a noise pollutant. However, in recent years, studies have begun to focus on seal bombs as a potential threat to marine life. The present study is the first long-term regional study on seal bomb explosions, and the first to closely examine their use within the purse-seine fishery. More research on impacts and the implementation of potential regulations on their use are greatly needed.

During peak times, seal bombs were likely one of the major anthropogenic noise sources off Southern California, with great potential to affect the marine environment and the behavior of marine animals, like cetaceans, which depend on hearing as their primary sensory mode. Extensive seal bomb noise has also been recorded in the vicinity or even inside National Marine Sanctuaries (the Channel Islands and Monterey Bay), which is especially problematic as anthropogenic interference should be minimal in these protected areas. The Southern California Bight is an important squid fishing ground and local communities depend on it. Fishermen have expressed, that damaged nets and predation on the catch by sea lions is a serious problem that results in significant economic losses. The results of our study suggest that this may be a particular problem for the market squid fishery. Taking an ecosystem-based approach as a basis, management and regulation should ensure that conservation and sustainable use are promoted in an equitable way. Therefore, communication and collaboration with fishermen are of great importance to cooperatively find a solution, as they will be able to add valuable information on the importance of seal bombs to their catch success and possibly on potential alternatives to seal bombs as deterrents.

Kerr and Scorse (2018) recommend that state and federal agencies immediately review their policies and invest more toward research and monitoring of seal bombs, as they pose a risk to the marine environment in California. The results of this study support NOAA in its objective to implement the proposed guidelines for "Safely Deterring Marine Mammals" (NOAA, 2020), as they would be the first to regulate seal bomb usage. The guidelines recommend the following regulations: The use of seal bombs is prohibited when cetaceans are present within a 100 m radius and a visual scan for cetaceans must be repeated before each deployment. For pinnipeds, a minimum safe distance (phocids 20 m, otariids 2 m) and a 180 s silent interval between deployments must be kept. If visibility is poor ($<$100 m) seal bomb use is prohibited. Additionally, seal bombs must explode behind an animal and not in front of it.

Our research indicates that simultaneous use of seal bombs by multiple fishing vessels in one area should also be considered for regulations, as such an occurrence would increase local impacts and make it difficult to ensure the 180 s silent period between deployments, which is necessary to give animals time to flee before hearing damage due to cumulative exposure is reached. As our results have also shown high sound exposure levels within a National Marine Sanctuary, further regulations to protect these sensitive areas, for example a buffer zone around protected areas, where seal bomb use is restricted or prohibited, could minimize negative impacts.

Not every recording site showed high correlations of explosions and squid landings. This means that there is likely another fishery using seal bombs and landings from other nighttime fisheries outside the purse-seine sector should also be tested for correlation with explosions. Research on more recent explosion occurrence off Southern California is needed to determine if seal bomb use has increased again with the recovery of the squid fishery after the warm water events. Another explosive deterrent, namely cracker shells, has recently (in 2019) been exempted from ATF regulations[2]. As they can now be purchased without a permit when used for legitimate wildlife control purposes, they might become more attractive for marine mammal deterrence within fisheries.

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[2] Stoneco Energetic Systems LLC. https://www.stonecowildlifecontrol.com/12-gauge-shellcracker.html (10/04/2021).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SB-P and AK designed the study. AK, AR, SB-P, SW, KF, FR, and JT were responsible for signal detection, programming, and data analysis. JR and AS contributed data and information on seal bomb use in Monterey Bay. AK and AR created graphical output. AK wrote the manuscript. SB-P, AD, and H-US provided conceptual guidance. All authors provided comments to improve the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.796849/full#supplementary-material

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Supplementary Material Chapter 1

Supplementary Table 1. Location, deployment depth (average over all deployments), years and total number of days with acoustic recording effort for the 21 passive acoustic monitoring sites in the Southern California Bight and the Monterey Bay area.

Site	Latitude (N)	Longitude (W)	Depth (m)	Years	Total days
Southern California Bight					
A	33° 15.1'	118° 15.4'	340	2005 – 2007	419
A2	33° 13.7'	118° 16.1'	1130	2008 – 2009	419
B	34° 16.4'	120° 01.5'	590	2006 – 2015	2504
C	34° 19.0'	120° 48.0'	780	2005 – 2015	2657
E	32° 39.1'	119° 28.9'	1310	2006 – 2009	802
G	32° 55.6'	118° 38.1'	440	2007 – 2008	397
G2	33° 08.4'	118° 52.8'	1120	2009	265
H	32° 50.8'	119° 10.6'	1000	2007 – 2016	2424
J	34° 08.4'	119° 59.3'	260	2008 – 2009	365
K	33° 50.2'	120° 07.3'	300	2008	124
K2	34° 00.0'	120° 32.5'	560	2008 – 2009	137
K3	33° 54.8'	119° 33.9'	990	2009	133
LJP	32° 53.4'	117° 24.0'	700	2015 – 2016	389
M	33° 30.8'	119° 14.9'	910	2009 – 2015	1907
N	32° 22.2'	118° 33.8'	1280	2009 – 2016	2006
P	32° 53.6'	117° 22.9'	480	2009 – 2010	127
Q	33° 49.2'	118° 37.7'	680	2009 – 2010	266
R	33° 09.6'	120° 00.5'	1200	2009 – 2011	484
S	32° 29.1'	118° 16.3'	1380	2009 – 2011	356
Monterey Bay area					
M1	36° 45.6'	122° 01.4'	890	2015 – 2016	352
PS	36° 17.9'	122° 23.6'	1120	2009 – 2012	837

Supplementary Table 2. Overview of explosion counts per site and season: % of EPD, median explosion counts per EPD and maximum daily explosion counts.

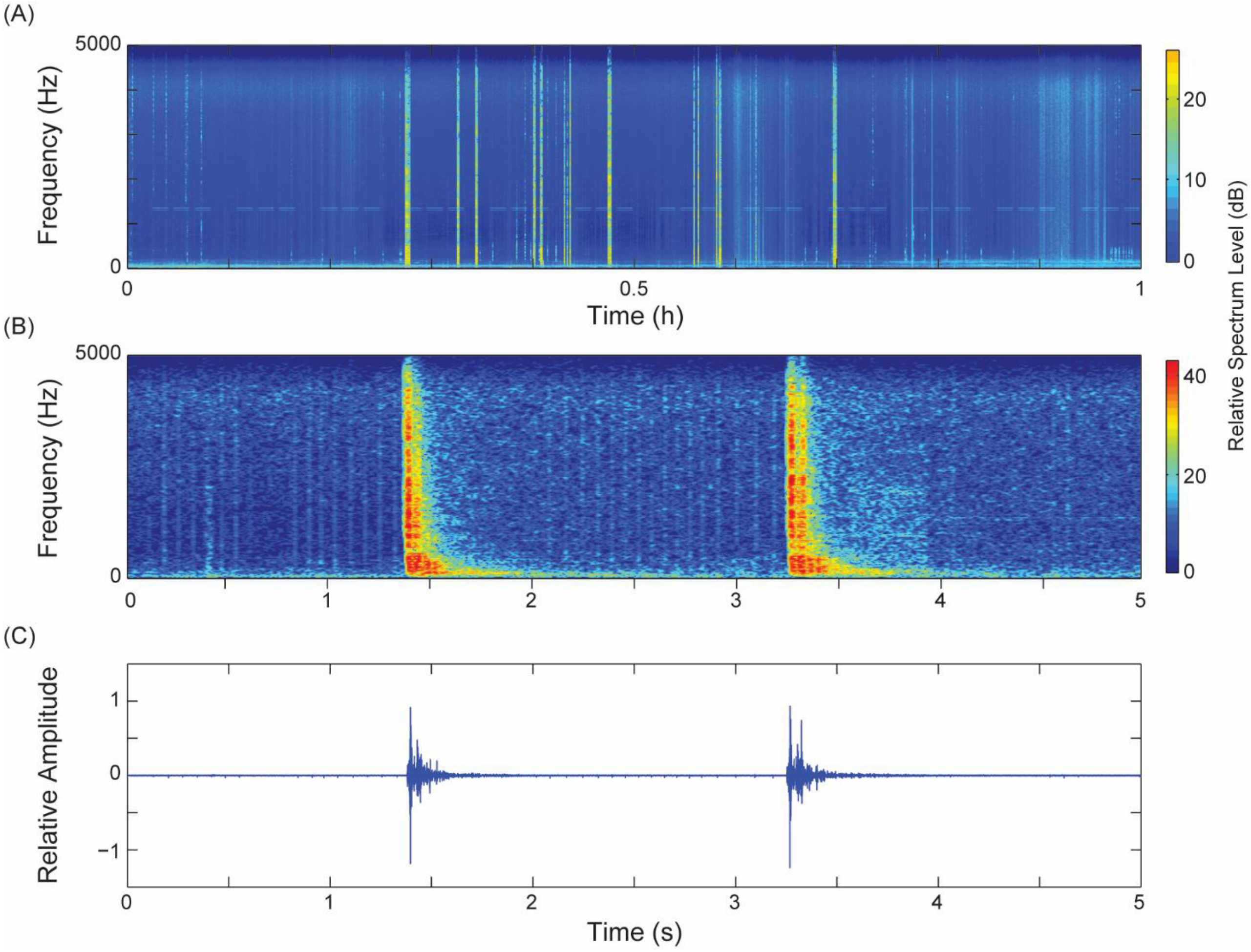
Site	Category	Winter			Spring			Summer			Fall		
		% EPD	Median/EPD	Daily Max.	% EPD	Median/EPD	Daily Max.	% EPD	Median/EPD	Daily Max.	% EPD	Median/EPD	Daily Max.
Southern California Bight													
G2	High	79.2	116	2,798	66.7	36	2,077	93.5	208	1,718	68.6	74	1,007
Q		85.7	150	1,825	64.1	8	219	80.4	8	153	98.2	640	2,041
A		73.2	120	1,169	NA	NA	NA	81.6	17	272	84.9	49	759
A2		80.7	35	1,134	79.9	29	1,186	96.7	60	305	54.5	3	81
K3		NA	NA	NA	100	30	46	22.9	10	253	92.0	556	1,815
M	Medium	28.6	19	1,076	26.3	10	867	52.1	64	700	43.2	73	1,493
B		25.0	53	992	26.9	13	511	42.6	42	709	47.7	35	2,153
H		36.2	15	2,620	41.2	14	1,557	79.6	65	1,521	67.2	40	1,508
J		92.6	263	1,518	75.0	21	22	25.3	5	149	28.9	4	1,770
E		27.5	4	740	29.0	5	1,122	48.0	12	570	25.5	4	215
G		48.6	25	361	16.3	3	81	48.4	3.5	40	78.2	65	667
P		80.0	15	594	51.9	7	37	NA	NA	NA	77.4	4	50
N		25.1	2	223	27.8	2	69	45.3	9	347	39.2	33	559
S	Low	36.0	14	240	22.1	6	63	84.1	18	338	11.5	2	6
LJP		34.1	5	96	49.1	5	95	67.3	6	206	70.6	11	124
R		7.1	3	163	9.2	1	7	14.3	2	49	34.3	5	893
C		1.5	3	16	1.4	3	103	17.6	19	212	4.8	20	238
K2		13.1	7	81	NA	NA	NA	NA	NA	NA	NA	NA	NA
K		NA	NA	NA	NA	NA	NA	0	0	0	0	0	0
Monterey Bay area													
M1	Low	4.4	2	9	29.3	3	10	46.2	16	162	46.2	25	279
PS		4.8	7	57	6.3	4	11	34.9	12	191	18.8	16	69

Supplementary Table 3. Results for parameters included in the GAMs for explosions counts, squid, CPF and HMS landings. The smooth term (calendar week) with a cyclic cubic regression spline is shown with estimated degrees of freedom and categorical factors (year and site) are indicated with standard error. Significance of predictors is indicated as following *p<0.05, **p<0.01, ***p<0.001. The Tweedie power parameter (Tweedie), AIC, R-squared adjusted and deviance explained are provided as well for each model. Only estimates from the best models are presented here.

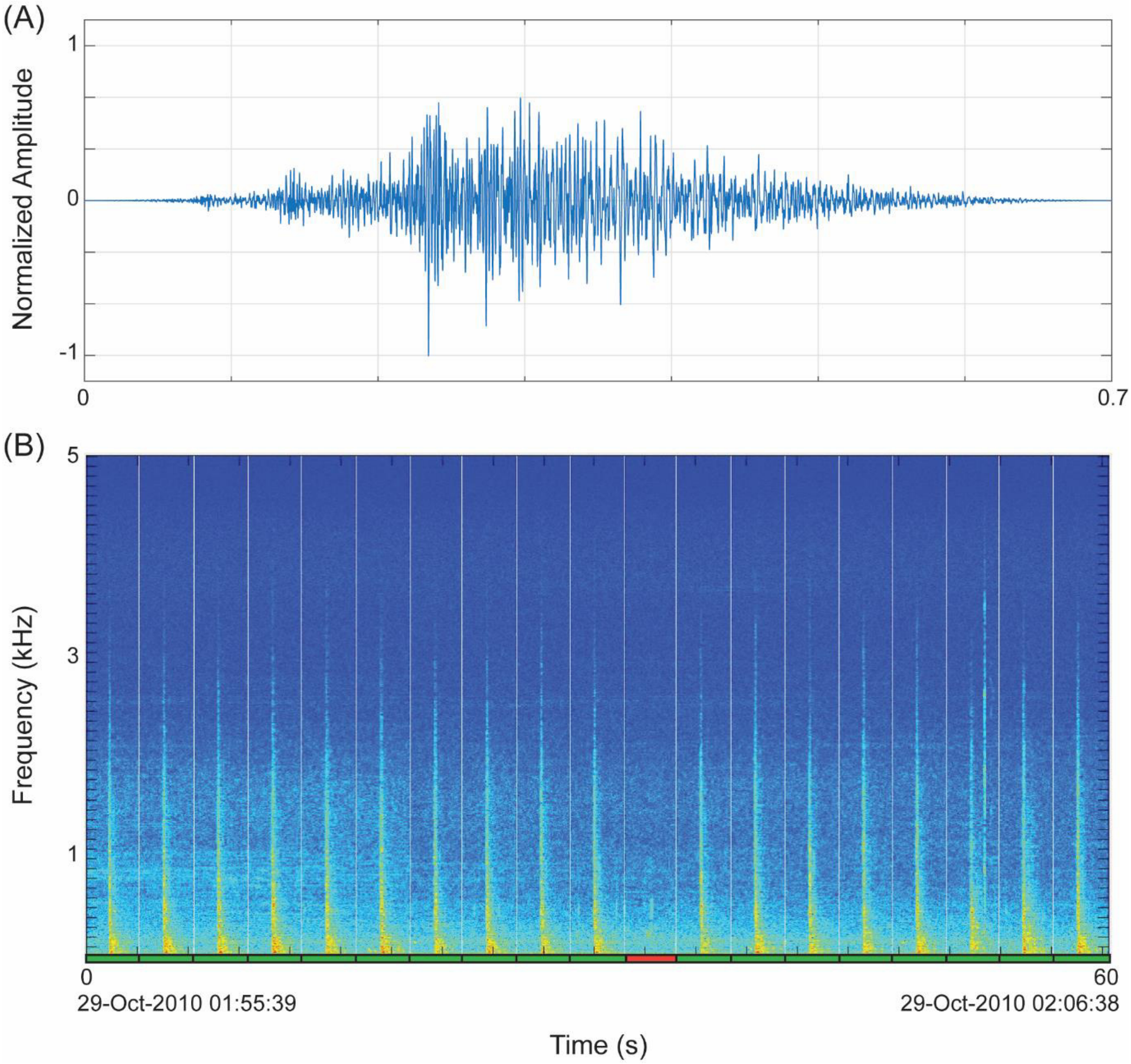
Model	**Explosions**	**Squid**	**CPF**	**HMS**
Tweedie	1.80	1.68	1.62	1.53
Week	7.41***	7.78***	7.61***	9.97**
Intercept	0.41***	0.22***	0.22***	50.26
Year				
2006	0.51			
2007	0.50			
2008	0.52*			
2009	0.51***			
2010	0.52***			
2011	0.52***			
2012	0.52*			
2013	0.53			
2014	0.52			
2015	0.55			
2016	0.68			
Site				
A2	0.48*	0.40	0.36	
B	0.41***	0.25	0.32***	
C	0.40***	0.27***	0.50***	
E	0.43***	1.15***	0.63***	
G	0.49***	0.40**	0.40**	
G2	0.51***	0.48	0.57***	
H	0.41***	0.38***	0.41***	
J	0.49***	0.36	0.61***	
K	NA	0.65	1.30***	
K2	0.81***	0.58	1.61***	
K3	0.59***	0.48	0.95***	
LJP	0.59***	NA	NA	
M	0.42***	0.29***	0.41***	
M1	0.62***	0.66*	0.58	
N	0.43***	0.30***	0.42***	
P	0.63***	0.96***	1.92***	
PS	0.51***	0.35***	0.45***	
Q	0.51*	0.42	0.48	
R	0.54***	0.81***	NA	
S	0.54***	0.45***	0.73***	
AIC	23,868	29,266	16,166	4,959
R-sq. adj.	0.18	0.20	0.18	0.03
Dev. expl.	32.6 %	41.0 %	58.4 %	41.2 %

Supplementary Table 4. Statistics of Theil-Sen regression model (slope) and Daniel's Trend test (Spearman rank correlation coefficient rho) with significance level (*** <0.001, ** <0.01, * <0.05, ^{x} not significant) per site for weekly explosions vs. market squid, CPF and HMS landing receipts. NA indicates no fishing effort or insufficient data for analysis.

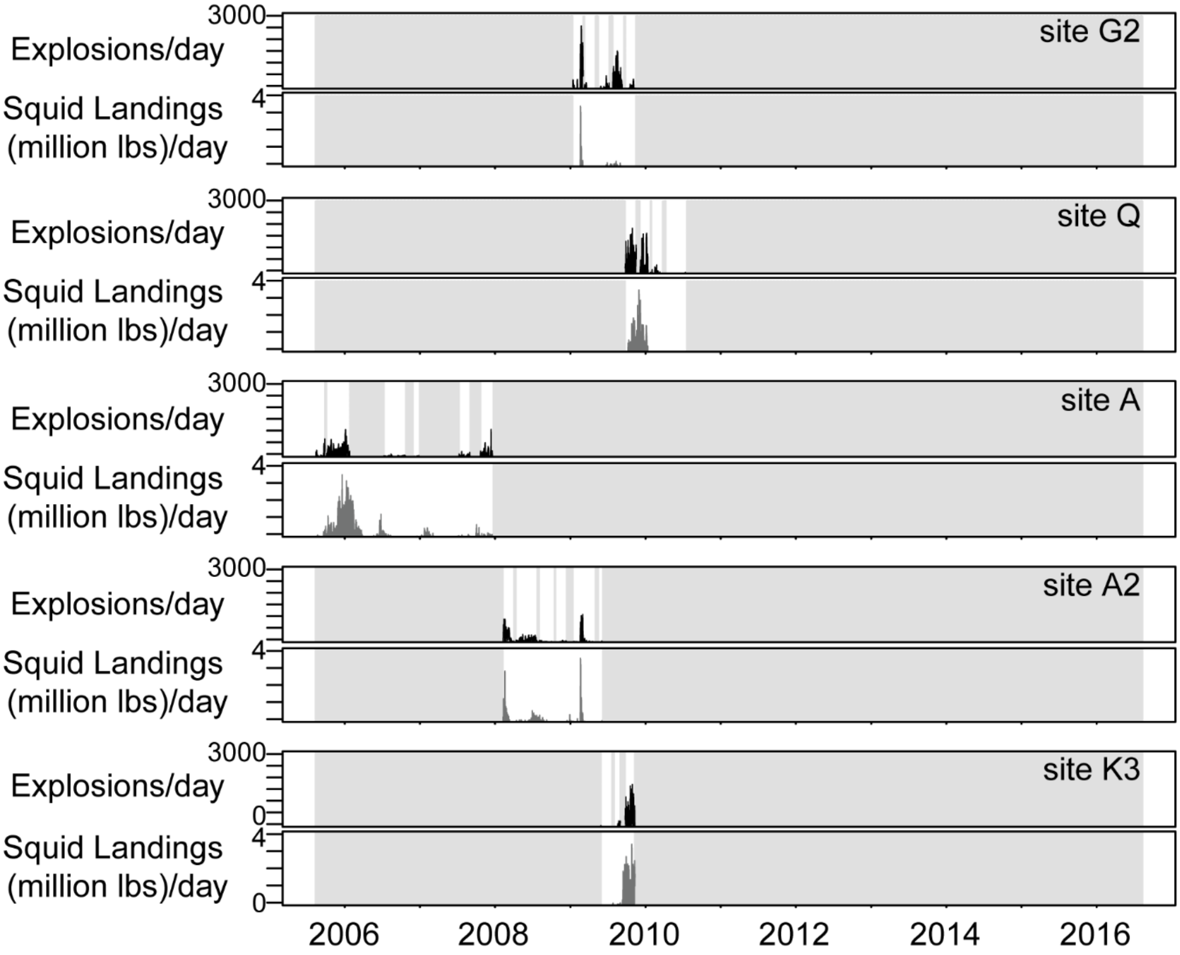
Site	Category	squid		CPF		HMS	
		slope	rho	slope	rho	slope	rho
Southern California Bight							
G2	High	97.45***	0.83***	30.60*	0.16^{x}	2,968^{x}	0.63^{x}
Q		36.25***	0.66***	2.75^{x}	0.19^{x}	NA	NA
A		16.30***	0.77***	-0.45*	-0.01^{x}	82.50^{x}	0^{x}
A2		32.52***	0.68***	2.16***	0.19^{x}	0.25^{x}	0.21^{x}
K3		31.80***	0.88***	-0.83***	-0.18^{x}	NA	NA
M	Medium	33.60***	0.34**	4.50^{x}	0.13^{x}	NA	NA
B		10.12***	0.46***	0.00^{x}	-0.06^{x}	-11.50*	-0.39^{x}
H		266^{x}	0.21^{x}	50.00^{x}	0.05^{x}	407.4***	0.55^{x}
J		9.43***	0.46**	-15.75^{x}	-0.24^{x}	64.33^{x}	0.15^{x}
E		NA	NA	230.00^{x}	0.00^{x}	171.50***	0.57^{x}
G		0.15^{x}	0.18^{x}	-2.00***	-0.26^{x}	22.00^{x}	0.50^{x}
P		NA	NA	NA	NA	NA	NA
N		6.18*	0.26^{x}	3.75^{x}	0.13^{x}	2.71^{x}	0.30^{x}
S	Low	213.5^{x}	0.63^{x}	60.25^{x}	1.00^{x}	NA	NA
LJP		NA	NA	NA	NA	NA	NA
R		NA	NA	NA	NA	NA	NA
C		10.86***	0.53***	NA	NA	NA	NA
K2		0^{x}	-0.02^{x}	NA	NA	NA	NA
Monterey Bay area							
M1	Low	13.08***	0.76**	0.00^{x}	-0.09^{x}	NA	NA
PS		0^{x}	0.01^{x}	0.00^{x}	0.00^{x}	NA	NA



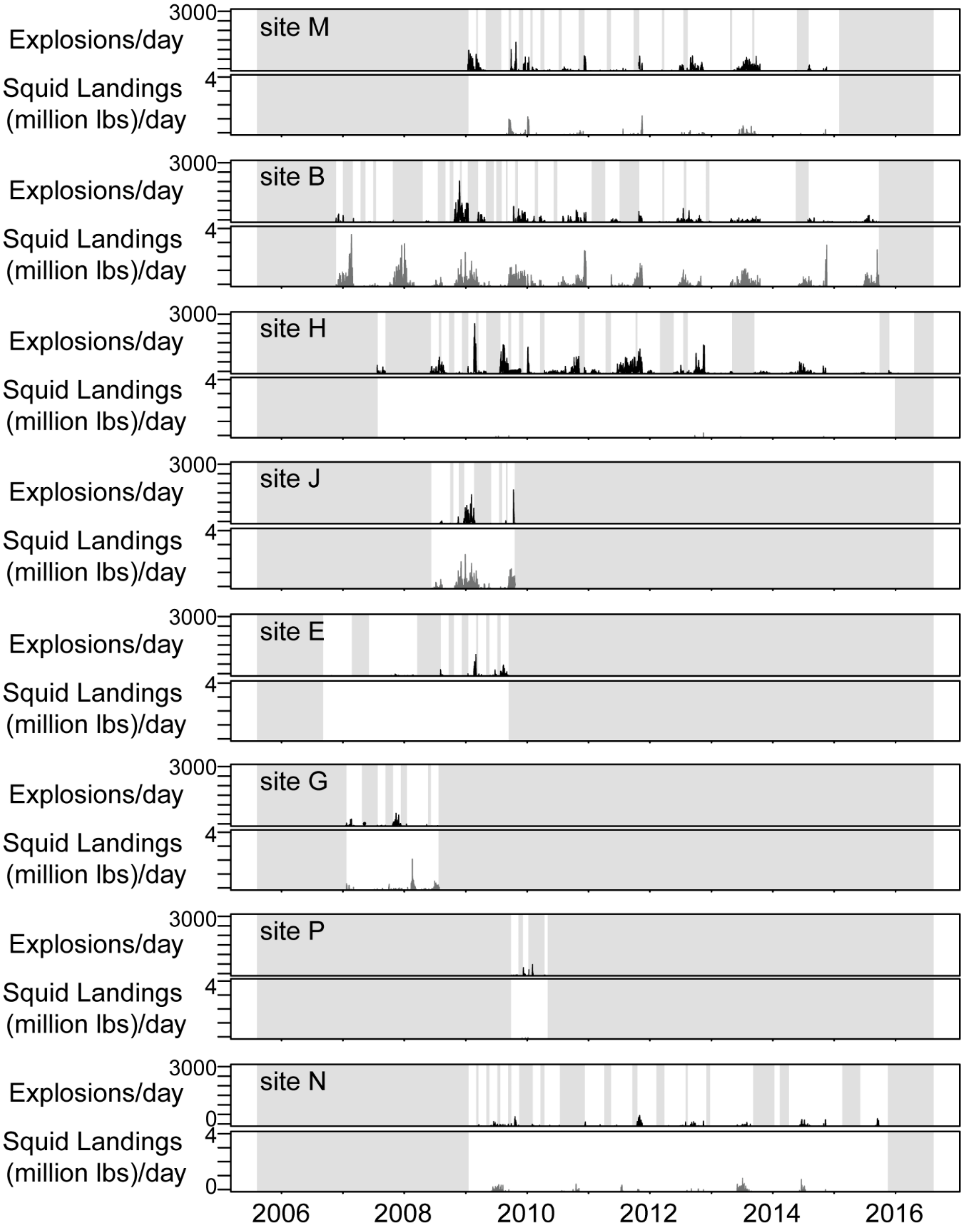
Supplementary Figure 1. Example of explosions on January 6, 2009 at site J in a (A) 1-h long-term spectral average, (B) 5-s spectrogram with 500-point fast Fourier transform length and 90% overlap, and (C) 5-s waveform.



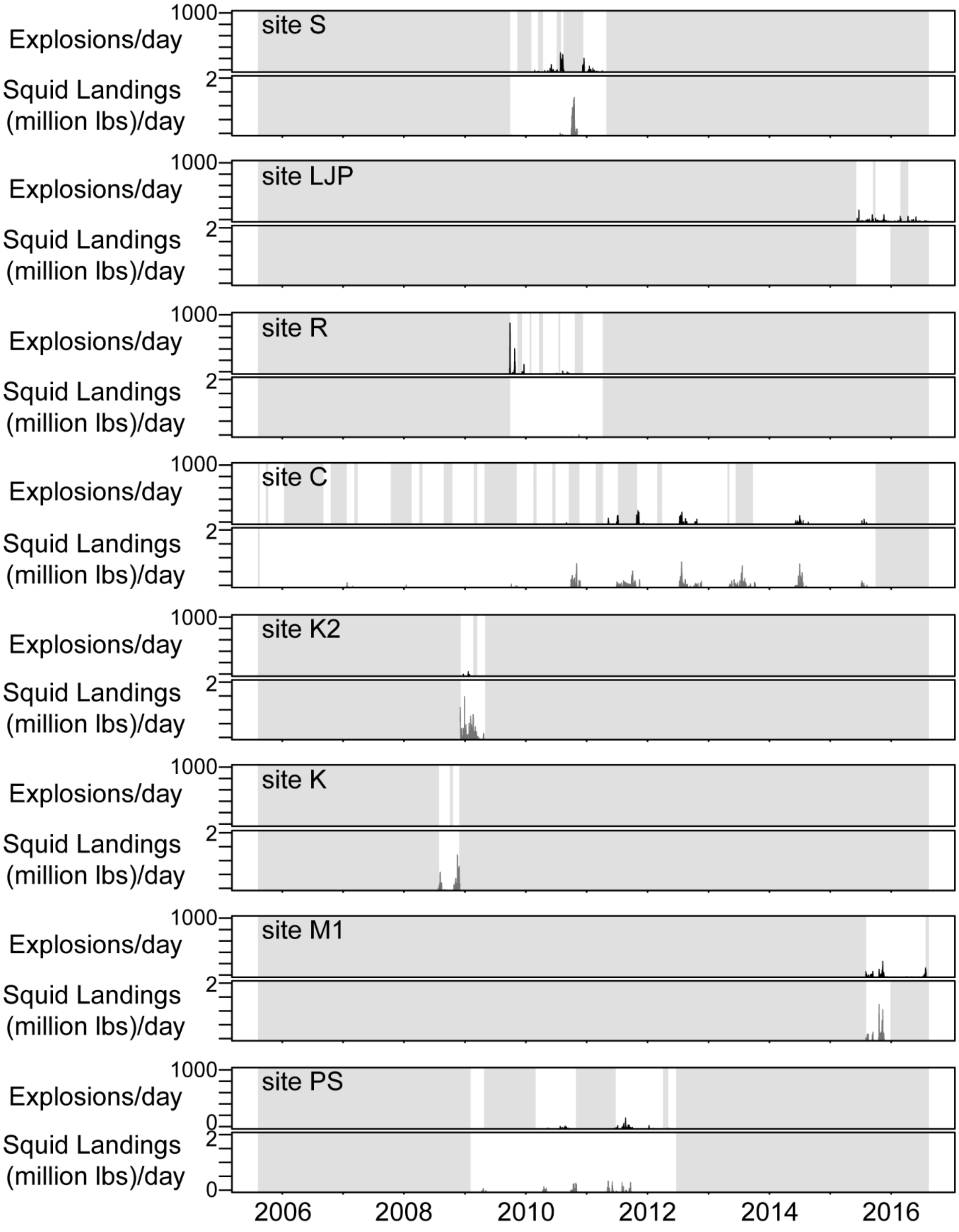
Supplementary Figure 2. (A) Amplitude normalized waveform of the template explosion signal used for explosion detection. (B) Example of manual verification stage of explosion detection process. Concatenated spectrograms of detected explosions are shown at site J on October 29, 2009. Green along the bottom evaluation line indicates true detections and red indicates false detections. Detections are shown with 1 sec. padding time before and after the signal, resulting in 60 sec depicted in sum by the figure.



Supplementary Figure 3. Timeseries of daily explosion counts (black) and daily squid landings (grey) at sites with high explosion occurrence. Grey shading denotes periods with no recording effort.



Supplementary Figure 4. Timeseries of daily explosion counts (black) and daily squid landings (grey) at sites with medium explosion occurrence. Grey shading denotes periods with no recording effort.



Supplementary Figure 5. Timeseries of daily explosion counts (black) and daily squid landings (grey) at sites with low explosion occurrence. Grey shading denotes periods with no recording effort.

Chapter 2: Seal Bomb Explosion Sound Source Characterization

This paper was published in the Journal of the Acoustical Society of America in 2021. The experiment was planned by me together with my advisor Dr. Simone Baumann-Pickering. The field experiment at sea was carried out by me together with Dr. Sean Wiggins, Dr. Simone Baumann-Pickering and Dr. LeRoy Dorman. Dr. Sean Wiggins analyzed the data and wrote most of the manuscript. I co-authored the manuscript.

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JASA ARTICLE

Seal bomb explosion sound source characterization

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ABSTRACT:
Small explosive charges, called seal bombs, used by commercial fisheries to deter marine mammals from depredation and accidental bycatch during fishing operations, produce high level sounds that may negatively impact nearby animals. Seal bombs were exploded underwater and recorded at various ranges with a calibrated hydrophone to characterize the pulse waveforms and to provide appropriate propagation loss models for source level (SL) estimates. Waveform refraction became important at about 1500 m slant range with approximately spherical spreading losses observed at shorter ranges. The SL for seal bombs was estimated to be 233 dB re 1 μPa m; however, for impulses such as explosions, better metrics integrate over the pulse duration, accounting for the total energy in the pulse, including source pressure impulse, estimated as 193 Pa m s, and sound exposure source level, estimated as 197 dB re 1 $\mu\text{Pa}^2\ \text{m}^2$ s over a 2 ms window. Accounting for the whole 100 ms waveform, including the bubble pulses and sea surface reflections, sound exposure source level was 203 dB re 1 $\mu\text{Pa}^2\ \text{m}^2$ s. Furthermore, integrating the energy over an entire event period of multiple explosions (i.e., cumulative sound exposure level) should be considered when evaluating impact.
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I. INTRODUCTION

Seal bombs, also known as explosive pest control devices and seal deterrent devices, among other names, are hand-thrown pyrotechnic devices capable of exploding underwater and are used as a means to deter marine mammals during commercial fishing operations. For example, seal bombs were used at least as early as 1980 in the eastern tropical Pacific (ETP) yellow fin tuna purse-seine fishery to control dolphin swimming direction during all stages of net setting (Cassano *et al.*, 1990). More recently, underwater recordings of thousands of explosions per month were spatially and temporally correlated with commercial landings data of California market squid, suggesting that seal bombs were used extensively during squid fishing operations (Meyer-Löbbecke *et al.*, 2016).

A primary concern with the use of seal bombs is potential harm to marine mammals, especially animals in close proximity to the explosions. While non-hearing physical damage was estimated for close ranges (<4 m; Myrick *et al.*, 1990a), hearing related impacts such as temporary threshold shift (TTS) and permanent threshold shift (PTS) or loss of hearing may occur at more distant ranges (e.g., Finneran, 2015). Furthermore, behavioral responses to explosions of the targeted animals, in addition to non-targeted marine mammals, may cause harm by altering biologically significant behaviors such as foraging (e.g., Southall *et al.*, 2007).

Seal bomb source characterization is needed to provide metrics for managing marine noise pollution and mitigating effects on marine mammals due to high sound pressures from these explosions. We describe an experiment offshore of Southern California in which seal bombs were deployed and exploded at various ranges from an underwater sound recorder. The received sound pressure waveforms were analyzed, and various metrics were estimated to provide a characterization of the seal bomb source, including source level (SL), an important metric for marine noise management.

II. METHODS

A. Experiment overview

Experimental operations were conducted in late spring 2017, offshore of Southern California, when more than 600 seal bombs were individually exploded underwater over three days and recorded with an autonomous hydrophone. The free-floating autonomous hydrophone recorded these explosions at various ranges from less than 300 m to more than 8 km while deployed a few hundred meters beneath the sea surface above seafloor depths ranging from 635 to 870 m (Fig. 1 and Table I). Global positioning system (GPS) receivers were attached to both the seal bomb deployment ship, Scripps Institution of Oceanography Research Vessel (R/V) Saikhon, and a sea surface float above the hydrophone

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TABLE I. Autonomous acoustic recorder nominal locations for three deployments.

Deployment number	Date	Latitude (N)	Longitude (W)	Hydrophone depth (m)	Seafloor depth (m)
01	30 May 2017	32° 52.034′	117° 29.235′	265	715
02	01 Jun 2017	32° 52.052′	117° 27.750′	265	635
03	02 Jun 2017	32° 51.443′	117° 32.802′	265	870

to provide source-receiver ranges. These ranges along with measured sound pressures at the hydrophone receiver provided the measurements needed to estimate seal bomb source levels.

B. Seal bombs

Seal bombs are similar to pyrotechnic firework salutes that generate a loud report (i.e., bang) along with a bright flash when their explosive material, flash powder, is ignited. Flash powder is a low explosive that deflagrates (i.e., burns and builds up and then decreases pressure over the time of the explosion), although at a much faster rate than black powder (gunpowder), and should not be confused with detonation of high explosives, such as trinitrotoluene (TNT), where a shock wave (i.e., a wave front traveling faster than the speed of sound) is generated and maximum pressure is sudden but decays quickly and exponentially.

While there are different seal bomb manufacturers around the world using various amounts (~2–6 g) and different formulations of flash powder (Myrick *et al.*, 1990b), this study was limited to one type of seal bomb, the Seal Cracker Device, manufactured by Stoneco Energetics Systems LLC (Prescott Valley, AZ). The Seal Cracker Devices, from here onward referred to as seal bombs, were ~8.3 cm long × 1.7 cm diameter cardboard tubes wrapped with yellow paper and a bright orange label with a ~6.7 cm long × 0.3 cm diameter green fuse protruding from one of the plastic-plugged ends [Fig. 2(a)]. Inside the tube were two chambers: a lower one with silica sand used to provide weight so that the seal bomb will sink upon deployment and an upper one containing flash powder and the unlit end of the fuse for deflagration initiation [Fig. 2(b)]. The seal bomb had a visco fuse that had a black powder core and was coated with nitrocellulose for water resistance so that it would continue to burn after deployment underwater. The fuse burn duration before explosion was about 8 s. Explosion depths were estimated to be 1–4 m (Myrick *et al.*, 1990b).

The seal bombs used in this study had a charge mass of 2.33 g of flash powder and used a standard formulation of about 64.0% potassium perchlorate ($KClO_4$) as the oxidizer and a fuel of 25% aluminum powder and 10% sulfur (Stonebraker, 2018). This charge mass was similar to common M-80 salutes classified as consumer fireworks.

During the experiment, the free end of the seal bomb fuse was ignited using a standard home-improvement-style push-button torch hose kit connected to a 400 ml (14 fluid oz) bottle of propane. After ignition, the seal bomb was tossed by hand into the water 5–10 m starboard and off the rear quarter of the R/V Saikhon while under way at ~3 m s^{-1}

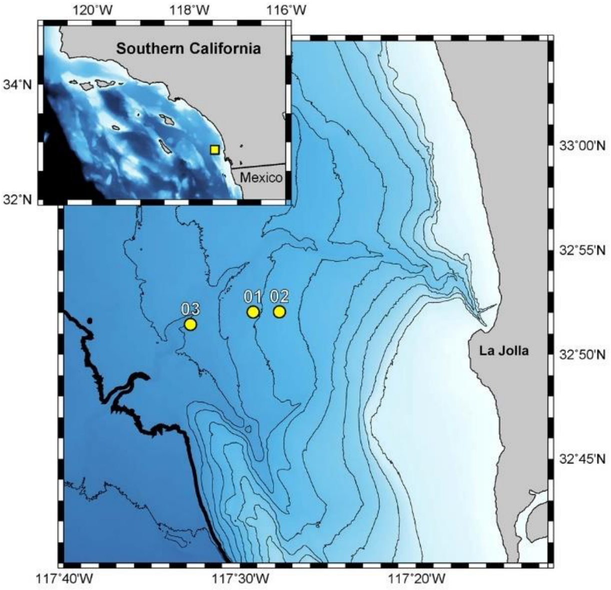

FIG. 1. (Color online) Bathymetric map of experiment area offshore of La Jolla, CA. The inset map yellow square shows the study area. Yellow circles 01, 02, and 03 were autonomous hydrophone deployment sites for 30 May and 1 and 2 June 2017, respectively. Thick contour was 1000 m depth, with thin contours at 100 m increments. Dark colors were deeper and farther offshore.

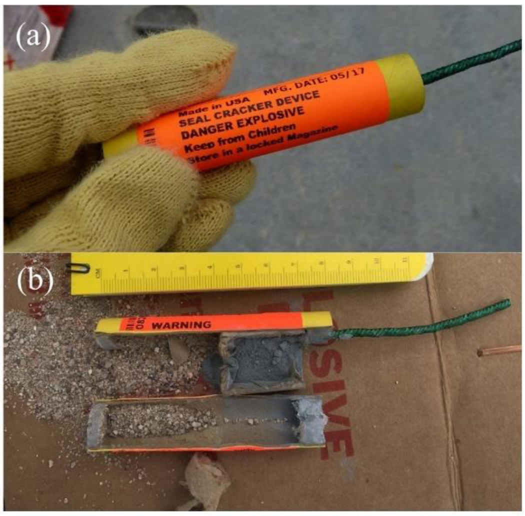

FIG. 2. (Color online) Seal bomb—Stoneco Energetics System, LLC Seal Cracker Device. (a) Seal bomb prior to ignition and deployment. (b) Seal bomb cut long-axis showing internal contents with two chambers: silica sand for sinking weight and gray flash powder with green fuse for underwater explosion.

(11 km h^{-1}; 6 kn). Seal bombs were deployed approximately every 30 s along a transit line, marked with the ship's GPS. Notes were logged for each seal bomb deployment including time, location, and type of explosion (good, dud, shallow) along with changes in deployment schedule due to deviations in ship track or pauses during marine mammal, fish, or bird presence to avoid their use in the proximity of marine animals.

C. Underwater recordings

To measure sound pressures of seal bomb explosions, recordings were made using an autonomous high-frequency acoustic recording package (HARP; Wiggins and Hildebrand, 2007). The HARP was configured to record at a 200 kHz sample rate with 16-bit samples onto laptop computer type hard disk drives. Since seal bombs generate high sound pressures and some source-receiver ranges were relatively short, the sensitivity of the hydrophone was reduced from standard HARP hydrophones by about 40 dB to prevent signal clipping. The hydrophone was constructed of two sensors: Benthos (North Falmouth, MA) AQ-1 for frequencies below 10 kHz and International Transducer Corporation (Santa Barbara, CA) 1042 for frequencies above. The sensors are specified as having approximately the same sensitivity of −201 dB re 1 V/μPa. The hydrophone signal conditioning electronics gain was set to be 10 dB with a full system peak clip level ~200 dB re 1 μPa, and the full band frequency response (10 Hz–100 kHz) was calibrated in our lab at Scripps Institution of Oceanography so that absolute received sound pressures could be measured.

Typically, HARPs are deployed on the seafloor as bottom-mounted instruments or in a mooring configuration including an acoustic release system used for jettisoning ballast weight and instrument retrieval. For this study, the data logger housing and hydrophone were suspended beneath the sea surface in a multiple float and weight system such that the hydrophone was decoupled from vibrations and motions of the sea surface float (Fig. 3). The hydrophone was placed at 265 m depth, well below the thermocline to avoid problems with acoustic raypath refraction. Attached to a flagpole on the sea surface float about 1.5 m above the waterline in a plastic bag was a dog collar GPS [Garmin (Schaffhausen, Switzerland) Astro 32 with T5]. The dog collar transmitted positions every 2 min via radio frequencies to its receiver onboard the R/V Saikhon for logging. Float drift rate was less than 0.06 m s^{-1} (2 km h^{-1}; 0.1 kn). The receiver for the dog collar GPS also was used to record the ship GPS positions.

After recovery of the recorder, the hard disk drives were removed, and disk image files of raw data disks were generated for archiving and processing. Processing raw data into working data included uncompressing and creating multiple 37.5-min audio (wav format) files with high precision time stamps. The audio files were used to make long spectrograms to provide a graphical index for the data, allowing quick and easy access to sound events of interest (see the acoustic analysis software package, *Triton*; Wiggins and Hildebrand, 2007).

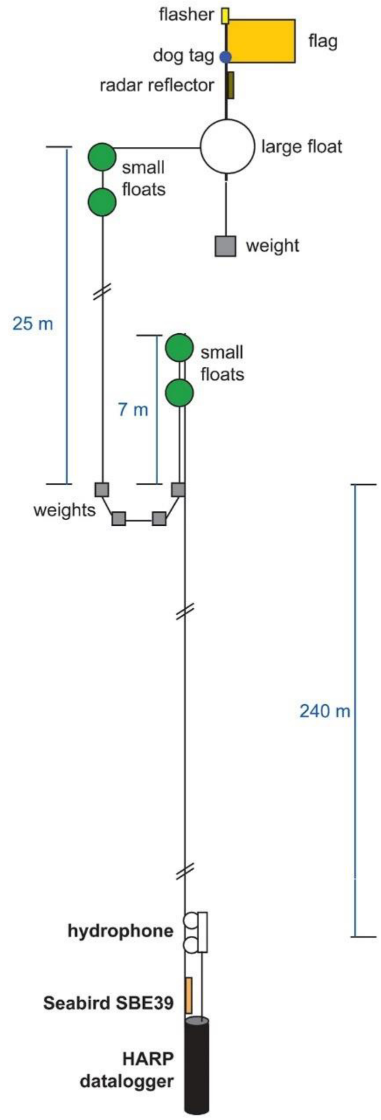

FIG. 3. (Color online) Autonomous acoustic recorder mooring configuration. The large white float was at the sea surface and included a flag, flasher, and radar reflector to prevent being struck by nearby transiting vessels. Also, attached to the flag was a dog collar GPS receiver, which transmitted locations back to R/V Saikhon. Beneath the sea surface on the mooring line was a system of floats and weights to decouple the sea surface motion from the hydrophone at 265 m depth. Hydrophone depth was confirmed via Seabird temperature-pressure logger.

Software was developed in MATLAB (Mathworks, Inc., Natick, MA), to filter, automatically detect, measure amplitudes, and save snippets of received seal bomb shots from the audio files. An eighth order Chebyshev type 2 low-pass filter (LPF) with a stop band edge at 10 kHz was used on the waveforms to reduce apparent high-frequency transient effects from the hydrophone. We did not anticipate any effect from the filter on sound pressure estimates as most of the energy for shallow depth explosions is below 1 kHz with the source spectrum falling off rapidly to at least 20 dB lower around 10 kHz (Weston, 1960). The detector was a simple energy detector with the 0-peak sound pressure threshold set to ~16 Pa (i.e., peak sound pressure level threshold = 144 dB re 1 μPa) to identify pulse first-arrival times. Snippet waveforms from 0.1 s before detection to 1.0 s after detection were saved as binary files. Additional software was developed to evaluate seal bomb shots, including metric calculations and plots.

D. Impulse metrics

Different metrics are used to describe different types of sound pressure signals, expressed in Pa. For example, continuous pressure wave signals from sources such as ships and sonar pings are typically reported as root mean square (rms) of the sound pressure, $p(t)$, over a time window, T,

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt}, \tag{1}$$

where the time window is typically defined as the signal width 3 dB down from the peak sound pressure, the signal width 10 dB down from the peak sound pressure, or from 5% to 95% of the signal's total energy, described as −3 dB, −10 dB, and 90% rms, respectively. Impulsive sounds are usually not well-represented as rms because rms depends on the analysis window duration, which for transient signals is critical (e.g., Madsen, 2005). For example, the rms for a smoothly varying impulse, such as a Gaussian function or underwater explosion, is typically lower for 90% rms than for −3 dB rms because of a longer time window for the 90% rms metric.

Impulsive or transient sounds, such as those from seismic air guns or underwater explosions, are often described as 0-peak (p_{pk}) or peak-to-peak ($p_{\mathrm{pk\text{-}pk}}$) sound pressures; however, these metrics do not account for different pulse shapes and durations. The sound pressure exposure, with units Pa^2 s, accounts for the shape of the pulse and provides a useful comparable metric for transient signals by integrating the squared-pressure of the pulse waveform time series over a time window,

$$E = \int_0^T p^2(t)dt. \tag{2}$$

Another useful and comparable metric for transient signals is the positive acoustic impulse, or pressure impulse, with units Pa s. The positive impulse is often used for studies on the effects of explosions on animals (Richardson *et al.*, 1995) and is the integral of pressure over the duration of the pulse,

$$J_p = \int_0^T p(t)dt. \tag{3}$$

Peak and rms sound pressures are often presented as levels in dB. To convert peak and rms pressures to levels, 20 times the base-10 logarithm of the pressures was used such that $\mathrm{L} = 20\log_{10}(P/P_0)$, where $P_0 = 1$ μPa was the reference value of sound pressure, and L = sound pressure level (SPL) or the peak sound pressure level ($\mathrm{L_{pk}}$) when P was p_{rms} or p_{pk}, respectively. Similarly, for the sound pressure exposure, the sound exposure level (SEL) was calculated as $SEL = 10\log_{10}(E/E_0)$, where the reference value was $E_0 = 1$ μPa^2 s. All metric terminology, units, and reference values were presented as per the International Organization for Standardization document for underwater acoustics (ISO 18405:2017, 2017).

E. Source level estimation

Source level is rarely measured in the field directly as it is referenced at 1 m range, which can be prohibitively close to the source, introducing complexities associated with the near field acoustic environment. Instead, SPLs were measured at ranges much greater than 1 m and range-dependent corrections for acoustic propagation loss, PL (reference value 1 m^2), were applied to estimate SLs at 1 m (reference value 1 μPa m) via the sonar equation,

$$\mathrm{SL} = \mathrm{SPL} + \mathrm{PL}, \tag{4}$$

where values were in dB units (Urick, 1983). Similar to PL, but between two specified locations, neither of which was the source, was transmission loss (TL), expressed in dB and often a linear function of the base-10 logarithm of the range between the two locations such that

$$\mathrm{TL} = \mathrm{X}\log_{10}(\mathrm{R_2/R_1}), \tag{5}$$

where $\mathrm{R_{1,2}}$ were the ranges in meters from the source to locations 1 and 2, and X was the regression coefficient, or slope, of a linear regression model of SPL versus $\log_{10}$(R).

Estimating SLs from acoustic waves that propagate along straight paths is typically much less complicated than from raypaths with additional energy loss from refraction, reflection, and absorption. For example, the sound pressure loss in a homogeneous, unbounded, and non-absorptive medium from a source radiating outward equally in all directions is termed spherical spreading, and X = 20 in Eq. (5) for short ranges and low frequencies (e.g., Urick, 1983). When the medium is bounded by top and bottom parallel planes, sound is reflected off of the planes and spreads cylindrically, propagating in a waveguide, resulting in a lower loss with X = 10; however, additional losses at the bounding planes can occur due to surface roughness scattering, waveform destructive interference, and, in the case of the seafloor boundary, refraction into substructure. Water column refraction can increase or decrease losses via focusing or defocusing sound waves as they bend toward or away from a receiver in a non-homogeneous medium. These complexities in losses arising from environmental factors need to be considered when estimating how SPL varies with distance from a source, for instance, when evaluating source impact on marine mammals.

F. Sound speed profile

The speed of sound in the ocean typically varies with depth, which affects how sound travels from source to receiver, including causing sound raypath refraction (i.e., bending) and creating shadow zone regions where direct raypaths are attenuated. Sound speed is a function of salinity, temperature, and pressure, with the latter two parameters having the largest effect through the water column. Temperature and pressure were measured and recorded using a Seabird (Bellevue, WA) SBE-39 attached to the line between the data logger pressure housing and the hydrophone (Fig. 3). This configuration provided two casts per deployment day, one down when the recorder was deployed and one up when the recorder was recovered. The three days of recording provided six casts, which were averaged to provide an overall mean temperature profile for the experiment. This temperature profile was used to estimate the mean sound speed profile using the Chen and Millero (1977) equations with a constant 35 ‰ salinity.

The sound speed profile was used to evaluate how raypaths travel between source and receiver in the area of the experiment. To estimate raypaths from source to receiver, we used BELLHOP, a ray tracing model software program run in MATLAB (Porter, 2011), along with the mean sound speed profile.

III. RESULTS

Over three experimental days, 648 seal bombs were deployed; 46 were logged as unexploded, and 542 were detected with the automatic detector (Table II). Unexploded seal bombs may not have been lit properly or had some other fault with the fuse or explosive. Seal bombs that were not detected either did not explode or likely had received sound pressures lower than the detector threshold due to sound propagation limitations such as long range or very shallow explosion depths (i.e., near the sea surface pressure release boundary).

A. Example single nearby shot

Seal bomb shots near the hydrophone receiver provided the highest received levels and best signal-to-noise ratio (SNR) for evaluating the arriving pulses. A shot from the closest-point-of-approach (CPA), where the explosion was nearly directly above the hydrophone on 2 June 2017, clearly shows four distinct pulses within the first 75 ms (Fig. 4). The direct arrival from the shot, ∼262 m from the hydrophone, was a fast rising and slower decaying pulse, which was then reflected off the sea surface, causing a phase reversal and resulting negative pulse [Fig. 4(a)]. At about 37 ms after the first arrival, the first bubble pulse peaked, but with a slower rise time than the direct pulse, which was also reflected off the sea surface [Fig. 4(b)]. The third positive and negative pulses at ∼56 ms were from the second bubble pulse and had the same initial steep character and phase as the first pulse and its sea surface reflection (SSR) [Fig. 4(c)]. The third bubble pulse and its SSR arrived ∼69 ms after the direct pulse and at lower amplitude than the first two bubble pulses. All SSRs were around 4 ms after preceding positive pulses, indicating an approximate shot depth of 3 m using a 1500 m s^{-1} sound speed. The time difference between the positive pulse and its SSR for the third bubble pulse was ∼0.25 ms less than for the first bubble pulse, indicating the third bubble pulse was shallower than the first. In general, with all recorded shots, the time between the direct first pulse arrival and the bubble pulses varied by a few milliseconds, showing slight variability in shot depth.

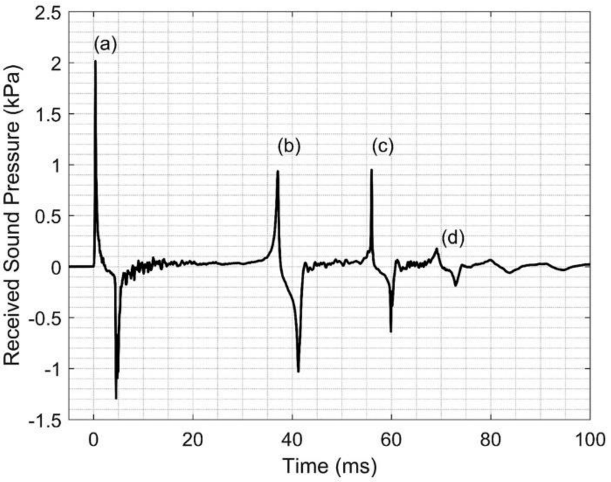

FIG. 4. Received sound pressure waveform for close range (262 m) seal bomb shot. (a) Initial pressure wave (0 ms) and its SSR (4 ms). (b) First bubble pulse (37 ms) and its SSR (41 ms); (c) second bubble pulse (56 ms) and its SSR (60 ms); (d) third bubble pulse (69 ms) and its SSR (73 ms). All SSR occurred ∼4 ms after preceding arrivals, indicating the explosion depth was 3 m using 1500 m s^{-1} sound speed.

TABLE II. Seal bomb experiment days, deployed, unexploded, and detected.

Experiment day	01	02	03	Total
Date	30 May 2017	01 Jun 2017	02 Jun 2017	3 days
Deployed seal bombs	144	288	216	648
Unexploded seal bombs	18	19	9	46
Detected seal bombs	91	245	206	542

A more detailed evaluation of the first 2 ms from the CPA seal bomb shot (Fig. 5) showed the unfiltered (dotted) waveform had a leading transient with positive and negative pulses 30 μs apart, which we attributed to the hydrophone electronics. These transients only occurred on the direct and the second bubble pulses, likely due to their higher frequency content than the first and third bubble pulses, and were most prominent for close shots, decreasing with range. The LPF waveform showed a reduction in high frequencies and the leading transient but retained the pulse shape and area underneath the curve (i.e., pressure impulse, J_p), allowing various metrics to be calculated (Table III).

B. Peak sound pressure levels versus range

To examine our study area propagation environment, measured peak sound pressure levels from seal bomb shots

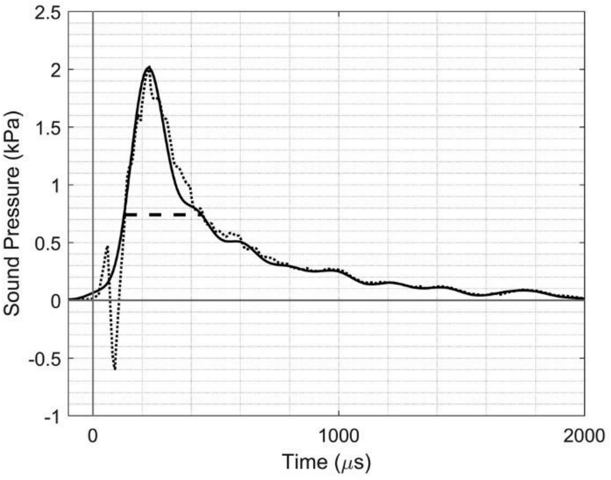

FIG. 5. Sound pressure waveform from recorded seal bomb explosion at CPA. Seal bomb with 2.33 g of flash powder was exploded at 262 m range from the hydrophone receiver. Dotted line, the unfiltered pulse with electronic noise; solid line, the filtered pulse using an eighth order Chebyshev type 2 LPF with a stop band edge at 10 kHz to minimize hydrophone electronic noise induced leading transient with positive and negative pulses.

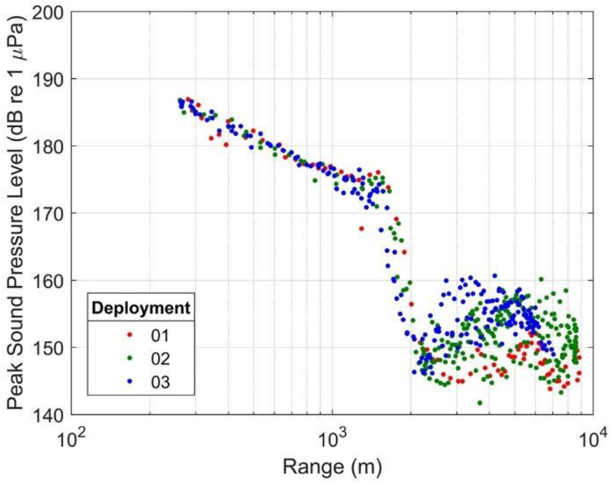

FIG. 6. (Color online) Seal bomb shot peak sound pressure levels versus logarithm base-10 ranges. Three distinct propagation regions: low-loss (260–1200 m), high-loss (1500–2000 m), and variable-loss (2000–9000 m). Dot colors represented deployment number. Linear regression models for the low-loss region showed spherical spreading (X = 20) between 260 and 340 m and were less lossy (X = 19, 17) between 400 and 800 m and between 800 and 1200 m, respectively.

were plotted against their ranges using a base-10 logarithm scale (Fig. 6). Three distinct regions grouped by ranges were apparent: low-loss (260–1200 m), high-loss (1500–2000 m), and variable-loss (2000–9000 m).

A linear regression model for peak sound pressure levels versus $\log_{10}(R)$ for the low-loss, short-range region provided a slope, or regression coefficient, $X = 18$, which was slightly less lossy than spherical spreading. Closer inspection of this region showed three sub-regions (260–340, 400–800, and 800–1200 m), each with slightly different and decreasing slopes of approximately 20, 19, and 17, respectively, becoming less lossy with increased range due to refraction focusing and eventually creating caustic-like effects ∼1200–1500 m. When the recorded pulse waveforms from the low-loss region were scaled by their range and regression coefficient (i.e., $R^{X/20}$), they were all nearly identical for the first 500 μs of the pulse, showing low variability in shot pressure signatures at close ranges.

Refraction was the cause of high losses in the region between 1500 and 2000 m, with defocusing creating a TL slope of $X \approx 130$ in a region where direct raypaths were strongly attenuated. Greater than 2000 m range, the raypath arrivals were complicated by sound waves reflecting off the seafloor and sea surface, in some cases multiple times, and there was no clear range-dependency of TL, showing more than 10 dB of peak sound pressure level variability (Fig. 6).

TABLE III. Seal bomb received peak sound pressure level, SPLs, pressure impulse, and SEL with charge mass of 2.33 g at CPA (i.e., 262 m range) over the frequency band 10 Hz–10 kHz.

Metric	Value	Time window (ms)
0-peak sound pressure levels	186 dB re 1 μPa	—
$\text{SPL}_{-3\,\text{dB}}$	185 dB re 1 μPa	0.120
$\text{SPL}_{-10\,\text{dB}}$	182 dB re 1 μPa	0.350
$\text{SPL}_{90\%}$	178 dB re 1 μPa	1.095
Pressure impulse	0.737 Pa s	2.00
SEL (primary pulse only)	149 dB re 1 μPa^2 s	2.00
SEL (primary + bubbles + reflections)	155 dB re 1 μPa^2 s	100

C. Refraction

To better understand the slight decrease in TL as range increases from the CPA and then the large increase in loss around 1500–2000 m range shown in Fig. 6, two-dimensional ray tracing in a depth-dependent sound speed model was performed and showed the effects of refraction. The sound speed profile for the model was estimated from an average of six depth-temperature casts during the experiment (Fig. 7).

The profile showed a large decrease in sound speed in the first ∼20 m of depth, resulting in a large sound speed gradient near the sea surface. The amount of raypath curvature (i.e., refraction) is directly related to the magnitude of the sound speed gradient, with raypaths bending more in higher-gradient environments and when traveling more perpendicular to the direction of the gradient. For example, a raypath initially traveling horizontally (perpendicular to the direction of the sound speed gradient) in the upper 10 m of this model curved downward away from the sea surface such that a receiver at the same depth as the source received levels less than spherical spreading (i.e., defocusing) and a receiver at a deeper depth received levels greater than spherical spreading (i.e., focusing) for sufficiently close ranges.

A graphical example of this refraction effect showed raypaths traced from a 3 m deep shot with angles relative to the sea surface from $-3°$ to $45°$ in $2°$ increments for two

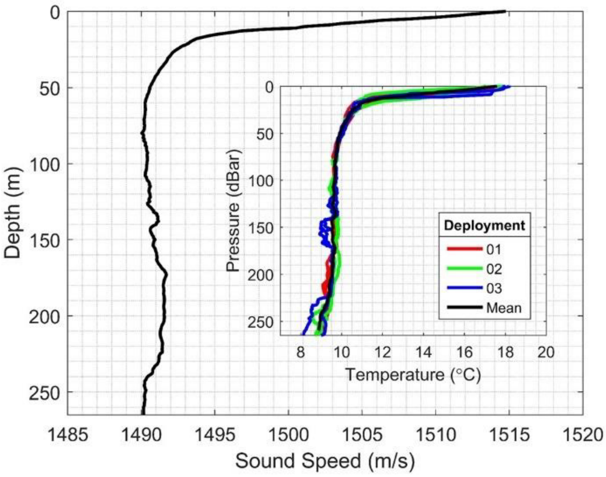

FIG. 7. (Color online) Sound speed and temperature profiles for study area. Sound speed profile was estimated based on the method of Chen and Millero (1977) using the mean (black line) temperature profile (inset) from two casts from each deployment (red, green, blue) and salinity of 35‰.

sound speed profiles: the one measured during this experiment and a homogeneous 1500 m s^{-1} profile exhibiting spherical spreading. In the refraction model [Fig. 8(a)] at the receiver depth (blue horizontal line), the area focusing raypaths was shown at ranges greater than ~1200 m up until the last ray (shot toward the sea surface) ~1700 m range. Beyond 1700 m, a shadow zone resulted, an area void of raypaths with very high TLs. The homogeneous sound speed model produced straight rays and no acoustic shadowing or focusing [Fig. 8(b)].

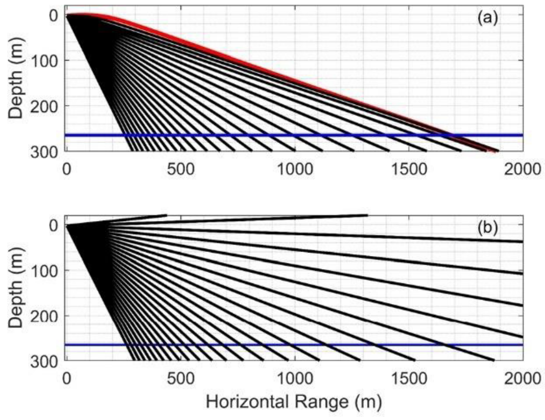

FIG. 8. (Color online) Raypaths traced in two models with different sound speed profiles. Rays were shot from a depth of 3 m in 2° increments from −3° to 45° relative to the sea surface. The blue horizontal line represents the hydrophone receiver at 265 m depth. (a) Sound speed profile from Fig. 7 with a strong gradient near the sea surface created strong refraction with rays becoming closer together as the range increased until the maximum range was reached (red raypath was shot toward the surface at −3° but refracted downward). (b) Homogeneous sound speed throughout the model caused all raypaths to be straight and evenly spaced in angle without refraction-caused shadow or focusing zones. Note that depth and range were at different scales (~1:2).

D. Estimated source metrics

To estimate seal bomb SLs from the sonar equation [Eq. (4)], we used the SPL measurements from the CPA shot at 262 m (Table III) and a spherical spreading PL ($20\log_{10}(262\ \mathrm{m}) = 48$ dB re 1 m^2). The resulting SL was 233 dB re 1 μPa m over a 0.120 ms time window (Table IV). Similarly, SEL and pressure impulse were measured over a 2 ms window at CPA (Table III) and spherical spreading PL was applied, resulting in a sound exposure source level of 197 dB re 1 μPa^2 m^2 s and pressure impulse estimated 1 m from the source (source pressure impulse) of 193 Pa m s. Using a longer time window to include the bubble pulses and the surface reflections (100 ms) in addition to the primary pulse increased the sound exposure source level by 6 dB to 203 dB re 1 μPa^2 m^2 s (Table IV).

We chose the CPA shot levels because it was the closest shot to the reference 1 m providing good SNR with the least amount of PL, its raypath was straight and direct without adverse refraction effects, and other shots near CPA were nearly identical to the CPA shot when scaled by range. Without closer range measurements and with water depths much greater than source/receiver propagation paths, spherical spreading was an appropriate propagation model for these low-frequency, omni-directional seal bomb sources (Urick, 1983). Further supporting spherical spreading in this region was the TL slope from CPA to ~340 m, measured to be X = 20 (Fig. 6).

IV. DISCUSSION AND CONCLUSIONS

To characterize seal bomb sound pressure signatures, we recorded calibrated underwater received levels of shots and found the environment (i.e., temperature profile) had a significant effect on sound propagation for sources near the sea surface due to raypath refraction or bending, highlighting the need for good PL models to properly estimate received levels from SLs. For example, in the acoustically refractive model with a source at 3 m depth [Fig. 8(a)], a receiver near the sea surface and at ~500 m range would not receive direct raypaths, only steep angle rays reflected off of the seafloor, and received levels would be less than predicted by spherical spreading. Conversely, the same receiver

TABLE IV. Peak source level, SLs, source pressure impulse, and sound exposure source level estimates over the frequency band 10 Hz–10 kHz from seal bomb with charge mass of 2.33 g.

Metric	Value	Time window (ms)
0-peak source level	234 dB re 1 μPa m	—
SL$_{-3\,\mathrm{dB}}$	233 dB re 1 μPa m	0.120
SL$_{-10\,\mathrm{dB}}$	230 dB re 1 μPa m	0.350
SL$_{90\%}$	226 dB re 1 μPa m	1.095
Source pressure impulse	193 Pa m s	2.00
Sound exposure source level (primary pulse only)	197 dB re 1 μPa^2 m^2 s	2.00
Sound exposure source level (primary + bubbles + reflections)	203 dB re 1 μPa^2 m^2 s	100

at ~100 m range may receive sound at higher levels than predicted with spherical spreading because of raypath focusing, and waveforms would likely be complicated with constructive and destructive interference from SSRs due to low grazing angles both from source and to receiver at shallow depths.

While our seal bomb estimated SL was a high SL in the ocean (e.g., Hildebrand, 2009), it was possible that nonlinear propagation with higher losses than spherical spreading occurred for seal bomb explosions at shorter ranges than measured in our experiment if seal bomb flash powder fast deflagration was similar to high explosive detonations generating a shockwave. For example, for a similar size charge of high explosives, the generated pulse would propagate nonlinearly to about 60 m with an additional ~5 dB loss, or a factor of ~1.8, before becoming linear propagation (Cole, 1948; Arons, 1954; Chapman, 1985), suggesting the SL could be as high as 238 dB re 1 μPa m. However, without additional measurements from shorter ranges than present here, we were required to use a spherical spreading PL model to estimate SL from the closest shot's received SPL.

While little is known about damage to marine mammals from underwater explosions, seal bomb source (i.e., at 1 m range) pressure impulse was estimated in this study to be at levels previously shown to cause tissue injury to medium-size terrestrial mammals held underwater (Yelverton *et al.*, 1973), and based on an open-water seal bomb explosion study, Myrick *et al.* (1990a) suggested seal bombs cause damage to dolphins and other marine mammals if exploded within 4 m range.

In addition to physical tissue damage from close explosions, impulsive sounds may cause TTS or PTS damage in marine mammal hearing (e.g., Finneran, 2015). The National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) estimated PTS threshold for unweighted peak sound pressure level for earless seals (phocid) was 218 dB re 1 μPa, that for eared seals (otariid) was 232 dB re 1 μPa, and those for cetaceans ranged from 202 to 230 dB re 1 μPa, with TTS estimated as 6 dB lower, or effectively at farther ranges than PTS (National Marine Fisheries Service, 2018). These thresholds are all at or lower than the levels estimated for seal bombs at short ranges. This suggests PTS and TTS may be occurring for animals near seal bombs used in fisheries that employ them to deter marine mammals from depredation and accidental bycatch.

Peak levels and SPL are often used to describe underwater signals; however, they are incomplete for characterizing impulsive signals such as explosions, because no information on pulse shape is provided. Pulse duration provides additional details on the amount of energy that was contained in the pulse and the rate at which it was released. Time-integrated metrics, such as pressure impulse and SEL, are more comparable for impulsive signals because they account for the total energy in the pulse, not just the sound pressure amplitude. Furthermore, the complete received waveform from a seal bomb, not just the first pulse, should be considered when evaluating impact because of additional impulsive sounds present from explosion bubble pulses and reflections off the sea surface. The total energy received was higher when the complete 100 ms waveform was used with sound exposure source level that was 6 dB higher than just the first 2 ms pulse. Furthermore, since seal bombs are often used repeatedly during fishing operations (Meyer-Löbbecke *et al.*, 2016), cumulative SEL over the full period of event activity should be used to estimate the total amount of sound energy emitted into the environment. Expanding one step further, to properly assess how SEL relates to auditory injury thresholds in marine mammals, filtering of the full period time series by animal auditory frequency weighting functions during cumulative SEL calculations should be conducted (Southall *et al.*, 2019).

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Chapter 3: Seal Bomb Noise as a Potential Threat to Monterey Bay Harbor Porpoise

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

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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

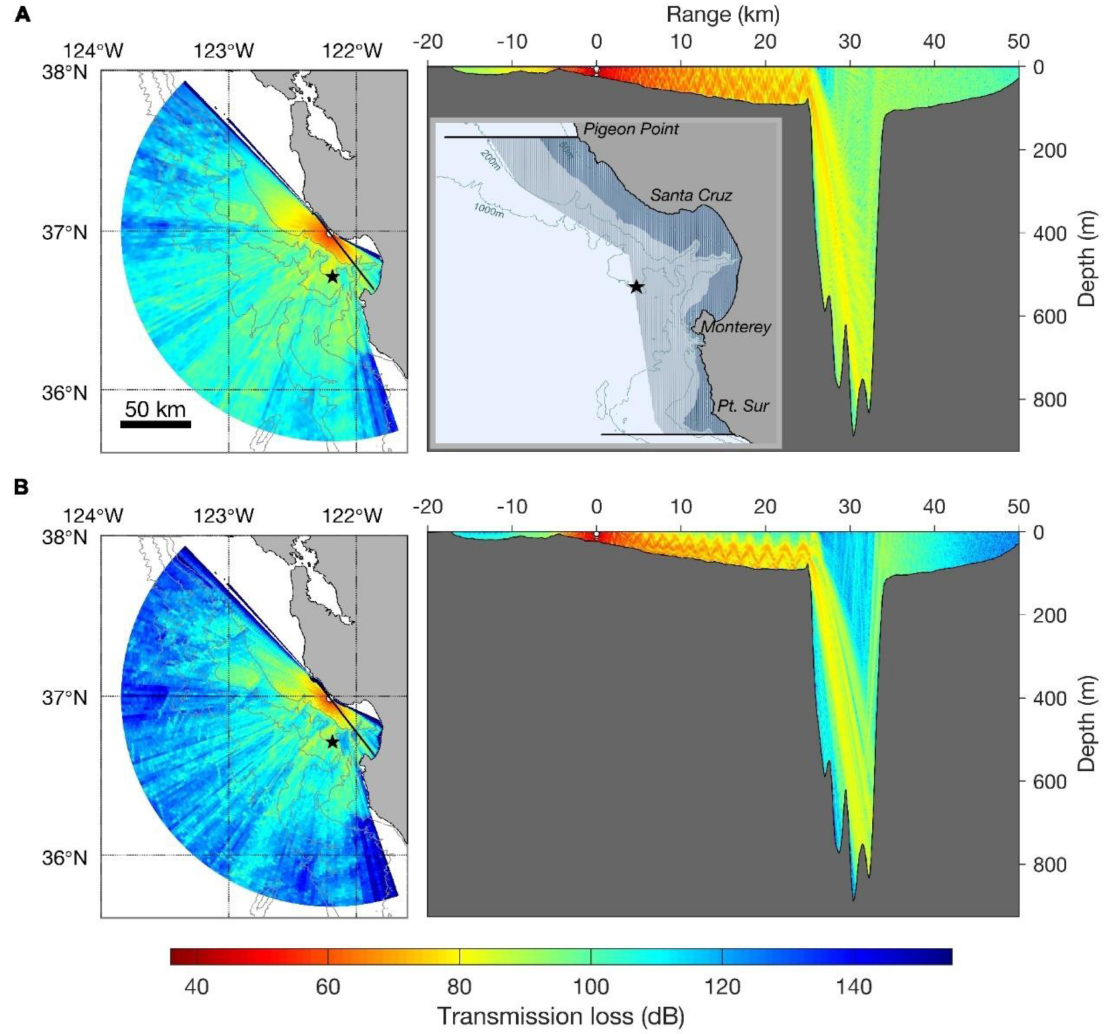

FIGURE 1 | Transmission loss model at 250 Hz **(A)** and 1000 Hz **(B)** for a seal bomb explosion (3 m depth, 36°59′6.20″N, 122°11′44.53″W, average August sound speed profile). Isobaths are 200, 1000, 2000, and 3000 m. Color indicates transmission loss at 20 m depth (left) and at all depths (right). Black star shows position of Monterey Accelerated Research System (MARS) cabled observatory (891 m), active since 2015, and where seal bombs have been acoustically detected. The right vertical profile shows the transmission loss model along a transect line (bearing 322° and 142° from the source; transect is shown by black thick line in horizontal range map). The inset map (top right) shows the distribution of the Monterey Bay harbor porpoise stock (black horizontal lines show recognized stock boundaries). Darker blue shading is primary habitat [<50 fathoms = 92 m] and medium blue shading shows the offshore extent of stock range. Isobaths in range map are 50, 200, and 1000 m.

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 μPa at 1 m, and estimated source sound exposure level (SEL) of 203 dB re 1 $\mu Pa^2 s$ 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

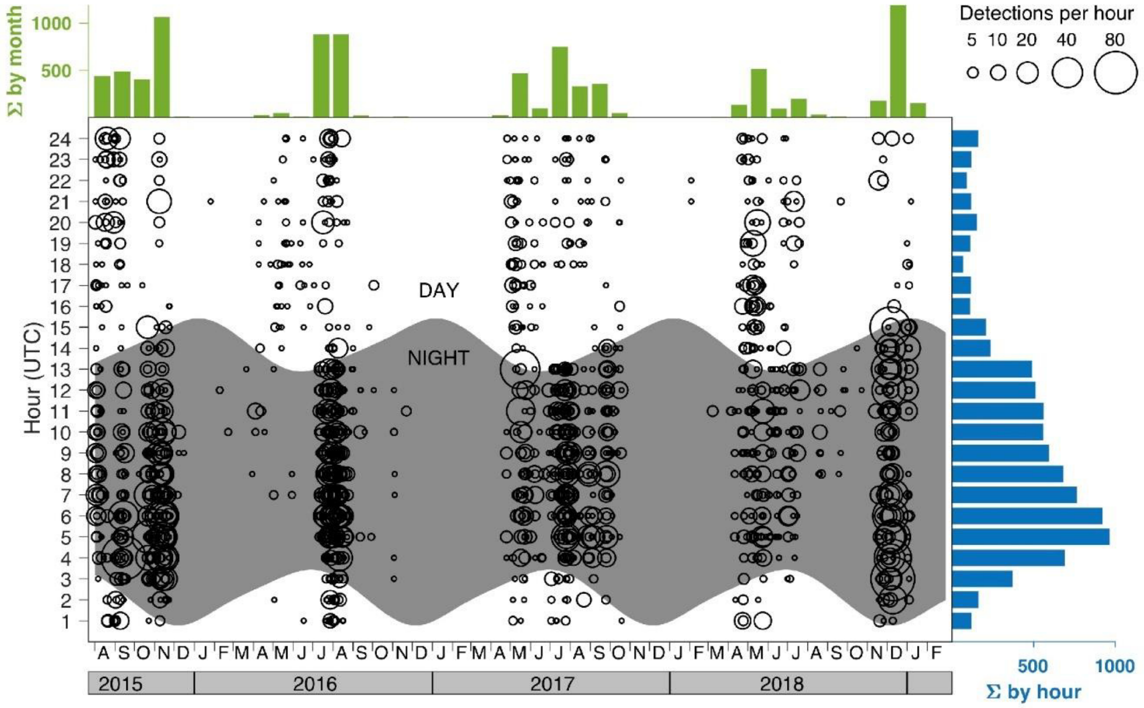

FIGURE 2 | True positive detections of seal bomb explosions in recordings from the MARS cabled observatory (https://www.mbari.org/at-sea/cabled-observatory/). Circle size represents the number of explosions per hour, for every hour of every day. Times are shown in UTC (Pacific Standard Time is UTC –8 h). Nighttime is shaded. Cumulative histograms are shown by hour and month. Figure reproduced with permission from Ryan (2019).

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.

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

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 (Pirotta 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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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.

Chapter 4: Opposite Effects of Seal Bomb Noise on Two Dolphin Species in Southern California

This manuscript is currently prepared for submission. I designed the study, conducted the signal detection (for dolphins and explosion signals), analyzed and interpretated the data and wrote the manuscript. Manual dolphin signal detection was partly also carried out by Ella B. Kim (as part of her summer internship and Bachelor thesis, that I both supervised), and other members of the lab (prior to the beginning of my Ph.D. thesis research).

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Opposite Effects of Seal Bomb Noise on Two Dolphin Species in Southern California

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Abstract

Explosive deterrents, so called "seal bombs", used by the commercial market squid fishery have been revealed to occur thousandfold throughout the Southern California Bight, yet effects on cetaceans are unexplored. Therefore, passive acoustic monitoring data from 2005-2011 from 12 sites in the Southern California Bight were analyzed regarding occurrence, habitat overlap, noise exposure and effects of seal bomb explosions on the acoustic behavior of two dolphin species, Risso's (*Grampus griseus*) and Pacific white-sided dolphins (*Lagenorhynchus obliquidens*). Risso's dolphin echolocation encounters were most frequently detected at night while diel patterns of Pacific white-sided dolphins were more variable and different between sites. Overlap with noise from explosions was stronger for Risso's dolphins. Around Santa Catalina Island, Santa Cruz Island and Santa Monica Bay the animals were exposed to seal bomb noise for more than 30 % of the hours they spent around these sites, with mean cumulative sound exposure levels per hour of 160-170 dB re 1 µPa^{2}s and mostly more than 50 % of hours exceeding 170 dB re 1 µPa^{2}s. For Pacific white-sided dolphins, only one site north of San Clemente Island showed considerable overlap with explosions (18 %) and considerable dolphin presence at the same time, while the dolphins were occasionally exposed to high levels of seal bomb noise. Generalized additive models revealed effects of seal bomb noise on both species to be opposite. Risso's dolphins seemed to tolerate the noise, while Pacific white-sided dolphins

seemed to avoid it, at least during times of high noise exposure. During these days, Pacific white-sided dolphins were more frequently encountered during the day, when seal bomb noise is mainly absent, while Risso's dolphins were still more often detected during the night. The different effects can be explained by their feeding preferences. Risso's dolphins prey heavily on squids, while Pacific white-sided dolphins are more opportunistic feeders. Risso's dolphins and the fishery mainly using seal bombs, share squids as their main target, which leads to the observed strong overlap. However, a lack of response should not be interpretated as a lack of impact, as Risso's dolphins may suffer from physiological effects with biological costs of avoiding crucial foraging areas simply being too high.

Introduction

Effects of anthropogenic underwater noise on cetaceans depend on a variety of factors, like sound type, source and received level, frequency bandwidth, exposure duration but also on species, sex, age, individual physiological state, experience and motivation or activity, thus, if the animal is currently feeding, mating, socializing, migrating, or resting (Southall et al. 2007, 2019; Weilgart 2007). Accordingly, responses to noise can be behavioral (vigilance, avoidance, attraction, change in diving or foraging behavior etc.), acoustic (changes in level, frequency, duration, or timing of vocalizations to account for masking) and/or physiological (stress hormones, auditory threshold shifts) (Tyack and Janik, 2013; Nowacek et al. 2007; Dolman et al. 2004).

In Southern California waters, studies have focused on the effects of shipping noise (Croll et al. 2001; McDonald et al. 2006, 2008; McKenna 2011) and mid-frequency active sonar operations (Melcón et al. 2012; DeRuiter et al. 2013; Goldbogen et al. 2013) on cetaceans. However, in recent years the issue of so called "seal bombs" (Figure 1.C) has come into focus of scientists, agencies, and the public. Seal bombs are explosive deterrents commercially produced and used within commercial fisheries especially along the North American west coast to keep pinnipeds away from the nets and catch. U.S. made seal bombs usually contain about 2.3 g of an explosive flash powder mixture and are designed to explode a few meters below the water surface (Myrick et al. 1990; Wiggins et al. 2021). Wiggins et al. (2021) conducted a field experiment off San Diego with seal bombs and calculated peak source pressure levels of 234 dB re 1 µPa m and sound exposure source levels (SEL) of 203 dB re 1 µPa^{2}s over a 100 ms window. As these high source levels (un-weighted) exceed threshold levels (weighted) for permanent and temporary auditory thresholds shifts (PTS/TTS) for different marine mammal hearing groups (NMFS 2018), seal bombs likely cause permanent or temporary hearing damage to cetaceans within close range. Although weighted and un-weighted metrics can of course not be compared one to one, auditory injury is especially likely when effects of multiple exposures are considered (Kastelein et al. 2016). Using long term passive acoustic monitoring data (2005-2016), Krumpel et al. (2021) revealed high numbers of seal bomb explosions of up to 2,800/day during periods of peak occurrence at sites off Southern California. Due to a significant correlation and similar spatio-temporal patterns of market squid landings (*Doryteuthis opalescens*) and explosions, Krumpel et al. (2021) conclude that the California market squid purse-seine fishery, one of the largest fisheries in the state both in terms of volume and value, is a major source of recorded seal bomb explosions, while no correlation for purse-seine fisheries for other coastal pelagic species, like sardines, mackerels or anchovies was found. The described persistence of reoccurring explosions in combination with high source levels present a threat for cetaceans. Simonis et al. (2020) described potential effects of seal bomb noise to the Monterey Bay harbor porpoise (*Phocoena phocoena*) stock. While harbor porpoises are known to be sensitive to acoustic disturbance, the limited distribution, non-migratory nature, and small population size of the Monterey Bay stock make them particularly vulnerable to local impacts. Based on a local transmission loss model for seal bombs in Monterey Bay, Simonis et al. (2020) estimated that harbor porpoises would experience a PTS and TTS at ranges out to 150 and 650 m from a seal bomb explosion, respectively. A TTS from cumulative exposure of 2 seal bomb explosions was estimated to occur within 1 km or for 6 explosions within 2 km range, while the potential range of behavioral responses of > 50 km is much more far reaching.

Aside from physical injury, there is growing concern that interruption of essential behavior, like foraging, may pose a serious threat also on the population-level (Nowacek et al. 2007; Wisniewska et al. 2018). The vast majority of recorded seal bomb explosions in Southern California occurred at nighttime (Krumpel et al. 2021) - the time when deep scattering layers rise and various dolphin species focus their foraging effort (for the Southern California Bight (SCB) e.g., Soldevilla et al. 2010a, b;

Simonis et al. 2017), two of them are Risso's (*Grampus griseus*, RD) and Pacific white-sided dolphins (*Lagenorhynchus obliquidens*, PWSD; Figure 1.A and B).

Figure 1 (A) Risso's dolphin, (B) Pacific white-sided dolphin during a research cruise (December 2009) on R/V Robert Gordon Sproul (photos: Micheal H. Smith) and (C) a seal bomb (Stoneco Energetics System, LLC Seal Cracker Device) during a field experiment on R/V Saikhon (May 2017) in the Southern California Bight (photo: Anna Krumpel).

RD are distributed worldwide in tropical and temperate ocean waters. They prefer temperatures between 15 and 20 °C (Henderson et al. 2014a) and usually don't occur within waters colder than 10 °C and therefore not in polar regions (Jefferson et al. 2013). They represent the fifth largest member of the family Delphinidae with up to 4 m length. RD in the Eastern pacific are distributed between the Gulf of Alaska in the North and Tierra del Fuego in the South (Leatherwood et al. 1980). Animals along the U.S. West coast probably belong to a single population (Caretta et al. 2004). Most studies based on stomach content analyses suggest that they are teuthivores, thus, almost exclusively preying on a broad variety of cephalopods (Cockcroft et al. 1993; Blanco et a. 2006; Luna et al. 2021), in the SCB mainly on market and jumbo squid (*Dosidicus gigas*) (Orr 1996; Kruse 1989). However, Benoit-Bird et al. (2019) pointed out using active acoustic methods, and tagging data, that RD in the SCB also switch from squid to more generalist feeding throughout the day.

PWSD is a cold-temperate, pelagic species, which is endemic to the North Pacific (Leatherwood et al. 1984). Along the U.S./Mexican West coast two distinct populations of PWSD exist, a northern California/Washington/Oregon population and a southern Baja California population (Lux et al. 1997); both occur in the SCB and are probably distinguishable by different click types and seem to have different diel patterns (Soldevilla et al. 2010b). They are opportunistic feeders, preying on small schooling fish, like Northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax*), Pacific whiting (*Merluccius productus*), Pacific herring (*Clupea pallasii*), Pacific saury (*Cololabis saira*), and cephalopods, like market, boreal clubhook (*Onychoteuthis borealijaponica*) and armhook squids (Gonatidae); both during day and night (Stroud et al. 1981; Black 1994; Heise 1996).

Both, RD and PWSD, are understudied species (Smith 2017) compared to other odontocete species, e.g., bottlenose dolphins (*Tursiops truncates*) or harbor porpoises. Information on hearing abilities and especially on effects of anthropogenic noise for both species is very scarce.

A PWSD was tested for underwater hearing sensitivity by Tremel et al. (1998). The dolphin had a typical U-shaped audiometric curve with best hearing at frequencies between 2 and 128 kHz. Lowest sensitivity was observed at 100 Hz and 140 kHz. For RD three published audiograms exist, one from an older individual with high-frequency hearing loss (Nachtigall et al. 1995) and another from a stranded cup suffering from a viral infection (Nachtigall et al. 2005), showing sensitive hearing range of up to 150 kHz. Mooney et al. (2015) showed most sensitive hearing at 11 kHz and from 40 to 80 kHz and a decrease in sensitivity above 100 kHz while hearing limits for this 15 years old RD individual were detected at 128 kHz. In general, the hearing abilities of these species are comparable to other dolphins, e.g., bottlenose dolphins.

Effects of noise on PWSD and RD so far, have only been investigated within less than a handful of studies. Henderson et al. (2014b) reported that 9 out of 10 sighted groups of PWSD near San Clemente Island responded either acoustically and/or by changing their surface behavior in response to mid-frequency active sonar with dolphins usually stopping to vocalize and often leaving the area. Groups of PWSD also split in response to sonar with a mother-calf pair getting separated from the group. As no groups of RD were present during sonar exposure, no conclusions on their reaction to noise could be drawn. Visser et al. (2011) described that the abundance of whale watching vessel off the Azores had a strong influence on daily resting patterns of RD and concluded that their reaction is likely induced by vessel noise. RD also showed negative responses to different engine sounds in Scotland (Evans 1987). A pre-study conducted by Gatto (2020) in the Gulf of Taranto indicated that emitted signals of RD varied in terms of rate and characteristics when anthropogenic noise was present.

If and how both species are affected by seal bomb noise in unknown. Due to different feeding preferences, we hypothesize that reactions to seal bomb noise might differ between the two species in the SCB. RD most likely depend on squids as primary prey and might not leave a crucial foraging area although exposed to seal bomb noise, with seal bombs especially used within the market squid fishery (Krumpel et al. 2021), while PWSD as opportunistic feeders might respond with avoidance. This study therefore aims to describe (1) the general acoustic activity and diel patterns of the two dolphin species throughout the SCB, (2) investigate if areas of seal bomb use and market squid fishing overlap with dolphin foraging habitat, (3) assess the extent of noise exposure and (4) effects of seal bomb noise on their acoustic behavior.

Materials and Methods

Acoustic recordings

Between 2005 and 2011, autonomous High-Frequency Acoustic Recording Packages (HARPs) collected long-term passive acoustic data at twelve different sites throughout the SCB (Figure 2). HARPs were all set to a sampling frequency of either 200 or 320 kHz with 16-bit quantization (effective bandwidth 10 Hz–100 or 160 kHz, respectively). For further technical specifications of HARPs see Wiggins and Hildebrand (2007, 2016). Recorders were all bottom-moored at average seafloor depths between 260 and 1,280 m. Of the 79 deployments in total, most sampled continuously, but 16 deployments had duty-cycled recordings (with 5 min of recordings occurring at 7 to 15 min intervals, Figure 3). The analyzed periods varied strongly between sites, from about four months at site K to over five years at site C. Cumulatively, 5,159 days of data were analyzed in total for this study (Figure 3, Table 1).

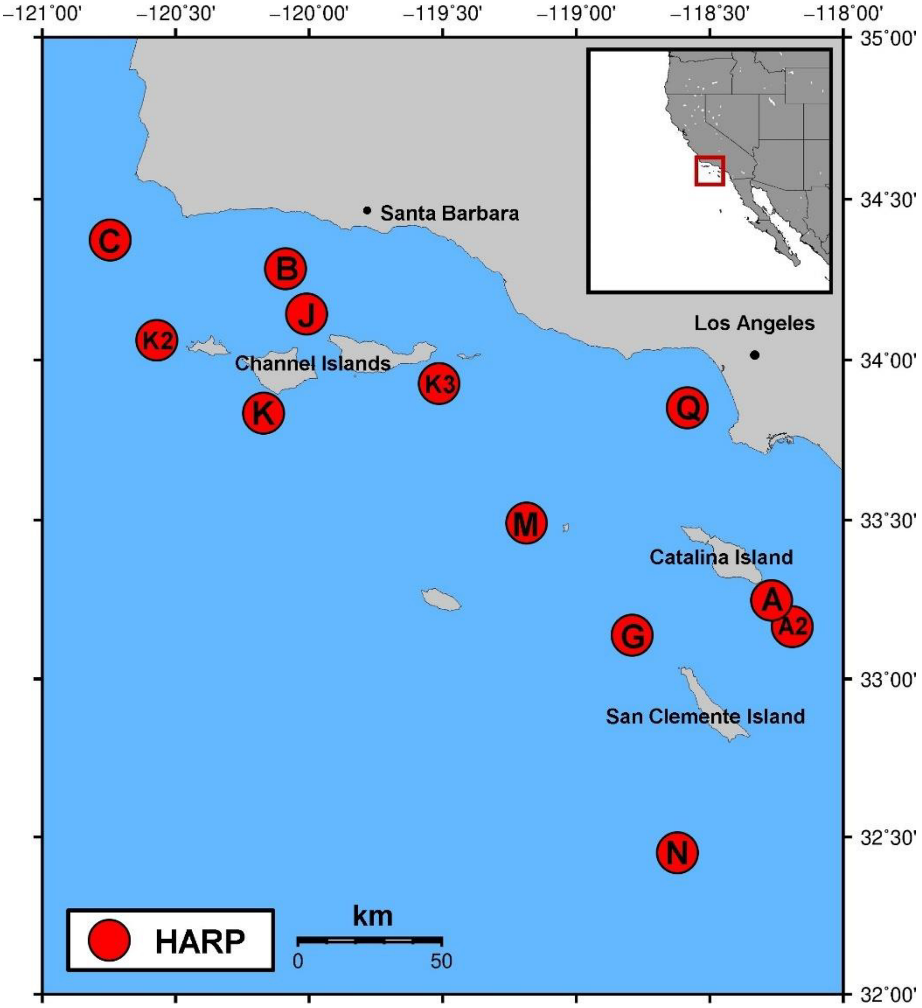

Figure 2 Locations of 12 HARP sites (red circles) deployed between 2005 and 2011 in the Southern California Bight (SEATURTLE.ORG Maptool. 2002. SEATURTLE.ORG, Inc. http://www.seaturtle.org/maptool/ (2022/04/15).

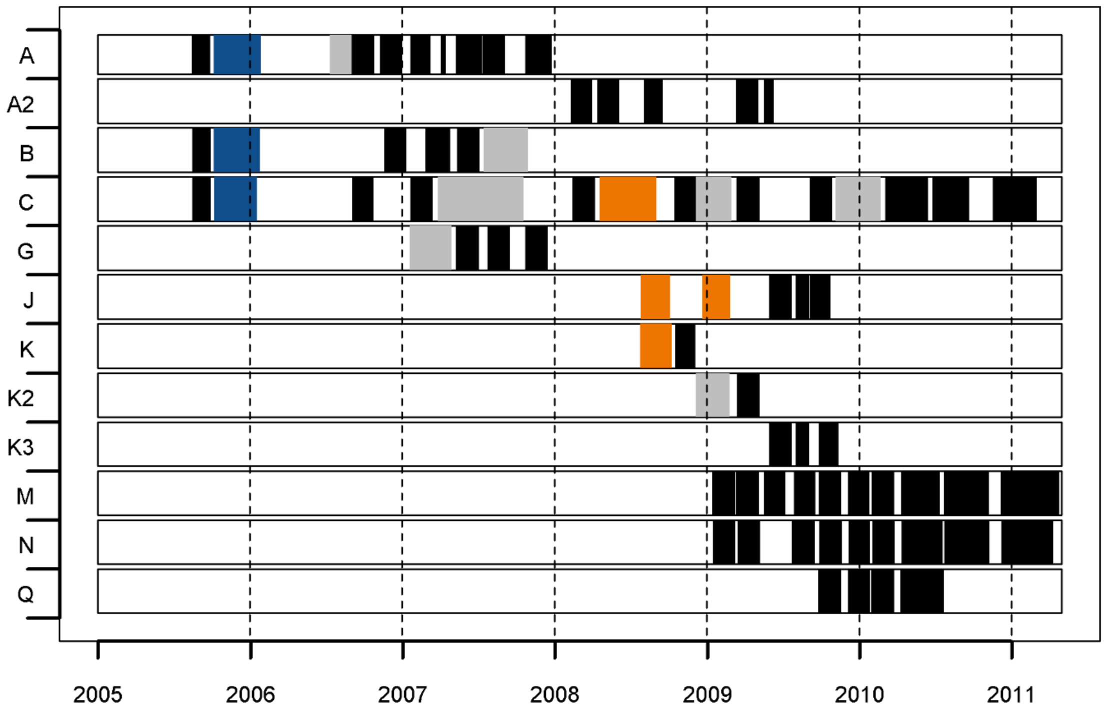

Figure 3 Overview of acoustic recording periods with effort for dolphin click encounter analysis between 2005 and 2011 at 12 HARP sites (A to Q) in the Southern California Bight. Black (continuous recordings) and colored areas (duty-cycled recordings; recording duration (min)/recording interval (min): orange=5/7, grey=5/10, blue=5/15) represent times of effort for dolphin click encounter and seal bomb analysis.

Signal detections and metrics

Dolphin click encounters

For manual detection of RD and PWSD click encounters, acoustic data were analyzed with TRITON (https://github.com/MarineBioAcousticsRC/Triton), a custom MATLAB program (Mathworks, Natick, MA). For visual detection, full bandwidth data were compressed by creating long-term spectral averages (LTSAs; Wiggins and Hildebrand 2007). LTSAs are created using the Welch algorithm (Welch 1967) by averaging 500 spectra created from 2000-point, 0% overlapped, Hann-windowed data and aligning those averages over time, to create effective long-term spectrograms. Hourly LTSAs, with a 5 s time and 100 Hz frequency resolution, were scanned from 0 to 100 kHz for RD and PWSD click bouts. Echolocation clicks from RD and PWSD have unique species-specific spectral characteristics with distinct spectral peaks and notches first described by Soldevilla (2008), which make them easily identifiable within the LTSA. RD clicks have four peaks at about 22, 25, 31 and 39 kHz (Soldevilla et al. 2010a), while for PWSD two click types exist; type A with three peaks at about 22, 27.5 and 39 kHz and type B with three peaks at about 22, 26 and 37 kHz (Soldevilla et al. 2010b). For subsequent analyses we did not account for PWSD click types. Example LTSAs with click bouts from RD (Supplementary Figure 1) and PWSD (Supplementary Figure 2) from this study can be found in the supplement. Start and end times, as well as frequency of spectral peaks were identified and logged by trained analysts and finally stored in the Tethys metadata database (Roch et al. 2016). Click encounters were logged as distinct when they were separated by at least 30 minutes.

Explosions

For automated detection of explosions, data were decimated by a factor of 20 to create an effective acoustic bandwidth from 10 Hz to 5 or 8 kHz, respectively. Explosion signals were automatically detected using a MATLAB-based matched filter detector algorithm. It cross-correlated the Hilbert envelope of a template explosion signal, which is a filtered composite set of recorded example explosions, with the envelope of 75 s recording segments to capture similarities. Afterwards it was digitally filtered with a 10th order Butterworth band-pass filter, with a band-pass between 200 Hz and 2 kHz. Once potential matches were found, specific empirically established detection thresholds (for duration and for dB differences during vs. before and after the signal) were applied to the timeseries waveform containing the potential explosion signal. For more details on the detection algorithm see Krumpel et al. (2021). As the algorithm can produce >85% false-positive detections, each automated explosion detection was manually reviewed and verified by trained analysts. For details on the verification process also see Krumpel et al. (2021). Afterwards, metadata of all positive detections were again stored in the Tethys database (Roch et al. 2016).

SEL was calculated via custom MATLAB scripts for each detected explosion signal by integrating the sum-of-square pressures over the duration of the pulse (see equation 5 in Southall et al. 2007) using undecimated and unfiltered raw data as a basis. Calculated SEL values are received, not source values, from explosions with unknown distance to the hydrophones and are therefore influenced by various distance and surrounding noise effects. Cumulative SELs (SEL_{cum}) per hour were calculated using the following equation:

$$SEL_{cum} = 10 \times \log_{10} \sum_{k=1}^{n=total\ no.explosions/h} \times 10^{(SEL_k/10)}\ [dB\ re\ 1\ \mu\text{Pa}^2\text{s}]$$

Fishery data

Information on commercial market squid landings and receipts were provided by the California Department of Fish and Wildlife (CDFW). Only squid caught as target species (≥ 50 % of the weight recorded on landing receipt) with purse-seine and other encircling nets were chosen for analyses. CDFW data included daily amounts of landings and number of landing receipts per fishing block (11 x 9 nm, except for blocks along the coast). The distances between the center of each fishing block and each of the 12 HARP sites were calculated, and only squid landing and receipt data from fishing blocks with up to a maximum distance of 20 km and within the recording period of the HARP sites were included for subsequent analyses on potential habitat overlap with dolphin forging habitat. A maximum of 20 km was chosen to only include fishing blocks with HARPs located inside as well as directly adjacent blocks.

Statistics

All statistical analyses were done using R 4.2.0 (R Core Team 2022). Dolphin echolocation activity is described using detection positive time units, like % of detection positive days (DPD) per recording period. DPD are days with at least one dolphin encounter. Using finer time resolutions, % of detection positive hours (% DPH/d) and minutes per day (% DPM/d) were calculated as well. For assessing diel patterns % DPM per hour was used. For each site, daily sunrise and sunset data were obtained from the National Oceanic & Atmospheric Administration Earth System Research Laboratory website (NOAA solar calculator). A Kruskal-Wallis rank sum test was used to examine whether differences were significant between day and night, in total and per site.

Habitat overlap was described by calculating the number of hours with concurrent dolphin and explosion presence relatively to the total number of recorded hours and to the count of DPH, per site. The extent of explosion noise exposure during dolphin presence was described using means of SEL_{cum} per site as well as the corresponding proportion of SEL_{cum} >170 dB re 1µPa^{2}s. 170 dB was used to describe exposure, that has the potential to physically harm dolphins. This is considered the threshold for TTS onset in mid-frequency cetaceans for impulsive sounds (NMFS, 2018); while NMFS threshold is based on weighted SELs cumulated over 24 hours, using it during this study can still provide an important basis for estimation of potential physical harm.

Effects of explosions on RD and PWSD acoustic activity per hour were analyzed via generalized additive modelling (GAM) testing SEL_{cum} (as variable uniting information on amplitude of individual explosions and explosion counts per hour) as linear predictor, Julian day (as proxy for seasonal development throughout the year) and normalized time of the day in relation to sunset (as proxy for diel patterns), both as cyclic cubic smooth functions, as well as year and site as categorical factors to account for spatial and annual variability. Only sites with considerable dolphin presence (> 15% DPD) were chosen for modelling (RD: all, but site N; PWSD: site A, C, G, K, K2).

Beforehand, all potential explanatory variables were tested for multicollinearity using the Variance Inflation Factor (VIF). A VIF > 5 indicates that an independent variable is highly collinear with other variables in the model. Therefore, variables with VIF > 5 were removed one at a time, recalculating VIF values and only keeping non-correlated ones in the model. Within this process, the variables season, day/night-time, DPM/h of explosions and median SEL were excluded from the analysis.

We accounted for zero-inflation of the response variable (DPM/h) by selecting a compound-gamma distribution model, a member of the Tweedie family, which are specifically appropriate to handle zero-inflation, especially under variable sampling effort by site. A logit link function was used. We simplified the GAM structure through a bottom-up, stepwise procedure, selecting the best model with the minimum Akaike Information Criterion (AIC) that retained significant predictors. Removed insignificant variables were hours since last explosion and explosion counts. Basic residual plots were used for model validation. Important packages in R were *mgcv* (v.1.8-36; Wood 2021) for GAM and *statmod* (v.1.4.36; Smyth et al. 2021) to calculate parameters of Tweedie distributional family.

Squid data were not considered as explanatory variable within the GAM for two reasons. First, fishery data is not available on an hourly basis. Second, information on landings is only available on a daily not hourly basis. Second, the presence of landings confirms the presence of squid, but the absence of landings does not necessarily mean that squids are absent, as squid vessels will operate close to Los Angeles port whenever possible (Brady 2008). The low numbers of squid landings at site K2 for example, could therefore be potentially explained by either the absence or low numbers of squid or the higher distance to major ports in comparison with other sites. Therefore, landings are not a straightforward proxy for prey availability.

The ratio between echolocation activity (DPM) per photoperiod (night vs. day) was compared between days with no or low explosion counts (<100/d) and days with higher explosion counts (>100/d) for all sites combined per species to evaluate if they might alter their foraging focus during high explosion noise exposure, which is known to mainly occur during the night (Krumpel et al. 2021). A Kruskal-Wallis rank sum test was used to examine whether differences were significant.

Results

Dolphin echolocation activity

RD click encounters were detected at all 12 sites on 40 % of all recording days, in total. PWSD encounters were identified at 11 sites (not at site A2). They were less frequent with 15% of days having at least one acoustic encounter, in total.

RD click encounters were most often detected at island-associated sites, especially at the southern sites of the Channel Islands (site K, K3) and at Catalina Island (site A, A2) with % of DPD ranging between 67-85% and 57-74%, respectively per region. At those sites, DPH/d ranged between 12-15%. RD clicks were detected least frequent at site B within the Santa Barbara Channel (16 % DPD) and at site N (8% DPD), an offshore site in the southern part of the SCB (Figure 2, Table 1).

Click encounters of PWSD were most often identified around the Channel Islands (K, K2) with 39-55% DPD and north of San Clemente Island (site G) with 51 % DPD. 4-10% DPH/d were recorded at those locations. They were least frequent at site A2 (absent), site B, as well as site K3, Q, M (central/northern-central part of the SCB) and N with 2-8% DPD, per site (Figure 2, Table 1).

A significant (Kruskal-Wallis test p<0.001) diel pattern was evident for RD click encounters with 75% of total DPM occurring at night. In total, PWSD clicks were also significantly (p<0.001) encountered more often during the night with 64% of all DPM (Figure 4). For RD this pattern was significant (p<0.001) at all 12 sites with 58-88% of DPM per site occurring at night. However, for PSWD this pattern was not consistent among sites. At four sites no significant differences were found (sites A, B, K, M), at four sites dolphin activity was significantly (p<0.001) higher during the night (sites C, G, K2, N) and at 3 sites (J, K3, Q) significantly higher (p=0.02) during the day (Table 1). Overall, for RD most DPM were detected between 20:00 and 04:00, with a strong decrease within the early morning hours. After a slight increase around 10:00-12:00, values decrease steadily until the late afternoon. A steep increase was evident at 19:00 (Figure 4.A). For PWSD, differences between hours were not as pronounced as for RD, but the overall pattern was comparable with highest values between 19:00 and 06:00, a slight decrease with the early morning followed by a slight increase around 10:00-12:00 and lower values again until late afternoon (Figure 4.B).

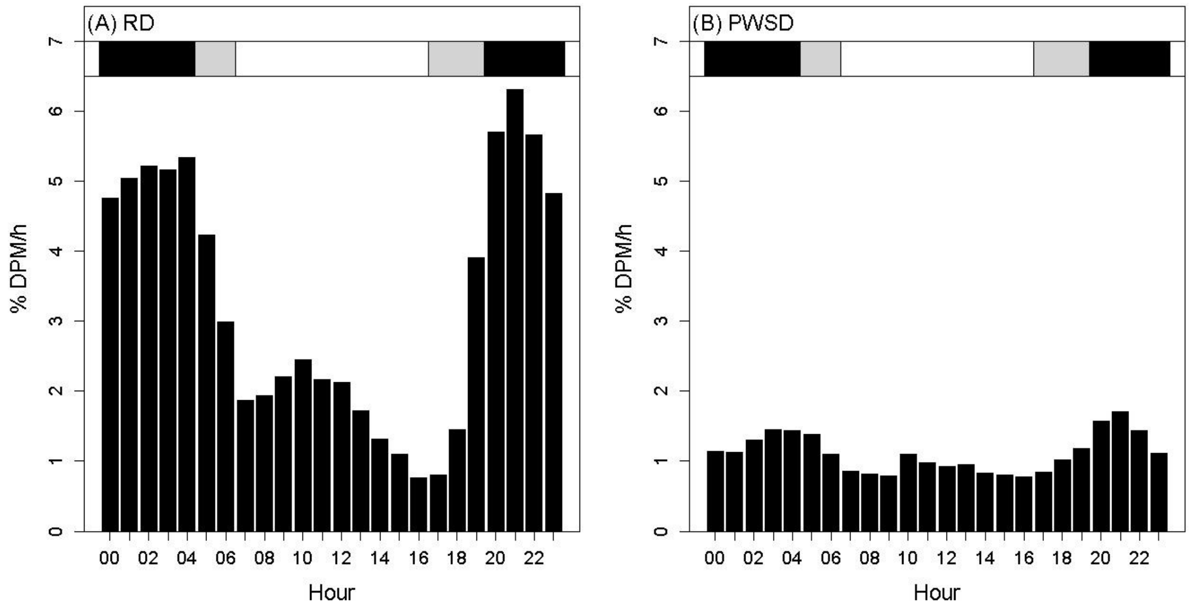

Figure 4 Diel pattern of (A) Risso's (RD) and (B) Pacific white-sided dolphins (PWSD) echolocation activity in % of detection positive minutes per hour (% DPM/h) combined across the 12 HARP sites. Black vertical bars represent % DPM per hour of the day, horizontal bars indicate photoperiod (black=night, white=day, grey=day or night depending on time of year).

Table 1 Overview of Risso's (RD) and Pacific white-sided dolphin (PWSD) echolocation activity in % of detection positive days and hours per day (%DPD, %DPH/d) and percentage of day- and night-time activity, explosion occurrence (in %DPD, average counts/d), landings of market squid (in average lbs/d) with catch origin within 20 km radius and during recording period of the corresponding HARP (rounding to tens for values <100, to thousands for >1,000) and days with recording effort (* for recordings of dolphins) for the twelve monitoring sites within the Southern California Bight.

Site	**RD**				**PWSD**				**Explosions**		**Squid landings**	**Effort**	
	%DPD	%DPH/d	% day	% night	%DPD	%DPH/d	% day	% night	%DPD	counts/d	lbs/d	Days effort*	Recording period
A	73.5	15.3	28.2	71.8	17.1	3.1	55.2	44.8	80.9	105.0	103,000	569	08/2005-12/2007
A2	56.5	11.7	32.7	67.3	0.0	0.0	NA	NA	78.6	87.6	52,000	230	02/2008-06/2009
B	15.6	1.6	39.1	60.9	2.1	0.2	26.1	73.9	21.6	11.2	0	436	08/2005-10/2007
C	33.8	4.8	12.1	87.9	20.2	2.7	18.8	81.2	1.1	0.04	60	1,315	08/2005-02/2011
G	35.2	3.8	26.7	73.3	50.9	9.8	40.5	59.5	51.6	41.4	0	267	01/2007-12/2007
J	47.0	6.8	37.8	62.2	8.9	1.1	64.2	35.8	39.5	75.5	56,000	281	07/2008-10/2009
K	84.7	15.4	17.4	87.6	54.8	9.5	50.0	50.0	0.0	0.0	6,000	124	07/2008-12/2008
K2	55.0	8.1	7.1	92.9	38.6	3.8	3.0	97.0	7.9	1.7	2,000	140	12/2008-05/2009
K3	66.9	12.8	42.4	57.6	6.6	0.7	75.7	24.3	50.0	229.4	70,000	136	05/2009-11/2009
M	49.2	6.3	24.1	75.9	7.7	1.3	58.5	41.5	40.1	58.4	6,000	727	01/2009-04/2011
N	8.4	0.9	18.3	81.7	6.9	0.6	15.8	84.2	42.4	11.2	0	666	01/2009-04/2011
Q	41.4	6.7	34.6	65.4	1.9	0.1	78.2	21.8	81.0	252.6	5,000	268	09/2009-07/2010

Habitat overlap and noise exposure

RD echolocation activity overlaps more often with explosion noise than PWSD, both in terms of total hours of overlap and relative proportion of overlap compared to hours of dolphin presence. Consequently, RD are more often exposed to higher SEL_{cum}, whereas PWSD for most sites are only occasionally exposed to seal bomb noise (Table 2, Figure 5).

Table 2 Overview of noise exposure and habitat overlap of dolphin echolocation activity of Risso's (RD) and Pacific white-sided dolphins (PWSD) and explosions with % of total recording hours with overlapping dolphin and explosion occurrence (hOverlap), % of detection positive hours (DPH) for concurrent dolphin echolocation and explosion occurrence relative to total DPH of dolphins (DPH_Overlap), mean cumulative sound exposure level (SEL_{cum}) of explosions during overlapping hours and % of those hours with SEL_{cum}>170 dB re 1µPa^{2}s relative to all SEL_{cum} overlapping with dolphin occurrence.

Site	RD				PWSD			
	hOverlap %	DPH_ Overlap %	SEL_{cum} dB	SEL_{cum} >170dB %	hOverlap %	DPH_ Overlap %	SEL_{cum} dB	SEL_{cum} >170dB %
A	5.3	30.0	160	13.0	0.3	15.9	167	42.9
A2	4.4	37.7	168	55.0	0	0	NA	NA
B	0.08	7.1	164	0	0	0	NA	NA
C	0	0	NA	NA	0	0	NA	NA
G	0.9	21.8	155	0	2.1	17.6	159	0
J	1.7	24.4	174	68.5	0.09	7.8	160	33.3
K	0	0	NA	NA	0	0	NA	NA
K2	0.09	1.1	148	0	0.06	1.6	145	0
K3	4.5	34.5	170	56.9	0.03	4.3	165	0
M	0.7	10.8	153	1.9	0.2	14.2	153	3.0
N	0.08	7.3	140	0	0.02	3.8	138	0
Q	2.7	39.4	165	46.3	0.05	33.3	159	0

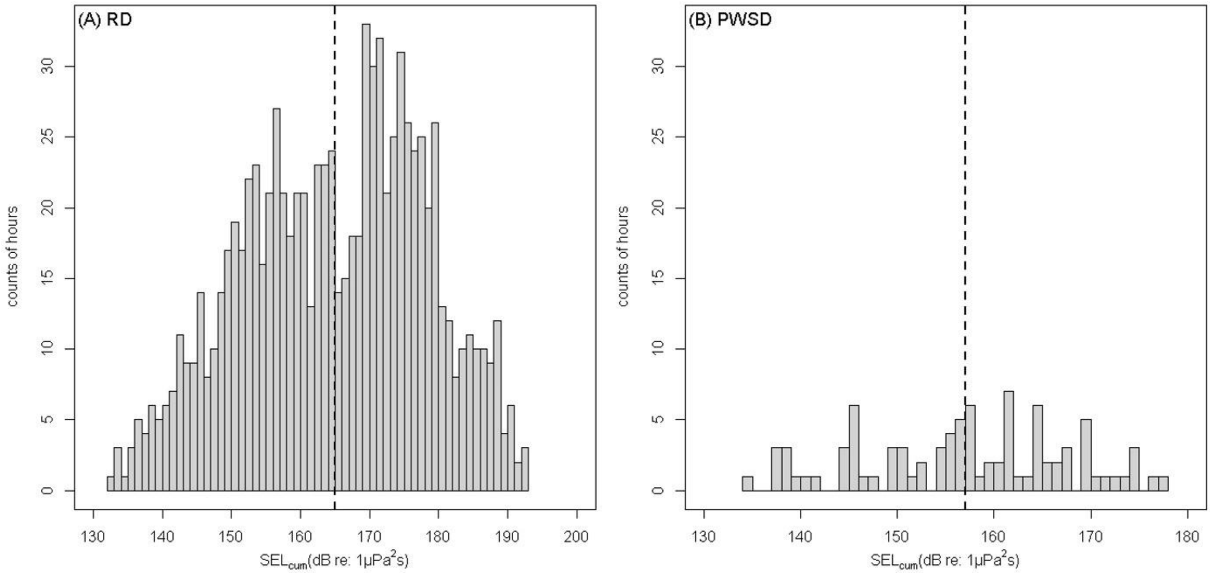

Figure 5 Distribution and frequency of received cumulative sound exposure level (SEL$_{cum}$) per hour in dB re 1µPa^{2}s during hours of (A) Risso's (RD) and (B) Pacific white-sided dolphin (PWSD) presence with mean (dashed line).

For RD, overlapping hours with explosion occurrence were highest at site A, A2 as well as site K3 and Q (Figure 6.A, B and Supplementary Figure 3). For certain times, an overlap with market squid fishing activity was visible there as well. At those sites, more than 30 % of all DPH overlapped with explosion occurrence while RD were exposed to mean SEL$_{cum}$ of 160-170 dB re 1µPa^{2}s during overlapping hours. For a considerable number of hours high SEL$_{cum}$ of over 170 dB re 1µPa^{2}s have been recorded while RD were present. However, at site B, C, K, K2 and N overlap was marginal or absent (Table 2, Supplementary Figure 4).

For PWSD, concurrent dolphin presence and overlap with explosions, both in considerable amounts, has only been detected at site G (Figure 6.C). There, PWSD have been exposed to mean SEL$_{cum}$ of 159 dB re 1µPa^{2}s. At most other sites overlap has been marginal or absent or dolphin activity has been low (Table 2, Supplementary Figure 5-6).

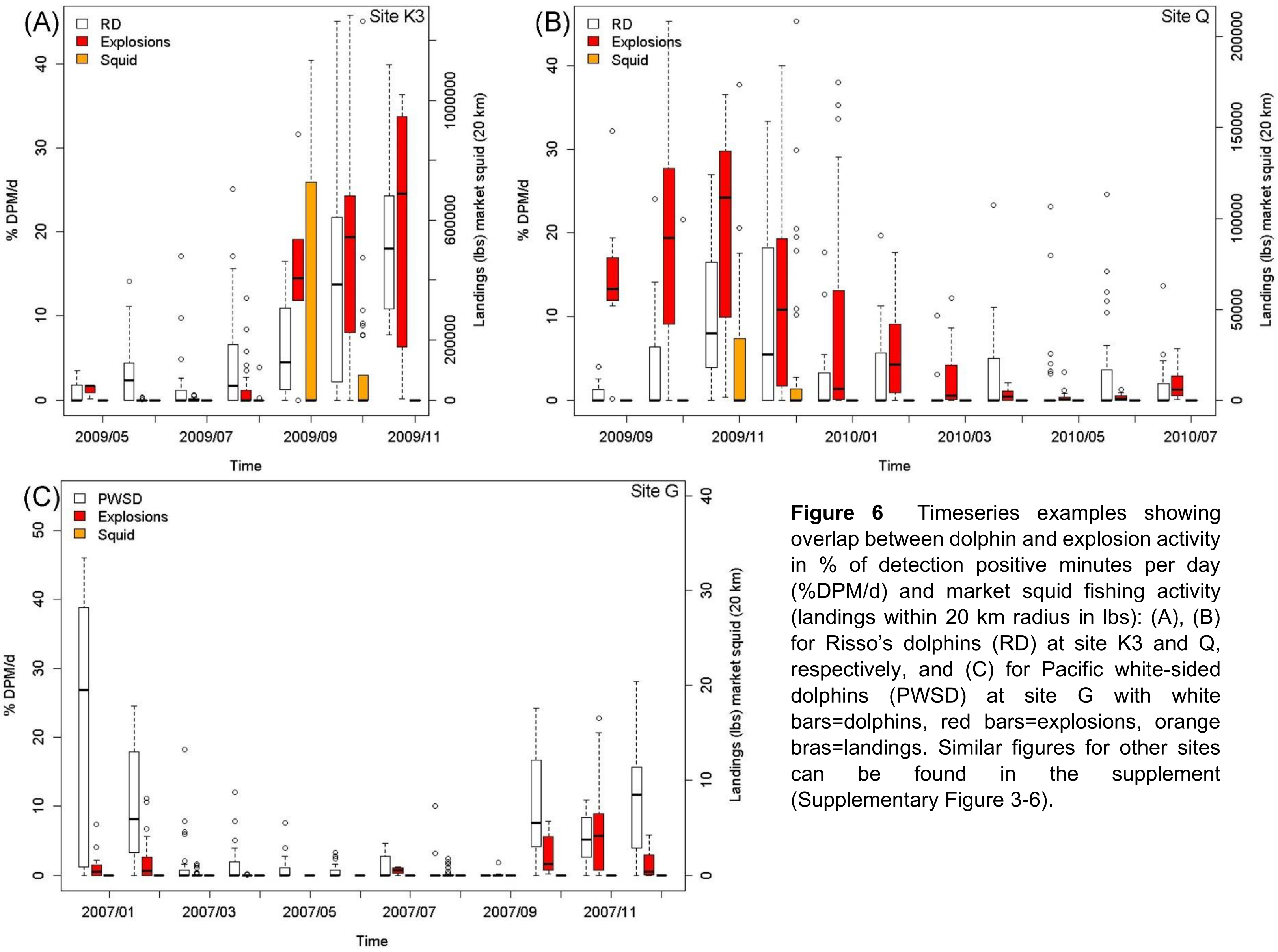

Figure 6 Timeseries examples showing overlap between dolphin and explosion activity in % of detection positive minutes per day (%DPM/d) and market squid fishing activity (landings within 20 km radius in lbs): (A), (B) for Risso's dolphins (RD) at site K3 and Q, respectively, and (C) for Pacific white-sided dolphins (PWSD) at site G with white bars=dolphins, red bars=explosions, orange bras=landings. Similar figures for other sites can be found in the supplement (Supplementary Figure 3-6).

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Effects of explosions on dolphins

A comparison of the ratio for DPM/photoperiod (night vs. day) during days with no or relatively low explosion counts (0-100/d) and days with higher explosion counts (>100/d) revealed significant differences with reduced night-time activity during high explosion occurrence for both species (Figure 7). This effect was much more pronounced for PWSD (Figure 7.B), reducing their mean night-time activity from 67% to 45%, while a reduction for RD was lower with 76% to 70% on average (Figure 7.A). However, sample size (n) for days with high explosion occurrence and dolphin presence was much lower compared to days with no or low explosion counts.

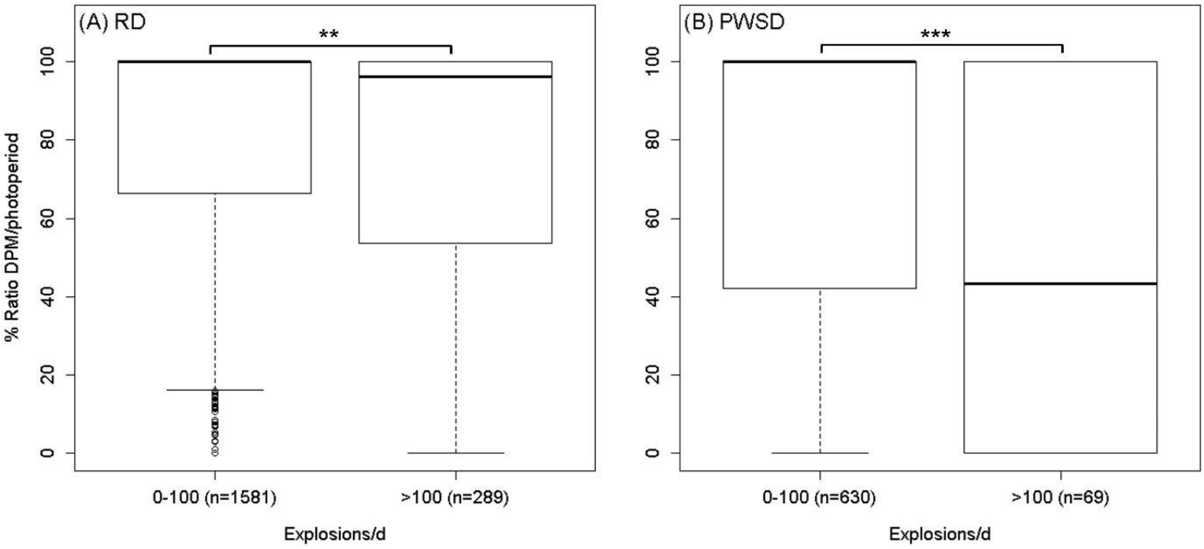

Figure 7 Ratio (%) of night vs. day-time echolocation activity in detection positive minutes (DPM) per photoperiod on days with <100 to zero explosions/d and on days with >100 explosions/d for all sites combined for (A) Risso's (RD) and (B) pacific white-sided dolphins (PWSD) with number of days (n) for each case. Significance is indicated with **p<0.01 and ***p<0.001(Kruskal-Wallis rank sum test).

A GAM for all sites with DPD > 15 % combined revealed highly significant effects of Julian day and normalized time of the day on RD and PWSD acoustic presence per hour. For RD, a peak in DPM/h was evident during fall and during night-time hours, whereas drops were detected in summer and in the afternoon. For PWSD, a peak was shown during late spring/summer and winter as well as during the night. Overall, year and site were significant predictors as well. SEL_{cum} for explosions was a significant predictor for both species, with a positive effect on RD and a negative on PWSD. However, confidence intervals for SEL_{cum} were large, making the overall predictive power of this variable low (Figure 8, 9, Supplementary Table 1). Additionally, deviance explained for best model fits were relatively poor, with 12.7% for RD and 13.7% for PWSD, indicating that other parameters affecting the occurrence of both dolphin species were missing in the models. Also, strong site-specific differences may have led to the low explained deviance.

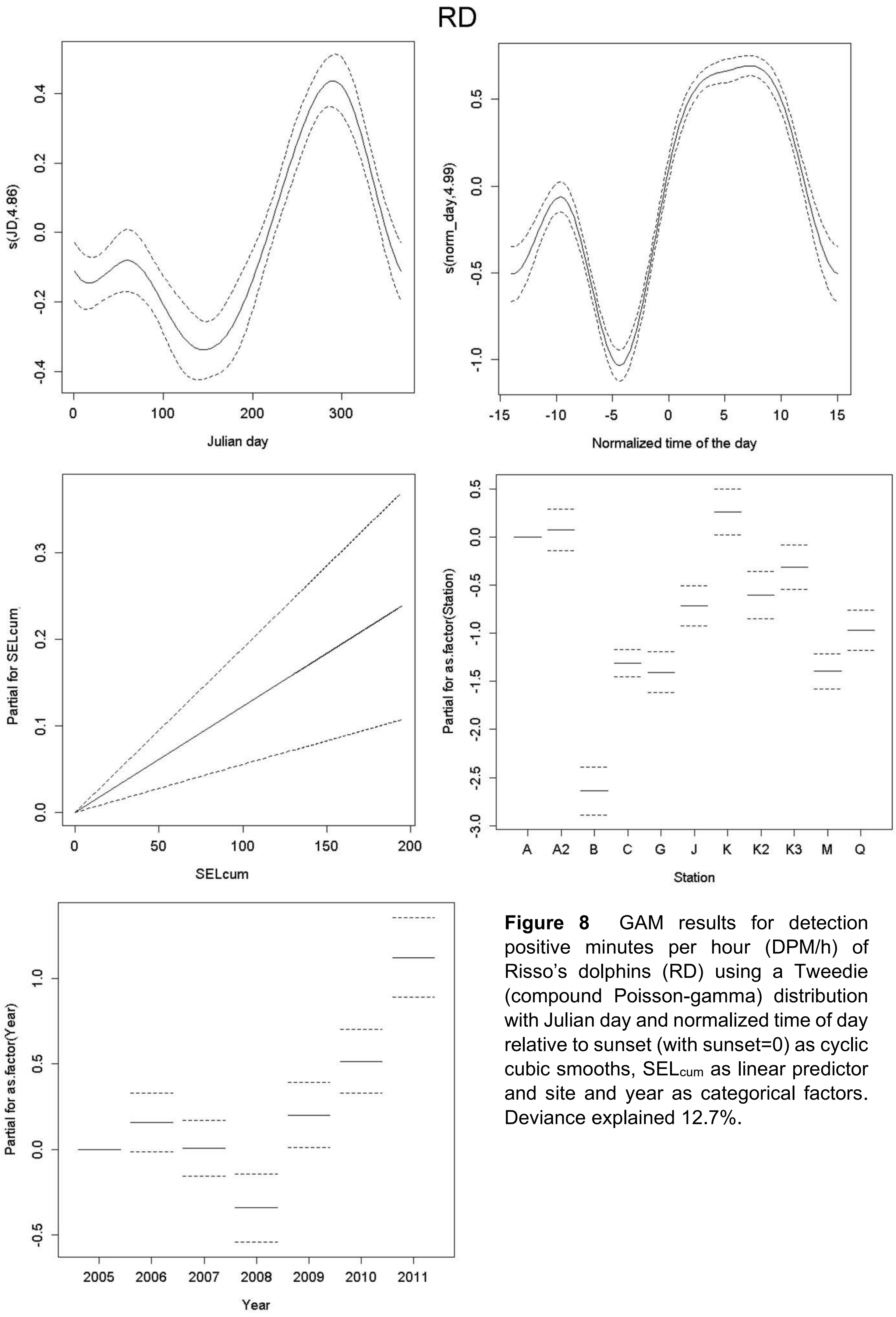

Figure 8 GAM results for detection positive minutes per hour (DPM/h) of Risso's dolphins (RD) using a Tweedie (compound Poisson-gamma) distribution with Julian day and normalized time of day relative to sunset (with sunset=0) as cyclic cubic smooths, SEL_{cum} as linear predictor and site and year as categorical factors. Deviance explained 12.7%.

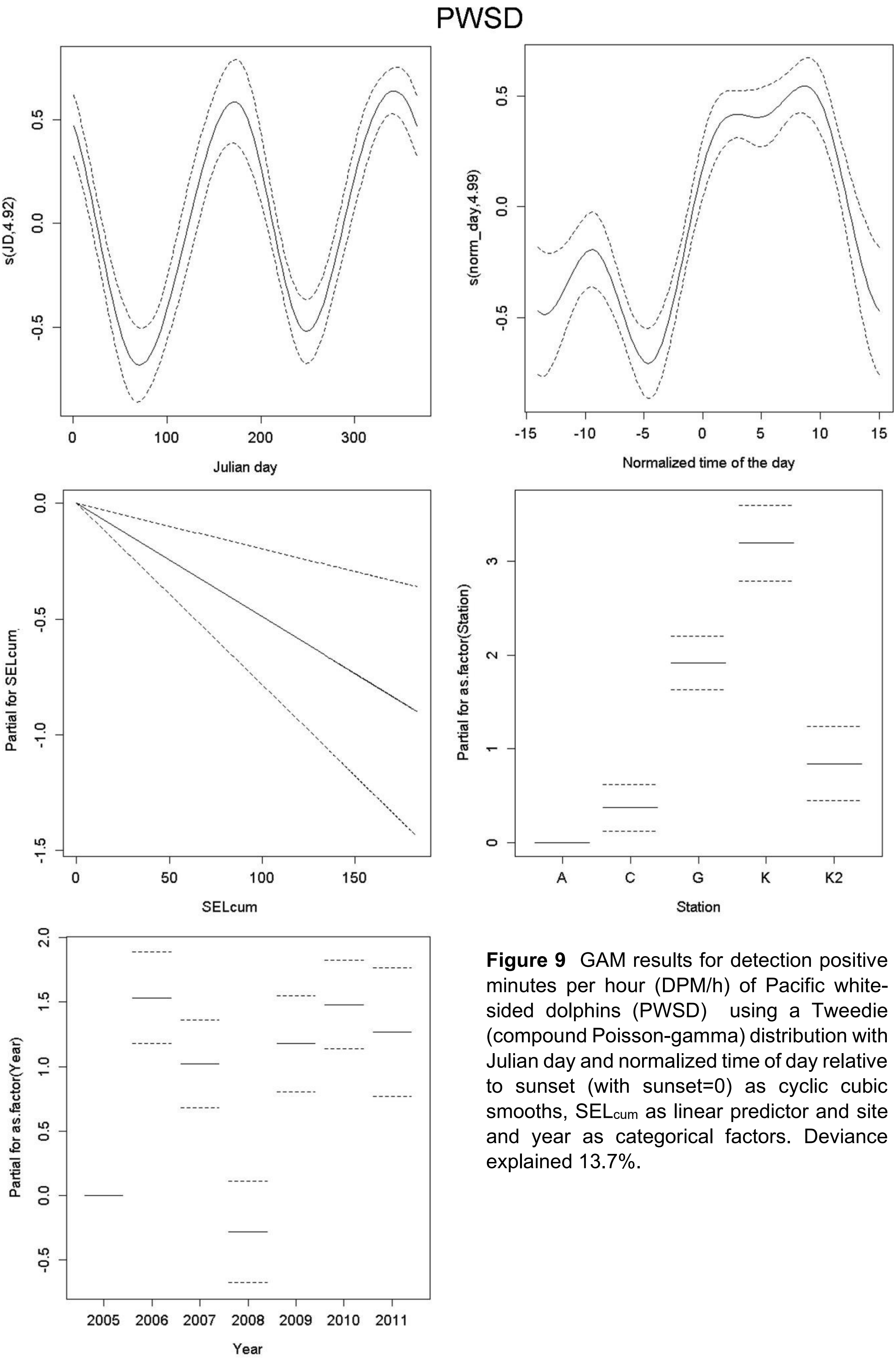

Figure 9 GAM results for detection positive minutes per hour (DPM/h) of Pacific white-sided dolphins (PWSD) using a Tweedie (compound Poisson-gamma) distribution with Julian day and normalized time of day relative to sunset (with sunset=0) as cyclic cubic smooths, SEL_{cum} as linear predictor and site and year as categorical factors. Deviance explained 13.7%.

Discussion

Both dolphin species were mostly detected at island-associated sites, like the Channel Islands (both species), Santa Catalina Island (RD) and San Clemente Island (PWSD). Especially RD showed a strong diel pattern with most echolocation activity during the night, whereas patterns of PWSD were more variable (Table 1, Figure 4). That RD forage primarily at night, has been shown in several studies (e.g., Au et al. 2013; Smultea et al. 2018; Soldevilla et al. 2010a). However, foraging has also been described to occur during the day, while foraging behavior and depth seems to follow the diel vertical migration of the deep scattering layer, depending on time of the day (Benoit-Bird et al. 2019; Visser et al. 2021). Therefore, seal bomb noise occurring in almost 95 % of all cases at night (Krumpel et al. 2021), might have a different impact on these animals than other noise sources, which are more pronounced during the day, e.g., vessel traffic.

For RD, considerable habitat overlap with explosions has been shown, with dolphins being exposed to seal bomb noise for more than 1/3 of the time they spent around certain sites, like sites at Catalina Island or at Santa Cruz Island within the eastern part of the Channel Islands, sites where RD have been recorded frequently. Especially those areas are known hotspots for commercial market squid fishing in the SCB (Maxwell et al. 2004; Table 1), which makes an overlap with mainly squid eating RD and seal bomb noise likely (Krumpel et al. 2021). Despite, the limited numbers of available studies, other authors have described overlap or interactions with RD and squid fisheries as well. Mussi et al. (1999) described RD to prey on squids caught by the illuminated handline-fishery in the Tyrrhenian See. There, RD were reported to wait near fishing boats until larger amounts of squid had assembled due to light attraction and then preyed on them. Around the Azores, RD were reported to interact with the local hand-jig squid fishery with the species being responsible for >90 % of all depredation events within this fishery. RD depredated on squid about 1.5 hours after fishing activity started and remained around the fishing boats for about 1.5-2 hours. The use of pingers to reduce these interactions was ineffective. Depredation by RD did not change with pinger brand or condition and no change in dolphin behavior was documented (Cruz et al. 2014). Thus, pinger noise did not prevent RD from getting an easy meal. However, no published interactions with RD and the market squid fishery in the SCB exist. Therefore, overlap with seal bombs used within this fishery might not necessarily mean that the animals actively interact with the fishery but that both share a main target and occur where squid is abundant and/or easily accessible.

GAMs used to explain occurrence of dolphin and effects of seal bombs explained only a small part of the deviance (13-14 %), while SEL_{cum} of seal bomb explosions was a significant but weak explanatory variable. The low explained deviances found in this study indicate that important variables needed to explain dolphin echolocation activity were missing. Soldevilla et al. (2011) revealed that sea surface temperature, chlorophyll concentration or upwelling were important habitat variables to explain RD and PWSD activity in the SCB. Croll et al. (2001) also found that cetaceans responded more to oceanographic changes or prey features, rather than to noise from low-frequency sonar. Therefore, these models likely oversimplify the results, and responses to seal bomb noise are likely more complex and/or variable. However, having these limitations in mind, the results may still give first insights into responses of cetaceans to seal bomb noise.

For RD, no changes in acoustic behavior due to seal bomb noise, like avoiding an area (less acoustic activity) or switching from preferably night- to more day-time activity was detected (Figure 7.A, 8). However, a lack of response should not, potentially incorrectly, be simply interpretated as a lack of effect. If animals are strongly motivated to stay in certain areas because they are important for feeding or breeding, and therefore crucial for their survival and fitness, they might accept negative impacts, even to the point of potential hearing damage or other physiological effects (Beale & Monaghan 2004; Rolland et al. 2012; Weilgart 2007). At sites with strong overlap of RD and explosions, the animals were exposed to mean SEL_{cum} of up to 160-170 dB re 1µPa^{2}s. For some sites more than 50 % of recorded hours with concurrent RD and explosion occurrence had SEL_{cum} of more than 170 dB re 1µPa^{2}s and up to >190 dB re 1µPa^{2}s (Table 2, Figure 5.A). Onset of PTS for impulsive sounds in mid-frequency cetaceans, like RD and PWSD, was estimated to begin at 185 dB re 1µPa^{2}s (weighted SEL cumulated over 24h) while TTS onset was estimated to be 15 dB less, based on limited amount of available impulsive data for marine mammals (NMFS, 2018). While SEL_{cum} calculated within this study are non-weighted and cumulated over a shorter period, the partly high number of hours RD spent at sites with

>170 dB re 1µPa^{2}s, sometimes between 180-190 dB re 1µPa^{2}s, still leads us to assume, that the animals may have endured TTS, at least at certain sites and times. Beside TTS, potential physiological effects can include changes in metabolism, respiration, food consumption or enhanced stress levels. For example, a beluga whale (*Delphinapterus leucas*) showed a neural-immune response with enhanced levels of stress hormones, after suffering from a TTS due to seismic air gun noise (Romano et al. 2004) while killer whales (*Orcinus orca*) respiration rate changed in response to shipping noise (Williams et al. 2014). To determine how such impacts contribute to reduced fitness and therefore effects on population-level is still challenging (Williams et al. 2020). However, cetaceans remaining in areas with high noise exposure despite potential negative impacts and responses depends on motivation or activity of the animals. Migrating humpback whales (*Megapetra novaeangliae*) in Australia avoided seismic air-guns at received levels of 157-164 dB re 1 µPa^{2}s while resting pods with cows and calves already moved away from the source at 140-143 dB re 1 µPa^{2}s (McCauley et al. 2000). Whereas migrating bowhead whales (*Balaena mysticetus*) in the Beaufort Sea responded with avoidance to air gun noise at received levels of 120-130 dB re 1 µPa, while feeding animals during the summer responded not until 158-170 dB re 1 µPa (Richardson et al. 1995, 1999). In the SCB, blue whales (*Balaenoptera musculus*) responses to simulated mid-frequency sonar were strongly influenced by their behavioral state with non- and deep-diving animals changing and surface-feeding animals not changing their behavior (Goldbogen et al. 2013).

PWSD showed less overlap, both in terms of total and relative presence, with explosions compared to RD. At sites with considerable PWSD activity (A, G, M), they spent about 15 % of their time in the presence of explosions. There, they were exposed to mean SEL_{cum} of 153-167 dB re 1µPa^{2}s and 3-40 % of hours with concurrent explosions and dolphin presence had SEL_{cum}> 170 dB re 1µPa^{2}s (Table 2). During days with high explosions counts they were more active during the day than during the night, which could be a sign of avoiding night-time seal bomb noise (Figure 7.B). However, sample size for days with high explosion counts and concurrent PWSD presence was low and hence remains more anecdotal. The GAM, despite of its low explanatory power, showed decreased dolphin presence with increasing SEL_{cum} (Figure 9). Despite the methodical limitations, the results taken as a whole indicate that PWSD might at least avoid areas and times with high levels of seal bomb noise.

Overlap might also be smaller as hydrophones may not have been located within their preferred habitat or a combination of the two explanation possibilities. Behavioral changes, like avoidance, induced by noise, are well described for different cetacean species. As stated before, PWSD at San Clemente Island left the area due to mid-frequency active sonar (Henderson et al. 2014b). Harbor porpoises reacted with avoidance (decreased detection rates) of up to 10 km distance and more as a response to impulsive pile-driving noise during construction of offshore wind farms in the North Sea (Dähne et al. 2013; Benhemma-Le Gall et al. 2021). To name a few, killer whales, sperm whales (*Physeter macrocephalus*), long-finned pilot whales (*Globicephala melas*), northern bottlenose whales (*Hyperoodon ampullatus*), humpback whales and minke whales (*Balaenoptera acutorostrata*) showed avoidance over a range of different distances due to naval sonar signals (Miller et al. 2012; Silve et al. 2015; Wensveen et al. 2019).

The apparent opposite effects of noise from seal bomb explosions on RD, with strong overlap, severe noise exposure and potential physiological responses, and PWSD, with less overlap and possible avoidance at least during times of high explosion occurrence might in fact be explained by differences in feeding preferences: RD being specialized feeders and relying heavily on squids as their primary but not sole prey and PWSD as more opportunistic feeders. Thus, responses to seal bomb noise might be matter of weighting biological costs or in other words, a matter of existence versus lack of comparably good alternatives of foraging habitat and prey.

Conclusion and Outlook

To minimize noise impacts on dolphins and other marine animals the use of seal bombs needs to be regulated. In 2020, NOAA proposed the implementation of guidelines (NOAA 2020) regulating different acoustic deterrence devices including seal bombs. The regulations contain safe distances that are to be complied with (100 m for cetaceans, 20 m for phociids, 2 m for otariids) and a 180 second silent interval between consecutive seal bomb deployments. The results of this study strongly support NOAA in this objective. However, the guidelines mainly aim to reduce the risk of tissue and hearing damage. But even with a 180 second silent period, which does not consider that during peak times multiple squid vessel might be engaged in seal bomb usage and silent periods can only be overseen per boat, 20 seal bombs per hour per boat would still be allowed. These amounts will likely induce behavioral and physiological effects in cetaceans. One way of reducing impacts is to take critical habitats into account. The results of this study show, that the Channel Islands National Marine Sanctuary e.g., is heavily used by both RD and PWSD. At the same time, noise from seal bombs propagates into the waters of the sanctuary. A buffer zone, for example, around such protected areas, where seal bomb use is further restricted or prohibited, or clear thresholds on how much seal bomb noise may reach the sanctuary zone, could minimize negative impacts.

Researching effects of seal bomb noise on marine life still stands at the beginning. More research on effects on other species and taxa as well as on current extents of seal bomb use in more recent years are greatly needed to support sustainable marine management decisions. To deepen the knowledge of effects on RD and PWSD specific studies on their foraging behavior and success in relation to seal bomb use, e.g., additionally using tagging-data and observations from fishing vessels, would be helpful. Cooperation with fishermen to develop useful alternatives to seal bombs is a key aspect to reduce noise impacts and support sustainable fisheries on a long-term basis.

Conflict of Interest

The 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.

Author Contributions

A.K. designed the study. A.K., E.B.K., K.E.F., S.B.P. and S.M.W. were responsible for signal detection and/or data analysis. A.S.B. provided guidance on model statistics. A.K. was responsible for statistics, created graphical output and wrote the manuscript. S.B.P., A.D. and H.U.S. provided conceptual guidance and comments to improve the manuscript.

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*CDFW acquires data from its own fisheries management activities and from mandatory reporting requirements on the commercial and recreational fishery pursuant to the Fish and Game Code and the California Code of Regulations. These data are constantly being updated, and data sets are constantly modified. CDFW may provide data upon request, but, unless otherwise stated, does not endorse any particular analytical methods, interpretations, or conclusions based upon the data it provides.

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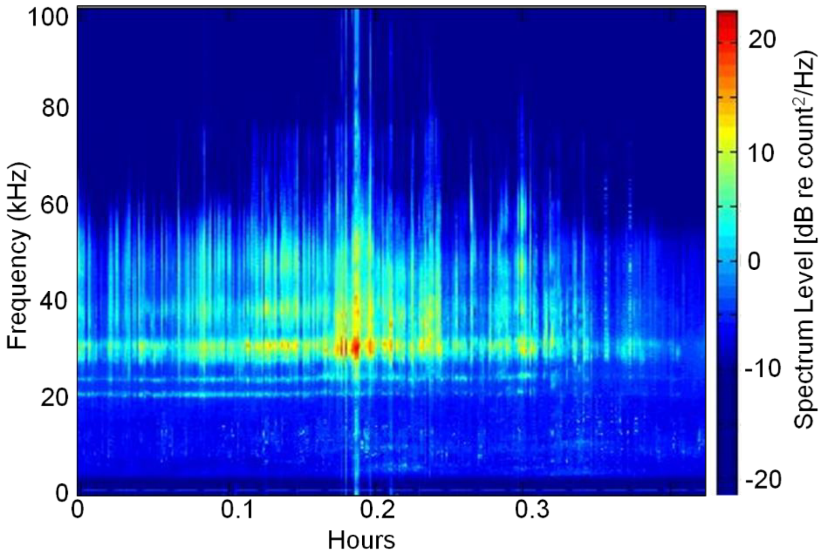
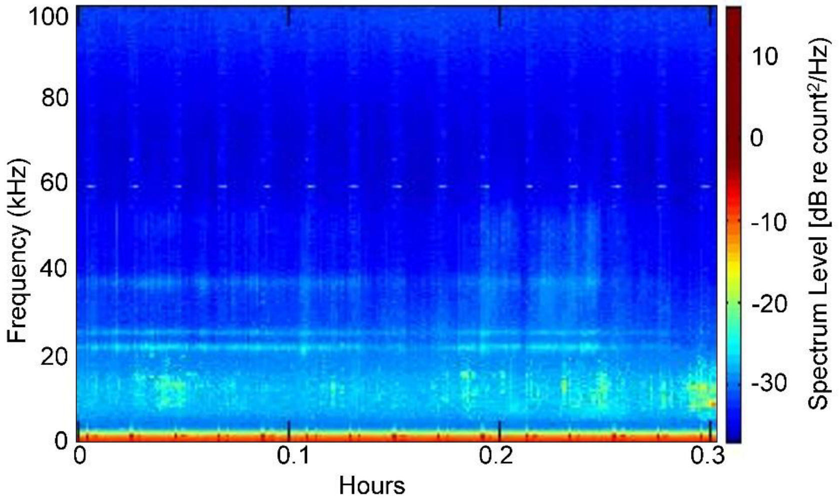
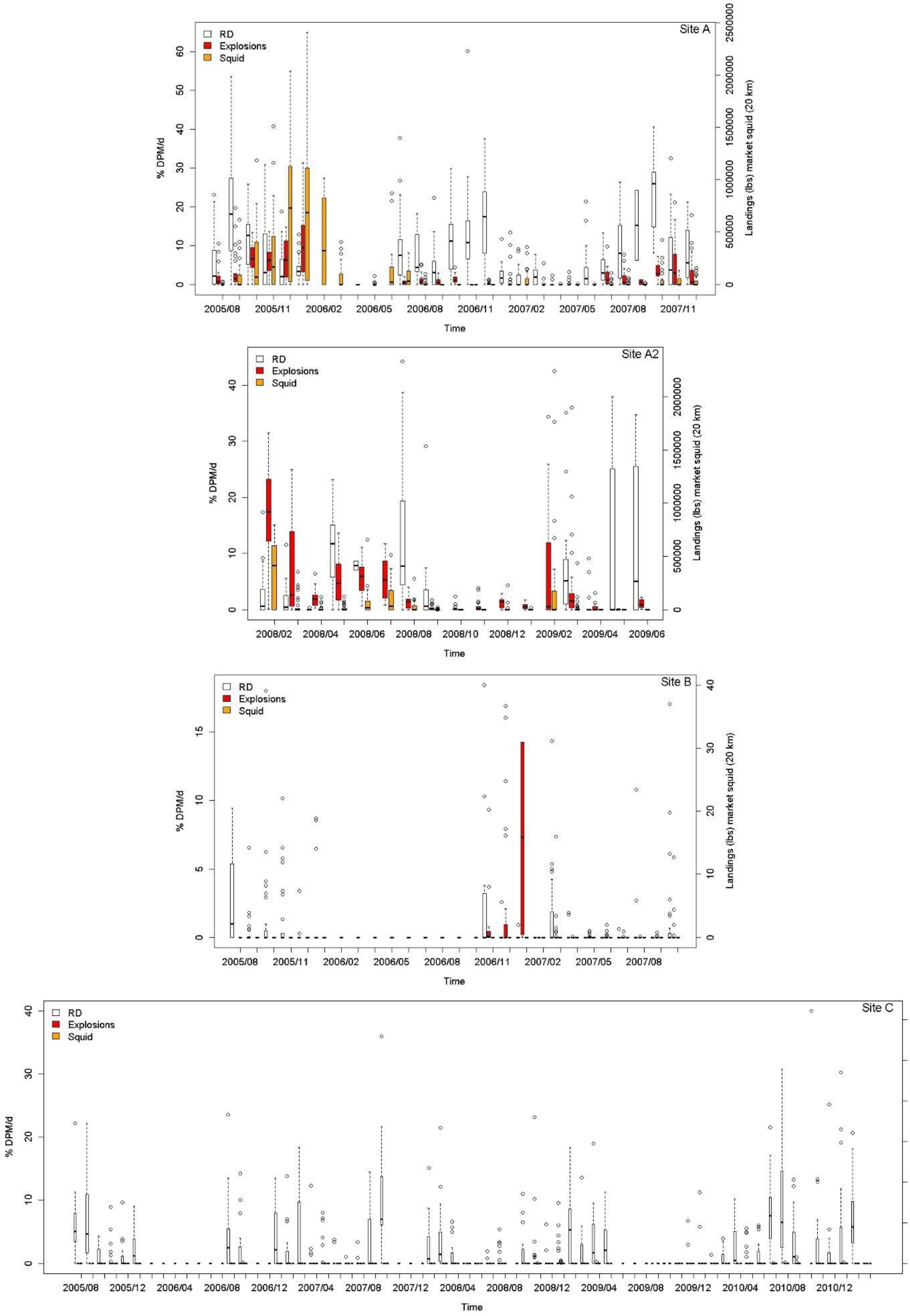
Supplementary Material Chapter 4



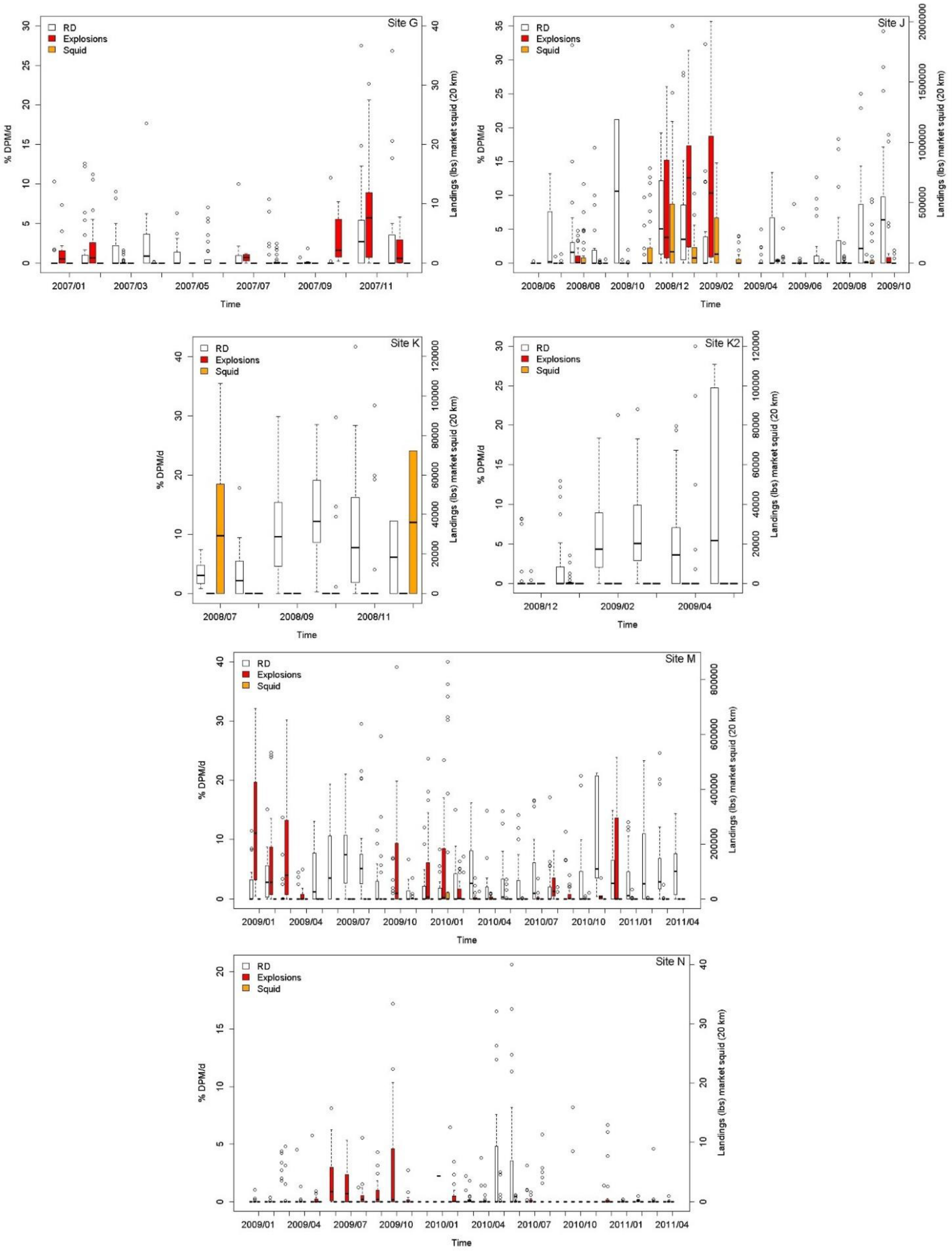
Supplementary Figure 1 Example LTSA of a echolocation click encounter of a Risso's dolphin with unique spectral peak and notch structure at 21, 24, 31 and 39 kHz recorded at site M on 01/19/2009. LTSA spectogramms with 100 Hz and 5 s resolution, represents coherent averages created using 2000-point, 0%-overlapped, Hann-windowed data.



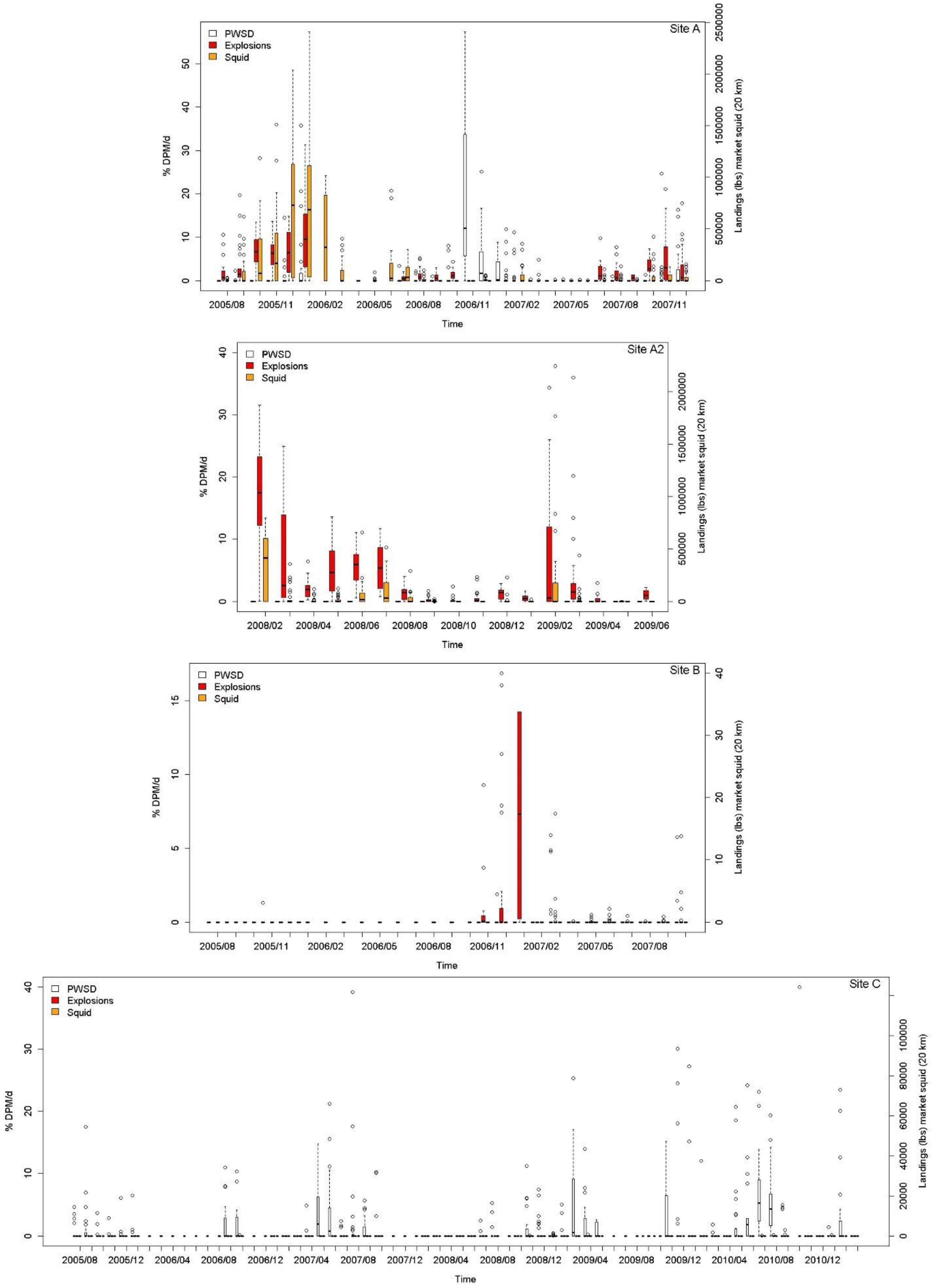
Supplementary Figure 2 Example LTSA of a echolocation click encounter of a Pacific white-sided dolphin with unique spectral peak and notch structure at 22, 25 and 37 kHz recorded at site K3 on 10/14/2009. LTSA spectogramms with 100 Hz and 5 s resolution, represents coherent averages created using 2000-point, 0%-overlapped, Hann-windowed data.



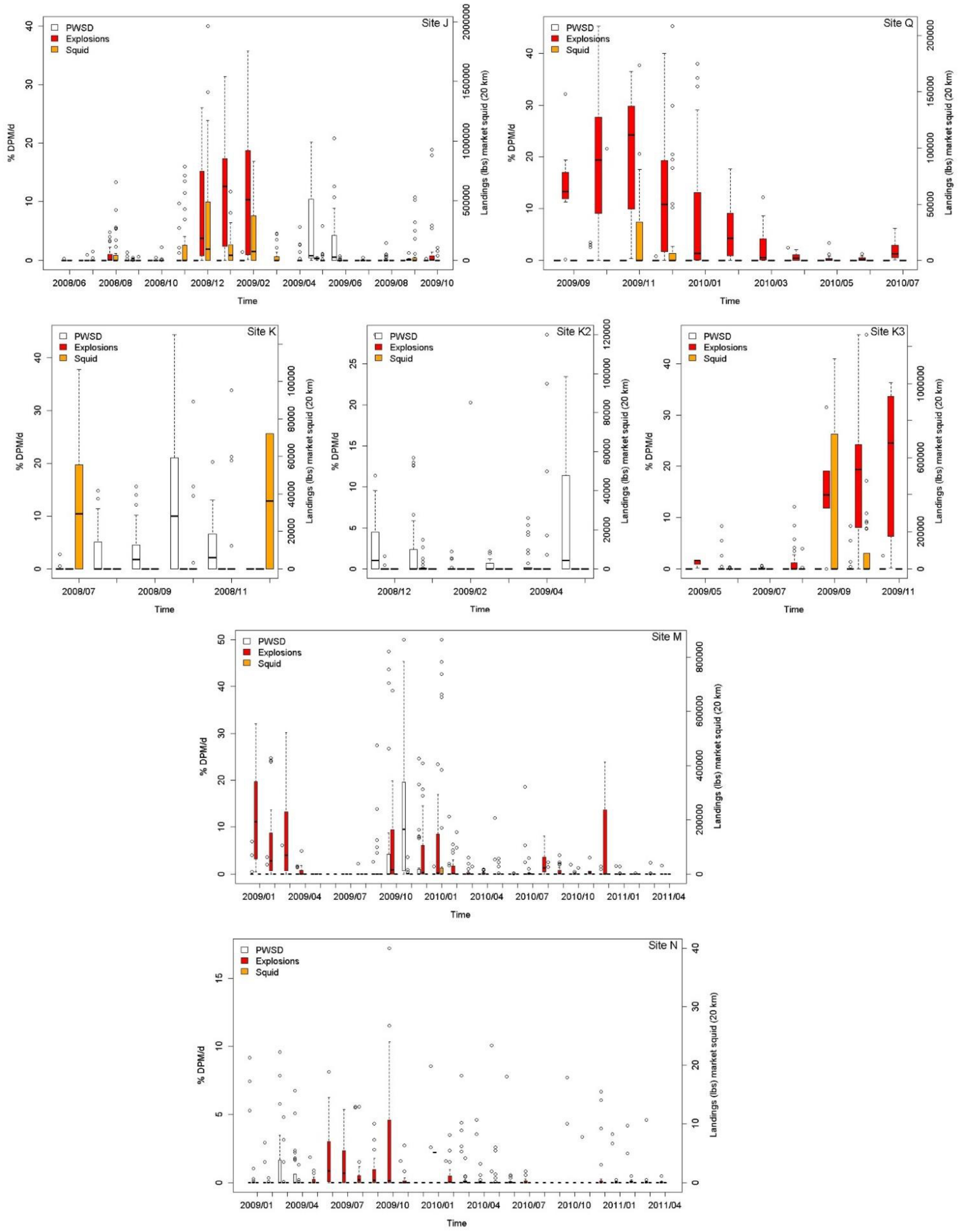
Supplementary Figure 3 Timeseries of Risso's dolphin (RD) echolocation (white) and explosion (red) occurrence (% DPM/d) as well as landings of market squids (orange) (within 20 km radius in lbs) at site A, A2, B and C.



Supplementary Figure 4 Timeseries of Risso's dolphin (RD) echolocation (white) and explosion (red) occurrence (% DPM/d) as well as landings of market squids (orange) (within 20 km radius in lbs) at site G, J, K, K2, M and N.



Supplementary Figure 5 Timeseries of Pacific white-sided dolphin (PWSD) echolocation (white) and explosion (red) occurrence (% DPM/d) as well as landings of market squids (orange) (within 20 km radius in lbs) at site A, A2, B and C.



Supplementary Figure 6 Timeseries of Pacific white-sided dolphin (PWSD) echolocation (white) and explosion (red) occurrence (% DPM/d) as well as landings of market squids (orange) (within 20 km radius in lbs) at site J, Q, K, K2, K3, M and N.

Supplementary Table 1 Results for parameters included in the GAMs for Risso's (RD) and Pacific white-sided dolphins (PWSD). The smooth terms (Julian Day and normalized time of the day) with a cyclic cubic regression spline (k=7) are shown with estimated degrees of freedom, linear terms (SEI_{cum}) and categorical factors (year and site) are indicated with standard error. Significance of predictors is indicated as following ^{x} insignificant, *p<0.05, **p<0.01, ***p<0.001. The Tweedie power parameter (Tweedie), AIC, deviance explained are provided as well for each model. Only estimates from the best models are presented here.

Model	**RD**	**PWSD**
Tweedie	1.36	1.38
s(JD)	4.86***	4.9***
s(norm_day)	4.99***	4.99***
Intercept	0.07***	0.17***
SEL_{cum}	0.001***	0.001***
Year		
2006	0.08^{x}	0.18***
2007	0.08^{x}	0.17***
2008	0.10***	0.20^{x}
2009	0.09*	0.19***
2010	0.09***	0.17***
2011	0.12***	0.25***
Site		
A2	0.11^{x}	
B	0.12***	
C	0.07***	0.13**
G	0.11***	0.14***
J	0.10***	
K	0.12*	0.20***
K2	0.12***	0.20***
K3	0.11**	
M	0.09***	
Q	0.10***	
AIC	104,005	32,075
Dev. expl.	12.7 %	13.7 %