Dynamics of seal bomb use in Channel Islands and Monterey Bay National Marine Sanctuaries

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Acronyms

NOAA	National Oceanic and Atmospheric Administration
NMFS	National Marine Fisheries Service
CDFW	California Department of Fish and Wildlife
CINMS	Channel Island National Marine Sanctuary
MBNMS	Monterey Bay National Marine Sanctuary
ONMS	Office of National Marine Sanctuaries
VIIRS	Visible Infrared Imaging Radiometer Suite
BIA	Biologically Important Area
IUCN	International Union for Conservation of Nature
MMPA	Marine Mammal Protection Act
ESA	Endangered Species Act
NMSA	National Marine Sanctuaries Act
SIO	Scripps Institute of Oceanography
MBARI	Monterey Bay Aquarium Research Institute
TTS	Temporary Threshold Shifts
PTS	Permanent Threshold Shifts
ATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
SST	Sea Surface Temperature

Objectives

Our overall objective is to evaluate how California market squid fishing pressure and the use of marine mammal acoustic deterrents known as “seal bombs” affect acoustic habitat around Monterey Bay and Channel Islands National Marine Sanctuaries. This project will:

- Assess the dynamics of seal bomb use by correlating spatial and temporal distribution of squid fishing activity with confirmed seal bomb detonations recorded on historic and current passive acoustic monitoring data sets.
    - Contextualize these dynamics by analyzing how abiotic shifts, including sea surface temperature, influence squid fishing pressure, and in turn seal bomb usage.
- Expand the geographical scope of analysis by spatially overlaying squid fishing pressure with existing cetacean biologically important areas, highlighting where regions of high-intensity squid fishing pressure, *a proxy for seal bomb use*, may overlap with important cetacean habitat.
- Provide recommendations to the National Marine Fisheries Service and the State of California with management options for fisheries to lessen impacts to acoustically sensitive marine mammals.

Significance

California is home to four National Marine Sanctuaries that are part of a vast network of marine protected areas for the state. The two most southern sanctuaries, Channel Islands and Monterey Bay, are home to a dense assemblage of marine organisms that rely on these safe havens for much of their lifetimes. Both sanctuaries seek to preserve the scenic beauty, biodiversity, cultural history, and economic productivity of some of California’s most precious ocean treasures. The sanctuaries are visited annually by migratory cetaceans that travel between Baja California and British Columbia. Unfortunately, oceans face increasing anthropogenic pressures, and noise pollution is a growing concern. Exposure to acute, and often cumulative, sound poses a significant risk to acoustically sensitive cetacean species that are protected under the Marine Mammal Protection Act and the Endangered Species Act.

This project will provide an analysis of the acoustic impacts of a legal marine mammal acoustic deterrent known as a “seal bomb”. These deterrents are small underwater explosives used to deter nuisance marine mammals from interfering with fishing operations. Pinnipeds are the primary target for seal bomb use, as they often compete with fishing boats for their catch, however, there may also be acoustic impacts to cetaceans and other marine mammals. The analytical products from this project will provide integrative information needed to advise the National Marine Fisheries Service's proposed rule guiding acoustic deterrent use. By providing insight into the effects of seal bomb use on cetacean species of concern, fisheries and regulatory agencies may be able to collaborate to avoid high impact times and locations while maintaining efficient fishing practices.

Background

National Marine Sanctuaries

Located off the coast of southern and central California, the Channel Islands and Monterey Bay National Marine Sanctuaries are home to endangered species, vital marine habitats, and historically and culturally significant resources. It is the goal of NOAA's Office of National Marine Sanctuaries (ONMS) to protect all resources found within sanctuary bounds.

Channel Islands National Marine Sanctuary

Established in 1980, the Channel Islands National Marine Sanctuary (CINMS) protects 1,470 square miles of ocean surrounding the four Northern Channel Islands and Santa Barbara Island. CINMS boundaries extend from the mean high tide to six nautical miles offshore around each of the islands (National Marine Sanctuary Foundation, 2021). Located just below Point Conception in the Southern California Bight, CINMS is the confluence point of the colder California Current and the warmer California Countercurrent. The mixing of these two systems creates unique conditions in the Santa Barbara Channel. Wind patterns in the Channel drive upwelling and force cold, nutrient-rich water to the surface, which increases primary production. For this reason, the Channel is home to expansive forests of giant kelp (*Macrocystis pyrifera*), as well as eelgrass (*Zostera*) and surfgrass (*Phyllospadix scouleri*) (National Parks Service, 2017). These algal species provide a three-dimensional habitat structure for a variety of marine invertebrates, fish, and elasmobranchs. In addition to its ecological importance, CINMS also has a rich cultural history. The Channel Islands are a historically significant place for the Chumash Native Americans, who were the only native inhabitants of the islands.

Monterey Bay National Marine Sanctuary

Monterey Bay National Marine Sanctuary (MBNMS) extends from Cambria up to San Francisco, protecting nearly a quarter of California's coast. The sanctuary extends from mean high tide to anywhere from 30 to 50 miles offshore, for a total of 6,094 square miles of protection. This sanctuary is home to a diverse ecosystem that supports 36 species of marine mammals, 180 species of shorebirds and seabirds, as well as diverse invertebrate and marine algal species. Monterey Bay's two-mile-deep sea canyon, rocky reefs, seamounts, nutrient-rich waters, and coastal estuaries create valuable ecosystems worthy of conservation (Monterey Bay National Marine Sanctuary, n.d.).

Marine Mammals & Legislation

The International Union for Conservation of Nature (IUCN) mammal review suggests that marine mammals are negatively impacted by mankind's increasingly intensive use of the world's oceans (Schipper et al. 2008). The birth of marine mammal science was formed out of the growing recognition that marine mammal populations are actively decreasing, therefore, ocean use must be addressed and regulated (Boyd, 1993).

Cetaceans

The taxonomic order of Cetacea consists of whales, dolphins, and porpoises, which are divided into two suborders – the mysticetes (baleen species) and the odontocetes (toothed species). Baleen species generally have large mouths and bodies which allow for robust fat reserves required for seasonal migrations and for prolonged periods of fasting when in less productive waters (Wursig, 1989). Toothed species have evolved sophisticated echolocation, which allows them to listen to high-frequency clicks that are sent into an ocean soundscape and returned as an echo to identify distances, size, shape, and texture of objects (Kellogg, 1959). Sound is an important sensory modality for cetaceans.

Baleen cetaceans generally produce lower frequency sounds than toothed cetaceans. These sounds may serve to communicate with other cetaceans over tens of kilometers, although it has been hypothesized that long-distance communication can span entire ocean basins (Schevill, 1964). Songs produced by the baleen humpback whale are sung primarily by adult males as a way to communicate their sex, location, and readiness to mate with other whales in the area (Tyack, 1981). Toothed cetaceans' vocalizations are often rich, varied, and tend to have higher frequencies than baleen species. Odontocetes utilize two basic sound types: pulsed clicks and un-pulsed, frequency-modulated whistles which are both used for communication and echolocation. Toothed cetaceans utilize echolocation to orient themselves in the water, avoid obstacles or threats, interact socially, and pinpoint their food sources. Their food sources include pelagic fish species and squid, but seals and diving seabirds are sometimes targeted as well.

As mentioned above, the Santa Barbara Channel experiences two ecologically distinct current systems that meet to create what is called a "transition zone". Combined with a large amount of nutrient upwelling occurring in the region, the Santa Barbara Channel attracts large concentrations of diverse marine mammals. The vast abundance and distribution of marine mammals in the channel is a great indicator of ecosystem health and ecological wholeness within CINMS. These specific oceanographic factors attract cetaceans that almost always travel as familial pods and take part in vast migrations to low-latitude mating and calving grounds in the winter and productive high-latitude feeding grounds in the summer. At least 14 cetacean species can be found within the Southern California Bight year-round or appear in substantial numbers as they migrate through the area.

Large cetaceans (12-26 meters maximum length) that have been spotted in the channel include the mysticete species of the gray whale, humpback whale, blue whale, fin whale, sei whale, right whale, bowhead whale, and Bryde's whale as well as the odontocete species of the sperm whale and Baird's beaked whale. Medium-sized cetaceans (up to 13 meters in length) that have been sighted in the Santa Barbara Channel include the mysticete species of minke whale, as well as the odontocete species of pilot whale, Risso's dolphin, Cuvier's beaked whale, killer whale, and even the occasional false killer whale. Lastly, small cetaceans (less than 4 meters maximum length) that are present in the channel include the Dall's porpoise, the Pacific white-sided dolphin, the northern right whale dolphin, common dolphin, and the bottlenose dolphin. Pygmy sperm whales, dwarf sperm whales, striped dolphins, harbor porpoises, and rough-toothed dolphins have also been reported as occasional vagrants within the Santa Barbara Channel and are considered to be rare visitors to the Channel Islands (Leatherwood et al. 1987). The Southern California Bight straddles major migratory pathways and the coast serves as a crucial reference point for some migrants, therefore, it is not uncommon for other rare species to be sighted within the region. Species composition may alter significantly in the coming years in response to shifts in ocean conditions, so this characterization of species composition and abundance is very much subject to change.

Pinnipeds and Rookeries

The taxonomic clade of Pinnipedia is made up of semi-aquatic fin-footed marine mammals such as seals, sea lions, and walruses. Pinniped distribution generally lies within continental shelf regions, and they are, for the most part, cold water animals that are found in areas with high productivity. Upwelling zones, such as the Southern California Bight, are focal points for many foraging pinniped species. Globally, 47 species make up this charismatic group of marine mammals, with one in three species considered threatened. A decrease in pinniped populations has occurred largely due to hunting as well as loss of breeding and resting habitat as a result of human encroachment (Gittleman et al. 2001). According to the IUCN, thirteen of the pinniped taxa are classified as threatened, three taxa are critically endangered, six taxa are endangered, four taxa are vulnerable, and 26 taxa are of least concern. Of these least concern taxa, the California and Baja subpopulations of the California Sea Lion have shown noticeable population declines during strong El Niño years but have historically recovered quickly from such reductions. For this species, secondary threats include local indirect fisheries interaction, island habitat disturbance, and changing climate.

Amongst all pinnipeds, fisheries interactions are considered to be the most dominant, currently recognized threat. Accidental mortality from fisheries operations, or bycatch, is known to be an acute threat for critically endangered pinniped species, while indirect fishery interactions are a threat to the entirety of the taxa. Large scale impacts from noise pollution have been the subject of concern for many marine mammals, mainly with respect to cetaceans; however, these impacts have not been documented for pinnipeds as of yet (Kovacs et al. 2002). Although noise pollution is a known threat to marine mammals, small-scale deterrents, such as seal bombs, have been consistently utilized by commercial fisheries in an attempt to separate catch and mitigate bycatch threats.

The California sea lion is the most commonly sighted pinniped in the region, with its range extending from the west coast of Mexico to southern British Columbia and its breeding range extending from the Gulf of California to the northern Channel Islands (Antonelis & Fiscus, 1980). Known prey of the California sea lion includes the Pacific lamprey, northern anchovy, rockfish, and squid (Ainley et al. 1977). Pinnipeds often form annual breeding aggregations at traditional locations, such as the northern Channel Islands, known as rookeries. These reproductive sites are a crucial component of pinniped life history patterns and are formed at specific times and locations to optimize the reproductive success and survival of offspring. Most rookeries occur in areas where oceanographic conditions result in high primary productivity. High productivity increases the availability of prey for foraging adult female pinnipeds, which must feed constantly during the pupping season (Antonelis, 2009).

MMPA, ESA, & NMSA

Several federal laws facilitate the protection of cetaceans and pinnipeds including the Marine Mammal Protection Act (MMPA), Endangered Species Act (ESA), and National Marine Sanctuaries Act (NMSA), all established in 1972. The MMPA facilitates the recovery of marine mammal populations including California sea lions (Lake et al. 2018). The majority of California sea lions rookeries are found on the northern Channel Islands and the population has reached an optimum sustainable population level. This has led to increased interactions with fishing operations (Alaska Fisheries Science Center, 2018).

While policies like the Marine Mammal Protection Act and Endangered Species Act work towards the preservation of vulnerable species, they are often criticized for a lack of enforceability and insufficient stock management practices (Buck, 2001). The National Marine Fisheries Service is responsible for the management of whales, dolphins, porpoises, seals, and sea lions; however, there is an unfortunate shortage of enforcement officers that are able to actively enforce key environmental laws. Due to the migratory nature of marine mammals and the challenges of adequate enforcement at sea, threats to cetacean species are very difficult to monitor and mitigate. Additionally, the MMPA has been criticized for not addressing indirect impacts to marine mammals including prey depletion, toxic oil spills, disease, and anthropogenic noise.

The National Marine Sanctuaries Act (NMSA) act allows for the Secretary of Commerce to grant protection to areas that hold national significance by establishing those areas as

National Marine Sanctuaries (National, 2021). Both the Channel Islands and Monterey Bay National Marine Sanctuaries were established under this statute. This act also gives NOAA the power to issue sanctuary regulations that limit certain activities within the sanctuary. The MMPA guides NOAA regulations and policies on the usage of seal bombs (NOAA, 2021).

Seal Bomb Use & Acoustic Impacts

Ocean Noise

Ocean noise is a growing concern for marine life, as current and projected levels of anthropogenic noise have increased significantly since the 1960s (Swaddle et al. 2015; Buxton et al. 2017). Efforts are underway to better understand sanctuary soundscapes; the cumulative contributions of physical ocean processes, biological sound sources, and anthropogenic sound sources. The concern is particularly high for marine mammals, because they rely on vocalization to communicate, find food, and navigate. The addition of anthropogenic noise, most notably from commercial shipping traffic, but also recreational and commercial boats, aerial activity, military sonar, research, oil and gas seismic surveys, and fishing activities, all contribute to significant changes in the ocean soundscape. Regardless of the presence of cetaceans within the immediate vicinity of these anthropogenic sound inputs, the noises created from these activities have the potential to interfere with cetacean communication, especially for baleen species that rely heavily on low-frequency and long-distance communication.

ONMS is guided by the NMSA to facilitate resource protection within sanctuary waters and monitors all public and private uses of marine resources in their jurisdiction. Underwater noise presents a unique challenge, because it is widespread, variable, and baseline soundscapes have only been characterized across sanctuaries since 2018 (NOAA National Marine Sanctuaries, 2020). Elucidating the spatial and temporal dynamics of how soundscape components overlap can inform marine spatial planning to create or refine policies on when, where, and how anthropogenic sound production can and should be managed.

Seal Bombs

In the past, fishers have used lethal force to deter nuisance pinnipeds, often injuring or killing individuals. However, this violates the MMPA and ESA. To avoid these illegal offenses, NMFS instead encourages the use of legal, non-lethal deterrence methods. Such methods include auditory, physical, and chemical sensory assaults meant to signal an animal to vacate. Acoustic deterrents used to prevent economic loss to fisheries, namely seal bombs, have become noise sources of concern. The use of such deterrents has increased in recent decades because interactions with “nuisance” marine mammals have become more common. Seal bombs are powerful firecrackers that can be thrown into the water to detonate a few meters below the surface. The intention is that these explosions will acoustically deter nuisance pinnipeds, prevent catch from being stolen, and reduce damage to fishing gear.

The Marine Bioacoustics Research Collective at Scripps Institution of Oceanography (SIO) conducted initial investigations into seal bombs as a source of underwater sound. Results indicate that they reach source levels of 234 decibels per 1 micro Pascal and can travel underwater for tens of miles depending on topography (Simonis et al., 2020, Wiggins et al. 2021). At these levels, it is likely that seal bombs are causing temporary hearing loss to target pinnipeds, and highly possible that permanent hearing damage is also occurring for individuals in close proximity to explosions (Southall et al. 2019). Furthermore, the acoustic impacts of seal bombs often reach beyond the target pinnipeds, impacting sensitive non-target species in the region (Simonis et al. 2020). SIO has also reported correlations between seal bomb explosions and fishing activity in CINMS revealing that through 2014, it was largely market squid fishing activity tied to recorded seal bomb explosions in space and time (Meyer-Loebbecke et al. 2016, Krumpel et al. 2021). The highest daily seal bomb use recorded at a listening station south of CINMS was >3,500 in 2006 (Meyer-Loebbecke et al. 2015). In MBNMS, the Monterey Bay Aquarium Research Institute (MBARI) has recorded similarly concerning use of seal bombs annually. Peak seal bomb use in MBNMS occurs in the summer, with counts as high as 88 explosions in one hour and 335 in one day, recorded in 2018 (Simonis et al. 2020). While there is evidence that suggests a steady decrease in seal bomb activity in CINMS since 2010, there has not been an integrative analysis of this management issue since 2014 nor have analyses been expanded to include other regions of interest like MBNMS across any time scale. Therefore there is a strong need for a comprehensive analysis of the temporal and spatial dynamics of this issue at the scale of California sanctuaries.

Bureau of Alcohol, Tobacco, Firearms & Explosives

Seal bombs, and other explosive pest control devices, fall under the jurisdiction of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Current regulations require a federal explosives license for distribution and a permit for purchase and use. Since seal bombs are considered to be “high explosives” by ATF, there are additional restrictions for their storage that require specific magazines for indoor and outdoor storage on a fishing vessel. Following the misuse of seal bombs and other explosive deterrents in 2011, ATF increased enforcement of the Safe Explosives Act of 2002 (ATF 2020).

Acoustic Impacts

Different sound sources have variable impacts across taxa. Studies indicate that responses depend on the frequency, decibel level, and proximity to the source, eliciting changes in cetacean communication tendencies or causing deviation from their natural migratory pathways (Williams et al. 2015, Melcón et al. 2012). Small, localized cetacean populations may be especially vulnerable to impacts associated with deviation, as individuals removed from their primary habitat may experience reduced foraging or mating success or be exposed to increased threats of predation and bycatch (Simonis et al. 2020). Specific frequencies and decibels may mask communication used for feeding, mating, and predator avoidance by preventing recognition or detection of important natural sounds. Cumulative impacts of sound exposure are less well documented, ranging from minimal behavior shifts to physical damage or strandings (Clark et al. 2009).

While the implications of overlap between cetaceans and seal bomb use are varied, the potential impacts are significant. Some odontocetes share squid as prey, resulting in another pathway for overlap with squid fishing activity. Studies from Jaquet & Gendron (2002) found a significant change in sperm whale distribution in response to decreases in abundance of squid from 1998 to 1999. Therefore, the use of seal bombs while squid fishing may have more direct impacts on these species' ability to catch prey. Unlike some odontocetes, the mysticetes do not target squid as prey but may experience equally negative effects from seal bomb use. Squid and baleen whales may share a prey source in copepods and krill, and this overlap in range could result in closer proximity to threats. Seal bomb use may deter cetaceans into shipping lanes, crab fisheries, or the shoreline as they avoid acoustic disturbances. Interference from acoustic disturbance may also cause alterations to migratory pathways and/or hinder social interactions.

While mysticete experts suggest that it is difficult to know the impacts of acoustic deterrents, they agree that it is likely dependent on the duration of use, source level, frequency, and density (Long et al. 2015). A working group in 2015 recommended seal bombs to be "potentially prohibited for use" for both odontocetes and mysticetes, but not for pinnipeds. Response thresholds have only been determined for a few groups of species and sound sources, but are variable even within species (Richardson & Wursig 2009). In general, characterized acoustic deterrent devices below 135 dB for pinnipeds, and below 179 dB for cetaceans, were judged to be below the level to cause Temporary Threshold Shifts (TTS) in hearing for the most sensitive species (Richardson & Wursig 2009). These shifts are temporary increases in the audibility threshold of a specific frequency for a species above a baseline level. By contrast, Permanent Threshold Shifts (PTS) are irreversible increases in a species' hearing range above a reference level (Long et al. 2015). While these decibel limits provide a baseline for a single occurrence of acoustic deterrent use, they do not account for the impacts of sustained or cumulative sound exposure experienced by marine mammals at peak times of deterrent use.

Current Guidelines & Proposed Rule

NMFS is currently addressing the concern surrounding unregulated seal bomb use. In August 2020 the agency proposed a rule that would provide guidance for the use of legal, non-lethal methods to safely deter marine mammals from damaging fishing gear or catch, damaging personal or public property, or endangering personal safety (NOAA Fisheries, 2020). NMFS is currently considering the submitted public comments in response to the proposal and will finalize the rule at a later date. Since 2018 a team of government and academic researchers has been passively recording the underwater soundscape through a project called "SanctSound", which established new listening stations across national marine sanctuaries. Relevant to this analysis include three stationary monitoring locations in MBNMS and five stationary monitoring locations in CINMS. Additionally, NOAA has been supporting a Noise Reference Station in Channel Islands National Marine Sanctuary since 2014. These stations combined with the SIO and MBARI long-term listening stations provide great spatial and temporal coverage of CINMS and MBNMS to extract acoustic detections of seal bomb explosions and examine this issue.

Squid Fishery

While it has been noted that other fisheries may be involved in seal bomb usage, it has been established through previous studies (Meyer-Loebbecke, 2016 and Krumpel et al. 2021) that the squid fishing industry is the predominant user in California.

California Market Squid

California market squid (*Loligo opalescens*) is a common species found along the west coast of North America and Baja California (Van Noord, 2017). Having a relatively short lifespan, the market squid lives ~7 to 10 months (Macewicz, 2004). Squid are migratory species and travel together in large pods. They are generally found deep in the water column (up to 2,600 feet below the surface) except while spawning when they return to shallower waters, which is where a large portion of them are caught (California Sea Grant, 2017). Spawning has been recorded to occur year-round, with a peak season in May and June (Macewicz, 2004). The California Wetfish Producers Association (CWPA) manages a program studying the long-term population dynamics of coastal pelagic species, including the California market squid. CWPA has collaborated with CDFW and NOAA's Southwest Fisheries Science Center to maintain a long-term time series of squid paralarvae abundance in both southern California and Monterey Bay. The program's time series is used to better understand squid population dynamics and the influence of environmental conditions that may alter recruitment, density, and abundance (California Wetfish Producers Association, 2020).

The market squid is of great importance to California ocean ecosystems, as it is the prey of many species of seabirds, fish, and marine mammals. It is an integral part of the cetacean food web, as it is an important dietary component for Dall's porpoise, the Pacific striped dolphin, Risso’s dolphin, the short-finned pilot whale, and the sperm whale (Fields, 1965). The squid also holds a large economic value, as one of the most important fisheries in California (Van Noord, 2017). Squid remain at deeper depths throughout the duration of the day and move up to the sea surface to feed at night. Like many other squid species, the California market squid is highly attracted to bright light (Vojkovich, 1998). While they are feeding at the sea surface, squid become attracted to bright lights that may be emitted from fishing vessels. Historically, California market squid fishing has occurred predominantly at night, however, that trend seems to be shifting over time with technological advances and is addressed in detail below.

Fishing Industry Background

The California market squid fishery opened in Monterey Bay in 1860 when Chinese fishermen began fishing the local population. At this time, the bright light from torches was used to attract squid and woven nets were used to scoop up small pods. This catch was consumed locally in San Francisco or was dried and sent back to Asia (Vojkovich, 1998). The fishery slowly grew in size, but boats maintained relatively low catch sizes (around 270 tons annually). The majority of the landings remained around Monterey Bay until the early 1950s when the Southern California fishery began to increase in intensity and annual catch size began to steadily increase. Currently, both regions experience high fishing intensity, with Monterey Bay experiencing increased fishing pressure in the summer months and southern California experiencing increased pressure in the winter months. The California market squid fishery has been the state's largest fishery both in tons and value since 1993 (Pomeroy, 2001).

Historically, the fishery has survived the impacts of major El Niño events, with large declines in annual catch occurring during these time frames. While it is unconfirmed whether or not squid are simply migrating, it is thought that fluctuation in catch volume is due to drastic changes in population size. Although the mechanism behind this fluctuation has not been directly identified, it is thought that squid population size decreases in years with unfavorable water temperature conditions due to their short lifespan and either a lowered fecundity rate or a decreased rate of larval survival (Perretti, 2016). According to the California Department of Fish and Wildlife, the 2014-2015 El Niño event drastically impacted the fishery, dropping from an annual landing of 229.38 million pounds in 2014 to just 81.14 million pounds in 2015. The squid population eventually rebounded in 2017 with an annual landing of 137.59 million pounds, however, the population has been experiencing an overall decline since then.

Current Operations

Modern squid fishing operations involve purse seiners or “light boats” that utilize bright lights to seek out and attract squid. These vessels use purse seine nets that work to scoop up their catch from below. Industry vessels have historically largely operated at night, with most activity occurring from May to September for the Central California fleet, and October through February for the Southern California fleet (Pomeroy, 2001). There are three major ports in which squid landings are documented; the Monterey and San Pedro ports, which originated from Italian fishing villages, and the Ventura harbor, whose background comes from Slav fishing communities. About 70% of squid fishermen in California stated that the job has been in their family for many generations (Pomeroy, 2001).

After the explosive and unregulated growth of the fishery in the 1980s, regulations were finally set in place in 1997 with a cap on vessel numbers and a permitting fee. In addition, California began designing and implementing multiple networks of protected marine areas after the California Marine Life Protection Act was passed in 1999. Some of these systems were established as no-take MPAs, further restricting the squid fishing industry's potential catch. Current regulations on the fishery as stated in the California Department of Fish and Wildlife Market Squid Fishery Management Plan establish a seasonal catch limitation of 118,000 tons. In addition, the fishery remains closed from noon Friday to noon Sunday from the U.S.-Mexico border to the California-Oregon border.

Market Significance

According to the California Department of Fish and Wildlife, the market squid fishery is one of the most economically important fisheries in the state. California SeaGrant reports that it became the most valuable California fishery in 1996 due to the steady demand and price for the squid, with the 2018-2019 season bringing in more than 33.3 million in revenue. However, the market is greatly influenced by environmental factors and the fluctuating squid population (Monterey, 2020).

Data & Methods

General Approach

To provide recommendations for fisheries management options that lessen impacts to acoustically sensitive marine mammals, we used spatial analysis to identify key areas within CINMS and MBNMS that we recommend could serve as the basis for “seal bomb limitation zones” to protect at-risk marine mammals. Additionally, we assessed temporal overlap to identify specific time spans that could serve as “seal bomb limitation periods”. When designing limitation zones and periods, ecological factors including cetacean distribution, as well as anthropogenic factors, such as fishing pressure and rate of acoustic deterrent use, were important characteristics to consider. Lastly, we used our spatial and temporal analysis to provide insight into the most optimal method for tracking seal bomb use across marine sanctuaries and neighboring waters. The output of our data analysis will help to inform management decisions and strengthen conservation within NOAA's network of National Marine Sanctuaries.

Study Site Data

Sanctuary Bounds

This dataset consists of two separate shapefile boundary layers of Channel Islands National Marine Sanctuary and Monterey Bay National Marine Sanctuary. They are based on the legal definition of each sanctuary as defined in the Code of Federal Regulations, at 15C.F.R. Part 922 and the subparts for each national marine sanctuary. All GIS data for designated National Marine Sanctuaries was created by NOAA and can be accessed at Geographic Information System Data | Office of National Marine Sanctuaries (noaa.gov).

Environmental Data

Sea Surface Temperature

Each ASCII file was individually downloaded from the MURSST NOAA DATA access portal from January 2017 to December 2020 as Esri ASCII files. Latitude was set to 32.0 to 42.0 with a stride of 1. Longitude was set to -117.0 to -126.0 with a stride of 1. Next, the ASCII files were imported into ArcGIS Pro by month, (eg., January ASCII from 2017, 2018, 2019, and 2020, then February 2017-2020, etc.) and the average sea surface temperature was calculated using the Raster Calculator tool in the Spatial Analysis Toolbox, by adding the rasters together then dividing by 4. This step was repeated for each month (January - December). The outputs from this step are .tiff files, so we then used the Raster to ASCII tool to convert files into a MaxEnt-compatible file type. See Appendix A for ArcGIS model builder graphic, outlining final data preparation steps.

Bathymetry

Bathymetry data were downloaded from GEBCO as a .tiff file to cover the California coastline. The user interface only had the option to manually select the region of interest, so we were unable to select by latitude and longitude. Therefore, we then imported the bathymetry .tiff file into ArcGIS Pro to clip the extent to match the sea surface temperature rasters using ArcGIS Pro’s Extract by Mask Tool. This raster was later used as the “master extent” and was used in model builder to delineate the extent of all other rasters before input into MaxEnt. Next, we used the Raster to ASCII tool to export as an ASCII file for import to MaxEnt to use as an environmental variable. Additionally, a binary classification of depth from 0m to -100m was created for the bias file for MaxEnt. The raw bathymetry file was reclassified for all depths in this range to 1 and all other values to “No Data” as shown in the image in Appendix B.

Chlorophyll

We downloaded each individual ASCII file from NOAA VIIRS on the ERDAPP Portal from January 2017 to December 2020, setting the latitude to 32.0 to 42.0 with a stride of 1. The longitude was set from -117.0 to -126.0 with a stride of 1. Each ASCII file was imported into ArcGIS Pro by month. The average chlorophyll for each individual month (January-December) was calculated using the Raster Calculator tool in the Spatial Analysis Toolbox. Since the outputs are .tiff files, the Raster to ASCII tool was used to convert files into a MaxEnt-compatible ASCII file. The model builder graphic of data preparation can be found in Appendix C.

Ecological Data

Biologically Important Area (BIA) Data

All biologically important area data from the West Coast were downloaded from NOAA's CetSound Program and .shp files were downloaded into ArcGIS. Using the Select by Attribute tool in ArcGIS, we selected only species that are present on the West Coast. This gave us our target species; the blue whale, humpback whale, gray whale, and harbor porpoise. A new layer was saved with only these species. For each of the four species, the Select by Attribute tool was used to only select Biologically Important Areas with a range that fell within the California coastline (subsetting from the greater U.S. West Coast). This BIA data will soon be updated and revised to identify the full extent of BIAs in U.S. waters and provide new BIAs where appropriate. A new BIA scoring and labeling system will improve the utility of the BIAs by generating an overall “Importance Score” for each area. Lastly, each BIA will be updated to include an indicator of boundary uncertainty and spatiotemporal variability. These changes aimed to be incorporated by December 2022.

Cetacean Density Data

Predictive models of cetacean density in the California Current ecosystem were gathered from Becker *et al.* (2020). These models have been utilized by the U.S. Navy to assess potential impacts on cetaceans in compliance with the ESA and MMPA. The Becker Species Distribution model geodatabase was downloaded from the NOAA website and loaded into ArcGIS. These .shp files for fall/summer and winter/spring predicted annual mean density habitat-based density models for 13 different species. Since we wanted to focus on July and November (high fishing pressure months) which both fall under the fall/summer model category, we did not use any of the winter/spring shapefiles.

Squid Fishing Pressure Data

Fishing Block Grid

The shapefile grid set by CDFW delineates specific blocks for landing recordings and each block's associated identification number. The specific grid pattern and size is based on the delineations set by CDFW in the 1930s. The block landing grid for all of California can be accessed at filelib.wildlife.ca.gov - /Public/R7_MR/MANAGEMENT/.

Ticket Landing Data

Information regarding fishing activities in California's fishing blocks from 2015 - 2018 was provided by the California Department of Fish and Wildlife through partners at Scripps Institute of Oceanography. Data from 2019 and 2020 was obtained through partners at NOAA. The ticket landing data were summarized in order to protect individual vessels' sensitive location information. Ticket landing data lists monthly squid catch in lbs from 2013-2019. The tabular CSV dataset was divided by year, month, and fishing block number.

Fisheries data were obtained from CDFW. 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.

VIIRS Squid Fishing Vessel Detections

These data are satellite-derived imagery from a NOAA and NASA-associated platform and sensor. Global Fishing Watch pre-processed the data using an algorithm that records specific occurrences of squid fishing vessels. The algorithm uses AIS (Automatic Identification System) and Visible Infrared Imaging Radiometer Suite Day/Night Band to locate where bright lights indicate the possible presence of squid fishing boats. Detections that could be matched to AIS vessel categories outside our scope (e.g. "cargo" or "pleasure craft") were removed, and detections that could be matched to AIS with a vessel class as "fishing" were kept. It is important to note that detections that *could not* be matched to AIS data are also included in the dataset. The VIIRS data CSV includes a timestamp (year, month, day), as well as latitude and longitude coordinates. This specific VIIRS dataset that focused on squid jiggers was accumulated for us in a partnership with Global Fishing Watch and is only available to the public upon request. The CSV of VIIRS detections was loaded into ArcGIS, using the latitude and longitude coordinates to visualize detections. The California coastal region was selected by performing a spatial intersection between the CDFW fishing block grid data and VIIRS point data.

Acoustic Data

Listening ranges for each hydrophone described below may be different for each site and can fluctuate over time due to seafloor bathymetry, water column temperature, and general influences of weather. Due to variability in hydrophone listening ranges, some seal bomb explosions may be more difficult to detect.

SanctSound SoundTrap Data

The SanctSound (Sanctuary Soundscape Monitoring Project) deploys SoundTrap recorders throughout National Marine Sanctuaries to characterize soundscapes through passive acoustic monitoring. Hydrophones were deployed at specific sites for ~4 month periods and recorded broadband sound continuously at a sampling rate of either 96kHz or 48kHz. These continuous sound data are stored in the form of .wav files, which were initially processed with the Triton Explosion Detector and then manually processed for seal bomb explosions by SanctSound analysts. Seal bomb detection data from MBNMS and CINMS were provided for this project in the form of CSV tabular data separately for each sanctuary and hydrophone. Data for this program begins in 2018 and extends through 2021, however, the SanctSound Project ends in 2022. CINMS has five sound traps located around the Channel Islands. MBNMS has three sound traps within the sanctuary, two in the bay and one that is identified as a HARP hydrophone described below. Listening ranges for each individual hydrophone may be different for each site and can fluctuate over time due to seafloor bathymetry, water column temperature, and general influences of weather.

Scripps & SanctSound HARP Data

Scripps Institute of Oceanography has two High Acoustic Recording Package (HARP) hydrophones located in the Santa Barbara Channel north of the National Marine Sanctuary referred to here as CINMS C and CINMS B. Additionally, one HARP hydrophone is located just outside of MBNMS referred to here as MB03 which samples at a rate of 200kHz. These hydrophones are located in deeper water than the SanctSound SoundTraps and record at a sampling rate of 96kHz. These hydrophones have recorded soundscapes continuously over multiple deployments since 2016 and into the present, therefore providing a wider range of seal bomb detections through time at those specific locations. This project reviews data through the end of 2021 from the HARP hydrophones. Some of the deployments were processed and manually assessed by Scripps staff for seal bombs, however, some other deployments had not yet been processed at the start of this analysis. Unprocessed data were assessed through methods described in the next section by the team and Scripps staff.

MBARI MARS Data

In addition to SanctSound and HARP hydrophones located in MBNMS, Monterey Bay Aquarium Research Institute has a cabled Monterey Accelerated Research System (MARS) hydrophone 32 miles offshore just outside the mouth of the bay. Because MARS is cabled, recording can be truly continuous and is maintained at a sampling rate of 256 kHz. The Google Artificial Intelligence Perception team, working with MBARI, created and tested a machine-learning algorithm to detect seal bomb explosions. Detections were both statistically and manually reviewed for accuracy and converted from Coordinated Universal Time (UTC) to Pacific Standard Time (PST) to match the rest of the detections for analysis. Similar to the HARP hydrophones, MARS provides a wider temporal range of data, from July 2015 until the present. This project reviews data through the end of 2021 from the MARS hydrophone.

NOAA Noise Reference Station NRS Data

In partnership with the National Parks Service, a separate NOAA sound monitoring program known as the Ocean Noise Reference Station (NRS) Network has 12 hydrophones placed in coastal waters around the nation. NRS-05 is located on the south side of Santa Cruz Island in ~1000 meter depth just inside the CINMS boundary. The team accessed the third deployment of NRS-05 which recorded from 2018 to 2020. This location is significant because of the historic records of high squid fishing pressure in the corresponding CDFW block. It’s also on the edge of a deep canyon, meaning sound sources even from far away are likely received. These data were not processed for seal bombs at the start of this analysis, so the team completed all of the processing and manually validated detections with the methods described below.

Acoustic Data Processing

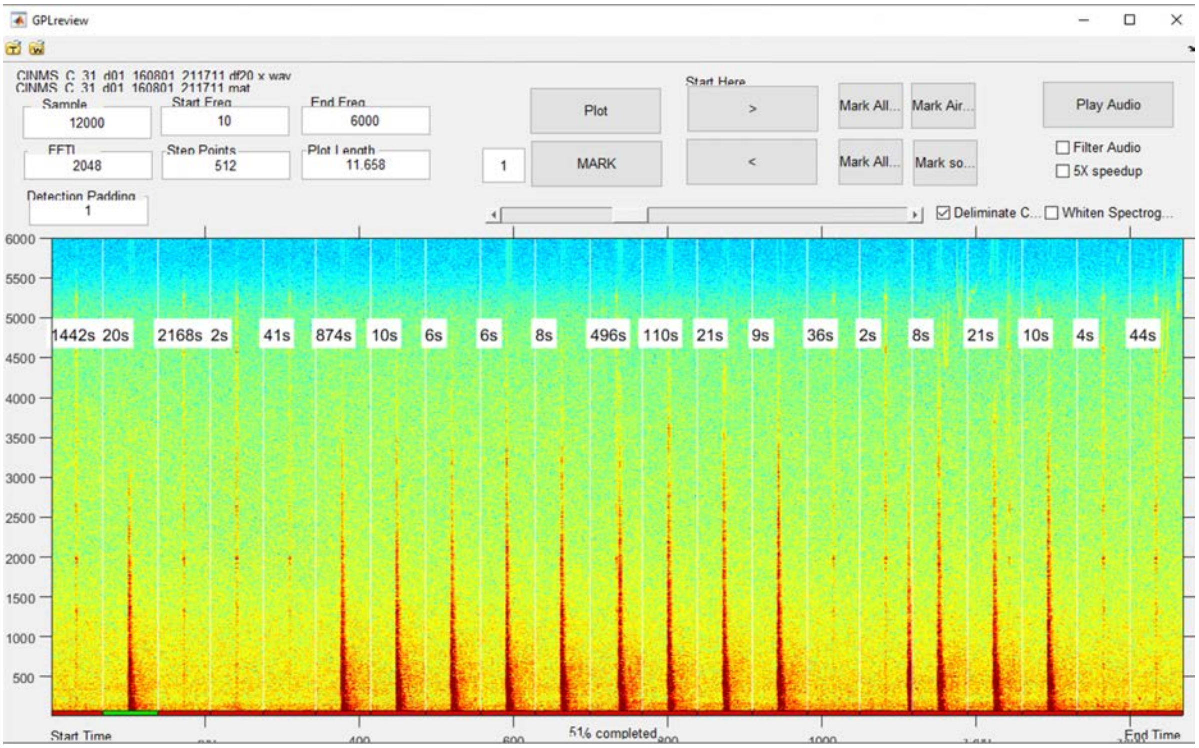
For the unprocessed hydrophone data from Scripps HARP and NRS hydrophones, the team conducted a hybrid approach of automatic detection and manual processing for seal bombs following methods developed by Scripps researchers. The program Matlab was used to run explosion detectors and the graphical user interface used for manual confirmation of seal bomb detections. Both steps required download of code from Marine Bioacoustics Research Collaborative on GitHub accessed at https://github.com/MarineBioAcousticsRC.

Explosion Detector in Triton

After downloading the Triton repository from GitHub and adding it to the MatLab path, we ran the Triton and selected the remora “explosion detector”, which is specifically designed to identify broadband sounds. To process a specific deployment, we selected the audio base .wav file of raw sound data and set a path for the explosion outputs. Running the detector would create an output of timestamps which indicated that the model “detected” a possible seal bomb. The user is then able to confirm or deny whether it is actually a seal bomb through the methods described in the next subsection.

Manual Detection in GPLReview

After downloading the GPLReview repository from GitHub and adding it to the MatLab path, we opened up the user interface through MatLab. We manually entered the settings of sample rate at 12,000 with a starting frequency of 10kHz and an end frequency of 6,000kHz. Next, we set the FFTL to 2048 and the step to 512. We plotted 60s with a detection set to 1, and checked the “Deliminate Calls” box. We then selected the outputs from the explosion detector, starting with the first “detected seal bomb” from the current deployment. Since the time stamps were included in the output, we added the whole audiobase .wav file and MatLab was able to match the audio with each potential detection. The user then clicks ‘Plot’ and the spectrogram of the associated output and audio file appears in the user interface as shown below (**Figure 1**). To confirm the detection was or was not a seal bomb, the user would playback the audio and assess the spectrogram, marking the explosion as a ‘yes’ or a ‘no’. At the end of each deployment, the user would write the confirmed seal bomb detections to a CSV file of datetime stamps in MatLab.



CINMS C 31 d01 160801 211711 df20 x wav
CINMS C 31 d01 160801 211711 mat

Sample: 12000
Start Freq: 10
End Freq: 6000
FFTL: 2048
Step Points: 512
Plot Length: 11.658
Detection Padding: 1

☑ Deliminate C...
☐ Whiten Spectrog...
☐ Filter Audio
☐ 5X speedup

Figure 1. Spectrogram of the output and associated audio file for seal bomb detections in GPLReview.

Contextualizing Seal Bombs

Due to disparate spatial and temporal coverage of the datasets (seal bomb acoustic detections, VIIRS vessel detections, and CDFW fishing landing data), the challenge of how to relate the three datasets was presented. In addressing seal bomb dynamics especially, the inconsistency of hydrophone location and temporal range of deployment created difficulties in understanding the difference between changes in actual seal bomb use and changes in recording effort. To create a more complete picture of seal bomb use, fishing pressure data was used as a proxy for seal bomb use when acoustic data could not cover the same spatial or temporal span.

Bland-Altman Analysis of Fishing Pressure Data

The two fishing pressure datasets, VIIRS vessel detections, and CDFW fishing landing receipts, were compared using a Bland Altman analysis to assess the level of agreement between the two datasets in their reporting on the number of fishing vessels present off the California coast. This analysis also helped to inform the effectiveness and statistical uncertainty that may be observed when choosing one dataset over another in the other components of our technical approach (Appendix J).

Seal Bombs Relation to Fishing Pressure: VIIRS & CDFW Regressions

To assess the relationship between seal bomb usage and squid fishing pressure, linear regressions were run separately with the two squid fishing pressure datasets; VIIRS vessel detections and CDFW ticket landing data. Since all datasets do not extend through time, we wanted to assess the relationship between all three.

Between VIIRS and Seal Bombs

Using R, VIIRS squid vessel detections were binned into a resolution that matches the CDFW fishing blocks resolution to accurately derive the number of VIIRS detections within each individual fishing block for each month of available data. Linear regression was then performed between the number of seal bomb acoustic detections per hydrophone against the number of VIIRS vessels detections within each hydrophone's estimated listening range, in order to assess the correlation between the two datasets (Appendix J). There is an overlap between the two datasets only for the years 2017 and 2018.

Between CDFW and Seal Bombs

Two linear regressions were then performed between the number of seal bomb detections per hydrophone and the CDFW landing data in pounds of squid caught and number of receipts that occurred within each hydrophone's estimated listening range, in order to assess the correlation between the two datasets. The first regression used the number of landing receipts and the second used the pounds of squid catch (Appendix J).

Identifying Temporal Seal Bomb Trends

To assess the seasonality of seal bomb use, two time series analyses were conducted for the detonations recorded on hydrophones within both CINMS and MBNMS. Additionally, temporal analyses assessing the time of day that seal bombs are most frequently used were conducted for both MBNMS and CINMS along with a time series of all detected seal bombs that occurred over time for each individual hydrophone (Appendix J).

Contextualizing Impacts to Cetaceans

Without consistent spatial and temporal coverage of seal bomb use, it is difficult to make assertions about wholescale overlap between cetacean distributions and regions of high seal bomb use over time. To navigate this, we used Maximum Entropy modeling (MaxEnt) (Version 3.4.4, Phillips et al. 2016) to create a predictive model of squid fishing pressure and associated seal bomb use, which we later spatially overlaid with biologically important cetacean distributions for each month of the year. This not only allows for visualizing present and past impacts but future predictions can also be made for how changes in environmental conditions may shift areas of interaction.

Generating Presence Points for MaxEnt

Using R, VIIRS squid fishing vessel detections were filtered for points that only occur within 0-100 meter depths, since squid fishing occurs predominantly within that depth range (CA Sea Grant, 2017). The remaining VIIRS detections were then separated by month of detection. The vessel detections for each month, across all years of data, were written into its own CSV, resulting in 12 CSV files. This processed data served as occurrence data presence points for the MaxEnt analysis described below (Appendix I).

MaxEnt Analysis

Our approach is based on Koslow & Allen (2011), which references sea surface temperature, chlorophyll levels, substrate type, and bathymetry as the determining variables in squid presence. It is important to note that, unlike Koslow & Allen, our analysis is aimed at identifying locations where squid are present *and* fishing is likely to occur. A folder for each month was created containing the ASCII files of the average monthly temperature, chlorophyll, and bathymetry data from 2017-2020. Substrate data covering the entire California coast at an adequate resolution was not available and was omitted from the analysis. A folder for the presence data was also created containing the latitude and longitude coordinates of VIIRS vessel detections, separated monthly as explained above. For each MaxEnt model run, we made a new output folder titled “month_output” for each respective month.

Within MaxEnt, the VIIRS data for the month was loaded into the “Samples” tab. The environmental variables mentioned above were selected to be included in the model run, ensuring each was labeled “continuous”, and “Auto Features”, “Hinge Features”, and “Threshold Features” were unclicked. The jackknife feature was turned on to allow for alternate assessments of which variables are most important in the model. Under “Advanced Settings”, the “baseline_bath.asc” file was selected to restrict MaxEnt to areas within 100 meters of depth. The “Replicated run type” was set to “Crossvalidate” and “Replicates” was set to 5. After establishing these settings, the Maximum iterations were changed to 50,000 for the final iteration of the model run each month. Finally, the model was repeatedly run for each month (January - December). See Appendix D for images of model outputs.

Binning VIIRS vessel detections through time indicated that early summer months June and July had robust data. Similarly, late fall to winter (October - February) had sufficient data to produce model results. Therefore, all twelve months were run in MaxEnt to produce monthly fishing pressure outputs, but models that had less than 30 presence points and an area under the curve (AUC) below 0.660 were omitted from further analysis (Appendix E).

For each monthly probability surface that was retained, the Reclassify by Table tool was used to reclassify the output rasters based on a threshold of 0.5 (Liu et al. 2013, Merow et al. 2013) to a binary classification of a “presence” of high probability of fishing pressure (above 0.5), or “absence” of high probability of fishing pressure (below 0.5). Next, the Raster Calculator was used to generate seasonal fishing pressure layers by multiplying rasters together as shown in Appendix F. We repeated the raster calculation step for summer (June/July) and winter (January/February, and November/December). This portion of our analysis provided us with multiple monthly and seasonal fishing pressure rasters.

Biologically Important Area (BIA) Analysis

In ArcGIS Pro, the BIA dataset was filtered through the “Select by Attribute” function in the Attribute Table to select solely “West Coast” regions. Next, using the “cmn_name” column, each BIA that corresponds with gray whales were selected and the “Make Layer from Selected Attributes” feature was utilized to create a shapefile for only gray whale BIAs. From that subset, the “BIA_time” column was used to select all BIAs for the month of January. Again, the “Make Layer from Selected Attributes” function was used to create a new layer that contained all of the BIAs for gray whales in January. The same process was used for each month, producing 12 separate layers representing monthly BIAs for gray whales. This same process was then used for blue whale, humpback whale, and harbor porpoise to produce 12 separate layers for each species. Next, the “Merge” tool was used to combine all four species layers for a given month into one layer. This process was completed for each month, resulting in 12 different layers that display the BIAs for all four species.

Next, the monthly ASCII file outputs that were created from the MaxEnt model runs were imported into model builder. In order to create maps that display both the BIAs and fishing pressure, an ASCII file for a specific month was checked on the map, as well as the corresponding BIA month containing the four species BIAs. For example, the January fishing pressure map was selected as well as the all species January BIA layer. This produced a final product of 12 maps that display the MaxEnt modeled fishing pressure for a given month and the BIAs of that month for all study species overlaid on top (Appendix G).

Additionally, a hotspot map was created due to our identification of strong overlap of all four species, including endangered species, interacting with fishing pressure during the month of July. To do so, the July BIA layer was selected and the “Raster Calculator” tool was used to select areas in which all four species BIAs overlapped in that month. The “Raster Calculator” tool was utilized again to select areas where the two endangered whale’s BIAs overlapped in July. These two hotspot layers were then displayed over the fishing pressure ASCII file for July.

Species Distribution Analysis

For each individual species- the striped dolphin, sperm whale, small beaked whale, short beaked common dolphin, Risso’s dolphin, pacific white sided dolphin, Northern right whale, humpback whale, Dall’s porpoise, bottlenose dolphin, blue whale, Baird’s beaked whale, and fin whale- the “primary symbology” was set to graduated colors. Density was selected for the “field”, quartile was selected for “method”, and the “classes” were set to 4. Next, the first three quartiles were set to “no color” so that only the top quartile displayed color. This method yielded 13 different graphics- one for each species that displayed their predicted top quartile of density (animals-km^2) along the coast of California. Each species was then given a unique color value.

In order to create comparison maps for fishing pressure and species distribution, the ASCII files for modeled fishing pressure in July and November (created in the previous Maxent analysis) were loaded into ArcGIS. Next, one individual species was selected and the fishing pressure layer for July was overlaid on top to create the comparison map. This process was done for each species and was then repeated for November, ultimately creating 26 unique maps (Appendix H).

It is important to note that the Becker species distribution models model the areas with the highest predicted density of a specific species within the California Coast. This data is temporarily summed to a summer/fall categorization, meaning that the distribution models we used for this project were a sum of the months of July through November. When comparing the July and November maps for this section we are selecting the same species distribution for both (summer/fall) and highlighting either July or November for the fishing pressure layer.

Hydrophones in BIAs

A CSV containing latitude and longitude points of hydrophone locations was compiled given the various sources of our acoustic data. This CSV was then uploaded into ArcGIS Pro through the “XY Table to Point” function, mapping a point for each hydrophone location. The symbology for each point was changed to a sound image. The hydrophone points were then laid over each monthly BIA layer (created in the above BIA analysis methods) to create 12 separate maps.

Results

Seal Bomb Use

Temporal and Seasonal Patterns

Across both sanctuaries, seal bomb use peaks in the early morning and late at night, with less use during the middle of the day. In MBNMS, seal bomb use is heaviest in the early morning with a similar peak in the evening (**Figure 2**). Use throughout the day is comparatively much lower. Seal bombs recorded in CINMS are concentrated from early evening (around 5 pm) to midnight, however, there is some heavy usage in the early morning and intermittent use throughout the day **(Figure 3**). All times are shown in Pacific Standard Time (PST).

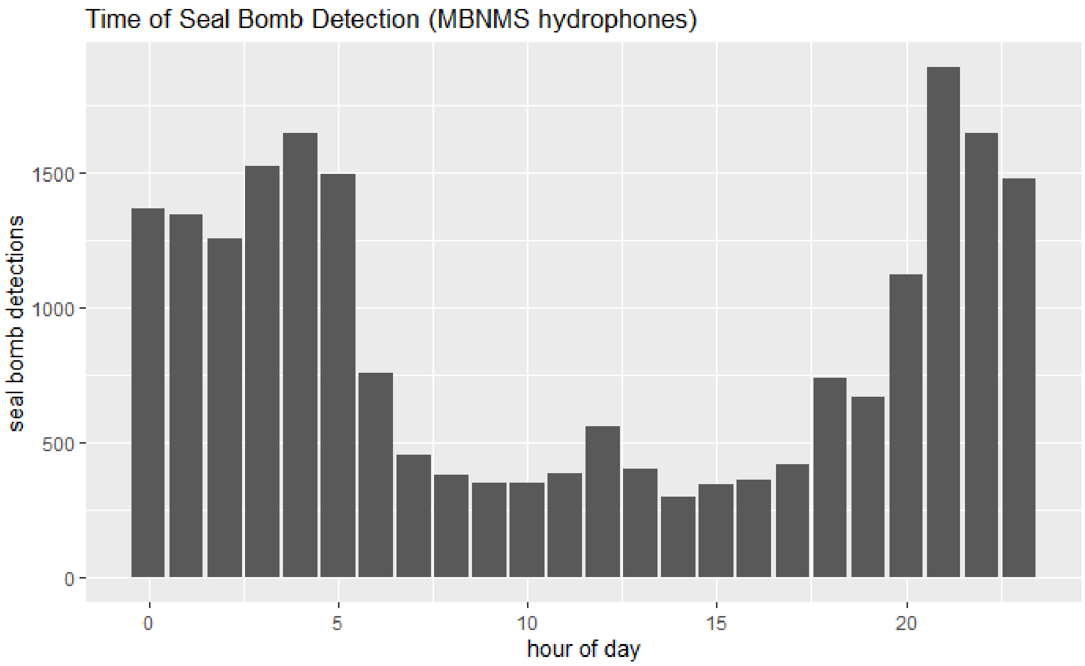


Figure 2. Time series analysis (2015-2020) for seal bomb detonations recorded on hydrophones located in MBNMS in PST.

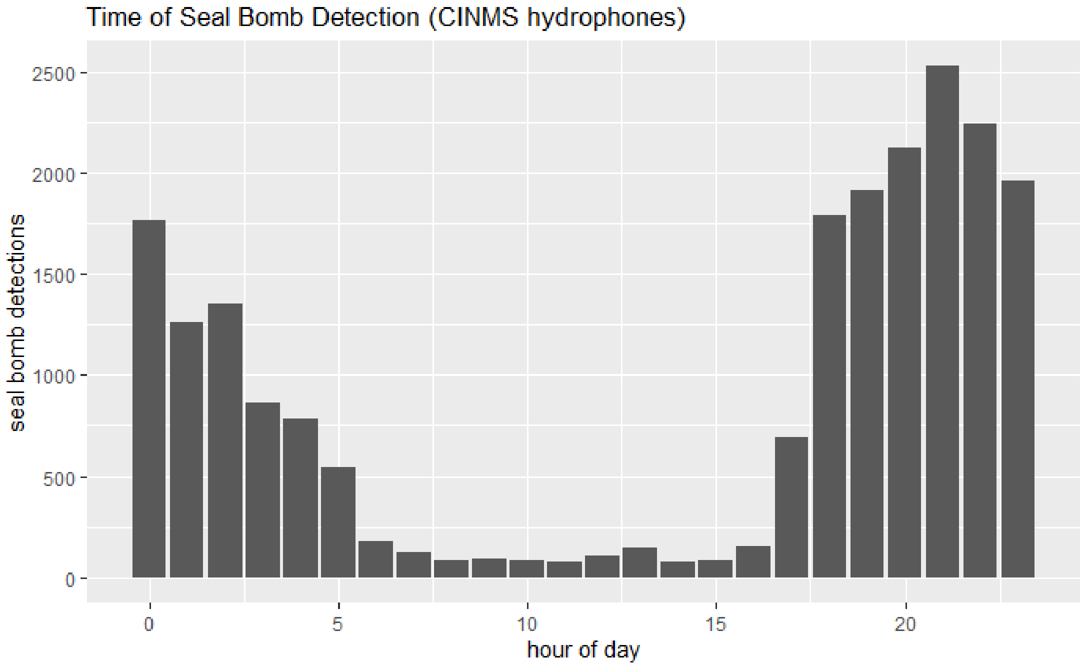


Figure 3. Time series analysis (2015-2021) for seal bomb detonations recorded on hydrophones located in CINMS in PST.

Seasonal analysis of results across all years shows that seal bombs are more heavily used in the summer months (May-August) in MBNMS, while seal bomb use peaks in the winter (November-February) in CINMS (**Figure 4**). It is important to note that these results are not normalized for recording effort (i.e. how many hydrophones were actively recording).

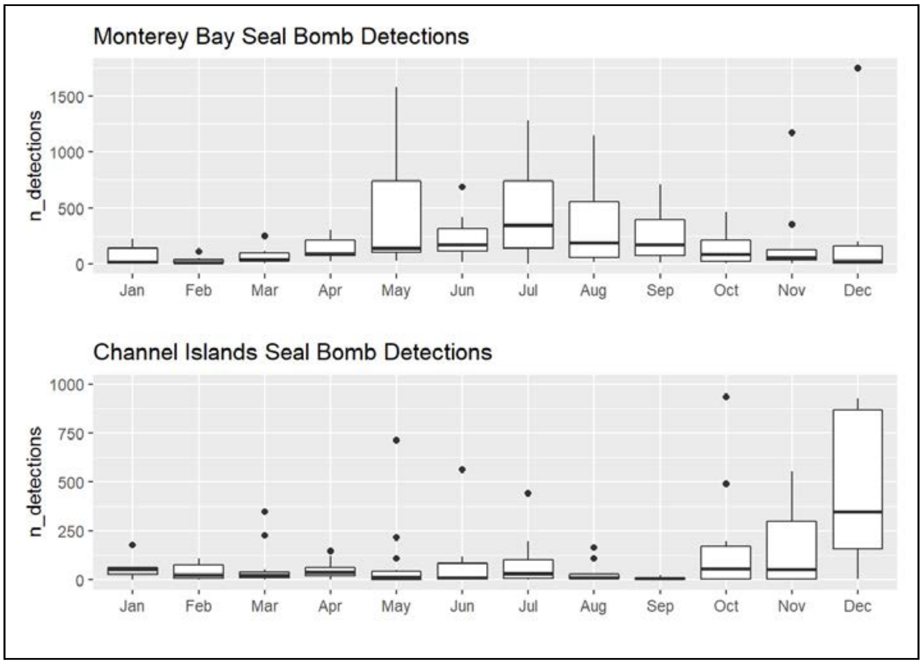


Figure 4. Monthly distribution of seal bomb detections aggregated across all years (2015-2020) for both sanctuaries.

Fishing Pressure

CA Market Squid Landing Seasonality

Seasonal analysis of landings for each year of data shows a general pattern of increased reported squid caught (lbs) for the Monterey Bay region to occur during the summer months (June through August) and for the Channel Islands region, increased reported squid caught (lbs) tends to occur Fall and Winter (October through February) (**Figure 5**). The designation for each region is approximated, consisting of the vertical between Santa Rosa, CA and Santa Maria, CA for the "Monterey Bay region", and between Santa Maria, CA and the US/Mexico border for the "Channel Islands region".

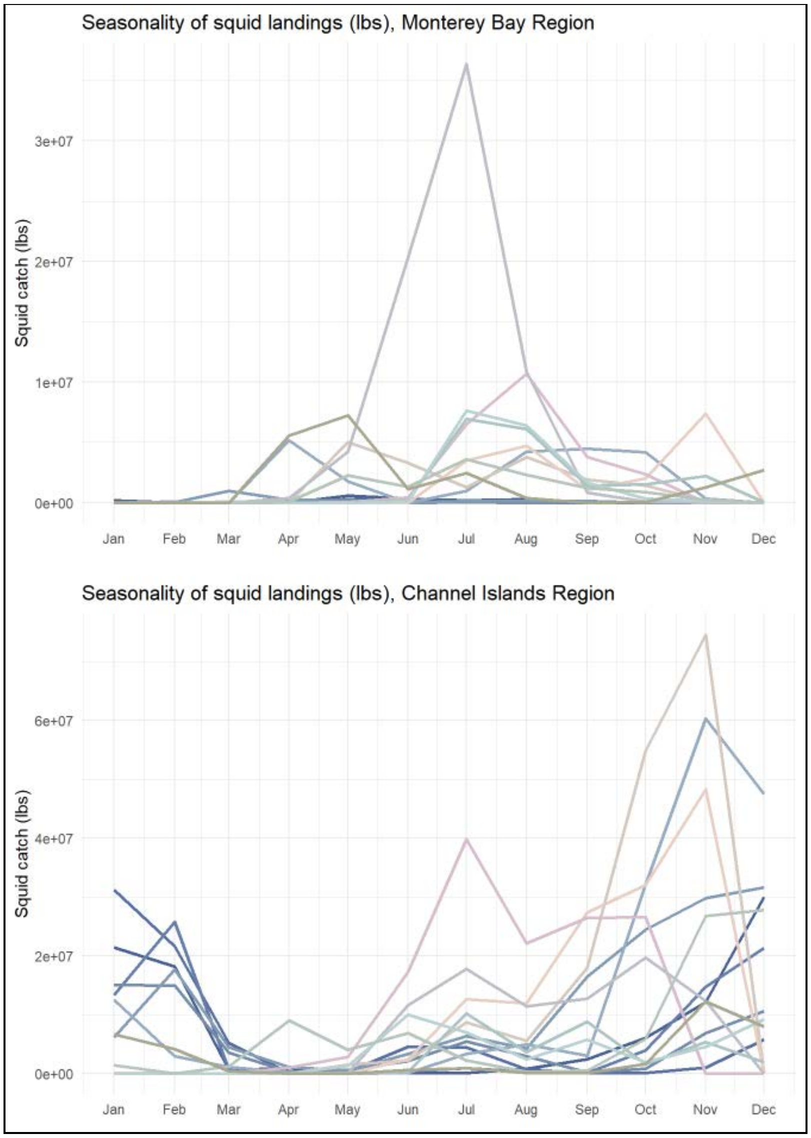


Figure 5. Amount of squid caught (lbs) across all fishing blocks found within each region, for each year of data from 2005 - 2018.

VIIRS Vessel Detection Seasonality

Seasonal analysis of results across all years shows an increase in VIIRS vessel detections in summer months (June and July) and the highest increase in vessel detections starting in October and peaking in November and December (**Figure 6**).

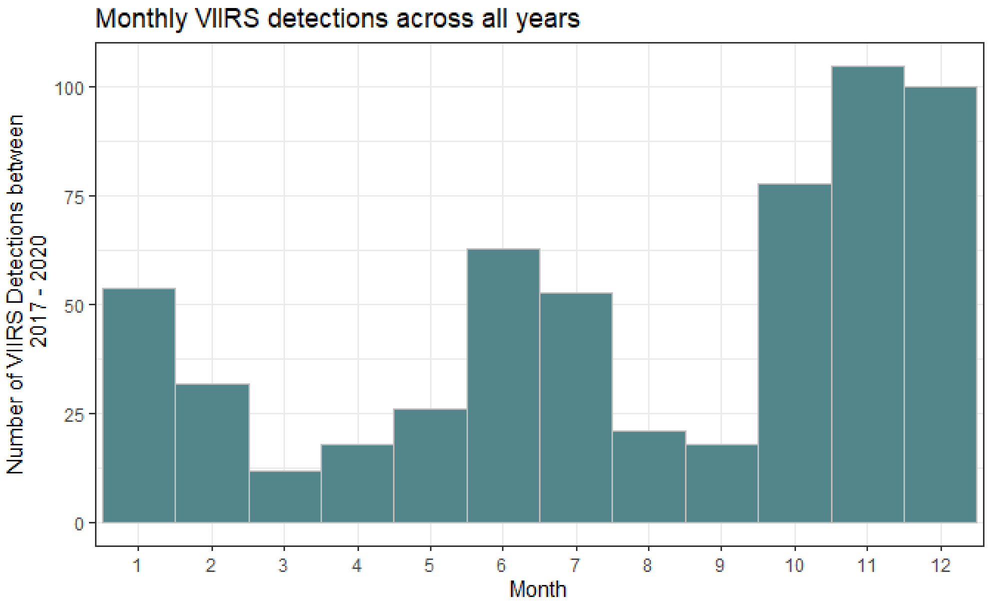


Figure 6. Average monthly VIIRS detections of squid fishing vessels from 2017-2020.

Correlation between VIIRS Detections and CDFW Ticket Landings

Assessing the agreement between the two fishing pressure datasets with the Bland-Altman analysis shows that the difference in means is not close to zero as the averages get larger, which indicates that the two metrics; CDFW receipts and VIIRS vessel detections are producing different results. In this case, VIIRS vessel detections are underpredicting fishing pressure compared to CDFW landing data (**Figure 7**).

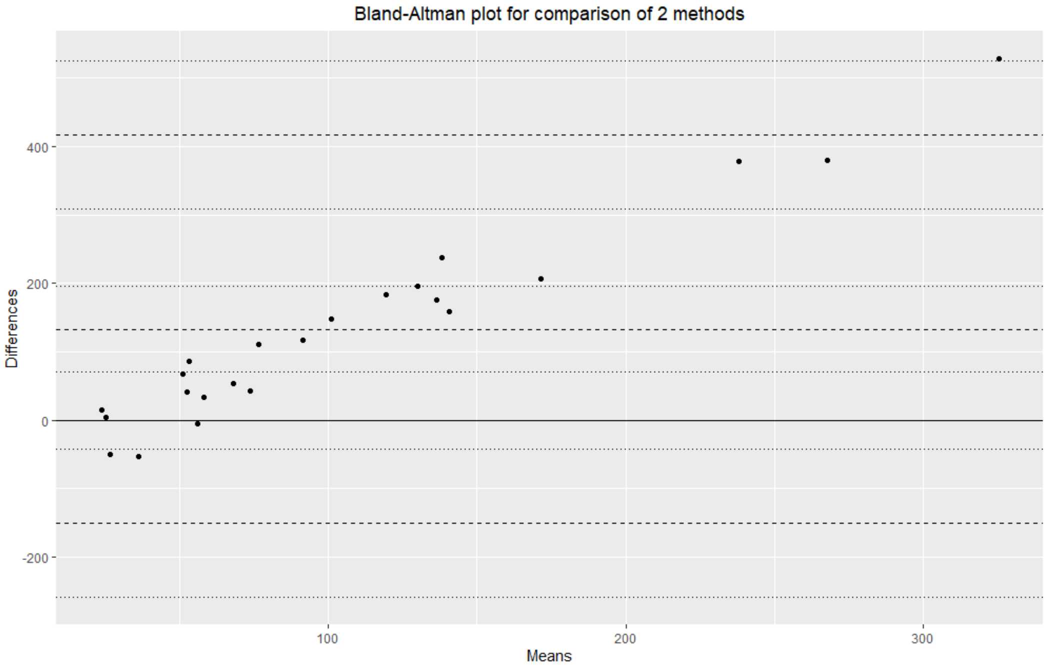


Figure 7. Bland Altman analysis between the two squid fishing pressure datasets; CDFW ticket landings and VIIRS vessel detections. Solid black line indicates that the difference between the mean number of tickets and VIIRS vessel detections is zero, while the dotted lines show increasing difference between the means of the two datasets (2017 - 2018).

Linear Regression of Seal Bombs and Squid Landings

The linear regression between the seal bomb acoustic detections and the number of CDFW landing receipts yielded an R^2 value of 0.49 (*p-value* < 0.0001), showing a moderate positive relationship (**Figure 8**). The linear regression between the seal bomb acoustic detections and the CDFW reported number of pounds of squid caught yielded an R^2 value of 0.25 (*p-value* < 0.001), showing a similar moderate positive relationship (**Figure 9**). Lastly, the linear regression between the seal bomb acoustic detections and the number of VIIRS vessel detections yielded an R^2 value of 0.01 (*p-value* = 0.57), showing a weak negative relationship (**Figure 10**).

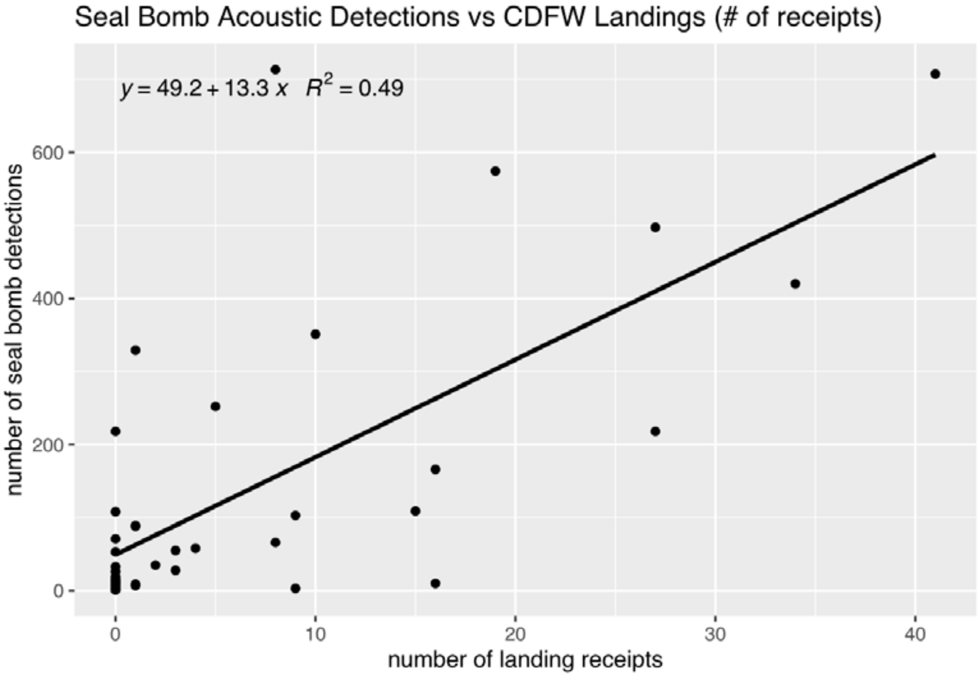


Figure 8. Linear regression correlating the number of seal bomb detections from all hydrophones and the number of CA market squid landing receipts from CDFW across all years (2005-2018).

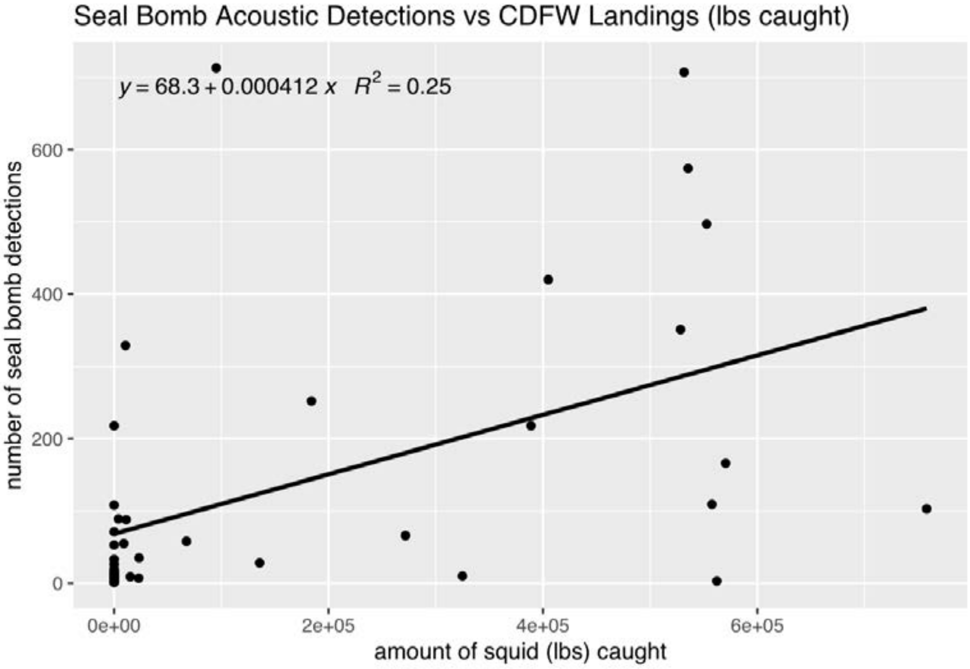


Figure 9. Linear regression correlating the number of seal bomb detections from all hydrophones and pounds of CA market squid caught across all years (2005-2018).

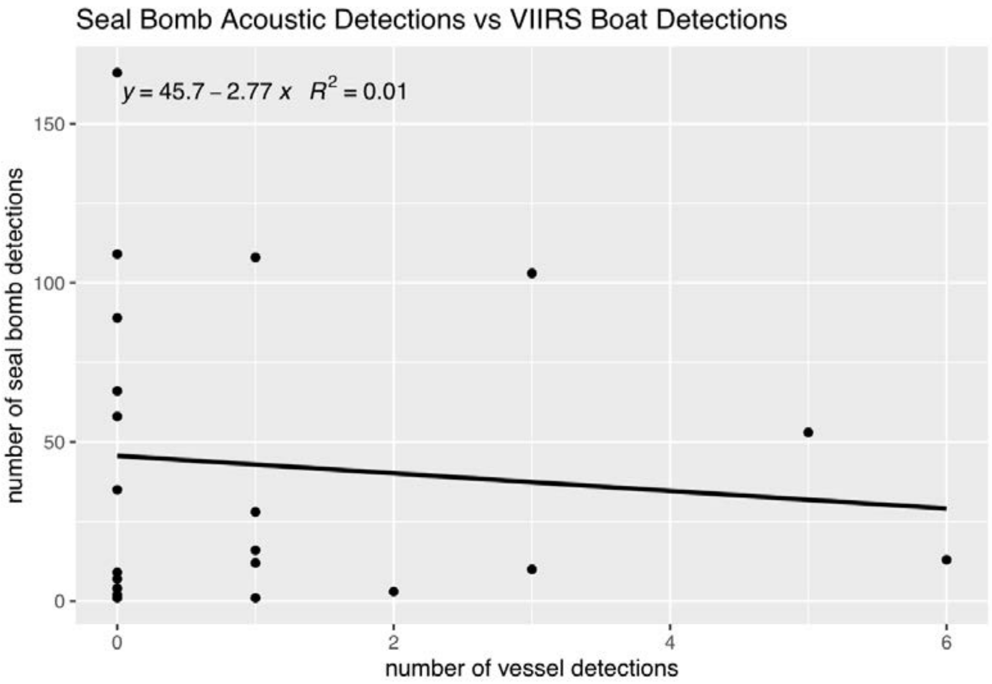


Figure 10. Linear regression correlating the number of seal bomb detections from all hydrophones and the number of VIIRS vessel detections within that hydrophone's estimated listening range for that month.

MaxEnt Outputs

In November, MaxEnt predicted high fishing pressure in Southern California, specifically around the Channel Islands (**Figure 11**). In July, there is high modeled fishing pressure in Northern California, specifically around Monterey Bay, and in some areas around the Channel Islands (**Figure 13**).

November

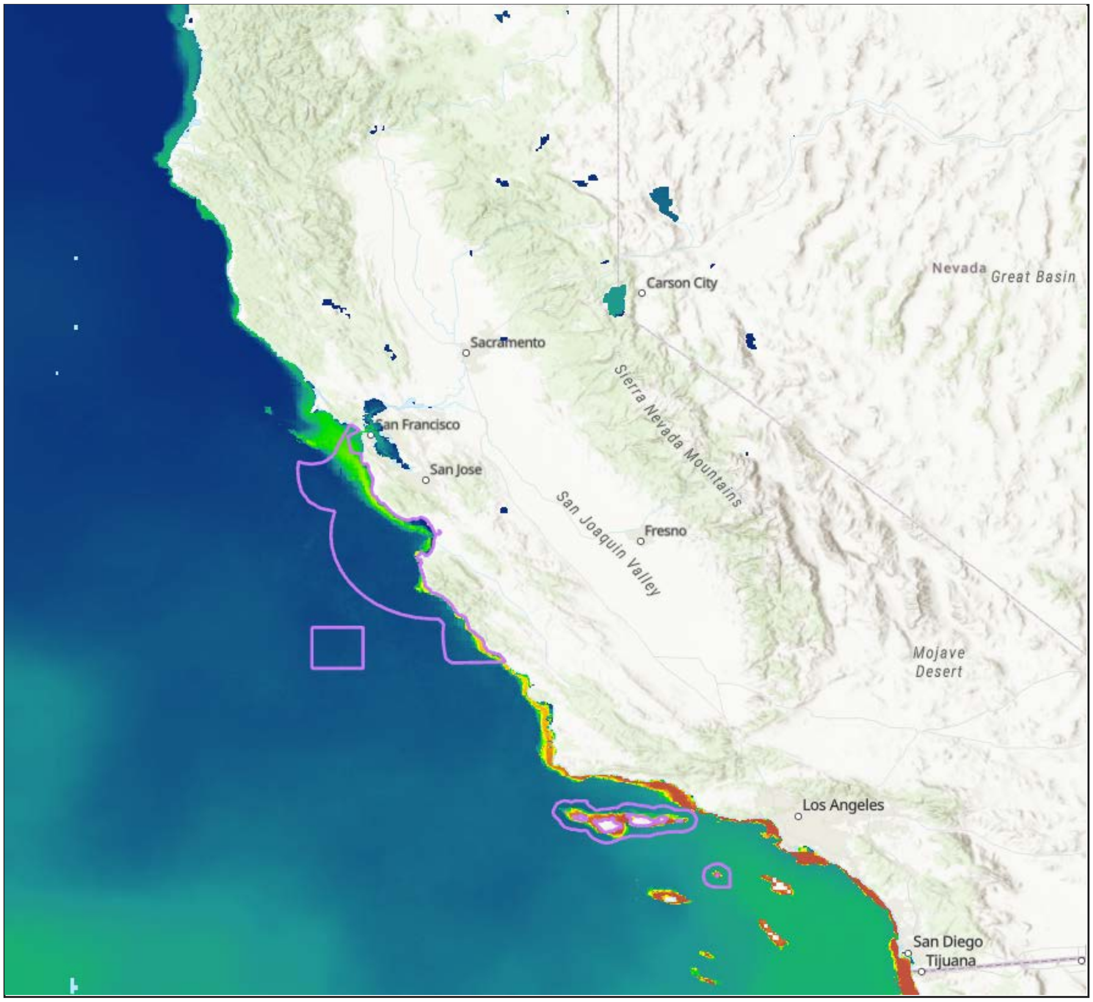
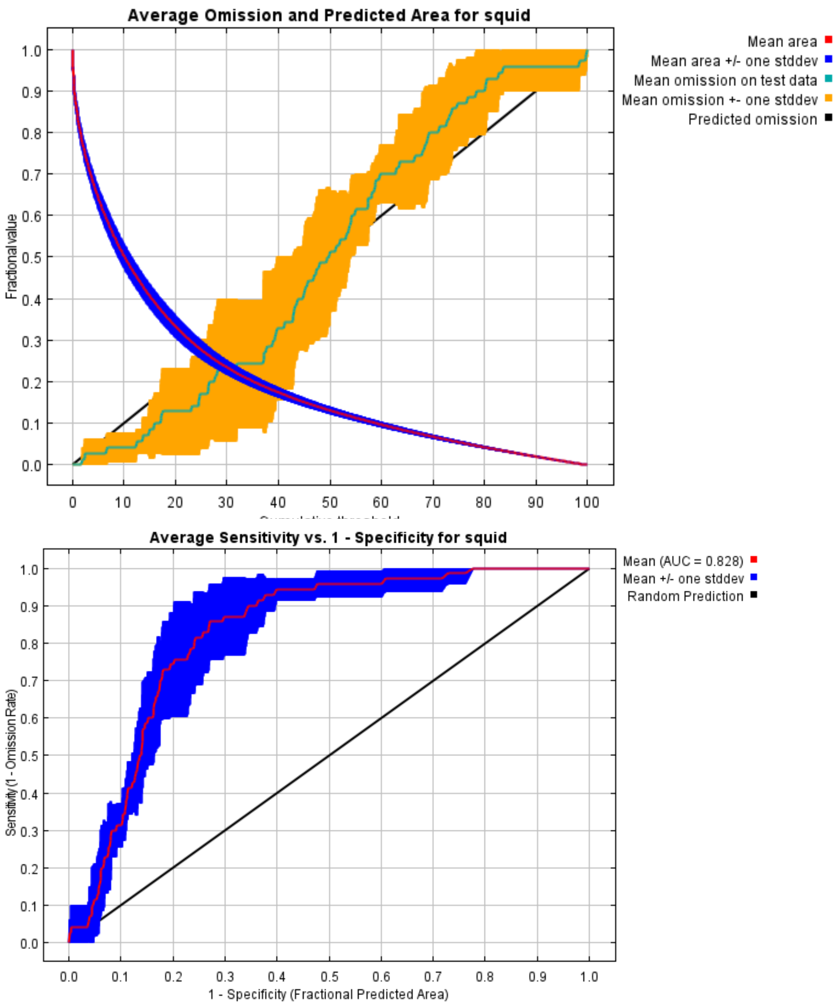


Figure 11: Map of fishing pressure in November (2017-2020) based on historical monthly sea surface temperature and chlorophyll data along the California coast, with high fishing pressure concentrated in Southern California.



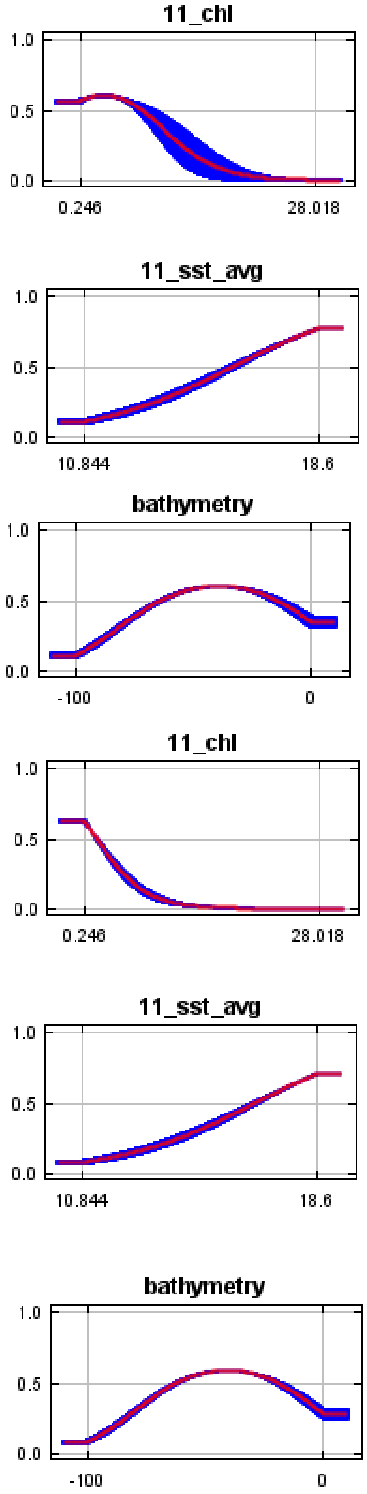


Figure 12: The top figure on the left shows the omission rate for the November MaxEnt model iteration, which is relatively close to the predicted omission rate, with an AUC of 0.828. The top three response curves on the right show how each variable marginally influences the model prediction. The bottom three plots show the prediction power of an individual model run with that variable.

July

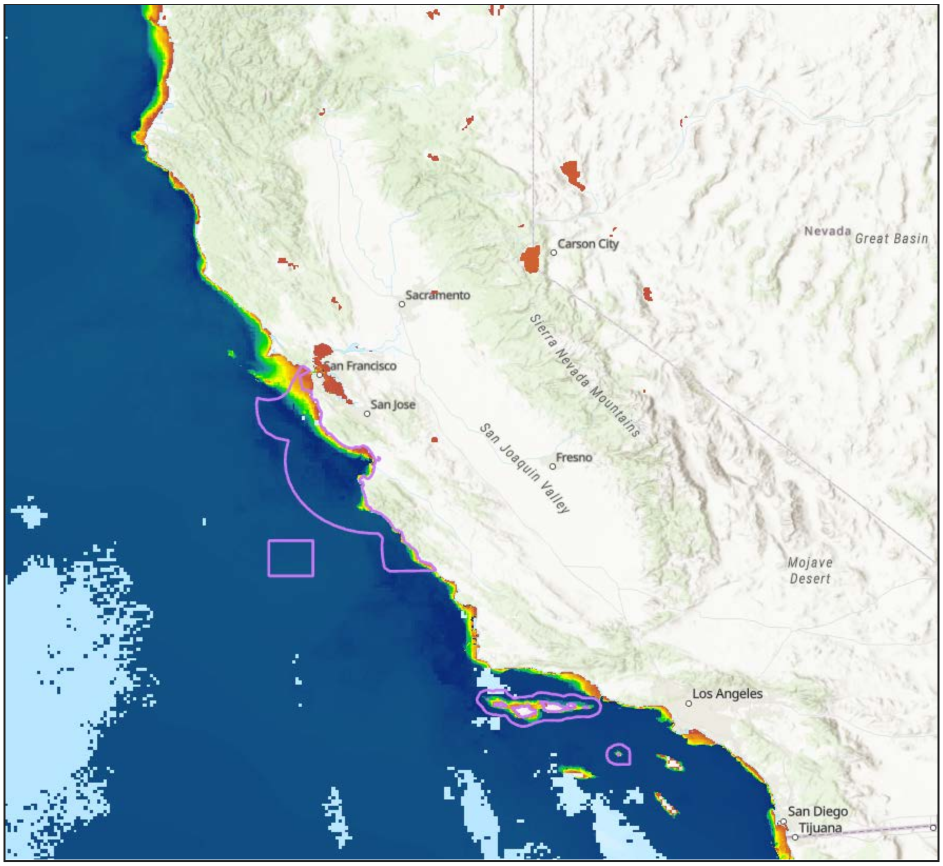
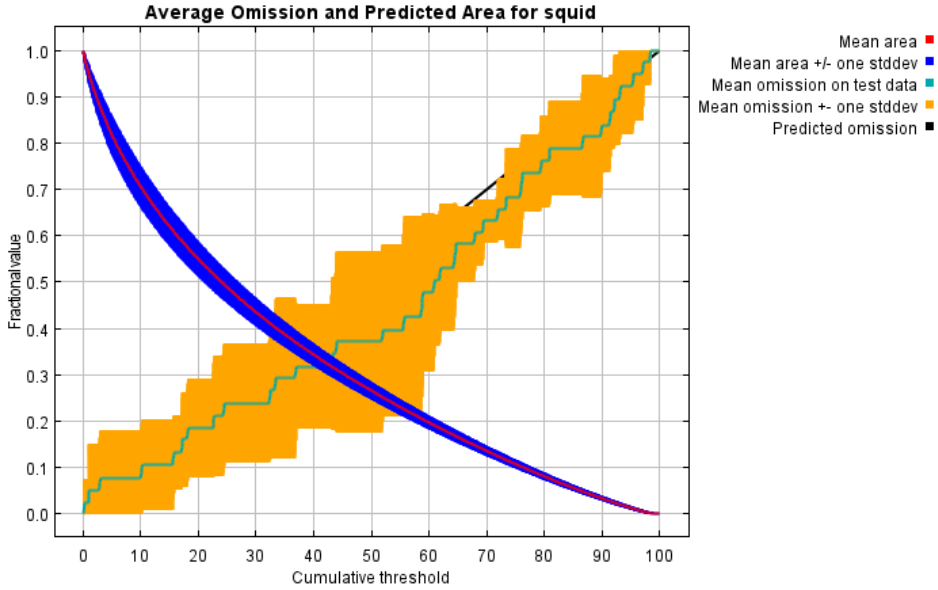
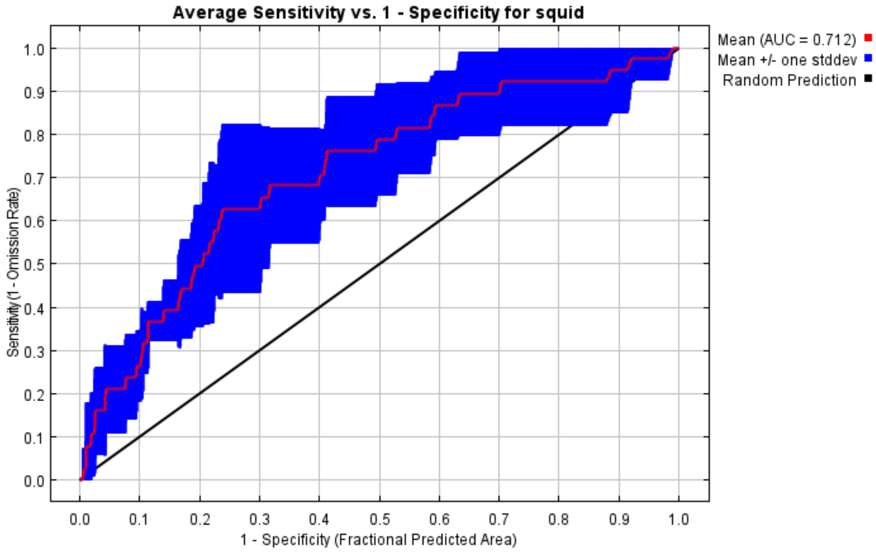


Figure 13: Map of fishing pressure in July (2017-2020) based on historical monthly sea surface temperature and chlorophyll data along the California coast, with high fishing pressure spread across Northern and Southern California.





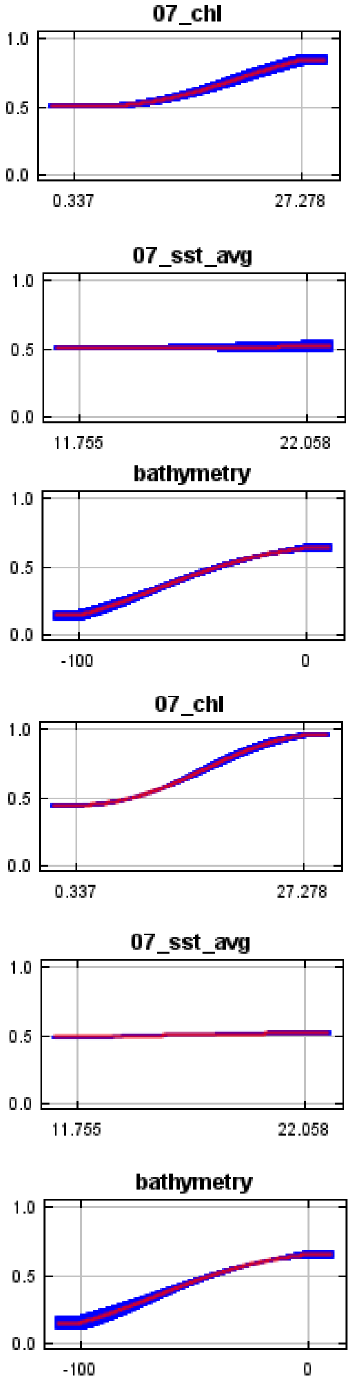


Figure 14: The top figure on the left shows the omission rate for the July MaxEnt model iteration, which is relatively close to the predicted omission rate with an AUC of 0.712. The top three response curves on the right show how each variable marginally influences the model prediction. The bottom three plots show the prediction power of an individual model run with that variable.

Biologically Important Area Maps

Fishing Pressure around Biologically Important Areas

In the summer, high fishing pressure geographically overlaps with or is in close proximity to all four species' BIAs in Northern California and around the Channel Islands (**Figure 15**). In July, high fishing pressure overlaps or borders "BIA hotspots'' containing all four species BIAs, overlap with the endangered blue whale, and overlap some subpopulations of the northeast Pacific humpback whale (**Figure 17**). In November, and continuing into the winter, when fishing pressure is the highest in Southern California, the only BIA overlap that occurs is with gray whales (**Figure 16**). During both seasons, hydrophones that record high levels of seal bomb usage overlap with multiple species' BIAs (**Figure 18,19**).

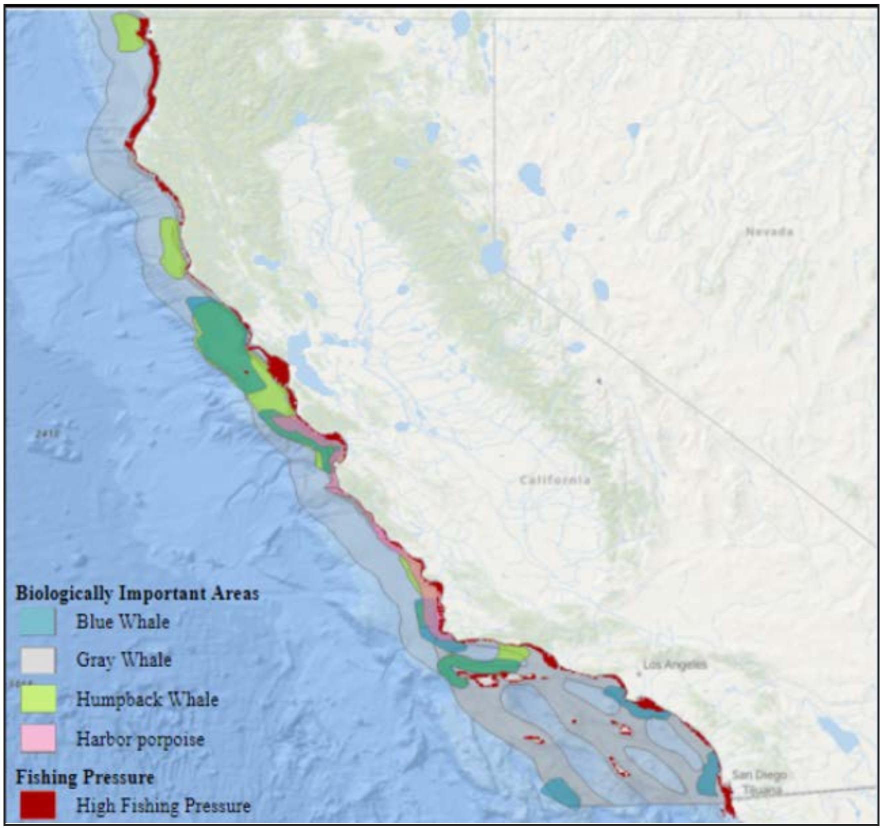


Figure 15. Modeled fishing pressure (MaxEnt probability surface >.5) and Biologically Important Areas for blue whales, gray whales, humpback whales, and harbor porpoises along the California Coast in **July**.

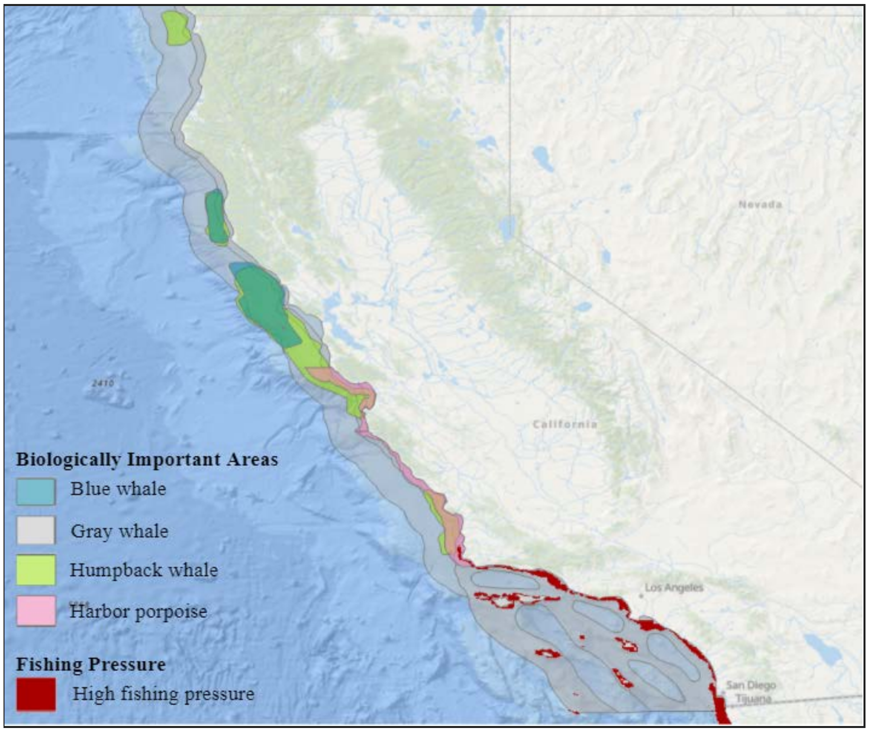


Figure 16. Modeled fishing pressure (MaxEnt probability modeling of >.5) and Biologically Important Areas for blue whales, gray whales, humpback whales, and harbor porpoises along the California Coast in **November**.

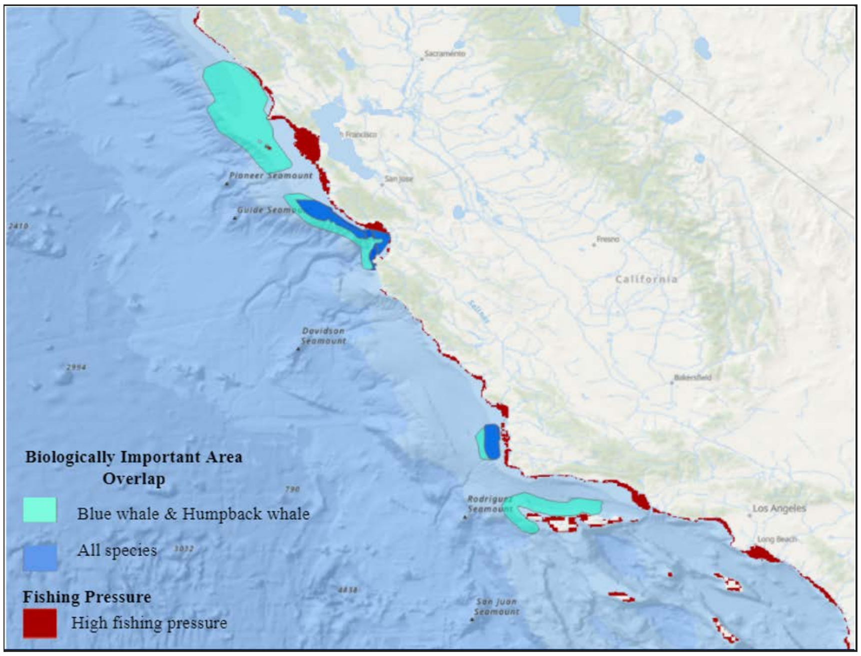


Figure 17: MaxEnt model of high fishing pressure in **July** (MaxEnt probability modeling of >.5) and “hotspots” where blue whales, gray whales, humpback whales, and harbor porpoise BIA’s overlap (dark blue) and where the endangered blue and humpback whale’s BIAs overlap (light blue).

Hydrophone Locations within BIAs

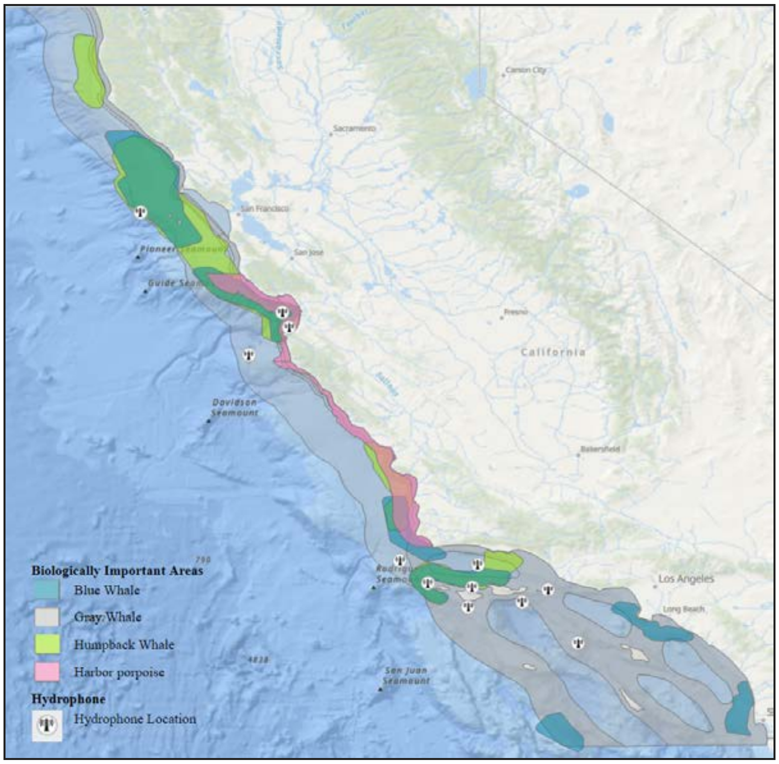


Figure 18: Hydrophone locations and Biologically Important Areas for blue whales, gray whales, humpback whales, and harbor porpoises along the California Coast in **July**.

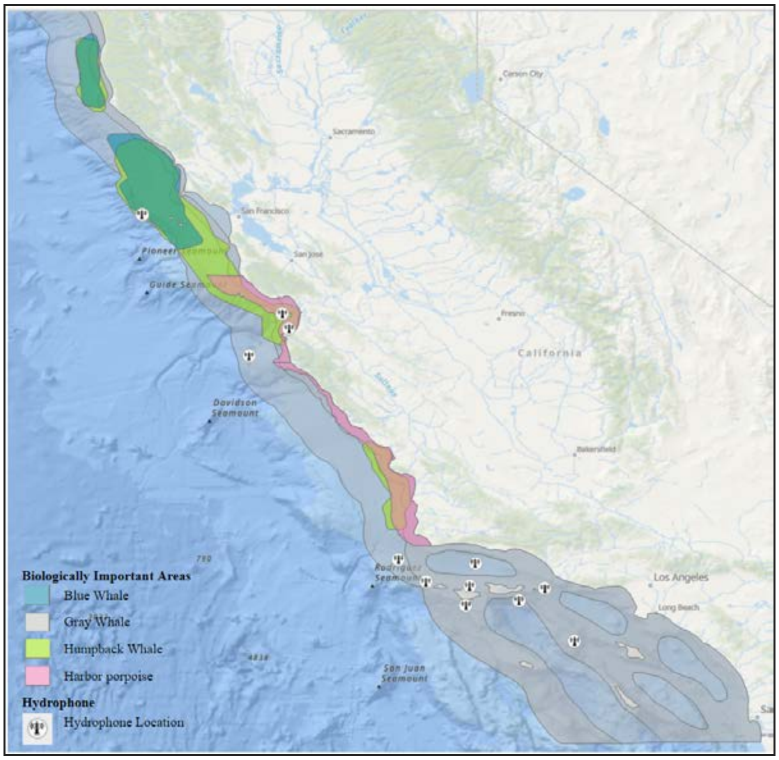


Figure 19: Hydrophone locations and Biologically Important Areas for blue whales, gray whales, humpback whales, and harbor porpoises along the California Coast in **November**.

Cetacean Distribution Maps

During the summer, when fishing pressure is at its highest in Northern California and in some areas around CINMS, pressure either overlaps with or borders areas experiencing predicted high-density distributions of the Risso's dolphin and four endangered cetaceans–the sperm whale, northern right whale, blue whale, and fin whale (**Figures 21, 22, 23, 24**). During November, when fishing pressure is the highest in Southern California, the Risso's dolphin, endangered fin whale, and blue whale all overlap with high squid fishing pressure (**Figures 20, 23, 24**).

Figure 20A. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of Risso's dolphins in **July**.

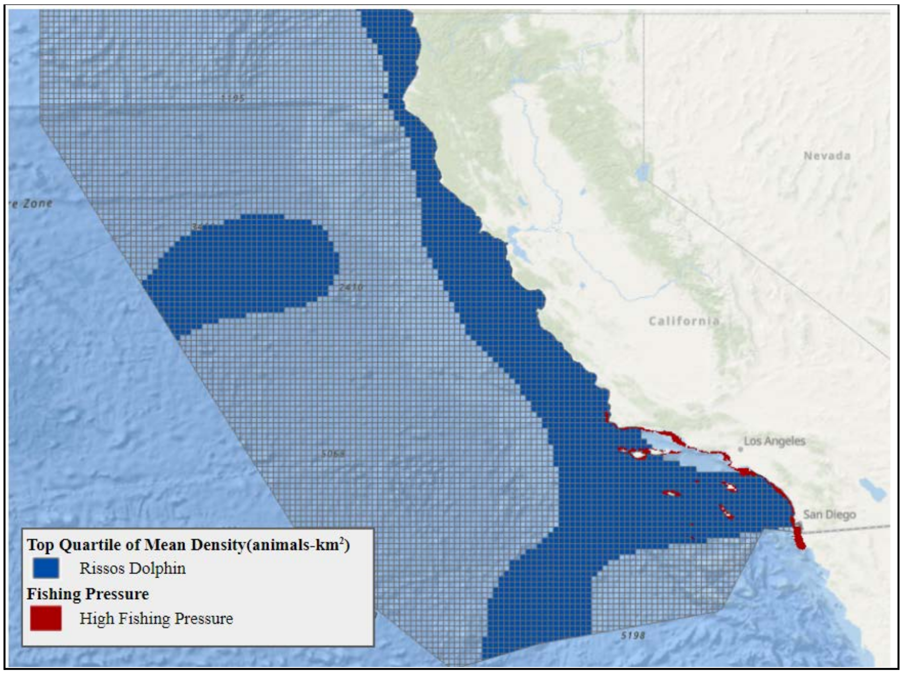


Figure 20B. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of Risso's dolphins in **November**.

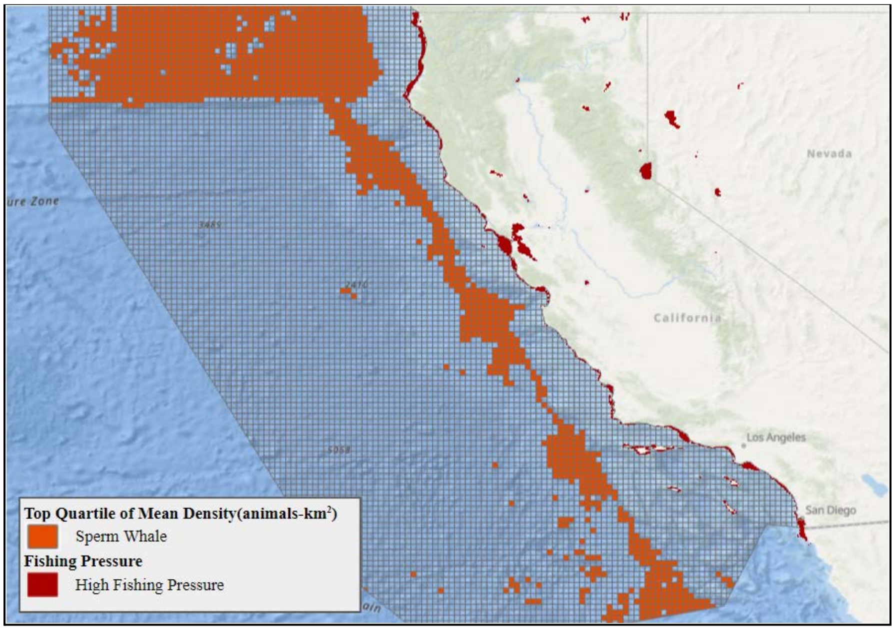


Figure 21A. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of sperm whales in **July**.

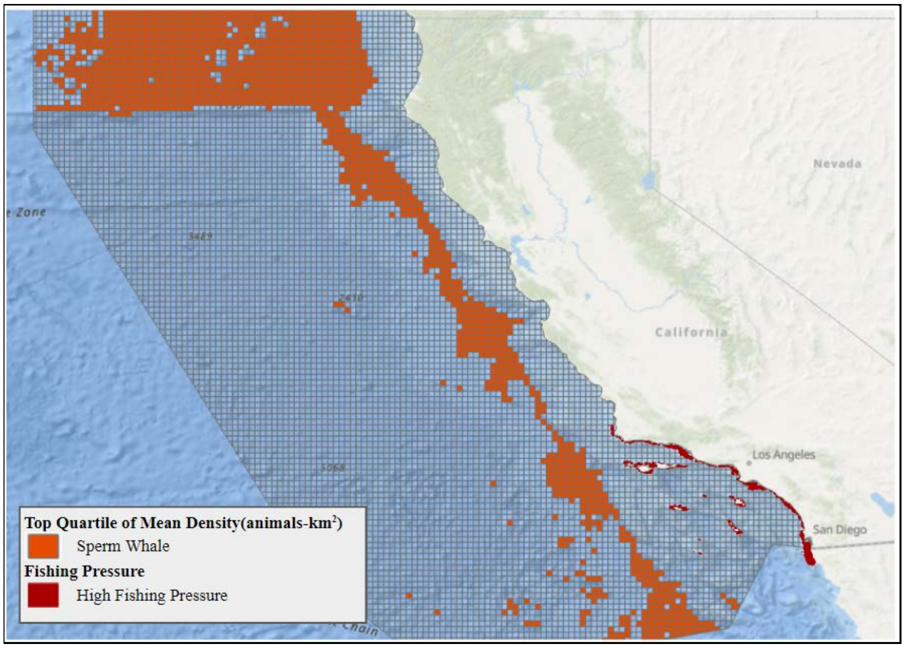


Figure 21B. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of sperm whales in **November**.

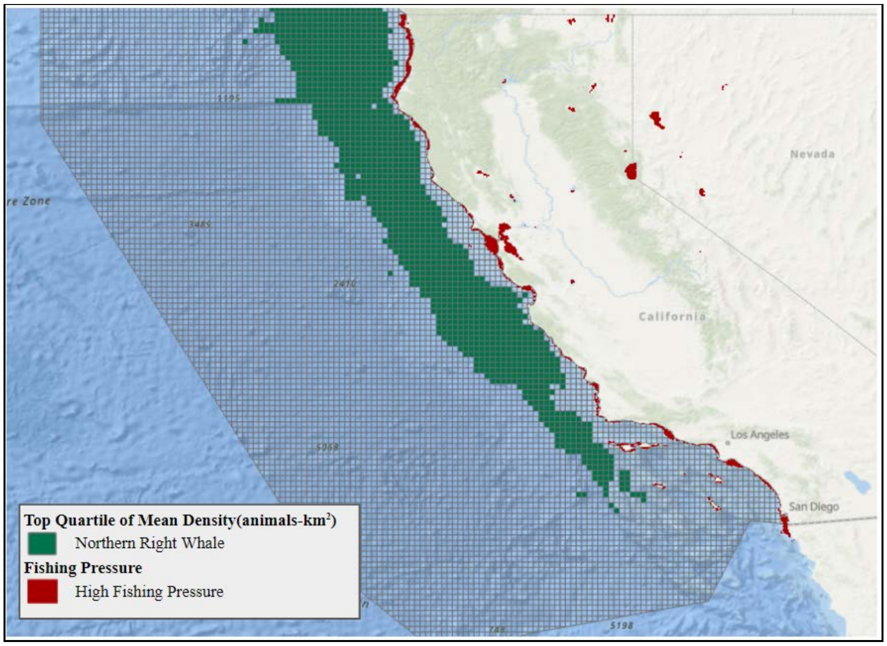


Figure 22A. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of northern right whales in **July**.

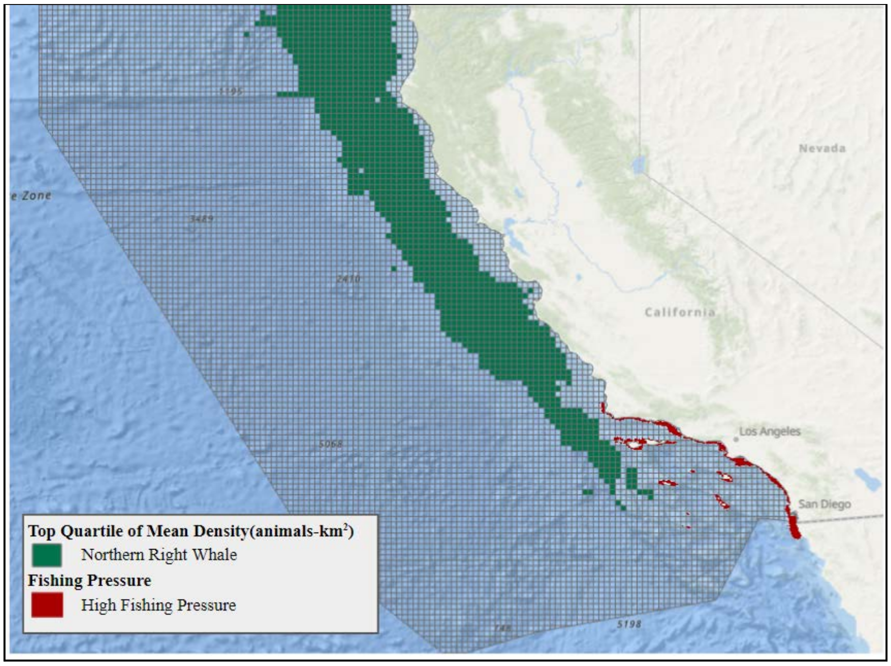


Figure 22B. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of northern right whales in **November**.

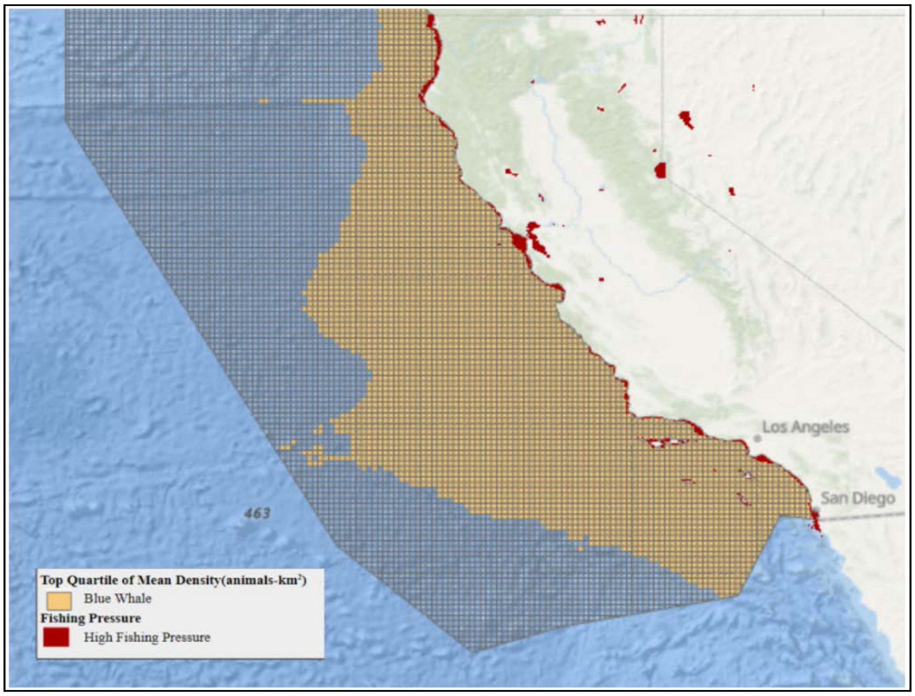


Figure 23A. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of blue whales in **July**.

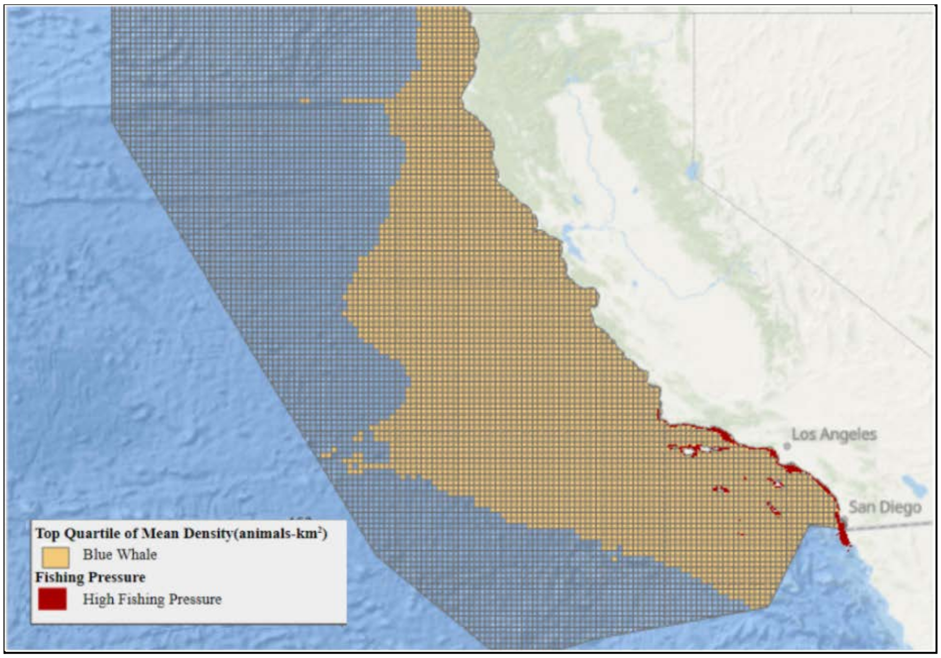


Figure 23B. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of blue whales in **November**.

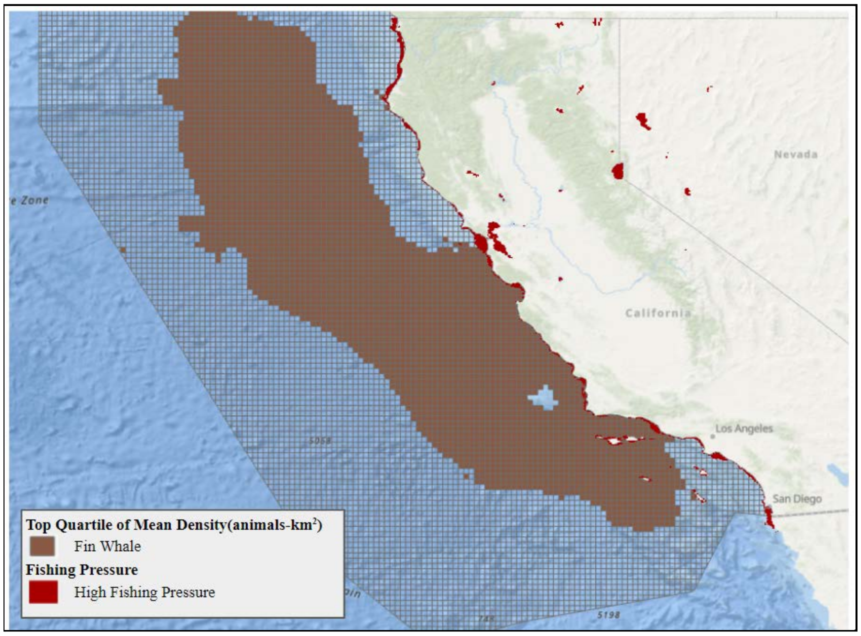


Figure 24A. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of fin whales in **July**.

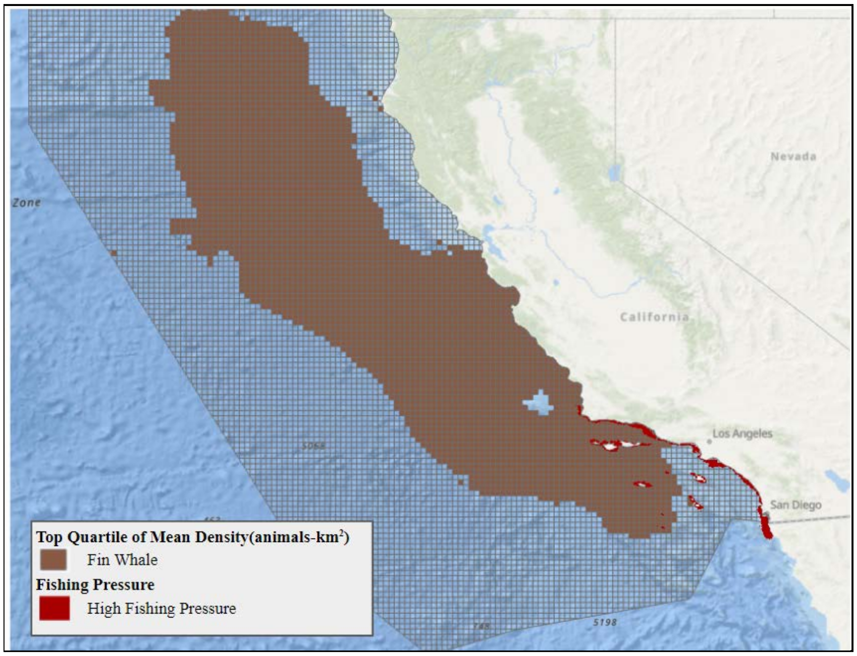


Figure 24B. Modeled fishing pressure (MaxEnt probability surface >.5) and the area of the predicted top quartile of mean density (animals-km^2) of fin whales in **November**.

Discussion

Conversations with Squid Fishermen

To better understand the complexities of the CA market squid fishing industry, squid distribution, and the perception of seal bomb use, we reached out to two separate commercial fishermen for comment. The Ventura Harbor Marine and Commercial Fisheries Manager graciously put us in contact with someone directly involved with the squid fishing industry for our first conversation. Based out of Ventura and Monterey harbors, this fisherman was delighted to speak with students conducting research around an industry that his family has been working in for generations.

There were many takeaways from this discussion, some of which were unbeknownst to us despite extensive literature review. Most notable is that squid fishing now occurs all hours of the day, differing from the industry's historic night-only fishing operations. This is likely due to an increase in industry competition and aggressive fishing tactics, as squid fishing vessels are now traveling from Alaska and Baja California to fish in California waters. This squid fisherman also claimed that fishing operations seem to be more aggressive in Monterey than in the Channel Islands region. This is most likely due to the geographical size of Monterey Bay in comparison to the Santa Barbara Channel where squid fishers are concentrated inside of the bay, and further supports our results of higher fishing pressure occurring in Monterey during the summer months (May-August), compared to the Channel Islands. Lastly, this squid fisherman had very strong opinions on the use of seal bombs. He stated that his fleet only use seal bombs as a method of pinniped deterrence, however, the pinnipeds often hear seal bombs as "dinner bells" and rather than be deterred by the devices, they are attracted to the sound. This raises the question, why keep using seal bombs if they are having the opposite effect desired? He stated that he and his crew would prefer to not use seal bombs, as they are very expensive, sometimes running as much as $500 per case. Unfortunately, he noted that seal bombs are essential to squid fishing operations due to the extreme nuisance of pinniped interference and he does not foresee their use halting anytime soon.

The second squid fisherman we had the pleasure of speaking with owns a squid fishing vessel as well as a recreational fishing boat in the Channel Islands (Oxnard) harbor. He was happy to speak with us about our research surrounding the CA market squid industry and our conversation with him provided many key takeaways, although differing from the insights provided by the first fisherman we spoke to. A positive piece of information he provided is that he believes there is a significant amount of squid spawning occurring within marine reserve boundaries, suggesting the efficacy of the CA marine reserve network. Interestingly, it was noted by this fisherman that seal bombs are essential to the CA market squid industry as a method to steer squid into their purse seine nets. In this case, seal bombs potentially increase fishing efficiency because when they are used as a steering mechanism, their nets are in the water for a shorter period of time. This allows fishers to use less fuel and reduce their potential bycatch impact on non-target species.

Lastly, this fisherman had an interesting opinion on seal bombs, stating he believed they should be rebranded as “squid bombs,” because his crew doesn’t necessarily use them as pinniped deterrents at all. He believes that a name change would reduce the negative connotation associated with acoustic deterrent use.

The anecdotal information we have gathered from people working in the squid fishing industry serves to bolster the need for our analysis, the utility of our findings, and the discussion surrounding the implications of our results found below.

Implications of Results

Spatiotemporal Squid Dynamics

It is important to note discrepancies with location and time when drawing conclusions about changes in seal bomb use. Previous research from Krumpel et al. (2021) provides valuable insight when compared with our research. Results from that study show that seal bomb occurrence was much higher in Southern California than occurrence recorded in northern parts of the state. This is likely compounded by less recording effort in Monterey Bay and greater numbers of active hydrophones in Southern California.

Generally, Northern California experiences higher fishing pressure in the summer months, and Southern California experiences higher fishing pressure in the winter months. This generalization lines up with the information we gathered from squid fishermen, as the squid population and resulting fishing pressure shift further south in the colder months and further north in the warmer months. Additionally, during El Niño years, the survivorship of squid massively decreases due to above-average surface and subsurface water temperatures. According to accounts from the fishermen, squid are often starved and anemic during El Niño years with a noticeable decline in body mass. This account of negative impacts on squid from El Niño effects is reflected in the total catch across the entire California market squid fishery, which tends to exhibit a sharp decline in post-El Niño years (**Figure 25**).

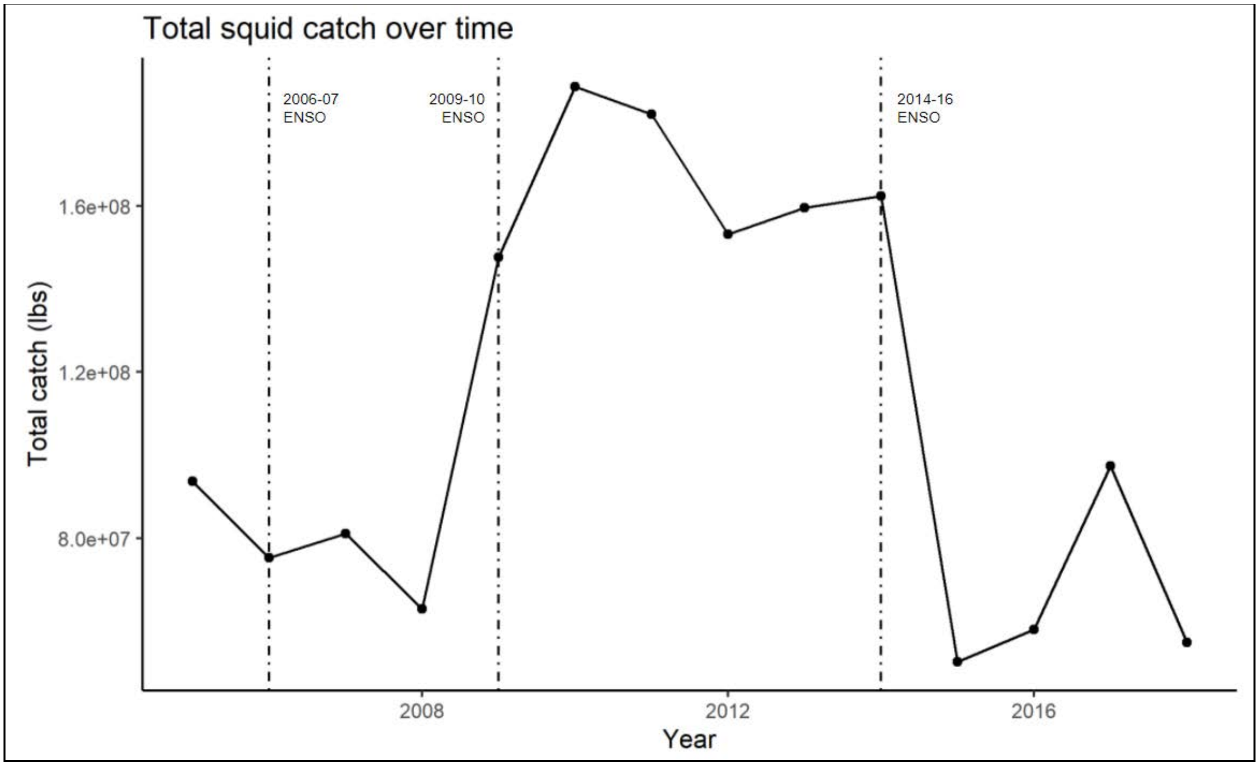


Figure 25. Time series of the total catch (lbs) of market squid across all fishing blocks (2005 - 2018). Total catch exhibits a slight lag effect with a sharp decline in post-El Niño (ENSO) years.

A persistent and widespread marine heatwave (warm water "blob") was experienced throughout the California Current system between 2015 and 2017. This warm anomaly is evident in elevated sea levels (**Figure 26**). This event had large implications for squid distribution and abundance, with large die-off events and reduced spawning occurring throughout northern and southern California (CWPA 2020). During this El Niño event, the survivorship of squid may have been higher in the Channel Islands region compared to Monterey due to the warmer sea surface temperature experienced at northern latitudes.

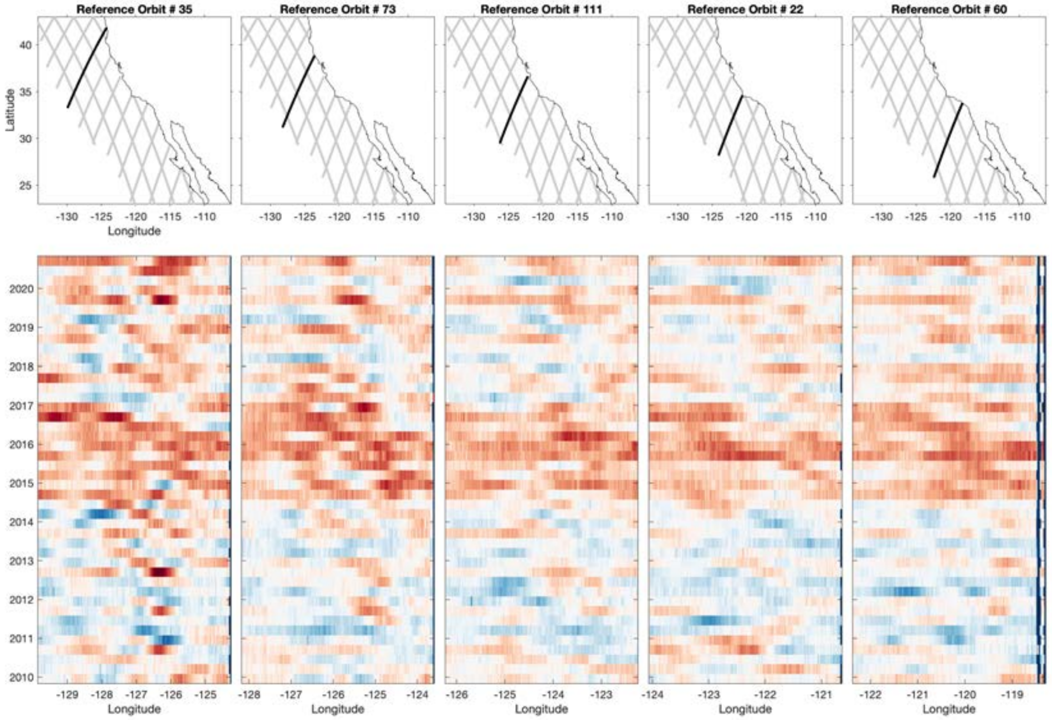


Figure 26. Hovmoller plot showing changes in sea level along satellite radar altimeter ground tracks in the California Current region between 2010 and 2020. Red colors indicate positive sea level anomalies caused by anomalously warm conditions. Credit: John Ryan, Monterey Bay Aquarium Research Institute.

Seasonal trends from CDFW ticket landing data show squid catch is highest in the fall and winter with peaks in October and November. Smaller but notable peaks occur in the summer months through June and July. This trend is echoed through the VIIRS vessel detection data. Vessel detections peak in November and December, with smaller but significant peaks in June and July. These results agree with prior knowledge of high fishing pressure in Southern California during the winter months and in Northern California during the summer months.

While these two datasets show agreement in overall seasonal trends, analysis from the Bland Altman statistical test shows that VIIRS vessel detections severely underpredict fishing pressure, and likely seal bomb activity as well. This is expected, since the Joint Polar Satellite System (JPSS) spacecraft, which includes the Suomi National Polar-orbiting Partnership (S-NPP) and houses the VIIRS instrument, passes over twice daily and observations are taken from just one of those times; between 8:00 AM and 11:00 AM. The Global Fishing Watch processing selects a single flyover to account for seal bombs, only capturing a small portion of the fishing activity occurring over the course of the entire day. Similarly, cloud cover may also mask some fishing activity. Coastal California and the Channel Islands are often covered in dense fog in the mornings, which may interfere with the morning satellite pass over time. With these two limitations in mind, it is then understandable that VIIRS, while preserving spatial accuracy, underestimates the magnitude of squid fishing activity along the California coast.

In contrast, CDFW ticket and landing data more accurately illustrate the magnitude of squid fishing effort in our study area, however, these data have a much coarser spatial resolution. Because fishing blocks are inherently much larger, reported landings give only a rough idea of fishing activity location. Additionally, fishers typically will not disclose locational information or identify landing blocks with complete accuracy to prevent further competition in the industry. When considering which dataset is “better” for analyzing fishing pressure in relation to seal bomb use, it is important to note that neither dataset can be used as a perfect one-to-one correlation. Results from regression analysis of seal bombs with both fishing pressure datasets show that CDFW has a stronger relationship with seal bomb use, while VIIRS data has an understandably lower correlation. This tells us that while patterns of fishing pressure are useful to expand analysis, roughly, there is no substitute for more comprehensive hydrophone data when tracking seal bomb use geographically and temporally.

Spatiotemporal Seal Bomb Dynamics

With seal bomb detection data from the MARS hydrophone in Monterey Bay and the CINMS B HARP hydrophone in Southern California (both extending from 2015 to 2021), there is an interesting comparison to be made between the two long term datasets in static locations (**Figure 27**). This longer-term view also supports the consideration of additional influences on seal bomb use.

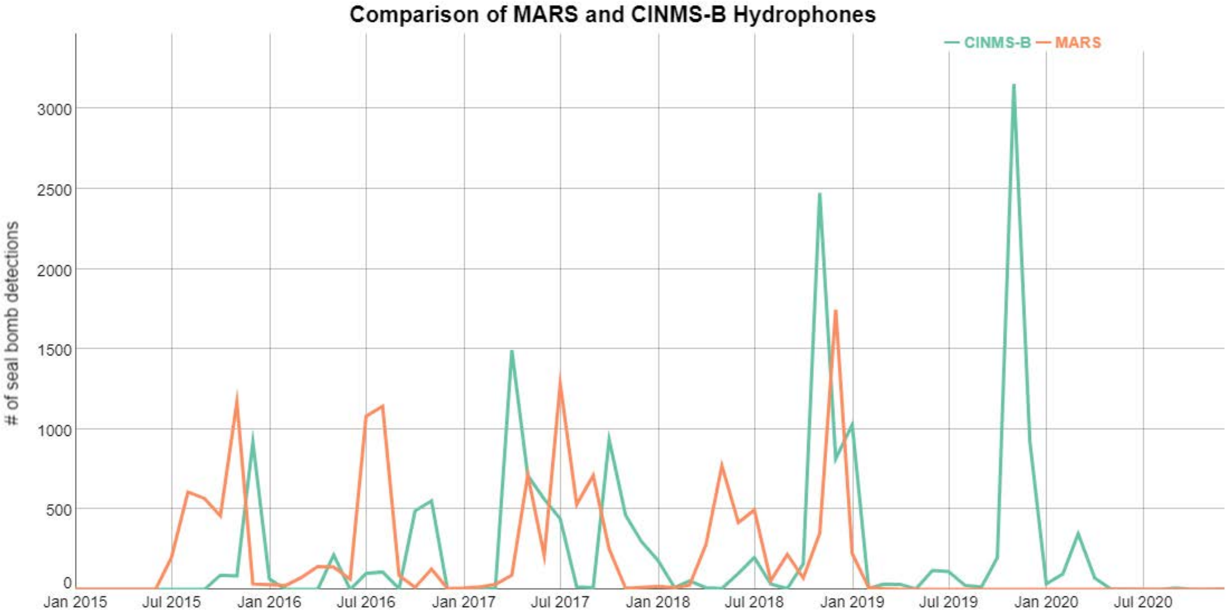


Figure 27. Comparison of seal bomb detections over time between the MARS hydrophone in Monterey Bay, and the CINMS-B hydrophone in the Santa Barbara Channel (2015 - 2020).

For example, beyond the typical summer peak in seal bomb detections in the Monterey Bay region, an exceptionally high number of explosions were detected during July 2020 (**Figure 28**), when the COVID-19 pandemic was strongly influencing human activities including trade and eco-tourism. The possibility of elevated seal bomb use during this early period of COVID impact was raised by both NOAA researchers and private and non-profit organizations during 2020. These longer records of observations permit examination of the potential dimension of pandemic influences on human behavior.

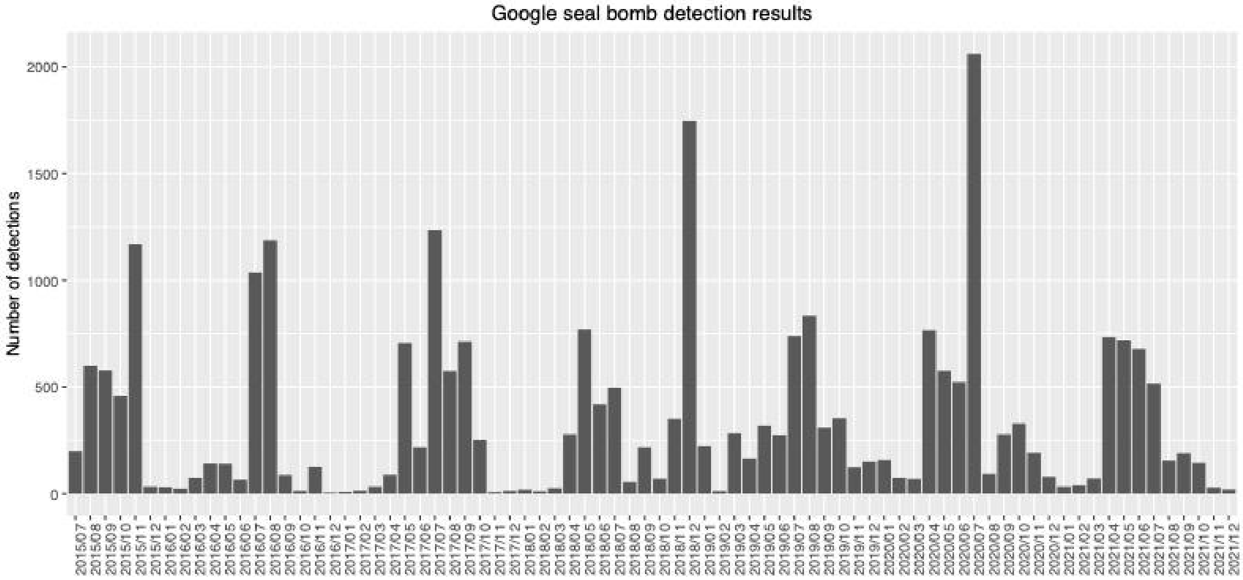


Figure 28. Google AI detections of seal bomb detonations at MARS in Monterey Bay National Marine Sanctuary from 2015 - 2021. Credit: John Ryan, Monterey Bay Aquarium Research Institute.

In addition to comparing the two National Marine Sanctuaries, our analysis of the 2018 - 2020 period when SanctSound hydrophones became active revealed areas of high seal bomb use within each individual sanctuary.

In MBNMS, May 2020 experienced the peak of 1,573 seal bomb detections at hydrophone MB-01, located in the center of Monterey Bay. Similarly, in July 2020 there was a peak of over 2,000 seal bomb detections from the MARS hydrophone just outside of Monterey Bay. These recordings are in close spatial and temporal proximity to each other and are significantly higher than the 100-500 range that is commonly recorded for most of the year and across the other MBNMS hydrophones. These results corroborate our findings from the MaxEnt model and the assessment of VIIRS and CDFW ticket landing data, which indicate that fishing pressure and seal bomb use are higher in northern California in the summer months. These results also indicate much higher seal bomb use in MBNMS when compared to the CINMS hydrophones in the same time period. For example, even MB-02, which typically experiences lower than average detections for MBNMS, showed seal bomb detections in the mid 200s, which is a high value relative to most CINMS hydrophones.

Our result of southern California experiencing higher fishing pressure and predicted seal bomb use in the winter months was confirmed through analysis of the CINMS hydrophone data. While there was one occurrence of high seal bomb use in July 2020 at the CINMS C HARP hydrophone, our records show that use was predominantly higher in the winter months during the 2018 - 2020 period. During this time frame, there were two notable peaks of seal bomb detections at the CINMS C HARP hydrophone and the CI-03 SanctSound hydrophone. The peak number of seal bomb detections in CINMS was far smaller than in MBNMS despite there being a higher “listening effort”, with more active hydrophones in and around the Santa Barbara Channel. These findings agree with our assessment of southern California experiencing higher fishing pressure and seal bomb use in the winter months; however, it also indicates that seal bomb use is comparatively much lower in CINMS than MBNMS at these specific locations. Generally, the number of detections for CINMS hydrophones was often below 100 and rarely exceeded 200 seal bomb detections per month, which is much lower than the MBNMS hydrophones which often record thousands of seal bomb detections. In addition, peak seal bomb use was much lower in CINMS than in MBNMS. For example, 329 seal bombs were detected at NRS-05, on the backside of Santa Cruz Island, in November 2018. Similarly, in December of 2019, there were 346 seal bombs detected at CI-03, near Santa Barbara Island.

An interesting case at Santa Barbara Island (CI-03 hydrophone) illustrates a discrepancy between fishing pressure and seal bomb detections. From 2019-2020, over 250 seal bombs were detected at this hydrophone, however, there are no VIIRS vessel detections around the island within that date range or historic CDFW landing receipts in the surrounding fishing blocks. This indicates that there may be a possibility of discrepancies in squid catch locational reporting, or that seal bombs are being used outside of the CA market squid fishery. From our discussions with local squid fishermen, seal bombs are not commonly used in other fisheries except the sardine fishery. However, it is possible that some seal bomb detonations recorded at Santa Barbara Island can be attributed to Commercial Passenger Fishing Vessels that take recreational fishers to the islands and are known to occasionally use seal bombs. Our conversation with fishermen also informed us that squid are not commonly found around Santa Barbara Island, due to the surrounding rocky substrate not providing the conditions needed for squid spawning. Another possible explanation may be that the detections occurring around Santa Barbara Island are a result of ocean conditions and seafloor bathymetry, allowing for seal bombs used around the northern Channel Islands to be heard all the way from the hydrophone located on the north side of Santa Barbara Island. Further analysis using a propagation model and a comparison with NRS-05, the hydrophone located on the backside of Santa Cruz Island, would help to clarify this issue.

Cetacean Impact

This study did not address direct physical damage to marine mammals as a result of seal bomb detonations. While there is some important preliminary research suggesting impact from seal bombs and other impulsive acoustic sounds, there is little research describing the proximity and physical damage to marine mammals from seal bomb detonations specifically. Research identifying acoustic impact to high, low, and medium frequency cetaceans indicates that impulsive sounds can cause damage to the inner ear, known as either Permanent Threshold Shifts (PTS) and Temporary Threshold Shifts (TTS) depending on the severity of the damage (NMFS 2018). Future studies across specific species will be important in understanding if and at what distance seal bomb detonations are causing PTS or TTS, and whether this impact constitutes a violation of the Marine Mammal Protection Act. Our results focus on behavioral shifts including avoidance as assessing physical harm as described through PTS and TTS is outside of the scope of this study.

Impacts from acoustic pressure can likely cause displacement of cetaceans (Simonis et al. 2020). Those that are displaced from their “primary habitat” may experience decreased foraging success and survival. According to Simonis et al. (2020), harbor porpoise populations may be negatively affected by seal bomb detonations. Expanding from these observations, when cetaceans’ primary habitat is in close proximity to or overlapping with seal bomb detonations it is likely that they will exhibit some avoidance behavior. When considering implications to cetacean species, it is noted that there may also be some positive benefits of avoidance behavior. Because seal bombs are generally used within depths of 100 meters, cetaceans may be deterred out of shallow water environments.

These considerations, in the context of our MaxEnt results which predict areas of high squid fishing activity, illustrate the potential for cetaceans to be impacted by acoustic detonations beyond biologically important areas that directly overlap or are in close proximity to areas of high fishing pressure. However, the question still remains as to exactly how sensitive are cetaceans to picking up seal bomb detonations compared to hydrophones or other acoustic data collection technology.

When southern California fishing pressure is highest in November - January, we see surprisingly little conflict with cetacean presence with our analytical approach. The only observable BIA overlap during this time of year occurs with the gray whale when the species are migrating south through the Channel Islands. However, the cetacean distribution maps using data from Becker *et al.* (2020) reveal that there is also a high overlap with the Risso’s dolphin and the endangered fin whale. Conversely, when northern California fishing pressure is highest in the summer months, there is an overlap with all four target species’ BIAs (blue whale, gray whale, humpback whale, and harbor porpoise), indicating a high probability for acoustic impacts in this area and during this time. Additionally, there is a summer overlap with the Becker cetacean distribution maps for all four endangered whales (sperm whale, northern right whale, blue whale, and fin whale). Regardless of ESA classification, all marine mammals are protected under the MMPA, therefore this information poses the question of whether or not “take” is occurring with seal bomb use overlap and whether that take is legally allowed in sanctuary boundaries.

This further supports the need for our analysis and the review of the NMFS proposed rule on seal bomb use.

The coast of southern California is an important feeding habitat for blue whales in October, according to the species distribution models used in this study. It is important to note here that other species distribution models indicate a high probability of blue whale presence around the Channel Islands during the summer and fall (Calambokidis et al. 2015). Similarly, hydrophone data from SanctSound regularly detects blue whales during the fall and summer as well. Concurrently, our analysis suggests October is the start of high squid fishing pressure around the Channel Islands, with noticeable peaks in fishing pressure and seal bomb use occurring in November. If the squid fishing season begins early or if changing environmental conditions cause squid populations to spawn earlier, there may be an increased acoustic impact on blue whales in the future. When assessing cetacean BIA "hotspots", there are multiple locations where all four species are in close proximity to regions of high fishing pressure. There are additional regions where the blue whale and humpback whale also overlap with areas of high fishing pressure.

Sanctuary Management

Implications for Proposed Rule

This analysis of the geographical overlap of seal bomb use, cetacean distribution, and their biologically important areas provides an opportunity to create recommendations that bolster the effectiveness of the NMFS proposed rule for safely deterring marine mammals. Currently, this federal guidance allows for the use of legal, non-lethal impulsive acoustic deterrent methods, therefore allowing the use of seal bombs. The proposed rule indicates that seal bomb users must visually assess the area surrounding their vessel beforehand to avoid potential impact to marine mammals and other non-target species. Additionally, the rule states that seal bomb use is restricted when visibility is less than 100 meters (e.g., at night or with thick fog). However, our findings indicate that seal bomb use may impact cetaceans within a much larger spatial radius than will likely be assessed by seal bomb users. Our findings also indicate that peak seal bomb use occurs at night and into the early morning which may violate the NMFS proposed rule restricting use to times with >100 meters of visibility. It is unlikely that conducting a marine mammal visual assessment at night will be sufficient due to lack of sunlight.

Under section 101(a)(4)(A), the MMPA currently allows the owner of fishing gear and catch to use measures that deter marine mammals from damaging fishing gear, catch, and personal property, *as long as those measures do not result in death or serious injury of marine mammals*. Our findings show the potential for direct and indirect impact to cetaceans in the areas that seal bomb use and cetacean presence overlap. In addition, sound propagation allows for extended overlap, as the anthropogenic sounds created by seal bombs have the ability to travel far distances underwater. This creates cause for concern, as this may constitute “take” under the MMPA and the ESA. If seal bomb use is indeed causing serious injury to nearby pinnipeds through temporary and permanent auditory threshold shifts, the cumulative effects of seal bomb use may violate this section of the MMPA. However, section 101(a)(4)(B) of the MMPA provides fishers with protection from liability for “take” by specifying that any actions taken to deter marine mammals that are consistent with guidelines are *not* a violation of the MMPA. Proposed guidance and specific measures, however, are not mandatory. If death or serious injury to a marine mammal occurs from deterrent use, the protection of liability from this section would not apply and the “take” of the affected marine mammal would constitute a violation of the MMPA.

With these regulations in place, it is essential that NOAA consider all potential violations of the MMPA, ESA, and the proposed rule for safely deterring marine mammals. The findings from this research project serve to highlight regions of central and southern California that experience overlap of high seal bomb use and cetacean presence, therefore, presenting potential areas that may experience “death or serious injury of marine mammals”. Further research is needed to adequately evaluate the direct impacts that seal bombs may pose to cetacean behavior and physiology, however, seal bomb use may still pose indirect threats to nearby cetaceans that ultimately lead to serious injury or death. With these factors in mind, the seal bomb “limitation zones” we have identified may stregthen the efficacy of the NMFS proposed rule if factored in and identified.

In addition, our conversations with squid fishermen have brought to our attention the possibility for an alternate use of seal bomb acoustic deterrents. If “steering” squid is a trend across multiple squid fishing vessels and the unpermitted use of seal bombs is dominant to their permitted use, this may open up the possibility of new strategic management options. Clarifying the intention of seal bomb use may shift the focus of future research and the goals of marine sanctuary management to address how to steer California market squid in a less harmful manner. If seal bombs are predominantly being used as a steering mechanism, this raises a couple of questions. How does this change the legality of their use? How does this affect the relationship between impacts from use and potential “take” of marine mammals under the MMPA? Will this require seal bombs to be removed from the NMFS list of “acoustic deterrents”?

Implications for Continued Monitoring

While the SanctSound project ended in 2022, continued monitoring through passive acoustic listening stations will be an important component of ongoing ocean noise management within sanctuaries. Based on our analytical findings that suggest fishing pressure does not fully encompass seal bomb use, the best way to continue monitoring seal bombs is through hydrophone collected acoustic recordings. Analysis from MARS and CINMS B & C hydrophones show the value of long-term static listening station locations which allow for comprehensive analysis through time. Additional locations that are important for passive acoustic monitoring would be sites to the south of Santa Cruz and Santa Rosa Islands near the current location of NRS-05.

Assumptions and Limitations

Detecting seal bombs from passive acoustic data is largely a subjective process that may include human error during the manual confirmation of seal bombs. Multiple people from different agencies worked to process the data used in this project, which introduces varying levels of error.

MaxEnt is a powerful tool for predicting ranges based on environmental conditions, however, as with all models, it has limitations. Our analysis used presence-only data from VIIRS vessel detections. As discussed previously, this underrepresents fishing pressure, sometimes significantly, along the California coast. While MaxEnt is equipped to handle presence-only data and does not require absence data to run a successful model, it cannot fully reflect the extent of squid fishing effort. It is therefore important to acknowledge that the predicted “high probability of squid fishing” is likely conservative and spatially under-representative of actual fishing pressure.

The Santa Barbara Channel and Monterey Bay are regions of extremely high biodiversity. Our analysis of cetacean overlap using Biologically Important Areas only considers four species in the west coast region due to data limitations. Therefore, this analysis is not comprehensive of all species present in areas of high fishing pressure, so some impacted species may be left out of this analysis. While the Becker models begin to address this data gap, the underlying assumptions between datasets make for an indirect comparison.

When using the BIA and Becker species distribution datasets, there are some obvious discrepancies and loss of accuracy in data summarization. It is important to note that the distribution maps group June - early December under the “fall/summer” category, so specific monthly movements and less-used habitat are lost in summary. Additionally, the distribution maps are only displaying the probabilistic highest density of areas for each species, meaning that there are other areas of use not displayed within the maps. BIA migration patterns also do not guarantee presence at a specific time. This study can therefore only be applied to the population level, not individuals.

Finally, some species may be more sensitive than others. For example, Risso's dolphins’ and toothed whales’ primary prey species are squid, making impact and proximity to seal bombs more likely for those species. Furthermore, our analysis does not account for differences in hearing between species. Krumpel et al. (2021) suggests that marine mammal size can also affect the acoustic impact experienced by an organism.

Considerations for Future Analysis

We recommend future research be conducted to study how seal bombs impact Temporary and Permanent Threshold Shifts in cetaceans and pinnipeds and how they might change other important behaviors such as breeding, feeding, and migration. This may provide insight on the specific species that are most likely to be physically impacted by acoustic deterrent use. Additionally, further research on the physiological capabilities of cetaceans to hear underwater acoustic deterrents is needed. This could shed light on whether cetaceans or passive acoustic monitoring systems are better suited for hearing, or picking up, anthropogenic ocean noise.

This study highlights the importance of passive acoustic monitoring systems using a broad geographic range. The difficulties matching temporal ranges of acoustic data across multiple regions also emphasizes the value of having static hydrophone locations through time. Understanding changes in the ocean soundscape is also best analyzed across a long time period to better understand long-term impacts. Therefore, we recommend that future data collection focuses on implementing a static and standardized deployment schedule.

This project also highlights how regions with increased monitoring are critical for improving our understanding of anthropogenic impacts on marine soundscapes. The proposed Chumash Heritage National Marine Sanctuary in central California will be monumental for protecting many marine organisms and ecosystems that are at risk of being harmed by increased human activity and climate change. If created, the proposed sanctuary will bridge an important spatial data and physical gap between the Channel Islands and Monterey Bay National Marine Sanctuaries. Future research should prioritize sound monitoring within this area in order to connect the two sanctuaries’ monitoring efforts and provide robust recommendations for tri-sanctuary management.

Recommendations

Immediate Action

We suggest establishing seasonal seal bomb limitation zones in hot spot areas of northern California in the summer to lessen the probability of cetacean impact. This could take many forms, including a ban on seal bomb use for specific areas, a limit on the number of seal bombs cases that a single vessel can purchase at one time, or a requirement for the usage of alternate types of pinniped deterrents. There is less urgency for establishing a southern California winter limitation zone; however, there is still a presence of endangered fin whales, Risso’s dolphins, and other marine mammals (**Appendix H**) that are likely to overlap with high squid fishing pressure. We suggest that these limitation zones be embedded within NOAA’s proposed rule on pinniped deterrence as it undergoes further review.

In addition, sound propagation expands acoustic overlap well beyond geographic overlap. In order to better understand the potential impacts from seal bomb use to cetaceans, this analysis could be further supported with sound propagation modeling. To factor in varying seafloor bathymetry and oceanographic conditions, we suggest NOAA creates a sound propagation model for each individual hydrophone location.

Future Action

As sea surface temperatures warm, both the squid spawning season and migration patterns of cetaceans are likely to shift. In addition, the CA sea lion population has increased in recent years. If the population continuously increases, this may lead to more seal bomb usage by the squid fishing industry in an attempt to keep up with the increasing pinniped population. This may cause more interactions between cetaceans, pinnipeds, and areas of high squid fishing pressure, resulting in a higher impact over time.

We suggest further research be conducted on how future sea surface temperature, migration patterns, and population abundance may change over time to observe these potential impacts. Furthermore, we suggest incorporating other species distribution models predicting cetacean presence in and around high-impact areas to increase the accuracy of our predicted impact. This may result in changed or additional precautionary seal bomb limitation zones and periods.

Conclusions

Well-managed national marine sanctuaries can provide substantial benefits and play a key role in protecting threatened and endangered marine species. However, to be successful, they require the consideration of all potential impacts to coastal and marine resources, including anthropogenic noise. Analysis of marine soundscapes can help resource managers and government agencies like NOAA provide guidance on national marine sanctuary use that actively protects the migratory species that visit them and the sanctuary resources that are conserved within their boundaries.

The results of the spatial and temporal analysis conducted in this report confirm that high fishing pressure and increased seal bomb use occurs during the fall and winter in the Channel Islands National Marine Sanctuary, while peak fishing pressure and seal bomb use occurs during the summer in the Monterey Bay National Marine Sanctuary. Additionally, recorded seal bomb detections are noticeably higher in MBNMS than CINMS. Our research also found that fishing pressure cannot be used as a complete one-to-one proxy for seal bomb use. Satelite-derived detections of fishing activity severely underpredict seal bomb use and while CDFW recorded landings data provide a better proxy for seal bomb use, they cannot substitute the efficacy of using hydrophones for identifying seal bomb detections. Passive acoustic monitoring systems will provide the best tools for understanding the future temporal and spatial dynamics of seal bomb use, as well as predicting future impact on cetaceans.

While this study does not definitively identify whether seal bomb acoustic deterrent use constitutes a violation of the MMPA, our results indicate that there is significant overlap and close proximity of cetaceans and seal bomb use in both MBNMS and CINMS. Our findings of seal bomb use near non-target species emphasize the need for further research on how seal bombs directly and indirectly impact cetaceans and pinnipeds. These nuances are complex and the species mentioned in this report will likely require more than the proposed guidance for long-term protection, however, creating a well-planned management strategy for marine mammal deterrent use is a meaningful starting point and could provide benefits to these irreplaceable species in the long term.

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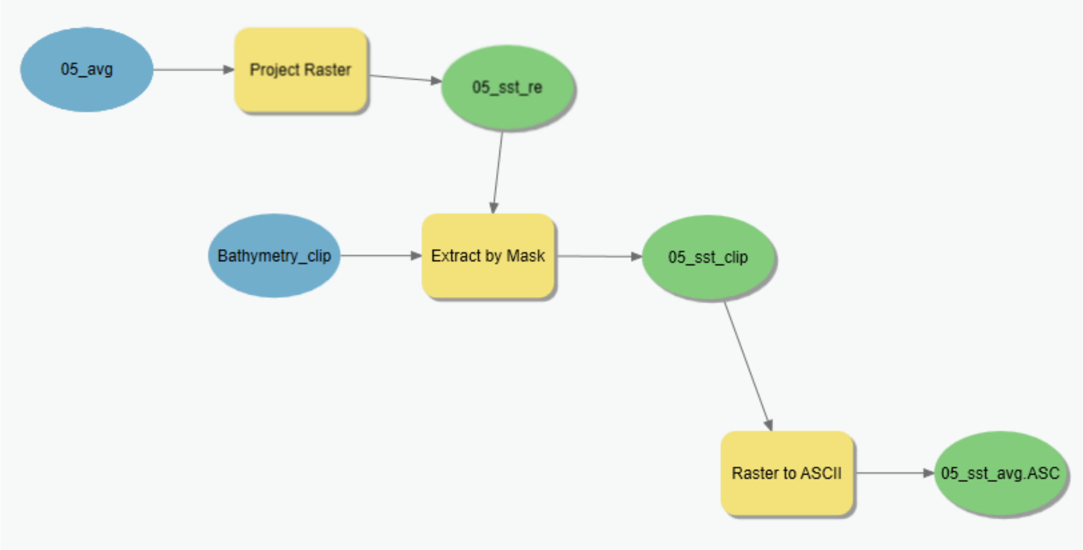
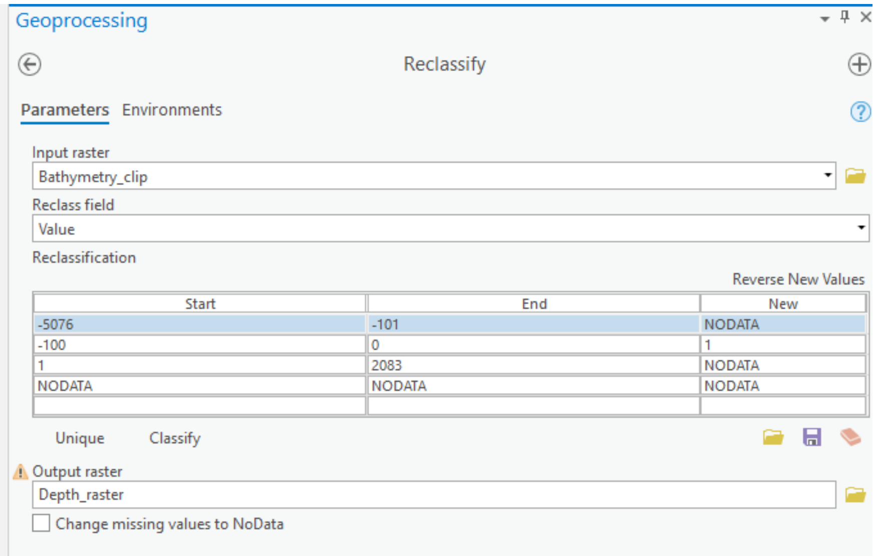
Appendix

Appendix A. Sea surface temperature data processing in ArcGIS Pro Model Builder.



Appendix B. Bathymetry Reclassification



Input raster
Bathymetry_clip

Reclass field
Value

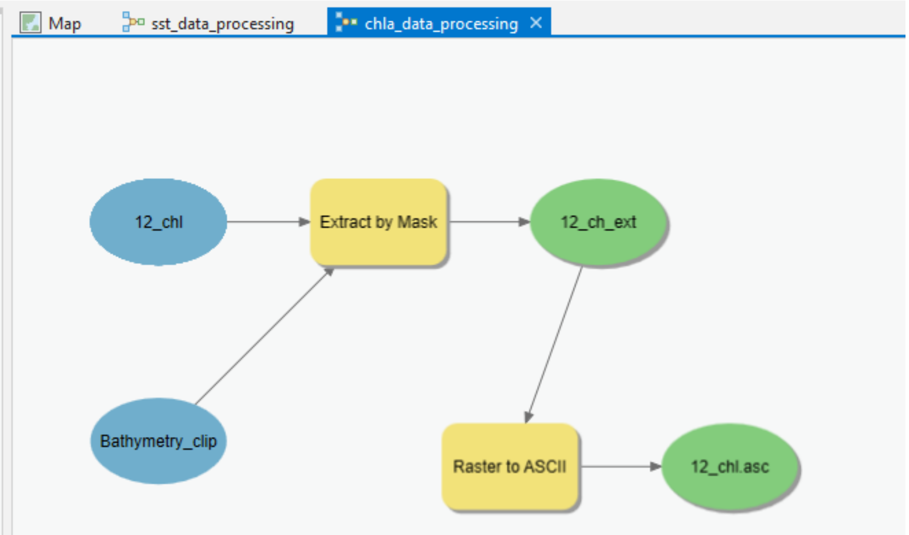
Reclassification

Start	End	New
-5076	-101	NODATA
-100	0	1
1	2083	NODATA
NODATA	NODATA	NODATA

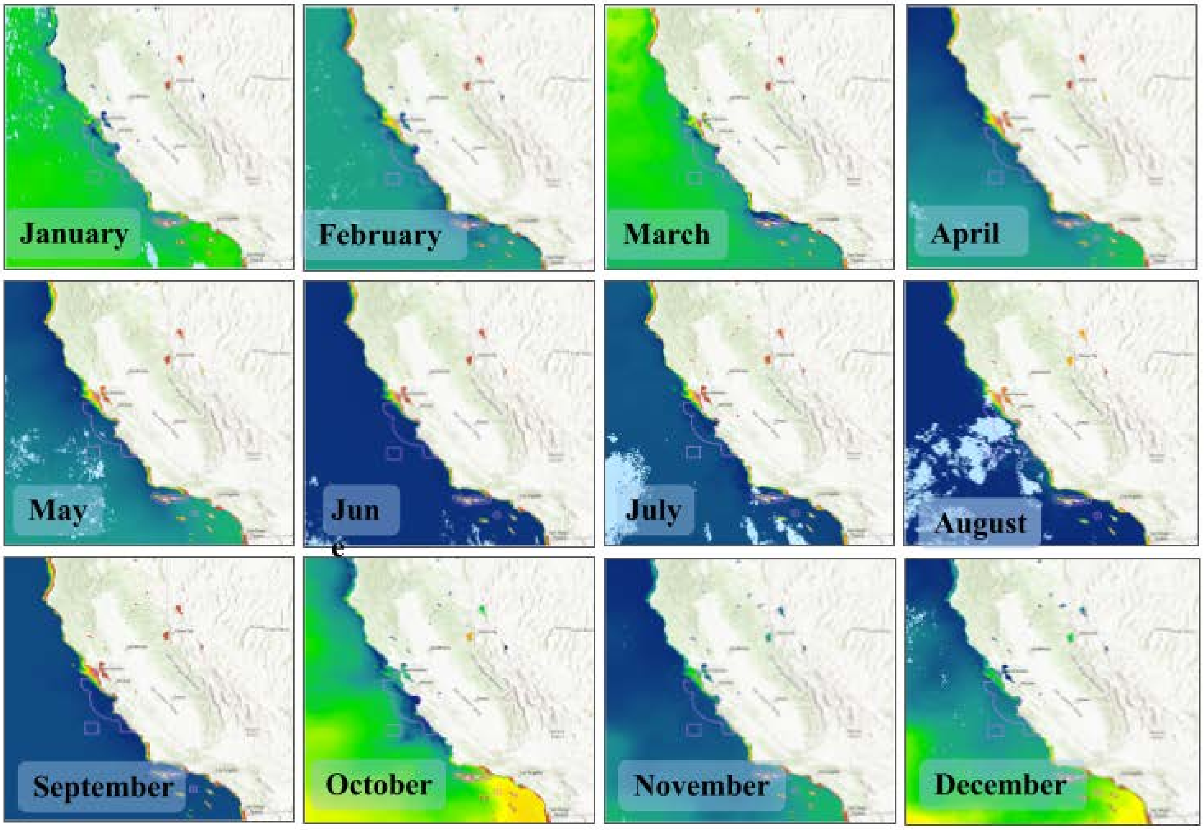
Output raster
Depth_raster

☐ Change missing values to NoData

Appendix C. Chlorophyll-a data processing in ArcGIS Pro Model Builder.



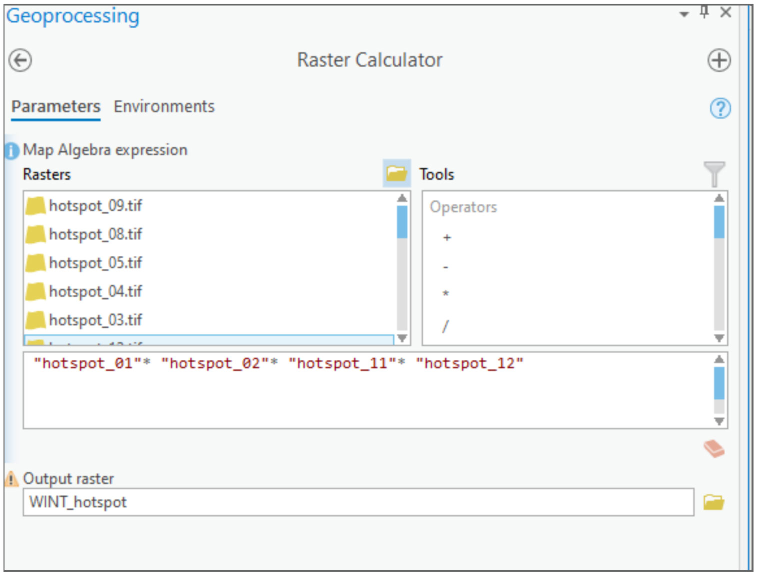
Appendix D. MaxEnt output of probabilistic squid fishing pressure by month



Appendix E. Model Statistics from MaxEnt outputs

Month	AUC	Presence points	Omitted or Retained
1	0.766	54	Retained
2	0.660	32	Retained
3	0.642	12	Omitted
4	0.547	18	Omitted
5	0.581	26	Omitted
6	0.753	63	Retained
7	0.712	53	Retained
8	0.744	21	Omitted
9	0.574	18	Omitted
10	0.729	78	Retained
11	0.828	105	Retained
12	0.795	100	Retained

Appendix F. Raster calculator tool- Seasonal Fishing Pressure

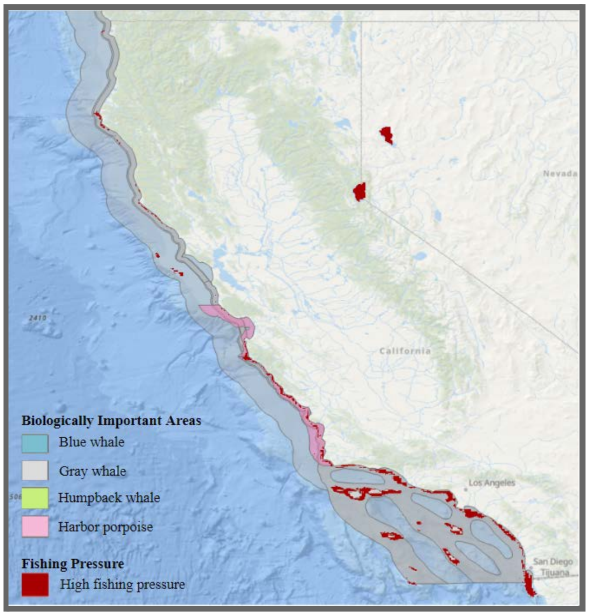


```
"hotspot_01"* "hotspot_02"* "hotspot_11"* "hotspot_12"
```

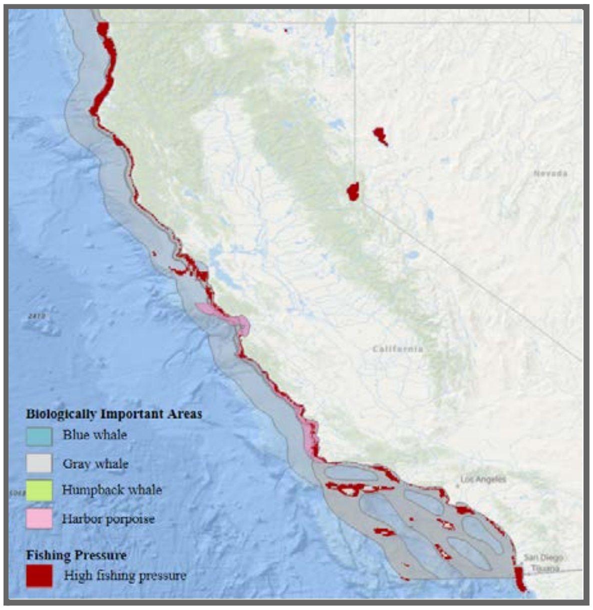
Output raster: WINT_hotspot

Appendix G. BIA overlap with binary reclassification of high fishing pressure

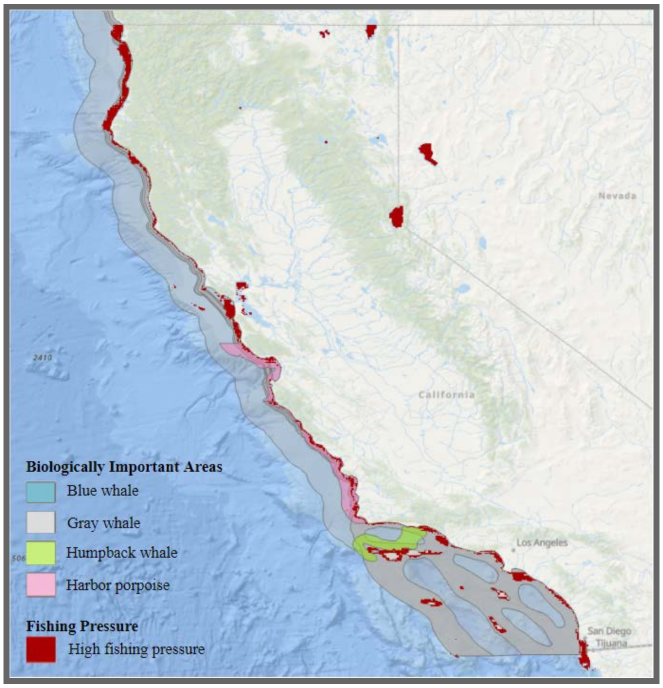
January



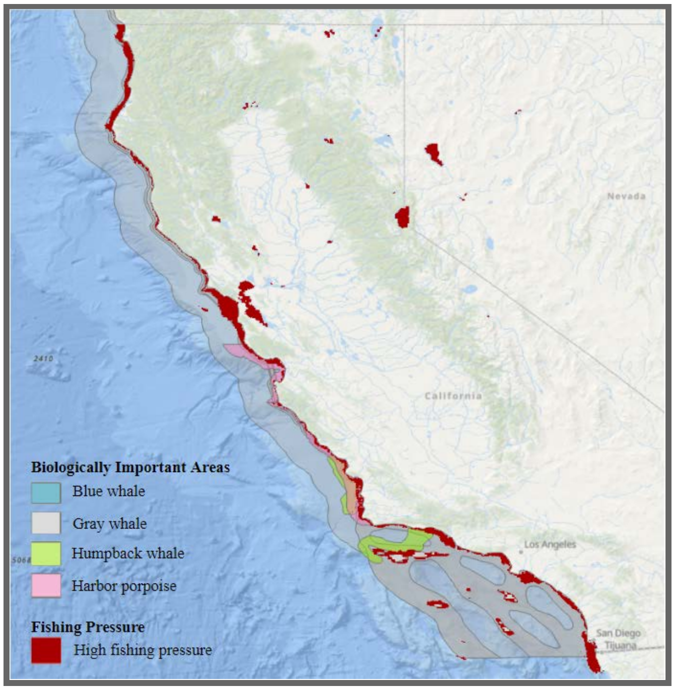
February



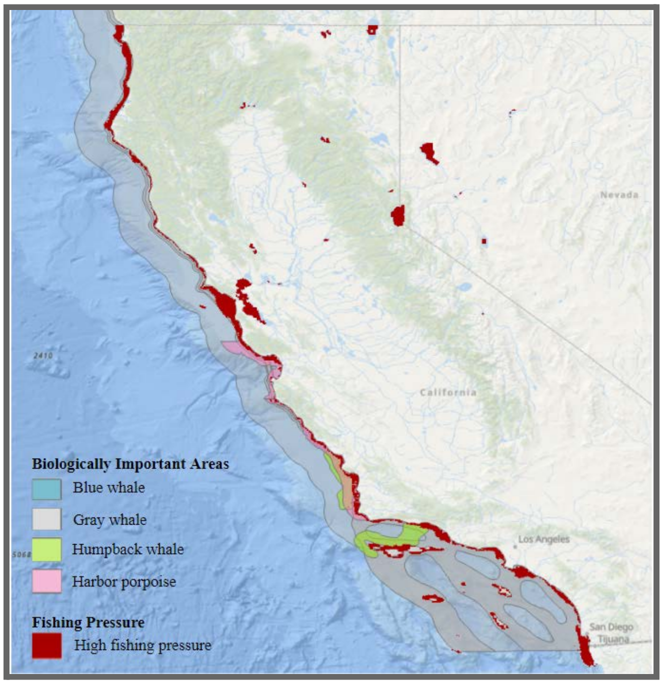
March



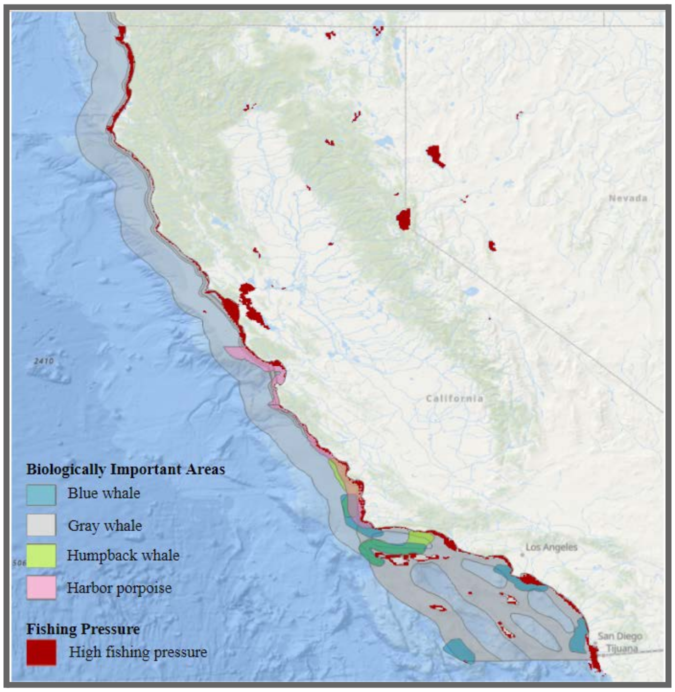
April



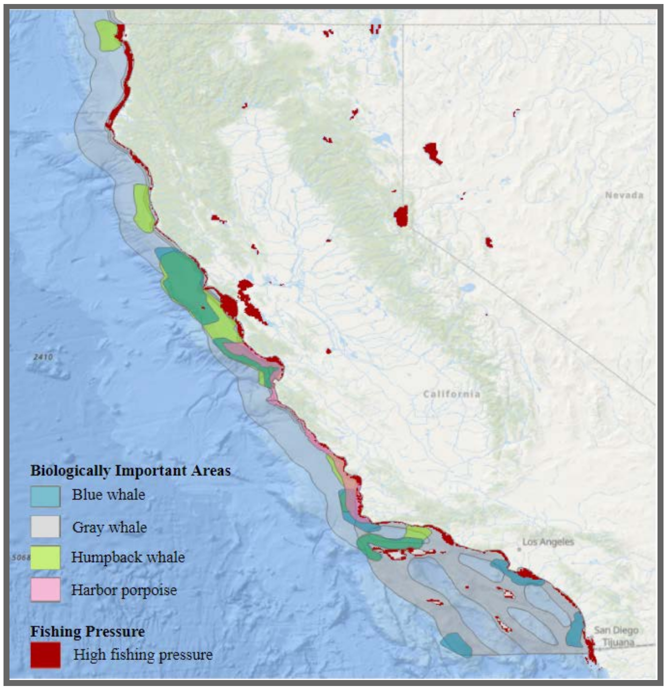
May



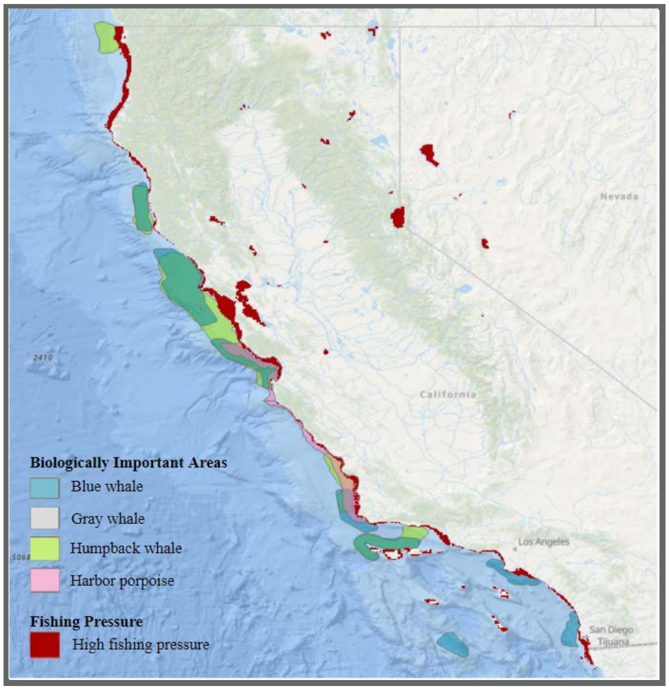
June



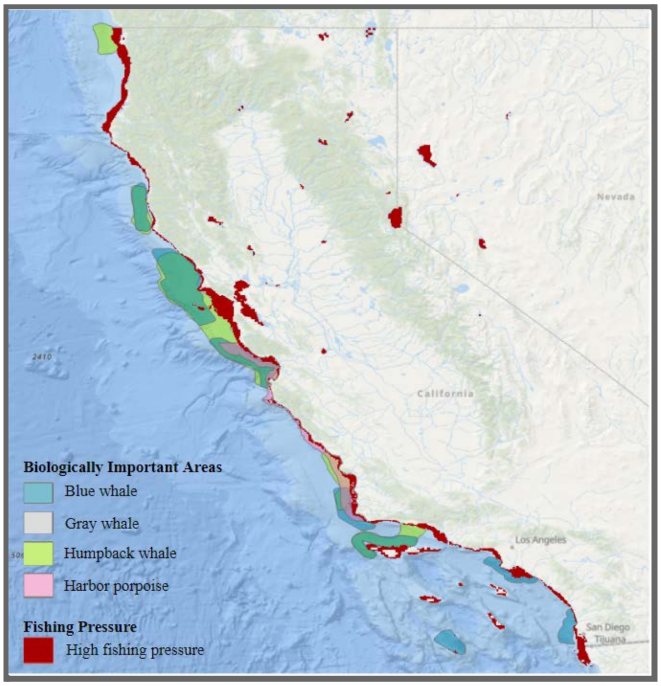
July



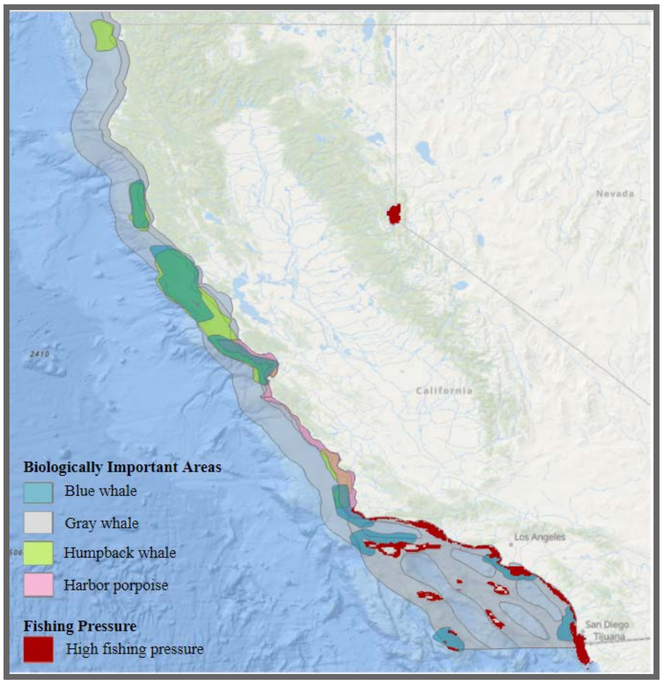
August



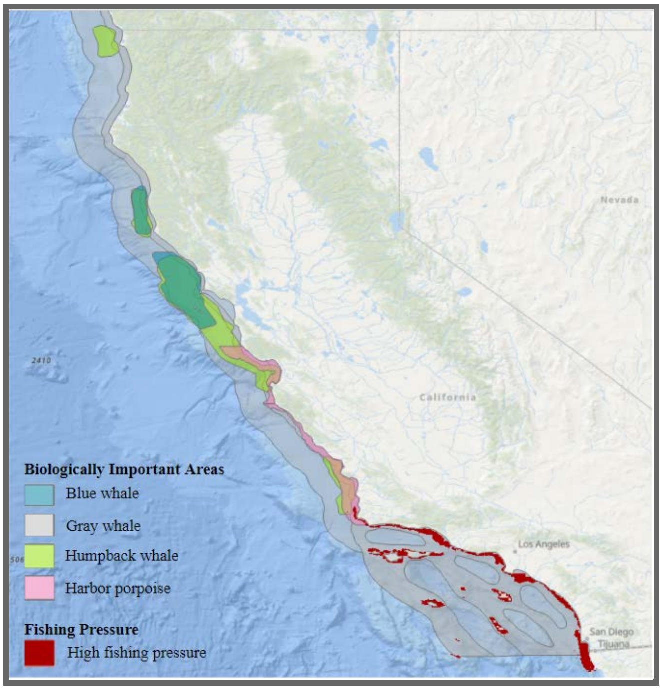
September



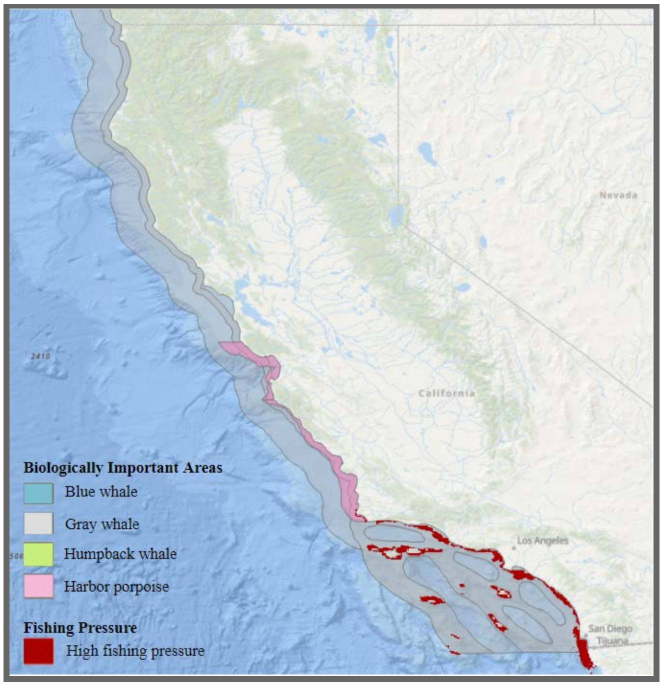
October



November



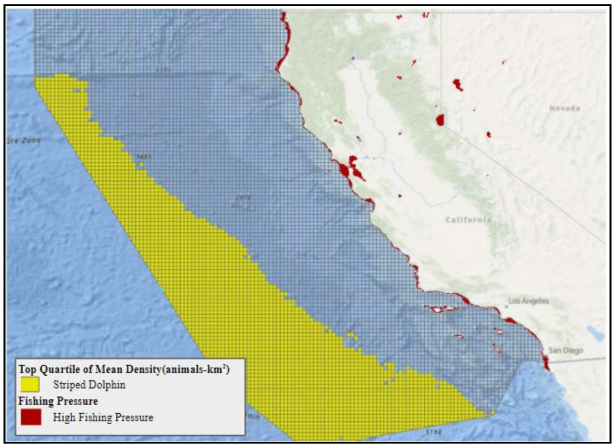
December



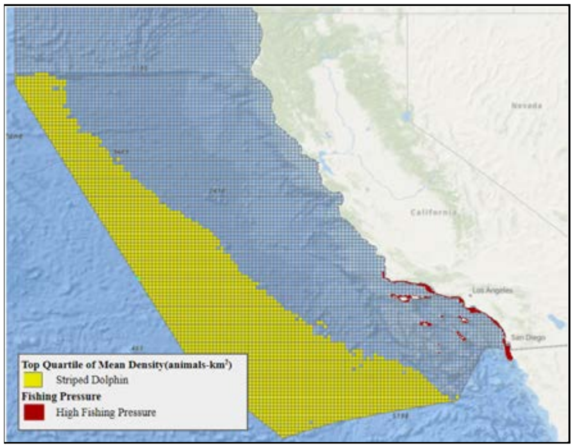
Appendix H. Becker population distribution models with binary reclassification of high fishing pressure

Striped dolphin

July



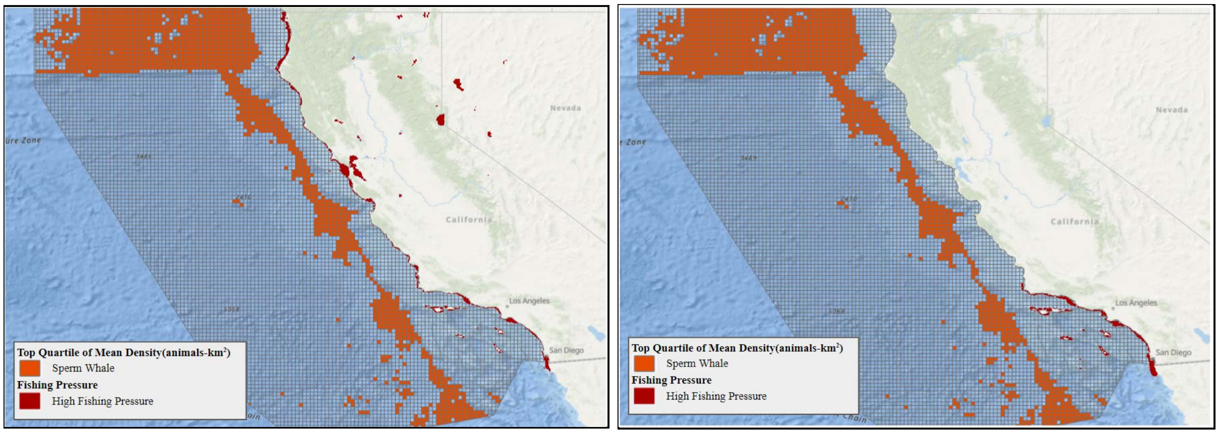
November



Sperm whale

July

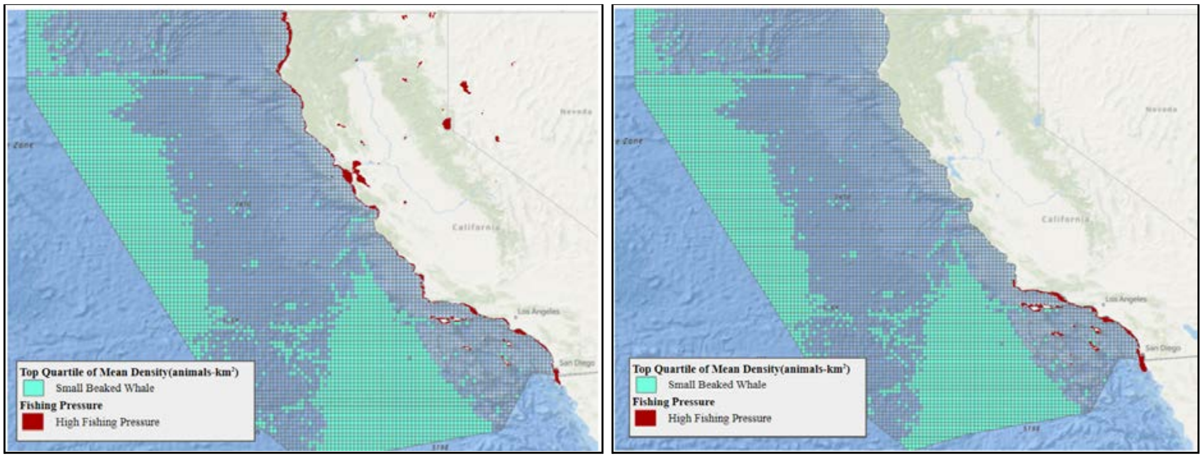
November



Small beaked whale

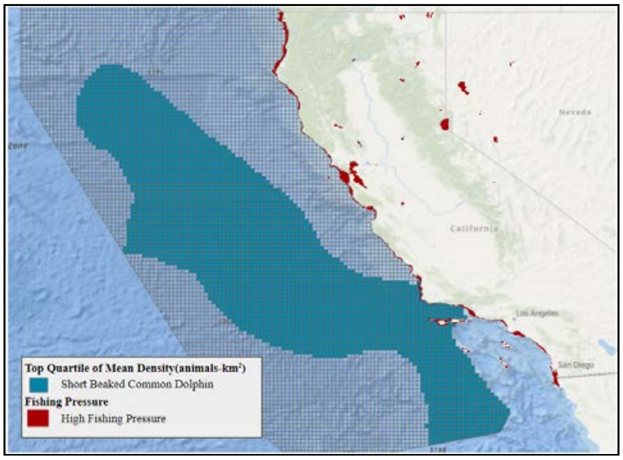
July

November

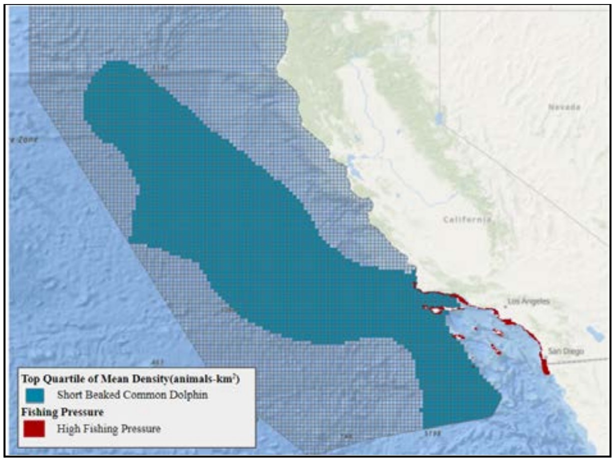


Short beaked common dolphin

July

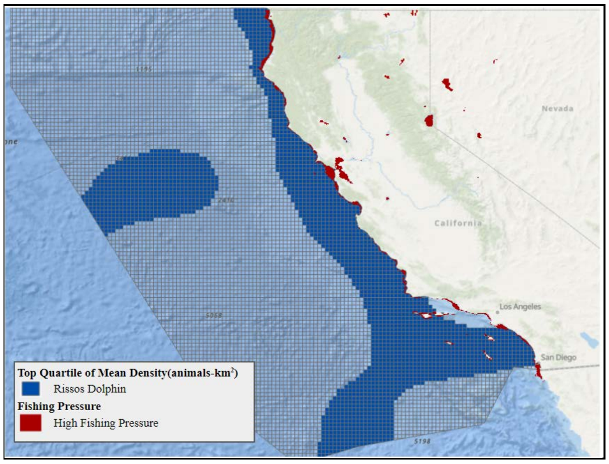


November

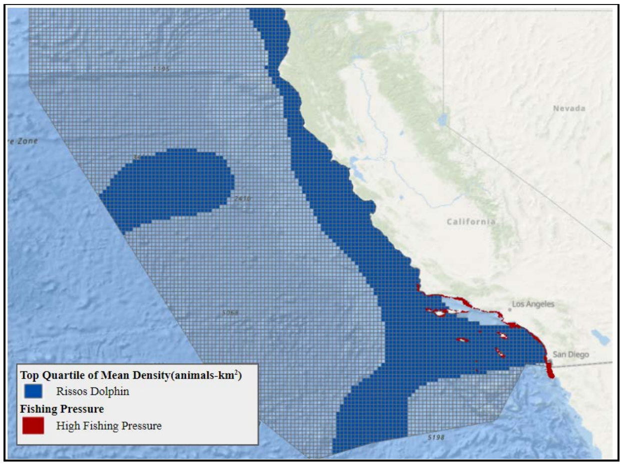


Risso's dolphin

July

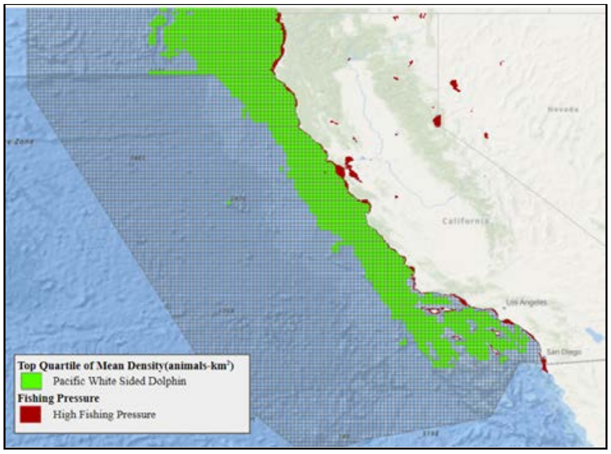


November

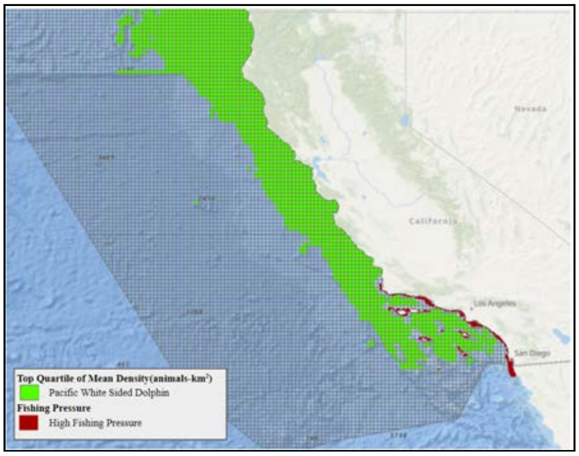


Pacific white sided dolphin

July

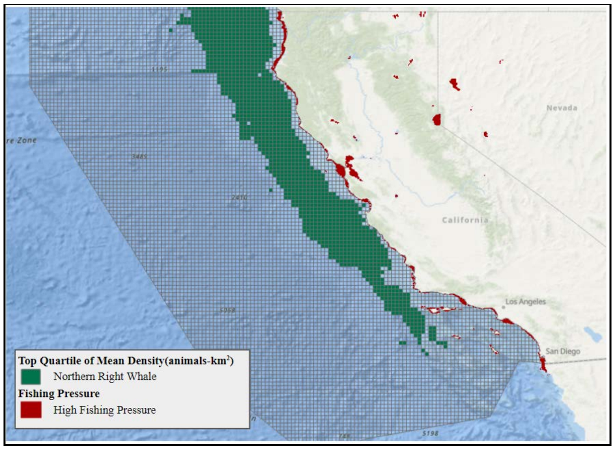


November

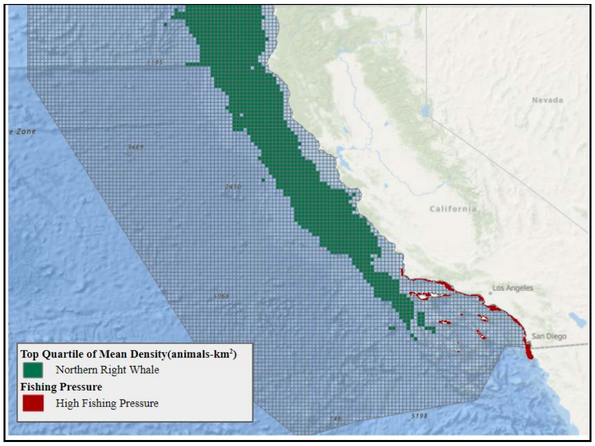


Northern right whale

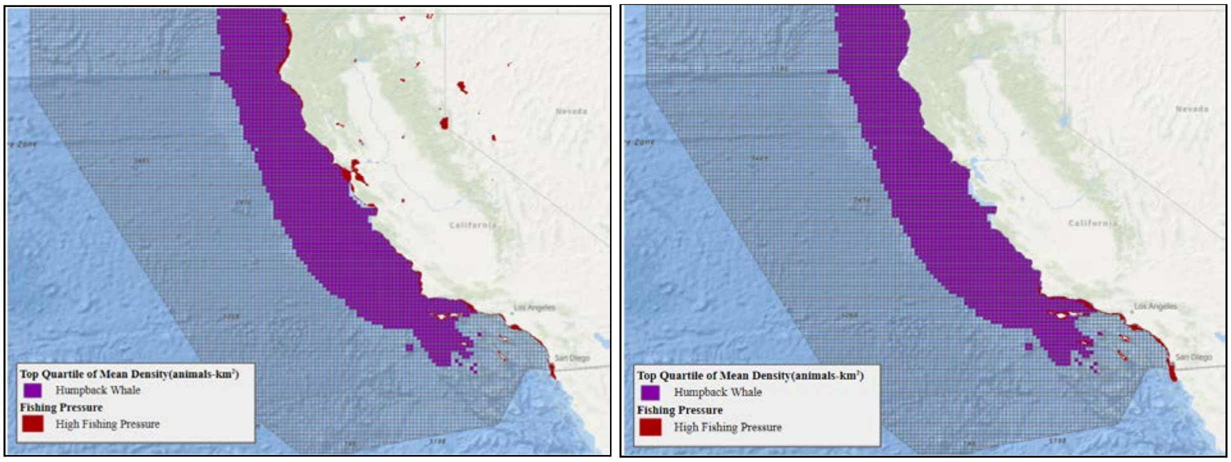
July



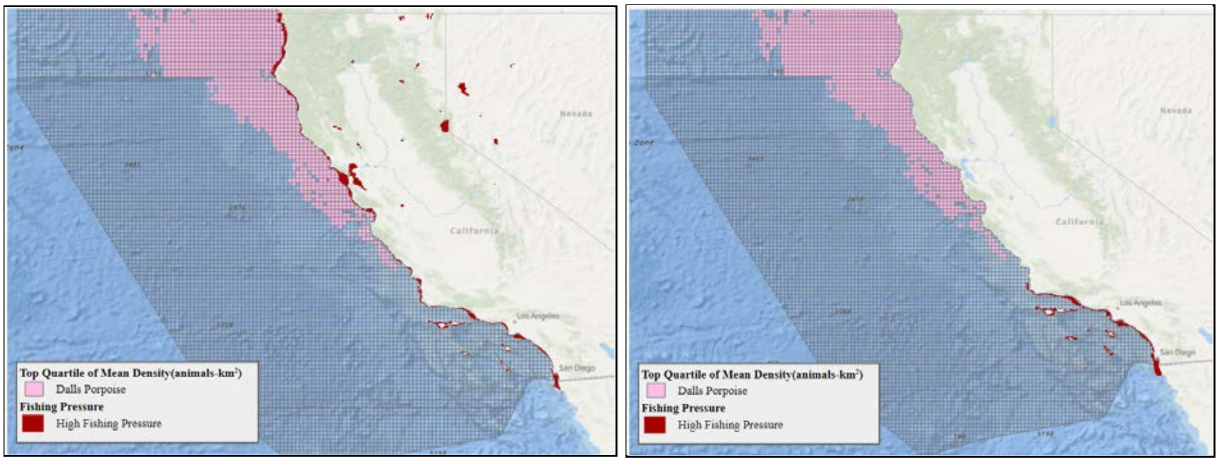
November



Humpback whale

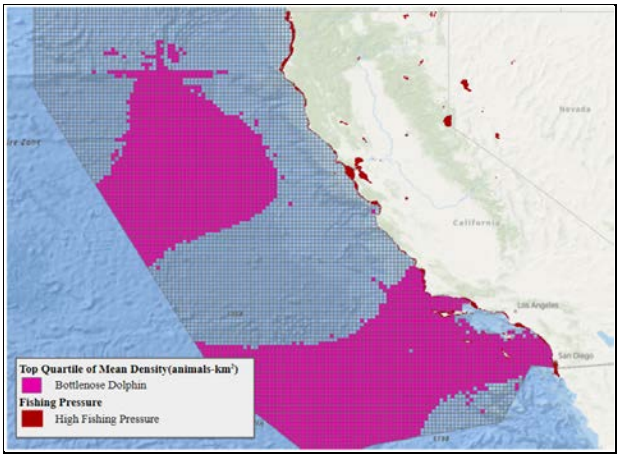


Dall's porpoise

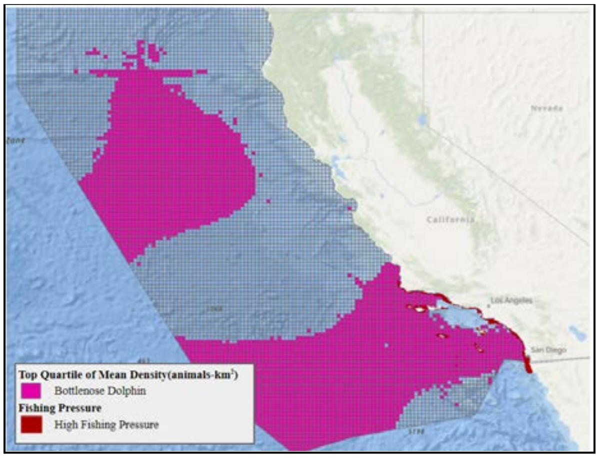


Bottlenose dolphin

July

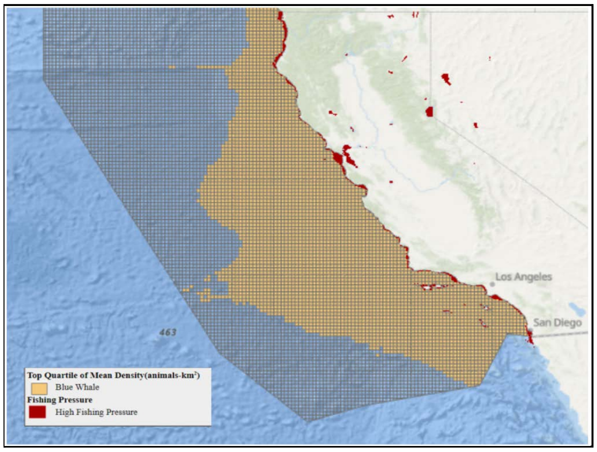


November

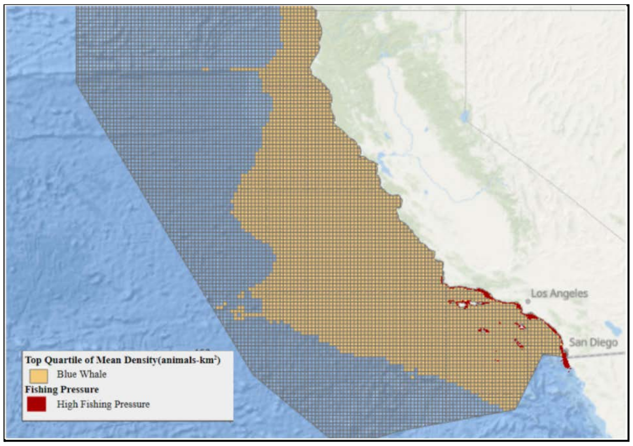


Blue whale

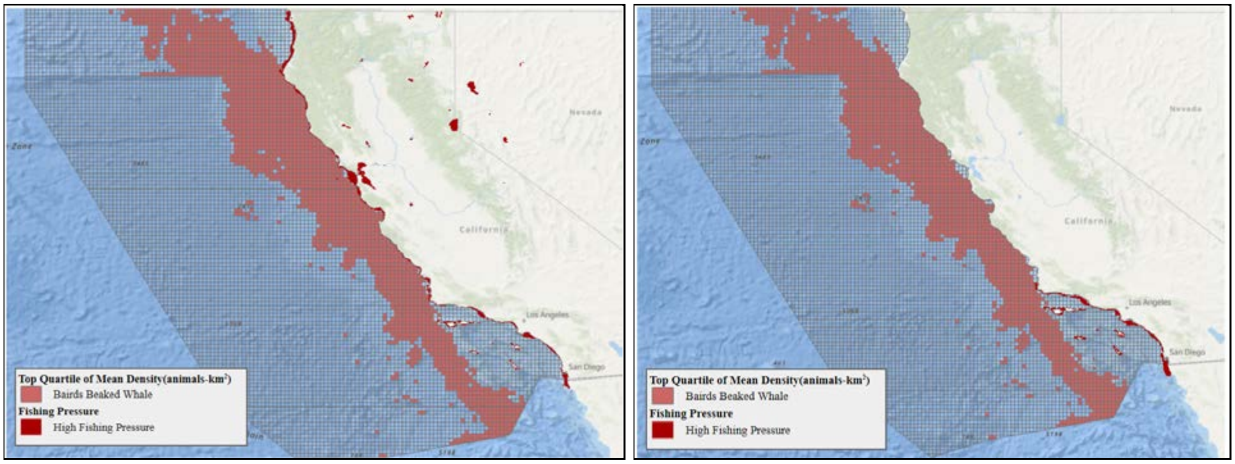
July



November

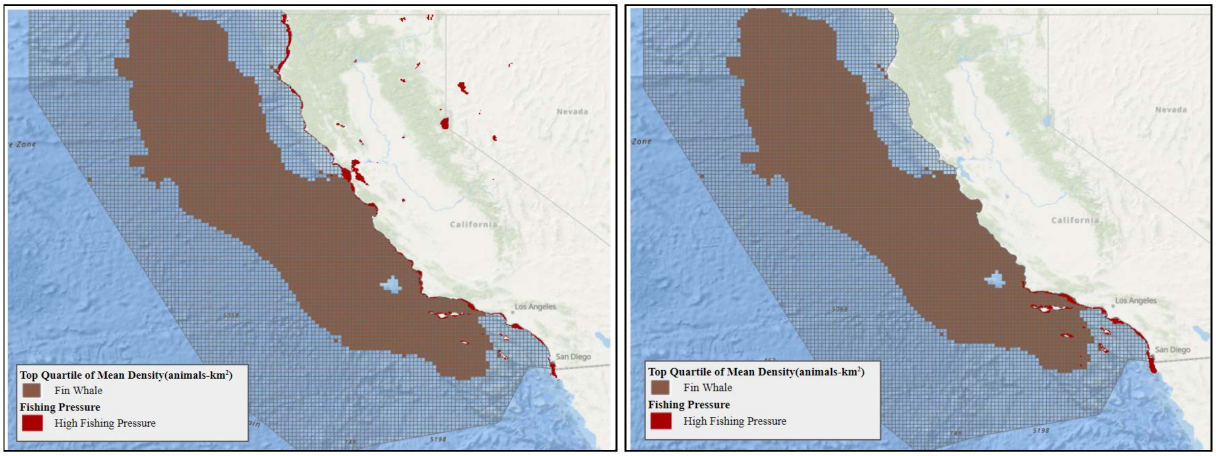


Baird's beaked whale


July

November

Fin whale

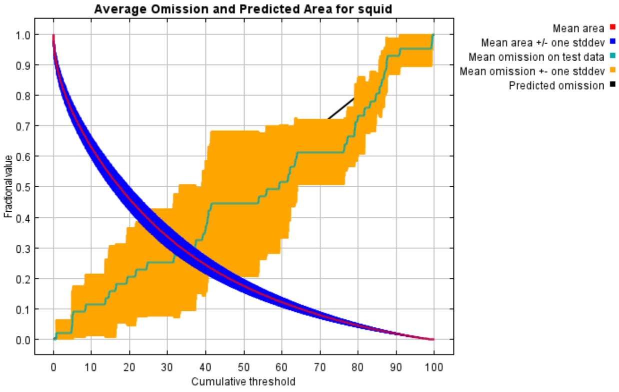

July

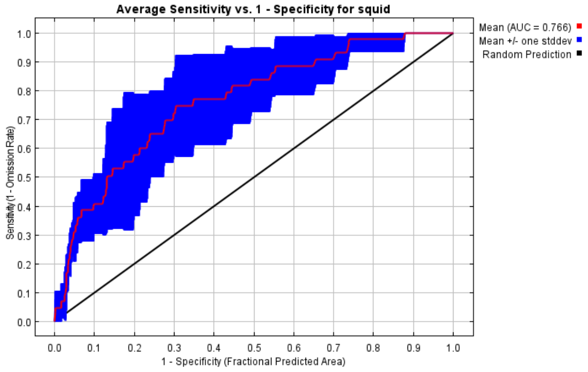
November

Appendix I. Maxent omission rate, areas under curve (AUC) and variable response curves

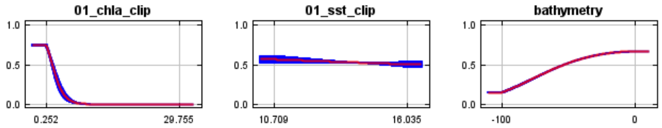
July and November results are in the body of the report. March, April, May, August, and September were omitted based on model performance and lack of data. They are not shown here.

January

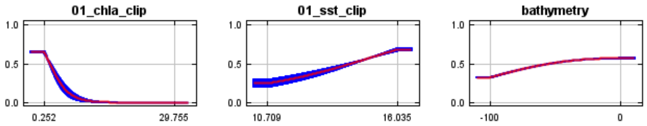




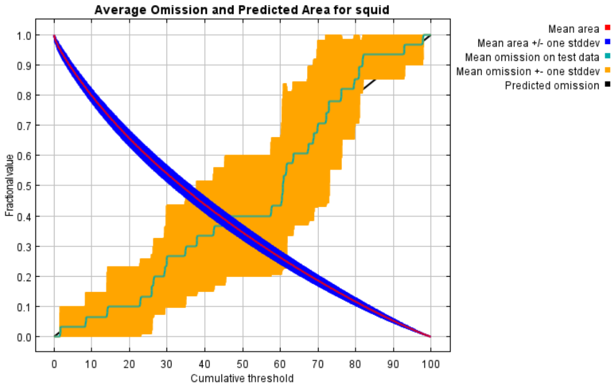
Marginal Response Curves:

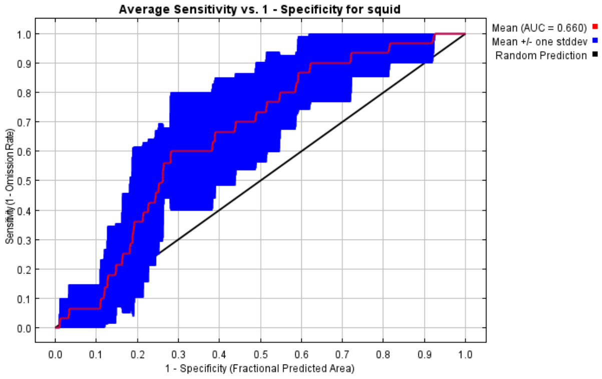


One Variable Model Response Curves:

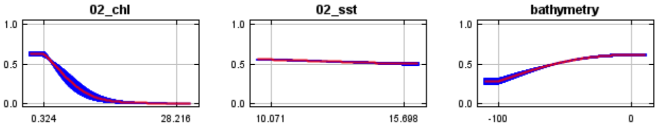


February

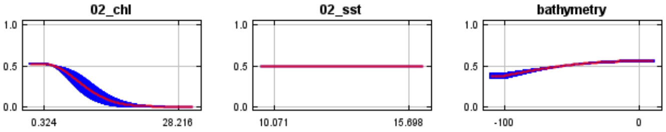




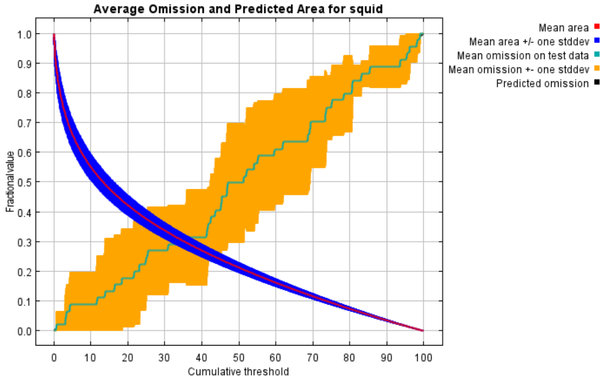
Marginal Response Curves:

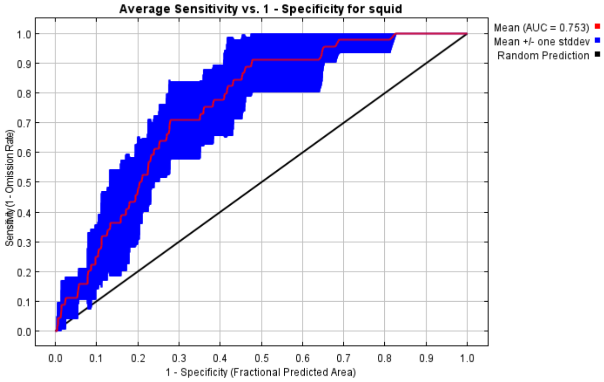


One Variable Model Response Curves:

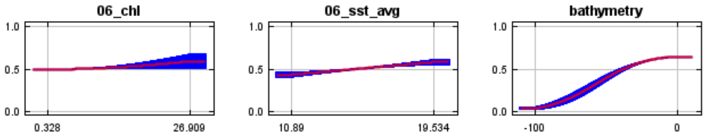


June

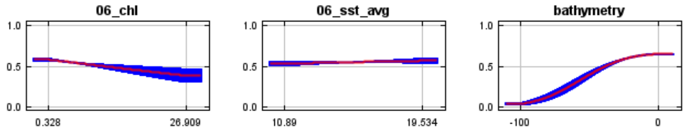




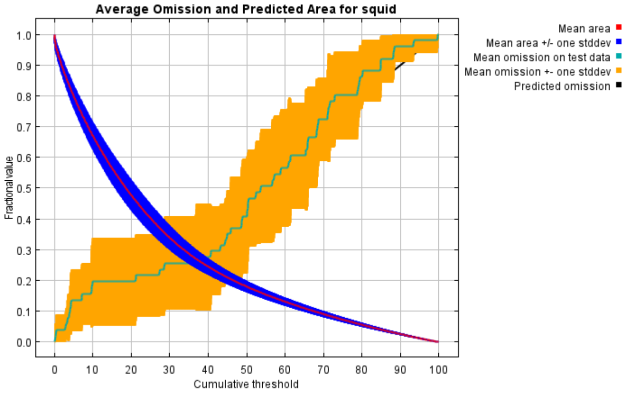
Marginal Response Curves:

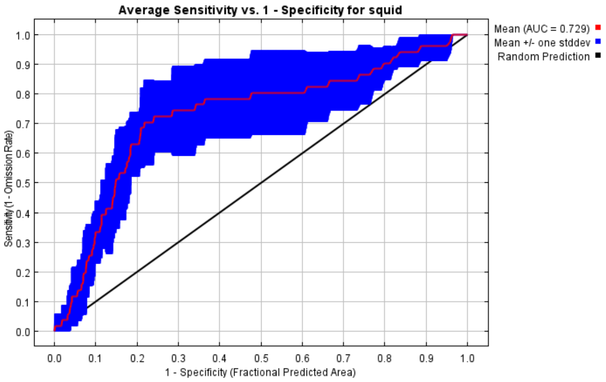


One Variable Model Response Curves:

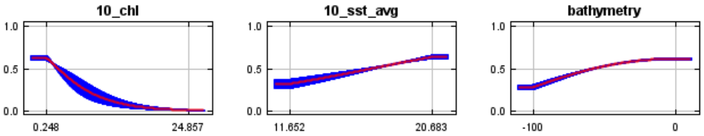


October

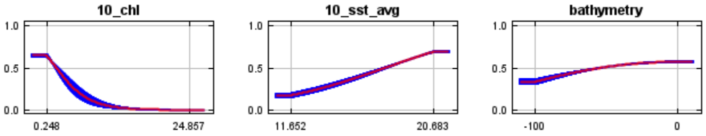




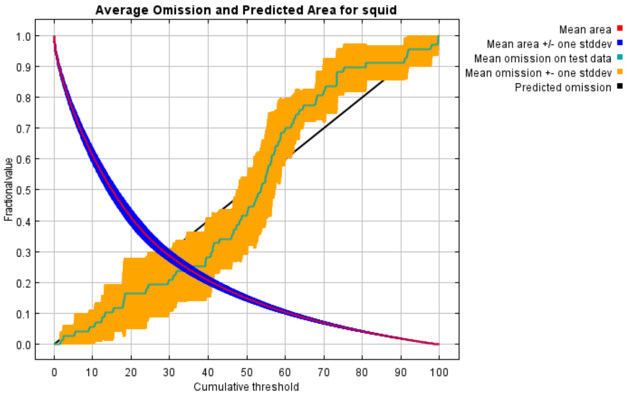
Marginal Response Curves:

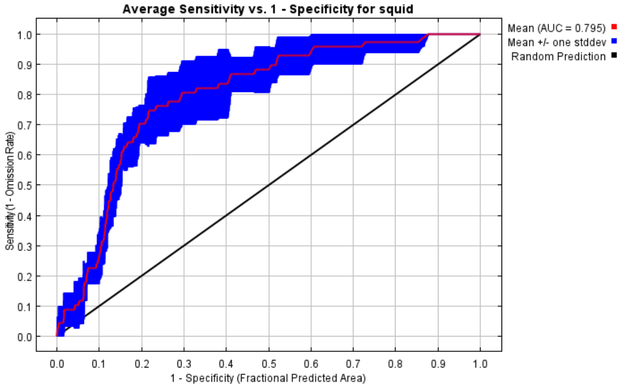


One Variable Model Response Curves:

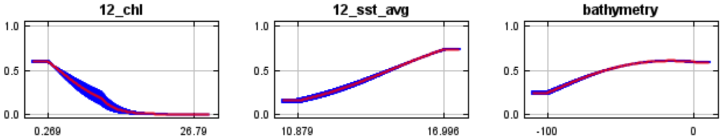


December

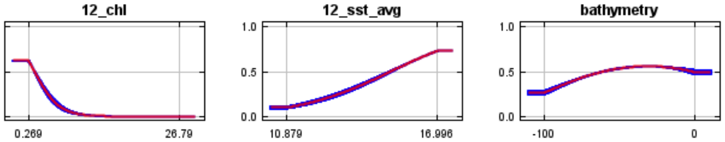




Marginal Response Curves:



One Variable Model Response Curves:



Appendix J. Link to GitHub Repository

All code for processing and analyzing the data outside of MaxEnt and ArcGIS maps can be found in the repository below.

https://github.com/BrennieDev/sealbombsquad