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Predictive model identifying locations of fishing gear loss or accumulation in Pacific Mexico

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Introduction

The negative impacts of abandoned, lost, and discarded fishing gear (ALDFG) are a growing concern in Mexico. Whether intentionally discarded or accidentally lost, ALDFG is one of the deadliest forms of marine litter. It catches and wastes target and non-target marine species through a process known as ghost fishing where animals continue to be caught in the gear after. It also damages marine and nearshore habitats, poses navigation risks, and is expensive and hazardous for fishermen and marine communities to deal with (Macfadyen et al., 2009; National Oceanic and Atmospheric Administration Marine Debris Program, 2016; NOAA, 2015). Of the fishing gears used in the Mexico, nets, traps and fish aggregation devices (FADs) are identified as the most harmful types of ALDFG due to their risk of loss and the negative impacts they cause after loss (Gilman et al., 2021; Huntington, 2016).

Solving this problem on a global scale has gained momentum with the efforts of the Food and Agriculture Organization (FAO), the United Nations Environmental Program (UNEP), and the International Maritime Organization (IMO); the creation of the Global Ghost Gear Initiative (GGGI); and the establishment of the Joint Group of Experts on the Scientific Aspects of Marine Environmental Pollution (GESAMP) Working Group 43. FAO recently published the *Voluntary Guidelines for the Marking of Fishing Gear* (VGMFG) to help prevent negative impacts from ALDFG in the world's fisheries (FAO, 2018). GGGI is a multi-stakeholder alliance of over 100 organizations, business and governments that brings seafood stakeholders together to address ALDFG at all points along the seafood supply chain. GGGI recently updated its *Best Practices Framework for the Management of Fishing Gear* in wild capture fisheries (BPF). This document provides management strategies to prevent harm from ALDFG directed at 12 different seafood supply stakeholders, including fisheries managers (GGGI, 2021). The GESAMP Working Group 43 was established to develop a report of sea-based sources of marine litter identifying extent, causes, impacts, and recommended solutions to the global problem of marine litter from sea-based sources, including ALDFG. Its final report was published in late 2021 (GESAMP, 2021).

Mexico became a formal member of the GGGI and a charter member of the High Level Panel for the Sustainable Ocean Economy (HLPSOE) in 2020 and, as such, is addressing the problem of ALDFG within the contexts of ocean plastics and fisheries management. As a member of the HLPSOE, Mexico made a commitment to ensure fisheries sustainability, including eliminating ALDFG (High Level Panel for a Sustainable Ocean Economy, 2020). Mexico is working with the GGGI to develop a national ALDFG action plan and collaborating on efforts to expand fishing gear collection and recycling.

This project aims to provide an initial baseline of information about probable locations of loss of fishing gear and locations where lost fishing gear is accumulating and potentially negatively affecting species and habitats in the Pacific region of Mexico, including the Gulf of California. The systematic identification of likely places to document ALDFG will assist in evaluating the scope of the problem and potential preventive action in Mexico, including planning for ground-truthing surveys and recommended specialized education programs for fishing industry stakeholders (UNEP CAR/RCU, 2014). Predictive models may also improve efficiency of future ALDFG removal activities (Martens and Huntington, 2012).

Development of this ALDFG predictive model is one component of a larger project led by GGGI that also includes predictive model development of eastern Mexico fisheries, fisher surveys, ALDFG retrieval, end of life fishing gear collection and recycling, and policy development.

Fisheries in Pacific Mexico

The Mexican Departmento de Pesca (Fisheries Department) manages Mexico's fisheries according to the General Law on Sustainable Fisheries and Aquaculture, which regulates food safety and imports and exports of fish and fishery products. Mexico is a member of several regional fishery bodies, including the Commission for Inland Fisheries and Aquaculture of Latin America and the Caribbean (COPESCAALC), the Inter-American Tropical Tuna Commission (IATTC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), the International Whaling Commission (IWC), the Latin American Organization for Fisheries development (OLDEPESCA), and the Western Central Atlantic Fishery Commission (WECAFC) (FAO, 2003). Mexico supports fishing off of the Pacific Coast, Gulf of Mexico, and the Caribbean Sea. The coastline reaches 11,500 km with almost 3 million km^2 within the Economic Exclusion Zone (EEZ).

The Mexican Secretariat of Fisheries report on the National Fisheries Inventory, last published in 2012, reports that Mexico has 43 fisheries in total: 27 on the Pacific coast and 16 in the Gulf of Mexico and the Caribbean Sea, targeting approximately 616 species. There are eleven Mexican states on the Pacific side, with 37 Fishery management units (FMU), and six states with 28 FMUs on the Gulf of Mexico and Caribbean side (Díaz-de-León et al., 2004). Mexico has the third-largest catch volumes of Latin America, with approximately 1,628,700 tonnes in 2017, targeting primarily sardines, tuna, squid, and shrimp in marine waters.

In 2011, 97% of the marine fleet in Mexico targeted small-scale fisheries, with 70% of those fisheries being on the continental shelf (Fernández-Méndez et al., 2011). The marine commercial fishing sector concentrates in the Gulf of California. Total national catch is dominated by landing in the Pacific which account for 77% of the total. Landings from the Gulf of Mexico account for 21% of the national total, and just 2% are landed in the Caribbean. (Fernández-Méndez *et al.*, 2011). Of the industrial vessels, 70% of shrimp trawlers, 79% of tuna vessels, and all the sardine and anchovy vessels fish in the Pacific. Of the artisanal fleet, 54% fish in the Pacific, with 27% concentrating their efforts in the Gulf of California. In 2018, the total number of registered (powered) commercial fishing vessels in Mexico was 77,483 (Table 1); a 27% decrease from the 106,100 ten years prior (in 2009) (OECD 2021). Small scale vessels, <12 m in length, account for over 97% of the fleet, most of which are made of fiberglass and powered by outboard engines called "pangas." There were 74,599 registered small scale fishing vessels as of 2018. The industrial sector comprises around 1,800 deep-sea vessels (mostly shrimp trawlers) 56 tuna seiners and longliners, 10 sardine seiners, 42 vessels targeting sharks, and 52 river boats. Of the shrimp trawl vessels, approximately 55% are based in the Gulf of Mexico, while the remaining 45% are based on the Pacific Coast[1]. This report covers the Pacific Ocean and Gulf of California fisheries specifically.

[1] Estimates based on data compiled from multiple resources: OECD 2021; FAO 2019; https://geo-mexico.com/?p=6594

Table 1. Breakdown of Mexico's commercial fishing fleet by overall vessel length (LOA) categories; shown in number of vessels and total gross tonnage (GT). Source OECD 2021 stats

Overall Length (LOA)	#Vessels	Gross Tons (GT)
0 - 5.9m	19,501	20,375
6 - 11.9m	55,998	105,957
12 - 17.9m	459	11,713
18 - 23.9m	1,278	70,647
24 - 29.9m	166	10,449
30 - 35.9m	28	2,169
36 - 44.9m	4	549
45 - 59.9m	12	4,412
60 - 74.9m	30	16,390
75m+	7	2,714
Total	**77,483**	**245,375**

Shrimp trawling vessels dominate the industrial fleet, and around 86% of the registered shrimp vessels are over 40 gross register tonnage (GRT). Tuna vessels tend to be larger, with 75% of the fleet being larger than 100 GRT and some up to 750 GRT. 47% of the sardine fleet vessels are between 40-80 GRT, with 24 vessels categorized as over 100 GRT (FAO, 2003). The information below is from the 2012 Mexican Secretariat of Fisheries report on the National Fisheries Inventory (Ministry of Agriculture, Livestock, Rural Development, Fishing, 2012).

The Pacific shrimp fishery has approximately 906 participating fishers, with five target species and five incidental species. Regulations on the industrial shrimp trawling fleet consider fishing effort, the number of vessels, and specific trawl gear, with zones that establish areas restricted from trawling from 0-9 m (0-5 fathoms) of depth. All trawl gear is required to have turtle excluding devices. Vessels are typically larger than 10 GRT and equip two trawl nets. Typically, six fishers operate industrial-sized vessels. Smaller shrimp vessels are 6-7m in length and are operated by two fishers. An outboard motor is used (55-150 hp) with a maximum of two hillock casts. The trawls used by small vessels are known as Magdalenas.

The crab industry is an alternative fishery when the shrimp fishery is closed. On the coast of the Pacific Ocean, 2,700 small vessels operate (as of 2012), and 79% fish in the Gulf of California. Two fishers typically operate small crab boats in panga-type boats with an outboard motor, or canoes. Crab are caught in Chesapeake style traps with maximum dimensions of 60 cm long x 60 cm wide x 40 cm high, made of metal mesh with an approximately 7 cm opening, with four conical inlets and a compartment for bait. Alternative gear includes crab rings with a mesh net equal to or greater than 76 mm and a diameter not greater than 70 cm, and punches, which are used exclusively in Nayarit with a size minimum of 76 mm mesh and 1 m long metal hooks. In the Gulf of California, management directives keep the catch per unit of average daily effort at 0.35 kg/gear/day (annual 84 kg/gear), and in Chiapas, the management recommendation states that the catch levels are maintained at around 400 t per year. The rest of the states take necessary measures if the annual catch per entity decreases below the historical average.

The lobster fleet has 23 permits to cooperatives and 9 private permit holders, with approximately 73 vessels. Lobster vessels consist of smaller embarkation (panga) around 5 to 9 meters long and use outboard motors (40-75 hp). Self-cast fishing gear, called trap lobster trays, are constructed from wood, galvanized wire, mesh, or plastic. Despite the lack of permits, the unregistered lobster fishing is considerable. According to estimates from fishing logs of INAPESCA studies, approximately 32 cooperatives fish lobster without permission. Around 197 unpermitted vessels operate with a catch per cooperative of 1.5 to 3 tonnes per season (Nov-June).

Black cod on the Mexican Pacific coast has been a smaller fishery compared to others in Mexico but has a significant demand on the international market. In 2010, there were two large commercial fishing vessels for black cod, and to date, there have been no further applications for commercial permits. These two vessels are larger than 10 GRT and employ up to 20 fishers. Fishing gear used for black cod includes trap and longline. There are typically 500-1000 traps on board, and each longline has between 15,000 to 20,000 hooks, usually baited with sardine. Fishing trips can be as short as 15 days and as long as 50 days. The fishery was at peak number of vessels in 1979, with 11 vessels operating, but was closed in 1981. The fleet gradually downsized to two vessels, and the annual average catch in the period 1985-2006 was 48.9 tonnes. There is still a small fishery, but the catches are much lower than in other countries in the region.

The skipjack fishery in Mexico spans 3 regions (9 including subregions) and comprises artisanal vessels with outboard motors, which operate off the Mexico coastline from 60 to 100m isobaths. The directed fishery uses hand lines and trolling to catch skipjack. Different regions focus on different subspecies of skipjack, and the catches have had significant fluctuations over the last 50 or so years, ranging from 1000 tonnes to 14,000 tonnes since the 1970s. The artisanal fleet fishes year-round near Puerto Escondido and Puerto Angel, Oaxaca, and surrounding areas. Skipjack are managed through permits for commercial-scale fishing.

There are multiple species of croakers, or drum fish, in Mexico, but fishing effort centers around *Curvina golfina*. Fishing effort for curvina occurs primarily in the upper Gulf of California using 14.6 cm of light mesh hand-thrown gill nets in a maximum of 160 fathoms in length. This fishery tends to be pretty close to shore, near the Colorado River delta. The fishery takes place between February to April when the curvina are heading to the river to spawn and is closed from May 1 to August 31 every year with permits specifying access and quota. The fishery occurs for only three to five days a month, around the time of the full moon when the fish are spawning. The vessels are artisanal panga boats varying in size from five to seven meters in length—vessels fish with three crew members, with trips lasting eight to ten hours. Curvina is caught as bycatch by shrimp boats, gill nets, and hand lines in other fisheries.

Rockfish in Mexico are harvested from small boats with outboard motors, operating from the shoreline to fishing areas between the 60-meter and 100-meter isobaths. Different species are targeted regionally, with different gear types used, including hooks and lines, gillnets, trawl nets, and traps. Species that reach sizes over 50 cm are part of sport fishing. In Baja California, fishing accounts for 98% of fishery production, and the smaller fleet captures more than 90% of the fish for production. Management is conducted through permits for commercial fishing.

Minor pelagics, consisting of sardine, anchovy, mackerel, and charrito, are some of Mexico's most economically valuable fisheries. Only one active vessel is larger than 10 GRT and is equipped with a purse seine and operated by up to ten fishers. The rest of the fleet has changed over time. The most common vessels (40.3% of the fleet) are 25-28 meters in length with 140-180 tonnes of hold capacity, followed by vessels 23-25 meters with 101-140 tonnes of capacity (37.5%). 9.7% of the fleet comprises vessels under 100 tonnes of capacity, and 12.5% have a capacity over 180 tonnes. Minor pelagic landings in Mexico represent approximately 30% of the national catch and almost 10% of the country's economic value. Minor pelagics are highly variable resources driven by environmental conditions brought on by El Niño and La Nina events. Management measures include minimum size limits on fish and income is limited with permits based on vessel capacity and net size. The maximum purse seines size is determined by vessel GRT category; less than 80 GRT means a maximum purse seine size of 366 meters; between 81-120 GRT, 549 meters; between 121-150 GR, 585 meters; between 151-200 GRT, 604 meters, and more than 200 tons, 640 meters. Performance is optimized when catches are on the order of 700,000 t, and it is estimated that the total industrial processing capacity in the northwest is oversized by about 40%.

Swordfish are harvested commercially and recreationally in Mexico, where the commercial fleet uses longlines and gillnets, and sport fishing uses rods and reels. The commercial fishery operates approximately 50 miles off the Western Baja California Peninsula, with recreation fishing on the Baja states' west coast, Southern California, and Sinaloa. Swordfish is unique in Mexico as it is the only species where commercial fishing permits include resource reservations for sport fishing. As of 2012, there were 40 active longlining and gillnetting vessels total, with 39 larger vessels holding commercial fishing permits. There are 33 longlining vessels and 1 gillnetter for a total of 34 large active vessels. These vessels tend to operate off the western coast of the Baja Peninsula, California, and catch swordfish, sharks, and other demersal resources.

There are two types of commercial tuna targeted by Mexico, yellowfin and bluefin tuna, though other associated species, such as bigeye and albacore tuna, are occasionally caught. Mexico fishes for tuna both inside and outside of the Mexican EEZ. Tuna fishing is conducted primarily with purse seines, typically with 150-1540 metric tons hold capacity. Some of these purse seines can be as large as 1,850 meters in length, and 18 meters in depth for yellowfin and 23 for bluefin. Smaller vessels, strand boats, have a smaller capacity, holding 100-110 tonnes—these vessels fish primarily with rods, using anchovy and sardine as bait. As of 2012, there are 69 larger vessels active with purse seine fishing gear, 13 using rods, and one using trolls. There is also a sport fishery for tuna on small charter vessels which use rods and reels. Tuna are managed with a global quota system. When the Maximum Sustainable Yield is achieved throughout the Eastern Pacific, fishing is restricted. Temporary exclusions are applied to the entire eastern Pacific to reduce yellowfin tuna and bigeye tuna fishing mortality. There is no specific Mexican management measure in place for bluefin tuna.

For several years, as part of the United Nations Plan of Action to Prevent, Deter, and Eliminate illegal, unregulated, and unreported (IUU) fishing, all Mexican flagged fishing vessels with inboard motors greater than 80 HP were required to install a vessel monitoring system (VMS), so activity can be tracked through a centralized system within CONAPESCA (ORBCOMM 2017). This was implemented on over 2,000 Mexican fishing vessels; approximately 1,100 in the Pacific, and 950 boats in the Gulf of Mexico. The small-scale fleets are not equipped with VMS.

Lost Fishing Gear in Pacific Mexico

There are limited published works related to ALDFG in the Pacific Mexican fisheries. Ghost fishing from abandoned traps was documented during research in the *Cancer johngarthi* fishery in 2008, resulting in a recommendation to address this potential impact to harvest during the fishery development (Ramírez-Rodríguez and Arreguín-Sánchez, 2008). Ghost fishing by ALD gillnets is documented well in other regions (GESAMP, 2021; Gilman et al., 2021) but not in Mexico. News reports of turtle deaths in Oaxaca in 2018 and 2021 point to possible ghost fishing mortality (BBC News, 2021, 2018).

While ALDFG can be linked to IUU fishing (Gilman, 2015; Macfadyen et al., 2009), nowhere in Mexico is this linkage more apparent than in the northern Gulf of California. Bycatch of the vaquita (*Phocoena sinus*), the world's smallest cetacean, in active shrimp and mackerel gillnets and lost or abandoned gillnets has been documented for decades in the Gulf of California (D'Agrosa et al., 2000). More recent challenges related to the illegal trade in totoaba swim bladders has added another level of threat from ALD gillnets (Taylor et al., 2017). Recent efforts by the Mexican government, fishers, and NGOs to remove abandoned and illegal totoaba gillnets from the area to protect both the vaquita and the endangered totoaba have yielded over 1,000 retrieved gillnets (PESCA ABC, 2018). However, the lure of high payoff for totoaba swim bladders on the black market continues to motivate illegal fishing with gillnets in the area.

In 2018, thirteen (13) fishers active in the Peñasco Biological Fisheries Corridor in northeastern Gulf of California were surveyed about ALDFG. They fished from Puerto Peñasco south to Puerto Lobos. All indicated that ALDFG was of concern, identifying lost traps, nets, and lines, noted lost in the area. More systematic surveys of fishers are planned as a component of this project, with results anticipated in 2022.

While the rate and extent of fishing gear loss in Pacific Mexico is not documented, two recent studies attempted a global estimate of rates of fishing gear loss. Richardson et al. (2019b) estimated that 5.7% of fishing nets, 8.6% of traps and pots, and 29% of fishing lines used globally are lost, abandoned, or discarded into the environment. Lively and Good, (2018) estimated that 3 to 7 net panels/boat/year or 38,535 tons of nets/region/year and 7%-50% of traps and pots/year were lost. Both these studies were based largely on northern hemisphere records. With the exception of the northern Gulf of California, where IUU fishing skews our understanding of rates of gear lost during normal fishing activity, it is reasonable to assume that the loss of fishing gear in Pacific Mexico fisheries occurs at rates comparable to other fisheries around the world.

Predictive Model Methodology

Documented and accessible point locations of ALDFG in Pacific waters of Mexico are sparse. Gear recovery efforts associated with vaquita conservation in the upper Gulf of California have produced several data points. However, specific point locations of recovered fishing gear in the vaquita area was not provided for this modeling project. Approximate locations of derelict gear recovery were derived from figures in CIRVA (2017 & 2019) to review against the predictive model results. The unique situation in that geographic area, where retrieval activites primarily addressed illegally set fishing gear and abandoned illegally set fishing gear, restricted our use of this data in our analysis. Only four other known ALDFG locations in the Mexican Pacific were available and accessed through the archived Global Ghost Gear Portal (GGGI 2018); they included three “nets” and one “line”, all of which appeared to be found on the coastline, rather than in the water. No other metadata were available for these gear items. Also, systematic fisher surveys related to lost fishing gear locations and reasons for loss in Mexico were not completed in time for this modeling, and therefore such data was not used to develop the predictive model for potential gear loss locations. For these reasons, the predictive model presented here is considered *preliminary*, and project partners intend to refine this model when further data associated with fishing gear loss becomes available.

Therefore, to develop a predictive model for ALDFG from the marine fisheries in the Pacific waters of Mexico, we relied on variables representing the primary reasons for gear loss that are well accepted in the global ALDFG community. Those include inclement weather, strong ocean currents, conflicts with vessel traffic, snags on seafloor obstructions, bathymetric variance and depth profiles, and fishing intensity (Macfadyen et al. 2009; Richardson et al. 2018; Gilman et al. 2021). Environmental and fisheries data were used to represent these variables associated with gear loss. Due to the predominance in size of the small-scale fleet in Mexico, and the multi-gear nature of the fisheries, this model focuses on the three primary gear types used within the small-scale sector: gillnets, pots/traps, and longlines. These are also often considered to be the most common and harmful types of ALDFG (Huntington 2016). Purse seines and trawl gear, primarily from the industrial fisheries, and hook-and-lines (non-longline) were not specifically included in this preliminary model; however, most of the environmental variables included in the model represent reasons for fishing gear loss of any type, and therefore should have some value in predicting where loss of these gears are likely to occur. Of note, fish aggregating devices (FADs), commonly associated with pelagic fisheries such as tuna purse seine, and a known concern in the suite of ALDFG types, are not used in Mexican Pacific fisheries.

Spatial analysis using ESRI ArcGIS 10.5 with the Spatial Analyst Tools extension was conducted to design a linear additive model to predict varying levels of likelihood of ALDFG occurrence in Pacific marine waters of Mexico. Analysis began with individual analysis of series of base layers, each used to represent a specific reason for gear loss (Table 2); for consistency and processing requirements across layers, datasets were set to the World Geodetic System (WGS) 1984 geographic coordinate system. Following data review and pre-modeling processing, the modeling analysis for each individual layer included clipping the layer extent to include only the Pacific marine waters of Mexico’s EEZ, then ranking values between 0 and 5 to represent low to high probability of gear loss to occur at that location based on values estimated to influence gear loss.

Table 2. List and description of spatial datasets used to represent primary causes for fishing gear loss, used to develop a predictive model for ALDFG in Pacific waters of Mexico.

Cause of Gear Loss	**Representative Dataset**	**Description & Source**
Delineation of Study Area	Mexico National Waters	Shapefile map of Exclusive Economic Zone (EEZ), including detailed coastline (FMI 2019)
Fishing Effort/ Intensity	Fishing Effort	Fisheries landings (tonnes/km^2) per species per gear type per 0.5° grid cell in the Mexico EEZ extracted from Global Landings Data 4.0 (Watson 2020).

Bathymetric profile	Bathymetry	Raster data for water depth (m) at 15 arc-second grids for Mexico EEZ, obtained from GEBCO (2021)
Inclement Weather	Wind Speeds	Mean annual values (m/s) per 250 m grid cells within Mexico EEZ (Global Wind Atlas 2021)
Ocean Currents	Ocean Current Speeds	Monthly mean northward and eastward current speeds (m/s) per 0.25° grid cell in the Mexico EEZ extracted from the Copernicus-Globcurrent model, obtained from EU Copernicus Marine Service Information (CMEMS 2021)
Conflict with Vessel Traffic	Vessel Traffic Density	Observed ship movement from 2015 – 2020 within 500 m grid cells inside Mexico EEZ. Obtained from World Bank Catalog Data (Cerdeiro et al. 2020)
Snags on Seafloor Obstructions	Reef Locations	Point data at locations of rocky and coral reef structures inside Mexico EEZ, obtained from UNEP Global Distribution of Coral Reefs (UNEP 2021; Santander-Monsalvo et al. 2018).
Snags on Seafloor Obstructions	Reef Areas	Amount of area (hectares) of rocky and coral reef distribution within 22 km grids in the Gulf of California (Aburto-Oropeza et al. 2017).
Bathymetric Variance	SD_{slope}	Processed GEBCO bathymetry raster to depict standard deviation of slope within 3-cell neighborhood (GEBCO 2021; this study)

To spatially represent fishing effort and intensity by gear type, multiple datasets were reviewed in absence of official fishing effort distribution statistical data from Mexican authorities. It is expected that pending delivery of specific data requests will assist to further refine the model presented here. In the meantime, the most comprehensive dataset available was extracted from the Global Landings Data 4.0 to cover annual landings by gear type within 0.5° cells throughout the Mexican Pacific EEZ. These data include estimates of industrial, small-scale, and illegal capture. Data were summed per cell over the six-year period 2010 – 2015 that the dataset covers and reviewed by primary gear type. For the purpose of this study, we combined gillnet, traps/pots, and longline data for final analysis. Fishing effort (tonnes /km^2) was binned by quantile in five categories (1 – 5), representing high (5) to low (1) probability of gear loss simply based on the intensity of effort occurring within each cell (Table 3; Figure 1).

Table 3. Probability ranking for fishing effort/intensity as a cause of gear loss based on harvest from gillnets, traps/pots, and longlines per km^2.

Fishing Effort	Rank	5	4	3	2	1
	Value Bins (tonnes/km^2)	3.49 – 1.97	1.97 – 1.53	1.53 – 1.14	1.14 – 0.21	0.21 – 0.001

Because the spatial representation of fishing effort available was relatively coarse (0.5° cells), bathymetry data were also used to distinguish areas where fishing effort most likely occurs. Studies suggest that the majority of small-scale fisheries in western Mexico occur within 0 – 15 m water depths, yet that trap fisheries commonly occur out to 30 m, and in some cases possibly deeper (Lopez-Martinez et al. 2014; Turk-Boyer et al. 2014). Gillnets are primarily used in the subtidal waters out to 30 m depths, while longlines and some deep nets usually fish in waters out to 150 m deep, and even some longline fishing for certain species targets areas up to 300 m deep (Turk-Boyer et al. 2014). Using these and other anecdotal information, with a focus on gillnets, longlines, and traps, the bathymetric depth variable was binned into five categories, with 5 being the highest probability for lost gear presence, and 1 being the lowest (Table 4; Figure 1).

Table 4. Probability ranking for bathymetry as a cause of gear loss based on fishing intensity within depth bands.

Bathymetry	Rank	5	4	3	2	1
	Value Bins (m)	0 - 30	30 - 100	100 - 150	150 - 350	350 - 7,163

The Global Wind Atlas dataset provided mean annual wind speed (m/s); wind direction was not analyzed. Assuming there is a direct correlation between higher wind speeds and what would be considered *inclement weather* at sea, the mean wind speeds were split by quantile into four bins, and then classified by rank order 1 – 4, with 4 being the highest wind speeds and most likely to cause gear loss, and 1 being the lowest (Table 5; Figure 1).

Table 5. Probability ranking for wind speed as a cause of gear loss based on association with inclement weather within velocity bands.

Wind Speeds	Rank	4	3	2	1
	Value Bins (m/s)	12.30 - 6.54	6.54 - 5.74	5.74 - 4.71	4.71 - 1.43

From the ocean currents data obtained from CMEMS, the monthly mean current speed (m/s) were summarized by month per 0.25° cell within the study area over the three year period 2018 – 2020. For a simple analysis of this parameter as a reason for gear loss, we chose to eliminate the current direction and focus only on current speed. Therefore, each cell was represented by the mean absolute value of current speeds per month over the three year period. Due to resolution of the dataset, there were some small areas along the coastlines without original values. In these locations, values were assigned by calculating the average current speeds of all immediately neighboring cells. As it pertains to contributing to lost fishing gear, we treat current speed similar to wind speed, such that the potential for gear loss increases with the increase in ocean current speed. The ranking values for ocean currents were split by quantile into four bins of values ranked 1 – 4, from low to high probability of gear loss, respectively (Table 6; Figure 1).

Table 6. Probability ranking for ocean current speed as a cause of gear loss within velocity bands.

Ocean Current Speeds	Rank	4	3	2	1
	Value Bins (m/s)	0.69 – 0.22	0.22 – 0.18	0.18 – 0.16	0.16 – 0.06

Vessel traffic density as a variable representing potential gear loss due to conflicts with vessel traffic was represented by the dataset showing all observed ship movement from 2015–2020 within 500 m cells. Values were split by quantile in to three bins, with a fourth bin representing a zero value where no vessel traffic has been recorded. The bins ranking from 0 – 3 represent low to high probability of gear loss occurring due to conflict with passing vessels (Table 7; Figure 1).

Table 7. Probability ranking for vessel traffic density as a cause of gear loss within density bands.

Vessel Traffic Density	Rank	3	2	1	0
	Value Bins (v/cell)	29,037,808 – 13.664,850	13,664,850 – 3,416,212	3,416,212 – 0.0001	0

Reef structures were used to represent *underwater obstructions*, with the potential for gear loss and/or accumulation as they can snag and foul both passive and active fishing gears. Spatial distribution of reef structures, including rocky reefs, corals, and pinnacles inside Mexico's Pacific waters were collected from two datasets; that from Aburto-Oropeza (2017), which covers only the Gulf of Mexico, and the UNEP global reef dataset (UNEP 2021). Features from both datasets were summarized by area within a 0.25° cell grid covering the entire EEZ; providing area of reef structure (km^2) per cell. Due to the difference in coverage between the two datasets, the values from each source were normalized as a percent of total and combined to provide a percent of total known reef area within the study area per cell. Therefore, this does not represent specific known reef locations, rather a density of reef locations relative to the entire study area. Values per cell were binned by quantile into five categories, with 1 – 4 representing low to high density of reef structures and associated gear loss, and 0 where the documented presence of reef structures are not a factor (Table 8; Figure 1).

Table 8. Probability ranking for reef structure density as a cause of gear loss due to snags on underwater obstruction, with density bands represented in percent of total.

Reef Structures	Rank	4	3	2	1	0
	Value Bins (%)	1.65 – 0.38	0.38 – 0.12	0.12 – 0.08	0.08 – 0.0001	0

Another way to analyze seafloor features is through bathymetric variance, as abrupt changes in water depth and the ruggedness of benthic terrain can cause gear loss. To identify areas of high bathymetric variance, the bathymetry data was processed to determine the standard deviation of slope (SD_{slope}) within a 3-cell radius neighborhood, which is one of several ways to identify changes in terrain (Grohmann et al. 2009). High values of SD_{slope} represent greater complexity in the benthic terrain, and therefore areas we assume to have greater chances of causing fishing gear loss and/or accumulation. Values ranged from 0 – 45, and were split by quantile into four bins, 0 – 3, representing zero (0), and low to high probability of ALDFG presence (Table 9; Figure 1).

Table 9. Probability ranking for standard deviation of slope as a cause of gear loss due to bathymetric variance and ruggedness of terrain, with value bands represented in percent of total.

Bathymetric Variance	Rank	3	2	1	0
	Value Bins (SD_{slope})	50.0 – 27.9	27.9 – 0.35	0.35 – 0.18	0.18 - 0

It should be noted that the differences in number and values of bin rankings per dataset were the result of determining the best fit for the model after analysis of each individual dataset. In some cases, a standard number of bins per variable can often cause models to be overwhelmed by vast spans of high probability areas or understated with a paucity of high probability areas. Further, the reliability of the data and the importance of each reason for gear loss is considered during analysis and contribute to the decision process. These considerations can be narrowed when known locations of ALDFG are available to analyze as part of the modeling process.

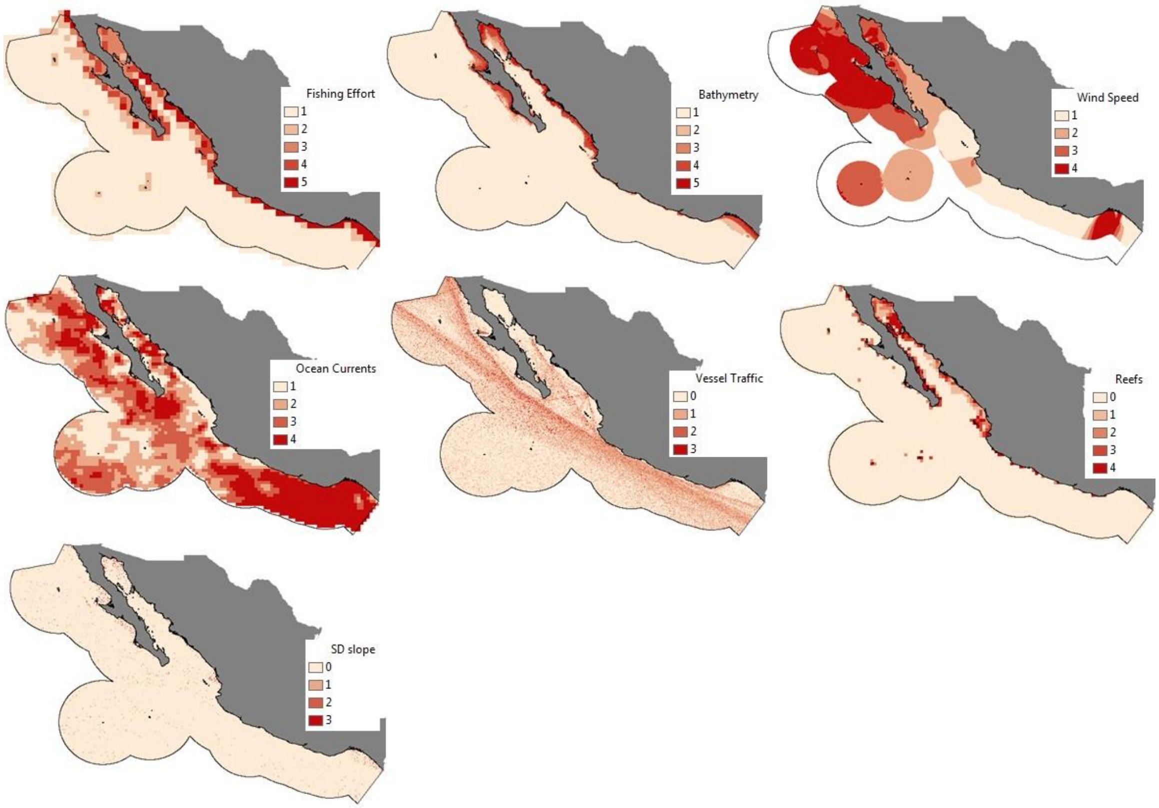

Figure 1: Seven input variables re-classed to represent probability of ALDFG occurrence in Pacific waters of Mexico based on available datasets. Low Probability (0)-High Probability (5).

Using ArcGIS Spatial Analyst, all datasets that were not in raster format were converted to raster, and the values of each of the seven variables were reclassified by their value bins. All re-classed raster sets were input into the ArcGIS Cell Statistics Tool and summed. The output result was a full coverage raster with cell values ranging from 0 to 24, with 0 representing the lowest probability of gear loss occurrence and 24 representing the highest probability.

Predictive Model Results and Discussion

Using spatial representation of variables known to influence the probability of fishing gear loss including concentration of fishing effort, bathymetric depths, wind speed, current speed, vessel traffic, and benthic terrains, the probability model reported here provides integer values from 0 to 24 representing low to high probability, respectively, of ALDFG within the Pacific marine waters of Mexico. For visual analysis, the final product of the probability mapping includes binned groups of these values for final ALDFG probability ranking from 1 to 8, with 8 being the highest probability rank (Figure 2).

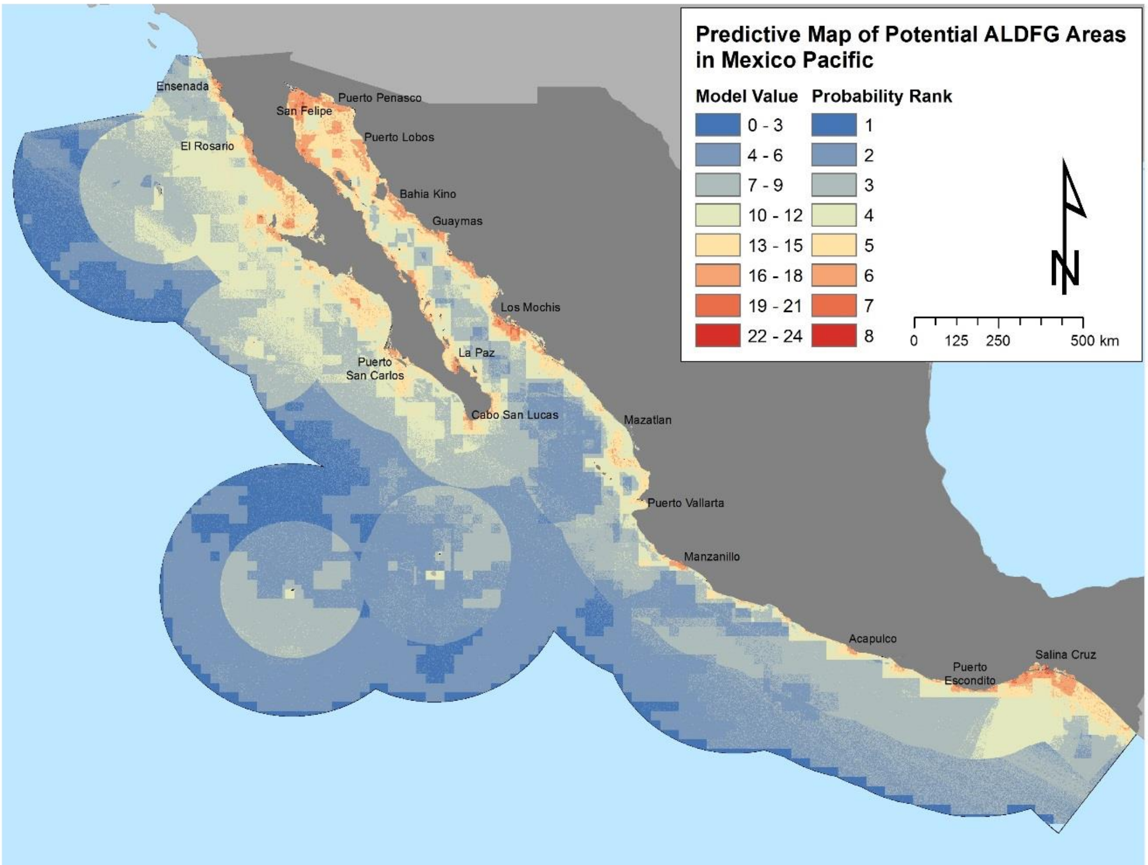

Figure 2: Predictive model result; areas of low to high potential for ALDFG occurrence based on spatial analysis of multiple data layers in Pacific marine waters of Mexico.

The total predictive model covers 2,354,602 km^2, with the low half of probability rankings (1 – 4) accounting for 92% of the total study area, with the remaining 8% in the upper probability rankings (5 – 8). Table 10 shows the breakdown of probability rankings by size and percent of total area covered within the study area. The final probability rankings are distributed throughout the study area, in a relatively expected manner, with the patches of highest values nearshore along the coastline, generally becoming exceedingly lower further offshore and in deeper waters (Figure 2). This reflects the importance placed on water depth ranges and the focus on gillnets, traps, and longlines, exclusively. The concentrated patches of higher ranked areas occur along both coastlines of the Gulf of California, particularly in the northern areas near San Felipe and Puerto Peñasco, and near major fishing ports such at Guaymas and Los Mochis. Along the western coast of Baja California high probability areas occur around Ensenada, El Rosario, and Puerto San Carlos (Bahia de Magdalena). To the south, high probability areas occur in small patches round Manzanillo and Acapulco, with a large patch extending from Puerto Escondido south to Salina Cruz and further (Figure 2).

Table 10. Probability ranking for standard deviation of slope as a cause of gear loss due to bathymetric variance and ruggedness of terrain, with value bands represented in percent of total.

Model Value	Probability Rank	Probability	Total Area (km^2)	% of Study Area
0 – 3	1	Lowest	189,284	8.04%
4 – 6	2		898,579	38.16%
7 – 9	3		741,069	31.47%
10 - 12	4		339,563	14.42%
13 - 15	5		135,286	5.75%
16 - 18	6		46,326	1.97%
19 - 21	7		4,356	0.18%
22 - 24	8	Highest	139	0.01%
Total			**2,354,602**	**100.00%**

Of particular significance is the concentration of high probability areas in the northern Gulf of California, which is corroborated by the estimated locations of derelict gillnets (n = 163) removed reported in CIRVA (2017 & 2019). Probability rank values at estimated locations of recovered derelict gillnets ranged from 4 (moderate) to 8 (highest), with a mean rank value at derelict gillnets of 6 (mod – high). These numbers support the predictive model, yet unfortunately highlights further challenges facing the vaquita, as their distribution range hosts high levels of co-occurring variables that cause lost fishing gear, such as strong winds and currents, and areas of complex benthic terrain; in addition to the most apparent issues of illegal fishing and gear abandonment in the area (Figure 3).

It should be emphasized that these are not "hot spot" maps; yet we believe that they can provide guidance when determining where to apply resources to address ALDFG and can be used to identify potential ALDFG survey locations. The high probability areas shown here were developed through a predictive model based on input data from publicly available datasets and known characteristics of ALDFG. The one input feature that did not exist in these models were any known locations of ALDFG. The purpose of this is to assist interested parties in identifying where the potential for ALDFG presence is more likely and help guide assessments in survey investigations. As the first iteration of this model in Mexico, it is most valuable if considered a working model that is updated as more information becomes available. We intend to refine this model as records of lost gear locations are collected, and follow-up survey interviews are conducted with the fishing fleet members.

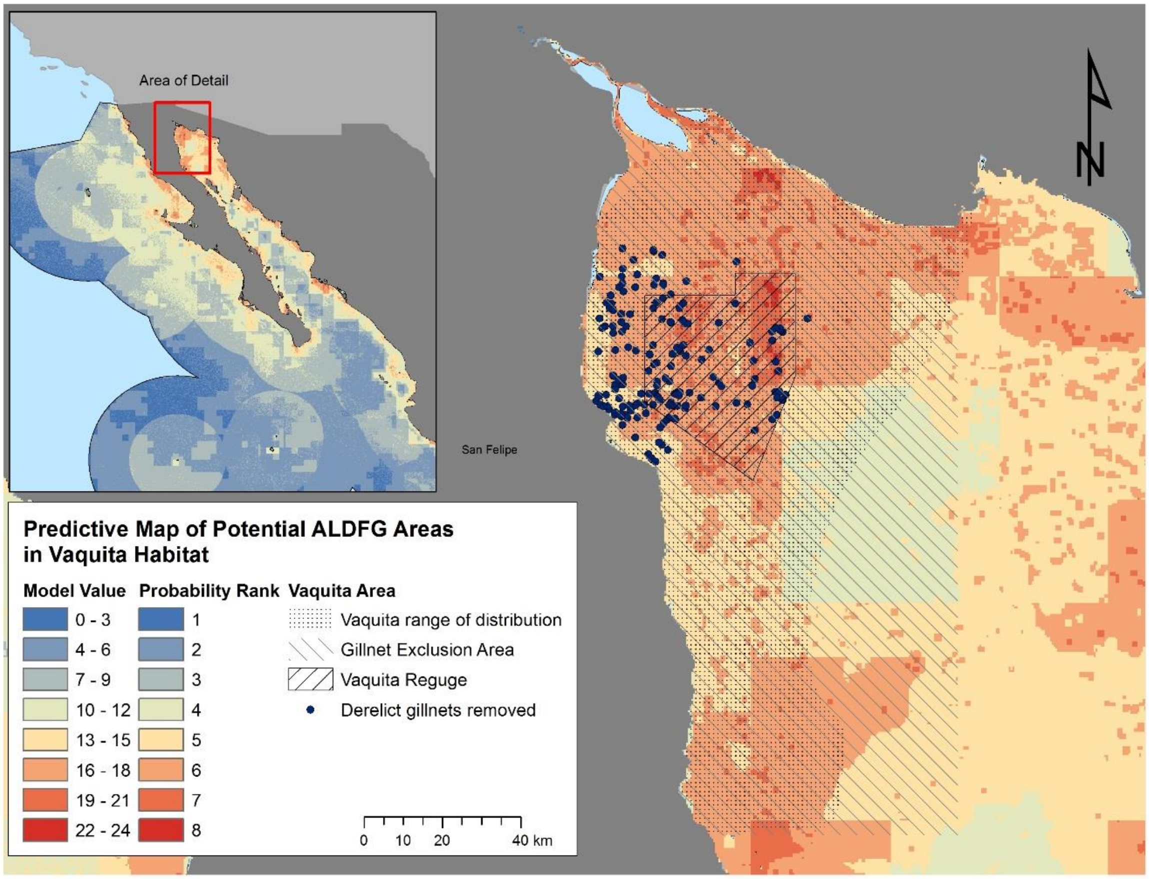

Figure 3: Predictive model in highlighted vaquita habitat; locations of removed derelict gillnets, gillnet exclusion zone, and vaquita refuge area.

Accompanying this report are three datasets for use in ArcGIS. They include:

- mexpacmod_v1a – raster file of the final data map with values depicting Probability Rankings (1 – 8).
- MexicoPacificModel_v1.shp – vector shapefile with 25 features, each representing coverage of the modeled values 0 – 24, with attributes describing their area, percent of total area, and corresponding probability rankings.
- MexicoPacificModel_v1a.shp – vector shapefile with 8 features, each representing coverage of the Probability Rankings 1 – 8, with attributes describing their area and percent of total area.

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