Spatial estimates of Blue Shark, Salmon Shark, Pacific Sleeper Shark and Bluntnose Sixgill Shark presence in British Columbia

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SPATIAL ESTIMATES OF BLUE SHARK, SALMON SHARK, PACIFIC SLEEPER SHARK AND BLUNTNOSE SIXGILL SHARK PRESENCE IN BRITISH COLUMBIA

by

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Abstract

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Spatial information on ecologically important species is needed to support marine spatial planning initiatives in British Columbia's (BC) marine environment. For data deficient taxa, such as shark species, species distribution models that integrate presence-absence data from different sources can be used to predict their coastwide distributions. Here we provide spatial estimates of the distribution of Blue Shark (*Prionace glauca*), Salmon Shark (*Lamna ditropis*), Pacific Sleeper Shark (*Somniosus pacificus*) and Bluntnose Sixgill Shark (*Hexanchus griseus*). These estimates were generated using spatial generalized linear mixed effects models and are based on data from two scientific surveys and the commercial hook and line, midwater trawl and bottom trawl fisheries. For each species, we provide predicted probability of occurrence and prediction uncertainty at a 3 km resolution for the British Columbia coast, and parameter estimates for model covariates (depth, slope, year, data source). Results show variable predicted distributions across species, with Blue Shark and Pacific Sleeper Shark showing higher probability of presence along the continental slope, while Salmon Shark show low probability of occurrence coastwide and Bluntnose Sixgill Shark show the highest probability of occurrence in the Strait of Georgia. The results from this study can support ongoing marine spatial planning initiatives in the BC and support the conservation and management of these important species.

Résumé

Proudfoot, B., Thompson, P.L., Vaidyanathan, T. and Robb, C.K. 2024. Spatial estimates Of Blue Shark, Salmon Shark, Pacific Sleeper Shark and Bluntnose Sixgill Shark presence in British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 3600: vi+ 27 p.

Des données spatiales sur les espèces d'importance écologique sont nécessaires pour soutenir les initiatives de planification spatiale marine (PSM) dans l'environnement marin de la Colombie-Britannique. En ce qui concerne les taxons pour lesquels les données sont insuffisantes, comme les espèces de requins, on peut utiliser les modèles de répartition des espèces qui intègrent les données sur la présence et l'absence provenant de différentes sources pour prédire leur répartition à l'échelle de la côte. Nous présentons ici des estimations spatiales de la répartition du requin bleu (*Prionace glauca*), de la taupe du Pacifique (*Lamna ditropis*), de la laimargue du Pacifique (*Somniosus pacificus*), et du requin griset (*Hexanchus griseus*). Ces estimations ont été obtenues grâce à un modèle linéaire généralisé à effets mixtes, et elles sont fondées sur des données provenant de deux relevés scientifiques et des pêches commerciales avec ligne et hameçon, au chalut pélagique et au chalut de fond. Pour chaque espèce, nous fournissons la probabilité d'occurrence prédite et l'incertitude de prédiction à une résolution de 3 km pour la côte de la Colombie-Britannique, ainsi que les estimations des paramètres pour les covariables du modèle (profondeur, pente, année et types de données). Les résultats montrent que les répartitions prédites varient d'une espèce à l'autre : le requin bleu et la laimargue du Pacifique présentent une probabilité d'occurrence plus élevée le long du talus continental, tandis que la taupe du Pacifique présentent une faible probabilité d'occurrence sur l'ensemble de la côte et le requin griset présentent la plus forte probabilité d'occurrence dans le détroit de Georgia. Les résultats de cette étude peuvent soutenir les initiatives de PSM en cours dans la région du Pacifique et favoriser la conservation et la gestion de ces espèces importantes.

1 Introduction

On the Pacific coast, Marine Spatial Planning (MSP) is underway in two planning areas: Pacific North Coast (Northern Shelf Bioregion) and Southern BC (the Strait of Georgia and Southern Shelf bioregions). The overarching goal of MSP is to inform the management of marine spaces to achieve ecological, economic, cultural and social objectives. This can include marine use plans that identify suitable areas for marine activities and areas which need special conservation measures. Science staff at Fisheries and Oceans Canada (DFO) are working to develop spatial data products that can support the future creation of marine spatial plans. In the Southern BC planning area, MSP efforts have focused on continuing to advance early planning phases (coordination, information gathering) and engaging with MSP partners and stakeholders. In the Pacific North Coast planning area, MSP efforts have focused on the collaborative implementation of the Marine Protected Area (MPA) network. The development of MSP-related spatial data products in the Pacific Region is a highly collaborative process, which ensures that the spatial data products are as useful and complementary as possible in order to support MSP objectives and other initiatives underway in the same geographic space. Many of these datasets are being included in an interactive bioregional marine atlas[1] being created to support MSP efforts that identifies the location of current activities, ecologically and biologically significant areas, ecologically significant species and community properties, degraded areas, and depleted species.

Sharks play an important role in maintaining marine ecosystems by controlling the populations of many prey species and transferring food energy within and across ecosystems over broad spatial and temporal scales due to their highly mobile nature (McFarlane and King 2020). Sharks are also prey for other large marine predators. Despite their important role in marine ecosystems, the spatial distributions of shark species are a known data gap. A first attempt to fill this knowledge gap was the mapping of species occurrences in commercial fisheries for all elasmobranch species found in BC (McFarlane et al., 2010). In 2007, DFO released a "National Plan of Action for the Conservation and Management of Sharks (NPOA-Sharks; DFO 2007). The report outlined the state of management of shark species in Canada, identified gaps, research priorities and the associated actions and strategies required to address the gaps. In 2012, a progress report (DFO 2012) on the implementation of the NPOA-Sharks describes the activities undertaken since the initial report was released. These reports, coupled with the assessments conducted by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and assessments under the Species at Risk Ask (SARA) provide the most comprehensive overview of the conservation and management status of shark species in the Pacific Region. Additionally, six shark species, including all species in this current study, were identified as ecological conservation priorities (ECPs) in the Northern Shelf Bioregion (NSB) MPA Network Process (Gale et al. 2019) due to their vulnerability, trophic level and role in nutrient transport. However, data for spatial analyses for use in the MPA Network process were only available for North Pacific Spiny Dogfish, while the remaining conservation priority shark species (Basking Shark, Blue Shark, Bluntnose Sixgill Shark, Pacific Sleeper Shark and Salmon Shark) were highlighted as data deficient in the MPA Network Action Plan (MPA Network BC Northern Shelf Initiative 2023b) and identified as a data gap.

Species distribution models (SDMs) developed using the best available data can provide important information to support the conservation and management of these important species. While occurrence data for sharks are available from a variety of scientific surveys and commercial fisheries (as illustrated in McFarlane et al. 2010), the data are not comprehensive for the full coast (i.e., the data do not capture the full spatiotemporal extent of the species habitat). However, SDMs are a powerful tools that can integrate data from a variety of sources to extract valuable information and inferences about the

[1] Canada Marine Planning Atlas - Pacific (dfo-mpo.gc.ca)

distribution of species, and make predictions in areas where occurrence data is lacking. In this study, spatial data on shark species from different longline and trawl data sources was compiled to develop species distribution models that represent the probability of presence of four shark (Blue Shark, Salmon Shark, Bluntnose Sixgill Shark, Pacific Sleeper Shark) species on the Pacific coast of Canada to fill a priority data gap and better understand the spatial distribution of these important species.

Shark species

Blue Shark (*Prionace glauca*)

The Blue Shark's range covers both inshore and offshore waters in the Atlantic, Pacific and Indian Oceans and extends from 50°N to 50°S. Blue Sharks are pelagic, oceanic sharks that are common in BC, particularly in the summer months off the west coasts of Vancouver Island and Haida Gwaii and in Queen Charlotte Sound and Hecate Strait (McFarlane and King 2020; McFarlane et al. 2010). Blue Sharks are top predators in the Central North Pacific (Kitchell et al. 1999), with diets varying by geographic location. Diets of Blue Sharks occupying deeper oceanic waters tend to be comprised of pelagic cephalopods and myctophid fish while the diets of sharks inhabiting coastal waters include Pacific Hake, Pacific Herring, Pacific Sardine and Pacific Salmon (McFarlane and King 2020; Brodeur et al. 2014). Additionally, Blue Sharks are highly migratory, and follow warming waters from offshore to inshore and from California to Alaska and (Love 2011). Blue Sharks also contribute to nutrient transfer between coastal feeding and open-ocean spawning areas (McKinnell and Seki 1998; Beamish et al. 2005). In British Columbia, there is no targeted commercial or recreational fishery for Blue Shark but they are caught incidentally in longline and trawl fisheries (McFarlane and King 2020).

Salmon Shark (*Lamna ditropis*)

In the eastern north Pacific, the Salmon Shark range extends from the Bering Sea, through the Gulf of Alaska south to northern Baja California (McFarlane and King 2020; Compagno 2001) and the species is known to occur in the Gulf of Alaska and the Bering Sea throughout the year (McFarlane et al. 2010; Seitz 2019). Salmon Sharks are also highly migratory, and females can migrate as far as Baja California and Hawaii after mating in the Gulf of Alaska (Love 2011). In BC, the species is most common off the West Coast of Vancouver Island, and in Hecate Strait, Queen Charlotte Sound and Dixon Entrance (McFarlane and King 2020; Weng et al. 2008; McFarlane et al. 2010; Du Preez et al. 2022). While Salmon Sharks are considered a surface species, they have been found at depths up to 375 m and inhabit both nearshore and deep oceanic waters (McFarlane and King 2020). In subarctic waters, Salmon Sharks are opportunistic top predators, feeding mainly on fish (primarily Pacific salmon, but also forage fish, Spiny Dogfish, Sablefish, and rockfish and squids (Nagasawa 1998; Hulbert et al. 2005)). In British Columbia, there is no commercial fishery for Salmon Sharks, but the species is allowed to be retained by recreational fishers.

Pacific Sleeper Shark (*Somniosus pacificus*)

In the eastern North Pacific, Pacific Sleeper Sharks range from the Bering Sea south to Baja California. In British Columbia, the species is typically encountered in deeper waters off the West Coast of Vancouver Island, Queen Charlotte Sound, and the West Coast of Haida Gwaii (McFarlane and King 2020). Pacific Sleeper Sharks are apex predators known to feed on a variety of pelagic and benthic prey, including flatfish, Walleye Pollock, Pacific salmon, rockfishes, shrimp, squid, octopus, crab and marine snails as well as marine mammals (McFarlane and King 2020; Love 2011). They are known to scavenge on whale falls and also feed on benthic invertebrates (Love 2011). Pacific Sleeper Sharks tagged in the Gulf of Alaska continuously move up and down the water column throughout the day, usually occurring between 150 and 450 m (Hulbert et al. 2006) but the species has been recorded at depths of 2000 m (McFarlane and King 2020). Diel vertical migrations (up to surface at night, down below photic zone during the day) were also observed (Hulbert et al. 2006). In British Columbia, there is no commercial fishery for the Pacific Sleeper Shark. The species is caught as bycatch in trawl and longline fisheries, and small sharks are sometimes encountered in sablefish traps (McFarlane and King 2020).

Bluntnose Sixgill Shark (*Hexanchus griseus*)
The Bluntnose Sixgill Shark is listed as and a species of Special Concern under Canada's Species at Risk Act (SARA) and by the COSEWIC (COSEWIC 2007). Their range extends from Alaska to California. In British Columbia, adult Bluntnose Sixgill Sharks occupy deeper waters (up to 2500 m) in Queen Charlotte Sound, and along the west coasts of Vancouver Island and Haida Gwaii, while juveniles occupy shallower waters in bays and inlets in the Strait of Georgia and West Coast of Vancouver Island (McFarlane and King 2020). Bluntnose Sixgill Sharks are generalist scavenger-predators that primarily forage nocturnally on cephalopods, crustaceans and bony fishes such as Pacific Hake, Pacific Herring, flatfish, cod, Pacific Salmon and rockfish (McFarlane and King 2020). The species is also known to feed on other sharks (Pacific Spiny Dogfish), skates, carrion we well as marine mammals (porpoises, dolphins and sea lions; McFarlane and King 2020). There is currently no commercial fishery for Bluntnose Sixgill Sharks, although directed fisheries did exist in the past. In the Strait of Georgia, the species has also been the focus of dive tourism and recreation, however this activity has decreased in recent years as the species has shifted its distribution in response to increased water temperatures (McFarlane and King 2020).

Other species not included in current study
Tope Shark (*Galeorhinus galeus*) and Basking Shark (*Cetorhinus maximus*) and were investigated for inclusion in this analysis but found to be data deficient across all data sources and thus could not be included. For these species, alternative survey approaches may provide insights into their distributions (e.g., aerial and line transect surveys (Surry and King 2015; Campana et al. 2008)).

North Pacific Spiny Dogfish (*Squalus suckleyi*) was also excluded because predictions for this species are available on OpenData (Thompson et al. 2022) and efforts are currently underway to model the distribution of this species through other methods, as the species is also targeted in the commercial fishery.

2 Methods

Data

The species distribution models (SDMs) are based on data from two fishery independent scientific surveys and from the commercial hook and line, midwater trawl, and bottom trawl fisheries, which are all conducted within Canadian Pacific Waters (**Figure 1**). The scientific surveys include the Fisheries and Oceans Canada (DFO) hard bottom longline surveys (Lochead and Yamanaka 2006, 2007; Doherty et al. 2019) and the International Pacific Halibut Commission (IPHC) fishery-independent setline survey (IPHC 2021). We based our analyses on data collected from 2006-2019, 2006-2023 and 2006-2023 for the IPHC, HBLL and commercial data, respectively. The year 2006 was selected as the starting year because species presence data and the spatial location of commercial catch were not consistently recorded in years prior to 2006 (King and Surry 2019; **Figure S1**). **Table 1** shows the total number and proportion of presence/absence observations for each species and data source. **Figure S2** shows the proportion of presence observations by data source. The study area is bound by the outer convex hull of the data sources (**Figure 1**). Other DFO research surveys, such as the groundfish synoptic bottom trawl surveys

(Sinclair et al. 2003; Anderson et al. 2019), the small mesh multispecies bottom trawl surveys (Flemming 2022), midwater (de Blois et al. 2020) and surface trawl (King et al. 2023; Boldt et al. 2024) and sablefish trap surveys (Lacko et al. 2021) were investigated as potential data sources but found to have insufficient presence observations for the species of interest to warrant their inclusion in the analysis.

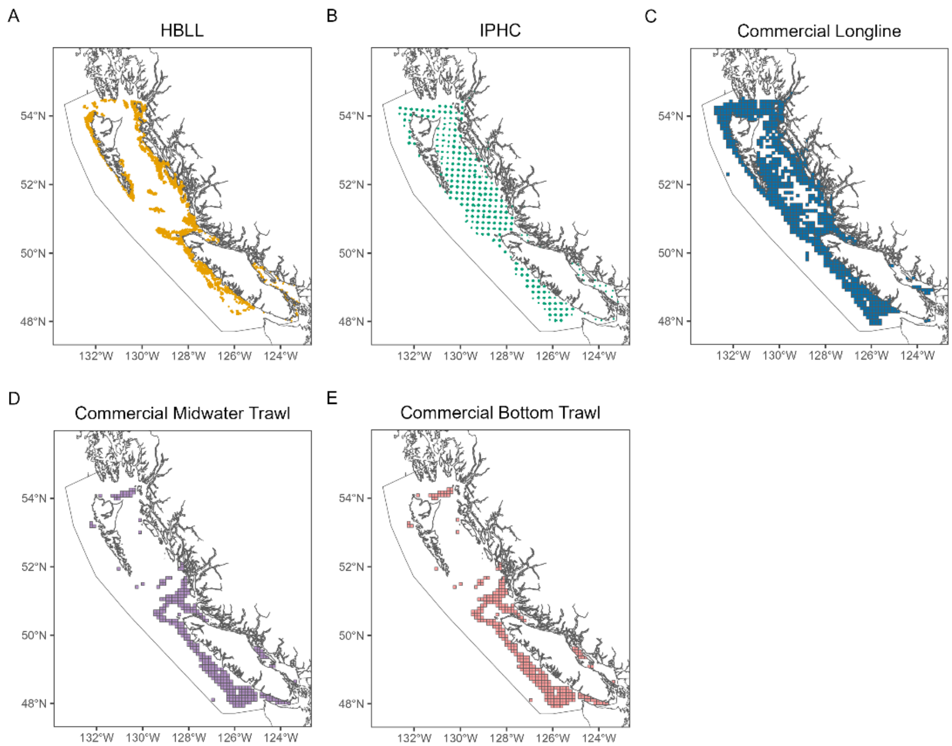

Figure 1: Study area maps showing the distribution of catch data across the different data sources: A) HBLL = Hard Bottom Longline surveys; B) IPHC = International Pacific Halibut Commission setline survey, C) commercial longline fishery, D) commercial midwater trawl fishery, E) commercial bottom trawl fishery. Point locations of commercial catch data cannot be shown due to privacy considerations, so the data were overlaid on a 10 km x 10 km grid and any cells with fewer than five unique vessels were excluded from the map. The bounding polygon represents the extent of the prediction grid.

Hard Bottom Longline (HBLL)

The hard bottom longline surveys are conducted by DFO and occur in most near-shore, hard-bottom substrates off the coast of British Columbia (**Figure 1A**). These surveys employ a random depth-stratified methodology on a two km^2 block and are used in areas where trawl surveys cannot operate. Longline surveys involve standardized 'snap and swivel' gear that are deployed on the ocean-floor and use frozen-squid as bait . The surveys are separated into inside and outside surveys, with inside surveys occurring in inlets and protected waters on the eastern side of Vancouver Island, and the outside surveys along most of the remainder of the BC coastline. The inside and outside surveys are further divided in to northern and southern regions and surveys occur in alternate years. The inner surveys employ 13/0 circle hooks, and the outer surveys employ 14/0 circle hooks. Despite this minor difference in hook size, we assume that the catchability, and ability to detect presence/absence of our focal species to be the same across the two surveys.

International Pacific Halibut Commission (IPHC)

The International Pacific Halibut Commission fishery independent setline survey (IPHC-FISS) covers nearshore and offshore waters of the IPHC regulatory areas in the waters of the United States and

Canada (**Figure 1B**). IPHC-FISS data is collected along the intersection of a 10 by 10 nautical mile grid, at the depth range of 18-732m at which Pacific Halibut are observed in the summer months. The IPHC survey expanded its coverage in 2018, and in 2021 added the use of snap gear in certain regions (in addition to fixed gear) to compare the catch between the two methods. The survey uses chum salmon as bait, and at each station employs between five and seven 549 m skates, each comprising 100 (16/0) circular hooks per skate (IPHC 2021). Because all bycatch is not consistently recorded in the IPHC surveys (i.e., in some years, only the first 20 hooks are recorded), our analysis includes years and sets where all bycatch was enumerated (2006-2019, excluding 2013).

Hook and line, midwater trawl and bottom trawl commercial fishery data

Catch and effort statistics for the British Columbia groundfish fishery have been collected by DFO since 1945. The commercial hook and line fisheries in British Columbia include directed fisheries for rockfishes, halibut, dogfish and lingcod and sablefish. The multispecies commercial trawl fishery targets a variety of species, including flatfishes, rockfish, thornyheads, Pacific cod, Lingcod, skates, Pollock, Spiny Dogfish and Sablefish. Data sources include daily vessel logbooks, landing records and dockside fisheries observations. Catch is calculated from the most spatially detailed information available on how much of each species was harvested per set or per area. Typically, this is catch reported in observer logs or vessel logbooks. The spatial locations of individual fishing events cannot be mapped because of the proprietary nature of the information. As such, to illustrate the spatial extent of the commercial fishery data, the point locations were overlaid on a 10 km x 10 km grid, and grid cells with fewer than 5 unique vessels were excluded from the visualization (**Figure 1C, 1D, 1E)** but still included in the analysis.

Table 1: Percentage of presence and absence observations by species and by source.

Species	HBLL data (n=3,000) 2006-2023		IPHC data (n=2,627) 2006-2019		Commercial longline data (n=239,857) 2006-2023		Commercial midwater trawl (n=63,912) 2006-2023		Commercial bottom trawl data (n=159,461) 2006-2023	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent	Present	Absent
Blue Shark	5.17%	94.83%	7.00%	93.00%	3.47%	96.53%	0.21%	99.79%	0.02%	99.98%
Salmon Shark	0.2%	99.8%	0.27%	99.73%	0.11%	99.89%	0.18%	99.82%	0.01%	99.99%
Pacific Sleeper Shark	0.10%	99.9%	2.21%	97.79%	0.80%	99.20%	0.10%	99.9%	0.27%	99.73%
Bluntnose six-gill shark	0.17%	99.83%	1.22%	98.78%	0.50%	99.50%	0.02%	99.98%	0.75%	99.25%

*HBLL: Hard bottom longline; IPHC: International Pacific Halibut Commission

Modelling approach

For each species, we fit a suite of generalized linear mixed effects models (GLMMs) using the sdmTMB package (Anderson et al. 2022). The sdmTMB package includes the option of utilizing a spatial (and spatiotemporal) random field, which captures additional variation in species occurrences due to environmental variables that were not included in the model (Thompson et al. 2022), such as sea surface temperature, distance from shore or variation due to dispersal patterns or biotic interactions. The sdmTMB package has been used in the Pacific Region to model the distribution of groundfish species based on longline and bottom trawl surveys (Thompson et al. 2022), and to model the distribution of Dungeness Crab using multiple different data types (Nephin et al. 2023). For this analysis, spatial patterns present across all years are estimated by the spatial random field. A spatiotemporal random effect was not included in this analysis because estimating temporal change was not the goal of this study. For each species, we fit four models, each with a different set of fixed effects/environmental predictors (**Table 2**).

Environmental predictors

We obtained the slope and log seafloor depth at resolutions of 1 km (Becker et al. 2009) and matched them to each survey/catch spatial location by taking the mean of the start and end coordinates for each longline set (HBLL and IPHC) or the point location associated with the commercial catch data. Seafloor depth was selected as a model covariate because it is known be an important predictor of the distribution and abundance of groundfish species in BC (Thompson et al. 2022), and is correlated with other variables, such as substrate (Gregr et al. 2021), bottom temperature and dissolved oxygen which might be important for benthic sharks such as Bluntnose sixgill shark and Pacific sleeper shark. Slope was also included as a model covariate because it is associated with other covariates, such as surficial geology (Gregr et al. 2021), circulation and current patterns (Thomson 1981) – variables that influence the distribution and abundance of prey species, which might be important for pelagic sharks such as Blue shark and Salmon shark. Not all candidate models included slope and depth as environmental fixed effects, but where relevant, these variables were included using a penalized spline smooth term (Wood 2003, 2017) with *k* set to 4. To account for temporal variability in species' occurrences, year was also included as a penalized spline. We standardized slope and log seafloor depth by subtracting their mean and dividing by their standard deviation prior to model fitting.

Statistical models

For each species, we modelled the occurrence Y_{st} at location *s* and time *t* using a binomial observation model and a logit link:

$$Y_{st} = \text{logit}(\mu_{st}), \quad \mu_{st} = X_{st}\beta + \omega_s$$

$$\omega = MVNormal(0, \Sigma_\omega)$$

Where μ_{st} represents the mean occurrence, and X_{st} represents the vector of environmental predictors (slope and/or depth depending on model; **Table 2**). The spatial random effect is presented by ω_s and is assumed to be drawn from a Gaussian random field with a covariance matrix (Σ_ω) constrained by a Matérn covariance function (Cressie and Wikle 2015). We modeled the spatial components of the analysis as random fields using a predictive process approach with a triangulated mesh (Lindgren and Rue 2015) and bilinear interpolation between vertices (**Figure S3**). We constructed the mesh such that vertices had a minimum gap ("cut off") of 15 km (Thompson et al. 2022). We applied a coastline physical barrier in which we assumed the spatial range (distance at which two data points are effectively independent) was 0.1 of the in-water range (Bakka et al. 2019). To fit the models, the sdmTMB framework uses the following elements: maximum marginal likelihood using a mesh constructed by INLA (Rue et al. 2009; Lindgren et al. 2011; Lindgren and Rue 2015), a model template coded in TMB (Kristensen et al 2015), the marginal likelihood function maximized with the non-linear minimizer nlminb (Gay 1990) in the R statistical language (R Core Team 2013), and the random effects integrated over via the Laplace approximation (Kristensen et al. 2015).

Candidate models and model comparison

For each species, we compared the predictive power of four models, with each model having a different combination of environmental predictors (i.e., slope, depth, slope + depth, none). A summary of the candidate models is provided in **Table 2**. All models included the smoothed term of year and the spatial random effect described above. Data sources were integrated using a categorical fixed effect, “source” (i.e., HBLL, IPHC, commercial longline, commercial midwater trawl or commercial bottom trawl), to account for methodological differences between the different surveys/data sources (Thompson et al. 2022).

Table 2: Candidate models. Each model was fit for each of the four species, and the best model (model with the highest log likelihood) was selected to make predictions

#	Candidate model structure	Random effects
1	Presence/absence ~ 0 + source + year	Spatial
2	Presence/absence ~ 0 + source + slope + year	Spatial
3	Presence/absence ~ 0 + source + depth + year	Spatial
4	Presence/absence ~ 0 + source + slope + depth + year	Spatial

We evaluated and compared the models by partitioning data into training and testing folds using spatial block cross-validation. We arranged three folds (north-south) over 24 equally sized blocks (**Figure S4**). For each species, we selected the model with the highest predictive accuracy (assessed using the predicted log likelihood based on the cross-validation) as the best fit. For each selected model, we then estimated the predictive accuracy by combining predictions of the withheld data across all folds, as opposed to averaging across folds because the folds did not contain an equal number of data points. We reported the area under the curve (AUC; Pearce and Ferrier 2000) and Tjur’s R^2 (the coefficient of discrimination; Tjur 2009) for each selected model.

Estimated response curves

For each species, we quantified the variation in probability of presence across environmental and temporal gradients using the selected model to make estimates across gradients of depth, slope and time and across source (categorical variable). This was done while holding all other variables at their mean values. Source was set to IPHC (the dataset with the most even spatial distribution of data points and the highest proportion of presence observations for each species). For each environmental gradient (e.g., slope and depth), we estimated response curves across the full range of values present in the data. We set random field values to zero, which removes any uncertainty introduced by the spatial random field from the estimated response curves.

We also calculated and visually inspected model residuals using the DHARMa package (Hartig 2017), which involves simulating new observations with all model parameters at their maximum likelihood estimates. Quantile-quantile plots are shown in **Figure S5**.

Spatial species distribution predictions

We made predictions of species occurrence using the selected model and a 3 km resolution spatial prediction grid. Our predictions were made for the entire BC coast, and species distribution predictions were made using models fit to the full dataset, as opposed to models fit using cross-validation. We made predictions with year set to 2014 (the approximate midpoint of the dataset) and source set to IPHC (the dataset with the most even spatial distribution of data points and highest proportion of presence observations for each species). Thus, these values represent predictions for what the IPHC survey methodology would catch if it were used across the full region in 2014. The choice to use 2014 is somewhat arbitrary as year only affects the mean predicted occurrence but does not change the spatial pattern of occurrence probability predicted by the model.

We obtained confidence estimates of species occurrences by drawing 500 simulated values from the joint precision matrix of the selected models. We mapped the mean, lower (10%) and upper (90%) quantiles on the spatial grid to illustrate occurrence hotspots.

Because limited survey and commercial catch data exists for deep areas off the continental shelf, predictions in these areas are likely more uncertain than predictions on the shelf. To illustrate this, uncertainty (standard deviation derived from the 500 simulated values from the joint precision matrix of selected models) was mapped across the full study area.

3 Results

Across all four species models that included slope and/or depth were selected as models with the best fit (**Table 3**). Predicted spatial distributions varied across species, with some species (e.g., Blue Shark, Pacific Sleeper Shark) showing a higher probability of presence in areas along the continental slope (**Figure 2**, **Figure 4**), while other species (e.g., Salmon Shark) showing relatively low probability of occurrence coastwide (**Figure 3**). Because these models are based on data that do not span the full spatiotemporal extent of the species' habitat (i.e., surface waters, and data across all seasons may not be captured), these results illustrate a snapshot of occurrence but do not account for more complex migration and movement patterns undertaken by these species. Additionally, these models represent the probability of detecting these species using IPHC methodologies.

Table 3: Summary of selected models for each species

#	Candidate Model	Species
1	Presence ~ 0 + source + year	
2	Presence ~ 0 + source + slope + year	Salmon Shark
3	Presence ~ 0 + source + depth + year	Pacific Sleeper Shark
4	Presence ~ 0 + source + slope + depth + year	Blue Shark; Bluntnose Sixgill Shark

All four species included in our analysis had an AUC of or above 0.78 (**Table 4**), indicating good discrimination ability (Pearce and Ferrier 2000). The Tjur R^2 scores were low (less than 0.076) for all species (**Table 4**), highlighting the rarity of the species. The rarity of the species is also evident in mapped predictions and the associated scales.

Table 4: Performance metrics by species. For each selected model, predictive accuracy was estimated by combining predictions across all cross validation folds. Area under the curve (AUC; Pearce and Ferrier 2000) and Tjur's R^2 (the coefficient of discrimination; Tjur 2009) are reported for each selected model.

Species	AUC	Tjur R^2
Blue Shark	0.89	0.076
Salmon Shark	0.78	0.001
Pacific Sleeper Shark	0.87	0.062
Bluntnose Sixgill Shark	0.87	0.046

The following figures show the species-specific outputs from the selected models (i.e., occurrence prediction maps, uncertainty maps, maps of the spatial random effects and environmental/temporal response curves).

Blue Shark (*Prionace glauca*)
As the most common shark species in this study, Blue Shark predicted occurrence is highest along parts of the continental slope, in the vicinity of Barkley and Nitinat Canyons, and along the west coast of Vancouver Island. Predicted occurrence is slightly higher at higher slopes (**Figure 2G)**, increases with depth until approximately 300 m (**Figure 2F**). However, these increases are small as indicated by the scale of the Y axis. Occurrence is also predicted to be slightly increasing through time, albeit with a lot of uncertainty, with a peak in 2019 (**Figure 2E**). Spatial uncertainty (**Figure 2I**) is highest in the Strait of Georgia, the Strait of Juan de Fuca, Dogfish Bank and in deeper areas off the continental shelf.

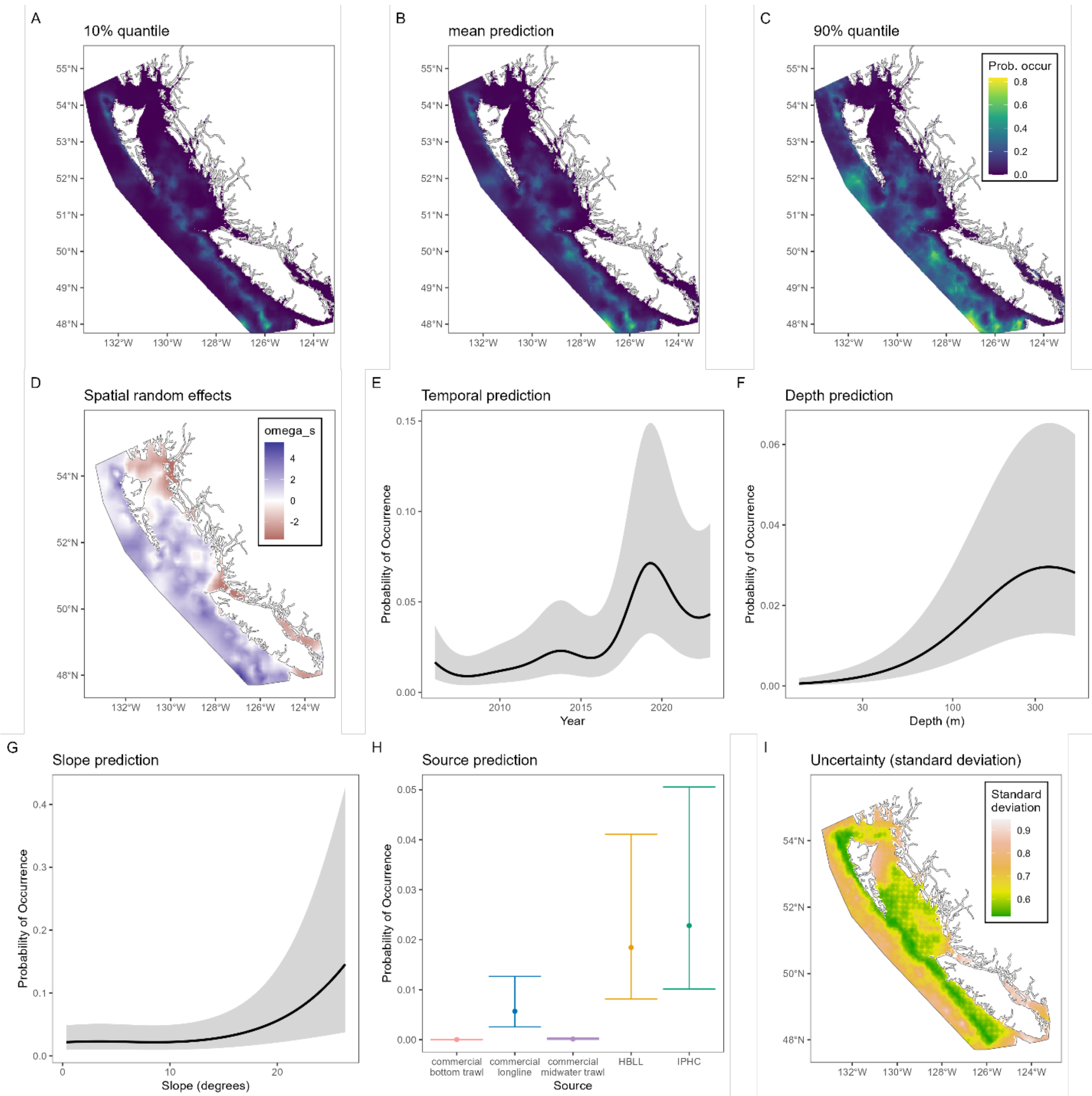

Figure 2: Predicted spatial distribution of Blue Shark occurrence and environmental response curves. The 10% quantile (A), mean (B) and 90% quantile (C) predicted probabilities of occurrence are illustrated for the full coast at a 3 km grid scale to show hotpots of Blue Shark occurrence. The spatial random effect (D) shows spatial patterns that contribute to variation in species occurrences due to environmental variables that were not included in the model. Panels E, F, and G show the response curves for year, depth and slope, respectively. Panel H shows the predictions for each of the data sources. Panel I shows the uncertainty of spatial predictions (standard deviation derived from simulated predictions). Bands and error bars represent 95% confidence intervals.

Salmon Shark (*Lamna ditropis*)

Salmon Sharks were the rarest species encountered in the data used in this study (**Table 1**) and coastwide predicted occurrence is low. The one hotspot predicted in Caamaño Sound (**Figure 3B**) could be an artifact of sampling (i.e., perhaps the same individual being repeatedly captured in multiple sets). Additionally, while the mapped predictions indicate a potential hotspot in this area, the colour scale indicates a low mean probability of occurrence (~0.2). Spatial uncertainty is highest in the Strait of Georgia, the Strait of Juan de Fuca, deeper areas off the continental shelf, and in Queen Charlotte Sound (**Figure 3I**).

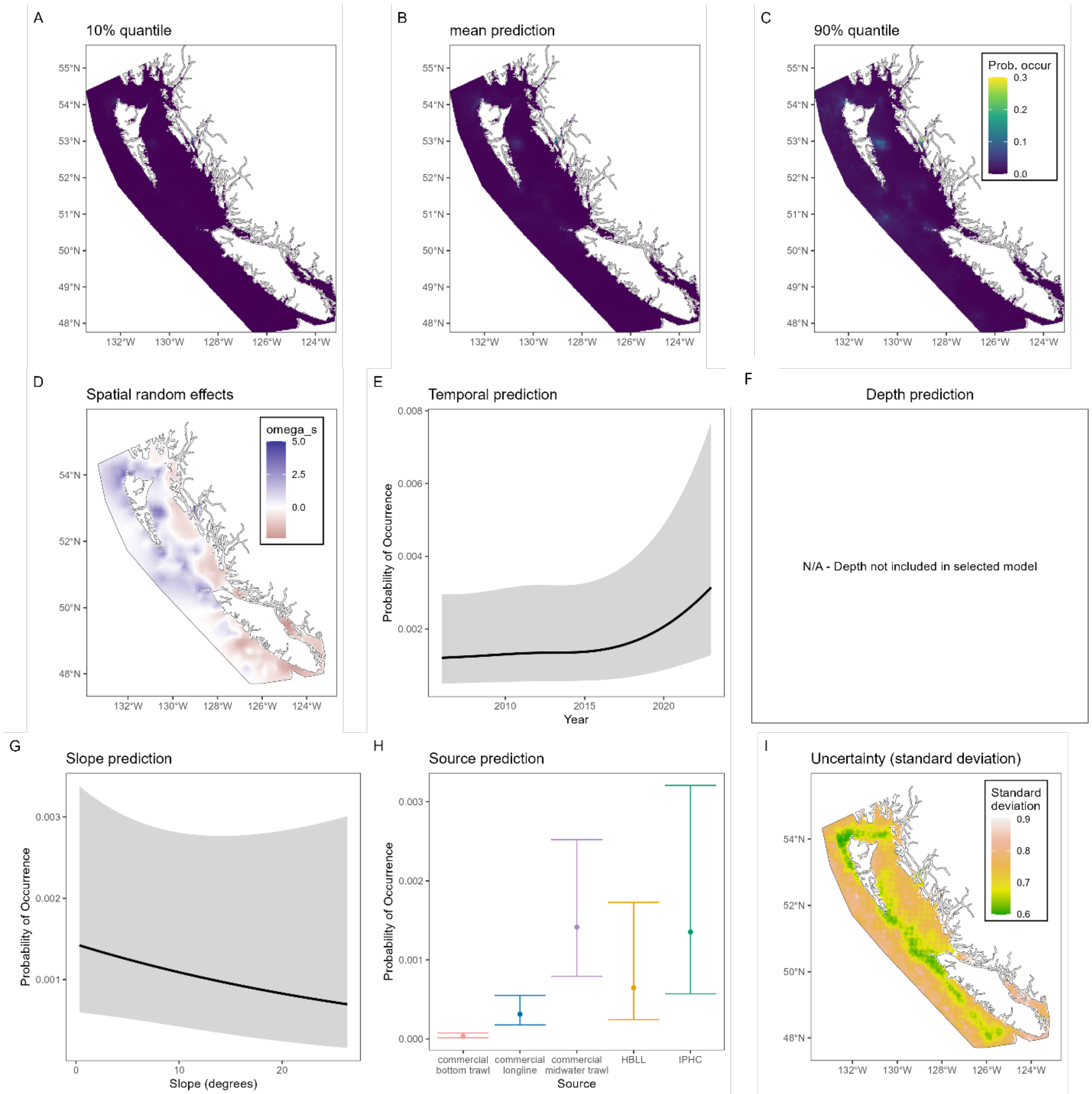

Figure 3: Predicted spatial distribution of Salmon Shark occurrence and environmental response curves. The 10% quantile (A), mean (B) and 90% quantile (C) predicted probabilities of occurrence are illustrated for the full coast at a 3 km grid scale to show hotpots of Salmon Shark occurrence. The spatial random effect (D) shows spatial patterns that contribute to variation in species occurrences due to environmental variables that were not included in the model. Panels E and G show the response curves for year and slope, respectively. Depth (F) was not included in the selected model for this species. Panel H shows the predictions for each of the data sources. Panel I shows the uncertainty of spatial predictions (standard deviation derived from simulated predictions). Bands and error bars represent 95% confidence intervals.

Pacific Sleeper Shark (*Somniosus pacificus*)

Across the different data sources, Pacific Sleeper Sharks were most commonly encountered in the IPHC surveys (**Table 1**). Predicted occurrence is highest along the northwest coast of Vancouver Island, extending north to the west coast of Haida Gwaii (**Figure 4B**). Patches with higher predicted occurrence values are also located in Caamaño Sound, Dixon Entrance, and in regions in Hecate Strait. Predicted occurrence is estimated to increase with depth (**Figure 4F**), and has been on a slight downward trend since 2014/2015 (**Figure 4E**). Like the Salmon Shark and Blue Shark, spatial uncertainty is highest in the Strait of Georgia, the Strait of Juan de Fuca, in deeper areas off the continental shelf, on Dogfish Bank and Queen Charlotte Sound (**Figure 4I**).

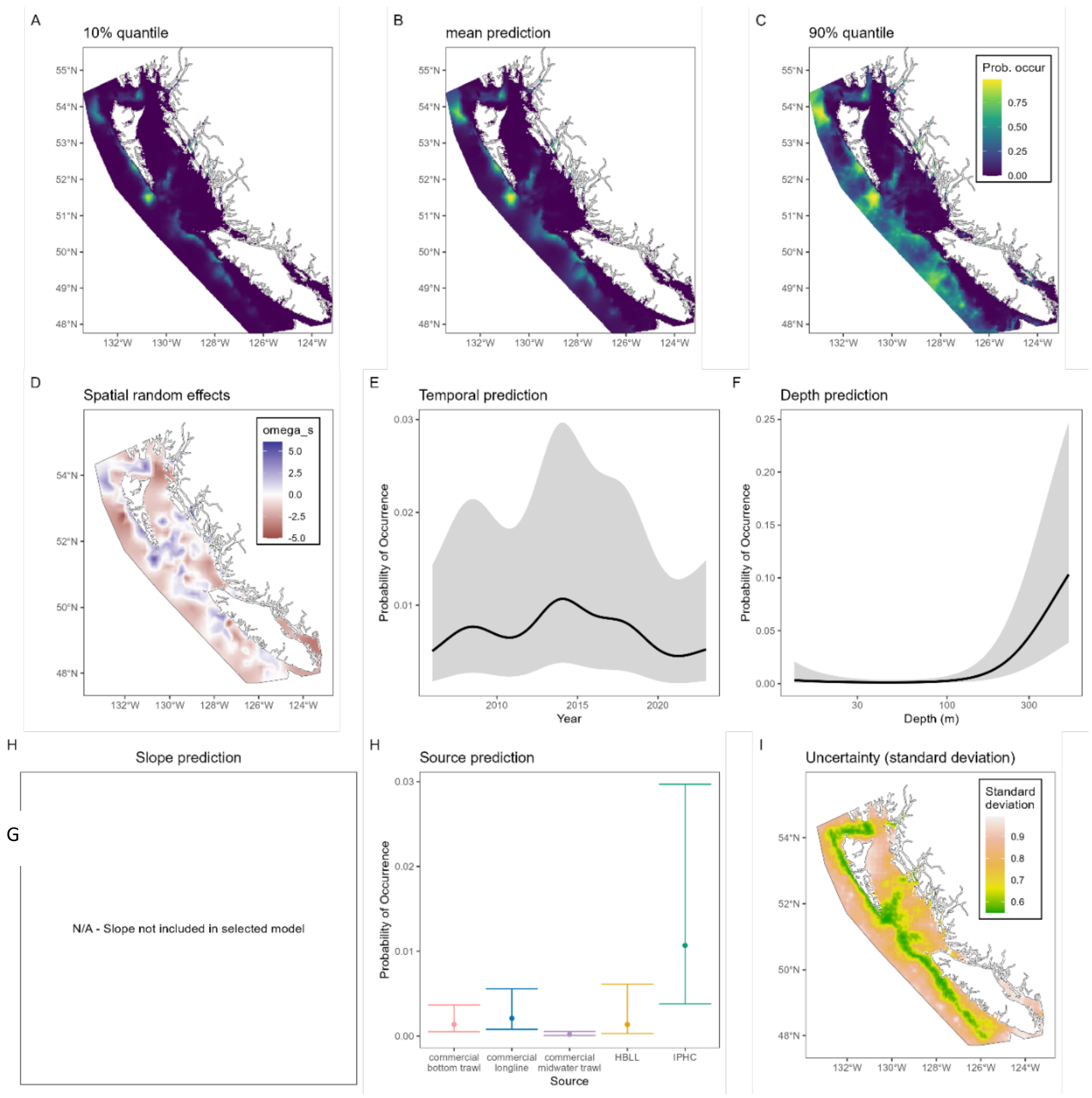

Figure 4: Predicted spatial distribution of Pacific Sleeper Shark occurrence and environmental response curves. The 10% quantile (A), mean (B) and 90% quantile (C) predicted probabilities of occurrence are illustrated for the full coast at a 3 km grid scale to show hotpots of Pacific Sleeper Shark occurrence. The spatial random effect (D) shows spatial patterns that contribute to variation in species occurrences due to environmental variables that were not included in the model. Panels E and F show the response curves for year and depth, respectively. Slope (G) was not included in the selected model for this species. Panel H shows the predictions for each of the data sources. Panel I shows the uncertainty of spatial predictions (standard deviation derived from simulated predictions). Bands and error bars represent 95% confidence intervals.

Bluntnose Sixgill Shark (*Hexanchus griseus*)

Bluntnose Sixgill Shark probability of occurrence is predicted to be low throughout most of the BC coast, but estimated to be highest in the Strait of Georgia, particularly in the southern region (**Figure 5B**). Small areas with moderate occurrence values are also predicted in the Strait of Juan de Fuca, Barkley Sound, and nearshore areas along the southwest coast of Haida Gwaii. Bluntnose Sixgill Shark occurrence is estimated to increase with depth (**Figure 5F**) and slightly with slope (**Figure 5G**). Occurrence is also predicted to be decreasing through time, however the magnitude of this temporal change is small (**Figure 5E**).

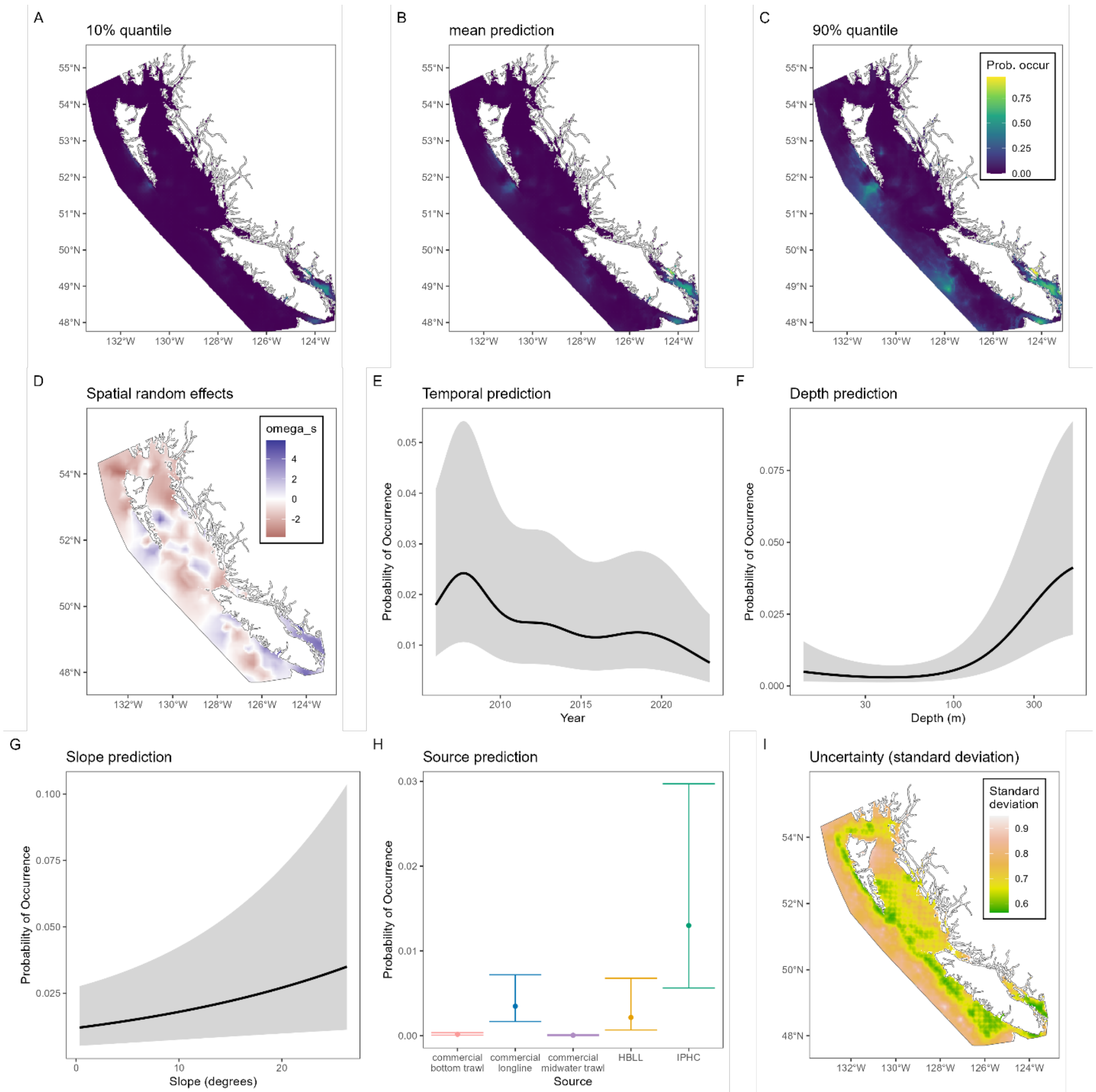

Figure 5: Predicted spatial distribution of Bluntnose Sixgill Shark occurrence and environmental response curves. The 10% quantile (A), mean (B) and 90% quantile (C) predicted probabilities of occurrence are illustrated for the full coast at a 3 km grid scale to show hotpots of Bluntnose Sixgill Shark occurrence. The spatial random effect (D) shows spatial patterns that contribute to variation in species occurrences due to environmental variables that were not included in the model. Panels E, F, and G show the response curves for year, depth and slope, respectively. Panel H shows the predictions for each of the data sources. Panel I shows the uncertainty of spatial predictions (standard deviation derived from simulated predictions). Bands and error bars represent 95% confidence intervals.

4 Discussion

This analysis provides spatial predictions for a subset of data limited shark species in British Columbia. Notable variation in the spatial predictions is evident across species. While these species are considered to be data limited, bycatch in the commercial hook and line, midwater trawl and bottom trawl fisheries provide a rich source of data. Because these models rely on the commercial catch data, it is important to note that the estimated declines in species occurrence through time (for Pacific Sleeper Shark and Bluntnose Sixgill Shark) are potentially due to reduced encounters with the commercial fishery (i.e., fishers are moving to other fishing grounds to reduce/limit bycatch). However, additional research is required to investigate the spatial distribution and redistribution of fishing effort through time to better understand the drivers behind these temporal trends.

Blue Shark

The Blue Shark is common in BC waters, and is the shark species most frequently encountered in the data used in this study. Blue Sharks are a pelagic species, with a depth range from 1-350 m (McFarlane et al. 2010). Our models estimate a increased probably of occurrence at higher slopes along the continental slope and in the vicinity of Barkley and Nitinat Canyons (**Figure 2**). A higher probability of occurrence is also estimated for an area on the northwest Coast of Haida Gwaii that overlaps the proposed Sasga K̲’ádgwii Offshore Continental Slope North site in the NSB MPA network (DFO 2024). The site overlaps the only currently documented seamount in the NSB (SAUP 5494; DFO 2024). However, these predictions represent the probability of catching Blue Sharks using IPHC methodologies (longline gear), but are informed by data from other gear types (midwater and bottom trawl). Blue Sharks are also encountered in the Integrated Pelagic Ecosystem Surveys (n = 23 since 2002; King et al. 2023; Boldt et al. 2024), which samples using trawls at 0 m and 15 m depths. These presence observations overlap with, or occur in close proximity to areas with moderate to high occurrence probability (high slope areas along the continental slope). However, the majority of the occurrences are on the continental shelf, adjacent to the high occurrence probability areas on the continental slope.

In British Columbia, Blue Shark occurrence is known to peak in late summer and fall, with the population segregating by sex and size (G. McFarlane, unpub. data; COSEWIC 2016). In 1987, the Canadian experimental squid driftnet fishery collected detailed biological data on Blue Shark and Salmon Shark bycatch and found significant differences sex ratios of the catch (McKinnell and Seki 1998). However, the experimental driftnet fishery was terminated in 1987 due to unacceptable levels of bycatch, indicating the species are common in the surface depths targeted by the driftnet fishery. Utilizing alternative, non-destructive methods such as aerial surveys and tagging studies have provided insights into the pelagic movement and habitat use by this highly mobile species (e.g,. Surry and King 2015). Blue Shark tagging studies conducted by DFO on the West Coast of Vancouver Island in 2007 and 2010 found that 85% (2007) and 77% (2010), respectively, were subadult females (COSEWIC 2016), which aligns with an existing model that predicts that most of the Blue Shark’s in Canada’s Pacific waters are subadult females (Nakano and Stevens 2008). Our models also predict that probability of occurrence is slightly increasing through time, which aligns with recent stock assessments (COSEWIC 2016) that suggest the North Pacific Blue Shark population is not in decline, and that the population has recently been at a relatively high abundance.

Salmon Shark

Salmon Sharks are generally considered a surface species (McFarlane and King 2020). As such, while our models estimate a low coastwide occurrence probability for this species (**Figure 3B**), it’s important to reiterate that these models represent the probability of catching a Salmon Shark using IPHC methodologies, but are informed by data from the other sources. Areas of moderate occurrence probability are estimated in close proximity to Cape St. James, Haida Gwaii and overlap the Gwaii Haanas National Marine Conservation Area Reserve (NMCAR) and proposed G̲angx̲id Kun SG̲aagiidaay Cape St. James NSB MPA network site (DFO 2024). However, Salmon Sharks are likely more common in surface waters. For example, in a study by Williams et al. (2010), a hotspot of pelagic shark occurrence (dominated by Salmon Sharks) was observed in summer months (2004-2006) in surface waters above Moresby Trough on the western edge of Queen Charlotte Sound (see Figure 1 in Williams et al. 2010). The authors hypothesize that the aggregation is seasonal, and that the sharks concentrate in this area to rest and to intercept adult salmon as the salmon return to their natal streams (Williams et al. 2010). Salmon Sharks are also encountered in the Integrated Pelagic Ecosystem Surveys (n = 19 since 2002; King et al. 2023; Boldt et al. 2024). The majority of these records occur in areas of low occurrence probability for this species, however the majority of the study area is predicted to have a low occurrence probability for this species. Utilizing other methods (aerial surveys, vessel-based transects) might be better able to collect observations of this highly mobile species in surface waters to make predictions about surface habitat use. Our models also suggest that the probability of occurrence of Salmon Sharks is increasing though time, which aligns with anecdotal reports of increased abundances in recent years due to warming temperatures and changes in management and protective measures for sharks (described in Okey et al. 2007; Seitz et al. 2019). Future work to better understand seasonal and annual variability Salmon Shark distribution would benefit not only to our understanding of the species, but also provide insights into how this variability might be impacting their primary prey – Pacific Salmon.

Pacific Sleeper Shark

The Pacific Sleeper Shark was most often encountered in the IPHC data used in this study (**Table 1**). In terms of their estimated spatial distribution, predicted occurrence is highest areas along the northwest coast of Vancouver Island, extending north to the southwest coast of Haida Gwaii (**Figure 4B**). Much of the area of high predicted occurrence of Pacific Sleeper Shark overlaps with the Shelf Break EBSA (Clarke and Jamieson 2006; Jamieson and Levesque 2014), and an area of high predicted occurrence on the West Coast of Haida Gwaii overlaps with the Gwaii Haanas NMCAR and the proposed Gwaii Haanas Extension site in the NSB MPA network (DFO 2024). The Lower Moresby Trough proposed MPA – an important oceanographic mixing area in the NSB (MPA Network BC Northern Shelf Initiative 2023) – also overlaps with an area of high occurrence probability of this species. Our models also predict an increase in probability of occurrence with depth, a trend supported by tagging studies done in the Gulf of Alaska that found that the sharks spent the majority of their time at depths between 150 and 450 m. Pacific Sleeper Sharks have also been encountered in the Sablefish Research and Assessment Trap Survey (n=9 since 2002; Lacko et al. 2021), and several of the presence observations overlap with or are in the vicinity of areas of high predicted occurrence in Caamaño Sound and Finlayson Channel. In other areas of BC, Pacific Sleeper Sharks observations from the Sablefish Research and Assessment surveys (n = 14) overlap areas of low to moderate predicted occurrence (0 – 0.3, with one occurrence at 0.84), however these observations are also located in areas with a wide range of uncertainty values (sd: 0 - 0.98).

Bluntnose Sixgill Shark

Our models estimate the probability of occurrence of Bluntnose Sixgill Shark to be low throughout most of the BC coast, but relatively high in the Strait of Georgia, particularly in the southern and central regions of the Strait (**Figure 5B**). The Strait of Georgia is known to be an important area for parturition and juvenile rearing for this species (King and Surry 2017). Additional known areas of juvenile occupancy are the inlets and sounds along the west coast of Vancouver Island (COSEWIC, 2007). However, our occurrence data do not extend into these areas, and the probability of occurrence estimates in these areas are likely underestimated. In their study, King and Surry (2017) used satellite tagging to understand the daily and seasonal depth and thermal habitats of juvenile Bluntnose Sixgill Sharks in the Strait of Georgia, and found that juvenile Bluntnose Sixgill Sharks remain in the Strait of Georgia and migrate into deeper offshore waters once they mature. Our models estimate that Bluntnose Sixgill Shark probability of occurrence increases with depth (**Figure 5**F), which aligns with studies indicating that this species prefers deep water (King and Surry 2017; McFarlane and King 2020). Unfortunately, our data sources did not cover the likely depths of adult habitat, i.e. depths along the continental slope. In terms of additional data sources, three Bluntnose Sixgill Sharks have been caught in the DFO synoptic trawl surveys in 2006, 2012 and 2015. Two of the observations are from the Strait of Georgia Synoptic Trawl Survey, which was only conducted in 2012 and 2015. The two observations in the Strait of Georgia overlap with moderate to low predicted occurrence (0.52, 0.01) values but moderate to high uncertainty values (sd =0.59, 0.73). The remaining observation is located in Swiftsure Bank. These occurrences suggest that the species is using soft sediment habitats, but unfortunately data in these areas (i.e, from bottom trawl data sources) are limited.

After the Bluntose Sixgill Shark was listed as a species of special concern under the Species at Risk Act (SARA) in 2009, a management plan was developed (DFO 2012b). The plan sets goals and objectives, identifies threats and indicates that main areas of activities to ensure that the species does not become threatened or endangered. One of the knowledge gaps identified in the management plan is information pertaining to the species distribution. The results of this study contribute to our understanding of the spatial distribution of this species, and can form the basis for additional hypothesis related to the seasonal, annual and life-stage related variability in the distributions of this species.

Uncertainty and Considerations

Although the models had relatively low uncertainty in the areas where the probability of occurrence is predicted to be highest (**Figures 2-5, panels I**), understanding the limitations of these model predictions is important. Spatially, areas with the highest uncertainty are at the margins of the study area and in the Strait of Georgia (except for Bluntnose Sixgill Shark, a species with higher probability of occurrence and low uncertainty in the Strait of Georgia), areas where there are fewer data points (particularly research data and HBLL survey points) to inform the models (**Figure 1**). Our residuals for the model showed a good fit to the data (**Figure S5**), so it is likely that these models are able to predict the probability of catching these species with longline gear in areas with ample data points, quite well.

Our models provide a snapshot of species occurrence and do not represent the full spatiotemporal extent of the species' habitat. Specifically, these models represent the probability of a species being caught using IPHC methodologies, and as such do not indicate habitat use at mid-depths, surface waters or seasonal variation in habitat use. However, the models are informed by information from the midwater trawl commercial data. Further, these results do not account for the complex migration and movement patterns undertaken by these species, although future studies could focus on the spatiotemporal variation in habitat use for these species.

The methods used in this analysis could also be used to investigate the distribution of other relevant species. The spatial distributions of several skate species (Big Skate, Longnose Skate and Sandpaper

Skate) have been modeled using hook and line and bottom trawl research survey data (Thompson et al. 2022). These species, along with the Roughtail Skate, have been identified as ECPs in the NSB MPA Network process. Future work could explore how the addition of commercial data influences these predicted distributions, and also explore whether spatial predictions for other data deficient skate species could be estimated.

5 Conclusions

This analysis has provided spatial predictions for four species of shark that have been identified as knowledge gaps in terms of their spatial distributions in British Columbia. There is variation in the predicted occurrence across species and in response curves for model covariates. This analysis provides habitat use information for these four species that should be incorporated into marine spatial planning processes currently underway in British Columbia. The results also provide outputs and predictions that can be used to guide potential future data collection and analyses related to these species their spatiotemporal distributions.

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Appendices and supplemental figures

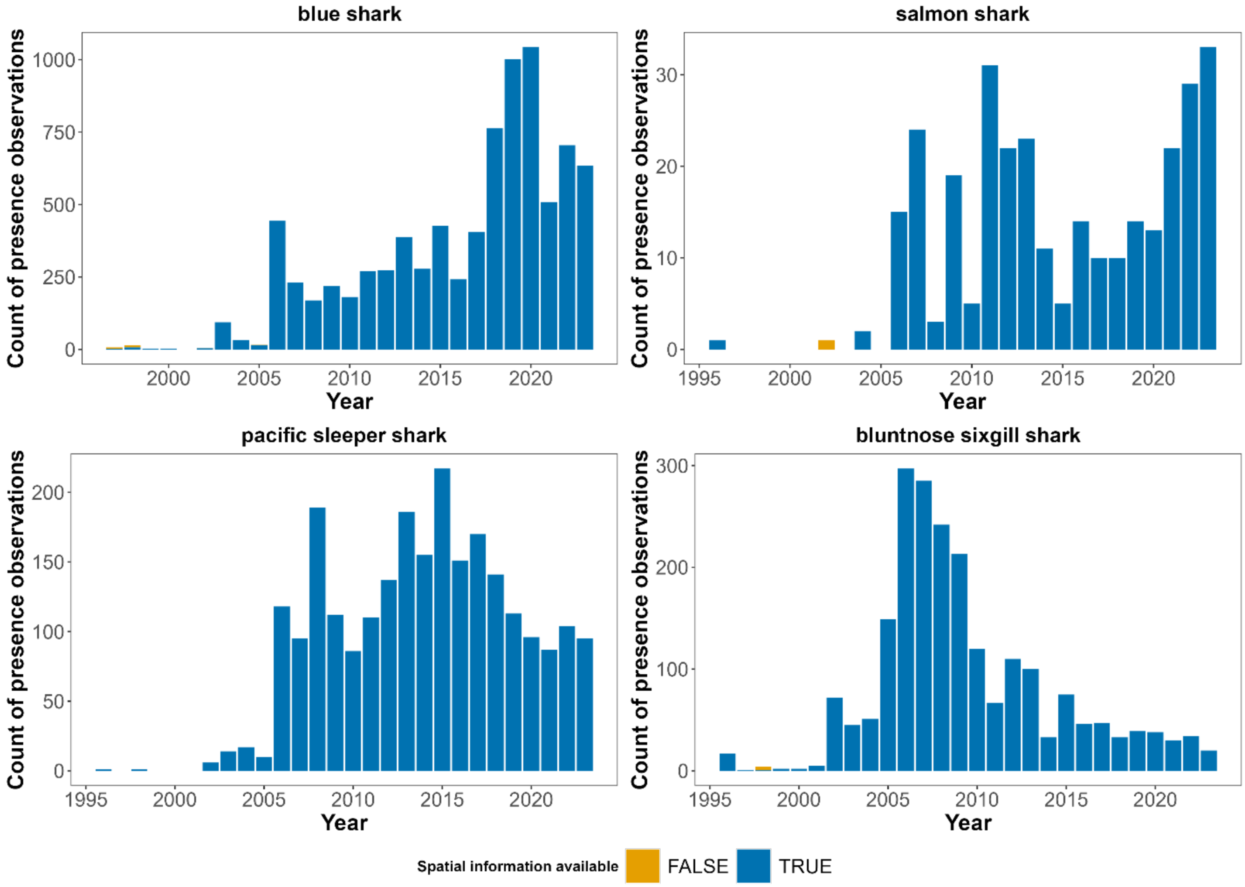

Figure S1: Proportion of presence observations in the commercial hook and line catch data with (blue) and without (orange) spatial information.

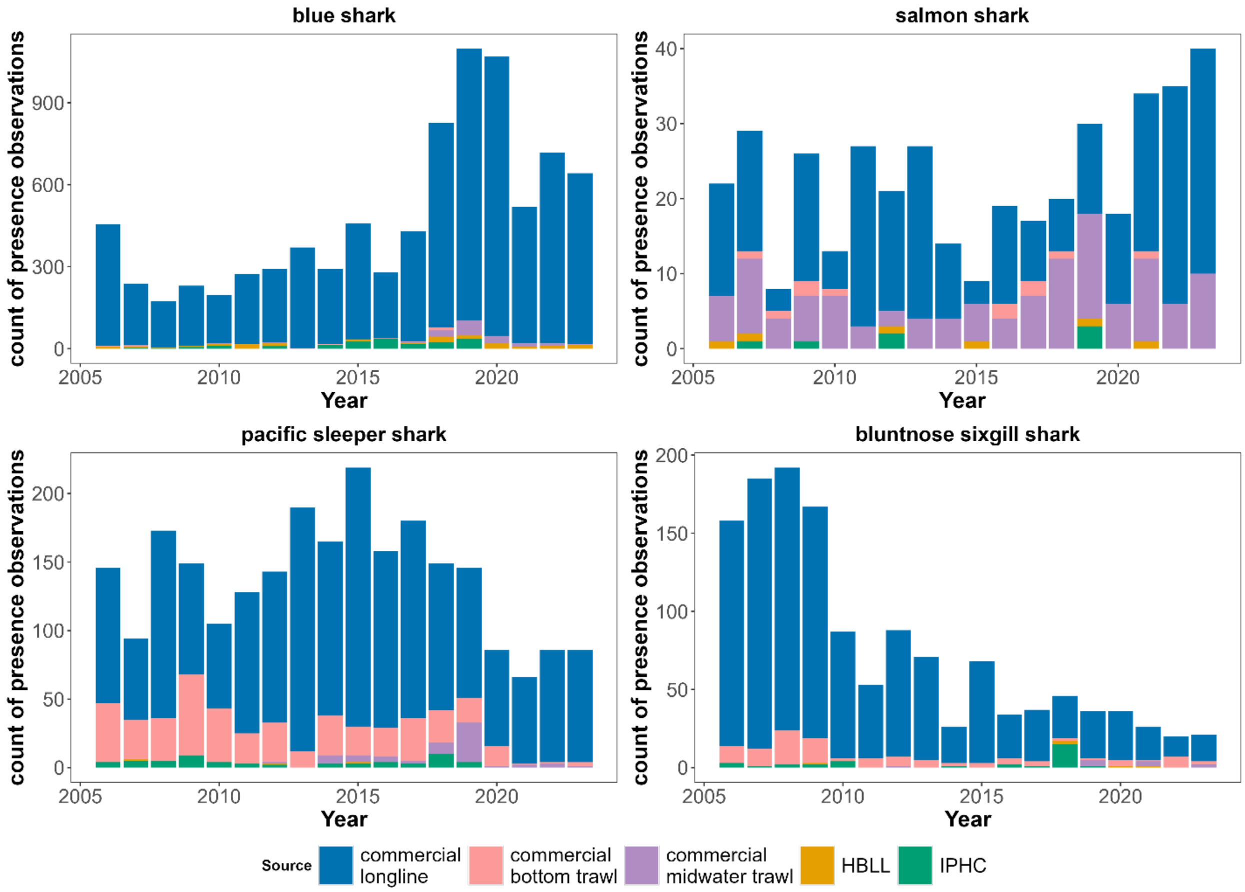

Figure S2: Number of presence observations in each year in commercial longline (blue), commercial bottom trawl (pink), commercial midwater trawl (purple), HBLL (orange) and IPHC (green).

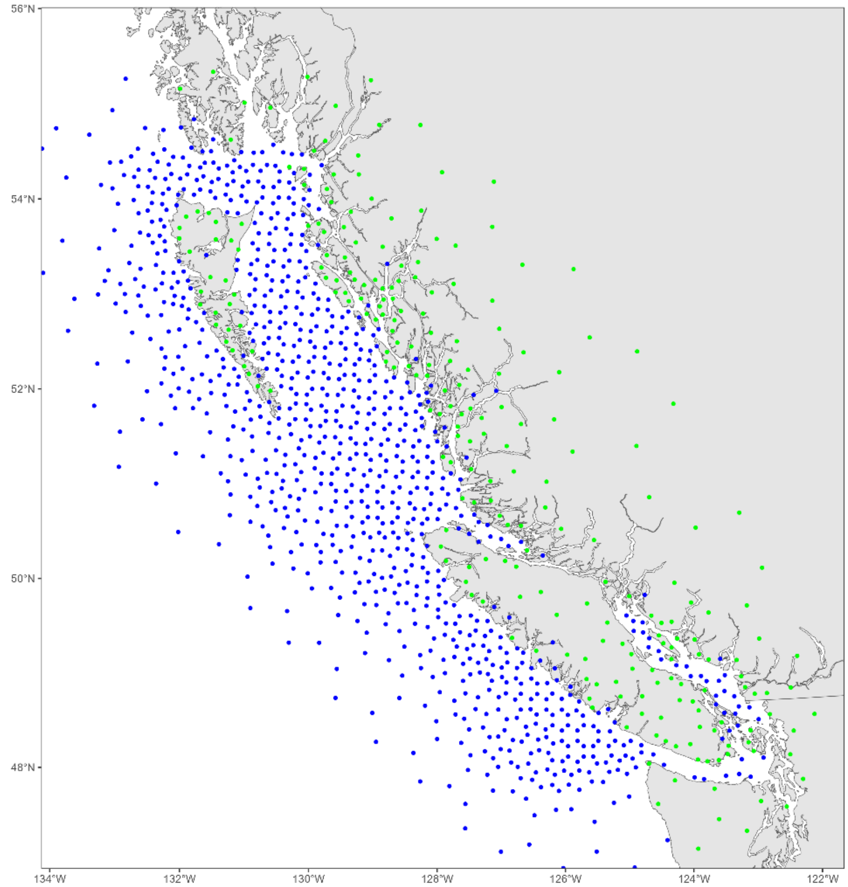

Figure S3:Map showing the mesh vertices used in the spatial random field. Blue points are located in the water, and green points are located on land. The map projection is NAD83/BC Albers.

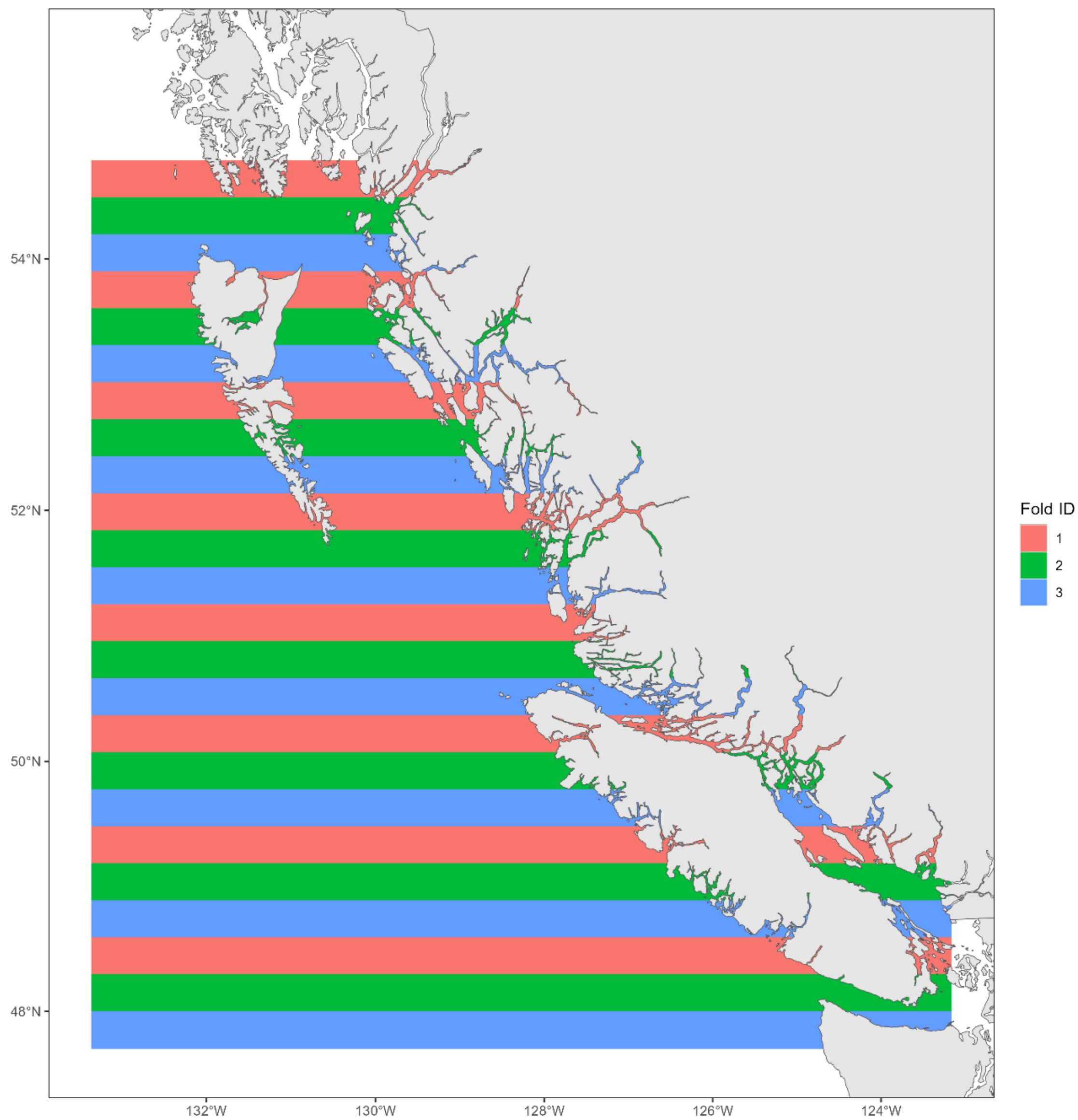

Figure S4: Spatial blocks used for cross validation. Twenty-four blocks divide the coastline equally from north to south, with each block assigned to one of three folds. Colours indicate the fold each point was included in for the cross-validation analysis. Map projection is NAD 83/BC Albers.

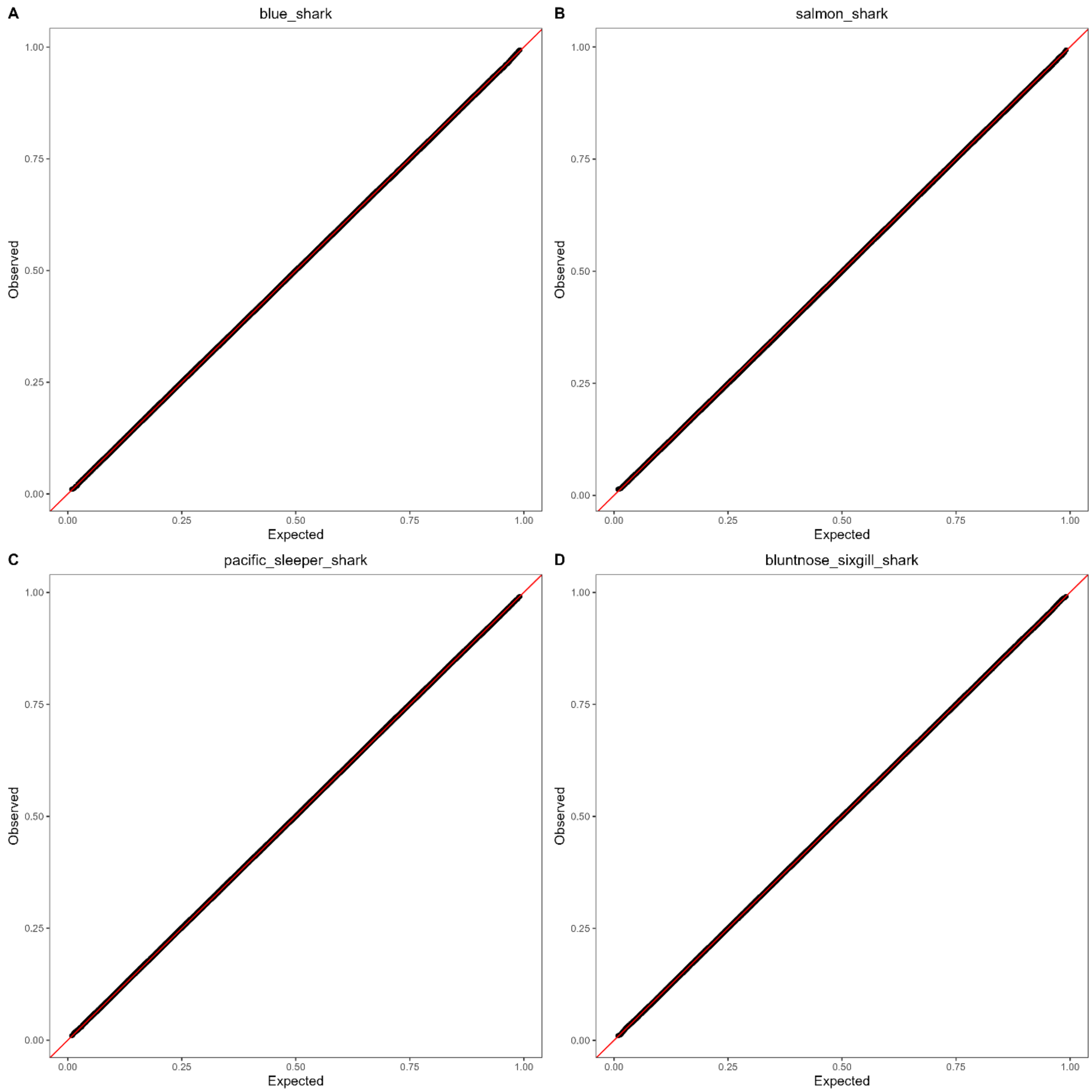

Figure S5: Quantile-quantile (QQ) plots of model residuals.