The following supplement accompanies the article

Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish): a flexible vulnerability assessment approach to quantify the cumulative impacts of fishing in data-limited settings

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Supplement 1

Text S1. Developing Relative Environmental Suitability (RES) maps for estimating stock distribution in the eastern Pacific Ocean.

In this study, the area occupied by each of 24 targeted and non-targeted species in the tuna fisheries in the eastern Pacific Ocean was estimated using modelled species distribution maps from AquaMaps (www.aquamaps.org). The modelling approach, adapted from the relative environmental suitability (RES) model developed by Kaschner et al. (2006), used species occurrences filtered by expert knowledge on distribution and habitat usage to estimate species tolerances for environmental variables used as predictors of species presence. These included depth, sea temperature, salinity, and primary production. Models of species distribution were derived by matching these environmental tolerances with local environmental conditions to determine the relative suitability of an area for a species, expressed as probabilities of occurrence at 0.5º latitude x 0.5º longitude (half-degree cell) spatial resolution.

Model input parameters

The AquaMaps model used point data, bounding box coordinates, FAO areas, depth ranges, and a pelagic flag as model input parameters. Point data consisting of geo-referenced occurrence records were sourced from online biodiversity information systems GBIF (Global Biodiversity Information Facility; gbif.org), OBIS (Ocean Biogeographic Information System; iobis.org), FishBase (fishbase.org), SeaLifeBase (sealifebase.org), and observer and logbook data held by the Inter-American Tropical Tuna Commission (IATTC).

Bounding box coordinates, composed of geographic coordinates defining the northernmost, southernmost, westernmost and easternmost extents of the known native range of a species, and FAO area assignments where a species naturally occurs (covering FAO areas 67, 77, 87 and 81, in this study) were extracted from FishBase for pelagic and mesopelagic teleosts, sharks and rays, and from SeaLifeBase for sea turtles and dolphins.

Depth data, covering the minimum and maximum values of both absolute and preferred or common depth ranges (in meters) recorded for a species based on literature, were mostly taken from FishBase and SeaLifeBase. For species with no published values, depth ranges were estimated from other information within these databases related to the species such as habitat description, depth range of congeners or other species of the same family, or minimum and/or maximum depths recorded from survey data.

A pelagic flag was also used to enable the model to consider whether the distribution of a species is related to the sea bottom. Data in FishBase and SeaLifeBase regarding the adult feeding and breeding behavior of a species were converted to True and False statements. True flags that a species is found in the water column well above and independent of the bottom (such as pelagic-oceanic and bathypelagic species). False indicates species occurrence is influenced by bottom depth (such as neritic, demersal and reef-associated species), and instructs the model to apply bottom filters when computing probability of occurrence of a species.

Environmental layers

The AquaMaps model used several environmental parameters related to physical and biological factors that structure the habitat of marine species, and can be used as predictors of species occurrence at large scales: depth, sea temperature, salinity, and primary production. The model in general also considers sea ice concentration but its contribution was negligible given that this study focused on species in tropical tuna fisheries. Environmental layers for these parameters were obtained at 0.5º x 0.5º resolution and stored as sets of cell attributes in a Half-degree Cell Authority File (HCAF). Each cell was geo-referenced and contained environmental parameter values for:

- Depth – minimum and maximum cell bathymetry derived from ETOPO 2min negative bathymetry elevation; in meters;
- Sea temperature – observed mean annual surface and bottom sea temperature derived from NCEP SST Climatology, NOAA (1982-1999); in degrees Celsius;
- Salinity – observed mean annual surface salinity provided by the World Ocean Atlas (1982-1999), and observed mean annual bottom salinity provided by the World Ocean Atlas Bottom Source Information (1990-1999); in practical salinity units (PSU);
- Primary production – Proportion of annual primary production in a cell from Sea Around Us, University of British Columbia; in $mgC \cdot m^{-2} \cdot day^{-1}$;
- Distance to land – distance of marine cell to nearest coastal cell from Sea Around Us, University of British Columbia; in kilometers.

Generating species environmental envelopes

A species environmental envelope is a response curve that describes the habitat usage or environmental tolerances of a species. In AquaMaps, the environmental envelopes assume a trapezoidal shape (Fig. S1), with four thresholds composed of the minimum and maximum values of the absolute (Min_A, Max_A) and preferred (Min_P, Max_P) tolerance ranges of a species for a given environmental parameter.

To generate the environmental envelopes, the bounding box coordinates were used to filter for point data falling within the species' native range. Where bounding box coordinates were unavailable, the limits of the FAO areas encompassing the range of the species were used. The filter process was performed as an independent verification of the validity of the occurrence records.

The filtered point data (treated as 'good points') were then used to identify half-degree cells within which they fall in the HCAF table. These cells (treated as 'good cells'), in turn, were used to extract parameter values in the HCAF from which the threshold values of the environmental envelopes of a species were computed. Absolute and preferred minima and maxima for all environmental predictors, except for depth, were computed from the environmental attributes of "good cells" using the following rules:

1. Min_A = 25th percentile - 1.5 × interquartile or absolute minimum in extracted data (whichever is lesser),
2. Max_A = 75th percentile + 1.5 × interquartile or absolute maximum in extracted data (whichever is greater),

3. Min_P = 10th percentile of observed variation in an environmental parameter,
4. Max_P = 90th percentile of observed variation in an environmental parameter.

Depth envelope threshold values were either taken directly or estimated from data in FishBase and SeaLifeBase.

Additional rules were further applied to prevent the use of nonsensical values or to conform to basic biological concepts. For instance:

- If Depth $Min_A \leq 200$ m, envelope computations for sea temperature and salinity were based on surface values, and conversely, on bottom values if Depth $Min_A > 200$ m.
- For all species with Temperature $Max_P \geq 25$ ºC, Temperature Max_A was set to Temperature $Max_P + 4.2$ ºC.
- Where Temperature $Max_A \leq 5$ ºC degrees (i.e. polar and deepwater species), the minimum distance between Temperature Min_P and Temperature Max_P was set to 0.25 ºC, and to 1 ºC where Temperature $Max_A > 5$ºC.

Computing relative probabilities of species occurrence

The AquaMaps model derives relative probabilities of species occurrence by evaluating how well local environmental conditions in a given half-degree cell match a species' environmental tolerances. Thus, the probabilities of occurrence were calculated by evaluating environmental attributes in the HCAF against a species' environmental envelope (Fig. S1), using the following rules:

1. If the value (mean) of an environmental parameter in a half-degree cell fell within the preferred range of the species for that parameter (i.e. within Min_P to Max_P), the probability of species occurrence was set at P=1.00,
2. If the value (mean) of an environmental parameter fell outside of either of the preferred range thresholds, the probability of occurrence was calculated to decrease linearly towards the species' absolute minimum or maximum parameter thresholds (i.e. from between Min_P to Min_A or from Max_P to Max_A),
3. If the value (mean) of an environmental parameter fell outside either of the absolute thresholds (i.e. lower than Min_P or higher than Max_P), the probability of species occurrence was set to zero.

The probability of occurrence was first calculated for each environmental parameter in a half-degree cell. Then the product of the individual probabilities was calculated to obtain the overall probability of occurrence in a given half-degree cell (P_c), that is:

$$P_c = P_{depth} \times P_{temperature} \times P_{salinity} \times P_{primary\ production}$$

All half-degree cells with overall probabilities of occurrence greater than zero ($P_c>0$) were then compiled for each of the 24 species used in the study and were sent to the C-squares Mapper (http://www.cmar.csiro.au/csquares) to plot the default predictive range maps for these species, and uploaded online at www.aquamaps.org.

In a final step, the default maps underwent verification. The predicted native range for the 24 species were reviewed against distribution information in FishBase and SeaLifeBase. Maps that required adjustments were edited using the Create-Your-Own-Map (CYOM) interface in aquamaps.org. Modifications typically included editing area restrictions (bounding box or FAO areas) of a species, and adjusting minimum and maximum environmental envelope thresholds, after which the maps were regenerated and finalised. The reviewed maps then served as the relative environmental suitability maps used in determining the preferred knife-edge probability-of-occupancy (Ψ) threshold value to define the area occupied by a stock in applying the EASI-Fish model to each of the targeted and non-targeted species in the EPO tuna fisheries assessed in the study.

LITERATURE CITED

Kaschner K, Watson R, Trites AW, Pauly D (2006) Mapping world-wide distributions of marine mammal species using a relative environmental suitability (RES) model. Mar Ecol Prog Ser 316:285-310

Table S1. Species, FAO species code, common name, number of observations, and preferred probability-of-occupancy (ψ) threshold value used for developing distribution maps using relative environmental suitability (RES) models (Kaschner et al. 2006) for each species assessed to be impacted by tuna fisheries in the eastern Pacific Ocean.

Species	**Code**	**Common name**	**Number of observations**	**Preferred probability of occupancy**
Thunnus albacares	YFT	Yellowfin tuna	10,591	0.50
Thunnus obesus	BET	Bigeye tuna	9,945	0.50
Kajikia audax	MLS	Striped marlin	5,368	0.50
Xiphias gladius	SWO	Swordfish	10,524	0.50
Katsuwonus pelamis	SKJ	Skipjack tuna	5,834	0.50
Thunnus alalunga	ALB	Albacore	8,030	0.50
Makaira nigricans	BUM	Blue marlin	10,240	0.50
Istiophorus platypterus	SFA	Indo-Pacific sailfish	969	0.70
Coryphaena hippurus	DOL	Dorado	12,542	0.60
Acanthocybium solandri	WAH	Wahoo	11,000	0.50
Carcharhinus falciformis	FAL	Silky shark	8,916	0.60
Prionace glauca	BSH	Blue shark	3,066	0.50
Alopias superciliosus	BTH	Bigeye thresher	379	0.60
Carcharhinus longimanus	OCS	Oceanic whitetip shark	1,627	0.60
Sphyrna zygaena	SPZ	Smooth hammerhead	515	0.50
Isurus oxyrinchus	SMA	Shortfin mako	2,102	0.50
Lepidocybium flavobrunneum	LEC	Escolar	2,378	0.50
Lampris guttatus	LAG	Opah	428	0.60
Mobula japanica	RMJ	Spinetail devil ray	726	0.70
Pteroplatytrygon violacea	PLS	Pelagic stingray	2,787	0.45
Dermochelys coriacea	DKK	Leatherback sea turtle	351	0.55
Lepidochelys olivacea	LKV	Olive Ridley sea turtle	1,382	0.80
Stenella attenuata	DSP	Pantropical spotted dolphin	1,364	0.50
Delphinus delphis	DCO	Common dolphin	1,301	0.90

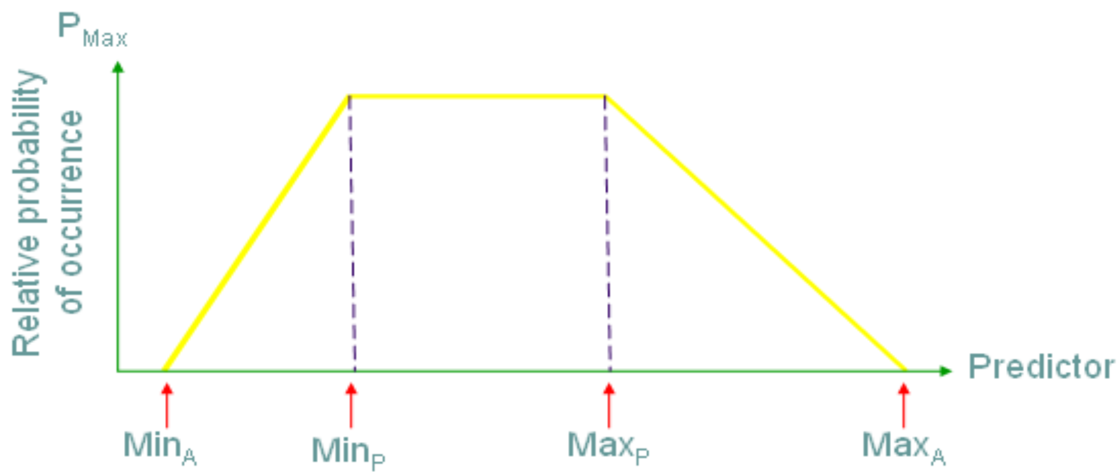

Figure S1. Graphical representation of a species-specific environmental envelope showing the minimum and maximim absolute (A) and preferred (P) tolerance range for one of four environmental parameters (depth, sea temperature, salinity, and primary production) used to predict the species' probability-of-occurrence in a given half-degree cell in the eastern Pacific Ocean.

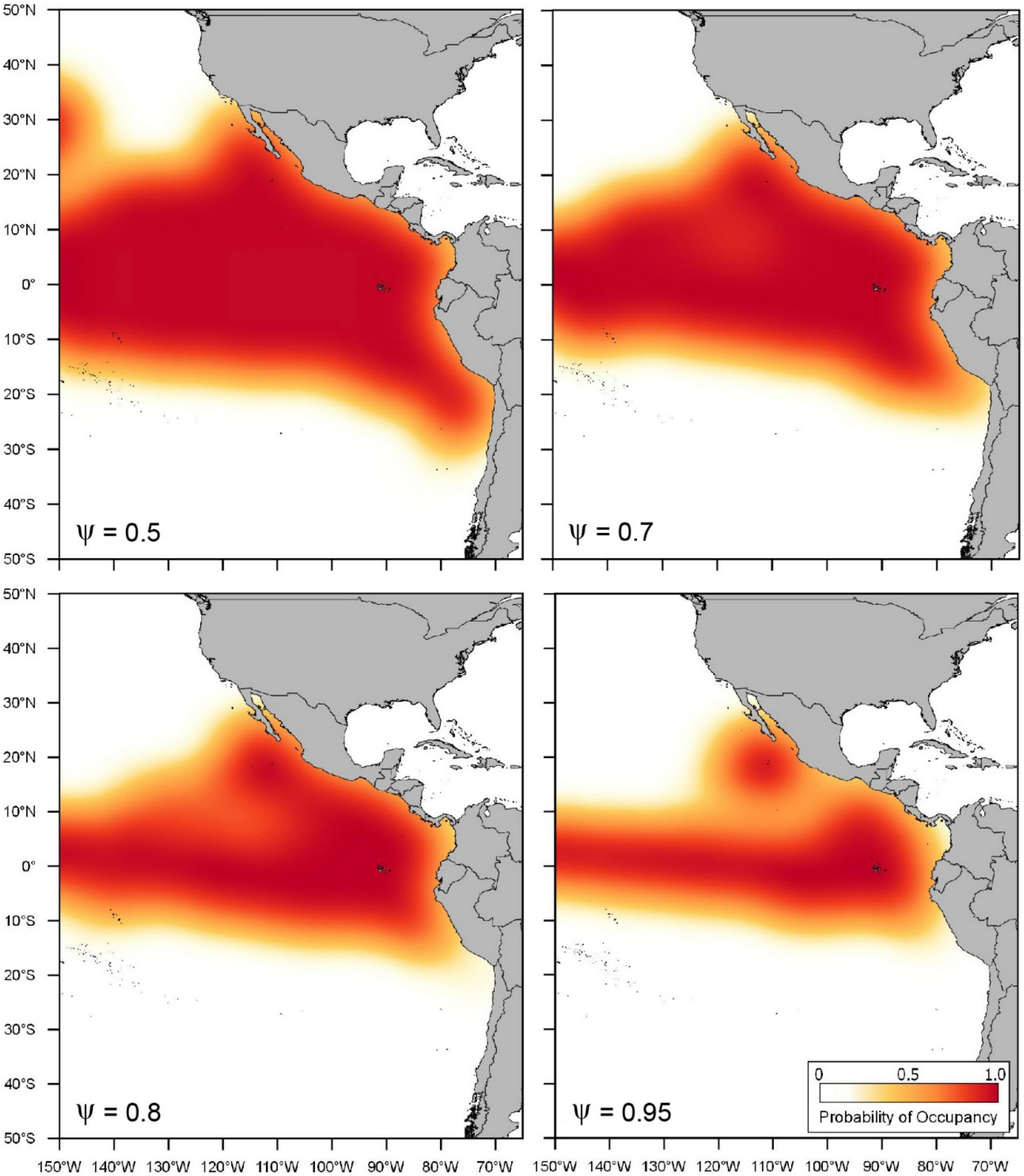

Figure S2. Maps showing the predicted distribution of *Mobula japanica* in the eastern Pacific Ocean using probability-of-occupancy (ψ) thresholds of 0.5, 0.7, 0.8 and 0.95 based on presence-only data in relative environmental suitability models described by Kaschner et al. (2006).