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Characterizing environmental and spatial variables associated with the incidental catch of olive ridley (*Lepidochelys olivacea*) in the Eastern Tropical Pacific purse-seine fishery

JOSE T. MONTERO,[1]* RAUL O. MARTINEZ-RINCON,[2] SELINA S. HEPPELL,[3] MARTIN HALL[4] AND MICHAEL EWAL[5]

[1]*Center of Applied Ecology and Sustainability (CAPES), Pontificia Universidad Catolica de Chile, Avenida Libertador Bernardo O'Higgins 340, Santiago, Chile*
[2]*Centro de Investigaciones Biológicas del Noroeste (CIBNOR), CONACYT Research Fellow, Avenida IPN s/n, La Paz, B.C.S. 23096, Mexico*
[3]*Department of Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, OR 97331, U.S.A.*
[4]*Inter American Tropical Tuna Commission, (IATTC) 8901 La Jolla Shores Drive, La Jolla, CA 92037-1508, U.S.A.*
[5]*Geomatic Research, Corvallis, OR 97330, U.S.A*

ABSTRACT

In the Eastern Tropical Pacific (ETP), a region of high fishing activity, olive ridley (*Lepidochelis olivacea*) and other sea turtles are accidentally caught in fishing nets with tuna and other animals. To date, the interaction between fishing activity, ocean conditions and sea turtle incidental catch in the ETP has been described and quantified, but the factors leading to the interaction of olive ridleys and fishing activity are not well understood. This information is essential for the development of future management strategies that avoid bycatch and incidental captures of sea turtles. We used Generalized additive models (GAM) to analyze the relationship between olive ridley incidental catch per unit effort (iCPUE) in the ETP purse-seine fisheries and environmental conditions, geographic extent and fishing set type (associated with dolphins, floating objects or in free-swimming tuna schools). Our results suggest that water temperature, set type and geographic location (latitude, longitude and distance to nesting beaches) are the most important predictor variables to describe the probability of a capture event, with the highest iCPUE observed in sets made over floating objects. With the environmental predictors used, sea surface temperatures (SST) of 26–30°C and chlorophyll-*a* (chl-*a*) concentrations <0.36 mg m^{-3} were associated with the highest probability of an incidental catch. Temporally, the highest probability of an incidental catch was observed in the second half of the year (June to December). Four regions were observed as high incidental catch hotspots: North and south of the equator between 0–10°N; 0–10°S and from 120 to 140°W; and along the Colombian coast and surrounding regions.

Key words: Eastern Tropical Pacific, General Additive Model, incidental catch, Inter American Tropical Tuna Commission, olive ridley, purse-seine, spatial prediction

INTRODUCTION

Human impacts on the world's oceans are extensive and sometimes devastating, requiring urgent management and comprehensive research to assess marine resources in a suitable way (Halpern *et al.*, 2008). One of the main activities of humans in the oceans is fishing, which can cause a decline in the population levels of target species and associated non-target species when the fishing operations are not managed in a sustainable way. A central issue of marine fisheries is bycatch, which corresponds to unwanted species that are caught and end up killed or severely damaged during fishing operations (Hall, 1996; Hall *et al.*, 2000). Some of the negative consequences of bycatch are gear damage, income and fishing time lost, as well as injury, stress and death for marine animals (Hall, 1996). The latter has been found to be a driver of population decline in several species of mega fauna, including sea turtles (Lewison *et al.*, 2004).

Loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles are more often caught in pelagic long lines fishing gears, followed by olive ridley (*Lepidochelys olivacea*) and green (*Chelonia mydas*) (Polovina *et al.*, 2003), hawksbill (*Eretmochelys imbricata*) and Kemp's ridley (*L. kempii*) (Ramirez and Ania, 2000). Bycatch and incidental catch can occur when the animals feed directly on bait, are entangled

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*Correspondence. e-mail: josetomontero@gmail.com

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or incidentally captured by the fishing gear (Pinedo and Polacheck, 2004). The probability of an incidental catch interaction increases when the spatio-temporal overlap between the critical habitat of the animals and the fishing activity is large and extensive. However, not all the interactions of fishing gear and accidentally caught animals correspond to a bycatch event. Bycatch refers specifically to captures ending in mortality and incidental catch when the untargeted specimen is released alive (Hall, 1996; Hall *et al.*, 2000).

To date, the factors leading to the incidental catch of olive ridleys in pelagic habitat associations in the Eastern Tropical Pacific (ETP) region have not been well understood. Most research has focused on describing local potential habitats of the turtles using satellite tracking and surveys conducted at small scales. For example, Peavey (2010) used three different modeling techniques to describe the preferred pelagic habitat and distribution patterns of olive ridleys, but the results were not fully conclusive as a result of missing data and small sample sizes (Peavey, pers. comm.). To determine the pelagic habitat and population distribution patterns of olive ridley, it is necessary to include additional abiotic and biotic factors and combine fisheries dependent and independent data in a model. Also, the seasonal and interannual variability of the population patterns can be key components to explain distribution patterns (Peavey, pers. com). For example, Roberts *et al.* (2009) studied the incidental catch of olive ridley in a small region of the ETP (7–20°N, 85–105°W) using the Inter American Tropical Tuna Commission (IATTC) olive ridley incidental capture data. His results suggested a strong influence of intra annual variability (nesting versus non-nesting season), sea surface temperatures (SST), chlorophyll-*a* (chl-*a*) concentration and eddy proximity over the turtle' incidental catch spatial distribution in the coastal region. Consequently, analyzing the purse-seine incidental catch data of olive ridley collected by the IATTC in the ETP at a large spatial scale is valuable to develop incidental catch risk maps (Roberts, 2006), infer habitat preferences and establish a methodology to analyze the same kind of data for other species of sea turtles recorded as bycatch or incidental catch. This can be possible through modeling the incidental catch per unit effort (iCPUE) against environmental predictors that have been shown to be important characteristics of the habitat of the species.

Purse-seine fisheries in the Eastern Tropical Pacific

During the 1950s, the ETP tuna fisheries started to use purse-seine nets. The tuna school is encircled with a large net (Hall and Roman, 2013), and then the bottom of the net is closed ('pursed') (Franco-Gonzales *et al.*, 1998). Tunas are captured under three circumstances: (i) *Log or FAD (Fish Aggregating Device) sets*: here, tuna are caught under or near floating objects. Usually, fish are attracted to floating objects for food and protection from predators. This method often leads to a high bycatch and incidental catch because floating objects attract a large number of untargeted marine species. The catches made over floating objects contains a wide variety of animals, including other tuna-like fishes, sharks, some billfishes and turtles (Hall and Roman, 2013); (ii) *School sets:* tuna are captured swimming or feeding on schools of prey, but not associated with floating objects or dolphins. The accidental catch and bycatch are generally less diverse than the ones made over or near floating objects. Primary bycatch is other tuna-like fishes (Hall and Roman, 2013); (iii) *Dolphin sets:* tuna schools are found associated with dolphins (Franco-Gonzales *et al.*, 1998; Hall and Roman, 2013). This type of fishing was temporarily reduced in the early 1990s owing to 'tuna safe' fishing requirements by the U.S. and European markets, leading to an increase in log sets and free school fishing (Hall, 1996). In the context of purse-seine fishing, the catch of olive ridley, in most cases, does not end with the death or injury of the turtle (Hall and Roman, 2013; Bourjea *et al.*, 2014), because the turtles are carefully released. Consequently, sea turtles captured in this fishery usually represent incidental catch but not bycatch (Hall, 1996).

Of the sea turtles present in the eastern Pacific, the olive ridley is the most numerous, and, therefore, it provides the best database to study the interactions with the fishery and the environment. In addition, the nations that participate in ETP fisheries have passed a number of resolutions to minimize the bycatches of all sea turtle species (ATTC resolution on bycatch, http://www.iattc.org/ResolutionsactiveENG.htm). Evaluation of the environmental characteristics of high incidental catch and bycatch areas is expected to contribute to this management goal.

We used generalized additive models (GAM) to identify hotspots of high incidental catch probability regions during purse-seine operations based on environmental and spatial variables. Additionally, the variables used can also have an influence over the distribution of olive ridley observed by the fisheries for tuna in the ETP, which also help to detect hot spots of high incidental catch probability. We utilized GAMs because of its statistical robustness, the capability to handle a variety of probability distributions of the response and to show non-linear responses through fitting smooth functions to the predictor variables. Also, GAMs have been widely used as a statistical modeling tool to analyze relationships between species distribution and the environment.

Our study was based on fitting non-parametric smoothing functions that allow a flexible interpretation of a complex species response to the environment as in the case of the olive ridley oceanic habitat in the ETP region (Leathwick *et al.*, 2006). Because the study is restricted to fisheries-dependent data, we identified characteristics of the environment and fishing behaviors that are most closely associated with incidental catch probability, rather than a comprehensive evaluation of olive ridley habitat.

METHODS

Study area

The ETP is a productive tropical system with frequent upwelling events (Fielder *et al.*, 1991). Nutrients are rarely depleted in the surface waters of the equatorial regions such as the Costa Rica Dome (Fiedler, 2002), Peru and Ecuador (Thomas, 1979), but are often very low in non-upwelling regions. The ETP ecosystem presents a large-scale spatial and temporal variability and unpredictability (Plotkin, 2010) driven by seasonal and inter-annual oceanic and atmospheric fluctuations (Reilly and Fiedler, 1994). For example, recurrent El-Niño Southern Oscillation events cause significant shifts in the oceanographic conditions and spatial-temporal differences in resources distribution (Fiedler, 1992).

Olive ridley records

The IATTC provided the olive ridley records used for this study (Fig. 1). Since 1979, the IATTC has been placing observers on-board purse-seine fishing vessels of cooperating nations that fish tuna in the ETP regions. Originally, the data collected were used for tuna population assessments to understand the spatial overlap and interactions between dolphin and tuna, and to identify methods to reduce dolphin mortality (IATTC, 2000). However, over the years, observers have been regularly collecting additional data including records of floating objects, sea turtles, sharks and billfish.

The sea turtle database, initiated in 1993, is comprised of incidental captures and sightings from observer trip logs. Sea turtle records are usually associated with the fishing activity, when the animals are incidentally captured, but some sightings (observations outside the purse-seine net) may be made while the vessel is sailing or drifting.

The following list of variables from the IATTC olive ridley records from 1997 to 2009 were used for exploration and modeling: Year and month of the set (from 1997 to 2009); Fishing effort (measured as number of sets); Latitude and longitude where the set was made; Adult female turtles; Only vessel class 6 (see Supporting Information for details); and Associations (Table 1).

Figure 1. The presence of olive ridley incidental catch per set type in the Inter American Tropical Tuna Commission (IATTC) observer database from 1997 to 2009.

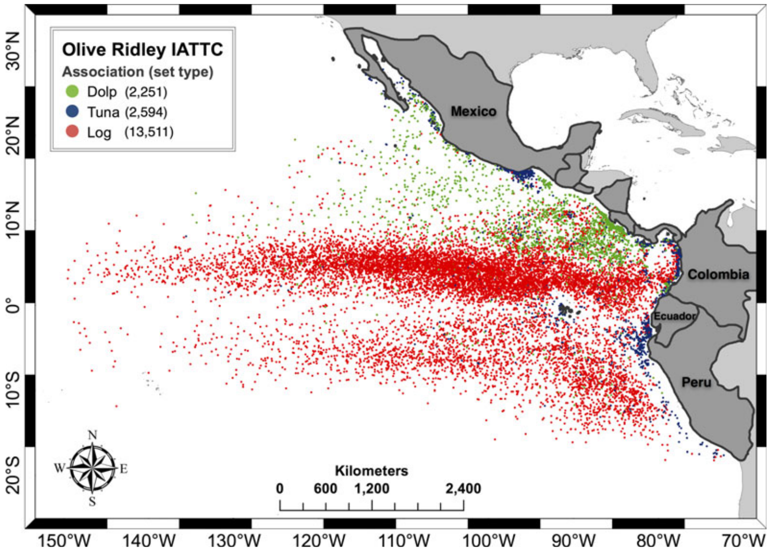


Table 1. Resolution, sources, description and scale of the explanatory variable used in the analysis.

Variable	Description	Spatial resolution	Temporal resolution	Source
SST	Veri High Resolution Radiometer (AVHRR)	5.5 km pixel^{-1}	Monthly	PATHFINDER v5 datasets NOAA
Chl-*a*	Sea-viewing Wide Field of View Sensor (SeaWiFS)	10 km pixel^{-1}	Monthly	NASA
SSH	Archiving, Validation and Inerpretation of Satellite Oceanographic Data (AVISO)	27 km pixel^{-1}	Monthly	Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO). Geoid referenced SSH measurements from ENVISAT, TOPEX/POSEIDON, JASON-1, and OSTM/JASON-2
Bathymetry	Gridded Global Relief Data ETOPO2	1 arc min	NA	USDOC, NOAA
DAN	Distance to arribada nesting beaches in the ETP	1 km pixel (euclidean)	NA	Derived from SWOT data points in ARCMAP 10
ONI	3-month running mean of ERSST.v3b SST anomalies derived from ENSO–3.4	NA	Monthly	NOAA (2013)
Latitude	Latitude where the set was made	NA	NA	IATTC
Longitude	Longitude where the set was made	NA	NA	IATTC
Association	Set type: Tuna, Dolphin (Dolp) and Floating Object (Log)	NA	NA	IATTC

chl-*a*, chlorophyll-*a*; SST, sea surface temperatures; SSH, sea surface heights; DAN, distance to arribada nesting beaches; ONI, Oceanic Niño Index.
Bathymetry was used in the exploratory analysis but not during the modeling process.

Predictor variables

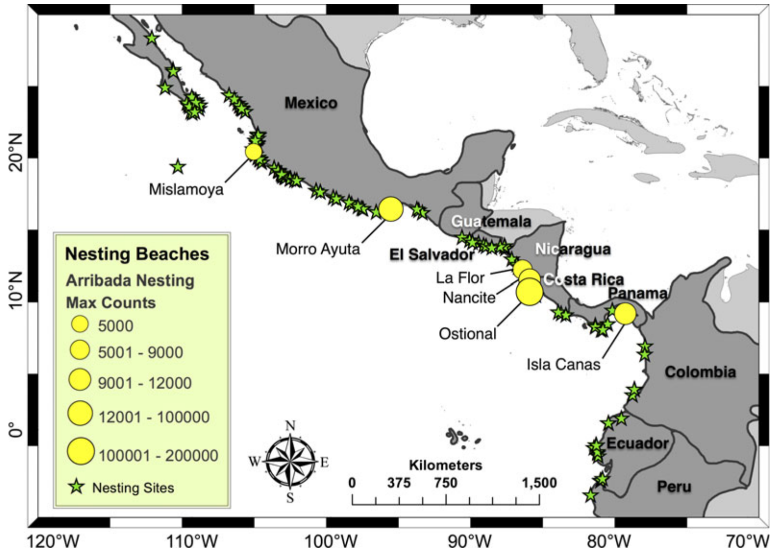
Satellite remote sensing data including chl-*a* concentration, SST, sea surface height anomaly (SSH) and satellite-derived bathymetry, were chosen as initial predictor variables (Table 1). Consistent with previous research describing the olive ridley pelagic habitat, encounters were in warm (24–31°C) and highly productive waters (Beavers and Cassano, 1996; Polovina *et al.*, 2004; Roberts, 2006). In addition, it has been documented that sea turtles such as loggerheads aggregate along SST and chl-*a* fronts (Polovina *et al.*, 2001, 2004) and olive ridley is apparently more frequent in purse-seine nets close to high-density fronts of chl-*a* and SST (Roberts *et al.*, 2009). Also, it is believed that sea turtles select their suitable habitats based on physical and biological conditions (Luschi *et al.*, 2003; Polovina *et al.*, 2004; Seminoff *et al.*, 2008), where zones high in chl-*a* concentration can be seen as a proxy for highly productive zones in the ocean. SSH was chosen because it can be used as a proxy for eddy presence (Griindlingh, 1995). It is known that animals aggregate in high-productive eddies as well as the Costa Rica Dome (Fiedler, 2002). We also included as an environmental predictor the Oceanic Niño Index (ONI), which is a 3-month running mean of Extended Reconstructed Sea Surface Temperature (ERSST.v4) anomalies in the El Niño 3.4 region (5°N–5°S, 120°–170°W) (Huang *et al.*, 2015). Plotkin (2010) described the potential effects of El Niño over the migration patterns behavior of olive ridley in the eastern tropical Pacific, so it is an important environmental variable to be considered in the modeling process.

Additionally, distance to 'arribada' (mass nesting events, Plotkin, 2007) nesting beaches (DAN) (Fig. 2) and month were included as predictor variables in order to explore the seasonal variability and the effect of proximity to the nesting grounds in the model.

Bathymetry and distance to nesting grounds

The bathymetry data were obtained from the high-resolution sonar 2-min Gridded Global Relief Data ETOPO2 (USDOC, NOAA, 2006). The ETOPO2 grid was imported to ARCMAP 10.1 and the bathymetry values extracted to match the incidental catch data. Even although there is not a clear understanding of why olive ridley associates to certain depths, bathymetry has been previously used as a predictor variable to described olive ridley habitat (Peavey, 2010) and can be a potential predictor of incidental catch.

Figure 2. Nesting grounds in the Eastern Tropical Pacific (ETP) region provided by State of the World's Sea Turtles (SWOT). The bubbles represent the positions for Arribada nesting beaches with counts extracted from Plotkin (2007). The green stars show the positions where olive ridley nests have been recorded but not in association with arribada.



The nesting ground positions (Fig. 2) in the ETP were provided by the State of the World's Sea Turtles (SWOT) (Kot *et al.*, 2014; Halpin *et al.*, 2009; SWOT Reports I-X). Only arribada nesting beaches were used to estimate the distance to nesting grounds (Fig. 2). However, it is important to notice that not all individuals generate arribadas, so the predictor variable refers to only the individuals that have this particular behavior. DAN was estimated by Euclidean distance in ARCMAP 10.1.

SST, SSH and chl-a

The oceanographic variables (SST, SSH and chl-*a*) were obtained as monthly averages from 1997 to 2009, matching the incidental catch data, trough R statistical package (R Development Core Team, 2015) using the 'xtracto3D' script, which is an adaptation of XTRACTO_3D_BDAP MATLAB coded for R, created by Bessey (2008). The 'xtracto3D' tool allows direct access to a set of oceanic variables provided by different sources and sensors at http://coastwatch.pfeg.noaa.gov/erddap/index.html (see Table 1).

Biological information and set type

As the IATTC database contains information of straight carapace length (SCL) for most of the incidentally caught turtles, it was possible to define the approximated life stage (adults, sub-adults and juveniles). Only adult turtles (SCL longer than 60 cm) were used for the modeling process, to make the distance to nesting beach variable relevant. This was 78% of total sea turtle observations in the database that included measurements of SCL.

The association (set type) was used as an additional categorical variable in the modeling process (Table 1). The set type where the turtle was recorded is listed as: sets made over floating objects (Log), schooling tuna (Tuna) and dolphins (Dolp). This is an important consideration for the modeling approach because it is well known that some species of sea turtles such as olive ridley are usually in association with floating objects (Pitman, 1992; Hall, 1996; Roberts, 2006; Roberts *et al.*, 2009). Consequently, purse seines would be expected to accidentally catch more turtles in sets made over those devices.

Data exploration and standardization

All the data were processed and analyzed with R (R Development Core Team, 2015). To standardize the IATTC data set and calculate the iCPUE, the point observations (Fig. 1) were converted to a grid of one-degree latitude per one-degree longitude for every month and year in each cell of the grid. Each cell collapsed information of the total number of sets, the total number of turtles, the average SCL, adult turtles and predominant set type (the most observed set type in the quadrant) for each month and year from 1997 to 2009. The oceanographic predictor variables were converted from the original format NetCDF to a gridded data frame of the same spatial and temporal resolution (monthly for each year per grid) and merged with the gridded incidental catches data set.

Extracted values for Bathymetry and DAN were added to the data set. Collapsing the data into a gridded region with monthly averages of the predictor variables, assumes that there is not variability within every month for the respective gridded region, adding bias to the results.

Incidental catch per unit effort

Catch rate standardization assumes a linear relationship between catch and effort as catch per unit effort CPUE = $C_t/E_t = qN_t$, where C_t represents the catch at time t, E_t the fishing effort, q the catchability coefficient and the local population size N_t. This relationship between catch rate and true abundance may be more complex than a simple linearity assumption from the formula above (Harley *et al.*, 2001; Gaertner and Dreyfus-Leon, 2004; Maunder and Punt, 2004; Haggarty and King, 2006). However, in this study iCPUE will be simply calculated as the relationship iCPUE = C_t/E_t, where C_t is the number of turtles caught in a 1°×1° cell size at month-year t and E_t as the number of sets made for the same cell at month-year t.

Spatial correlation between oceanic variables

After all the variables were extracted and tabulated into a data-frame, frequency distribution histograms were created and spatial correlations were performed for the environmental explanatory variables: SST, SSH, DAN, chl-*a* and Bathymetry. Spatial correlation is inherent in nature and occurs when the value of one variable can define another variable. The frequency histograms shown in Figure 3 suggest that turtles are mostly caught in waters 26–29°C; 3000–5000 m deep; −10 to −15 cm sea level height; intermediate distance from the DAN; and 0.1–0.5 mg m^{-3} chl-*a* concentrations. Bathymetry was strongly correlated with DAN (0.64) and chl-*a* (0.46). As bathymetry was correlated with two of the predictor variables, it was removed from the analysis.

Generalized additive models

A GAM (Hastie and Tibshirani, 1986, 1990) is a generalized linear model with a linear predictor. It involves a sum of smooth functions of the predictor variables (Wood, 2006). The general structure of the model is:

$$g(\mu_i) = X_i\theta + f_1(x_{1i}) + f_2(x_{2i}) + f_3(x_{3i}, x_{4i}) + \ldots \quad (1)$$

where $\mu_i = E(Y_i)$ and Y_i is an exponential family distribution. Y_i is the response variable, X_i is a row of the model matrix for any strictly parametric model component, θ is the parameter vector respectively and f_i are the smooth functions of the response variables x_i (Wood, 2006).

Modeling

The natural logarithm of olive ridley iCPUE was the response variable for the model and calculated as described in the data exploration section above, with a total sample size of $n = 2820$. The final predictor variables were: environmental variables: SST, SSH, ONI and chl-*a* (Table 1), spatial variables: Latitude, Longitude, DAN and association or set type: Tuna (unassociated), Dolphin and Log referring to floating objects. The model was constructed with all the predictor variables. Latitude and longitude were used as interaction terms.

The GAM used to predict olive ridley iCPUE was fitted in R (R Development Core Team, 2015) using the MGCV package version 1.7-19 (Wood, 2011), assuming a quasi-likelihood distribution. The quasi-likelihood distribution provides the ability to model count data that are more variable than the Poisson and Binomial distributions (see Wood, 2006 for further details). The final model fitted was:

$$\begin{aligned}\log(\text{iCPUE}+1) = {} & f_1(\text{Lon},\text{Lat}) + f_2(\text{SST}) \\ & + f_3(\log(\text{chl-}a)) + f_4(\text{SSH}) \\ & + f_5(\text{DAN}) + f_6(\text{ONI}) \\ & + f_7(\text{Month}) + \text{Association}\end{aligned} \quad (2)$$

Latitude and longitude were the only predictor variables that were included as an interaction term to explore the spatial distribution of iCPUE. The advantage of using latitude and longitude coordinates data in our model was to enable the model to fit the data with the geographic information for later spatial predictions of incidental CPUE.

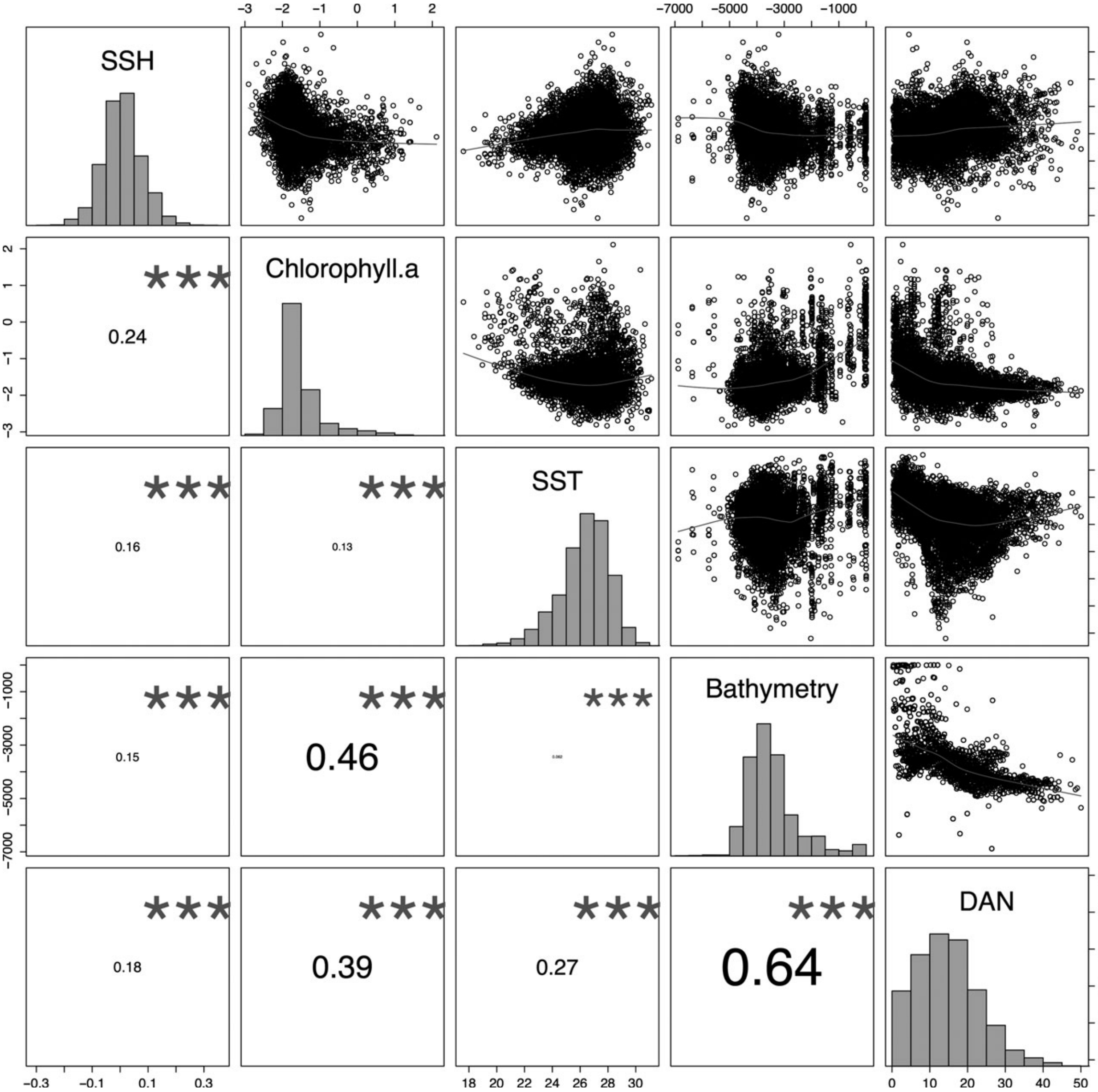
Relationship between predictor and response variables

To explore the relationship between olive ridley iCPUE and the predictor variables, we plotted the model response using partial dependence plots. These plots show the effect of a variable after accounting for the average effect of all other variables in the model (Friedman, 2001), thereby providing an indication of how iCPUE depends on each predictor variable.

Model performance

To evaluate the model performance, the data set was divided using a stratified random sampling into a training set with 70% of the data and a test set with the remaining 30%. As the original data were

Figure 3. Correlation matrix plot of each environmental predictor is displayed in the bottom left, including Pearson's Correlation coefficient describing the relationship between two variables. The significance code *** represent $P < 0.05$. Text is sized by the magnitude of the correlation (larger is high correlated; smaller is lower correlated). Bathymetry is highly correlated with log. Chl-*a* (0.46) and DAN (0.64).



not balanced, re-sampling was based on monthly strata to avoid bias in the results, particularly for calculation of the month effect. To compare the model performance, predictions were made with the test set. Then we used a Spearman's rank correlation coefficient (r_s) with its respective P-value to look at model accuracy. If the P-value is <0.05 and the $r_s > 0.1$ the test is considered passed (Lauria *et al.*, 2011). To assess model bias we performed a Wilcoxon's signed-rank test comparing observed versus predicted values. Wilcoxon's test compares the median observed versus predicted iCPUE, to test biased in the predictions. The test was considered passed if $P > 0.05$. Finally, the GAM.CHECK function was run to produce basic residual plots and information about the fitting process (see Supporting Information) and potential violation to statistical assumptions (Wood, 2006).

Spatial prediction

Spatial prediction maps of average, minimum, maximum and standard deviation of iCPUE were calculated from the trained model. The prediction was estimated using all the data not used for model training and included the predictor variables: SST, SSH, Chla-a, ONI, DAN, Association (Set type), latitude, longitude and month. Additionally, we interpolated predicted surfaces within a convex hull to fill the gaps where data were not available by fitting a Thin Plate Spline Regression Model over the predicted iCPUE containing spatial gaps.

RESULTS

Generalized additive model

Our fitted GAM explained 40% of the total deviance with an adjusted R^2 of 0.39. The smooth functions responses are shown in Figure 4. The model suggests higher values of iCPUE in purse seine sets made primarily over floating objects when SST is between 28–30°C, at low chl-*a* concentrations, mostly far away from the nesting beaches, when the ONI is positive and in the months of June to October. With respect to SSH, the relationship shown by the response curve suggests a higher iCPUE within negative and positive SSH anomalies. The effect plot of latitude-longitude suggests a high iCPUE to be inshore with two hot spots predicted: off the Colombian coast and in southern Mexico (Fig. 4).

Model performance

The Spearman's correlation to evaluate the model showed a significant positive correlation of observed versus predicted iCPUE ($r_s = 0.57$, $P \ll 0.0001$), suggesting fair model accuracy. In contrast, Wilcoxon's signed-rank test showed $P = 0.007$, suggesting bias in the model. This implies that the model is capable of describing the spatial distribution of iCPUE but it over and under predicts the observed values. The GAM diagnosis shows an approximately normal distribution of the residuals, a straight line in the Normal Q-Q plot, and a reasonable linear relationship between fitted values and response (see Supporting Information). Thus, the model appears to be correctly identifying areas of high iCPUE, given the information available.

Modeled spatial prediction

Our predicted maps shows four areas of high adult olive ridley incidental catch in the ETP (Fig. 5). Surprisingly, there was a low association of high iCPUE with arribada nesting beaches, probably because turtles spend most of the time feeding in oceanic waters far from shore, or because the timing of the arribada coincides with the fishing season. The highest incidental catch occurs in sets around floating objects, offshore between 0–10°N and 120–140°W, and 10°S and 100°W (Fig. 5). There was also a medium incidental catch predicted hot spot observed by the Colombian coast close to Isla Cana arribada nesting ground by Panama (Figs 2 and 5), where a considerable number of sets over floating objects are made.

DISCUSSION

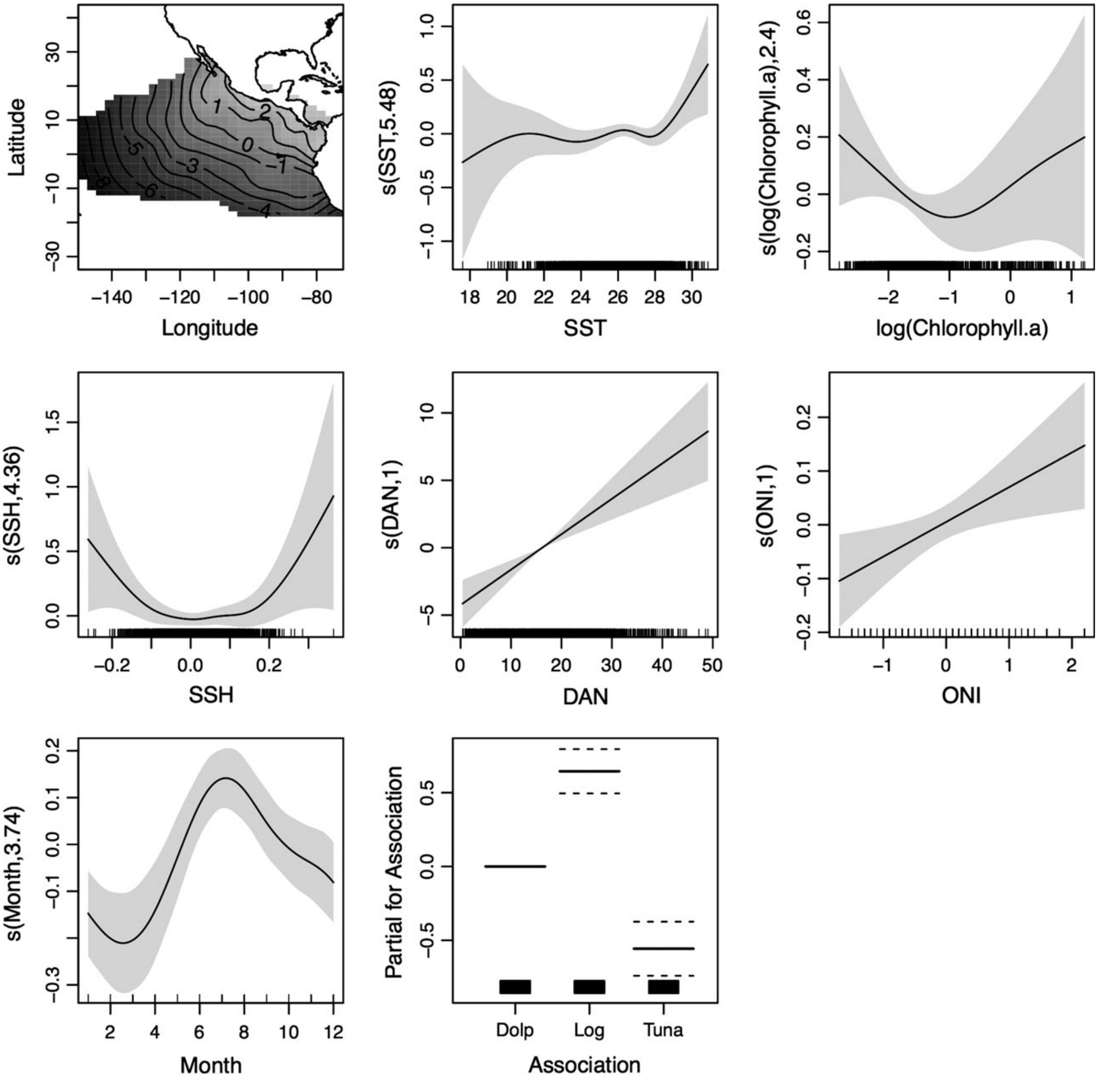
We successfully explained the spatial and temporal characteristics of olive ridley incidental catch by the ETP purse-seine fleet using observer data records from the IATTC. There is a considerable level of predictability in the relationship between the presence of olive ridley as incidental catch in the ETP within the set type, environment and spatial predictors. If we assume that the tuna fleet iCPUE is a fair representation of olive ridley abundance and distribution in the ETP, the model response allows inference about suitable habitats for this species of sea turtle. Preferred temperatures are 26–30°C, turtles are more likely to occur in areas of low chl-*a* concentrations (<0.36 mg m^{-3}) and are strongly associated with floating objects. Our results are consistent with Roberts (2006), who found that olive ridleys caught by the ETP tuna fleet are more common in areas of higher SSH along SST and in sets made over floating objects. However, our model predicts higher iCPUE along positive and negative SSH (Fig. 4). Roberts (2006) suggested that the turtles are found close to oceanographic convergences (sea level above average), but our results suggest that olive ridleys are also found in divergent zones below the sea level average.

The spatial component added in the model as an interaction of latitude and longitude was adequate to map high iCPUE regions on the coasts of Colombia and southern Mexico. These two high iCPUE regions might be associated with the arribada nesting grounds located in Isla Canas and Morro Ayuta, respectively (Figs 2 and 5).

Model response of the predictor variables

SST was the most important environmental predictor for olive ridley incidental catch in the purse-seine fishery. We observed that the olive ridley modeled iCPUE is higher in water between 26 and 30°C. A similar range of temperature (24–30°C) has been described as preferred for the species by Polovina *et al.* (2004).

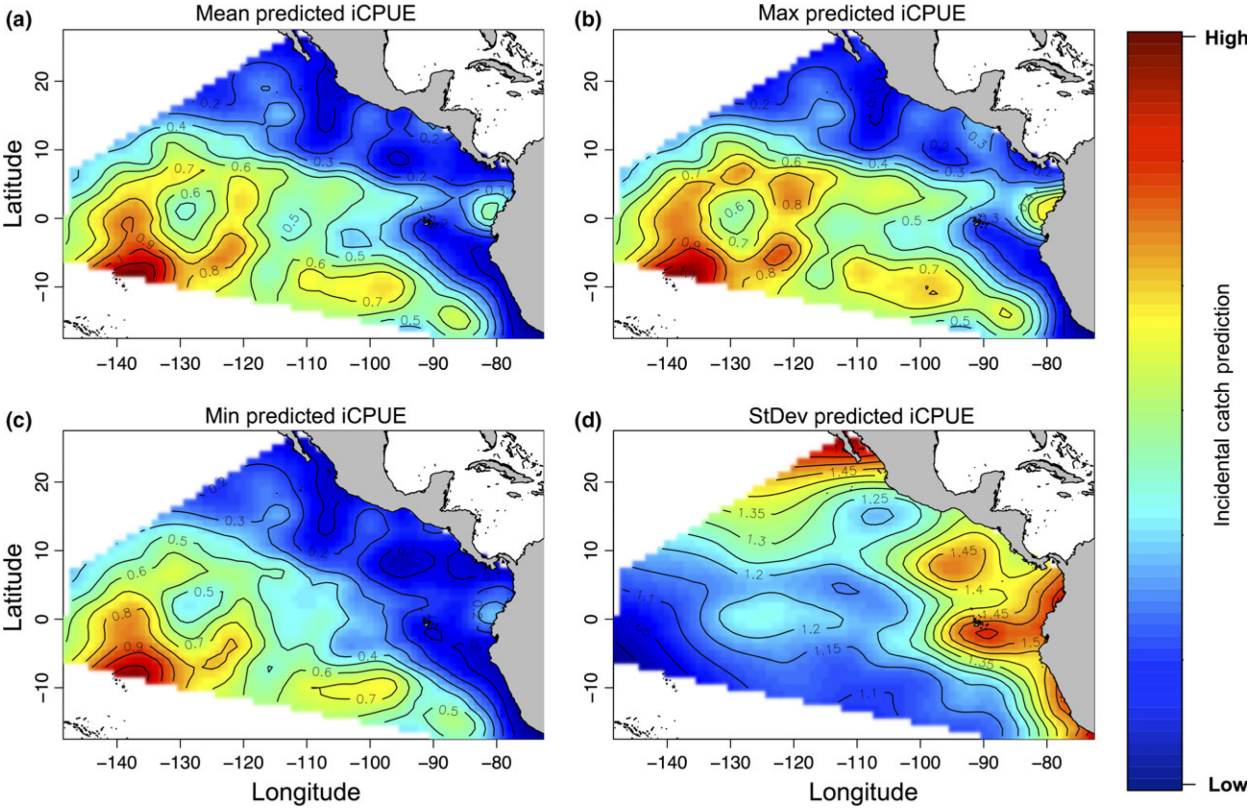
Figure 4. Variation of olive ridley incidental catch per unit effort (iCPUE) by the interactive generalized addictive model (GAM) using the environmental (sea surface temperature (SST), sea surface height (SSH), chlorophyll-*a* (Chl-*a*) and Oceanic Niño Index (ONI)], temporal (Month), spatial (DAN) and Set type (Dolp, Log and Tuna) as predictors. The *y*-axis represents the effect over log-transformed iCPUE. Shade regions and dashed lines represent confidence bands for smooths and parametric term (Association). Top left map: Effect of the location (Latitude, Longitued) over log-transformed iCPUE estimated from the GAM. White indicates high-predicted iCPUE and dark grey indicates low-predicted iCPUE.



Also, the majority of the turtles sampled in the study made by Peavey (2010), describing suitable habitats for olive ridley, showed preferred temperatures of 29.5–31.5°C. The results of this study for SST are also supported by the fact that ETP olive ridley presents complex movement patterns, where water temperatures are assumed to play a primary role influencing their spatial distribution (Plotkin, 2010) and perhaps the iCPUE spatial prediction.

The chl-*a* concentration was also an important environmental predictor of incidental catch, showing a negative relationship with olive ridley iCPUE within a range of 0.13–0.36 mg m^{-3}. Previous researchers have suggested that the olive ridley associates with

Figure 5. Predicted incidental catch of olive ridley across the fishery area in the Eastern Tropical Pacific (ETP) predicted from the generalized addictive model (GAM). (a) Mean incidental catch per unit effort (iCPUE); (b) Max of iCPUE; (c) Min iCPUE; (d) Standard deviation of iCPUE. The black lines are the predicted countours. NOTE: The mean prediction map was made averaging the predicted iCPUE by latitude and longitude for all the years and months included in the study to identify the mayor trends in the prediction of incidental catch.



chl-*a* of ~ 0.4 mg m^{-3} (Swimmer *et al.*, 2009). Additionally, Roberts (2006) suggested a higher interaction of olive ridley and purse-seine sets made at chl-*a* densities >0.25 mg m^{-3}. Our results also suggest an association of iCPUE with low-mid range productive patches. However, the relationship between chl-*a* and marine turtle distribution is not completely understood, but the chl-*a* gradients could influence marine invertebrates distribution which serve as preys for olive ridleys (Swimmer *et al.*, 2009). Moreover, olive ridley may be an opportunistic forager (Polovina *et al.*, 2001; Seminoff *et al.*, 2008), reacting to the productivity changes. Because of Roberts' (2006) suggestion that the most important predictor variables werefloating objects and a little influence of the environmental predictors, we explored the spatial relationship of the predicted iCPUE with Association and SST, chl-*a*, DAN and ONI (see Supporting Information). We also found that the highest predicted incidental catch of olive ridley is made on floating objects, and those seem to be the most influential predictor in our analysis. The prediction map (Fig. 5) suggests that the olive ridley iCPUE is higher where chl-*a* is low (north of the equator 0–10°N; south of the equator 0–10°S) and vice versa. Also, the predicted iCPUE is lower close to the coast, where chl-*a* is potentially high as a result of upwelling.

Our model showed a strong positive relationship of incidental catch and the ONI. These results are consistent with Plotkin's (2010) findings while tracking post nester olive ridley females, showing consistent changes in the migration patterns during a strong El Niño event. During El Niño, the appearance of strong winds produces eddies that move hundreds of miles off shore and could persist for several months (Stumpf and Legeckis, 1977). These cold upwelled nutrient-rich gyres can potentially provide resources and attract olive ridleys and other animals (Plotkin, 2010).

Month as a time variable was also an important predictor of iCPUE. The highest iCPUE was observed during the second half of the year, peaking at the months June through to September (Fig. 4). There is a clear segregation in the iCPUE by month factor in the GAM output. The highest iCPUE probability shown by the model happens one month before the nesting season, which peaks from August to October (Hughes and Richard, 1974; Cornelius and Robinson, 1986; Dash and Kar, 1990; Plotkin *et al.*, 1995; NMFS and USFWS, 1998). This result suggests that olive ridleys are more likely to be caught in this fishery right before the peak of the nesting season and that the iCPUE decreases when the olive ridley congregate to nest massively on shore. In contrast, the lowest predicted iCPUE observed (February–April) overlaps with the foraging season (January–May). Polovina *et al.* (2004) suggested that olive ridley spend only 20% of their swimming time at the surface and 40% of the time at 40 m, probably associated with feeding behaviours. Also, Kopitsky *et al.* (2004) described that olive ridley feed mostly in pelagic habitats over jellyfish and ctenophores in the ETP region, which suggests foraging behaviors at a depth of 150 m (Polovina *et al.*, 2004). This may suggest that the low iCPUE predicted during the foraging season is because of the fact that turtles are diving while looking for prey in those areas and time, escaping the purse-seine net before reaching more than 150-m depth during net deployment while fishing operations. Also, incidental catch is likely to happen in areas where turtles feed close to the surface, or in association with floating objects. Consequently, understanding the olive ridley feeding behavior can potentially reduce the number of turtles caught in the nets as previously described by Roberts *et al.* (2009).

It is not surprising to observe higher iCPUE in sets made over floating objects. Previous research suggested that olive ridley in the open ocean of the ETP region is often seen near floating objects, including anything from logs to plastic debris as well as dead whales (Pitman, 1992; Hall and Roman, 2013). The reason for the association is not totally understood; it is possible that the turtles feed on fish or invertebrates that also associate with floating objects (Pitman, 1992; IATTC unpubl. data). Data from IATTC observers indicate that 44% of olive ridley observations (sights made outside the purse-seine net) are in association with floating objects sets (Hall and Roman, 2013). Additionally, our analysis indicated that at least 75% of incidental catch records are in association with floating objects.

Spatial prediction of incidental catch

Three regions of high probability of incidental catch were observed (Fig. 5). All regions are located offshore, north of the equator and from 90 to 150°W between 0–10°N and 0–10°S (Fig. 5). The only high iCPUE coastal region predicted by the model was located close to the Colombian coast. This result may suggest a spatial–temporal overlapping of the arribada event (August–October) with high fishing activity close to the Colombian coast and Isla Canas (Figs 2 and 5), exclusively for this region. Although our results suggest a strong influence of oceanic conditions on the spatial distribution of olive ridley predicted iCPUE, it is challenging to identify the mechanisms behind to explain the observed patterns.

Although this research focused on a sea turtle species that is relatively numerous in the ETP, our results may help develop environmentally-based management approaches for the more endangered species, many of which are data poor because of their low frequency of encounter. The IATTC purse seine database covers a very broad region, and a period of over 20 yr, so it is a rich source of biological and ecological data on the species involved, even considering the caveats mentioned above. We anticipate that our analysis will contribute to sea turtle conservation efforts throughout the region.

Besides, the fishing nations of the area have passed resolutions (ATTC resolution on bycatch http://www.iattc.org/ResolutionsactiveENG.htm) to minimize the bycatches of all sea turtle species, and this type of study is expected to contribute towards that management goal.

The major limitations of this study are the use of fisheries-dependent data and the assumption that all fishing operations (each set made) has the same probability of catching a turtle, so inferences about the biology and incidental catch probabilities are biased by the nature of the data and fishery behavior, which is focused on catching tuna, not turtles. Consequently, any prediction for iCPUE can only be partially explained. The inclusion of fisheries independent or surveys designed specifically to detect and quantify olive ridley can considerably help to improve this study.

CONCLUSION

The prediction of olive ridley iCPUE using the data from the IATTC was satisfactory, with 40% of the variation explained by the predictor variables. The analysis indicates that even although iCPUE is primarily linked to sets made over floating objects, the environmental predictors such as SST (26–30°C), chl-*a* (<0.36 mg m^{-3}), distance to the arribada nesting beach (far from shore) and monthly variation (Month June–September) also contribute to olive ridley iCPUE-predicted values. Also, oceanic circulation may have a strong effect in the spatial distribution of the floating objects and perhaps the olive ridley iCPUE. As an example, to reduce the captures of olive ridley in this fishery, restrictions could have been implemented limiting sets made primarily over floating objects, north and south of the equator between 140 and 120°W, in waters between 26 and 30°C and a chl-*a* concentration lower than 0.36 mg m^{-3}. The conservation significance and impacts on the fishery of these measures need to be evaluated in the decision to implement. However, olive ridley populations are currently increasing within in a relatively short time period (Abreu-Grobois and Plotkin, 2008), so the restrictions may not prove necessary.

This information can be useful for future management plans as well as a baseline for monitoring the incidental catch of olive ridleys in the ETP region in different fishing fleets. Also, modeling incidental catch provides information about the oceanic conditions in which olive ridleys are more likely to be found in the ETP.

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REFERENCES

Abreu-Grobois, A & Plotkin, P. (IUCN SSC Marine Turtle Specialist Group). (2008) Lepidochelys olivacea. The IUCN Red List of Threatened Species 2008: e.T11534A3292503. 2015, doi: 10.2305/IUCN.UK.2008.RLTS.T11534A3292503.en. Downloaded on September.

Beavers, S.C. and Cassano, E.R. (1996) Movements and dive behavior of a male sea turtle (*Lepidochelys olivacea)* in the eastern tropical Pacific. *J. Herpetol.* **30:**97–104.

Bessey C. (2008) xtracto_3D_bdap: R code enabling the extraction of 3D environmental data via the NOAA-Coastwatch http://coastwatch.pfel.noaa.gov/xtracto/R/code/xtracto_3D_bdap.R. (accessed July, 2012)

Bourjea, J., Clermont, S., Delgado, A. *et al.* (2014) Marine turtle interaction with purse-seine fishery in the Atlantic and Indian oceans: lessons for management. *Biol. Conserv.* **178:**74–87.

Cornelius, S.E. and Robinson, D.C. (1986) Post-nesting movements of female olive ridley turtles tagged in Costa Rica. *Vida Silvestre Neotrop.* **1:**12–23.

Dash, M.C. and Kar, C.S. (1990) The Turtle Paradise, Gahirmatha: An Ecological Analysis and Conservation Strategy. New Delhi: Interprint, 295 pp.

Fiedler, P.C. (1992) *Seasonal Climatologies and Variability of Eastern Tropical Pacific Surface Waters.* NOAA Tech Memo NOAA-TM-NMFS-SWFSC-109.

Fiedler, P.C. (2002) The annual cycle and biological effects of the Costa Rica Dome. *Deep Sea Res. Part 1 Oceanogr. Res. Pap.* **49:**321–338.

Fielder, P.C., Philbrick, V. and Chavez, F.P. (1991) Oceanic upwelling and productivity in the eastern tropical pacific. *Limnol. Oceanogr.* **66:**1834–1850.

Franco-Gonzales, S.R., Méndez-Gómez-Humarán, I., Ortiz-Rosado, R. and Sanchez-Araiza, D. (1998) *Effect Of Purse Seine Vessel Harvesting In The Eastern Tropical Pacific Yellowfin Tuna Stock.* MTBI technical report. No. BU-1511-M: 169-188. 20 pp.

Friedman, J.H. (2001) Greedy function approximation: a gradient boosting machine. *Ann. Stat.* **29:**1189–1232.

Gaertner, D. and Dreyfus-Leon, M. (2004) Analysis of non-linear relationships between catch per unit effort and abundance in a tuna purse-seine fishery simulated with artificial neural networks. *ICES J. Mar. Sci.* **61:**812–820.

Griindlingh, M.L. (1995) Tracking eddiesin the southeastAtlantic and southwestIndian oceans with TOPEX/POSEIDON. *J. Geophys. Res.* **100:**24977–24986.

Haggarty, D.R. and King, J.R. (2006) CPUE as an index of relative abundance for nearshore reef fishes. *Fish. Res.* **81:**89–93.

Hall, M.A. (1996) On bycatches. *Rev. Fish Biol. Fish.* **6:**319–352.

Hall, M. and Roman, M. (2013) *Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. FAO Fisheries and AquacultureTechnical Paper.* No. 586. 249 pp.

Hall, M.A., Alverson, D.L. and Metuzals, K.I. (2000) By-catch: problems and solutions. *Mar. Pollut. Bull.* **41:**1–6.

Halpern, B.S., Walbridge, S., Selkoe, K.A. *et al.* (2008) A global map of human impact on marine ecosystems. *Science* **319:**948–952.

Halpin, P.N., Read, A.J., Fujioka, E. *et al.* (2009) OBIS-SEAMAP: the world data center for marine mammal, sea bird, and sea turtle distributions. *Oceanography* **22:**104–115.

Harley, S.J., Myers, R.A. and Dunn, A. (2001) Is catch-per-unit-effort proportional to abundance? *Can. J. Fish Aquat. Sci.* **58:**1760–1772.

Hastie, T. and Tibshirani, R. (1986) Generalized additive models (with discussion). *Stat. Sci.* **1:**297–318.

Hastie, T. and Tibshirani, R. (1990) Generalized Additive Models. London. Chapman & Hall. Chapman & Hall/CRC Monographs on Statistics & Applied Probability, 335 pp.

Huang, B., Banzon, V.F., Freeman, E. *et al.* (2015) Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4): part I. Upgrades and intercomparisons. *J. Clim.* **28:**911–930.

Hughes, D.A. and Richard, J.D. (1974) The nesting of the Pacific ridley turtle Lepidochelys olivacea on Playa Nancite, Costa Rica. *Mar. Biol.* **24:**97–107.

IATTC. (2000). Annual Report of the Inter-American Tropical Tuna Commission 1998. La Jolla, CA, 171pp.

Kopitsky, K.L., Pitman, R.L. and Dutton, P.H. (2004) Aspects of olive ridley feeding ecology in the eastern tropical Pacific. In: Proceedings of the 21st Annual Sea Turtle Symposium on Sea Turtle Biology and Conservation. M.S. Coyne & R.D. Clark (eds) NOAA Tech. Memor. NMFS-SEFSC 528, 368 pp.

Kot, C.Y., DiMatteo, A., Fujioka, E. *et al*. (2014) *The State of the World's Sea Turtles Online Database: Data provided by the SWOT Team and hosted on OBIS-SEAMAP*. Oceanic Society, Conservation International, IUCN Marine Turtle Specialist Group (MTSG), and Marine Geospatial Ecology Lab, Duke University. http://seamap.env.duke.edu/swot [accessed March 2015].

Lauria, V., Vaz, S., Martin, C.S., Mackinson, S. and Carpentier, A. (2011) What influences European plaice (*Pleuronectes platessa*) distribution in the eastern English Channel? Using habitat modelling and GIS to predict habitat utilization. *ICES J. Mar. Sci*. **68:**1500–1510.

Leathwick, J.R., Elith, J., Francis, M.P., Hastie, T. and Taylor, P. (2006) Variation in demersal fish species richness in the oceans surrounding New Zealand: an analysis usingboosted regression trees. *Mar. Ecol. Prog. Ser*. **321:**267–281.

Lewison, R.L., Crowder, L.B., Read, A.J. and Freeman, S.A. (2004) Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol. Evol*. **19:**598–604.

Luschi, P., Hays, G.C. and Papi, F. (2003) A review of long-distance movements by marine turtles, and the possible role of ocean currents. *Oikos* **103:**293–302.

Maunder, M.N. and Punt, A.E. (2004) Standardizing catch and effort data: a review of recent approaches. *Fish. Res*. **70:**141–159.

National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS) (1998) Recovery Plan for U.S. Pacific Populations of the Olive Ridley Turtle (Lepidochelys olivacea). Silver Spring: National Marine Fisheries Service.

NOAA (2013) *The Oceanic Niño Index, Climate Prediction Center, National Oceanic and Atmospheric Administration*. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ ensoyears.shtml [accessed July 15, 2015].

Peavey, L. (2010) *Predicting Pelagic Habitat with Presence-only Data using Maximum Entropy for Olive Ridley Sea Turtles in the Eastern Tropical Pacific*. M.S Thesis. Duke University, 76 pp.

Pinedo, M.C. and Polacheck, T. (2004) Sea turtle bycatch in pelagic longline sets off southern Brazil. *Biol. Conserv*. **119:**335–339.

Pitman, R.L. (1992) Sea turtle associations with flotsam in the eastern tropical Pacific. In: Proceedings of the Eleventh Annual Workshop on Sea Turtle Biology and Conservation. U.S. Dep. of Comm., NOAA Tech. Memo. NMFS-SEFSC-302. 195 pp.

Plotkin, P. (2007) Biology and Conservation of Ridley Sea Turtles. Baltimore: The Johns Hopkins University Press, 337 pp.

Plotkin, P.T. (2010) Nomadic behaviour of the highly migratory olive ridley sea turtle (*Lepidochelys olivacea*) in the eastern tropical Pacific Ocean. *Endanger. Species Res*. **13:**33–40.

Plotkin, P., Byles, R.A., Rostal, D.C. and Owens, D.W. (1995) Independent versus socially facilitated oceanic migrations of the olive ridley, *Lepidochelys olivacea*. *Mar. Biol*. **122:**137–143.

Polovina, J.J., Howell, E., Kobayashi, D.R. and Seki, M.P. (2001) The Transition Zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. *Prog. Oceanogr*. **49:**469–483.

Polovina, J.J., Howell, E., Parker, D.M. and Balazs, G.H. (2003) Dive-dpeth distribution of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific: might deep longline sets catch fewer turtles? *Fish. Bull*. **101:**189–193.

Polovina, J.J., Balas, G.H., Howell, E.A., Parker, D.M., Seki, M.P. and Dutton, P.H. (2004) Forage and migration habitat of loggerhead (*Caretta caretta)* and olive ridley (*Lepidochelys olivacea)* sea turtles in the central North Pacific Ocean. *Fish Oceanogr*. **13:**36–51.

R Development Core Team (2015) R: A Language and Environment for Statistical Computing. Vienna: R Foundation for Statistical Computing. Available online at http://www.R-project.org/.

Ramirez, P.A. and Ania, L.V. (2000) Incidence of marine turtles in the Mexican long-line tuna fishery in the Gulf of Mexico. In: Proceedings of the Eighteenth Annual Workshop on Sea Turtle Biology and Conservation, NOAA Technical Memorandum. NMFS-SEFSC-436:110.

Reilly, S.B. and Fiedler, P.C. (1994) Interannual variability of dolphin habitats in the eastern tropical Pacific I: research vessel surveys, 1986–1990. *Fish. Bull*. **92:**434–450.

Roberts, J.J. (2006) *Separating Sea Turtles From Fisheries: Oceanographic Habitat Models of Sea Turtles Encountered in the Eastern Tropical Pacific Tuna Fishery*. M.S. Thesis. Duke University. 49 pp.

Roberts, J.J., Sims, M., Lennert, C., Vogel, N. and Halpin, P.N. (2009) *Oceanographic Habitat Models of Olive Ridley Turtles Bycaught in the ETP Purse Seine Tuna Fishery*. Paper presented at the annual meeting of the International Marine Conservation Congress, George Madison University. http://citation.allacademic.com/meta/p297013_index.html [accessed June 2015].

Seminoff, J.A., Zárate, P., Coyne, M. *et al*. (2008) Post-nesting migrations of Galápagos green turtles *Chelonia mydas* in relation to oceanographic conditions: integrating satellite telemetry with remotely sensed ocean data. *Endanger. Species Res*. **4:**57–72.

Stumpf, H.G. and Legeckis, R.V. (1977) Satellite observations of meso-scale eddy dynamics in the eastern tropical Pacific Ocean. *J. Phys. Oceanogr*. **7:**648–658.

Swimmer, Y., McNaughton, L., Foley, D., Moxey, L. and Nielsen, A. (2009) Movements of olive ridley sea turtles *Lepidochelys olivacea* and associated oceanographic features as determined by improved light-based geolocation. *Endanger. Species Res*. **10:**245–254.

Thomas, W.H. (1979) Anomalous nutrient chlorophyll interrelationship in the offshore eastern tropical Pacific Oceans. *J. Mar. Res*. **37:**327–335.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center (2006) *2-minute Gridded Global Relief Data (ETOPO2v2)*. http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html [accessed June 5 2012].

Wood, S.N. (2006) Generalized Additive Models: An Introduction with R. Boca Raton, FL USA. Chapman and Hall/CRC, 392 pp.

Wood, S.N. (2011) Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *J R Stat Soc Series B Stat Methodol* **73:**3–36.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. This table shows the model output summary from the R console using the function *summary* (model). The upper table summarizes the parametric coefficients for the variables treated as a factor in the model for the association or set type variable and the lower table summarizes the significance of the variables included in the model with a smoothing function (See Wood, 2006 for details).

Figure S1. Model checking plots for the GAM fitted with log transformed iCPUE. The upper left normal QQ plot is very close to a straight line suggesting a reliable distribution assumption. The upper right panel suggests that the estimated variance is at some point constant as the mean increases. The histogram of the residuals in the lower left panel shows an approximated normal distribution and the bottom right plot of response versus fitted values shows a positive linear relationship. In general, nothing is problematic for the model fitted.

Figure S2. Seasonal variability of the fishing effort for the three different set types included in the analysis from (1997–2009). Sets: Tuna, Log = floating objects, Dolp = dolphins. In this figure it is clear to see that most of the sets were made over floating objects.

Figure S3. Histogram of the straight carapace length (SCL cm) for the incidentally caught turtles in the IATTC database used in this research for years 1997–2009.

Figure S4. Bar plots to explore the predicted iCPUE versus five of the environmental variables (SST, SSH, chl-*a*, DAN and ONI) grouped by set type: Tuna, Dolphin and Floating objects (Log).