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**Ecological risk assessment of a pelagic seabird species in artisanal tuna fisheries**

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# ABSTRACT

Fishery bycatch is a serious threat to several protected, endangered, and threatened species (PETs), requiring urgent action to develop and implement conservation measures. This study performs an Ecological Risk Assessment for the Effects of Fishing (ERAEF) using a spatially and temporally Productivity Susceptibility Analysis (PSA) to calculate the potential risk to great shearwaters (*Ardenna gravis*) from direct interaction with the metiers of the artisanal tuna fishing fleet at the Bay of Biscay (baitboats and trollers). The PSA incorporates productivity attributes based on the Fecundity Factor Index; and susceptibility attributes calculated from the species spatio-temporal abundance patterns obtained developing density surface models and distribution and intensity of fishing activity based on pooled Vessel Monitoring System and logbook data. The PSA shows an overall moderate risk to great shearwaters by the artisanal tuna fishery also revealing that baitboats are less risky than trollers (risk score of 3.12±0.09 and 2.70±0.05, respectively). Spatially, the likelihood of presence of high potential risk areas was associated with prey availability for both, the PET and the commercial fish species. The systematic, repeatable and standardised ERAEF followed in this study can be used to advice for ecosystem-based fisheries management to improve management measures for reducing bycatch of PETs around the world.

**Key Words:** artisanal fisheries,bycatch, ecological risk assessment, Productivity-Susceptibility Analysis, seabird, species distribution models.

# INTRODUCTION

Unintended catch of non-target species (*’*bycatch’) has long been identified as one of the most common anthropogenic threat causing at-sea mortality and driving population declines of several protected, endangered, and threatened species (PETs) (Read *et al.*, 2006; Oliver *et al.*, 2015; Dias *et al.*, 2019). Fisheries-related bycatch mortality has become a major conservation concern specially for long-lived and highly migratory species causing several ecological effects, either directly reducing species populations or indirectly changing dynamics of oceans systems (Lewison et al., 2014; McCauley et al., 2015). On one hand, an increase in adult mortality of long-lived species (*i.e.*, those withslow growth, late maturation and low fecundity) could cause a population decline over short timescale (*i.e.,* decades; Campioni *et al.*, 2020). On the other, highly mobile species perform wide‐ranging movements frequently encountering multiple fisheries and, often aggregating in high biological production areas (Schoombie *et al.*, 2018; Yurkowski *et al.*, 2019) coinciding with high fishing activity zones (Zhou *et al.*, 2019).

Bycatch assessment and mitigation has mainly focused on industrial fisheries, overlooking the impact of artisanal fisheries due to the scale of industrial operations (leading to higher level of bycatch), the relative wealth of data and the general consideration that artisanal fisheries are inherently more sustainable than industrial fisheries (Molina and Cooke, 2012; Temple *et al.*, 2018). However, artisanal fisheries which compose a large majority of the world’s fleets (Pauly, 2006), tend to operate in regions featuring high productivity and overlapping with megafauna high-use areas. While overall ecological impact of artisanal fishing might have similar effects to those of industrial fishing (Peckham *et al.*, 2007; Bugoni *et al.,* 2008; Alfaro-Shigueto *et al.*, 2010) artisanal fisheries are generally understudied and often unregulated, creating a knowledge gap representing a major challenge to sustainable fisheries management and the conservation of PETs (Fabio *et al.*, 2016). Though not all fishing gears pose the same degree of risk to PETs, baited hooks are particularly dangerous for seabirds offering the opportunity for an easily accessible resource, entailing a potential high risk of individuals being hooked and subsequently drowned (Pott and Wiedenfeld, 2017). In this regard, the knowledge regarding the bycatch in artisanal fisheries performed with hook-and-line is ever-growing, but mainly based on longline fisheries, while few studies have considered other fisheries such as pole and line or trolling (Bugoni *et al.*, 2008a; Miller *et al.*, 2017). Consequently, as a major conservation and welfare concern, artisanal fisheries bycatch assessments are urgently required, particularly in the context of Ecosystem-Based Fisheries Management (EBFM).

Spatio-temporal assessments of bycatch requires a scientific sound approach to be meaningful, applicable, and comparable among fisheries. In this context, a variety of ecological risk assessment frameworks have been developed (*e.g.* Waugh *et al.*, 2008, 2012; Tuck *et al.*, 2011; Small *et al.*, 2013; Brown *et al.*, 2015) based on the Ecological Risk Assessment for the Effects of Fishing (ERAEF) originally developed to assess the impact of fisheries in Australia (Hobday *et al.*, 2007). This hierarchical procedure are increasingly used to screen the potential risk posed by fishing bycatch to PETs enabling the impact of fishing on the species to be documented in a systematic, transparent and repeatable way, facilitating management and mitigation (Stobutzki *et al.*, 2001). To perform a spatially and temporally ERAEF it is necessary to cross-reference information at both fishery and species level to assess and map the fisheries potential risk and identifying areas of potential interaction from a spatially explicit perspective (Le Bot *et al.*, 2018).

Within this context, the northern Spanish artisanal tuna fishery operating in the Bay of Biscay (hereafter, BoB) targeting the albacore tuna (*Thunnus alalunga*) and secondarily the bluefin tuna (*Thunnus thynus*) is analysed in this study. Both target species perform large scale feeding migrations during the summer to the BoB and surrounding waters (Dufour *et al.*, 2010) making the fishery operates from June to October targeting migrating tuna schools (Arrizabalaga *et al.*, 2003). This fishing fleet operates during daytime with two main metiers, pole and lines (baitboats) and trolling lines (trollers; LHP and LTL, hereafter). For LHP fishing, tuna schools are attracted to one side of the vessel using alive small pelagic fishes as bait, and then, when the tuna are close to the vessel, spraying a water curtain over the water surface to hide the lines and the vessel, simulating a school of small pelagic fishes splashing at the surface. In the case of the LTL, up to 15 lines with artificial lures are towed behind the vessel near the surface at a certain speed (around 7 knots). Although both metiers are highly selective (Santiago *et al.*, 2016), a specific onboard monitoring programme of interaction with PETs, conducted between 2016-2019 at the BoB and adjacent waters, identified the great shearwater (*Ardenna gravis*) as the main species interacting with the artisanal tuna fishery of the BoB (accounting for the 66.1% of the individuals incidentally captured during the period 2016-2019; MSC, 2021).

In this study, we assessed the relative risk posed by the artisanal tuna fishery operating at the BoB to the main PET species bycaught in the fishery, the great shearwater. Firstly, spatio-temporal abundance patterns of great shearwater were obtained by developing spatial abundance models which integrates information of different ecosystem components collected during integrated ecosystem surveys. Secondly, a spatio-temporal ERAEF was developed using the best available spatial and temporal data on fishing effort, both from logbooks and VMS monitoring to assess the fisheries potential risk and highlight potential risk bycatch areas. This transparent, standardised and repeatable procedure developed across a 7-year period (2013-2019) enable to advance and achieve the EBFM goals.

# MATERIAL AND METHODS

**2.1. Data acquisition**

Seabird at-sea observations, biomass estimates of pelagic prey species and physical data were gathered during the JUVENA oceanographic surveys over the period 2013-2019. JUVENA surveys take place yearly during September covering offshore and shelf-slope areas of the BoB with the aim of acoustically assessing the biomass of the European anchovy (*Engraulis encrasicolus*) and other small pelagic fishes (Boyra *et al.*, 2013). The sampling strategy is based on parallel transects arranged perpendicular to the coast, regularly spaced at 15 nautical miles (nmi). Data were collected by two research vessels simultaneously covering the area potentially occupied by the European anchovy.

* + 1. **Seabird data**

Great shearwaters at‐sea observations were collected by two observers following visual line‐transect protocols (Buckland *et al.*, 2001) along acoustic transects when the R/V was navigating at constant heading and speed during daytime. For each species sighting, observers recorded detection distance and the angle with respect to the track line based on an angle meter. At the beginning of each observation period (*leg*), observers recorded the environmental conditions that could affect sightings (*i.e.,* Beaufort sea state, swell height and direction, wind speed and direction, cloud coverage, visibility, sun glare and an overall subjective assessment of detection conditions of the sightings). Observation effort was georeferenced every minute with the vessel’s GPS (García-Barón *et al.*, 2019).

* + 1. **Environmental and prey data**

Three different types of variables were considered: prey, physical and physiographic variables. Biomass of juvenile and adult European anchovy (hereafter, ANEJ and ANEA, respectively) and European pilchardus (*Sardina pilchardus*; hereafter, PIL) were selected as prey variables in accordance with previous spatial abundance studies of great shearwater performed in the area (Louzao *et al.*, 2019). Spatial biomass patterns of ANEJ, ANEA and PIL at different depths were obtained based on trawl-acoustic methodologies (Simmonds and MacLennan, 2005). Original biomass values of ANEJ, ANEA and PIL were laid over a grid of 0.1˚ spatial resolution and totalled for each cell. Finally, small pelagic fish biomass estimations were obtained using a combination of universal kriging and an automatic variogram fitting procedure using the R‐package *automap* (Stelzenmüller *et al.*, 2005, 2009; Louzao *et al.*, 2019) .

Six physical variables were used to model seabird’s spatial density, surface temperature (TEM; °C) and its spatial gradient (TEMg), salinity (SAL; psu), geostrophic velocity (GVel; m s−1), the depth of maximum temperature gradient (DTG; m) and the maximum temperature gradient (MTG; °C m−1). Spatial fields of physical variables were solved from vertical depth profiles (from surface to 200 m depth) of TEM and SAL obtained during CTD casts. Further methodological details about prey and physical variables can be found in Supplementary material. Data spatial resolution and correlation scales used for the interpolation allowed to solve the main mesoscale features in the area, including eddies and frontal areas.

Additionally, four physiographic variables were selected: bathymetry (BAT; m) and its spatial gradient (BATg; dimensionless), the closest distance to the coastline (DistCO; km) and to the shelf-break (measured as the distance to the 200 m-isobath; DistSB; km). The four physiographic variables were directly obtained or calculated at the spatial scale of the standard grid from ETOPO1 (Amante and Eakins, 2009).

Louzao *et al.* (2019) demonstrated that 3D environment of the great shearwater in the BoB were better explained by the shallowest physical and trophic conditions. Consequently, prey variables represented the sum of their biomass from 5 to 15 m depth and the physical variables TEM, SAL and GVel were described by the shallowest depth available, *i.e.,* 10 m depth. The remaining physical variables (DTG, MTG and TEMg) and the physiographic variables were not modified by any vertical criteria.

* + 1. **Artisanal tuna fisheries data**

Information on artisanal tuna fishing activity during the 2013-2019 period was obtained from the vessel monitoring system (VMS) and logbooks data provided by the Spanish General Secretary of Fisheries. Whilst the VMS data provide information on the identity, position, speed, and heading of the vessels (European Commission, 2011), the logbooks report the fishing gear used and the effort at an aggregated spatial scale. Thus, these data enable the analyses of the spatial and temporal distribution of disaggregated fishing activity to distinguish between metiers and fishing and non-fishing effort (Bastardie *et al.*, 2010). Finally, data on great shearwater bycatch events were obtained from an observer monitoring programme implemented by AZTI since 2016 and 2017 in LHP and LTL, respectively to monitor discards and interaction with PETs during the fishing season.

* 1. **Density surface modelling**
     1. **Species detectability based on environmental conditions**

Species detectability was modelled using Conventional and Multiple-Covariate Distance Sampling (CDS and MCDS; Buckland *et al.* 2001; Marques & Buckland 2004), the latter allowing to consider the effect of the environmental conditions during the observation effort. Detection functions were estimated pooling great shearwater sightings from the period 2013-2019 (Figure 1). Only sightings with a Beaufort Sea‐state ≤5, wave height ≤2 m and overall medium and good visibility conditions were used to fit the detection functions (García-Barón *et al.*, 2019). Perpendicular distances were truncated to exclude sightings beyond 600 m (around 5% of the individuals detected at the longest distances; Buckland *et al.* 2001) and sightings of individuals attracted to the ship or associated with human activities (individuals following the R/V or scavenging on fishing discards) were excluded from further analyses to avoid density overestimation (Authier *et al.*, 2018). Covariates considered in MCDS were only those descriptors related to the effort (Astarloa *et al.*, 2021) including Beaufort sea-state, swell height categorized, cloud coverage, visibility, overall detection conditions and year. Detection functions were fitted using forward stepwise model building based on Akaike’s Information Criterion (AIC) selection, as well as by inspection of Q-Q plots and Cramer-von Mises goodness of fit tests (Thomas *et al.*, 2010) using the R‐package *mrds* (Laake *et al.* 2015). Final detection function selection was made on parsimony grounds (similar explicative power but less parameters; Arnold 2010), when the two best detection functions did not show a difference in AIC > 2 (*i.e.,* ΔAIC < 2). The effective strip half‐width (ESW) was calculated as the perpendicular distance in which the missing detections at smaller distances were equal to the recorded detections at bigger distances. In the case of the MCDS detection functions, the ESW was calculated for each level of the covariate.

* + 1. **Model fitting**

Surveyed *legs* were subdivided into 10 km segments with homogeneous sighting conditions to limit the variability of the environmental characteristics within segments (García-Barón *et al.*, 2020). To fit the models on the best quality data, segments with a Beaufort Sea‐state ≤5, wave height ≤2 m and overall medium to good visibility conditions were used for further analysis. For every segment, we summed up the group size of the sightings and the centroid of each segment was used to assign the environmental data to the segments.

Density surface models (DSMs) were fitted using generalized additive models (GAMs) to identify the most important environmental covariates explaining great shearwater density patterns (Supplementary Table A.1). After checking for alternative distribution families (*e.g.,* Tweedie, zero-inflated Poisson), we selected a negative binomial distribution and a log-link function to account for overdispersion. Flexible smoothing splines were constrained to a maximum of two degrees of freedom (k=3) to avoid over-fitting of the data and a maximum number of four covariates was used to avoid over complexifying the models (Lambert *et al.*, 2017). The effective sampled area of each segment calculated as the length of the segment multiply by twice the ESW was included as an offset. Prior to modelling and to avoid co‐linearity, we calculated the pairwise Spearman-rank correlation coefficients (r) and did not include correlated variables (e.g., with r≥|0.5|; Dormann *et al.*, 2013). Thus, we selected the non‐correlated predictors by selecting the variable yielding the lowest AIC value corrected for small sample sizes (AICc) from univariate models of the two predictors.

GAMs were implemented following the Information-Theoretic approach using the *dredge* function of the R‐package *MuMIn* (Barton, 2016). We evaluated all the possible models by assessing their relative support compared with the others based on the AICc and the Akaike weight (ωi; normalized relative likelihoods that model *i* is the best model) (Burnham and Anderson, 2002). Models were ranked based on their AICc and, if no clear best model was identified (ωi > 0.95), a model averaging approach was used (Burnham and Anderson, 2002). Model averaging was performed using a 95% confidence set of models where the cumulative sum of ωi was ≥ 0.95, starting with the model with the highest ωi (Johnson and Omland, 2004). This 95% confidence set of models was used to obtain averaged coefficients and variance estimator. The relative importance of the explanatory variables was calculated as the sum of the ωi of the models in which the covariate was included and the response plots were constructed based on averaged coefficient of the 95% confidence set. Finally, selected models included within the 95% confidence set were used to predict the spatial density of great shearwater for every September. The density estimates presented here were uncorrected for any detection bias.

* 1. **VMS and logbook data processing**

VMS and logbook data were firstly cleaned removing: i) records with invalid positions (*e.g.,* records located on land or in ports), ii) records associated with high speeds (>20 knots) and heading outside compass range, iii) duplicated or pseudo-duplicated (<5 min) records and iv) records when arrival date occurs before departure date. Secondly, VMS and logbook data were linked removing unlinked records using the R‐package *vmstools* (Hintzen *et al.*, 2021). Thirdly, the artisanal tuna fishery was identified as those trips where > 80% of the catches were tuna species according with the logbook data. Then, the corresponding metier was assigned based on the Spanish National Fleet Census modalities. However, no vessels are registered as LHP or LTL since the same vessel change the gear through the different fishing seasons and the census only registers one main fishing gear. Thus, those vessels with > 80% of the catches being tuna species and registered on the Spanish National Fleet Census under the purse seiners modality were identified as LHP and the rest of the vessels registered in other modalities as LTL. Fourth, we used a vessel speed range to discriminate between fishing and non-fishing activity. Thus, all the records with speeds included within the range of 6-7 knots for LTL and of 0-3 knots for LHP were considered fishing effort (Fernandes *et al.*, 2019). The fishing effort in hours obtained for each metier, month and year were overlaid over a regular grid of 0.1x0.1˚ to obtain the same spatial resolution as great shearwater spatial density predictions. Finally, we explored the fishing effort performed by metier during the time-series 2013-2019 to select those months when the effort was higher.

* 1. **Ecological risk assessment**

The potential risk to great shearwaters from direct interaction with the metiers of the artisanal tuna fishing fleet was assessed using an explicit spatio-temporal procedure based on a Productivity-Susceptibility Analysis (PSA) (Hobday *et al.*, 2011; Tuck *et al.*, 2011; Waugh *et al.*, 2012; Brown *et al.*, 2015). This analysis addresses the potential risk from direct interaction of a species by considering the species productivity (*i.e.,* detailed species-specific biological information) and the fishery susceptibility (*i.e.,* information on the interaction of fisheries and species)allowing to screen LHP and LTL independently and highlighting potential bycatch risk areas for each metier. The productivity and susceptibility characteristics (called attributes) were scored between 1 (low risk) and 3 (high risk) and potential risk scores were calculated (Hobday *et al.* 2007). Finally, the risk scores were displayed graphically on an x–y plot (PSA plot).

* + 1. **Productivity**

Great shearwater productivity was assessed using the Fecundity Factor Index (FFI) proposed by Waugh *et al.* (2012) for seabird species. The FFI scores the species into three groups for two variables: the life-history strategy and the median age at first breeding (see Table 1). The great shearwater is an annual breeding species with single egg clutches (Ronconi *et al.*, 2018). However, their age at first breeding is unknown though may be similar to their relatives, the Short-tailed shearwater (*A. tenuirostris*) and the Cory’s shearwater (*Calonectris* borealis) which are first-time breeders at six or seven and nine years old, respectively (Powers *et al.*, 2020). Hence, due to uncertainty we apply a score of 2.5 to this attribute of the FFI (Table 1). Finally, FFI attributes were equally weighted, and the P score was calculated as the average of the FFI attributes scores.

* + 1. **Susceptibility**

The susceptibility to each metier was assessed by year for the period 2013-2019 allowing to highlight the potential interaction areas through time to assess the temporal persistence of risk areas. The overall susceptibility (S) score was calculated independently for each year and gear based on five attributes (Brown *et al.*, 2015): availability (a), encounterability (e), exposure (ex), selectivity (s) and potential for lethal encounter (ple). These attributes scoring from 1 to 3, where 1 indicate low susceptibility and 3 high susceptibility (see Table 1). Finally, the overall susceptibility score for each metier was calculated as a weighted geometric mean of these attributes (Brown *et al.*, 2015):

(1)

* Availability: an index of co-occurrence of species distribution and fishing activity (Hobday *et al.*, 2007) in terms of percentage of overlap. Spatial information on the species distributions was obtained from the predictions of the density surface models and the fishing activity of each metier from the VMS and logbook data. Since all the study area can be consider as occurrence area for great shearwaters we delimited the species distribution as their critical area based on the methodology used in García-Barón *et al.* (2019), *i.e.,* the highest 40% of the predicted abundance.
* Encounterability: score derived from Hobday *et al.* (2007) which assessed the potential for encounter with fishing gear based on species depth range in the water column in relation to the position of the fishing gear. In this study, the species is a shallow-diver species (Ronconi *et al.*, 2010) which access to the bait, both by diving or on the surface and the studied metiers are both surface gears facilitating the access to the bait. Thus, the encounterability was scored with the highest possible value.
* Exposure: score based on the species abundance obtained from the density surface models and the fishing activity per cell obtained from the VMS and logbook data (Brown *et al.*, 2015):

(2)

Then, exposure per cell, per year, was compared to mean exposure per cell assuming an even distribution of species and fishing activity over the time series and study area and log-scale converted:

(3)

(4)

* Selectivity: probability that the fishing gear captures individuals of great shearwater that encounters the gear. To determine the probability of capture, we used published information and data collected by the observer monitoring programme. Both LHP and LTL have low potential for capture seabirds (Bugoni *et al.*, 2008a; Miller *et al.*, 2017) compared to other gears such as longlines (Anderson *et al.*, 2011) or gillnets (Žydelis *et al.*, 2009). In accordance, the selectivity score assigned was low (*i.e.*, 1). However, using the data collected by the onboard observers we were able to ascertain that LTL is a less selective gear than LHP with a capture rate ± standard deviation of 0.18±0.33 and 0.01±0.07 birds/day, respectively. Then, the final assigned scores were 1.5 and 1 for LTL and LHP, respectively.
* Potential for lethal encounter: this attribute replaced the Post Capture Mortality attribute from Hobday *et al.* (2007) and was scored based on Brown *et al.* (2013) and the probability of the interaction between an individual and the gear to result in death, injury or neither. Thus, based on the data collected by the onboard observers, the interaction with both gears is more likely to result in injury than in dead and this attribute was scored as moderate (*i.e.*, 2).
  + 1. **Potential risk**

The potential risk (R) was calculated based on the productivity (P) and susceptibility (S) scores as the Euclidean distance from the origin on a two-dimensional plot of productivity and susceptibility:

(5)

Potential risk scores can ranged from 1 (all scores are equal to 1) to 4.24 (all scores are equal to 3) being considered a species to be at low risk if the potential risk score is lower than 2.64, medium risk if between 2.64 and 3.18 and high risk if greater than 3.18. Potential risk scores were calculated for each metier and on a cell-by-cell basis, stratified by year.

# RESULTS

* 1. **Spatio-temporal patterns of seabird abundance**

A total of 15,944 km were surveyed during the period 2013-2019 from which 12,050 surveyed km remained after filtering for weather conditions. A global number of 954 sightings of great shearwaters were recorded with a total of 3338 individuals observed (Table 2). Then, detection functions were developed based on 954 great shearwater sightings. The hazard‐rate function with no adjustment terms including year and swell height categorized as covariates was selected as the best‐fitting detection function based on parsimony grounds (Supplementary Table B.1, Figure B.1) from which the corresponding ESW were 193.44±75 m.

A total of 1306 segments of which 308 included 3338 individuals from 954 sightings were used to fit DSMs. Among highly correlated variables, BAT and DistSB were the least explicative variables (r ≥ |0.5| and higher AICc in univariate models; Supplementary Figure B.2) and they were removed. The number of models combined to achieve the 95% confidence set was 3 out of a total of 385 for which the explained deviances ranged between 14.7% and 15.2%. The main variables driving the spatial abundance patterns of the species were DistCO, SAL, TEM and TEMg (Figure 2), whilst BATg and PIL were the least important variables within the 95% confidence set. ANEJ, ANEA, DTG, MTG and GVel were not included in any of the models within the 95% confidence set. Densities of great shearwater increased as DistCO increase, with maximum values at approximately 125 km from the coast, whilst warmer TEM influenced the abundance negatively driving the higher abundances over the northern French continental shelf. Seabird densities also showed a quadratic relationship with SAL indicating a preference for medium to high values (> 35 psu) and a preference for lower values of TEMg, inducing higher densities far from the coast. Although highest density areas showed a high inter-annual variability (Figure 3), the area over the Armorican slope supports the highest densities most of the years (but 2015). Furthermore, the southern sector of the BoB also showed high densities, mainly located over the Cachucho and the area between Estaca de Bares and Cabo Peñas. Less dense areas were located over the southern French and eastern Spanish continental shelves (Figure 3).

* 1. **Fishing activity**

The fishing effort of the artisanal tuna fishing fleet (considering both metiers) during the period 2013-2019 concentrates in July to September (Supplementary Figure C.1). The spatial bycatch risk assessment focused on this period to locate the bycatch exposure areas where the potential risk of bycatch was higher. Briefly, the fishing effort performed within the study area by month during July-September was higher for LHP (LHP: 31973.8 ± 7587.4 h and LTL 21284.5 ± 12514.8 h). For both metiers, the effort performed was higher over the French and Spanish shelf-break, the Spanish continental shelf, and offshore waters of the BoB (Figure 4). In the case of LHP, fishing effort was also performed near Arcachon Bay and in areas near the influence of the Girond river. For both, LHP and LTL, 2014 was the year with the lowest fishing effort performed whilst during 2017 the effort was the highest of the time-series (Supplementary Figure C.1).

* 1. **Risk assessment**

The PSA showed that LTL generated the largest potential mean risk score (3.12±0.09) and were assessed as posing a moderate risk to great shearwaters (Figure 5) whilst LHP also posing a moderate risk to the species showed a lower potential risk on average (2.70±0.05) .The extent of co-occurrence, *i.e.,* availability, was higher for LTL due to the higher spatial coverage of fishing activity performed over the study area, generating higher scores for availability. Regarding the exposure, most of the cells showed moderate exposure for both gears with slightly differences of scoring in the case of LTL with more cells scoring with high risk and in the case of LHP with more cells scoring with low risk. These differences were attributed to the higher levels of co-occurrence of high fishing activity and high species density areas. Despite the high encounterability shown by both metiers, the abovementioned moderate levels of availability and exposure, together with the high selectivity of the metiers (low potential for capture) make the potential risk to the artisanal tuna fishery moderate.

Overall, the distribution and scale of potential risk differed between metiers (Figure 6). Regarding the scale of the risk, whilst LHP showed low and moderate values of relative risk, LTL mostly showed moderate values with a small number of cells showing high potential risk. Spatially, the maps evidenced that, for both metiers the cells scored as moderate risk dominated the area. Whereas LHP maps showed cells scored as low risk specially in the southern and south-eastern part of the study area, LTL maps showed scattered high-risk cells over the Armorican slope and adjacent waters.

# DISCUSSION

Conservation concern posed by fisheries-bycatch has led to set up major management and mitigation measures to reduce species mortality and improve the survival of discarded individuals while maintaining fisheries profitability. However, the understanding of their extent and magnitude, as well as their spatial patterns is a necessary first step to direct conservation actions where needed (Lewison *et al.*, 2014). Ecological risk assessments, such as ERAEF, are increasingly popular methods used for assessing the potential vulnerability of species impacted directly, or indirectly, by fisheries. In the BoB several studies aimed to perform ecological risk assessments, albeit focused in the short-beaked common dolphin (*Delphinus delphis*; Mannocci *et al.*, 2012; Peltier *et al.*, 2016, 2021) whilst to the best of our knowledge, this paper represents the first attempt to perform an ecological risk assessment for a seabird species in the area aiming to provide new insights to implement conservation strategies and to inform EBFM and mitigation measures.

* 1. **Spatio-temporal patterns of species abundance and fisheries activity**

The spatial density of great shearwaters was mainly driven by the distance to the coast, highlighting offshore waters as the preferred habitat for the species. In accordance with Pettex *et al.* (2017) and Louzao *et al.* (2019), the northern Armorican slope in French waters and offshore waters of the Spanish sector supported the highest densities of the species. Along the shelf edge (e.g. Armorican slope), tides generate internal waves that propagate both on- and off-shelf (Pairaud *et al.*, 2010), which seem to be responsible for significant mixing and nutrient upwelling at the shelf-break, where they have their maximum intensity, and thus their greatest impact on primary production (Lavín *et al.*, 2006). Consequently, these areas aggregate small prey species (Scott *et al.*, 2010) being highly relevant for top predator species (García-Barón *et al.*, 2019; Pettex *et al.*, 2017). In addition, the results showed high densities of great shearwater over the western Cantabrian coastal area. This great shearwater aggregation may be explained by the easterly winds favouring both, the arrival of great shearwaters from their breeding areas (Northwest Atlantic) to the BoB (Louzao *et al.*, 2015) and a coastal upwelling along the Cantabrian coast, stronger in the western area during spring-summer (Alvarez *et al.*, 2010). The latter, enhancing the aggregation of large biomass of small pelagic fish (Astarloa *et al.*, 2019) representing a potential feeding ground for great shearwaters.

Fishing activity performed by the Spanish artisanal tuna fishery were mainly located over the outer French (Armorican slope) and Spanish continental shelfs and adjacent waters, the Cantabrian Sea, and offshore waters of the BoB. Although the effort showed little inter annual variability over the study period, during 2014 the fishing activity drastically declined. That year, the albacore tuna shifted north-westward, driving the fleet outside the study area in search of more productive fishing grounds (Chust *et al.*, 2019).

* 1. **Assessing potential bycatch risk areas**

The results of the PSA indicated that both metiers of the artisanal tuna fishing fleet operating at the BoB represent an overall moderate risk to great shearwaters. While diving species suffer from bycatch in bottom set gears such as static nets, shallow-diver species tend to be incidentally captured during line setting operations when they are attracted by baited hooks (ICES, 2020). The great shearwater, as a shallow-diver species (Ronconi *et al.*, 2010) is captured when tried to capture the bait. In the case of the metiers of the artisanal tuna fisheries at the BoB, although both rely on surface fishing gears facilitating the access to baited hooks, the capture rate and the potential risk were lower compared to other gears, e.g., longline (Bugoni *et al.*, 2008b; Anderson *et al.*, 2011; Bi *et al.*, 2021) or gillnets (Hatch *et al.*, 2016). Furthermore, it is noteworthy that although capture rates of both metiers are low, the risk posed by baitboats (LHP) are lower than the risk posed by trollers (LTL) (R = 2.70 and 3.12, respectively). In the case of baitboats, shearwaters are frightened away by the movement of the lines but in the case of trollers, the risk of bycatch or collision is higher due to the deployment of the gear 20-50 m far from the boat, preventing shearwaters from scaring movements and facilitating the plunge to the bait.

Generally, ERAEF does not generate spatially or temporally explicit risk outputs. However, the PSA applied in this work allowed to combine modelled species abundance distribution, fisheries’ VMS, and logbook data with a risk assessment framework to map the distribution of the potential risk. In accordance with the PSA plot, showing the mean potential risk for the metiers of the artisanal tuna fishery, the resulted maps revealed similar spatial patterns of moderate potential risk for both metiers, covering most of the study area. Despite that most of the cells showed moderate potential risk, in the case of LHP the maps showed scattered low potential risk areas in contrast with LTL which maps showed high potential risk areas. These high potential risk areas revealed by the PSA were located over the Armorican slope and adjacent waters being a consequence of the overlap between shearwaters and target tuna species due to search of the same trophic resources. Great shearwaters, albacore and bluefin tunas consume mainly euphausiids as well as pelagic fish, being the European anchovy and pilchard the major preys in the shelf-break areas of the BoB (Pinnegar *et al.*, 2015) and one of the main baits used by the artisanal tuna fishing fleet (Arrizabalaga *et al.*, 2003). Along the northern Armorican slope, a persistent line of upwelling induced by a deep current impinging on the edge of the continental shelf (Lavín *et al.*, 2006), enhances primary and secondary productivity leading to the aggregation of these prey items, explaining the enhanced potential risk of interaction along the area. This result is in accordance with previous studies stating that shelf-break and upwelling areas increase the likelihood of fisheries interactions, thus being recognized as high-risk bycatch areas (Jiménez *et al.*, 2014; Scales *et al.*, 2018). Overall, areas of potential risk of bycatch by the artisanal tuna fishing fleet, seems to be driven by seabirds and tuna sharing the same resources. This finding is supported by previous studies evidencing tuna-seabirds positive interactions via foraging facilitation *i.e.,* tuna species drive prey upwards making them available to surface feeding seabirds (Veit and Harrison, 2017; Miller *et al.*, 2018) as well as by the well-known behaviour of tuna fisheries using the presence of seabirds as cue to detect tuna schools (Uranga *et al.*, 2019).

The ERAEF approach applied in this study must be interpreted within the limits of the data used. Even though such analyses are attractive because of their ease of implementation, a large volume of data, both for the species and for the fisheries, *e.g.,* at-sea census, spatio-temporal bycatch distribution, demographic or VMS data, are needed to obtain an absolute risk value. In the present study, the ERAEF approach applied through a PSA was based on the best quality spatial and temporal available data. Thus, the risk obtained should be considered a relative measure of the potential risk based on precise attribute values that are reduced to a categorical scoring.

Another insight of our ERAEF approach is that susceptibility is measured as the degree of overlap between great shearwaters and fishing effort distribution. The calculation of susceptibility in this study benefits from the predicted abundance distribution maps and the VMS data instead of the use of available species habitat suitability or coarse range maps of species and fishing effort, the latter limiting accuracy of the assessments, spatially and temporally (Small *et al.*, 2013). In addition, the data collected by the fisheries observer program also allowed the calculation of susceptibility showing the importance of these data providing the highest quality data on bycatch (Lewison *et al.*, 2004). This is an important consideration in the case of widely distributed species, such as the great shearwaters, and small localized fisheries, such as the artisanal tuna fishery, since the fine spatial and temporal resolution of the data used in this work enables us to calculate the susceptibility more reliably although with some uncertainty. We acknowledge that the PSA was limited by the lack of seabird data during the whole tuna fishing season; however, this data remains the most comprehensive and up-to-date information of the BoB, providing important evidence on the bycatch potential risk of the main PET species bycaught in the artisanal tuna fishery. Given the difficulty to perform oceanographic surveys to collect seabird data, due to the logistics and costs involved, one approach to overcome this limitation might be the use of bio-logging data to identify seabird’s habitat use. Furthermore, bio-logging data makes available fine spatio-temporal information improving the understanding of marine predator-fisheries interactions (Hatch *et al.*, 2016; Bonnet-Lebrun *et al.*, 2020; Pereira *et al.*, 2021). In this regard, a key future investigation may be the combination of real-time environmental data or seasonal forecasts and seabird bio-logging data to establish spatially dynamic bycatch reduction management measures.

Lastly, we assume that the relative potential risk bycatch areas located with our approach are a measure of spatial overlap, and not necessarily seabird-fishery interactions and as such, the results presented here should be interpreted as a proxy for potential bycatch risk. Even though our results demonstrated that the artisanal tuna fishery fishing fleet operating at the BoB posed a low to moderate risk to great shearwaters the fishery should continue to be routinely monitored, with higher risk areas revised regularly based upon changes in species and fisheries effort distribution. This is particularly important for the continuation of the certification achieved by trollers and baitboats of the North Atlantic tuna artisanal fishing fleet (MSC, 2021).

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# Author contributions

IG-B was responsible for conceptualization, methodology, writing, editing and data visualization. ML was responsible for conceptualization. IG analysed the fisheries VMS and logbook data. AA assisted in the analysis of the species data. LZ and EM assist in the analysis of the fisheries VMS and logbook data. GB provided the fisheries acoustics data. AR provided the physical-oceanographic data. IO provided the fisheries bycatch data. All authors contributed to the article and approved the submitted version.

# Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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# Data availability

Seabird sightings data are available from the corresponding author upon reasonable request. VMS data underlying this article were provided by the Spanish Secretary-General for Fisheries.

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# FIGURES AND TABLES

**Table 1.** Scoring thresholds and criteria used to calculate productivity (based on the Fecundity Factor Index from Waugh *et al.*, 2012) and susceptibility (modified from Brown *et al.*, 2015) attributes.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Attribute** | **High risk (Score = 3)** | **Moderate risk (Score = 2)** | **Low risk (Score = 1)** |
| **Productivity** | Life-history strategy | Biennial breeding, multiple-egg clutches | Annual breeding, single-egg clutches | Annual breeding, multiple-egg clutches |
| Median age at first breeding | ≥7.5 years | 1.5-7.5 years | <5 years |
| **Susceptibility** | Availability | >30% overlap between fishing activity and species critical area distribution | 10-30% overlap between fishing activity and species critical area distribution | <10% overlap between fishing activity and species critical area distribution |
| Encounterability | High overlap with fishing gear | Medium overlap with fishing gear | Low overlap with fishing gear |
| Exposure | >1 (exposure in cell 10 times mean exposure or more based on species population and fishing activity) | 0 (exposure equally mean exposure) | < -1 (exposure in cell less than on tenth of mean exposure) |
| Selectivity | High potential for capture | Moderate potential for capture | Low potential for capture |
| Potential for lethal encounter | Interaction with gear likely to result in death | Interaction with gear likely to result in injury | Interaction with gear unlikely to result in injury or death |

**Table 2.** Effort, filtered effort (*i.e.* Beaufort Sea‐state ≤5, wave height ≤2 m and medium to good general conditions), number of sightings, number of individuals, mean group size of the sightings ± standard deviation and encounter rate of great shearwaters during JUVENA surveys.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Year** | **Effort (km)** | **Filtered**  **effort (km)** | **Sightings** | **Individuals** | **Mean cluster**  **size ± SD** | **Encounter rate**  **(**ind km-1**)** |
| 2013 | 2165.85 | 1555.32 | 5 | 5 | 1±0 | 0.002 |
| 2014 | 2627.23 | 1759.53 | 113 | 310 | 2.74±5.11 | 0.118 |
| 2015 | 2549.60 | 2280.87 | 56 | 221 | 3.95±9.89 | 0.087 |
| 2016 | 2285.66 | 2169.32 | 279 | 707 | 2.53±5.08 | 0.309 |
| 2017 | 2147.13 | 1724.99 | 316 | 1280 | 4.05±11.39 | 0.596 |
| 2018 | 2522.40 | 1733.55 | 183 | 813 | 4.44±14.92 | 0.322 |
| 2019 | 1646.61 | 826.90 | 2 | 2 | 1±0 | 0.001 |

**Figure 1.** Maps showing the study area (blue polygon), the line‐transect sampling and the great shearwater sightings by year during JUVENA surveys (2013-2019). Bathymetry contours indicate the 50 m isobath and the edge of the continental shelf. Geographical references mentioned in the text are shown in the first map.



**Figure 2.** Main environmental variables driving great shearwater abundance patterns characterized by means of (a) relative variable importance and (b) smoothed fits of the main covariates where the x‐axis shows the predictor variable values, the y‐axis represents the centred smooth term contribution to the model on the scale of the linear predictor and the two vertical black lines indicate the 5 and 95% quantiles interval. Interpretation of relationships outside this range should be avoided, since the smooth splines may not be reliable. Blue shaded area indicates approximate 95% confidence bounds. TEM: temperature; SAL: salinity; DistCO: Closest distance to the coastline; TEMg: Sea surface temperature gradient; BATg: Depth spatial gradient; PIL: Biomass of European pilchard.



**Figure 3.** Great shearwater spatial density predictions in the Bay of Biscay during September (2013–2019) surveys. Bathymetry contours indicate the 50 m isobath and the edge of the continental shelf.



**Figure 4.** Mean fishing effort of the artisanal tuna fishing performed during the peak period (july-september) for the period 2013-2019 by a) baitboats (LHP) and b) trollers (LTL). Bathymetry contours indicate the 50 m isobath and the edge of the continental shelf.



**Figure 5.** Productivity-Susceptibility Analysis (PSA) plot for great shearwater and the gears of the Spanish artisanal tuna fishery fishing fleet, baitboats (LHP) and trollers (LTL). The x-axis scores derived from the Fecundity Factor Index from Waugh et al. (2012) that represents productivity of the species. The y-axis score derives from attributes that influence the susceptibility of the species to impacts from the different gears. The curved lines divide the PSA plot into thirds, illustrating cut-offs for low-moderate-high relative potential risk for species.



**Figure 6**. Potential risk scores from the Productivity-Susceptibility Analysis (PSA) for the metiers of the artisanal tuna fishing fleet a) baitboats (LHP), and b) trollers (LTL) and great shearwaters during the time-series 2013-2019. Bathymetry contours indicate the 50 m isobath and the edge of the continental shelf.

**Imagen que contiene Aplicación

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# SUPPLEMENTARY MATERIAL

# A. Environmental data

**Prey descriptors**

The acoustic equipment included Simrad EK60 split-beam echosounders (Kongsberg Simrad) of 38, 120 and 200 kHz (Boyra et al., 2013). Echo-trace characteristics and catches from the fishing hauls were used to identify fish species and to determine the population size structure. Biomass values (in tonnes) per ESDU (Echo integration Sampling Distance Unit) of 0.1 nmi were obtained by multiplying the abundance in number of individuals by the mean weight (Boyra et al., 2013).

**Oceanographic descriptors**

CTD casts using a SBE25 and a SBE911 on the R/V EB and RM, respectively were used to obtain vertical profiles of temperature (TEM) and salinity (SAL) at selected stations along transects. Based on these vertical profiles, density values (or specific volume) were obtained and integrated over depth to obtain the dynamic height relative to the next vertical, following the approach described in Rubio et al. (2009). Once dynamic height was interpolated over the study area, geostrophic velocity values (GVel) were obtained (further methodological details below).

To characterise water column stability, the depth of maximum temperature gradient (DTG) was computed by adjusting the vertical profiles of TEM to a logistic function following the methodology used in Caballero et al. (2016). The inflexion point of the logistic function (determined using the maximum of its first derivative) marks out the mean depth of the most intense gradient within the thermocline. Whilst the maximum temperature gradient (MTG) was calculated using linear differences in the points adjacent to the DTG, which is an indicator of the strength of the water column stratification.

To obtain horizontal fields of TEM, SAL, dynamic height, DTG and MTG, we used the optimal statistical interpolation (OSI) scheme described in Gomis et al. (2001) in a regular 33 × 54 grid, covering all the study area with regular node distances of 0.15 × 0.15°. For TEM, SAL and dynamic heigt horizontal analyses were performed using the data from the vertical profiles at 10m.

From dynamic height interpolated fields, GVel was obtained by the first derivative between adjacent grid nodes.. The horizontal interpolated fields of all the variables were finally re-sampled with the *raster* package (Hijmans and van Etten, 2014) to match the standard grid.

An additional variable to describe horizontal TEM changes were considered as a coarse indicator of oceanographic fronts. The shallowest TEM interpolated field was used to derive the spatial gradient of sea surface temperature (SSTg) by means of a spatial moving window within an area of 3 × 3 cells (0.1 × 0.1°) as follows:

**Table A.1.** Environmental covariates used for spatial density modelling of great shearwaters in the Bay of Biscay, their units, acronyms and source. Sea surface temperature gradient is derived from interpolated temperature fields from surface to 15 m depth (i.e., from TEM). ETOPO1 (Amante and Eakins, 2009, https://www.ngdc.noaa.gov/) was used to compute all the physiographic variables.

|  |  |  |  |
| --- | --- | --- | --- |
| **Type** | **Environmental covariate** | **Acronyms** | **Source** |
| Ocean dynamic environment | Temperature (°C) | TEM | CTD casts |
| Sea surface temperature gradient | TEMg | Derived from TEM |
| Geostrophic velocity (m s−1) | GVel | Derived from TEM, SAL |
| Depth of maximum temperature gradient (m) | DTG | Derived from TEM |
| Maximum temperature gradient (°C m−1) | MTG | Derived from TEM |
| Salinity (psu) | SAL | CTD casts |
| Prey | Biomass of adults of European anchovy (t) | ANEA | Acoustic and pelagic trawls |
| Biomass of juveniles of European anchovy (t) | ANEJ |
| Biomass of European pilchard (t) | PIL |
| Physiographic | Depth (m) | BAT | ETOPO 1 |
| Depth spatial gradient | BATg | Derived from ETOPO 1 |
| Closest distance to the coastline (km) | DisCO |
| Closest distance to the shelf-break (km) | DisSB |

# B. Density surface models

**Table B.1.** Results of the best fitted detection functions as part of Distance Sampling density estimation of great shearwater. Key: type of detection function; Co-variates: environmental covariates used to perform MCDS (Multi Covariate Distance Sampling) analysis; Cramér-von Mises P: p-value of Cramer-von Mises goodness-of-fit statistics; Pa: averaged detection probability; SE Pa: standard error of detection probability; Parameters: number of parameters included in the detection function; AIC: Akaike Information Criteria, ∆ AIC: delta AIC. Selected detection function is shown in blue.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Key** | **Co-variates** | **Cramér-von Mises *P*** | **Pa** | **SE Pa** | **Parameters** | **AIC** | **∆ AIC** |
| Hazard-rate | Year + Beaufort sea-state | 0.528 | 0.284 | 0.012 | 13 | 11363.10 | 0 |
| **Hazard-rate** | **Year + Swell height categorized** | **0.554** | **0.284** | **0.012** | **11** | **11364.25** | **1.15** |
| Hazard-rate | Year + Cloud coverage categorized | 0.559 | 0.286 | 0.012 | 11 | 11368.75 | 5.65 |
| Hazard-rate | Year | 0.486 | 0.287 | 0.012 | 8 | 11368.75 | 5.65 |
| Hazard-rate | Year + Beaufort sea-state categorized | 0.588 | 0.284 | 0.012 | 10 | 11368.96 | 5.85 |
| Hazard-rate | Year + Visibility categorized | 0.487 | 0.287 | 0.012 | 9 | 11370.75 | 7.65 |
| Hazard-rate | Year + Overall detection conditions | 0.498 | 0.287 | 0.012 | 10 | 11370.87 | 7.77 |
| Hazard-rate | Year + Visibility | 0.467 | 0.288 | 0.012 | 10 | 11372.23 | 9.13 |
| Hazard-rate | Year + Cloud coverage | 0.566 | 0.285 | 0.012 | 15 | 11373.10 | 9.99 |
| Hazard-rate | Beaufort sea-state | 0.790 | 0.279 | 0.013 | 7 | 11435.76 | 72.65 |
| Hazard-rate | Swell height categorized | 0.844 | 0.279 | 0.013 | 5 | 11448.31 | 85.20 |
| Hazard-rate | General conditions | 0.841 | 0.280 | 0.013 | 4 | 11448.94 | 85.83 |
| Hazard-rate | Visibility categorized | 0.848 | 0.281 | 0.013 | 3 | 11449.91 | 86.81 |
| Hazard-rate | null | 0.830 | 0.281 | 0.013 | 2 | 11450.12 | 87.02 |
| Half-normal | null | Failed to fit | | | | | |

**Figure B.1.** Great shearwater hazard-rate detection function with no adjustment terms and year and Beaufort Sea‐state as covariates showing histogram of perpendicular distance data for the sightings and the fitted detection probability (black line) predicted by the model. Perpendicular distance was truncated at 600 m (upper plot) and q-q plot of the detection function model selected (bottom plot).

Gráfico, Histograma

Descripción generada automáticamente

Gráfico, Gráfico de líneas

Descripción generada automáticamente

**Figure B.2.** Pairwise correlation between predictor variables by means of Spearman-rank correlation coefficient. Non-significant (p-value>0.05) Spearman correlation coefficients are indicated with a cross. See Table A.1 for abbreviations.

Gráfico

Descripción generada automáticamente

# C. Artisanal tuna fishing activity

**Figure C.1.** Artisanal tuna fishing effort performed during the fishing season by year and month by baitboats (LHP; purple) and trollers (LTL; yellow). Blue shaded area shows the months select to perform the spatial bycatch risk assessment. The total fishing effort performed by baitboats (LHP; purple) and trollers (LTL; yellow) during the months select is showed.

Gráfico

Descripción generada automáticamente

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