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Identifying priority areas for spatial management of mixed fisheries using ensemble of multi-species distribution models

Diego Panzeri[1,2] | Tommaso Russo[3,4,5] | Enrico Arneri[5] | Roberto Carlucci[4,6] | Gianpiero Cossarini[1] | Igor Isajlović[7] | Svjetlana Krstulović Šifner[8] | Chiara Manfredi[4] | Francesco Masnadi[5] | Marco Reale[1] | Giuseppe Scarcella[5] | Cosimo Solidoro[1] | Maria Teresa Spedicato[9] | Nedo Vrgoč[7] | Walter Zupa[9] | Simone Libralato[1]

[1]National Institute of Oceanography and Applied Geophysics – OGS, Trieste, Italy

[2]University of Trieste, Trieste, Italy

[3]Laboratory of Experimental Ecology and Aquaculture, Department of Biology, University of Rome Tor Vergata, Rome, Italy

[4]CoNISMa, National Inter-University Consortium for Marine Sciences, Rome, Italy

[5]National Research Council, Institute for Marine Biological Resources and Biotechnology, Ancona, Italy

[6]Department of Biology, University of Bari, Bari, Italy

[7]Institute of Oceanography and Fisheries, Split, Croatia

[8]Department of Marine Studies, University of Split, Split, Croatia

[9]COISPA- Technology and Research, Bari, Italy

Correspondence
Simone Libralato, National Institute of Oceanography and Applied Geophysics – OGS, Trieste, Italy.
Email: slibralato@ogs.it

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Abstract

Spatial fisheries management is widely used to reduce overfishing, rebuild stocks, and protect biodiversity. However, the effectiveness and optimization of spatial measures depend on accurately identifying ecologically meaningful areas, which can be difficult in mixed fisheries. To apply a method generally to a range of target species, we developed an ensemble of species distribution models (e-SDM) that combines general additive models, generalized linear mixed models, random forest, and gradient-boosting machine methods in a training and testing protocol. The e-SDM was used to integrate density indices from two scientific bottom trawl surveys with the geopositional data, relevant oceanographic variables from the three-dimensional physical-biogeochemical operational model, and fishing effort from the vessel monitoring system. The determined best distributions for juveniles and adults are used to determine hot spots of aggregation based on single or multiple target species. We applied e-SDM to juvenile and adult stages of 10 marine demersal species representing 60% of the total demersal landings in the central areas of the Mediterranean Sea. Using the e-SDM results, hot spots of aggregation and grounds potentially more selective were identified for each species and for the target species group of otter trawl and beam trawl fisheries. The results confirm the ecological appropriateness of existing fishery restriction areas and support the identification of locations for new spatial management measures.

KEYWORDS
demersal fisheries, distribution modelling, essential fish habitat, fisheries management, hot spots, Mediterranean Sea

1 | INTRODUCTION

Spatial management of fisheries is considered one of the pillars to achieve a sustainable exploitation of the marine renewable resources (Grorud-Colvert et al., 2021). In the Mediterranean Sea, for example, fisheries are largely managed through effort control, and, for rebuilding overexploited stocks, current management is mostly based on technical measures on selectivity and temporal bans (Bellido et al., 2020) as well as on spatial closures (Claudet et al., 2008; Pérez-Ruzafa et al., 2017; Scarcella et al., 2014) and other effective area-based conservation measures (OECM, sensu Gurney et al., 2021). The global deal for nature suggesting protection of 30% of the Earth for contrasting global impacts (Dinerstein et al., 2019), the coherent objective of protecting 30% of the sea by 2030 (O'Leary et al., 2016), the new EU biodiversity strategy and Nature Restauration Law (EU, 2022) entail defining new locations for the establishment of fishery-restricted areas (FRA). There is a wide consensus that such restricted areas must protect essential fish habitat (EFH) such as spawning and nursery grounds (Dambrine et al., 2021; Laman et al., 2018) in order to provide the best trade-off between effects on stock status and on fisheries yield.

Fish and other marine species depend on certain habitats for their survival and reproduction. These EFH are essential for the ecological and biological requirements of the critical life stages of the fish species being exploited (STECF, 2006). Therefore, designating areas within EFH where protection and restoration measures are to be implemented can improve the effectiveness of fisheries management by improving stock status and maintain long-term sustainability of exploitation, in line with the new EU Common Fisheries Policy (CFP, EU, 2013).

CFP is largely based on the adoption of spatial measures (such as FRAs), and its main objectives include the protection of increasingly large parts of the marine environment. There is a surprising lack of metadata and analysis on the distribution of exploited species and the definition of meaningful management areas, particularly in the Mediterranean Sea (Moore et al., 2016). This lack of large-scale processing and modelling is even more striking when compared to the availability of comprehensive environmental data on the freely available Copernicus and EMODnet platforms. One of the reasons for this problem is certainly the large effort required to collect and analyse biological data in combination with other information to describe the distribution of marine species and their EFH (Spedicato et al., 2019).

1.1 | Combining data models for an ensemble of species distribution models

Abundance and biomass data over space, as obtained from scientific bottom trawl surveys, are of paramount importance for setting appropriate EFH for demersal resources (Colloca et al., 2015). However, even if standard sampling protocols are used in scientific surveys, spatial and temporal mismatches among hauls as well as changes in catchability might occur and different modelling approaches have been developed for interpolation-extrapolation of trawl survey data (Thorson et al., 2015).

In this context, the application of species distribution models (SDM) to fit spatially explicit abundance data of marine demersal species, integrating also oceanographic and effort data, has large potential to be highly informative for spatial fisheries management (Robinson et al., 2011).

SDMs are widely used to infer the potential species distribution (either as presence/absence or abundance) based on geopositional and environmental data (Brodie et al., 2020). SDMs are applied to describe single species distribution at different scales (local, regional or global), by implementing a range of methods on density (e.g., number of individuals per unit of surface), presence/absence, or biomass (Barcala et al., 2019). In the demersal fishery context, SDMs are increasingly applied to describe the distribution of exploited and vulnerable species (Lauria et al., 2017) or to develop conservation measures (Colloca et al., 2015). Reliable SDMs are essential in mapping and protecting EFH (Druon et al., 2015; Fanelli et al., 2021; Fulton et al., 2011; Grüss et al., 2014; Luan et al., 2018; Sion et al., 2019).

Various approaches are used to develop SDMs, including linear models (LM), generalized linear models (GLM), generalized linear mixed models (GLMM), generalized additive models (GAM) (Maravelias et al., 2003; Olden & Jackson, 2002), machine learning methods such as random forest (RF) or artificial neural networks (ANN) (Breiman et al., 2018). Because predicted current and future distributions may vary among models (Moullec et al., 2019; Robinson et al., 2017) and a single general model is rarely applicable to multiple species (Colloca et al., 2015), a combination of approaches may provide a solution (Jones et al., 2012). An ensemble obtained by averaging results from different approaches allows for different species-specific conditions represented by data quality, explanatory variables, and specific trawl survey coverage, and helps to go beyond species-specific approaches (Jones & Cheung, 2015; Robinson et al., 2017).

1.2 | Integrating oceanographic variables and effort in SDMs

The ensemble approach can provide the basis for generalizing the integration of trawl survey data with other variables (geoposition, oceanographic and biogeochemical drivers, fisheries drivers) in order to obtain an accurate extrapolation of the hauls' information to the whole domain under study (Ben Lamine et al., 2022). Habitat variables may also be included if they are deemed important and are available at the desired scale and resolution.

The inclusion of physical and biogeochemical oceanographic covariates (such as temperature, salinity, or primary production) can improve the capabilities of SDMs to explain trawl survey data compared to using only spatiotemporal variables (such as latitude and longitude; Panzeri, Bitetto, et al., 2021). Oceanographic variables, in fact, have direct and indirect effects on species distributions that can be detected using statistical models (Chiarini et al., 2022). Although inclusion of oceanographic covariates in SDM is based on preliminary ecological considerations (Brodie et al., 2020), subsequent assessment of their significant contribution is always required to accurately represent the data (Thorson et al., 2015).

Effective fishing effort derived from vessel monitoring systems (VMS) can be used as a proxy for mortality but requires consideration of the temporal and spatial distances between commercial fishing and relevant impacts on population abundances (Wang et al., 2021), which requires more complex considerations and approaches combining behaviour of fishermen and explicit resource dynamics at a short time resolution (Russo et al., 2019). However, in a simplified approach, yearly effort data can serve as an indicator of high fish density and therefore can be used at the same time and place as scientific hauls to drive SDM (Lauria et al., 2017).

1.3 | Beyond FRAs and single species

The precise distribution of species can provide information useful not only for identifying FRAs. In the context of fisheries managers, an accurate description of the distribution of adult and juvenile fish assists in identifying hot spots of aggregation and may ultimately help to identify areas with high adult/ juvenile ratio (Thorson et al., 2015) to inform fisheries management actions. Indeed, areas where adults but not juveniles accumulate provide valuable information for fishers as an effective tool to avoid catching undersized specimens and as a strategy to indirectly increase fishery selectivity and mitigate the socioeconomic impacts of the landing obligation (Dolder et al., 2018).

Furthermore, in contexts where mixed fisheries are dominating, such as the Mediterranean Sea, defining the management areas on the basis of a single species might be questionable because FRAs neglect non-secondary effects on other species, reducing the overall efficiency of the measures, while for strategic analyses complex ecosystem models spatially explicit can be used for disentangling the multispecies impacts of spatial measures (e.g., Couce Montero et al., 2019). The advantage of using an ensemble of SDM approaches might provide basis for a more tactical and direct application by identifying cumulative EFH for several species. In particular, an ensemble could be used to evaluate management areas grouping species in accordance with the main target gear (Dolder et al., 2018). This might further provide insights for managers as the EFH resulting from the overlap of distribution of multiple species can shed light on spatial closure set by typology of gear, possibly distinguishing also between different kind of trawlers (beam trawlers vs. otter trawlers).

1.4 | Ensemble of multi-species distribution models for supporting management

In this work, a protocol (Panzeri, Bitetto, et al., 2021; Panzeri, Libralato, et al., 2021) for training and testing an ensemble of species distribution models (e-SDM) on scientific trawl survey data was applied, by evaluating the progressive inclusion of meaningful explanatory variables. Explanatory variables used in the protocol include geopositional, physical, and biogeochemical oceanographic variables, as well as fishing effort derived from VMS data. The e-SDM is used for describing EFH for 10 demersal species in the central part of the Mediterranean Sea (Adriatic and North Western Ionian Seas) that constitute approximately 60% of the demersal landings in the area. The objective is to provide robust determination of areas that are ecologically meaningful to increase the efficacy of spatial fisheries management by identifying EFH for juveniles and adults of marine species. Areas where species-specific EFH are overlapping enable identifying priority areas for spatial management of the two main and typical mixed fisheries of the area, i.e., the bottom otter trawl and the bottom beam trawl for the sake of rebuilding multiple exploited demersal stocks. Results also provide a basis for evaluating FRAs established or under evaluation. Moreover, mapping adult-to-juvenile fish ratios can be used to improve size selectivity by directing fisheries away from small fish, consistent with overall management objectives to reduce impacts on juveniles and support sustainable fisheries management.

2 | MATERIALS AND METHODS

2.1 | Study area

The e-SDM approach was tested in the central Mediterranean Sea, namely the Geographic Sub Areas (GSA) 17–18 and 19 as defined by the GFCM (General Fisheries Commission for the Mediterranean Sea) corresponding to the Adriatic Sea and the

North Western Ionian Sea (Figure 1). This spatial domain is rich in spatial heterogeneities connected with large gradients in oceanographic drivers and climatic factors (Cushman-Roisin et al., 2001; D'Onghia et al., 2017; Grilli et al., 2020). The northern Adriatic Sea is the shallow part of the Adriatic epi-continental shelf, with a maximum depth around 70 m and a mean depth of 30 m. Its physical and biogeochemical features are strongly influenced by the runoff of important rivers including the Po. In the central part of the Adriatic Sea, a depression with a maximum depth of 260 m (Jabuka/Pomo pit) is characterized by local discontinuity in the oceanographic conditions and is defined as a large FRA since 2017 (FAO, 2022; GFCM, 2017). The southern part of the Adriatic (GSA 18) is characterized by a steep continental slope reaching depths of approximately 1250 m. The north-western Ionian Sea (GSA 19) acts as a cross-road basin connecting the Levantine basin, the Strait of Sicily, and the south Adriatic Sea, where the so-called Adriatic Deep Water (ADW) spreads into the Ionian bottom layers (Budillon et al., 2010). The Adriatic and Ionian oceanographic features are notably interlinked and are subjected to relevant decadal variability associated with reversal of the Northern Ionian Gyre (Reale et al., 2017).

The species focus of the work is the most important species exploited by the bottom trawl fishery (otter or beam trawl) in the Adriatic and western Ionian Sea (FAO, 2022) and are monitored in scientific surveys. Key commercial demersal species are European hake (*Merluccius merluccius*, Merlucciidae), Norway lobster (*Nephrops norvegicus*, Nephropidae), red mullet (*Mullus barbatus*, Mullidae), Blackbellied angler fish (*Lophius budegassa*, Lophiidae), European horse mackerel (*Trachurus trachurus*, Carangidae), and shortfin squid (*Illex coindetii*, Ommastrephidae). In deeper areas (depth > 200 m) of the Southern Adriatic and North Western Ionian, the deep-water rose shrimp (*Parapenaeus longirostris*, Penaeidae) is also among the main commercial targets of otter trawlers. Common sole (*Solea solea*, Soleidae), mantis shrimp (*Squilla mantis*, Squillidae) and common cuttlefish (*Sepia officinalis*, Sepiidae) are extremely important for the fisheries economy of northern Adriatic Sea where the vast shallow

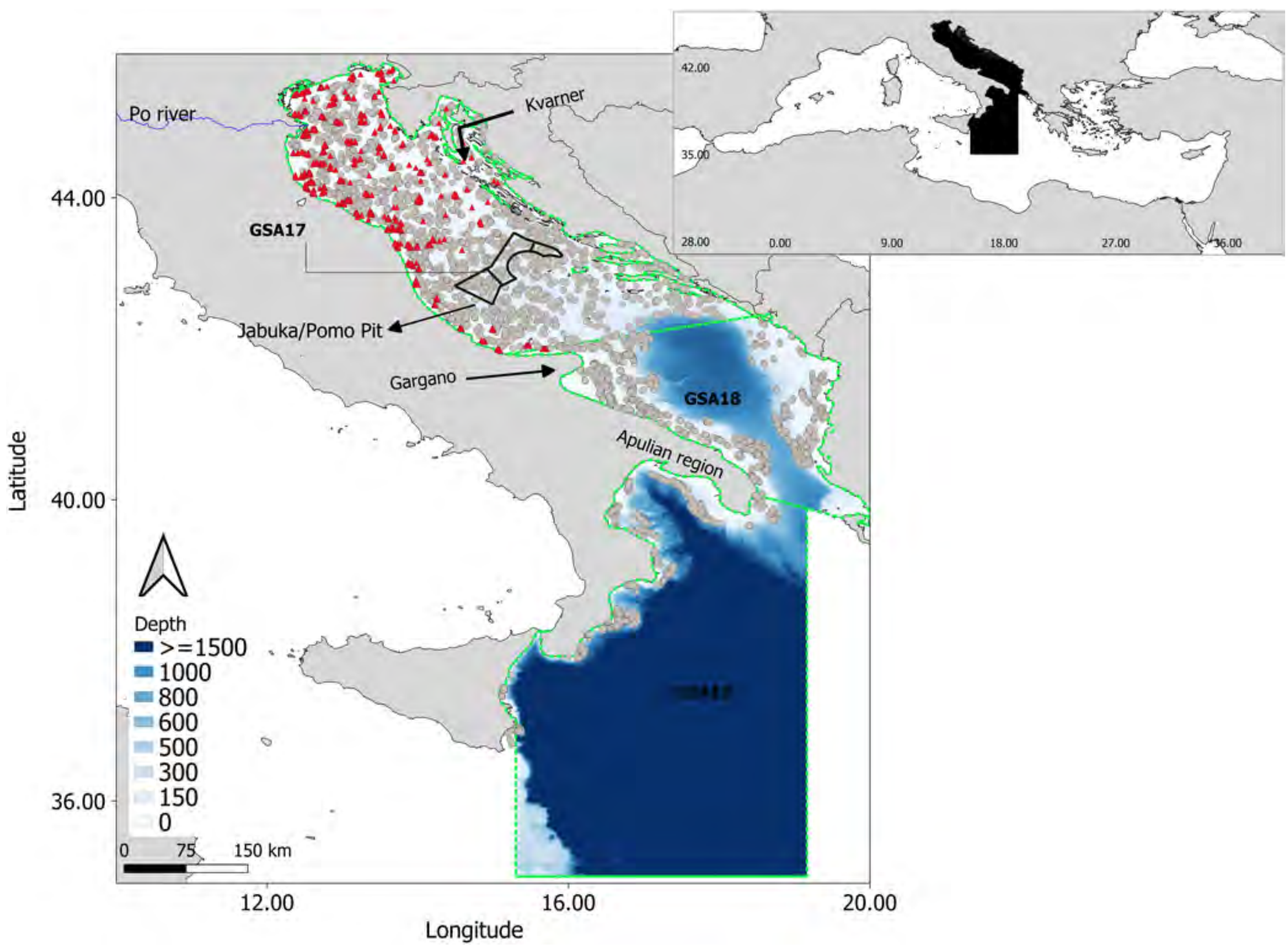

FIGURE 1 The study area of the Adriatic and north-western Ionian Sea covering the GSAs (Geographical Sub Areas) 17–18–19 (delimited by green dotted lines) with bathymetric layers up to 2000 m. Position of hauls for MEDITS (grey dots, years 1999–2018) and SOLEMON (red squares, years 2005–2018) trawl surveys are shown. Main geographical features and countries surrounding the domain are indicated, i.e., Italy (ITA), Slovenia (SVN), Croatia (HRV), Bosnia-Herzegovina (BIH), Montenegro (MNE), Albania (ALB). The map also reports established FRAs (solid black lines) according to FAO (2022).

trawlable area is exploited by different towed gears including the beam trawl (Pranovi et al., 2000). These species constitute ~60% of the total demersal fish landings in the GSAs 17, 18, and 19. Although the exploitation status of these 10 demersal species is evolving positively, many of them are still overexploited and the Regional Fisheries Management Organization (i.e., the GFCM) is envisaging the determination of new actions to include in the next multiannual plans, including spatial management areas (FAO, 2022).

2.2 | Input data

2.2.1 | Trawl survey data

Indices of demersal species density (number of individuals for unit of area or n/km^2) by haul for the years 2008–2018 were retrieved from the MEDITS (Mediterranean International Trawl Survey; Spedicato et al., 2019) bottom otter trawl (OTB) and from SOLEMON (Sole Monitoring; Grati et al., 2013; Scarcella et al., 2014) beam trawl (TBB) surveys. Both scientific surveys use standardized gears with small mesh size (codend stretched mesh size is 20 and 26 mm for MEDITS and SOLEMON, respectively) to capture also smaller specimens (Carpentieri et al., 2020).

The dataset consisted of an average 326 MEDITS hauls per year, mainly conducted in summer, in the GSA 17–19 and an average of 70 SOLEMON hauls per year, mainly conducted in winter, in GSA 17. Both scientific surveys are conducted independently of spatial management measures in force or modified over time and carried intrinsic uncertainty that is seldom quantified (Coro et al., 2022). By considering the efficiency of gear in catching each species, MEDITS trawl survey data were used for European hake, red mullet, angler fish, European horse mackerel, Norway lobster, deep-water rose shrimp and shortfin squid, while SOLEMON data were used for common sole, mantis shrimp, and common cuttlefish. Adult and juvenile densities were considered separately using a species-specific cut-off size based on the biological information reported in Table 1.

2.2.2 | Oceanographic variables

Physical and biogeochemical variables for the Adriatic Sea and North Western Ionian were extracted from two databases covering the Mediterranean Sea and available within the Copernicus Marine Environment Monitoring Service (CMEMS, https://marine.copernicus.eu/access-data). The datasets are the results of the integration of modelled and satellite data through advanced assimilation techniques (reanalysis) and cover the period 1999–2021 with an horizontal resolution of 1/16° and 72 uneven vertical levels (Cossarini et al., 2021; Simoncelli et al., 2019). These data are available with information on their uncertainty, which is specific for each variable. The variables considered in this work were sea surface temperature (°C, TMP_sst), sea bottom temperature (TMP_bot, °C), dissolved oxygen (mmol/m^3) at the bottom and surface (dox_bot and dox_sur respectively), water column concentration averages of nitrate (nit, mmol/m^3), phosphate (pho, in mmol/m^3), chlorophyll-a (chl, mg/m^3), particulate organic carbon (poc, mg/m^3), and pH, as well as surface salinity. These variables were included because of their effects on physiological processes (e.g., TMP_bot, dox_bot, pH), their ecological importance as proxies for favourable coastal conditions for juvenile fish (e.g., nit, pho, salinity), and as proxies for feeding areas also for adult fish (TMP_sst, chl). Oceanographic variables were used considering previous similar analyses for the selected demersal species (Ben Lamine et al., 2022; Bitetto et al., 2019; Carlucci et al., 2018; Chiarini et al., 2022; Coro et al., 2022; Mérigot et al., 2019; Panzeri, Bitetto, et al., 2021; Schickele et al., 2021). Additional information on sediment type (grain size) was considered for common sole, cuttlefish, and mantis shrimp due to the availability of data connected to TBB surveys. Conversely, although important for other OTB species such as Norway lobster, grain size was not considered due to lack of available data (Chiarini et al., 2022).

2.2.3 | Effort data

Effort of commercial trawl surveys was estimated for 2008–2018 by integrating Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data. The disaggregated VMS and AIS data include vessel-specific "pings" with information on vessel identity, position, speed over ground, and course. The VMS and AIS datasets were merged at the level of individual Italian and Croatian flagship vessels using the VMSbase platform (Russo et al., 2016). Fishing trips were then interpolated and gear positions (i.e., hauls) were separated from other non-fishing behaviours (steaming, resting, etc.; see Russo et al., 2014, 2016 for more details). Fishing effort was estimated per vessel/cell for bottom otter trawls (OTB) and beam trawls (TBB) and expressed as total trawling time (in hours) per year with a spatial resolution of 1/16 of degree. Effort was used as a proxy for species density so that effort at the same location and in the same year of each haul served as an explanatory variable (see also Panzeri, Libralato, et al., 2021).

2.3 | The ensemble of SDM (e-SDM)

The e-SDM was developed by applying 5 different individual models.

1. The generalized additive models (GAM, Hastie & Tibshirani, 1990) with delta approach (hereafter GAM-DELTA) were implemented in two steps: (i) a binomial occurrence model was used to fit presence/absence data (binomial family error distribution logit link function), (ii) distribution model with identity link function (with Gaussian family) on transformed densities for presence-only data. GAM-DELTA are considered highly opportune for zero-inflated data (Thorson et al., 2021), which is often the case for trawl survey data.

TABLE 1 Demersal species considered in the analysis.

Species	Common name	Presence/absence (*n* = 3934 MEDITS; *n* = 773 SOLEMON)	Size class limit (cm)	Source
Merluccius merluccius	European hake	Adults = 59%/41% juveniles = 52%/48%	24 TL	Flamigni (1983)
Mullus barbatus	Red mullet	Adults = 44%/56% juveniles = 44%/56%	9–10 TL	Jukić and Piccinetti (1981)
Nephrops norvegicus	Norway lobster	Adults = 27%/73 juveniles = 20%/80%	2.5 CL	Froglia and Gramitto (1988)
Parapenaeus longirostris	Deep-water rose shrimp	Adults = 40%/60% juveniles = 31%/69%	1.5 CL	https://www.faoadriamed.org/html/Species
Lophius budegassa	Blackbellied angler fish	Adults = 21%/79% juveniles = 25%/75%	33 TL	Jardas (1985) and Carlucci et al. (2009)
Illex coindetii	Shortfin squid	Adults = 34%/66% juveniles = 50%/50%	15 ML	https://www.faoadriamed.org/html/Species
Trachurus trachurus	European horse mackerel	Adults = 27%/73% juveniles = 41%59%	14 TL	https://www.faoadriamed.org/html/Species
Solea solea	Common sole	Adults = 73%/27% juveniles = 90%/10%	19 TL	Colloca et al. (2015)
Squilla mantis	Mantis shrimp	Adults = 57%/43% juveniles = 59%/41%	2.5 CL	Colella et al. (2016)
Sepia officinalis	Cuttlefish	Adults = 64%/36% juveniles = 60%/40%	10 ML	https://www.faoadriamed.org/html/Species/SepiaOfficinalis.html

Note: Number of hauls for MEDITS and SOLEMON trawl surveys and proportion of presence/absence data by species. Size class limit (threshold) used to divide adult and juvenile stages and literature source for the size class limit.
Abbreviations: CL, carapace length; ML, mantle length; TL, total length.

2. The generalized linear mixed models (GLMM), specifically developed to understand the distribution of marine species and including spatial and spatiotemporal fixed effects, were applied it considering the last update on this approach with sdmTMB implementing spatial random effects (sdm-TMB package; https://github.com/pbs-assess/sdmTMB; Anderson et al., 2022). using delta approach (hereafter GLMM-DELTA) in two steps: (i) logit link for presence/absence data and (ii) gamma function with link log on untransformed density data. For the delta approaches (GAM-DELTA and GLMM-DELTA) the final spatial distribution of species densities (in n/km^2) is obtained by multiplying the binomial and distribution model predictions in each grid point of the model's domain (Grüss et al., 2014; Lauria et al., 2017; Maunder & Punt, 2004; Punt et al., 2000).
3. GAMs applied using Tweedie (TW hereafter) probability distributions with a log link on untransformed density indices.
4. The random forest (hereafter RF, Breiman et al., 2018) was here applied with 5000 trees on log-transformed data (as log(X + 1), also in the following) for all species, with a minimum number of variables for each split equal to 1/3 of the explained variable (randomForest R package, Breiman et al., 2018). Although lacking direct ecologically interpretable parameters, the RF proved to be effective in species distribution modelling (Hao et al., 2019).
5. The gradient boosting machine method (hereafter GBM, Schapire, 2003) was also considered and 10,000 trees were applied with shrinkage of 0.01 (gbm package R, https://github.com/gbm-developers/gbm).

The e-SDM was thus developed using these 5 different individual models, i.e., GAM-DELTA, TW, RF, GBM, and GLMM-DELTA with sdmTMB implementing spatial random effects. Response variable was log density for all models except the binomial one that used presence/absence, the TW and the Gamma (GLMM-DELTA on positive data) that used untransformed density (n/km^2). Each approach used in this study has already been extensively described and discussed in several publications (Anderson et al., 2022; Evans et al., 2011; Friedman, 2001; Ridgeway, 1999). The explanatory geopositional, oceanographic, biogeochemical, and effort variables were preliminarily selected using the VIF approach (Variance Inflation Factor; Sheather, 2009) with a threshold of VIF < 5 to avoid collinearity (Orio et al., 2017; Sion et al., 2019).

For each species, life stage, and individual model (GLMM-DELTA, GAM-DELTA, TW, RF, and GBM), a forward-stepwise approach was used to select the most appropriate set of explanatory variables (see also Panzeri, Bitetto, et al., 2021). This started from minimal spatio-temporal model having UTM northing, UTM easting, depth, and year as explanatory variables (model ST in the following) to combine it with all the most meaningful additional physical, biogeochemical and fishing effort variables identified by VIF analysis (up to 10 models were tested). The forward-stepwise approach consisted of increasing the number of explanatory variables by successively adding those with high *F* statistics until obtaining the complete model with full explanatory variables by species and size (Tables S1 and S2). This protocol resulted in a set of models and approaches having different combinations of explanatory variables to select the best in representing the response variable (Panzeri, Bitetto, et al., 2021; Table S1).

2.4 | Protocol for model training and testing

Each model was subjected to a k-fold cross-validation process; thus, it was fitted on a spatial training dataset made by randomly choosing 70% of the data. The remaining 30% of records were used for testing the best-fitting of the model (Panzeri, Libralato, et al., 2021). The training and testing were repeated using 5 spatial folds each selecting randomly without replacement data from squared blocks using the BlockCV package (Valavi et al., 2019). Blocks were defined having side of approximately 36 km, equal to 6 cells of the 1/16° grid, as the best solution to reduce autocorrelation of the data and assure good spatial coverage (function cv_block_size, Valavi et al., 2019). Among the set of models having different combinations of explanatory variables, the best model (Table S1) was then selected based on measures of the model's performance, such as the explained deviance (%ED) and fitting performance (AIC, Akaike Information Criterion) of the training datasets and the mean absolute error (MAE) of the model predictions on the testing dataset (see also Panzeri, Bitetto, et al., 2021).

A regular lon-lat grid with the same resolution as the CMEMS reanalyses (1/16°) covering the study area (Figure 1) was constructed to predict the distribution of species density with the selected models (Tserpes et al., 2019). For each individual model and species stage, the performance of the best model was also evaluated using the root-mean-square error (RMSE; Figure 2 and Table S3) between model predictions and the log of original trawl data for all hauls of the period investigated. The best model for each of the 5 individual models, regardless of its RMSE, has the ability to capture some spatial patterns, and therefore, the best distribution was considered as the ensemble of all approaches (Hao et al., 2019). The e-SDM was obtained by the weighted average of the densities obtained with the 5 individual models, using the RMSE calculated on density data (log-transformed) as the weighting factor.

To assess average model bias, the differences between the survey data and the e-SDM estimates were calculated for each haul and year (i). In this way, the relative residual can be calculated as follows:

$$bias_i = \left(\frac{y_i - x_i}{x_i} \right) \quad (1)$$

where x_i is the survey data and y_i is the model prediction at the centre of the grid cell that contains the haul survey *i*. The bias values are used to develop maps by juveniles and adults of each species useful to evaluate visual model performances (Lauria et al., 2017).

To represent the uncertainty of e-SDM, we evaluate the confidence interval at 95% of the prediction in terms of log n/km^2 (Figure S6), in particular for the individual models GAM (GAM-DELTA & TW), we multiply the standard error (SE) of the grid prediction by

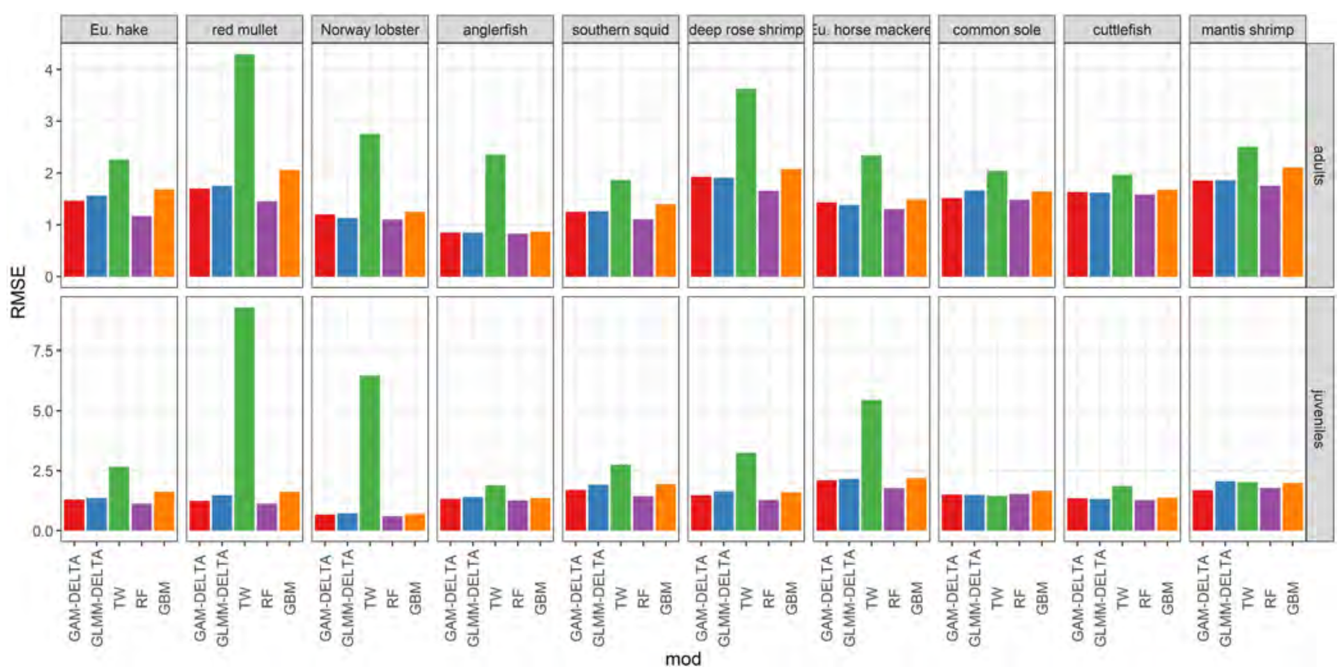

FIGURE 2 Root-mean-square error (RMSE) between log observed data and model outputs (see Table S3) of each modelling approach implemented (*x*-axis) for all species and life stage. RMSE calculated as a mean of 5-fold in *k*-fold cross-validation process. For the abbreviations in the *x*-axes see main text: GAM-DELTA, GLMM-DELTA, TW, RF, GBM.

a confidence interval of 1.96 at 95% and sum (we have it with the prediction values of Figure S6, say prediction ± SE × 1.96), while for GLMM-DELTA, RF, and GBM, we performed 500 n-simulations of the prediction and calculated the standard error and corresponding confidence interval of the n-simulation. The final uncertainty of the e-SDM is a weighted average based on the RMSE values (see previous paragraph and Table S3) of uncertainty of each model (Figure S6). Finally, we compare the mean prediction of each individual model (and relative standard deviation) and the mean observed data, representing the range of standard deviation of the observed data (red area Figure S4), including the final e-SDM model for both adults and juveniles.

2.5 | Hot spot detection

EFH for each species and stage were considered the areas of high aggregation (hot spots) and identified using the local Getis-Ord index (G^* hereafter; Getis & Ord, 1992) applied on the e-SDM prediction averaged over the years (see Figure S6). At each grid point i, the local Getis index G_i^* is positive (negative) when the density at grid point is larger (smaller) than the local average:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\left[\frac{n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}\right]}} \quad (2)$$

where x_j is the species density value for each neighbouring grid point j, $w_{i,j}$ are the spatial weights, n is equal to the total number of neighbouring grid points considered, $\overline{X}$ is the local average density and S is the standard deviation of the density. The spatial weights $w_{i,j}$ were set equal to $1/k$ where k is the number of neighbouring cells around the grid point i to be used for the spatial average. After evaluation of several alternatives (k = 4, 6, 8, 16) all of which resulting in a consistent pattern of hot spots, k = 8 was chosen as the value that allowed us to avoid the strong patchiness of results at lower k and the excessive smoothing at higher k. The hot spots were defined as those grid points with G^* values above the third quartile, and hot spots for mixed fisheries (separately for OTB and TBB) were identified as grid points defined as hot spots for multiple species. Overlapping hot spots for OTB were defined excluding red mullet because the trawl survey sampling period was considered not optimal to capture the distribution of this species. Furthermore, the difference of G^* values for adults and juveniles by each species (ΔG^*) was used to identify areas with high density of adults and low density of juveniles as potential selective fishing grounds. High values of ΔG^* indicate areas with potentially high selectivity for adults, i.e., very positive G^* adult and very negative G^* juvenile result in $\Delta G^* \gg 0$. Conversely, very negative values of ΔG^* indicate grounds where juveniles concentrate more than adults, i.e., difference between very negative G^* adult and very positive G^* juvenile result in $\Delta G^* \ll 0$. G^* differences between adults and juveniles cumulated among species allowed obtaining general maps of gradients of potential selectivity by gear as a tool for defining most and least selective fishing grounds.

3 | RESULTS

Results of the validation for each individual model (Figure S1) showed generally good performances with RMSE: excluding the Tweedie model for juveniles of Norway lobster, Eu. horse mackerel and red mullet, where the values were exceptionally high, for all other individual model and species RMSE values (Table S3) were satisfactorily ranging between 0.60 (RF for juveniles of Norway lobster) and 4.25 (TW for adults of red mullet). It is worth noting that RF, GLMM-DELTA, and GBM were performing very well for several species. In general, better performances were obtained for species as adults of anglerfish (e.g., RF = 0.82, GBM = 0.86, GLMM-DELTA = 0.84, see Table S2), or juveniles of Norway lobster (RF = 0.60, GBM = 0.69, GLMM-DELTA = 0.72).

The Variance Inflation Factor analysis resulted in non-collinearity (VIF < 5) for latitude (UTM), longitude (UTM), depth, year, bottom temperature, bottom oxygen, nitrate, phosphate, salinity, particulate organic carbon, and both OTB and TBB effort covariates for all species. For red mullet, non-collinearity was also found for surface temperature and chlorophyll-a. Table S1 shows all models and covariates chosen for each life stage and species after training and test steps (see the Supporting Information). The set of diagnostic indicators, i.e., %ED, AIC, MAE, showed that models using spatio-temporal, oceanographic, and effort variables (complete model) performed better than models including only spatio-temporal variables (Table S2). Inspecting the mean of log data and of predictions of all individual models and e-SDM (Figures S3 and S4) showed the benefit of the ensemble. The e-SDM performs better than any of the five individual models considered for European hake, Norway lobster, and red mullet (both adults and juveniles, Figure S4), cuttlefish adults and common sole juveniles. Furthermore, e-SDM had smaller dispersion of errors than any of the other model for common sole adults and juveniles. In other cases, e-SDM is performing in line with individual models (Figure S4).

Moreover, the e-SDM lack of relevant spatial patterns in bias (Figure S5), which is a quite desirable result.

3.1 | Hot spots of aggregation

The time average of G^* calculated on the e-SDM results for adults and juveniles shows hot spots of aggregation across stages and species, highlighting the EFH for each (Figures 3 and 4). The G^* for the OTB species (those better sampled by MEDITS otter trawl survey, Figure 3) shows that adults of the European hake are mainly concentrated in the eastern part of the Adriatic Sea, along the Croatian, Albanian, and Montenegrin coasts (Figure 3a). Similarly, the juveniles are located in the east-central part and along the South Adriatic Pit

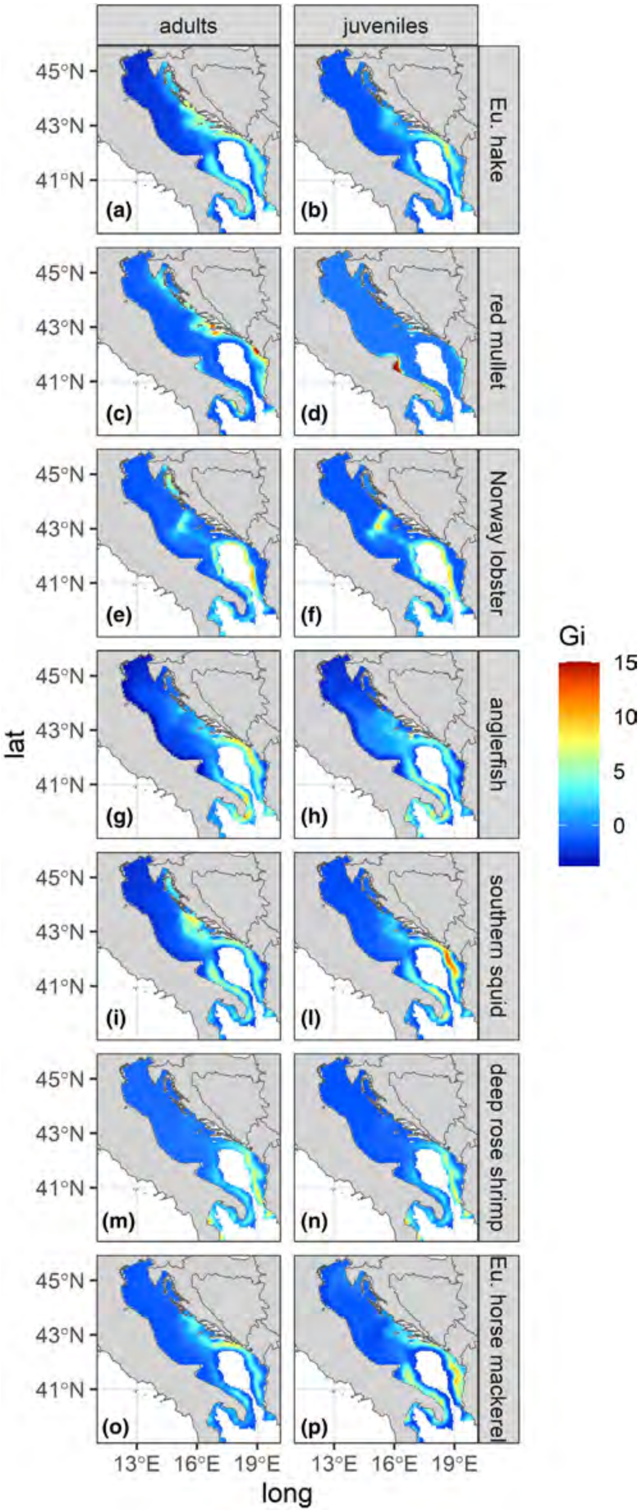

FIGURE 3 Maps of the Essential Fish Habitat (EFH) for each stage and each demersal species sampled with otter bottom trawl and investigated using MEDITS trawl survey data. EFH is identified independently for each species and stage by the high values of the Getis index (G^*), i.e., areas having G^* greater than the third quartile. Adults (left panel) and juveniles (right panel).

(Figure 3b). Adults of red mullet showed hot spots distributed in the southern Croatian and Montenegrin coast (Figure 3c) and juveniles also have hot spots in shallow areas in the North-Apulian region,

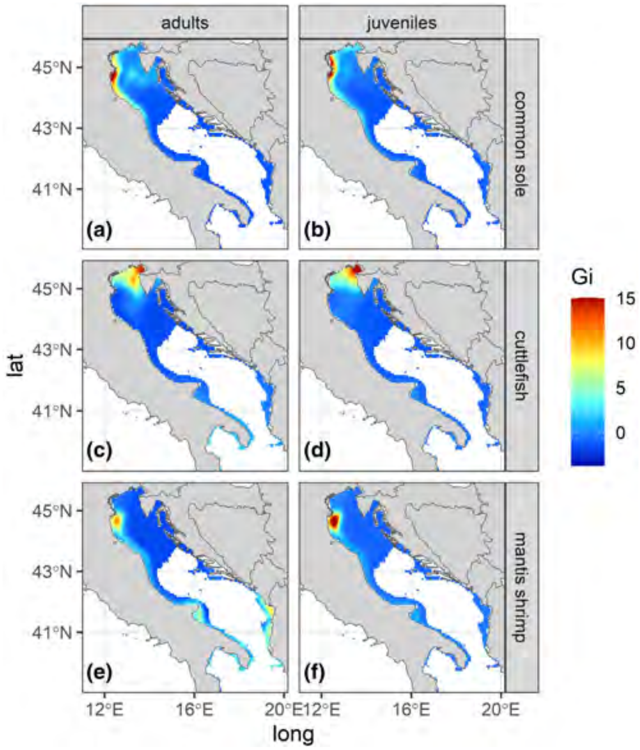

FIGURE 4 Maps of the Essential Fish Habitat (EFH) for each stage and each demersal species investigated using SOLEMON beam trawl survey data. EFH is identified independently for each species and stage by high Getis index value, i.e., areas having G^* greater than the third quartile. Adults (left panel) and juvenile (right panel).

close to the Gargano promontory, and along the Montenegrin coast (Figure 3d). Adults and juveniles of the Norway lobster show high-density areas located in the Jabuka/Pomo Pit area, in the Kvarner (Croatia) and along the South Adriatic Pit (Figure 3e,f). Both adults and juveniles of blackbellied angler fish are mainly concentrated in the eastern part of the South Adriatic Pit, along the Montenegrin coast and in the western part along the south Apulian coast (Figure 3g,h). The hot spots for the deep-water rose shrimp are located in the south part of the basin and in the western Ionian region, along the Calabrian coast (Figure 3i,l). Shortfin squid adults showed hot spots located in the Croatian coast and Kvarner island, in the east part of the basin (Figure 3m) while hot spots for juveniles are concentrated in the south part of the basin, along the Apulian region and Montenegrin coast (Figure 3n). The European horse mackerel hot spots resulted in the south-east part of the Adriatic Sea, close to the southern Croatian coast and Montenegro area, also in the west part around the South Adriatic Pit for both adults (Figure 3o) and juveniles (Figure 3p).

Areas of aggregation for adult and juvenile of the target species of beam trawlers (Figure 4) shows that adults of the Common sole are mainly concentrated in front of the Istria peninsula and northward of the Po River Delta (Figure 4a), while juveniles are especially concentrated in the southern part of the Po River Delta (Figure 4b). Both adults and juveniles of the cuttlefish have hot spots of aggregation

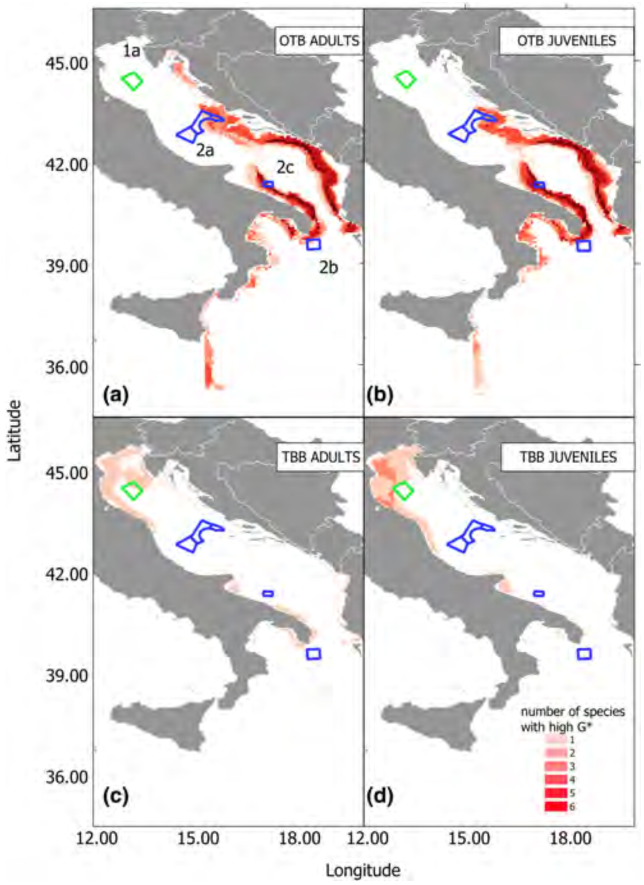

FIGURE 5 Results of overlapping Essential Fish Habitat for adults (left panels, a and c) and juveniles (right panel, b and d) for the species main targets of otter trawls (OTB, panels a and b) and beam trawlers (TBB, panels c and d). Values refer to the number of species having G^* greater than the third quartile in each grid cell. Delineated new FRAs under discussion in green (1a: Northern Adriatic Sanctuary) and already established FRA in blue (2a: Jabuka/Pomo Pit; 2b: Lophelia reef, 2c Bari Canyon).

located in front of the Istria peninsula, with highest values for juveniles (Figure 4c,d). The Mantis shrimp life stages are both mainly located in the southern zone of the Po River Delta (Figure 4e,f).

Figure 5 shows that adults of species targeted mainly by otter trawl (European hake, Norway lobster, European horse mackerel, Blackbellied angler) have common hot spots in the east part of the basin, along the Croatian and Montenegrin waters with large areas where up to 5 species share the EFH (Figure 5a). Similar areas are also common hot spots for a subset of juveniles of these species (Figure 5b). Cumulative hot spots for the groups of demersal species targeted mainly by beam trawl (Common sole, Cuttlefish and Mantis shrimp) are located in the northern Adriatic Sea: a narrow central strip in the Northern Adriatic represents an area where hot spots cumulate for the adults of these species (Figure 5c), while for juveniles (Figure 5d) the most relevant hot spots are located in front of the Po river and along the western coast, just south of it. The eastern Adriatic shores, especially in the southern Adriatic, have great potential to be EFH for adults of several OTB species (left). For juveniles, the gradients are less pronounced and highlight the importance of the Jabuka/Pomo Pit, the northern east Adriatic area influenced by the Po river as well as the Puglia region and Albanian coasts. For TBB, the areas with cumulative hot spots are those in front of the Po river for juveniles and closer to the Istria peninsula for adults.

3.2 | Potential selectivity in the fishing grounds

G^* index differences (ΔG^*) between adults and juveniles for demersal species are presented in Figure 6. Bluish areas are those with positive differences and preferred fishing grounds are indicated where the selectivity for adults of the species should be high. It can be seen how the most important area of adult (bluish colour) is located in the eastern area of the basin, especially for the MEDITS survey species, particularly for Norway lobster, European hake, red mullet, shortfin squid and European horse mackerel. For example, the Kvarner Gulf is a selective fishing ground for Norway lobster and the central-eastern Adriatic for shortfin squid, red mullet, European horse mackerel and European hake. The southern Adriatic coastal strip (both east and west) is showing high ΔG^* values and thus represents a selective fishing ground for the cuttlefish and the south Croatian and Montenegrin coasts for black-bellied angler fish. In the north-east part are highlighted important and better fishery areas for TBB target species, especially west of the Istria tip (adults of Common sole), Gulf of Trieste (juveniles of cuttlefish) and south Po River Delta (juveniles of mantis shrimp) (Figure 6).

Conversely, the areas with negative differences indicate places that should be avoided by fisheries, because the aggregation of juveniles overwhelms the aggregation of adults and thus are considered poorly selective fishing grounds (reddish areas in Figure 6). These areas include the Pomo Pit for Norway lobster, the northern-eastern Adriatic for Cuttlefish, the north-western Adriatic for Mantis shrimp, and the north strip coast of Istria for Sole (see Figure 6).

Cumulated ΔG^* for the species target of the two mixed fisheries (Figure 7) indicate large areas in the eastern part of the Adriatic Sea that should be more selective for otter trawl because they are areas where G^* for adults prevail over those for juveniles (bluish areas in Figure 7a), while the Gulf of Manfredonia, the Jabuka/Pomo Pit and the south-eastern Adriatic are areas to avoid (reddish areas Figure 7a). For beam trawl, an area in the northern Adriatic Sea, south of Istria, is identified as the more selective ones, while the Gulf of Trieste and an area off the Po river mouth should be the least selective areas (Figure 7b).

4 | DISCUSSION

A procedure combining six different spatial distribution models, trained and tested on trawl survey data, and gradually incorporating an increasing number of explanatory variables (environmental and fisheries) was successfully applied to the Adriatic Sea as a case

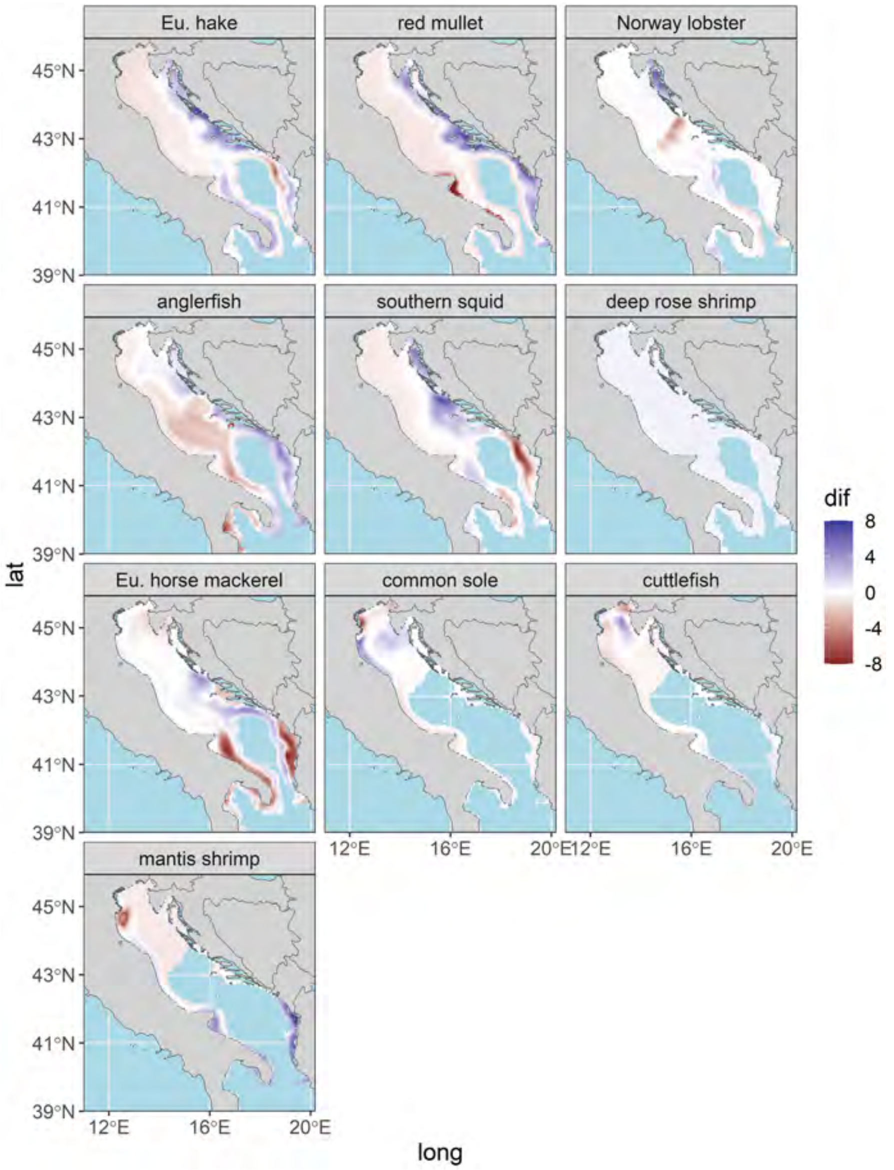

FIGURE 6 Difference (dif, dimensionless) between the index of hot spot of aggregation (G^*) for adults and juveniles by species: bluish areas indicate areas of aggregation of adults but not of juveniles and reddish areas of aggregation of juveniles but not of adults.

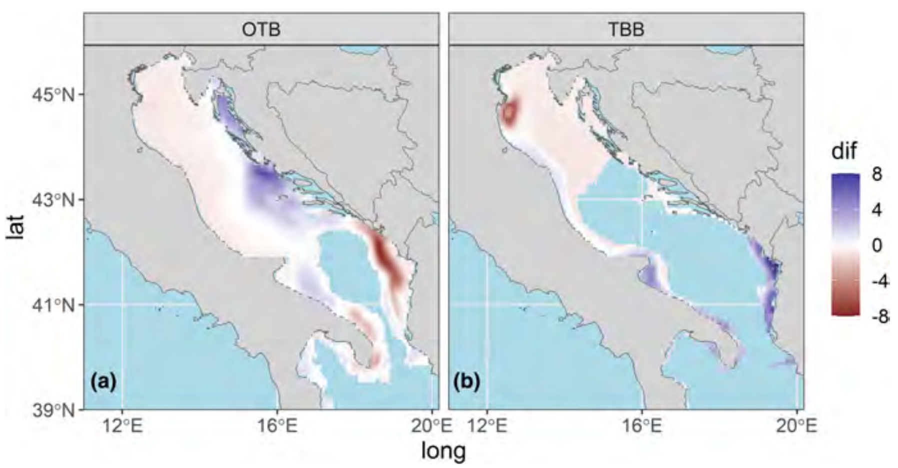

FIGURE 7 G^* differences between adults and juveniles for the species target of the two bottom trawl gears (a: OTB for MEDITS, b: TBB for SOLEMON). The darker the blue indicates areas with greater prevalence of adults and the darker the red areas with greater prevalence of juveniles.

study. The approach enabled accurate determination of the distribution of 10 demersal species and two stages (juveniles and adults), which were used to identify hotspots of aggregation and adult/juvenile ratios that support existing spatial management and provide insight into potential additional ecologically useful areas for fisheries management.

4.1 | On the application of e-SDM to demersal species

Results highlight the different capabilities of different SDM approaches in explaining the species and stages distribution. Looking at individual model performances across different species, RF, GBM, and sdmTMB are generally better both in terms of RMSE (Figure 2 and Table S3) and explained deviance (Table S2) compared to the other models. However, the ensemble of models weighted with RMSE assures robustness, good performances, and avoids distortions (Melo-Merino et al., 2020) and the e-SDM is used as an approach that can be generalized for different species and ensuring accurate distributions (Figure S4).

The e-SDM approach results into a replicable, robust and valuable protocol to define both the EFH of a single species (Figures 3 and 4), and the overlapping areas of aggregation for multiple species (Figures 5 and 6). A first result of this study is that the capacity of models to explain the survey data had a minimal but significant improvement by including oceanographic variables and effort data: such a result was consistent across models and species (Table S2). Similarly, to other attempts (Thorson et al., 2015), the improvement is not outstanding, in part because of the inherent high variability of species distribution (see also Panzeri, Libralato, et al., 2021), but this improvement has the potential to enlarge the unsampled areas where the extrapolation is reliable (Alglave et al., 2022; Meyer & Pebesma, 2021) and allow for future projections based on oceanographic climate simulations (Albouy et al., 2013).

The use of CMEMS variables allowed to improve capabilities of all individual models of the e-SDM to fit observed densities (Table S2), showing the benefits of integrating oceanographic variables into SDM (see also, Panzeri, Bitetto, et al., 2021). A close look at the partial effect of oceanographic and effort variables into individual models can be used to understand ecological processes driving distribution of stages and species (see Figures S1 and S2). For example, intermediate-high concentration of poc, low salinity, depths between 200 and 300 m resulted necessary to explain presence of adults of European hake and Deep Rose shrimp (see Figure S2), indicating their preference for productive upper slope-shelf sites with great accumulation of organic carbon. Although analogous considerations can be done for all species and stages, this would be out of the scope of the work.

Species distributions derived from e-SDM are coherent with EFH obtained in previous works (such as MEDISEH, 2013), in particular for the adult European hake, red mullet, deepwater rose shrimp, Norway lobster and shortfin squid (Colloca et al., 2015). However, as an effect of introduction of oceanographic parameters as explanatory variables, hot spot areas identified on the basis of e-SDM results showed greater continuity than hot spots identified in MEDISEH project, which were more accurate punctual and directly connected with trawl survey hauls (Colloca et al., 2015).

The results of this study confirm the importance of the Pomo/Jabuka pit area for species target of OTB, fully supporting the maintenance of the identified FRA (GFCM, 2018), especially for some life stages of the commercially important species such as European hake (adults) and Norway lobster (juveniles/adults), but also for shortfin squid (adults) (Figure 6). Furthermore, the results from e-SDM enable identifying overlapping hot spots for adults of target species of TBB in the north-east part of the Adriatic basin, close to the tip of Istria peninsula (Figure 5c), which coincides roughly with the area previously proposed and named as the "Northern Adriatic Sanctuary" (Grati et al., 2013; Scarcella et al., 2014). Nevertheless, the area west of the Istria peninsula tip and close to Po river mouth represents a poorly selective spot for the presence of juveniles, i.e., it is also an area with low ΔG^* for TBB (Figure 7b), thus suggesting the need for additional cost–benefit analyses to confirm the effectiveness of the proposed FRA in the Northern Adriatic. Furthermore, the deep areas in front of the Apulian region are also identified as hot spots, thus supportive of the argument for establishing an FRA in the Bari Canyon area (Capezzuto et al., 2018; Sion et al., 2019).

4.2 | Insights for fisheries spatial management

The hot spot results, however, suggest additional important areas that might be opportune to protect and are not under consideration at the moment. For example, the area in front of the Po River Delta which is important for juvenile stages of mantis shrimp and common sole (Figure 4) and only in part falls within the 3 NM banned to trawlers. Moreover, it is worth noting that off the southeastern coasts of the basin in front of Albania shelf there is a wide and highly important area for several demersal adult species targeted by OTB vessels (Figures 3 and 5). These resulted to be ecologically significant areas and might be considered in the future management plans as key areas for establishing spatial restrictions for fisheries.

Furthermore, contrasting adult and juvenile hot spots allows identifying the potentially most selective fishing grounds by species (Figure 6) and fisheries (OTB and TBB) (Figure 7). Maps obtained from e-SDM enable identifying areas (bluish) with high potential for catching adults while avoiding juveniles (thus increasing selectivity of the fisheries operations). Conversely, areas where juveniles are predominant (dark red) are thus areas where fisheries should be avoided both for the low presence of adults and high presence of juveniles, with a potentially large proportion of catches subjected to landing obligation (Celić et al., 2018). Figure 7 shows that areas with high adult and low juvenile density (bluish coloured) for otter trawl targets are mainly located in the eastern part of the Adriatic Sea. These locations are the most suitable and possibly profitable for OTB under landing obligation regime, while the western part of the Adriatic basin might be avoided for the high density of undersize specimens. For TBB, a central area in front of the Po river proved less selective, i.e., where more juveniles are aggregating (Figure 7b). Thus, although the main large areas of aggregation confirm previous results (Colloca et al., 2015), our results in terms of EFH highlight the relevant role of the southern and eastern Adriatic Sea as relevant OTB fisheries management areas both for overlapping hot spots (Figure 5a,b) and for the prevalence of adults (Figure 7a). In general, the approach implemented here might support optimization of the processes for establishing new spatial management measures that include FRAs, marine protected areas or other installations (e.g., offshore wind farms) that might influence distribution of fisheries. Results might be used to optimize the trade-offs between the increasing pressure for protecting marine biodiversity urged by the EU 2030 strategy (EU, 2022), the need for improving the state of commercial stocks (FAO, 2022), the calls for rebuilding fisheries welfare (EU, 2013) and the foreseen increase of maritime activities (Van Hoey et al., 2021).

It is worth noting, however, that the spatial definition of FRA and other spatial measures should consider additional aspects that go beyond the biologically significant areas as identified in this work. For example, it may be necessary to model non-target species as part of comprehensive spatial management to identify fishing grounds that allow exploitation with lower bycatch (Liu et al., 2018). Furthermore, for a full evaluation of best management areas also social and economic impacts should be considered, as well as effects of redistribution of effort (Russo et al., 2014) and indirect ecological impacts induced by setting spatial fisheries restrictions (Walters et al., 1999). Identified EFH and areas potentially with high selectivity might be areas where to focus analyses in order to establish optimal spatial management measures as foreseen by the Multiannual Management Plans (EU, 2019). Therefore, the identification of areas of overlapping EFH is just the first step for the identification of potential EFH and areas with high fishing selectivity for adults (where the adult-to-juvenile ratio is high).

Clearly, additional information on fisheries activities, costs for the implementation, control, and effectiveness, all need to be evaluated before fully establishing new management rules. For instance, trophic cascade effects of fisheries management in identified EFH and areas of high selectivity might be evaluated with complex multispecies models (e.g., EwE, Ecospace: Agnetta et al., 2019), while socio-economic effects of areas identified for management using e-SDM might be evaluated with opportune bioeconomic tools (Bitetto et al., 2019; D'Andrea et al., 2020). Such ecosystem approaches might also help in assessing if spatial fisheries management should be considered together with other measures for reducing effort in order to reach ecological and economic sustainability of fisheries. Nevertheless, the combined overlapping ecologically significant areas provide a general indication on where management actions are potentially having the best ecological efficacy on stock protection, considering the prevalence of mixed fisheries in the area, which is already an innovative and useful result for management at least in the Mediterranean sea (Alglave et al., 2022).

4.3 | Limitations and transferability of the approach

The EFH are more relevant for the species whose important aggregation phases (reproduction for adults, nursery for juveniles) coincide with the sampling period, i.e., summer for MEDITS (Tsikliras et al., 2010) and fall for SOLEMON species (Scarcella et al., 2014). Overall, ontogenetic shifts and movements are fairly well-represented for all species except *Mullus barbatus*, whose results may appear inconsistent with biological available knowledge, due to the mismatch between the survey and the maximum recruitment period (Tsikliras et al., 2010). This is why the overlapping hot spots in Figure 5 are calculated excluding the red mullet.

In addition, the selectivity of the net used in trawl surveys is a limitation to the representativeness of catches of smaller individuals or species with pelagic or benthic habits. To partially overcome this problem, we used the two different trawl surveys depending on the species' habits, but for Norway lobster, for example, the catchability of MEDITS is not considered representative (Chiarini et al., 2022), which explains the low performance of e-SDM for this species (Table S2). Similarly, the generally higher relative bias of e-SDM for juveniles (see Figures S4 and S5) should be considered a result of the lower selectivity for juveniles in the trawl survey, from which their generally lower predictability in e-SDM is derived.

The e-SDM approach allows for training and testing models with different numbers of explanatory variables that could be readily applied to identify distribution of species and possibly pinpoint the most opportune areas for fisheries management in other systems (see also Alglave et al., 2022). This should be done with caution where the coverage of scientific trawl surveys is limited: although the availability of explanatory variables allows for inferring hot spots even in areas where trawl surveys are not carried out, such extrapolation could be highly inaccurate (Meyer & Pebesma, 2021).

Application of the approach to pelagic species also seems promising (Muhling et al., 2020; Pennino et al., 2020), although it is expected that the high intra- and inter-annual variability, connected to recruitment, would increase the uncertainty of the e-SDM estimates. Furthermore, although the considerable movements of these species might decrease the reliability of annual or average maps of hot spots, the use of the e-SDM approach and hot spot detection focusing on key months might contribute to informing management also for the small pelagic spatial planning. Future developments of e-SDM need anyway to include full assessment of uncertainty of estimates, for example through reiterated applications to subsets of the data (see for example Coro et al., 2022).

The spatial resolution of 1/16 of degree used is quite good for a basin-wide analysis but further analyses might be done at a higher resolution to better identify local EFH, also considering recent advancements in the CMEMS products (Cossarini et al., 2021; Escudier et al., 2021) and the larger spatio-temporal coverage of effort data. Increasing coverage of effort data by fleets and countries (e.g., Albania) is expected to result in minor improvement of the accuracy of results, even at local scale, because very limited trawling capacity is missing from current analysis. Conversely, the approach might be improved by including variables representing benthic habitats (or other bottom features, e.g., rugosity), which can help increase the accuracy of the e-SDM and improve the definition of effective areas for fisheries management especially for some benthic species like

Norway lobster. Although inclusion of oceanographic variables in the e-SDM approach helps tracing densities and distributions to a specific month, future approaches should target high frequency and all-year-round data coming, for example, from the combined used of logbooks and VMS/AIS data.

Furthermore, the inclusion of oceanographic parameters in the e-SDM allows for future considerations of management areas in the context of climate change (Thorson et al., 2015). For instance, an e-SDM implementation based on projections of oceanographic data for different emission scenarios (Representative Concentration Pathway or RCP4.5 o RCP8.5; Reale et al., 2022; Taylor et al., 2012) could be an opportunity to understand the potential future changes of the area of aggregation or the centre of gravity for the analysed species. Furthermore, considering that environmental variables are the most important drivers for species distribution, these kinds of models and approach helps avoiding the distortion due to the geoposition of survey, that is impossible to prevent or extrapolate. This work has improved spatial resolution of SDM and is based on a longer time series than previous analyses (Colloca et al., 2015), and it has the potential to set the basis taking into account climate changes in future EFH and thus in fisheries spatial management.

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DATA AVAILABILITY STATEMENT

Raw trawl survey data and Vessel Monitoring system can be requested to the Ministry of Agriculture of Italy and Croatia. Oceanographic variables used in this work are available at Copernicus Marine Service (https://marine.copernicus.eu/it). All treated data are available at the project FAIRSEA platform (https://fairsea.inkode.it/#/login) and access can be requested from the corresponding author. Distribution maps of demersal species, hot spots of aggregation, and optimal fishing ground maps are available as dataset in Zenodo (https://zenodo.org) at the following DOI: 10.5281/zenodo.8383750.

ORCID

Diego Panzeri https://orcid.org/0000-0002-4267-4906
Simone Libralato https://orcid.org/0000-0001-8112-1274

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SUPPORTING INFORMATION

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