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PRIMARY RESEARCH PAPER

Can we gain new knowledge from the discarded fraction of the low-price commercial species of the bottom trawl fishery? An insight into the Eastern Mediterranean (Aegean Sea, Greece)

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Abstract In the Mediterranean, one of the main reasons for discarding commercial species is when fishers catch fish smaller than the minimum conservation reference size (MCRS). In reality though, other drivers that vary by country/region have greater impact on the discarding process. A notable illustration of the coexistence of different motives is the Greek bottom trawl fishery. Present work focused on the spatial analysis of discards of three commercial species subjected to MCRS with low market price and often discarded independent of their size (i.e., *Trachurus trachurus*, *Parapenaeus longirostris*, *Sardina pilchardus*). To model and map the spatial distribution of species discards, hierarchical Bayesian spatial models were utilized employing discards dependence on environmental inputs. Further information was gained, by calculating the spatial overlap between the spatial distribution of species discards and their known nurseries. Results showed that *S. pilchardus* discards had the highest estimated values in shallower waters, whereas *T. trachurus* and *P. longirostris* discards were distributed over greater depths. Only a small portion of species nurseries and discard grounds coincided, verifying that the reasons behind discarding were market-driven. Area-specific and species-specific management is essential to reduce discards, since local market demand and fishing restrictions have an impact on the discarding process.

Keywords Discards · Bottom trawl · Spatial analysis · Environmental parameters · R-INLA

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Introduction

Discards is an issue frequently tackled in the last decade, addressing mainly the estimation of discarded quantities, the species composition, and the reasons behind discarding (Bellido et al., 2011;

Catchpole et al., 2014; Tsagarakis et al., 2014; Gamaza et al., 2020). The spatial aspect of discards has also attracted increasing interest, as the implementation of any spatial management of discards needs an understanding of biological processes and knowledge of fishing conditions at a defined spatial scale (Bellido et al., 2019). In European waters, a number of studies have focused on the spatial distribution of discards and/or the determination of areas with high density of discards (e.g., Pennino et al., 2014, 2017; Vilela & Bellido, 2015; Calderwood et al., 2020; Gamaza et al., 2020). In Greek waters, studies on the spatial distribution of discards have focused mostly on total discards, groups of commercial species, and discards of non-commercial species (Maeda et al., 2017; Maina et al., 2018; Despoti et al., 2020, 2021), whereas, for the commercial species, there is no spatial analysis at species level.

In the Mediterranean waters, one of the main reasons for discarding commercial species is when fishers catch fish smaller than the minimum conservation reference size (MCRS; Damalas et al., 2015; Milisenda et al., 2017). Avoiding catching juvenile fish and protecting nursery grounds appears to be the key way to reduce discards of species subjected to MCRS. Thus, efforts have focused on improving gear selectivity (e.g., Massutí et al., 2009; Gamaza et al., 2015, 2018; Guijarro et al., 2017; Lucchetti et al., 2021), identifying sensitive habitats for protection (e.g., nursery grounds; Colloca et al., 2015; Druon et al., 2015) and areas with undersized catch (e.g., Milisenda et al., 2021). Even though, all these efforts can indeed contribute to discards reduction, they are not adequate to prevent unwanted catch, because in practice, some of the species subjected to MCRS are discarded also for other reasons, involving market demand and national fishing restrictions that play key role among countries and regions. Especially for commercial species with low market price, factors like market demand and/or the lack of space onboard rather than regulations may have the greatest influence (Tsagarakis et al., 2014). In European Union waters, variability in discard rates has been found to be greater between regions than between fisheries (Uhlmann et al., 2014). Particularly, in the Mediterranean Sea, discard rates of trawlers are lower in the eastern and southern part of the basin, related to communities' welfare, with wealthier societies being more selective in the use of fisheries resources (Tsagarakis et al., 2014).

A notable illustration of the coexistence of different motives behind discarding that cooperate synergistically is the Aegean Sea (Fig. 1) bottom trawl fishery. The present work focused on modeling the spatial distribution of discards of three species that present an important contribution to the Greek bottom trawl discards of the commercial species, i.e., the Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), the deep-water rose shrimp *Parapenaeus longirostris* (Lucas, 1846), and the European pilchard *Sardina pilchardus* (Walbaum, 1792). Deep-water rose shrimp is targeted by the bottom trawlers (Stergiou et al., 2003; Tserpes et al., 2016), whereas Atlantic horse mackerel and European pilchard are bycatch. All three are commercial species subjected to MCRS but with a low price that depends on market demand. On top the often-limited available onboard space can lead to both undersized and non-undersized individuals of all three species to end up in the discarded catch. Moreover, although not typically targeted by bottom trawlers, European pilchard schools are found, during the day, in proximity to the seabed in shallow waters (Giannoulaki et al., 1999) and can easily be caught by the bottom trawls. In this case, the catch can be damaged or of bad quality due to its small and slender body and subsequently being unsuitable for commercial use.

In this context, the aim was to identify the three species' discards spatial patterns and examine to what extent their discard grounds coincide with their known nursery grounds. Thus, hierarchical Bayesian spatial models (HBMs) were applied to discards data from the Aegean bottom trawl fishery along with satellite environmental data incorporating also the effect of spatial autocorrelation. The derived models were used to identify links between environmental variables and discards, and subsequently, applied over the Aegean Sea to map the estimated spatial distribution of discards of the three species. Next, the spatial overlap between potential areas with high discard values and nursery grounds was estimated.

Materials and methods

Study area: fishery information

The bottom trawl fishery in the Aegean Sea (Eastern Mediterranean) is a typical multi-species fishery

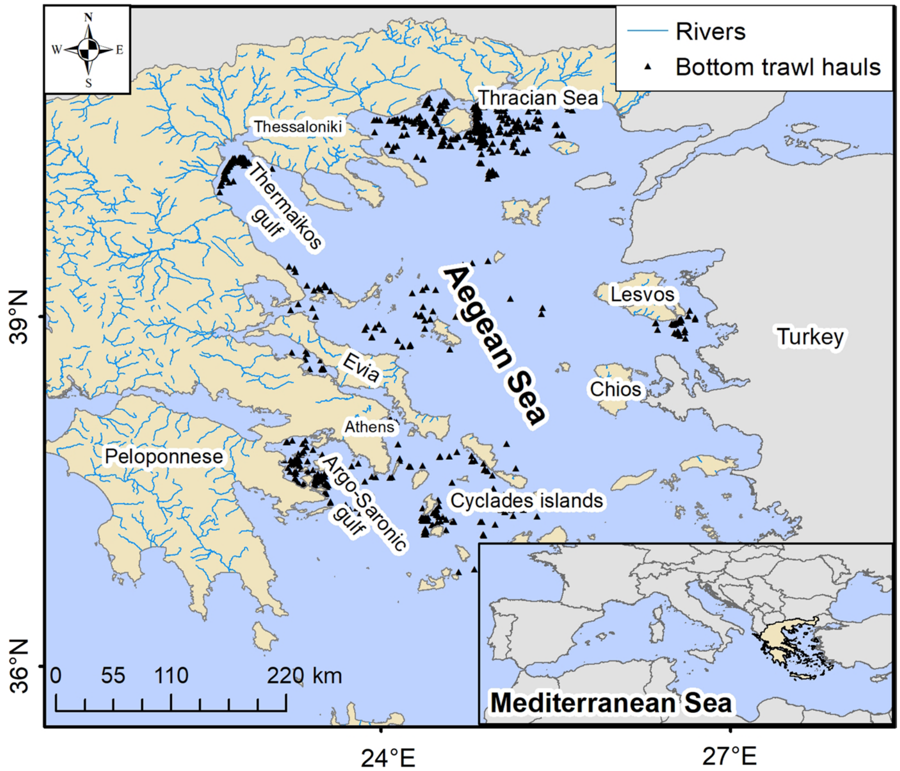


Fig. 1 Location map and sampling station (haul) positions collected by observers on board commercial bottom trawlers in the Aegean Sea (Greece, Eastern Mediterranean Sea)

(Stergiou et al., 2003; Tserpes et al., 2016). In 2020, the trawl fleet consisted of ~ 200 vessels, with landings around 12,700 tonnes (Anonymous, 2021). The largest part of the fishing effort (76% of total fishing effort) is recorded within the continental shelf (Kavadas & Maina, 2012; Maina et al., 2016) and mainly at depths from 50 to 300 m. There is a general prohibition on bottom trawls for water depth less than 50 m (EC, 2006) as well as a temporal prohibition from the 1st of June to the 30th of September (4 months) in Greek national waters since the late 1960s (Royal Decree 917/1966). The main target species of the fishery are European hake *Merluccius merluccius* (Linnaeus, 1758), red mullet *Mullus barbatus* (Linnaeus, 1758), musky octopus *Eledone* spp., common octopus *Octopus vulgaris* (Cuvier, 1797), and deep-water rose shrimp (Stergiou et al., 2003). These species made up the 48% of total landings per day (Stergiou et al., 2003; Tserpes et al., 2016).

Fisheries data

Fisheries data were collected by observers on board commercial bottom trawlers operating in the Aegean Sea (Greece, Eastern Mediterranean) under the European Union Fisheries Data Collection Regulation (DCR; EC, 2001) and the Data Collection Framework (DCF; EC, 2008). In total, 831 hauls were sampled during 2003–2006, 2008, and 2013–2014 (Fig. 1; Appendix: Table S1). Onboard commercial data despite any shortcomings (e.g., gaps in the data collection in 2007, 2009–2012), it is the best available information regarding catch and discards (Suuronen & Gilman, 2019). Data covered three seasons (autumn, winter, spring). The lack of data for the summer was due to a national prohibition for bottom trawling in Greek waters from the 1st of June to the 30th of September since the late 1960s (Royal Decree 917/1966). For each haul, the following information was recorded: date and time of sampling, coordinates (longitude, latitude), bottom depth, haul duration, and catch composition. Catch was divided into landings and discards by the crew of the vessel. Next, the discarded catch was sorted and identified at species level by the observers. The biomass of each species was standardized as kilograms per hour (kg/h) in each haul. Three low-price commercial species were selected for the analysis, namely, Atlantic horse mackerel, deep-water rose shrimp, and European pilchard. These species hold an important proportion of the bottom trawl's discarded part of the species subjected to MCRS (~29% Atlantic horse mackerel, ~24% deep-water rose shrimp, ~7% European pilchard based on discards per unit effort as kg/h; Appendix: Tables S1–S2) representing different reasons for discarding.

Modeling approach and explanatory variables

HBMs were applied to identify variables that could be related to species discards (in kg/h) and to map their spatial distribution. One of the advantages of HBMs is that they can better cope with data having a spatial dependency structure (Zuur et al., 2017a). Analysis was performed using the package "R-INLA" (www.r-inla.org) in R (R version 4.2.3; R Core Team, 2023). "R-INLA" implements the integrated nested Laplace approximation (INLA) method introduced by Rue et al. (2009) in order to provide accurate approximations of the posterior distributions of the model parameters in a less time-consuming and faster computational way than Markov Chain Monte Carlo simulation (Lindgren and Rue, 2015).

The initial dataset was divided into training and validation subsets. Specifically, 573 hauls were used to train the models, whereas 258 hauls were used to assess the predictive performance of the models. Both training and validation datasets were selected to cover evenly the spatial and temporal distribution of the hauls. The explanatory variables used in the analysis were satellite environmental variables, bottom depth (the recorded bottom depth of the haul; natural log-transformed), season, vessel horse power (kW; fleet register), and vessel capacity (in gross tonnage, GT; fleet register). Vessel variables, especially capacity, are considered as factors that could influence discards since they can limit the storage of fishing products (Rochet & Trenkel, 2005).

The satellite environmental variables were Sea Surface Chlorophyll [CHL in mg/m^3 (natural log-transformed); oceancolor.gsfc.nasa.gov], Particulate Organic Carbon [POC in mg/m^3 (natural log-transformed); oceancolor.gsfc.nasa.gov], Sea Level Anomaly (SLA in cm; www.aviso.altimetry.fr), Sea Surface Temperature (SST in °C, oceancolor.gsfc.nasa.gov) and Sea Surface Salinity (SAL in psu; marine.copernicus.eu). At each haul location, the monthly estimate of the environmental variables was retrieved at the best available resolution provided by the online satellite data distribution archives. This resulted in an average spatial resolution of ~4 km, adequately defining environmental spatial heterogeneity and the best available resolution of the explanatory environmental variables (Valavanis et al., 2008). Spatial models based on environmental variables are used to identify species ecological niche, to detect environmental variables, directly or not, related to species spatial distribution, and to predict species spatial distribution on unsampled areas (e.g., Moore et al., 2009; Martin et al., 2012; Pennino et al., 2013; Colloca et al., 2015; Lauria et al., 2015; Paradinas et al., 2015; Maina et al., 2016; Giannoulaki et al., 2017). Lately, they have also been used to predict and map the spatial distribution of discards (e.g., Pennino et al., 2014; Paradinas et al., 2016; Maeda et al., 2017; Maina et al., 2018). Moreover, climatic and environmental fluctuations have been found linked to discards variability of specific fish species in western Mediterranean Sea (Carbonell et al., 2018). Even though, the links between discards and environmental variables are not direct, environmental variables can serve as proxies which reflect the environmental characteristics of an area that favor the presence, abundance and population structure of a species or a group of species. In turn, the high abundance of a species or a group of species in a given area could result in high quantities of discards, especially if the species is not commercial or of low commercial value.

As bottom depth and environmental parameters showed a non-linear relationship with species discards, each of these explanatory variables was introduced in the models as a smoother. In order to build models with smoothers and consequently to have Generalized Additive Models using "R-INLA", the methodology of Zuur et al. (2017b) was followed. For each of the above-mentioned explanatory parameters, a cubic regression spline was defined using the "mgcv" package in R (R Core Team, 2020). Then, the smoother was used as an explanatory variable in the model.

A spatial random effect was also included in the models, which accounts for the residual spatial structure (spatial autocorrelation) that cannot be explained by the included explanatory variables. Including the spatial dependency in the inferential process provides additional insight knowledge and avoids biases in the estimations (Blangiardo & Cameletti, 2015). Due to the existence of physical barriers (i.e., islands, coastline) in our study area, a non-stationary spatial random effect was included in the models that takes into account the effect of physical barriers based on the methodology (i.e., the Barrier model) developed by Bakka et al. (2019). In "R-INLA", spatial dependency is implemented with the stochastic partial differential equation (SPDE) approach introduced by Lindgren et al. (2011). SPDE approach approximates a Gaussian field with a Matérn covariance function to a Gaussian Markov random field (Blangiardo & Cameletti, 2015). However, based on this model, the spatial dependency between two points relies on the "shortest distance" which is the shortest Euclidean distance between them (Bakka et al., 2019). The Barrier model (Bakka et al., 2019; Martínez-Minaya et al., 2019) re-parametrize the SPDE in order the spatial dependency between two points to rely on all the paths that exist between them, weakens the dependency almost to zero for the paths crossing the barrier area and then calculates the new "shortest distance" as an indirect result of the new collection of available paths (Bakka et al., 2019; Martínez-Minaya et al., 2019).

The construction of the spatial random field is based on the triangulation of the spatial domain resulting in a mesh. For the construction of the mesh, as input information about the spatial domain was used the polygon of the present study area, i.e., the Aegean Sea (Fig. 2). The spatial random effect depends on two hyperparameters the range (r) and the standard deviation (σ_u). Based on the approximation presented by Bakka et al. (2019) the range in the barrier area (r_b) (here is the land) is forced to be close to zero.

In Bayesian inference, parameters are treated as random variables and prior distributions are assigned for each parameter. In the present work, the default uninformative prior distributions of "R-INLA" were used for the fixed effects (i.e., a Gaussian distribution with mean equals to 0 and precision equals to 100). For the hyperparameters of the spatial random effect, the median of the prior range (r) was set to 30×10^3 (the extension of the area in meters) and the median for the standard deviation (σ_u) to 0.5.

Due to the presence of a large number of zeros in the data (zero-inflated continuous data), the modeling approach included two stages: (i) a presence–absence model and (ii) a given-presence model, according to the methodology of Zuur et al. (2017b). Zero inflation was ~32% for Atlantic horse mackerel (185 hauls with zero catch out of 573 hauls), ~38% for deep-water rose shrimp (211 hauls with zero catch out of 573 hauls), and ~71% for European pilchard (408 hauls with zero catch out of 573 hauls).

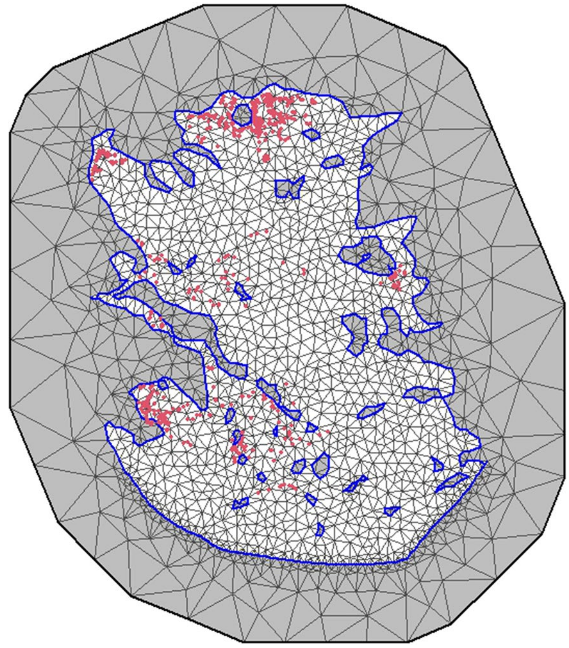


Fig. 2 The triangulation of the Aegean Sea. Grey area represents the land (i.e., the physical barrier). Red dots present the haul positions of the commercial bottom trawlers. Blue line represents the borders of study area

For the presence–absence model, data were divided into 1 and 0 for hauls with and without species discards, respectively, and modeled using a Bernoulli error distribution. The presence–absence model based on Zuur et al. (2017b) was defined as:

$$\text{Discards}_i^{01} \sim \text{Bernoulli}(\pi_i),$$

$$E(\text{Discards}_i^{01}) = \pi_i \text{ and } \sigma(\text{Discards}_i^{01}) = \pi_i * (1 - \pi_i),$$

$$\log(\pi_i) = \alpha * X_i + v_i,$$

where π_i is the probability of discards at the location i, α is the vector of the regression coefficients, X_i is the vector of the explanatory variables at location i, and v_i is the spatial random effect at location i.

For the given-presence model, only hauls with discards data were used and modeled using a Gamma error distribution. The given-presence model based on Zuur et al. (2017b) was defined as:

$$\text{Discards}_i^{>0} \sim \text{Gamma}(\mu_i, r),$$

$$\text{E}(\text{Discards}_i^{>0}) = \mu_i \text{ and } \sigma(\text{Discards}_i^{>0}) = \mu_i^{>0}/r,$$

$$\log(\mu_i) = \beta * M_i + \upsilon_i,$$

where μ_i is discards (in kg/h) at the location i, β is the vector of the regression coefficients, M_i is the vector of the explanatory variables at location i, and υ_i is the spatial random effect at location i. For the final predicted maps ("Mapping species discards distribution" section), the π_i and the μ_i at each location i were multiplied to have the final estimation of discards at each location i.

Only the explanatory variables that their 95% credible interval did not include zero were kept in the models as significant variables. The minimization of the deviance information criterion (DIC); Spiegelhalter et al., 2002), the Watanabe information criterion (WAIC; Watanabe, 2010) and the mean logarithmic of conditional predictive ordinate (LCPO; Gneiting & Raftery, 2007) led to the selection of the final model that better fitted the response variable.

Mapping species discards distribution

Taking the advantage of the availability of satellite environmental data over large areas, the final selected models were applied over a wider grid of mean monthly satellite environmental values at an average spatial resolution of ~4 km, covering the Aegean Sea from 30 to 600 m to predict discards of the three species. In cases that vessel variables (e.g., vessel capacity) entered the final model, a mean estimate of the available vessel data for the entire Aegean Sea was used to make predictions.

Monthly maps presenting the spatial distribution of discards of the three studied species (in kg/h) were constructed for the years 2005 to 2014 (10 years). For practical purposes, a single representative month for each season was used for prediction: October for autumn, January for winter, and April for spring. Finally, the average maps (from all three seasons and the period 2005–2014) were estimated at each grid point. Mapping was performed using the ArcGIS (ESRI, 2015).

Model validation

The final models were applied to the validation dataset to evaluate their predictive performance. The predictive performance of the presence–absence models was assessed using the area under the receiver-operating characteristic curve (AUC) estimated with the "PresenceAbsence" package in R (R Core Team, 2023). Whereas, the predictive performance of the given-presence models was assessed using the Pearson's r correlation coefficient.

Identification of annual hot-spot of discards and persistent areas of discards

Following the mapping over the wider Aegean Sea, hot spot analysis was applied to the mean annual maps of discards of each species to identify the annual density hot-spots. The Hot Spot Analysis (Getis-Ord Gi*) tool in ArcGIS (ESRI, 2015) which identifies statistically significant spatial clusters of high (hot-spots) and low (cold-spots) values (Getis & Ord, 1992), was used for the spatial hot-spot identification. Z-score, P-value, and confidence level Gi_Bin (that identifies statistically significant hot and cold spots) were estimated. The Getis-Ord G* statistic with a radius of 10 km and a 0.95 significance level (+/−2 bins) was selected to identify and locate spatial clusters of significantly higher discards. Thus, as "hot-spot" was classified an area with confidence level bin field (Gi_Bin) ≥ 2.

In a next step, in order to identify persistent hot-spot areas of discards through the years, the Index of Persistence (PI; Fiorentino et al., 2003; Colloca et al., 2009) was calculated. This index was obtained as a ratio of the number of years a given area was classified as a hot-spot to the total number of years according to the formula:

$$\text{PI}_i = 100 * \frac{1}{n} \sum_{j=1}^{n} \delta_{ij},$$

where $\delta_{ij} = 1$ when a grid cell i is included as a discard hot-spot in year j and $\delta_{ij} = 0$ otherwise, and n is the number of years. The PI decreases to zero when discard hot-spots have never been observed, while it increases to 100% when discard hot-spots occur year-by-year throughout the time series. Finally, areas presenting PI > 50% were considered indicative of medium to high persistency of discards, forming discard persistent hot spots.

Spatial overlap of discards with nursery grounds

For each species, the spatial overlap between the discard persistent hot-spots and the nursery grounds was estimated. The nursery grounds used in the analysis have been estimated within the MEDISEH (Mediterranean Sensitive Habitats) project based on GAMs and presence/absence approach for European pilchard and Atlantic horse mackerel (Giannoulaki et al., 2011, 2013a) and a COZIGAM model for deep-water rose shrimp (Colloca et al., 2013, 2015). For Atlantic horse mackerel and European pilchard, nursery maps involved (i) preferential nursery sites: areas with mean probability > 0.5 and low standard deviation values, (ii) occasional nursery sites: areas with mean probability > 0.5 and high standard deviation values (Giannoulaki et al., 2013b). Preferential and occasional sites were considered indicative of medium to high persistency and used to estimate the overlap with the discard persistent hot-spots (Giannoulaki et al., 2013a). For deep-water rose shrimp, nursery maps involved a persistence index ranging from 0 to 100% (Colloca et al., 2013). Similarly to the choices made for European pilchard and Atlantic horse mackerel, persistent index values > 20% were considered indicative of medium to high persistency, used to estimate the overlap with the discard persistent hot-spots.

The spatial overlap was estimated as the ratio of the extent of the cross-sectional area between the nursery grounds and the discard persistent hot-spots to the total area of the discard persistent hot-spots. All shapefiles used to estimate the spatial overlap were projected to the Lambert Azimuthal Equal Area projection coordinate reference system (ETRS_1989_LAEA). The spatial overlap was estimated using the "Tabulate Area" tool of ArcGIS (ESRI, 2015).

Results

Modeling species discards

The final presence–absence model of Atlantic horse mackerel included bottom depth, CHL, SST, and the spatial random effect (Table 1). Higher probability of discards' occurrence was estimated at depth 70–150 m and at colder waters (SST lower than 15°C) with CHL values lower than 0.45 mg/m^3 (Fig. 3). The final given-presence model included bottom depth, CHL, and the spatial random effect (Table 1) with higher values of discards estimated at depth 80–200 m and waters with CHL values ranging from 0.17 to 0.37 mg/m^3 (Fig. 3).

The final presence–absence model of deep-water rose shrimp included bottom depth, CHL, SLA, and the spatial random effect (Table 1). Higher probability of discards' occurrence was estimated at depths deeper than 150 m, CHL values lower than 0.37 mg/m^3, and SLA values ranging from 0 to 7.5 cm (Fig. 3). The final given-presence model included bottom depth, SLA, SST, and the spatial random effect (Table 1). Higher values of discards were estimated at a depth range of 70–200 m, waters with SST ranging from 15 to 17.5°C, and negative values of SLA indicating slight upwelling processes (0 to − 8 cm, Fig. 3).

The final presence–absence model of European pilchard included bottom depth, CHL, SST, and the spatial random effect (Table 1). Higher probability of discards occurrence was estimated at depths shallower than 90 m, when SLA values were 10–15 cm and at waters with SST ranging from 12.5 to 17.5°C (Fig. 2). The final given-presence model included bottom depth, SLA, GT, and the spatial random effect (Table 1). Higher values of discards were estimated at shallower depths (less than 70 m) and at waters with downwelling processes (SLA values ranging from 5 to 12.5 cm) (Fig. 3). Also, higher values of discards were estimated when vessel capacity (GT) was larger (posterior mean = 0.008; 95% CI = 0.0003–0.014).

Detailed model results for the final models are presented in the Appendix (Tables S3–S14).

Mapping species discards distribution

Mean maps indicated that the discards of European pilchard were located over the continental shelf at shallower waters and inside gulfs (Fig. 4). Contrary, discards of deep-water rose shrimp were more broadly distributed at deeper waters (Fig. 4). For Atlantic horse mackerel, discards were also more broadly distributed at deeper waters with higher

Table 1 Model comparison of final models with and without spatial random effect

Dependent variable	Response distribution	Explanatory variables	*n*	DIC	WAIC	LCPO
Trachurus trachurus						
Presence–absence model						
Presence, Absence	Bernoulli	*f*(DEPTH) + *f*(CHL) + *f*(SST) + *u*	566	572.2	574.1	− 0.507
		f(DEPTH) + *f*(CHL) + *f*(SST)	566	662.1	662.4	− 0.585
Given-presence model						
Discards (kg/h)	Gamma	*f*(DEPTH) + *f*(CHL) + *u*	381	804.0	808.6	− 1.109
		f(DEPTH) + *f*(CHL)	381	844.2	847.2	− 1.288
Parapenaeus longirostris						
Presence–absence model						
Presence, Absence	Bernoulli	*f*(DEPTH) + *f*(CHL) + *f*(SLA) + *u*	560	514.3	515.8	− 0.461
		f(DEPTH) + *f*(CHL) + *f*(SLA)	560	676.3	678.3	− 0.606
Given-presence model						
Discards (kg/h)	Gamma	*f*(DEPTH) + *f*(SST) + *f*(SLA) + *u*	349	506.3	520.1	− 1.227
		f(DEPTH) + *f*(SST) + *f*(SLA)	349	583.3	589.0	− 1.051
Sardina pilchardus						
Presence–absence model						
Presence, Absence	Bernoulli	*f*(DEPTH) + *f*(SST) + *f*(SLA) + *u*	573	391.4	393.0	− 0.344
		f(DEPTH) + *f*(SST) + *f*(SLA)	573	423.7	424.5	− 0.371
Given-presence model						
Discards (kg/h)	Gamma	*f*(DEPTH) + *f*(SLA) + GT + *u*	165	136.1	143.8	− 0.752
		f(DEPTH) + *f*(SLA) + GT	165	168.2	174.2	− 0.754

DEPTH natural log-transformed bottom depth (in m), *CHL* natural log-transformed sea surface chlorophyll concentration (in mg/m^3), *SST* sea surface temperature (in °C), *SLA* sea level anomaly (in cm), *GT* vessel capacity (in gross tonnage), *u* spatial random effect. Among species, differences in the number of observations (*n*) used for the presence–absence models are due to exclusion of outliers from the initial dataset ($n = 573$)

values of discards located at central and southern Aegean Sea compared to its northern part (Fig. 4).

Figure 5 displays the posterior mean and the standard deviation of the spatial random effect for all models. For Atlantic horse mackerel, for the presence–absence model, two hot-spots were detected at central and southern Aegean, implying higher probability of discards presence whereas for the given-presence model a hot-spot was observed between Greek mainland and Evia Island (Fig. 5), indicating higher discard quantities in this area. For deep-water rose shrimp, for the presence–absence model, a hot-spot was observed at northern Aegean Sea, whereas for the given-presence model, hot-spots were more widespread, with one observed at northern Aegean Sea, one at southern Aegean Sea at Argo-Saronic Gulf and few smaller ones in between (Fig. 5). Finally, for the European pilchard, for the presence–absence model, three hot-spots were observed, one to the northeast at Thracian Sea, one to central-east between Lesvos, Chios Islands, and the Turkish coasts, and one to the southern part of the Aegean Sea at Cyclades Islands; for the given-presence model two hot-spots were observed, one at Argo-Saronic Gulf and one between Lesvos, Chios Islands and the Turkish mainland (Fig. 5).

Model validation

For all final presence–absence models, AUC values ranged from 0.75 to 0.93 (i.e., 0.75 for Atlantic horse mackerel model, 0.82 for deep-water rose shrimp model, 0.93 for European pilchard model) indicating good model performance.

For all final given-presence models the Pearson's *r* correlation coefficient showed a significant positive correlation between the recorded and the predicted values ranging from 0.53 to 0.64 (i.e., 0.55 for Atlantic horse mackerel model, 0.53 for deep-water rose shrimp model, 0.64 for European pilchard model) indicating moderate model performance.

Spatial overlap of species discards with species nursery grounds

The overlapping between discard persistent hot-spots and nursery grounds varied greatly among species (Fig. 6). Specifically, for European pilchard the overlapping ratio was ~ 58%, whereas for Atlantic horse mackerel was ~ 11% and for deep-water rose shrimp was ~ 7%.

Discussion

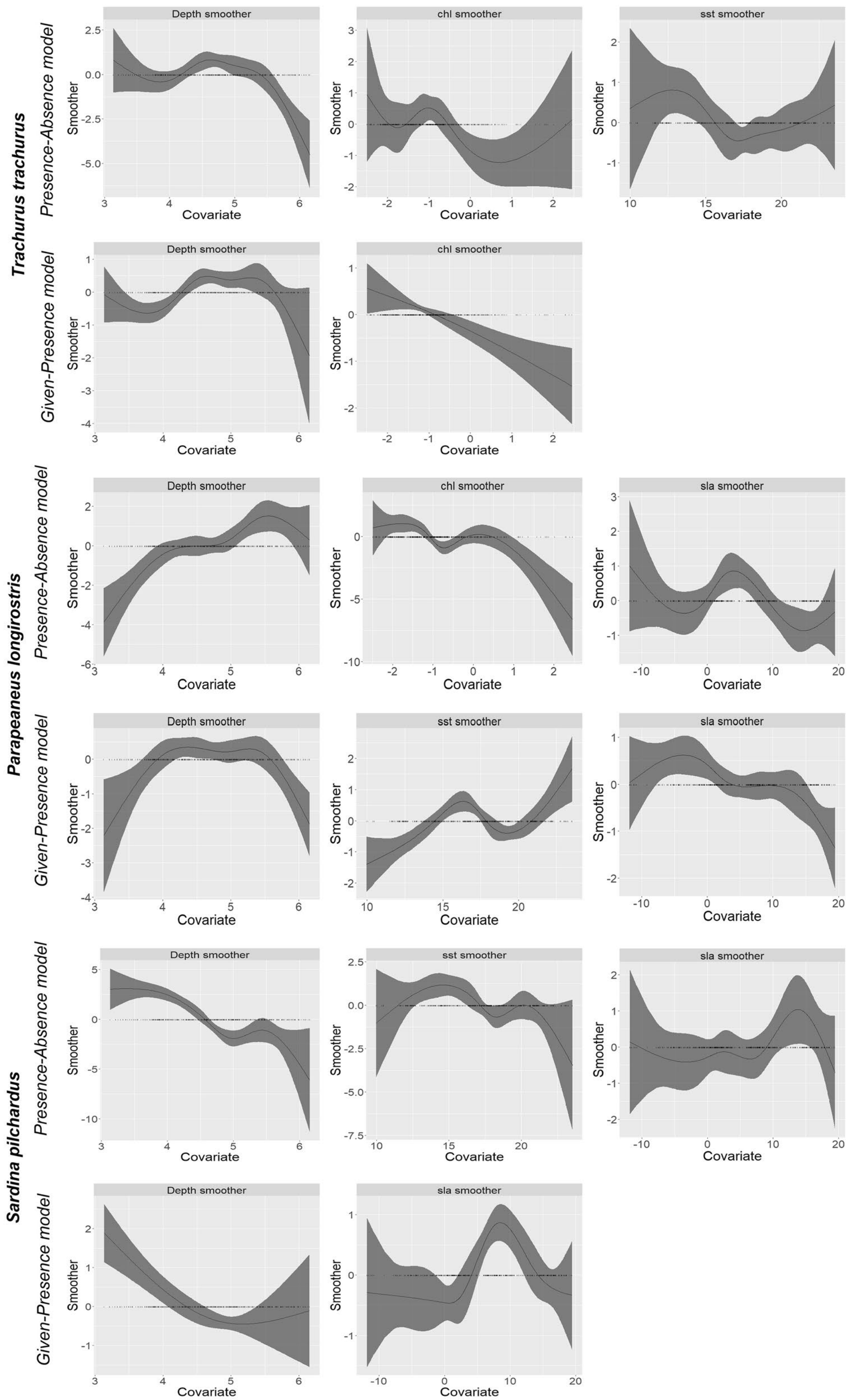
In the present work, links between environmental variables and discards of three low-price commercial species (i.e., Atlantic horse mackerel, deep-water rose shrimp, European pilchard) were identified, species discards distribution was estimated, and the overlap between species discards hot-spot areas and nursery grounds was explored.

The estimated depth range for the discards of Atlantic horse mackerel coincided with the bathymetric distribution of the species, commonly found at 100–200 m depth (Ragonese et al., 2003). Although our analysis did not allow discrimination between big and small sized individuals, we assume that the higher probability of discards biomass assessed in colder waters combined with low values of CHL, could be associated with the presence of smaller-sized individuals. Smaller-sized Atlantic horse mackerels probably end up to the discarded catch, whereas fish with larger size, even though of low price (Carbonell et al., 2018; Damalas et al., 2018), have a share in fish market. Rumolo et al. (2017) also mention that smaller-sized Atlantic horse mackerels in the Strait of Sicily, are found at deeper waters with lower values of temperature, salinity and chlorophyll in contrast to larger-sized, which are found at shallower waters with higher temperatures and salinity. This difference is ascribed to the feeding behavior of the species, which is linked to the environmental parameters favoring their prey (Rumolo et al., 2017).

Also, the market demand and subsequently the different feeding habits of the local populations are probably related with the gradual increase in Atlantic horse mackerel discards from northern to southern Aegean. At northern Aegean Sea, Atlantic horse mackerel may be preferred and consumed from the local population. Contrary, in the southern Aegean Sea (e.g., over Cyclades and Dodecanese Islands) areas where the market is largely governed by tourist traffic often resulting in greater demand for more highly priced commercial species. Communities' welfare plays role on how much and what species are discarded (Tsagarakis et al., 2014). Moreover, the fact that Atlantic horse mackerel has low price discarded at a larger length than its MCRS (e.g., Machias et al., 2004; Tsagarakis et al., 2017; Damalas et al., 2018; Despoti et al., 2020) was reflected to the extent of its discard persistent hot-spots which overlapped only for a small percentage with its known nursery grounds.

For the deep-water rose shrimp, results revealed higher probability of occurrence and higher values of discards at deeper and less productive waters. A result that reflected the environmental characteristics of the deep-water rose shrimp habitat which is mainly found at 100–400 m depth (Politou et al., 2008; Sbrana et al., 2019), waters that are often less productive (Stambler, 2014). In general, deep-water rose shrimp has a size-related bathymetric distribution with juveniles settling at the continental shelf, while larger individuals migrate to the slope (Ardizone et al., 1990; Politou et al., 2008). Also, higher quantities of deep-water rose shrimp discards were estimated at waters with SST ranging from 15 to 17.5°C. Deep-water rose shrimp is a species with a thermophilic preference presenting higher abundances in warmer waters (Abello et al. 2002; Benchoucha et al., 2008; Colloca et al., 2014). SST has been found to positively correlate to deep-water rose shrimp abundance in the Moroccan Atlantic waters (Benchoucha et al., 2008) and to the temporal trend of commercial catches in the Ligurian and North Tyrrhenian Sea (Ligas et al., 2011; Colloca et al., 2014). Sbrana et al. (2019) have also found a correlation between SST and the abundance of deep-water rose shrimp in the Mediterranean waters, with a different pattern though, highest abundances were associated with SSTs less than 14°C.

Mapping of deep-water rose shrimp discards revealed that locations with high discard values were estimated mainly within the deeper waters of the northern Aegean Sea. This area coincides with the main fishing ground (Maina et al., 2016) and the most important adult grounds of the species


Trachurus trachurus
Presence-Absence model
Given-Presence model
Parapeaneus longirostris
Presence-Absence model
Given-Presence model
Sardina pilchardus
Presence-Absence model
Given-Presence model
Depth smoother
chl smoother
sst smoother
sla smoother
Smoother
Covariate

◂**Fig. 3** Posterior mean values and 95% credible intervals (shadowed areas) of all smoothers obtained by the six final selected models. *DEPTH* natural log-transformed bottom depth (in m), *CHL* natural log-transformed sea surface chlorophyll concentration (in mg/m^3), *SST* sea surface temperature (in °C), *SLA* sea level anomaly (in cm)

(Politou et al., 2008). Also, the low estimated overlapping ratio clearly indicated that the most of discard grounds did not coincide with the main nursery grounds of the species. This result pointed out that discards of deep-water rose shrimp also included non-undersized shrimps. This should not be the case as deep-water rose shrimp is a species with commercial value. A possible explanation behind this finding is fishers' behavior in response to catch composition and in particular the total value to be landed (Gillis et al., 2008). When fishers catch a large biomass of deep-water rose shrimp, they may discard a part of it regardless of size, if they have caught more valuable fish that fetches a higher price.

Results concerning European pilchard indicated high probability of occurrence and high values of discards at shallow waters combined with low temperatures (12.5–17.5°C), and positive values of SLA (downwelling processes), when vessel capacity was larger. In Greek waters, a significant amount of information on the spatial distribution and suitable habitat of European pilchard is available both for the juveniles (Tsagarakis et al., 2008; Giannoulaki et al., 2011, 2014) and the adults (Tugores et al., 2011). European pilchard adult grounds, in early winter, are known to distribute at shallow coastal waters characterized by temperatures ranging from 14 to 17°C and slight upwelling (Tugores et al., 2011), being generally in agreement with the present findings. Results, also, revealed high percentage of overlapping between discard persistent hot-spots of European pilchard with its known nursery grounds. The high percentage of overlapping, though, did not necessarily indicate that the discarded fraction consisted mainly by undersized European pilchard. In the Aegean Sea, adult and nursery grounds of European pilchard largely overlap reflecting the fact that in the Mediterranean ecosystem favorable habitats for small pelagic species are localized (mostly driven by point sources of nutrients) and extended horizontal migrations from nurseries to spawning or feeding grounds is not the case (Giannoulaki et al., 2014). Moreover, large individuals of European pilchard could also be discarded as national fishing restrictions do not allow bottom trawls to trade high quantities of small pelagic species (i.e., European pilchard and European anchovy *Engraulis encrasicolus*) (Linnaeus, 1758) (Ministerial Decision 1519/2012). The present findings also noted the importance of vessel capacity, with high values of discards occurring upon bigger vessel capacity. Larger vessels often work far from port, operating for multi-day trips, having more expenses (at least in terms of fuel consumption) saving their valuable storage space for species allowing higher profit (Stergiou et al., 1998). In addition, as European pilchard body is very delicate and often damaged by the trawling operation itself, cannot be safely stored for days and often ends up into the discarded catch.

All things considered, results revealed that discards dependence on environmental variables and spatial distribution of discards was differentiated among the studied species. Understanding the relationships between environmental conditions and catch composition could contribute to the prevention of unwanted catches, as temporal and spatial fluctuations of biological processes such as recruitment, migration and habitat preference are linked to environment conditions and to catching unwanted fish (Carbonell et al., 2018). These environmental variations can dictate the spatial/temporal variation of discards and contribute to the identification of its spatial/temporal distribution which is essential in marine spatial planning (Dunn et al., 2011). In addition, the knowledge of the spatio/temporal patterns of discards can be utilized by fishers to amend their spatial/temporal exploitation patterns to avoid unwanted catches (Bellido et al., 2019; Calderwood et al., 2021).

Current spatial/temporal management of fisheries focuses primarily on nurseries protection by instituting seasonal and/or permanent closures to reduce mortality and discards of juvenile fish, as well as by establishing real-time closures that are associated with the appearance of juveniles in an area (Little et al., 2015; Perez Roda et al., 2019). In Greek waters, the majority of existing fisheries restricted areas are located mainly in coastal waters and were established either to protect nurseries or were based on local district decisions aiming to regulate different and often conflicting fishing activities (Petza et al., 2017). Present results, though, indicated that, for the studied species, discards grounds only partly coincided with their nurseries. Thus, protecting solely the nursery grounds, will not

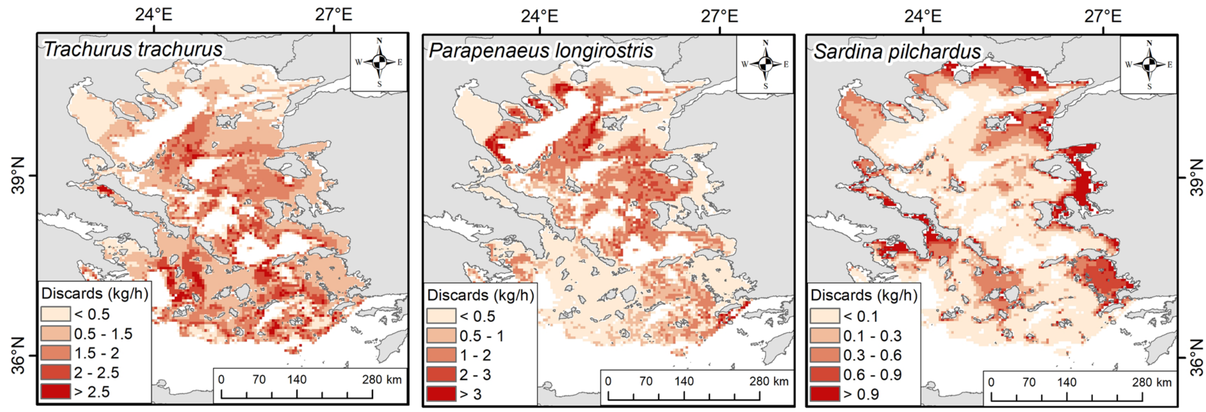


Fig. 4 Spatial distribution maps of model estimated discards (kg/h) for Atlantic horse mackerel *Trachurus trachurus*, deep-water rose shrimp *Parapenaeus longirostris*, and European pilchard *Sardina pilchardus*

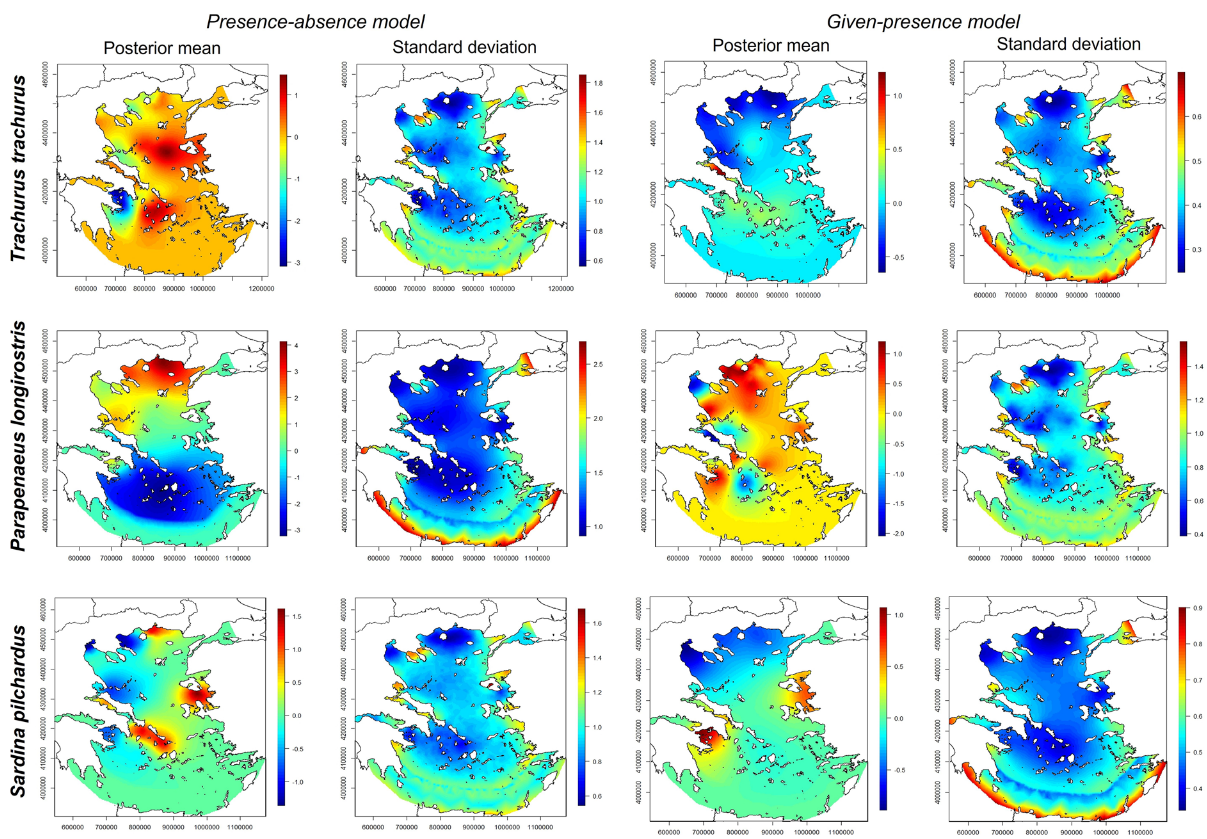


Fig. 5 Posterior mean and standard deviation of the spatial random field for the presence–absence and given-presence models for all species. Hot-spots are presented with red color, whereas cold-spots with blue

necessarily result into discards mitigation. Reduction of discards is more complicated in the study area as more than one motive coexists and act synergistically. So, it is essential to increase our knowledge of the spatial/temporal distribution of the actual discarded catch and incorporate it into the design of fisheries closures

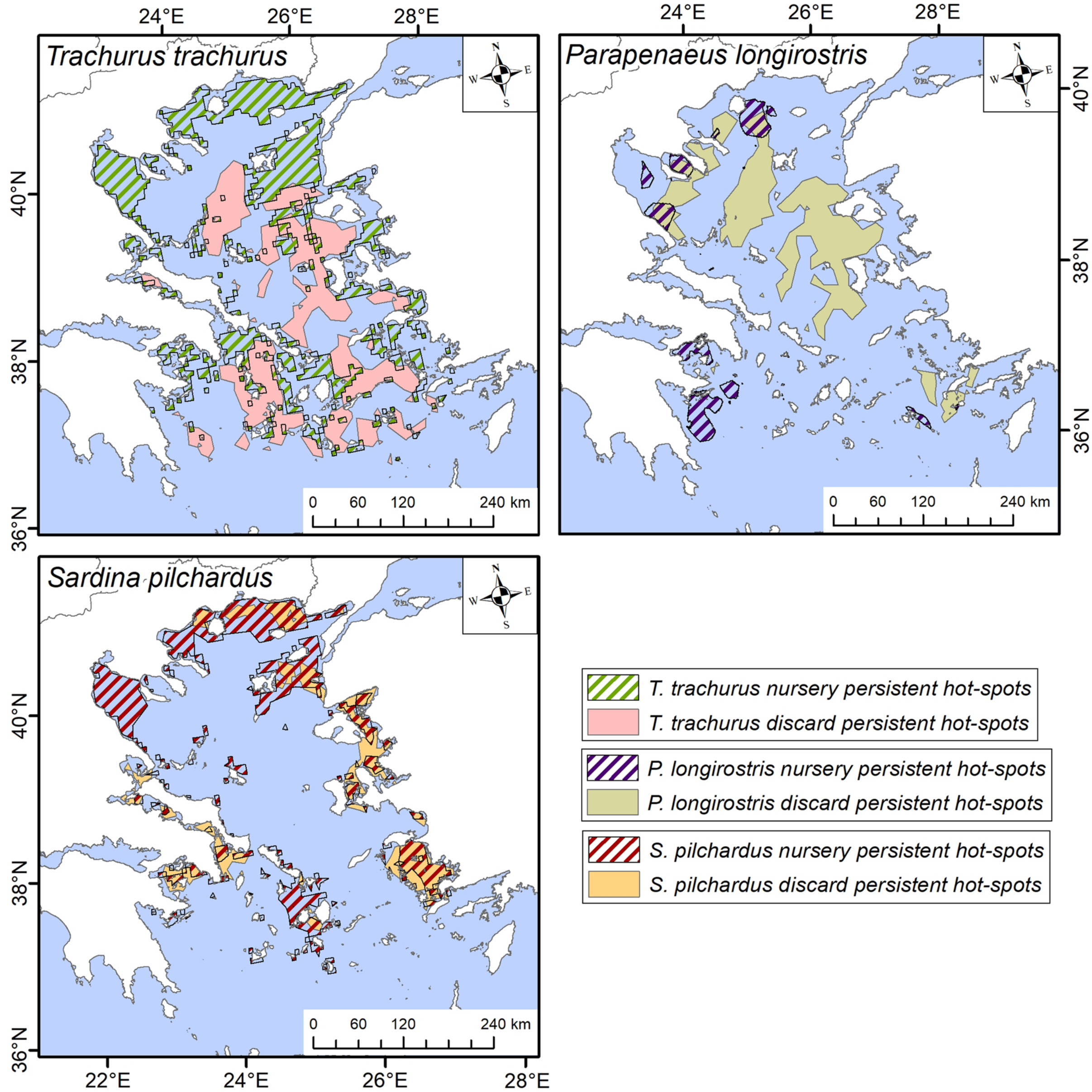


Fig. 6 Spatial overlap of nursery grounds with discard persistent hot-spots for Atlantic horse mackerel *Trachurus trachurus*, deep-water rose shrimp *Parapenaeus longirostris*, and European pilchard *Sardina pilchardus*

(Dunn et al., 2011). Nevertheless, the low overlapping among discard grounds and nurseries should also be considered in the light of certain limitations, such as the temporal differentiation between the assessed nursery and discard grounds. The nursery grounds were assessed based on survey data collected within a certain period of the year (here during summer; Colloca et al., 2013; Giannoulaki et al., 2013a, b), unlike the more extended discard grounds that were assessed using fisheries commercial data collected throughout the year.

Beyond the protection of coastal areas though, the protection of the marine environment on a larger scale is more imperative than ever within the EU Biodiversity Strategy for 2030 Framework, as it aims to protect a least of 30% of the EU's marine area by 2030 (EC, 2020). The present findings show that discards hot spots of deep-water rose shrimp and Atlantic horse mackerel were estimated in areas far from the coast. Incorporating this knowledge into spatial planning tools, such as MARXAN (Dunn et al., 2016) in conjunction with information on other species distribution and sensitive habitats can assist to the identification of key ecosystem areas. Such areas can be good candidates for protection under the framework of the EU Biodiversity Strategy for 2030 for the Greek waters.

Finally, results highlighted that fishers' behavior regarding what and how much to discard of the commercial catch does not solely depend on MCRS and can vary even over short distances in the Aegean Sea, affected by the local market demand and the local fishing restrictions. In Greek seas, horse mackerels and deep-water rose shrimp, as low-price commercial species are discarded when catch exceeds local market demand (Catchpole et al., 2014). All this makes area-specific and species-specific management imperative to reduce the discarded quantities (Uhlmann et al., 2014; Carbonell et al., 2018) in the particular fishery.

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Author contributions SD: Conceptualization, Methodology, Formal Analysis, Writing—Original Draft; KS, MG: Conceptualization, Writing—Review and Editing, Supervision; GT, VV, AA: Investigation; KT: Writing—Review and Editing; VV: Data Curation.

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Data availability The data analyzed in this study are subject to the following licenses/restrictions: environmental data can be found in freely available databases, fisheries catch data are subject to restrictions and a specific request should be addressed to DG MARE and/or DCF National correspondents. Requests to access these datasets should be directed to https://datacollection.jrc.ec.europa.eu/.

Declarations

Conflict of interest The authors declare no competing interests.

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